THE PERFORMANCE OF RAINSCREEN WALLS IN COASTAL BRITISH COLUMBIA

by

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Authors 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.

Abstract

The Performance of Rainscreen Walls in Coastal British Columbia

This thesis examines the widespread moisture problems which emerged over the past twenty years in buildings throughout coastal British Columbia, commonly known as 'leaky condos'. A literature review of building physics and a historical review of wood-frame construction in North America provide background for this review.

The purpose of this work is to report and interpret the performance of rainscreen walls in the coastal climate of Vancouver BC, based on extensive field data from five local buildings constructed or rehabilitated with rainscreen wall assemblies. Hygrothermal data was collected within exterior walls, and corresponding environmental data was recorded for each building. Driving rain loads at the five buildings across the city are calculated and compared to Vancouver airport data. Site factors are shown to have a significant impact on driving rain load, wind speed and direction.

The WUFI 4.1 hygrothermal model was compared with the field data collected and found to be accurate at predicting past performance. Applying this validated model to each wall assembly, further simulations were performed to determine the impact of boundary conditions and assembly details on wall performance.

Field measurements and modeling show that ventilated and drained claddings (i.e. rainscreen) reduce the sensitivity of wood frame buildings to moisture damage. Ventilation of the cladding is shown to be particularly important and natural buoyancy forces (from temperature and humidity differences between cavity and exterior) are usually sufficient to provide good drying. Exterior insulation is shown to further improve rainscreen wall performance by increasing the drying potential of the sheathing to both the exterior and interior.

Additional work performed included material testing of fiberglass-faced gypsum sheathing and air-leakage testing of individual suites in the monitored buildings. Elevated interior humidity, resulting from inadequate ventilation, is shown to be exacerbated by inter-zonal air-flow in multi-unit residential buildings.

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The air leakage testing component of this thesis was also a large field test undertaking which went smoothly thanks to the efforts of those involved. Foremost I would like to thank Colin Genge at Retrotec Energy Innovations for his volunteered guidance and assistance in addition to providing a van full of specialized equipment to perform the testing. I think I would be still testing the buildings right now if it weren't for Colin. To Hua Ge and Wendy Ye at BCIT, Chris Black, Matthew Mulleray, Shan Huang at RDH Building Engineering, Mark Lawton and Anik Teesdale St-Hilaire at Morrison Hershfield for assisting with the testing and providing discussion and input. In addition to all of those individuals who arranged access and the tenants of the suites for their understanding.

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EXECUTIVE SUMMARY

In the latter 1990's widespread moisture problems became apparent in newly-constructed housing stock of coastal British Columbia, particularly in Vancouver's renowned 'leaky condos'. Unlike historical moisture problems caused by cold weather diffusion or air leakage, many new failures were attributed to rain water penetration in poor water-managed face-seal or concealed barrier wall assemblies. Water infiltrated into walls via various pathways, then became trapped within the wall cavities and couldn't dry out. The resulting decay, corrosion and extensive rot required the total re-cladding of many affected buildings.

To reduce the potential for moisture damage, the municipality of Vancouver mandated drained and ventilated rainscreen wall assemblies for most new buildings, beginning in 1996. Most new buildings and many rehabilitated buildings in Vancouver and coastal areas of British Columbia are currently being built with rainscreen wall assemblies, on the premise that these assemblies are more tolerant of moisture infiltration and will limit wetting to a level which can be accommodated by the building materials.

The purpose of this thesis is to report and interpret the performance of rainscreen wall assemblies in the coastal climate of Vancouver, BC. This work is based on several years of field data collected from a large industry-sponsored project monitoring five local buildings constructed or rehabilitated with rainscreen wall assemblies. Three of those buildings are wood-frame assemblies, while two are steel-stud/gypsum frame. The monitoring project involved the collection of hygrothermal data within the exterior walls of all five buildings and the corresponding environmental data for each building. Further work supplementing the measured field data was also performed, including material testing of fiberglass faced gypsum sheathing and air leakage testing of individual suites in the monitored buildings.

A literature review of the relevant principles of building physics was performed, followed by a historical review of the development of wood-frame construction in North America, presenting the necessary background for this analysis.

Cladding ventilation plays a significant role in the performance of some rainscreen wall assemblies: recent field and laboratory research has shown that cladding ventilation has the potential to reduce wetting from absorptive claddings and sun-driven moisture. Cladding ventilation rates were calculated for the buildings studied, using applicable theories, and were found to be in the same range as previous field research. Higher ventilation rates were shown to reduce seasonal moisture contents for some of the wall assemblies evaluated.

Material testing was performed in laboratory conditions to correlate the electrical resistance of fiberglass faced gypsum sheathing with its gravimetric moisture content, and an equation was developed from these findings. The correlation was used to convert the raw electrical resistance readings collected from the two steel-stud and gypsum wall assemblies, for use as a performance measure. The gypsum moisture content relationship was further correlated to an equivalent wood moisture content, which can be measured using standard handheld meters calibrated specifically for wood.

Significant variations in the interior environment were observed between the nine monitored suites. The measured interior conditions were different across all five buildings and none could be considered average (i.e. controlled to 21°C). The temperature of each suite was occupant-controlled, and interior dewpoint and relative humidity varied considerably as a function of moisture generation and suite ventilation rates.

Air leakage testing of six suites in four multi-unit residential buildings was performed to quantify air leakage between adjacent suites, floors, common spaces and through the exterior walls. Three buildings from the monitoring study were tested, along with an additional building affected by interior moisture problems. The test method allowed the air leakage through the exterior building enclosure or other interior surface to be isolated and quantified, improving understanding of the impact of air-tightness and inter-suite leakage on the suite ventilation systems and interior relative humidity levels observed. Two case studies highlighted the importance of a properly sized and designed HVAC system to ensure sufficient ventilation of suites within air-tight building enclosures.

Evaluating exterior conditions, local climate was shown to vary across the Greater Vancouver area. Differences in rain, wind speed, wind direction, temperature, and relative humidity were observed between the microclimate of each of the five monitored buildings and the Vancouver airport.

Driving rain is a significant moisture load on the building enclosure. Driving rain measurements were compared across the five buildings and correlated with building height and wind exposure. Measured driving rain was correlated with empirical prediction methods by determining rain deposition (RDF) and exposure height (EHF) factors. The accuracy of empirical methods to calculate driving rain at a specific location on the building façade was good for well exposed locations, but less accurate for sheltered areas. Errors were observed as a result of complex wind and rain interactions at these buildings, which could not be predicted by the current empirical models.

The effect of roof overhang on driving rain deposition was also demonstrated, as similarly exposed buildings with overhangs showed less deposition than buildings without overhangs. At one four-storey building, driving rain loads were reduced to almost negligible levels (<5 mm/yr) by 1.2 m (4′) overhangs, and sheltering from adjacent buildings.

With an understanding of these boundary conditions, materials and relevant background, the performance of the five rainscreen clad buildings was presented and assessed. The interior-insulated rainscreen wall assemblies at the three wood-frame buildings showed satisfactory performance, however sheathing moisture approached cautionary levels between 20-25% for up to 6 months of the year. The relative humidity levels at the ventilated cavity and interior of the sheathing may be of additional concern, ranging between 80-90% for several months during the winter. The evidence suggests that rainwater leaks may still be able to cause damage to the sheathing, therefore further improvements to the wall assembly were investigated to reduce wetting events and to improve the drying performance of interior-insulated rainscreen wall assemblies.

The split-insulated stucco rainscreen wall assembly at one of the buildings was shown to perform poorly because of humid interior conditions. Monitored data and field observations indicate that water vapour flow by diffusion and/or air convection is wetting the stud cavity and exterior gypsum sheathing during winter months. High relative humidity within the stud cavity and elevated moisture contents of the gypsum sheathing were observed in all eight wall locations, following seasonal trends. The lack of a controlled ventilation system, combined with an air-tight wall assembly, occupant loading and lifestyle, contributed to the high overall relative humidity observed in the building.

The exterior-insulated stucco rainscreen wall assembly at the high rise building performed very well. Moisture sensitive materials were kept dry, and the relative humidity within the interior stud space remained only slightly above interior conditions. No evidence of exterior moisture penetration or condensation was observed at any of the wall locations.

Hygrothermal modeling was used to further understand the performance of these rainscreen wall assemblies. With WUFI 4.1 (a widely used hygrothermal simulation package), modeled enclosure systems can incorporate embedded sources and sinks of moisture and heat. This capability was used to model the effects of cladding ventilation and rainwater leaks. The hygrothermal model was validated with field data from the five buildings and found to be accurate at predicting past performance. Applying this validated model to each wall assembly, further simulations were performed to determine the impact of boundary conditions and assembly details on wall performance.

To improve the performance of the interior insulated wood-frame rainscreen wall assemblies, a layer of exterior insulation is suggested. Exterior insulation reduces the relative humidity at the sheathing surface, and subsequently improves the drying potential. Modeling shows that the additional insulation provides a safety factor against wetting and allows for drying of potential rainwater leaks and or interior moisture sources. With as little as 25 mm of insulation to the exterior of the sheathing, the moisture content and relative humidity levels dropped to well within safe limits.

To address the moisture problems at one of the buildings, modeling showed that reducing interior relative humidity levels (via improved suite ventilation) was the greatest factor in improving wall performance. To further reduce wetting within the stud cavity, interior vapour and air flow control (using vapour retarding paint and air-sealing penetrations) was suggested.

Rainscreen walls are often perceived - by the public, as well as by sectors of the construction industry - as the panacea for moisture problems. While a drained and ventilated cavity reduces the likelihood of moisture damage to sensitive materials within a wall assembly, this does not guarantee problem-free performance. Good details continue to be required to prevent rain water penetration, and in addition, air leakage and vapour diffusion from the interior are ever present moisture sources and cannot be neglected in design.

1 INTRODUCTION

This chapter discusses the background, scope and objectives of this thesis: "The Performance of Rainscreen Walls in Coastal British Columbia".

1.1 BACKGROUND

The failure of building enclosures, primarily as the result of moisture related deterioration has received much public attention in the past decade. Coastal areas of British Columbia and Washington State were particularly hard-hit by this issue in the late 1990's with large scale wall failures of potentially thousands of buildings constructed during the 1980's and 1990's. In Vancouver, BC, the media coined the term "leaky condo" to describe the widespread failure of hundreds of wood frame condominium buildings, which were the first to be hit with moisture-related rot and decay problems. In time it would be realized that all types of buildings were affected, some worse than others, and that a number of causal factors were involved.

The failures were largely attributed to rain water penetration in poor water-managed wall assemblies. Water got into wall cavities via various pathways (the usual culprit being absent or poor interface details and leaky window frames), was absorbed into the wood framing members and couldn't dry out. This lead to extensive rot and decay often required the total re-cladding of buildings. Steel stud and gypsum framed buildings were also affected, the severity of their problems escalating to the dangerous occurrence of large pieces of cladding falling off high-rise façades in some cases. Fortunately there have been no directly reported deaths due to the problem; however the health, sustainability, and economic damages resulting from the "leaky condos" have left a large scar on the industry. Questions still arise as to whether other locations could be susceptible to similar problems, and whether the way we are building today is any better than before.

Two provincial inquiries into the problems were launched by Dave Barrett, former Premier of BC, to determine the cause of the leaky condo phenomenon and develop some potential solutions. One of the first solutions adopted in Vancouver was the municipal-mandated use of a "rainscreen" wall, an idea that had been presented in Canada as early as the 1950's by the National Research Council's Neil Hutcheon. The concept of a rainscreen was to separate the cladding like a screen from the moisture-sensitive building structure, allowing drainage and potentially ventilation to remove any accidental accumulated moisture as a result of rainwater penetration. The construction and quality of windows and details at all interfaces were also improved, to increase the water shedding capability of wall assemblies.

At the time of their introduction in the late 1990's, rainscreen walls were largely untested in Vancouver's climate. However several earlier CMHC studies – in the early 1980's in Atlantic and Eastern Canada, and later laboratory studies in the late 1990's – showed promise for the performance of rainscreen walls. Anything had to be better than what they had done before, right?

Continuing Canada's leadership in building construction and research, a very large field monitoring program was implemented in 2000 to study the performance of rainscreen walls in Vancouver's coastal climate. The monitoring program was undertaken by RDH Building Engineering Ltd. (RDH), the Canadian Mortgage and Housing Corporation (CMHC), the Homeowner Protection Office (HPO), and the British Columbia Housing Management Commission (BCHMC). The primary purpose of this study was to understand the performance of rainscreen walls under local field conditions and to provide feedback to building industry about whether these walls and details were effective at preventing moisture problems.

To perform the study, five new or rehabilitated buildings (former leaky condos) constructed with rainscreen walls were selected for monitoring from the local housing stock. Within the five buildings, at least five different wall locations were instrumented with sensors to measure temperature, relative humidity, moisture content, relative wetness, and pressure differential across the wall assemblies. Temperature and relative humidity levels of interior suites were also monitored and weather stations were installed on each rooftop to measure wind, rain, temperature and relative humidity. Driving rain gauges were installed on two orientations of each building to further understand the exterior loads.

RDH presented series of progress updates and publications to the building industry from 2002-2007, and a summary report of the data was published in 2007. This thesis research develops from the point where the summary report left off: further analyzing data, performing additional investigation and testing, and examining trends and anomalies.

1.2 SCOPE

This thesis is a collection of building research focusing on the performance of rainscreen walls in coastal British Columbia. While the study focuses on the field performance of a range of wall assemblies in one climate type, the scientific fundamentals and discussion of this issue can be effectively applied to other climates. Certain chapters present general results of building climate loads or air-tightness of multiunit residential buildings in a broader context. These chapters are used to supplement the main thesis, understanding building enclosure performance holistically before applying its principles to specific wall assemblies.

The initial CMHC monitoring project provides much of the background data for the analysis and is presented in detail throughout the body of this thesis. Additional research performed and data collected build on this background to better understand the building enclosure in general and in particular rainscreen wall assembly behaviour under field conditions.

The additional research presented here includes: supplemental testing of the material properties of exterior grade fiberglass gypsum, to determine a moisture content/electrical resistance relationship; air leakage testing of individual suites within four multi-unit residential buildings (three from the previous monitoring study), to quantitatively determine air leakage paths and assess the impact of air tightness on building performance; analysis and correlation of measured driving rain with empirical prediction models; distillation of measured solar radiation data for use with hygrothermal models; and finally validation of a one-dimensional hygrothermal model to perform additional simulations on ventilated rainscreen wall assemblies, to determine the impact of several variables and allow further recommendations for improved design to be made on a much larger scale.

This thesis is presented as a collection of research where the individual chapters are interrelated but may be read as separate entities. Together, the chapters build on each other through the presentation of data, synthesis and conclusions. Raw data and supplemental information is provided in the Appendices for further consideration.

1.3 OBJECTIVES

The primary objective of this thesis is to study the performance of buildings in Vancouver's coastal climate, in particular those constructed with rainscreen wall assemblies. While this objective is very broad, it has been broken down into research components which address each performance variable.

First, an understanding of building physics is developed, specifically how heat, air, and moisture can impact the performance of building enclosures. Second, a literature review of the history of wood frame walls – leading up to and including the failures of thousands of buildings in the Pacific Northwest – is presented to understand fully how we built in the past, and why we build the way we do now. Recommendations for future practice can only be made if past mistakes are fully understood and therefore not repeated.

Third, the field monitoring program is introduced and a discussion of interior and exterior boundary conditions is presented to develop an understanding of the actual climate loads buildings are subjected to, and how well these loads reflect our current design assumptions for Vancouver.

Driving rain can be a significant load on the exterior building enclosure however it is difficult to predict. Understanding and predicting the stochastic relationship of wind and rain deposition on building façades has improved in past decades but field measurements are still limited. Measured driving rain data for the five buildings is therefore presented and compared to prediction models, to improve our understanding of wind-rain relationships.

Interior boundary conditions are another significant load on the building enclosure. To understand the monitored interior conditions and ventilation rates, air leakage testing was performed to quantitatively determine air leakage pathways at the monitored suites. The main objective of this testing was to understand air leakage paths within multi-unit residential buildings and how airtightness of the building enclosure and between suites/common areas may affect ventilation and make-up air. A case study of one of buildings is presented highlighting the importance of sufficient interior ventilation, and the impact of air leakage pathways on building performance.

Fourth, with an understanding of the building physics, historical background, and interior and exterior boundary conditions, the performance of the exterior walls is presented. The objective is to show the monitored performance but also to explain the trends and anomalies observed in the five years of data.

Fifth, material testing of fiberglass faced gypsum sheathing was performed to determine the relationship between moisture content and electrical resistance. The relationship is used to convert raw resistance readings into moisture content results for the two gypsum sheathed buildings presented. This testing further improved the understanding of gypsum sheathing when exposed to humid environments.

The sixth and final objective is to validate an existing hygrothermal model with the measured data from the five buildings and use the model to investigate the impacts of additional climatic or construction variables, determining possible methods to improve the performance of rainscreen walls. Modeling is also used to answer questions such as: can we accurately predict the performance of rainscreen walls? Could we have foreseen and avoided these problems in the past?

In conclusion all of the chapters are synthesized to report on the performance of rainscreen walls in Vancouver's climate. Looking ahead, potential improvements are discussed to improve rainscreen wall assemblies to make buildings more durable, sustainable, and healthy for occupants.

1.4 <u>APPROACH</u>

The approach to the research and to the written thesis is presented in this section.

1.4.1 <u>Research Methods</u>

The research for this thesis was carried out over a two year period from 2005-2007, and incorporates background data which was collected from 2001-2007 by the CMHC field monitoring project described previously. The research consisted of a literature review, field investigation and building review, laboratory material testing, air leakage testing of individual suites, hygrothermal modeling, and an analysis and presentation of the field monitored data.

The literature review looked at past building research from the 1930's at the beginnings of building science research in North America and forward to the present day. The review focuses on the historical development of the wood frame wall, discussing past failures and progress from ancient walls to the development of light wood-frame construction in North America in the 1800's, and through its developments from the 1900's to the present. A literature review of building physics, the climate of Vancouver, driving rain, air leakage testing, and hygrothermal modeling was also performed.

The installation of the field monitoring equipment and raw data collection was largely undertaken by RDH Building Engineering from 2001-2003 and collected from 2001-2007. The raw data from 2001-2006 was analyzed as part of this thesis.

Material testing was performed in the laboratory on exterior grade fiberglass faced gypsum to correlate moisture content and electrical resistance.

The buildings were reviewed on several occasions from 2005-2007 to perform condition assessments, collect the monitored data, and perform additional testing. Wall openings made at one building indicated very high moisture levels, confirming the monitored data on the condition of the wall assembly after years of service. Air leakage testing was also performed of the monitored suites in three of the five buildings to collect additional data about the construction and performance of the buildings.

The one-dimensional WUFI 4.1 Hygrothermal model was validated with the monitored data and is used to perform additional simulations.

Finally the monitored data was analyzed to understand trends and anomalies in the performance of the rainscreen walls.

1.4.2 Thesis

This thesis first presents a problem statement, background and history, then a discussion of the monitoring project which was used to investigate the performance of field buildings. This is followed be a discussion of the exterior and interior boundary conditions and the role these have on building performance. Results are then presented from air leakage testing to further understand the interior boundary conditions of these buildings. Next, the performance of the monitored wall assemblies is assessed with a discussion and explanation for the performance observed. The wood frame walls are discussed in a separate chapter from the steel stud and gypsum frame walls, as the results are significantly different. Summarizing the performance of rainscreen wall assemblies tested the impacts of interior and exterior boundary conditions and design variables are discussed. Looking ahead, potential improvements to rainscreen wall designs and building operation are investigated to reduce the likelihood of future problems. Finally conclusions are summarized and recommendations are made for the building industry and for future and continued research in this field.

Appendices are provided to supplement the thesis work and provide additional information referred to in the chapters. Included in the appendix are two secondary experimental projects: the testing of fiberglass faced gypsum sheathing to relate moisture content to electrical resistance and the development of a simple calculation model to compare the drying potential of walls in certain climates.

The chapters are introduced and a brief outline of each is provided.

1. **Introduction** – Develop the problem statement and provide an outline of the thesis work.
2. **Building Science Background** – Introduce the physics and calculations used later in the presentation of data and further discussion.
3. **Wood Frame Wall History** – Provide a historical background of wood-frame walls, and to understand why we build the way we do. The historical review leads up to and discusses the failures of the leaky condos in Vancouver and other moisture related failures across North America.
4. **Field Monitoring Program** – Introduce the monitoring program and its testing setup, methodology, goals, scope and background.
5. **Exterior Boundary Conditions** – Discuss the climate of Vancouver and the exterior loads on the building enclosure, including temperature, relative humidity, solar radiation, rain, wind and wind-driven rain.
6. **Present the Interior Boundary Conditions** – Discuss the measured interior conditions of the five buildings and provide data to help designers select appropriate design conditions.
7. **Air Leakage of Multi-unit Residential Buildings** – Present the test setup, methodology, background, and results of air leakage of tested suites within multi-unit residential buildings. Discuss the implications of these findings on the monitored building performance.
8. **Wood Frame Wall Performance** – Present the performance of Buildings 1, 2, and 4 in the study.

9. **Light-Gauge Steel Stud Wall Performance** – Present the performance of Buildings 3 and 5 in the study. Review and discussion of field openings made at Building 3.
10. **Lessons Learned and Moving Forward** – Discuss potential improvements to rainscreen wall assemblies.
11. **Synthesis** – Summary of conclusions from previous chapters.
12. **Conclusions** – General conclusions from the results of the thesis
13. **Recommendations** – Discuss potential for further research and building industry implementation.
14. **Appendices**
    a. Gypsum Sheathing Laboratory testing
    b. Hygrothermal Modeling
    c. Maximum Drying Potential Model
    d. Monitored Equipment and Sensor Information
    e. Building Description
    f. Supplemental Measured Data
    g. Air Leakage Testing Supplemental Data
    h. Solar Radiation Measurements and Calculations
    i. Quick Reference Guide (building information, sensor location etc.)

2 THE BUILDING ENCLOSURE AS AN ENVIRONMENTAL SEPARATOR

The fundamental function of the building enclosure is to separate the exterior and interior environments while maintaining healthy and safe indoor conditions for the occupants. The building enclosure will weather and gradually deteriorate over time and require ongoing work to maintain the appearance, performance, and efficiency. Moisture can accelerate the deterioration process, and if the balance between wetting, drying, and safe storage within the enclosure assembly is exceeded, lead to premature failure.

This thesis focuses on the performance of above-grade wall assemblies. Roof, floor, and below-grade wall assemblies are not discussed in detail in this chapter, however the same fundamentals and physics apply.

The psychrometrics of air and water vapour, moisture transport mechanisms, and rain control strategies are discussed in detail to understand how moisture can get into and affect wall assemblies.

With knowledge of the potential moisture sources, the potential wetting and drying mechanisms within wall assemblies and the concept of safe material storage is discussed.

Cladding ventilation plays an important role in performance of rainscreen wall assemblies, therefore a literature review of previous research and the fluid flow mechanics is presented. Cladding ventilation rates are calculated for the buildings in the monitoring study to further understand the impact of cladding ventilation on wall performance. The ventilation rates are further used in Chapter 10 to predict the performance of these walls using hygrothermal modeling.

Finally damage mechanisms resulting from excess moisture within enclosure systems including mould, structural decay, and corrosion are discussed.

2.1 BACKGROUND

As North Americans, we spend more than 90% of our lives within buildings. Because of the climate we live in, we require shelter from the elements for the majority of the year as it is uncomfortable or even harmful to our health. Instead we prefer a controlled and consistent interior environment, in which we live, work, play, or learn.

The basic building structure consists of the walls, roof, floors, and a foundation. The building enclosure forms a part-of or is supported-by the structure and separates the exterior and interior environments. The structure will typically last the life of the building, protected in a relatively static environment subjected to only the occasional change in temperature and relative humidity. The building enclosure however is subjected to temperature, moisture, and pressure differences between the exterior and interior and exposed to the influences of rain, snow, wind, and solar radiation on the exterior (Figure 2-1).

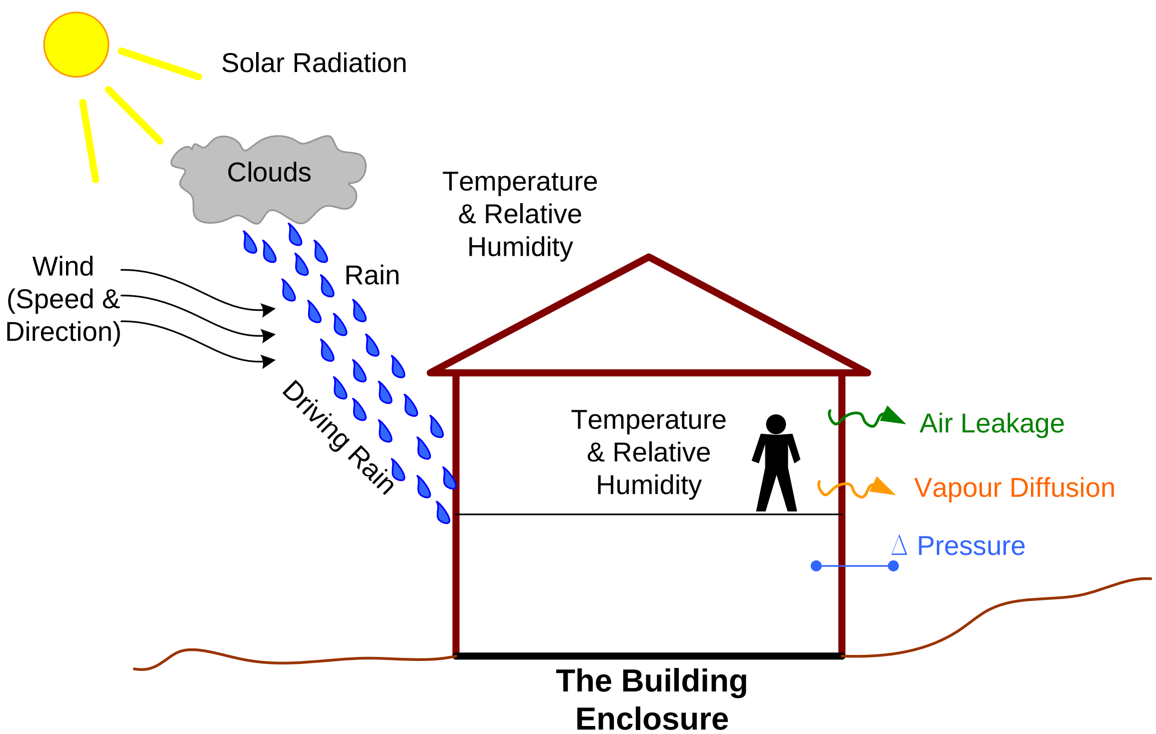


Figure 2-1: Interior & Exterior Climate Loads on the Building Enclosure

As a result of these climatic loads, the building enclosure will deteriorate over time and require ongoing maintenance to maintain the enclosure elements. If deterioration is accelerated for any reason, or occurs for too long, the enclosure can have negative health and safety consequences on the occupants and the public, and economic and aesthetic consequences for the owners.

As far as accelerating deterioration, moisture in all its physical forms is regarded as the single greatest threat to the durability and long-term performance of a building. Excessive moisture cannot only cause significant damage to many building materials and components, but can lead to unhealthy indoor environments.

The balance between wetting, drying, and safe storage is critical to the long term performance of building enclosures. Where wetting cannot be controlled to acceptable levels, safe storage within materials and drying become critical. Many common building materials have little safe storage capacity, that is, they cannot be exposed to high levels of moisture for long periods of time, particularly when at above-freezing temperatures. Wall "performance" is hinged upon this balance. A wall is said to have good performance when it is typically dry (safe storage and drying exceed wetting) and poor performance when it wetting exceeds the drying rate and safe storage of the material. A failed wall is one where damage mechanisms become present; including mould growth, metal corrosion, or loss of structural integrity (discussed in Section 2.6).

Moisture problems in buildings arise primarily from the exposure of materials to high relative humidity, liquid water from condensation, rain leaks, or other bulk water sources. Organic building materials such as wood, cellulose, or paper are attacked by micro-organisms when wetted and exposed to temperatures above freezing. Inorganic materials such as concrete or masonry are deteriorated when wetted and exposed to below-freezing temperatures. Metals will corrode when exposed to high humid environments or liquid water. Biological and chemical activity increases with temperature and duration of exposure. Inorganic insulation products, while moisture tolerant has a reduced thermal resistance when damp or wet. Other materials including plastics are degraded by ultraviolet (UV) radiation and high temperatures. Metals and glass are strongly affected by thermally induced contraction and expansion.

Very few building materials are immune to all environment factors. As there is not one material that can efficiently perform all required functions, modern building design incorporates several materials into an assembly to perform as a whole. Each material brings its strengths (whether structural support, insulation, vapour control, air control, or finish) while using the other materials to protect from its own inherent weaknesses. Components which are sensitive to moisture or UV are therefore put within the wall and protected.

In addition, with almost all construction projects, the goal is to reduce cost. Often the enclosure components are value-engineered and as a result lower-cost moisture sensitive materials may replace more durable and expensive components. A balance must therefore be achieved between the acceptable risk of damage within a particular assembly and the life-cycle cost.

The goal of building enclosure design should be to construct a building properly the first time, and avoid moisture problems such as that in Figure 2-1. Here, at a "leaky-condo" in Vancouver, BC, the exterior walls failed like thousands of others have in this climate (further discussed in Chapter 3).

Following a forensic investigation building science principles were applied to ascertain the failure was a result of driving rain penetration wetting a poorly constructed face-seal wall assembly. Water found its way into the wall assembly through penetrations, cracks, and unsealed joints. Because of the choice of construction and materials used, the wall assembly could not balance the wetting applied, with the drying and safe storage capacity. In less than a decade the steel studs corroded to a point where structural failure was imminent and the gypsum sheathing was deteriorated and covered in mould. Needless to say the building enclosure was harmful to the occupants and public, and the owners were out of pocket for the required repairs.

Figure 2-2: Leaky Condo Repair in Vancouver, BC

Building failures like this one and many others are not tolerated by society, both for the consequences of the owners and occupants but for the greater public as a whole. Failed buildings are wasteful of natural resources and consume excess energy which we all share a part of.

Building enclosure failures can be prevented. Failures can occur from accidents or acts-of-god, but all too often are as a result of improper design, poor construction, and insufficient maintenance. By understanding and applying the principles of building science in design, and a performing ongoing maintenance, most building enclosure problems can be avoided. This requires knowledge of the exterior and interior environmental loads; heat, air, and moisture transport mechanisms; and the properties and limitations of the materials and assemblies used.

2.2 PSYCHROMETRICS

Psychrometrics is the term used to define the relationship of air and water vapour content. A brief review of the fundamental air-moisture relationships used to calculate additional parameters (beyond measured temperature and relative humidity) is presented.

Water in its gaseous state is referred to as water vapour, and at any given temperature there is a maximum amount of water vapour the air can hold. The moisture content of air can be measured gravimetrically (kg of H_2O per kg of air) or by the partial pressure exerted by the water vapour (Pascals). When the maximum amount of water vapour the air can hold is reached, it is referred to as saturated. An approximation of the saturation vapour pressure at any given temperature can be approximated using the following formula:

$$P_{ws} = 1000 \cdot \exp(52.58 - \frac{6790.5}{T} - 5.028 \cdot \ln T) \qquad \text{(Eqn. 1)}$$

Where, *Pws* is the Saturation Water Vapour Pressure (Pa), and
T is the air temperature in (Kelvin = °C + 273.15)

Relative humidity is the ratio of the actual amount of water vapour in the air to the maximum allowable amount of water vapour in the air (saturation vapour pressure). This ratio is defined by Equation 2.

$$RH = \frac{P_w}{P_{ws}} \qquad \text{(Eqn. 2)}$$

Where, *Pw* is the water vapour pressure of the air (Pa)

As the relative humidity was measured by sensors in the monitoring study, and the saturation vapour pressure can be calculated for a given temperature, the actual vapour pressure can be determined as an absolute measure of the moisture in the air.

When the relative humidity is at 100% the air is considered at saturation. If saturated air comes into contact with a surface that is cooler than the air, moisture will condense. This temperature is known as the dewpoint temperature (t_d in °C).

$$t_d = \frac{4030}{18.689 - \ln\left(\frac{P_w}{133}\right)} - 235 \qquad \text{(Eqn. 3)}$$

For example if the interior conditions were 20°C and 50% the dewpoint temperature would be 9.1°C. Condensation will occur on any exposed surface that is colder than 9.1°C (for example a window frame that is 8°C).

The relationships between vapour pressure, temperature, relative humidity and dewpoint temperature are all related on a graph known as a psychrometric chart (Figure 2-3). The psychrometric chart is used by mechanical engineers and building scientists to understand and plot the relationships of water vapour and air.

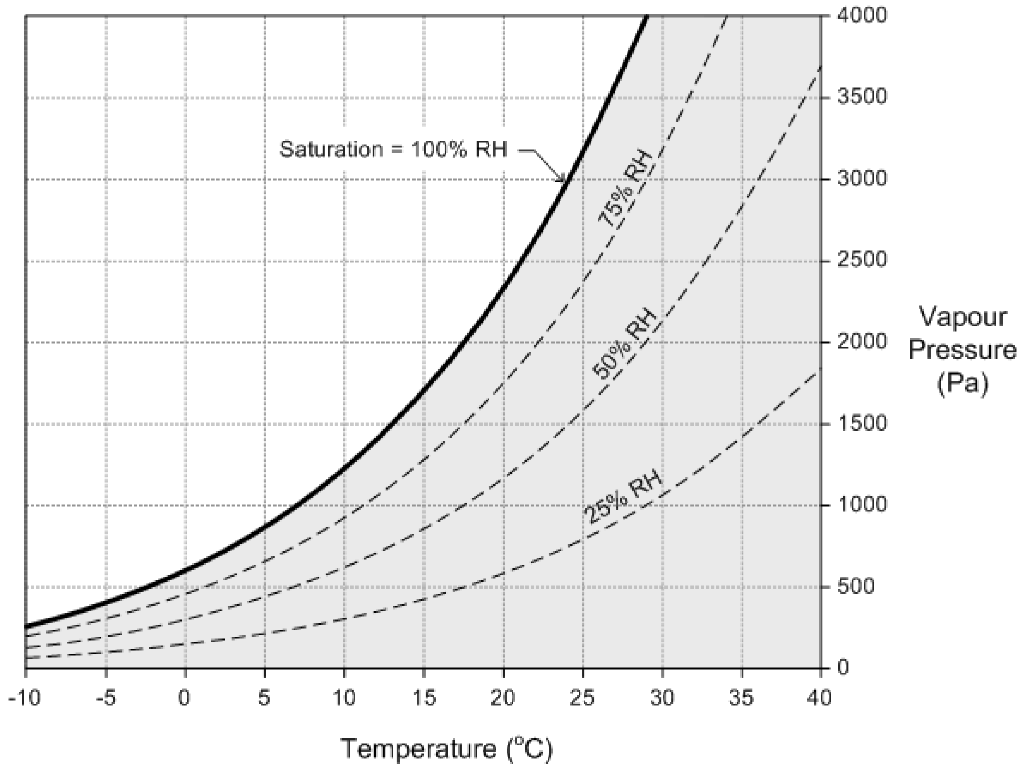


Figure 2-3: Psychrometric Chart

Moisture in air is one of the most important sources of wetting in building enclosures. Water vapour can be transported through and into the building enclosure by either convection (air flow) or diffusion.

Convection is the movement of mass or energy by movement of a fluid, either a liquid or gas. Convection is the transport of water vapour through the movement air by the building enclosure. Air leakage is used to describe the process of air movement through unintended locations within the building enclosure.

Diffusion is the transfer of mass or energy from a higher concentration to a lower concentration. Diffusion will occur when a difference in vapour pressure exists. In cold climates during the winter the occupied interior space typically has a higher vapour pressure than the cold dry outdoors and hence diffusion is outwards and commonly referred to as outward or wintertime vapour diffusion.

Diffusion is controlled in enclosure assemblies using vapour retarders or vapour barriers, and convection is stopped by and air barrier system consisting of air-impermeable materials and sealed details.

Diffusion is not commonly the source of severe moisture problems or damage as the condensation quantities in most diffusion problems are very small. Solar-driven moisture can result in fairly high diffusion rates, however occurs for limited periods of time. Cold weather diffusion occurs however only is a problem with walls with little interior vapour resistance or high interior humidity.

In contrast, air leakage condensation can result in significant accumulations of moisture, as air can hold a high amount of moisture. Small differences in pressure across the enclosure, resulting from stack effect (buoyancy), wind, or mechanical systems can cause significant air leakage through and condensation within the enclosure when the interior air dewpoint temperature is higher than the temperature of any surfaces within the wall assembly. The differences in moisture deposition quantities between vapour diffusion and air leakage is shown in Figure 2-4.

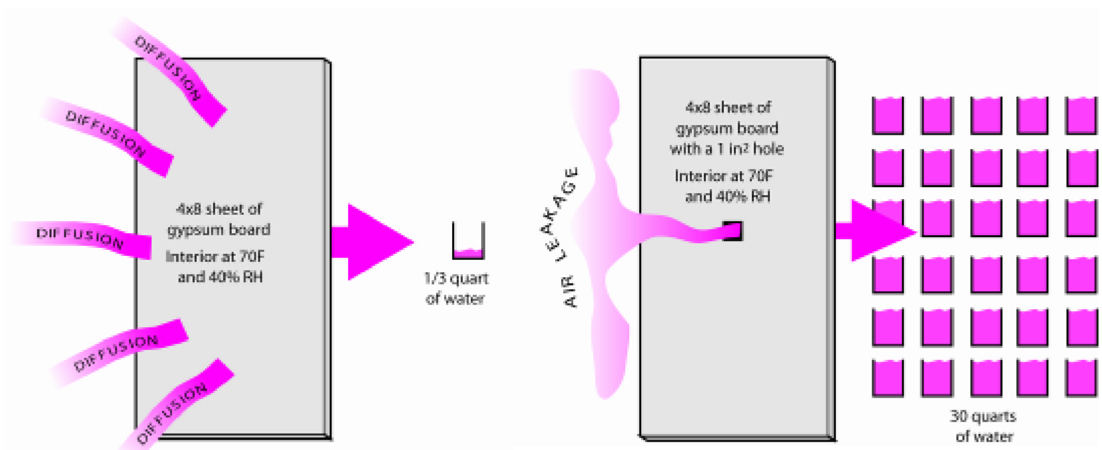


Figure 2-4: Differences in Moisture Transport between Vapour Diffusion and Air Leakage (Lstiburek 2005)

While air leakage has the ability to transport significant amounts of moisture, and can damage building enclosures, rain-water from the exterior has an even greater ability to cause wetting and damage. Rain-water deposition on exterior walls can be an order of magnitude or two higher than air leakage alone. Instead of 30 quarts (28 L) as shown for air-leakage (Figure 2-4), anywhere from 300 to 2000+ quarts could be deposited on a wall from driving rain. However, the quantity of rain that is able to penetrate into the wall assembly is dependent on building exposure and the rain control strategies employed.

2.3 <u>RAIN WATER CONTROL</u>

Driving rain is typically the largest source of moisture for above-grade building enclosures. Hence the control or management of rainwater is important to the performance of a building enclosure. Despite thousands of years of experience, problems with rain-related building damage still frequently occur. Several approaches to rain penetration control are discussed here.

Driving rain also referred to wind-driven rain is falling rain which is blown horizontally by wind and impinges on the surface of a building. Driving rainfall amounts can be as high as 2000 L/m²/yr in severe coastal climates, and hence a very significant load for the wall to handle. Driving rain loads for cities across Canada are presented in Figure 2-5 from work by Straube & Schumacher (2005). Driving rain theory and calculations are further presented in Chapter 6.

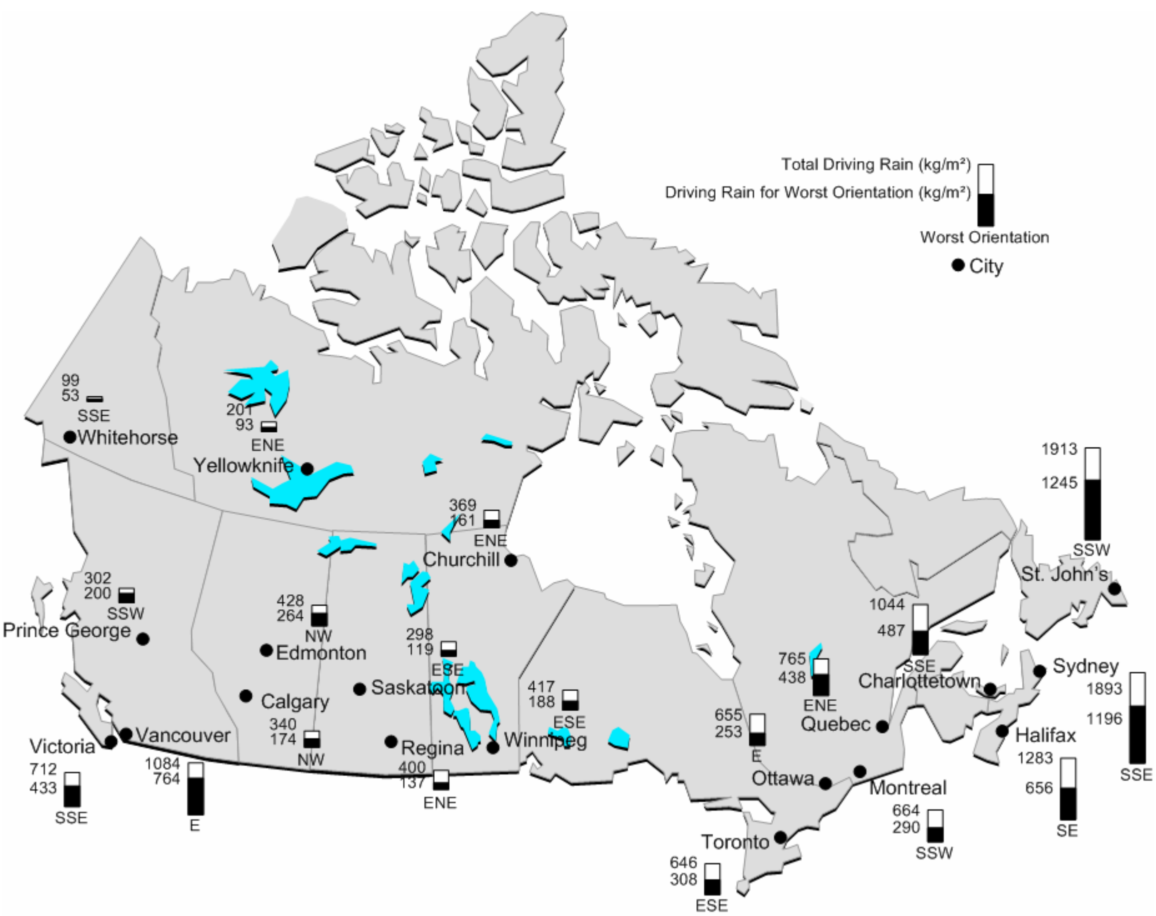
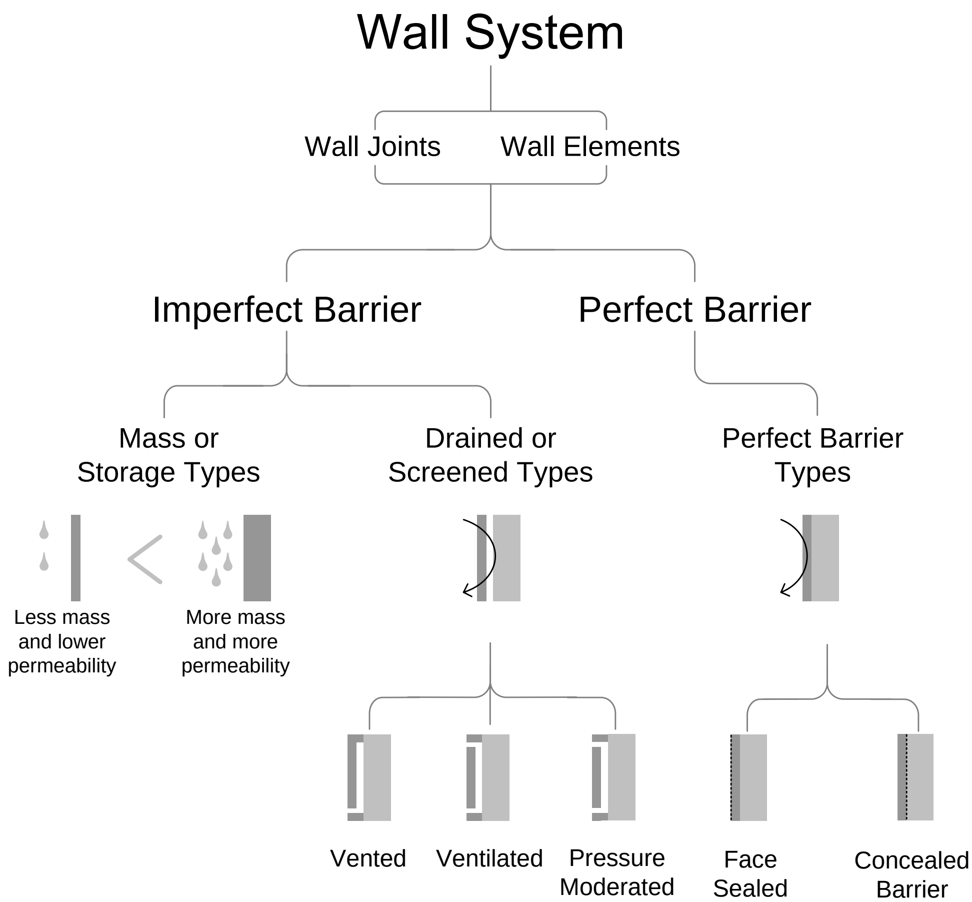


Figure 2-5: Driving Rain Loads Across Canada (Straube & Schumacher 2005)

Building shape, site location, and topography perhaps have the greatest influence on driving rain exposure, and can be controlled by the designer to reduce rain deposition. However complete protection from rain is rarely provided and some strategy to deal with rainwater that strikes the walls must be employed. The three fundamental rain control strategies are:

1. Storage (mass walls)
2. Exclusion (perfect barrier walls)
3. Drainage (drained and screened walls)

Straube and Burnett (2005) present a categorisation based on the method by which wall systems control rain penetration (Figure 2-6). The categories are comprised of elements (i.e. the plane of the wall), and joints between these elements (i.e. the sealants etc).



Notes:
1. The categorization is based on actual behaviour, not necessarily design intent.
   For the purposes of this classification system, the following definitions are necessary:
2. “Drained”: the large majority of the water that penetrates the screen is removed by gravity.
3. “Cavity”: a clear space or a filled space that facilitates gravity drainage and air flow and resists the lateral transfer of water (a capillary break).
4. “Ventilated”: allows a significant flow of air largely to promote drying by vapor movement.
5. “Vented”: allows some degree of water vapor diffusion through vents and by air mixing.
6. “Pressure-moderated”: an approach that moderates air pressure differences across the screen.

Figure 2-6: Wall System Categorisation (Straube & Burnett 2005)

The primary classification is whether a wall is considered a perfect barrier or an imperfect barrier. Two types of imperfect barriers are possible, either mass storage or drained/screened types.

Mass or Storage Wall Types

Mass or storage walls are historically the oldest strategy. The approach relies on the safe storage of the material to absorb the rainwater that is not shed or otherwise removed from the outer surface. The moisture that is absorbed is eventually removed by evaporation before it can reach the interior surface of the wall. Hence materials with very high safe storage capacities such as masonry, concrete, or natural stone are suited for the purpose (Figure 2-6).

Several examples of solid brick masonry or rubble stone buildings constructed centuries ago which rely on mass storage are still in service today and continue to perform well.

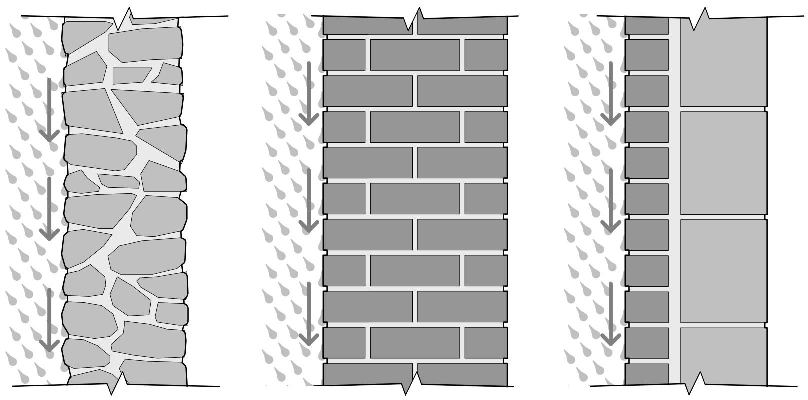


Figure 2-7: Mass or Storage Wall Assemblies (Straube & Burnett 2005)

Concrete and composite masonry walls are few of the modern equivalents to the mass-storage approach, as new rubble and solid masonry buildings are no longer constructed.

Drained or Screened Wall Types

Drained or screened walls are used where the wall structure does not have sufficient mass to safely store the amount of rain deposition that occurs. Since it has often been shown that lap siding (vinyl, fiber cement, or wood), stucco, and masonry veneers leak significant amounts of water, this design approach is the most realistic and practical for walls with such cladding (Straube & Burnett 2005). This category also includes “rainscreen” wall assemblies as discussed throughout this thesis. It should be noted that the cladding screen is more than a just a rain screen; but able to resist wind, snow, solar radiation, impact etc. and hence the term is not completely technically correct.

The principle of using drained claddings with a vented or ventilated cavity behind is not new, and has been used for several centuries. For example, brick veneer has typically been installed away from the sheathing since the late 19th century (although the cavity was often blocked with mortar droppings or filled with insulation).

Several modern drained and screened wall assemblies are shown in Figure 2-8.

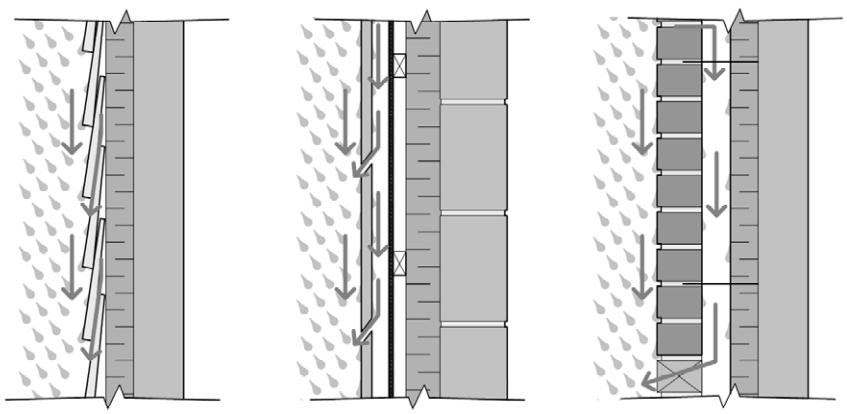


Figure 2-8: Drained or Screened Wall Assemblies (Straube & Burnett 2005)

Some definitions are useful. A ventilated wall is one which has vent openings at the top and bottom of an air cavity, to promote air circulation. A vented wall has vent openings only at the bottom of the wall, usually provided for cavity drainage. Some exchange of air between the exterior and cavity will occur in a vented wall, however the volume will be small and the area over which it acts is limited in comparison to a ventilated wall. The influence of ventilation on drying and the performance of drained or screened wall assemblies is discussed in Section 2.5.

In both ventilated and vented walls, the cladding is separated from the rest of the wall assembly by a gap or cavity. A WRB (water resistive barrier), which acts as a drainage plane and secondary capillary break, is provided to the interior of the cladding and ventilated cavity. The cladding and gap, while significantly limiting the amount of rain penetration, are not relied upon to stop all water. The WRB is also not expected to be completely water tight and may allow some small amount of liquid water penetration. The gap must be drained to the exterior using flashings at penetrations and at the base of wall.

The air space also acts as an effective capillary break between the cladding and remainder of the wall, reducing the transfer of liquid water from porous claddings (wood, cement board, stucco, brick etc) to the drainage plane. The drainage space becomes more critical the higher the rain load on the cladding.

To ensure the water that penetrates the cladding can drain down the backside of the cladding, a drainage space of 3 to 6 mm width is recommended, since this is approximately the gap size that can be spanned by water. To account for dimensional tolerances in construction, 9 to 12 mm is often quoted but may not be necessary in systems with good dimensional control. The required airspace for ventilation drying (if desired) is usually larger than that required for drainage (Straube & Burnett 2005).

Walls with very small air gaps (as small as 1 mm) have also been shown to drain well (Smegal 2006). However in practice, maintaining such a small and consistent gap is difficult to achieve. Some materials such as a two layers of rippled or textured house-wrap can provide sufficient gap width for drainage.

In most drained and screen wall assemblies vertical wood strapping is typically used to create the cavity airspace, and commonly available 13 mm (1/2”) or 19 mm (3/4”) thickness lumber is used. Vertical strapping used in an exterior insulated rainscreen wall assembly is shown in Figure 2-9.

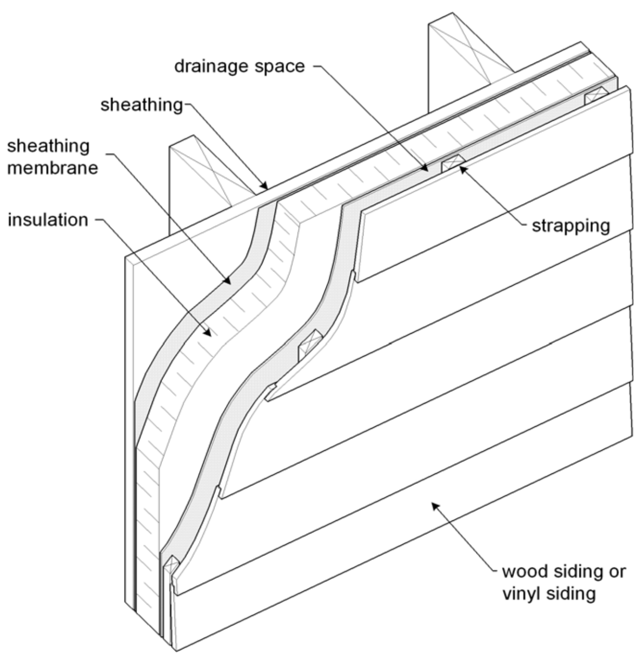


Figure 2-9: Exterior Insulated Rainscreen Wall Assembly (Straube & Burnett 2005)

Pressure moderation is also a function of a vented or ventilated wall assembly and can potentially be utilized to prevent water penetration into the wall assembly by neutralizing or equalizing the pressure drop across the cladding material (Figure 2-10).

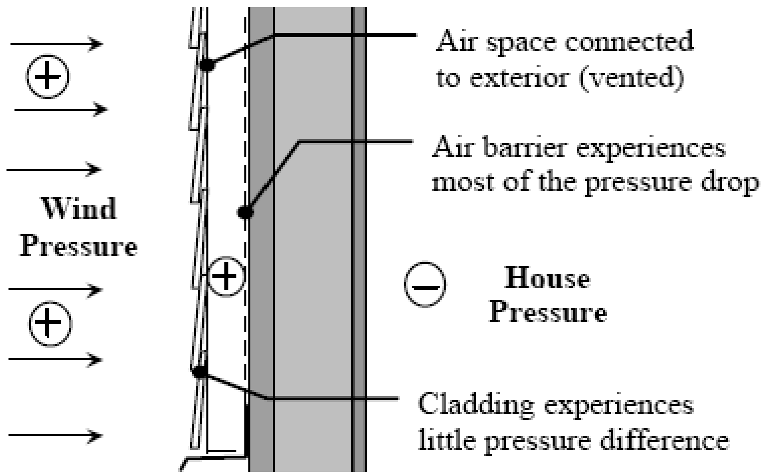


Figure 2-10: Pressure Moderation of Ventilated Wall (Straube & Burnett 2005)

In theory, by reducing the pressure difference across the cladding, rain will not be forced across openings or joints. However, field measurements (Quirouette 1996, Inculet & Surry 1996, Straube and Burnett 1995, Straube 1998) have shown that pressure equalization is rarely achieved in practice, and the term pressure moderation is preferred. Pressure moderation however does little to improve the performance of brick veneer, stucco and lap siding systems as these are inherently leaky without pressure applied do not exhibit fundamentally different leakage rates under any likely wind pressures (Straube 1998). Instead of trying to achieve pressure moderation or equalization, it is more prudent to design a wall that could allow for the penetration of moisture and safely drain and manage the moisture.

Experience from rain regions in Canada and the US has shown that drained and screened cladding systems are the preferred approach to reliably provide rain control. Drainage within the wall complements the drainage approach on the exterior surface (Straube & Burnett 2005).

Perfect Barrier Types

A perfect barrier stops all water penetration at a single plane. If the exterior most layer (cladding) is the plane of rain control this is termed face-sealed. If the intended plane of rain control is behind the cladding (e.g. the building paper or house-wrap) then it is referred to as a concealed barrier.

Perfect barrier systems are very sensitive to construction defects or material degradation (e.g. joints) and are difficult to construct perfectly in the field. Capillary transport from absorptive claddings (i.e. stucco) is not prevented in a face-seal or concealed-barrier approach, therefore even without a hole to leak through, the wall can still get wet. In addition, the joints between elements in perfect barrier walls are also perfect barriers (i.e. single joint of caulking). Caulking and other single joints have a poor record of field performance and require frequent maintenance to prevent rain entry. Examples of perfect barrier wall types are shown in Figure 2-11.

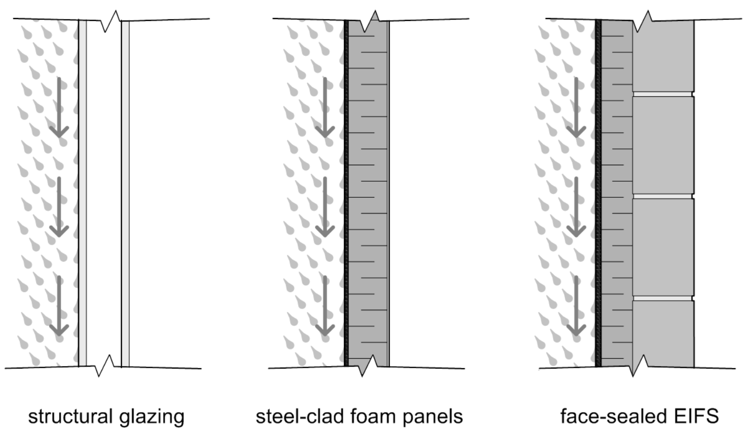


Figure 2-11: Perfect Barrier Wall Types (Straube & Burnett 2005)

The most common wall system to use a concealed barrier is stucco installed directly over building paper or house-wrap (Figure 2-12). The performance of such types of walls is further discussed in Chapter 3.

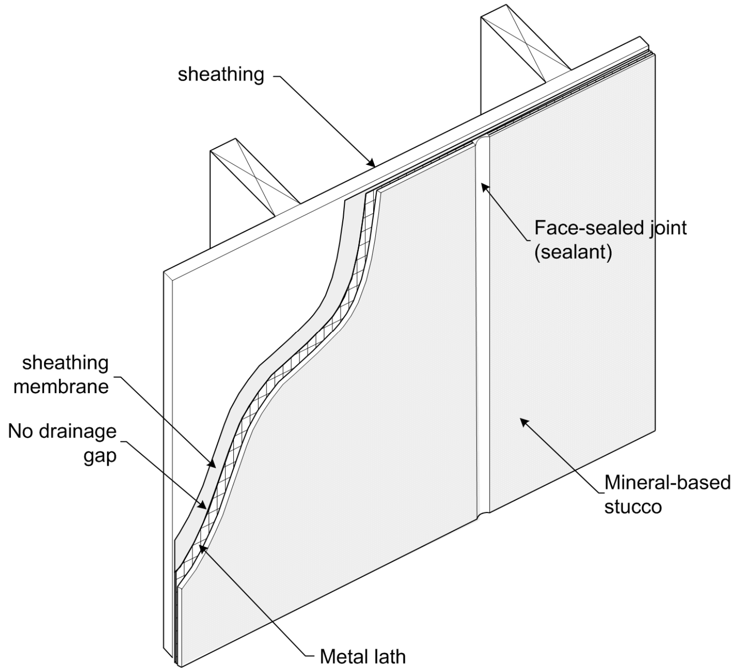


Figure 2-12: Stucco Concealed Barrier System Assembly

Perfect barrier systems, especially face-sealed versions often fail to perform as designed, if not initially, then after many years of exposure. Flaws in the barrier including cracks, penetrations, and unsealed joints can results in catastrophic failure when water is able to get into the wall assembly past the cladding (discussed in Chapter 3).

Quality control is essential for perfect barrier systems, but can be difficult to achieve in the field. Frequent maintenance of the cladding and joints is also important to maintain the water-tight exterior surface. Face-seal systems can work in low rain-exposure conditions, or where assembled under tight quality control (e.g. glazing units), or in assemblies where the back-up wall substrate can accept periodic wetting without damage (e.g. concrete or masonry).

As a result of the failures of buildings with perfect barrier wall assemblies, this type of construction is no longer permitted in some rain exposed locations of North America. The use of a drained and screened approach is preferred with obvious benefits over the perfect barrier approach.

2.4 WETTING, DRYING, AND SAFE STORAGE CAPACITY OF FRAMED WALLS

The balance between wetting, drying, and safe storage is critical to the long term performance of building enclosures. Where wetting cannot be controlled to acceptable levels, safe storage and drying become critical. Many common building materials have little safe storage capacity, that is, they cannot be exposed to high levels of moisture for long periods of time, particularly when at above-freezing temperatures.

Wall "performance" is hinged upon this balance (Figure 2-13). A wall is said to have good performance when it is typically dry (safe storage and drying exceed wetting) and poor performance when it wetting exceeds the drying rate and safe storage of the material. A failed wall is one where damage mechanisms become present; including mould growth, metal corrosion, or loss of structural integrity (discussed in Section 2.6).

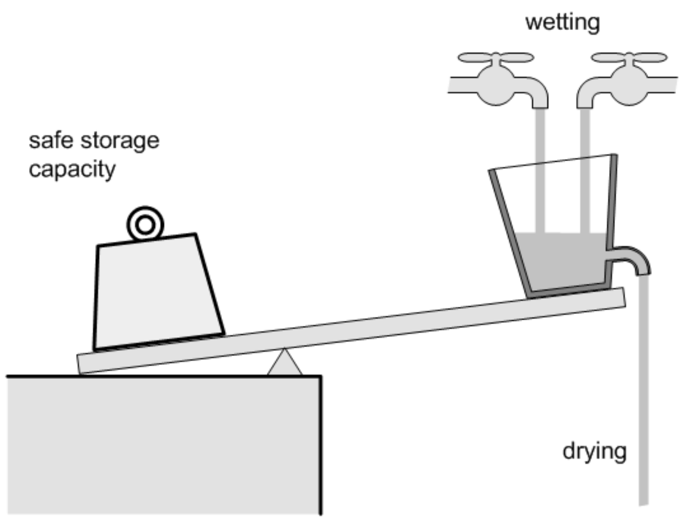


Figure 2-13: Balance of Wetting, Drying and Safe Storage Capacity Analogy (Straube & Burnett 2005)

In frame wall assemblies, the sheathing is one building component often made of moisture-sensitive materials placed directly behind the cladding, separated by only a thin sheathing membrane and air gap. For some periods of time, the sheathing can be expected to be exposed to rainwater wetting from the exterior or condensation wetting (air leakage or vapour diffusion) from the interior. Protecting the sheathing from moisture is seen as important and has been the goal of many product manufacturers, builders, and practitioners over several decades. However experience has shown that accidental leaks can still occur, and hence the role of drying is very important to the moisture balance.

Moisture can be transported by airflow (convection), diffusion, or gravity into and through an enclosure wall assembly. Drainage will remove much of the bulk moisture by gravity, when a drainage path is provided, however moisture can still remain adhered or absorbed to materials within the wall assembly. The amount of moisture that can be safely absorbed or stored depends on the material choice. Drying can occur by vapour diffusion, evaporation, desorption, or by air convection (ie. ventilation). Vapour diffusion is shown to be a relatively slow process particularly when low permeance materials are used within the wall assembly. Evaporation or desorption can only occur when moisture is able to get to the surface of the material (often only at the cladding or interior surface), and be removed by the flow of air. Allowing evaporation or desorption to occur at layers within the wall assembly, particularly at the sheathing and removing the excess moisture by ventilation to the exterior therefore provides a means to remove additional moisture directly from sensitive materials and improve the drying potential of some wall assemblies.

It is becoming more common in North America to construct drained and screened walls with claddings separated from the framed wall by an air cavity as a rain control strategy to eliminate capillary flow between the cladding and sheathing, provide drainage of incidental moisture, and provide some venting or ventilation to remove evaporated/desorbed moisture. Practitioners and builders have sometimes found this gap to be beneficial, particularly in rainy climates such as coastal British Columbia where so-called “rainscreen” wall assemblies are now required by code for most new buildings.

The separation of the cladding from the wall assembly has sparked much debate among the building science community. The functions and benefits of providing this cavity are not seen as necessary by all those parties involved, and the actual characteristics of the cavity and vent/drains has not been scientifically determined as a function of performance required. Although the drainage and a capillary break are obvious improvements, the need for and role of ventilation in improving drying is still debated. Recent ASHRAE-sponsored research however has been able to predict ventilation rates and show the benefits of ventilation on ventilation drying and reduction of inward solar-driven vapour (Burnett et al 2004).

The ability to model the impacts of ventilation within wall assemblies using hygrothermal models has so far been limited to a few research-grade two-dimensional research models. Recently IBP/ORNL enhanced their one-dimensional hygrothermal software, WUFI 4.1, which is used by many practitioners worldwide. The new enhancement can account for the two dimensional effects of ventilation within wall assemblies, by modeling heat and moisture sources or sinks at any layer within the wall. For example, the 1% driving rain load mentioned in the proposed ASHRAE 160P can be easily simulated. The WUFI 4.1 model is further discussed in *Appendix B: Hygrothermal Modeling* and the simulations are presented throughout this thesis.

It is well accepted that moisture is one of the primary causes of premature building enclosure deterioration. Excess moisture content combined with above-freezing temperatures for long enough will cause rot, mold growth, corrosion, and discoloration of many building materials. The four major moisture sources and transport mechanisms that can damage a building enclosure are (Figure 2-15):

1. precipitation, largely driving rain, or splash-back at grade);
2. water vapour in the air transported by diffusion and/or air movement through the wall (both to interior and exterior);
3. built-in and stored moisture, particularly for concrete or wood products;
4. liquid and bound groundwater, driven by capillarity and gravity.

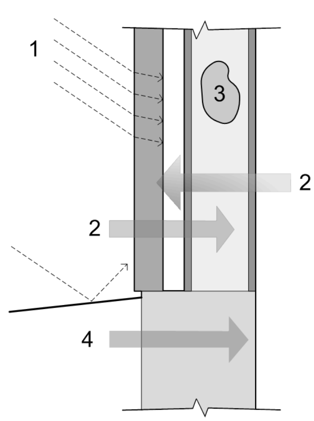


Figure 2-14: Wetting Mechanisms for Walls (Straube & Burnett 2005)

At some time during the life of a building, wetting should be expected at least in some locations. In the case of a bulk water leak, drainage, if provided, will remove the majority of the moisture from the wall cavity. However a significant amount of water will remain absorbed by materials and adhered to surfaces. This remaining moisture can be removed (dried) from the wall by the following mechanism (Figure 2-15):

1. evaporation (liquid water transported by capillarity to the inside or outside surfaces;
2. evaporation and vapour transport by diffusion, air leakage, or both either outward or inward;
3. drainage of unabsorbed liquid water, driven by gravity;
4. ventilation by convection through intentional (or unintentional) vented air cavities behind the cladding.

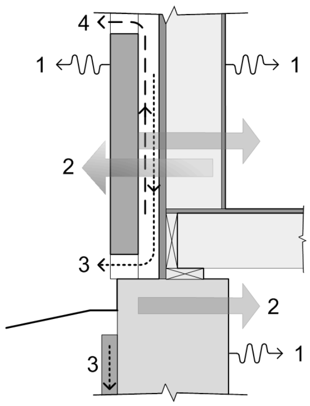


Figure 2-15: Drying Mechanisms for Walls (Straube & Burnett 2005)

A balance between wetting, drying, and storage is required to ensure the long term durability of the building enclosure. Some commonly used building materials are more sensitive to moisture (eg. paper faced gypsum and untreated wood based sheathings) and hence require a higher drying potential than the more durable materials they have replaced (eg. concrete, masonry or sawn timber). Several wide-spread building enclosure failures from the past decade including in several North American locations have further raised the awareness and impact of moisture and its impact on building materials (discussed in further detail in Chapter 3).

Recent building enclosure failures have shown that the drying potential of some wall assemblies in certain climates may be insufficient when exposed to accidental wetting or leaks. As a response to these failures, drained and screened walls have been widely recommended to deal with rainwater penetration. However, cladding ventilation may be needed or useful to increase drying for some wall assemblies in some climates. Ventilated claddings can also control wetting due to inward driven vapour from rain wetted absorbent claddings. The use of large ventilated and drained cavity has already been mandated by some building codes (NBCC 2005).

2.5 CLADDING VENTILATION

The use of ventilated air spaces behind claddings has been shown to influence the performance of some wall assemblies. Recently completed field and laboratory research has shown that cladding ventilation has the potential to increase drying and reduce wetting from absorptive claddings and sun-driven moisture. The previous field research, ventilation mechanics and driving forces are discussed here.

2.5.1 Field Research

As early as the late 1970's and early 1980's the role of ventilation behind wood claddings was being investigated in Atlantic Canada, as problems with warping and paint deterioration of wood sidings became apparent in some climates (Marshall 1983). Wood siding manufacturers performed in-house tests and found that placing wood siding over a strapped air cavity - 6 mm to 20 mm - reduced the occurrence of these moisture problems (Morrison Hershfield 1992).

Throughout the 1980's a growing number of moisture-related failures were discovered in the Canadian housing stock. Field exposure test huts were constructed in different Canadian climates to study the drying of wood-frame walls, particularly when constructed with initially saturated lumber as was common practice for parts of the country (McCuaig 1988, Forest & Walker 1990, Burnett & Reynolds 1991). These studies showed that drying built-in moisture was practical and possible, and also provided some evidence that cladding ventilation could improve drying. However, the studies were not conclusive, as test variables were insufficiently controlled to isolate the role of ventilation and its specific impact on drying.

In Europe, the Franhofer-Institut für Bauphysik (IBP) conducted field monitoring of ventilation flow and drying effectiveness for different panel claddings in several different projects. Popp et al. (1980) found that the drying rate of an initially wetted aerated concrete block-work wall was significantly faster when the cladding was ventilated or even vented compared to an impermeable cladding which was adhered directly to the concrete.

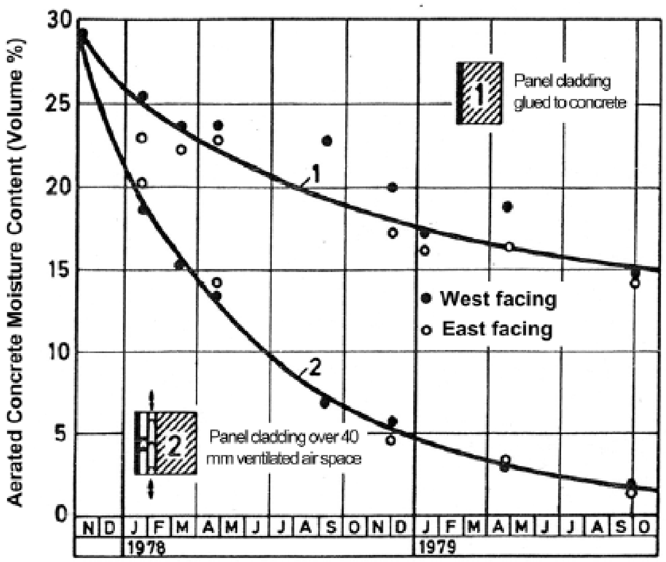


Figure 2-16: Ventilation Drying Observed in Two Wall Assemblies (Popp et al. 1980)

Similar results of ventilation drying effectiveness were also shown by Mayer and Künzel (1983) who measured ventilation behind large cladding panels on a three-storey building in service. The two forces affecting ventilation were found to be wind induced pressure differences and solar-induced thermal buoyancy. Cavity air velocities were measured between 0.05 and 0.15 m/s when the wind-speed was between 1 to 3 m/s. Wind direction influenced the ventilation air velocity more than wind-speed. From the testing they concluded that a clear cavity depth of 20 mm was generally sufficient for panel-type claddings, and although a large vent area is not absolutely necessary for acceptable wall performance, it is a practical means of removing trapped moisture. Finally it was recommended that if moisture sensitive materials are used in the backup wall, the upper and lower vent openings should be as large as possible for increased ventilation rates.

In the United States, the impacts of cladding ventilation on wood frame walls was also investigated by TenWolde and Carll (1992) and TenWolde et al (1995). These studies found that in walls with little or no air leakage (from the interior), cavity ventilation promoted drying. When air leakage was allowed it dominated the results.

In full-scale Canadian field studies, Straube and Burnett (1995) and Straube (1998) investigated the role of airspaces in ventilation drying and pressure moderation behind brick veneer and vinyl siding. The study outlined methods to calculate ventilation flow and found that cladding ventilation could be useful as a means to control inward vapour drives behind brick veneers.

Two Canadian laboratory studies investigated the role of ventilation drying of walls in Vancouver, BC in the late 1990's. The studies were directly as a result of the "leaky-condo crisis", where a large number of moisture failures were observed in the recently constructed residential housing stock in coastal British Columbia (Morrison Hershfield 1996, Barrett 1998). Both Morrison Hershfield (1999) and Forintek (2001) undertook laboratory studies to determine the impact venting or ventilation had on the performance of wood-frame wall assemblies.

In the Morrison Hershfield study (1999), full-scale insulated wall assemblies all with stucco cladding were built and initially wetted on the interior side of the sheathing. The walls were exposed to approximately 10°C exterior conditions with no air movement or solar radiation. The major conclusions of the study were that drying was slow for all wall types and that the ventilated rainscreen wall design did not enhance drying of water that penetrates into the stud cavity. Even though the parameters were untested, the authors concluded that solar radiation and wind would have no significant effect on drying, nor would other types of cladding. Applying the physics of thermal and moisture buoyancy described in the next section, calculated natural ventilation rates and driving temperature differences are very low for these walls and in hindsight it is clear why ventilation drying would not have been effective in these test conditions.

The Forintek Envelope Drying Rate Analysis (EDRA) study (2001) was larger and studied more parameters in simulated environments. Two phases were completed, one without simulated exterior wind and solar effects and one with. Solar radiation was simulated up to a 120 W/m^2 peak, equivalent to diffuse radiation on a north facing wall in Vancouver. Wind pressure differences of 1 to 5 Pa between top and bottom vents were also simulated. The walls were initially soaked to pre-wet the sheathing and studs, and hence had a relatively uniform distribution of moisture. The sample walls included both stucco and vinyl siding, vented and ventilated designs, SBPO and building paper sheathing membranes, and OSB and plywood sheathing. Some of the conclusions from the study included:

- Walls with cavities (vented and ventilated) dried faster than comparable panels without cavities (face-sealed). There was a substantial range in the drying rates: as much as three times higher drying rate for comparable walls with a ventilated cavity than for those without.

- Ventilation (top and bottom vents) resulted in marginally faster drying than vented (bottom vents) walls. The width of cavity was also important, and those walls with cavities of 19 mm dried faster than 10 mm.
- Walls with plywood dried faster than comparable walls with OSB sheathing. OSB has a lower vapour permeance than plywood and may have restricted the drying through the sheathing to the exterior.
- Solar radiation increased drying rates of the ventilated walls but had little effect on the face-sealed walls (all walls were restricted from drying to the interior by a low permeance interior vapour barrier).

Recently ASHRAE sponsored a large research and development project (ASHRAE TRP-1091) to study the mechanics of ventilation in wall systems and assess the potential for ventilation drying of common, above-grade residential wall assemblies. Three institutions were involved in this project, namely, the Pennsylvania Housing Research/Resource Center at Penn State (PHRC/PSU), the Building Engineering Group at the University of Waterloo (BEG/UW) and the Building Technology Center at Oak Ridge National Laboratory (BTC/ORNL). The project produced a total of 12 reports and numerous conference and journal papers and is summarized by Burnett et al. (2004).

A review of the literature and theory was performed, hygrothermal properties of several materials were determined, a study of ventilation flows was performed for brick veneer and vinyl siding, the impact of ventilation drying was determined, CFD simulations were performed, and the Moisture-Expert hygrothermal model was validated using the field data which allowed further parametric simulations to be performed. The following conclusions were made from the study:

- Ventilation rates are dependent on the cladding and venting configuration (size and type of openings) and strongly influenced by weather events (wind and solar radiation). Brick veneer walls had lower ventilation rates than vinyl siding walls.
- Solar-driven vapour diffusion can act to redistribute vapour from within the wall to the interior, where it can condense and in some cases, cause damage. Cladding ventilation reduces the magnitude of this flow as this vapour is directly removed to the exterior.

- Installing vents installed at both the top and bottom of a brick wall cavity was shown to benefit drying. Ventilation was more effective than venting (bottom vents only).
- For a 1.22 m wide by 2.4 m high wall with a 20 mm deep cavity with two open head joints (no bug-screen) at top and bottom, ventilation rates were predicted and confirmed to be between 0 to 90 ACH or 0 to 0.50 lps/m^2 of cladding.
- Plastic bug-screens typically installed in the vent openings are restrictive to flow and will significantly reduce this ventilation rate, by an order of magnitude.
- The vinyl siding profile tested allowed significant ventilation-induced drying with or without furring strips as it was inherently very leaky. Considerable flow occurs across the cladding, upward and downward and laterally as shown in Figure 2-17. Further work by van Straaten (2004) demonstrated ventilation pathways for wood siding systems as well (Figure 2-18).

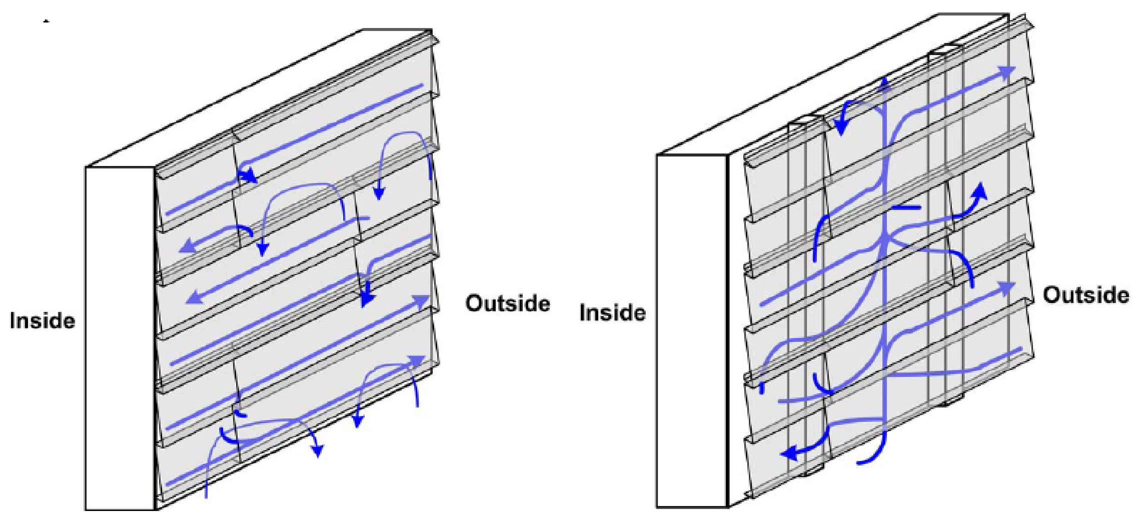


Figure 2-17: Airflow Pathways behind Vinyl Siding (Contact Applied at Left, Strapped at Right) (van Straaten 2004).

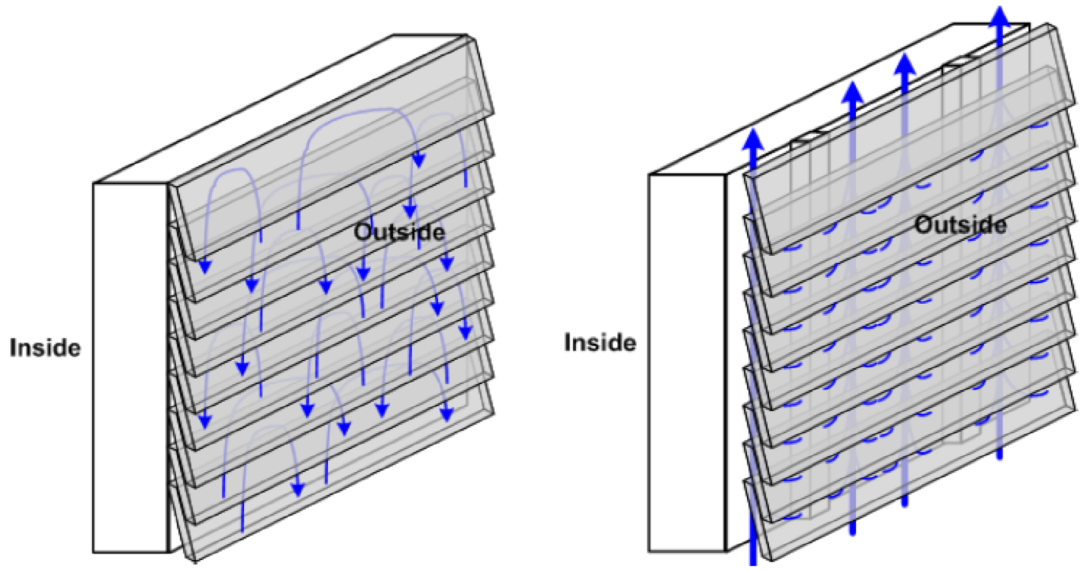


Figure 2-18: Airflow Pathways behind Wood Siding (Contact Applied at Left, Strapped at Right) (van Straaten 2004).

- For a 1.22 m wide by 2.4 m high wall, contact-applied vinyl siding can be expected to be in the range of 0.6 to 2.7 lps/m² for pressures of 1 to 10 Pa.
- The effective ventilation rate behind the cladding was dependent on both the wall system and exterior climate. High winds and high temperature gradients produced higher flow rates.
- Fast-drying wall designs can be repeatedly wetted over several years and remain in almost perfect condition without damage.
- Higher ventilation rates behind the cladding increased the drying rate of an initially wetted wall as shown in Figure 2-19.

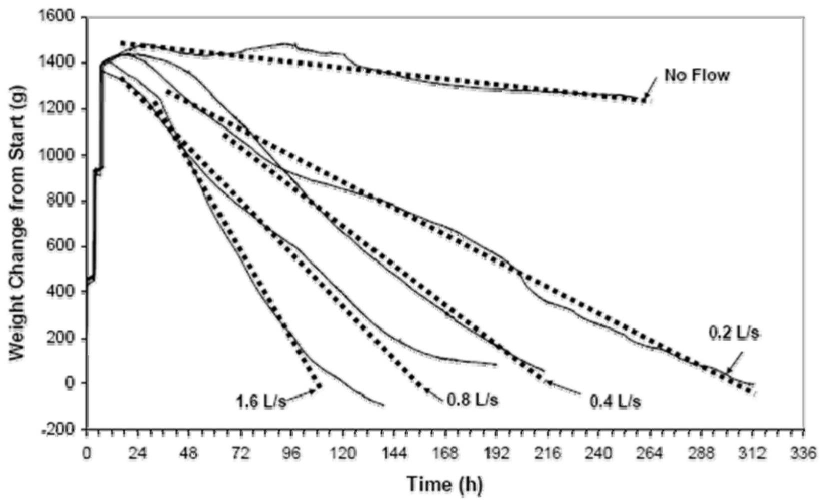


Figure 2-19: Drying Comparison for a 50 mm Cavity with Different Ventilation Rates (Schumacher et al. 2004)

Also part of the ASHRAE-1091 project, the MOISTURE-EXPERT hygrothermal model was validated with measured laboratory and field results of ventilated walls. Good agreement between the modeled and measured data was demonstrated (Karagiozis 2004). Using the model, parametric simulations were performed to make recommendations to other wall assemblies and in different climates.

Recently Bassett and McNeil (2006) measured ventilation flows behind several cladding types in a field exposed lab in New Zealand using Carbon Dioxide (CO_2) as a tracer gas. Claddings included fiber cement board, EIFS, and brick veneer. They found excellent agreement between calculated and measured results using equations provided by Straube and Burnett (1995) which are essentially the same as those presented in the next section by Straube et al. (2004). Calculated versus measured ventilation rates are shown in Figure 2-20 with good agreement for four different ventilation configurations tested. The drained and ventilated walls have top and bottom vents, open rainscreen walls have only bottom vents and drainage plane walls only have bottom vents but air flow is restricted by the use of a nylon drainage mat in the cavity.

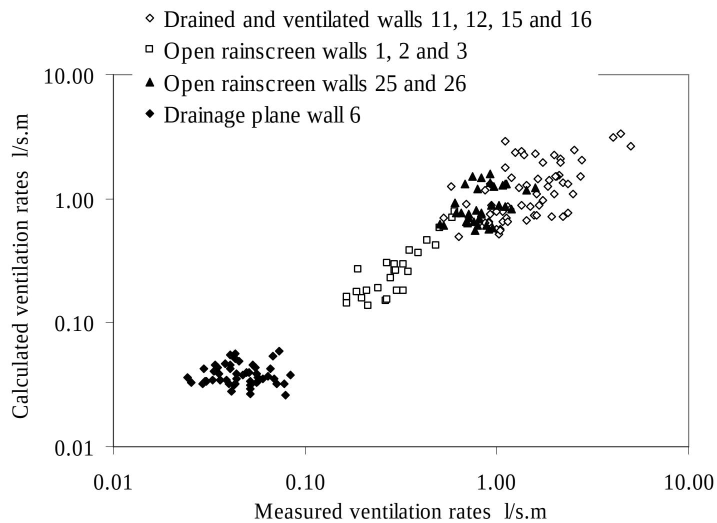


Figure 2-20: Ventilation Rates behind Claddings (Bassett and McNeil 2006)

Further work by McNeil and Bassett (2007) demonstrated the effects of the cladding ventilation configuration and drying time for a wetted wall. They found that drained and ventilated walls (rainscreen type assemblies) dried considerably faster than just drained or direct-fixed cladding (Figure 2-21). Note that the work was completed in New Zealand in the Southern Hemisphere; therefore south facing walls there would behave like our north facing walls, seeing little solar radiation.

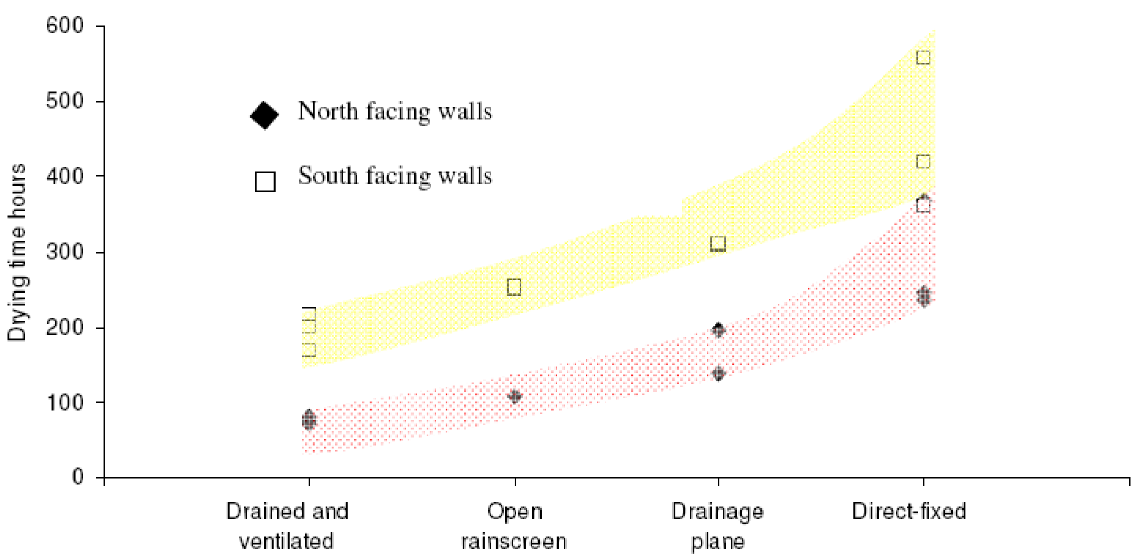


Figure 2-21: Drying Times for Different Ventilation Configurations (Bassett and McNeil 2007)

Recent studies of drainage spaces behind claddings further show the impact of cladding ventilation on wall performance. At the University of Waterloo, Smegal (2006) showed that while the majority of water that enters the cavity behind the cladding will be drained, some moisture will also remain after drainage stops, stored on surfaces by surface tension and/or absorbed into porous materials. Even vinyl siding will store a considerable amount of moisture in the drainage tracks and by capillary suction between laps. After drainage is complete (within a few seconds) the most effective way to remove this additional moisture from the wall assembly is by ventilation.

In summary, while some of the past research shows conflicting results, the consensus in recent years is that cladding ventilation can improve the drying potential of wood-frame walls when exposed to initial or periodic wetting events. Measured ventilation flow rates show good agreement with the presented theory, and can be predicted using CFD models. Therefore the ventilation theory could potentially be applied a hygrothermal model to predict field performance.

2.5.2 Ventilation Mechanics

Ventilation drying occurs when convective forces cause moist air to be moved out of an air space and replaced with drier air. Drying of an air space involves the evaporation or desorption of moisture from materials adjacent to the airspace, followed by convective transport of moisture to the exterior environment. Ventilation within a wall system therefore has potential as a means of drying for some wall systems.

Ventilation flow through a wall cavity is analogous to fluid flow through a pipe network with calculable pressure drops from cavity friction and vent openings. Fluid flow equations are well developed from civil and mechanical engineering applications and are presented in the current ASHRAE Handbook of Fundamentals (2005).

Methods to numerically calculate airflow rates through ventilation spaces behind cladding and determine the forces driving ventilation are presented by Straube and Burnett (1995), Straube (1998) and most recently by Straube et al. (2004) using empirical and well established fluid flow mechanics. Pressure differences between the top and bottom vents will drive ventilation flow through the cavity, and at equilibrium the pressure drop across the cavity and vent openings will equal the pressure difference as a result of the driving forces. Driving forces include thermal and moisture buoyancy and wind pressures.

The following equations developed in the ASHRAE TRP-1091 reports (Straube et al. 2004) are summarized here for a panel cladding with a continuous vent opening, and a brick veneer wall with discrete vent openings (at head joints).
The pressure balance through the ventilated cavity can be simplified to:

$$\Delta P_{Total} = \Delta P_{entrance} + \Delta P_{cavity} + \Delta P_{exit} \qquad \text{(eq. 1)}$$

For a panel cladding, such as stucco or cement board with continuous slot vents, the pressures can be determined from:

$$\Delta P_{Total} = C_{entrance} \cdot 0.5\rho \cdot V^2 + \frac{32 \cdot k_f \cdot V \cdot \mu \cdot L}{\gamma_c \cdot D_h^{\;2}} + C_{exit} \cdot 0.5\rho \cdot V^2 \qquad \text{(eq. 2)}$$

Where, C is a flow coefficient for the entrance/elbow/exit, from published literature,
ρ is the density of air (kg/m3),
V is the velocity, through the vent or cavity (m/s),
k_f is a correction factor for a rectangular conduit,
μ is the dynamic viscosity of air (18.1×10^{-6} N·s/m^2),
L is the cavity length (m),
γ_c is a cavity blockage factor to account for mortar protrusions etc, and
D_h is the hydraulic diameter of the cavity (m).

The ventilation flow path for a wall with top and bottom strip vent openings is shown in Figure 2-22.

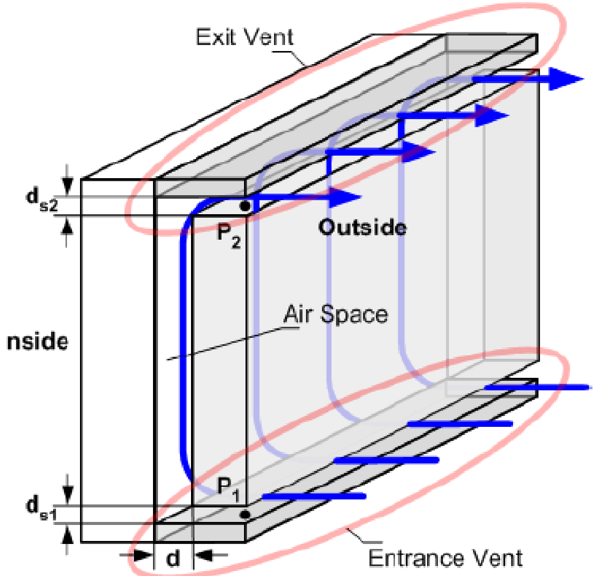


Figure 2-22: Wall with Top and Bottom Slots (van Straaten 2004)

For brick veneers, the top and bottom vents can be treated as standard sharp edge orifices (Straube and Burnett 1995), and the equation is simplified to:

$$\Delta P_{Total} = \left(\frac{Q_{vent1}}{0.6 \cdot h_{v1} \cdot w_{v1} \cdot \gamma_{v1}} \right)^2 + \frac{32 \cdot k_f \cdot V \cdot \mu \cdot L}{\gamma_c \cdot D_h^{\ 2}} + \left(\frac{Q_{vent2}}{0.6 \cdot h_{v2} \cdot w_{v2} \cdot \gamma_{v2}} \right)^2 \qquad \text{(eq. 3)}$$

Where, Qv is the airflow through each vent (m^3/s),
h_v and w_v are the vent height and width (m), and
γ_v is a vent blockage factor to account for bug-screens or other physical obstructions etc.

Guidance to selecting appropriate cavity or vent blockage factors can be found in Straube et al. (2004), and are related geometrically to correct for the actual versus intended size of opening (ie. a cavity blockage factor of 0.5 relates to a 50% restriction in size).

The ventilation flow path for a wall with top and bottom strip vent openings is shown in Figure 2-24.

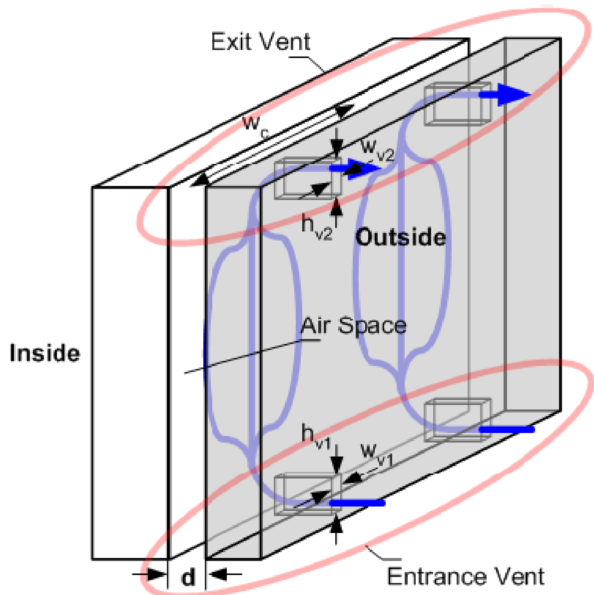


Figure 2-23: Wall with Top and Bottom Vent Holes

The equations presented here assume laminar flow, which typically occurs in the field. Where turbulent flows occur the equations can be modified accordingly. CFD modeling refinements by Piñon et al (2004) and Stovall and Karagiozis (2004) confirm the development of fully laminar air flows within the cavity and refine some loss coefficients in brick vents to reflect non-laminar flow.

Four typical North American wood-frame wall assemblies with ventilated claddings are compared below using the flow theory presented above. Details were selected to be representative of common practice and to show the relative differences in ventilation flows between cladding types as a result of the selected vent configurations. The four walls are described in Table 2-1, and using the presented equations, the air velocity and ventilation flow versus pressure is presented in Figure 2-24 and Figure 2-25.

Table 2-1: Ventilation Cavity and Vent Details for Four Cladding Types

	1. Cement Stucco on backer board on strapping	**2. Horizontal wood siding (or cement board) on strapping**	**3. Brick Veneer with top and bottom vents**	**4. Metal Panel with slot vents**
Cavity Notes	19 x 38 mm wood strapping at 400 mm o.c.	19 x 38 mm wood strapping at 400 mm o.c.	25 mm open cavity, brick ties as required	12 mm open cavity, steel z-girts at 914 mm o.c.
Cavity width	362 mm	362 mm	Continuous, per 1000 mm width	914 mm
Cavity depth	19 mm	19 mm	25 mm	12 mm
Cavity height	2743 mm	2743 mm	2743 mm	2743 mm
Cavity Blockage Factor - γ_c (0.01 to 1)	0.9 (assume slight bowing of stucco backer board when stucco is installed	1.0 (cladding is rigid enough to span between strapping)	0.8 (mortar protrusions in well constructed brick veneer)	1.0 (smooth metal panel)
Vent Notes	Continuous through-wall flashing at floor height top and bottom	Continuous through-wall flashing at floor height top and bottom	Spaced every 2 bricks top and bottom	Drilled or punched slot vents top and bottom
Vent dimensions	12 mm bottom, 12 mm top – both continuous	19 mm bottom, 19 mm top – both continuous	10 mm x 65 mm spaced @ 400 mm	6 mm x 25 mm spaced @ 456 mm (1.5′)
Vent Blockage Factor - γ_v (0.01 to 1)	0.5 - mesh bug-screen, estimate	0.5 - mesh bug screen, estimate	0.1 - plastic bug-screen insert (Straube 1998)	1.0 – open slots, no restrictions

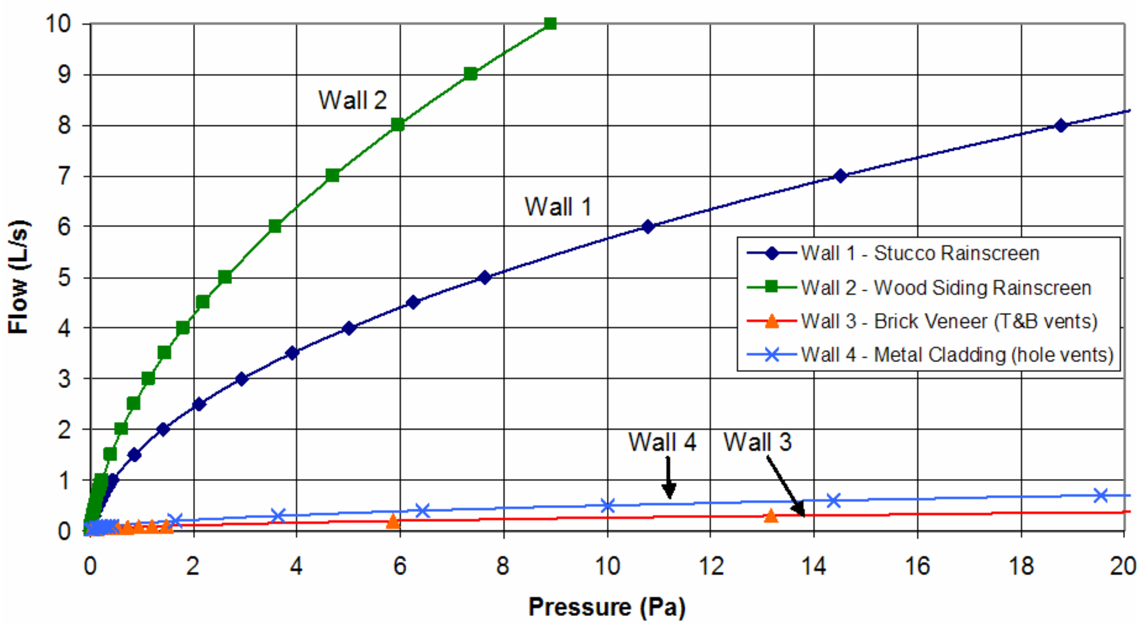


Figure 2-24: Velocity versus Pressure for Walls 1 through 4.

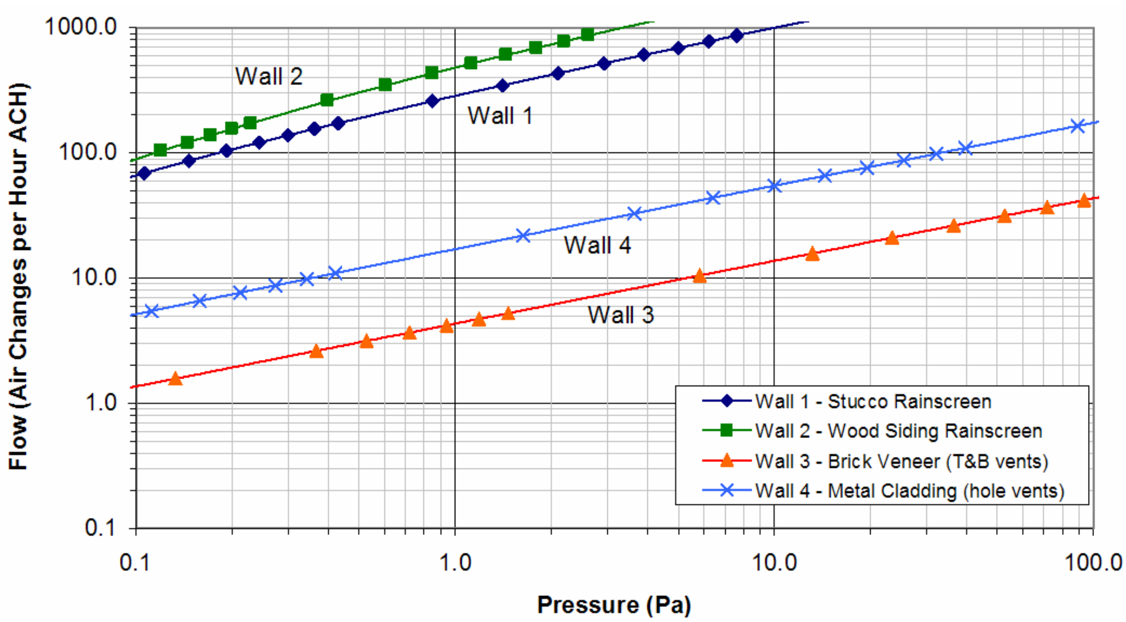


Figure 2-25: Air Flow versus Pressure for Walls 1 through 4.

As shown, the wall systems with large open vents (panel claddings) will have large ventilation rates at relatively low driving pressures. Therefore under normal conditions they will be well ventilated whereas wall systems with small restricted vents require much higher driving pressures to attain large ventilation rates.

Vinyl siding, while commonly used, was not compared above as ventilation flow cannot be accurately calculated. Laboratory testing has shown that vinyl siding profiles are very leaky and have numerous flow paths through and around the cladding (van Straaten 2004). For modeling purposes it can however be assumed that the ventilation rate is very high when vinyl cladding is used and one could calculate flows for a panel cladding (Equation 2) with wide open unobstructed vents as a reasonable estimate to account for the leakage through multiple paths, similar to Wall 2.

Once the flow versus pressure relationship is determined for a specific wall and vent arrangement, the driving pressures can be applied to determine the ventilation rate.

2.5.3 <u>Driving Forces</u>

Ventilation flow is driven by a combination of thermal buoyancy, moisture buoyancy and wind pressures. When a difference of pressure between the air cavity and exterior exists, ventilation flow will occur.

Thermal buoyancy and moisture buoyancy are relatively predictable and often steady, and can be high when the materials lining the ventilation cavity are wet. A difference in density between the air in the cavity and the exterior (as a result of temperature and vapour content) will drive buoyancy flows as shown in Figure 2-26.

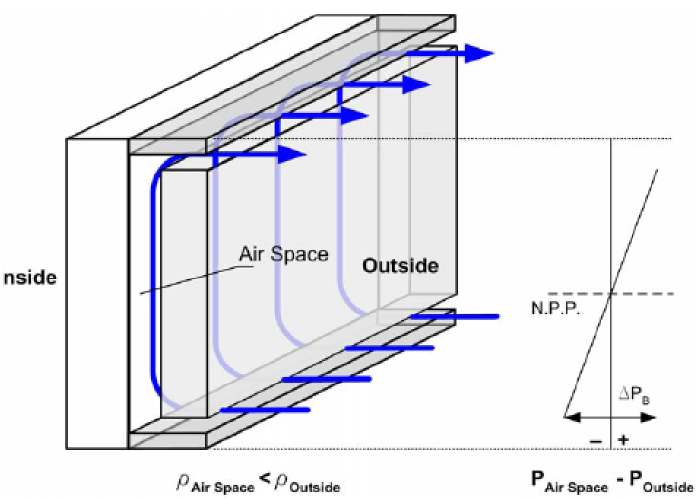


Figure 2-26: Buoyancy Ventilation Flow (van Straaten 2004)

Combined thermal and moisture buoyancy can be calculated from the following simple equation (Straube et al. 2004):

$$\Delta P_{buoyancy} = [\rho_{exterior} - \rho_{\mathrm{int}\,erior}] \cdot g \cdot L \qquad \text{(eq. 4)}$$

Where, ρ is the density of moist air at specific temperature and RH (ASHRAE 2005) and
L is the height of the ventilated cavity (m).

Wind pressures are highly variable, and can be very large for short periods of time. For wind to drive ventilation pressures, a pressure differential must occur between connected vent openings, and this pressure difference vary with wind speed and direction (Straube 1998, Straube et al. 2004). The differential pressures between top and bottom vent openings, which drives ventilation flow, can be difficult to determine. Simple stagnation pressure coefficients (C_p) factors have been developed for square building shapes and could be used for static cases, where the C_p factor at the top and bottom vent is determined, and the difference between the two is the ventilation factor (C_{pv}). Unfortunately the basic factors rarely represent buildings in the field (due to shape and other influences), and vary with wind direction. More accurately these C_p factors can be determined for a specific building with use of CFD modeling, wind tunnel studies, or field monitoring.

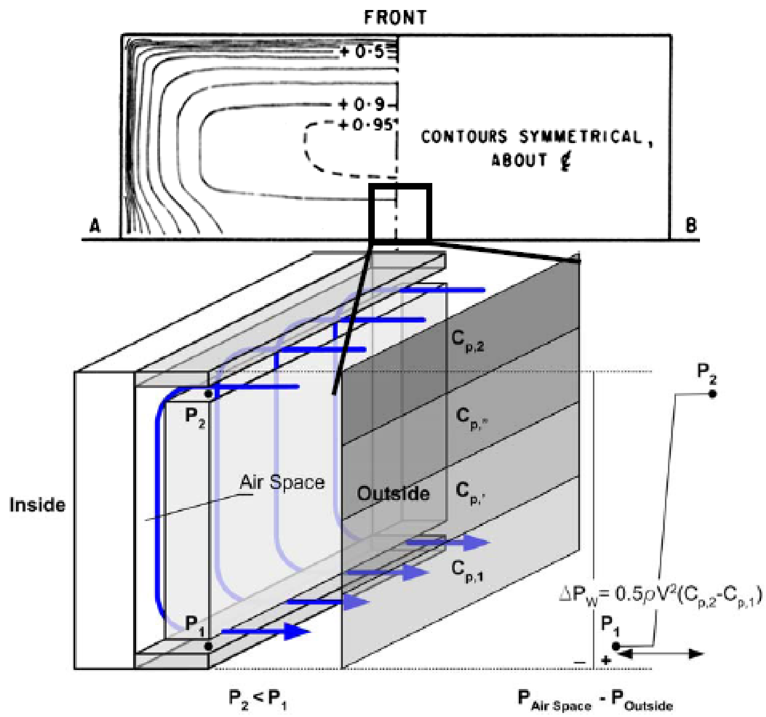


Figure 2-27: Wind Pressure Driving Ventilation Flow (van Straaten 2004)

The wind stagnation pressure ($P_{stagnation}$) on the wall is determined and correlated to a specific location using a ventilation pressure coefficient (C_{pv}), and finally the ventilation pressure ($P_{ventilation}$) is determined by:

$$P_{stagnation} = \frac{1}{2}\rho V_{wind}{}^{2} \qquad \text{(eq. 5)}$$

$$P_{ventilation} = C_{pv} \cdot P_{stagnation} \qquad \text{(eq. 6)}$$

Where C_{pv} is the difference in wind pressure between the top and bottom vent openings equal to:

$$C_{pv} = C_{p,top} - C_{p,bottom} \qquad \text{(eq. 7)}$$

Further assistance to estimating C_p factors for simple building shapes can be found in most Building Code commentaries, for example the NBCC 2005 Part 4, Structural Commentary.

2.5.4 <u>Predicted Ventilation Rates</u>

Ventilation rates are calculated in this section using field data from the three wood-frame buildings in this study (presented later in this thesis) and from the University of Waterloo's BEGHut test facility. A summary of the buildings is provided in Table 2-2 including the typical wall assembly and ventilation cavity details. The buildings in this study (Buildings 1, 2 & 4) are fully introduced and presented in Chapter 4, however used here to complete the discussion on cladding ventilation.

Table 2-2: Summary of Buildings used to Calculate Ventilation Rates

Vancouver – Building 1 4 storey, vinyl clad rainscreen walls – new construction	**Vancouver – Building 2** 4 storey, stucco clad rainscreen walls – rehabilitation project	**Vancouver – Building 4** 4 storey, cement board rainscreen (floors 2-4) and brick veneer (floor 1) – new construction	**Waterloo – BEGHut** 1 storey, brick veneer – field exposed test facility
			
- vinyl siding - 19 mm ventilated cavity (19mm treated wood strapping @ 400 mm) - 2 layers 30 min building paper - 13 mm plywood - 140 mm fiberglass batt - 6 mil polyethylene - 12 mm gypsum drywall - latex paint and primer	- 19 mm stucco cladding - 19 mm ventilated cavity (19mm treated wood strapping @ 400 mm) - 1 layer SBPO house-wrap - 13 mm plywood - 140 mm fiberglass batt - 4 mil polyethylene - 12 mm gypsum drywall - latex paint and primer	- 6 mm cement board - 19 mm ventilated cavity (19mm treated wood strapping @ 400 mm) - 2 layers 30-min building paper - 13 mm plywood - 89 mm fiberglass batt - 6 mil polyethylene - 12 mm gypsum drywall - latex paint and primer	- 89 mm clay brick - 38 mm ventilated cavity (openings at 400mm top and bottom) - 1 layer SBPO house-wrap - 12 mm OSB sheathing - 140 mm open or closed cell sprayfoam - 12 mm gypsum drywall - latex paint and primer
Continuous vent openings at 2^{nd} and 4^{th} floors (cavity flashing). Approx 12 mm opening between vinyl starter track and metal flashing.	Continuous vent openings at every floor level (cavity flashing). Approx 12 mm opening top and bottom vent with bug-screen.	Continuous vent openings at every floor level. (cavity flashing). Approx 12 mm opening top and bottom vent with bug-screen.	Brick vent slot openings, at every other brick, top and bottom (400 mm o.c.). 10 mm x 65 mm opening, with plastic bug-screen insert.

At one monitored location at Building 4 the wall assembly consisted of a brick veneer cladding over wood-frame wall, similar in construction to that at the BEGHut. However, the venting arrangement consisted of 10 mm x 65 mm open head joints at the base of the wall (without bug-screens) and a continuous 6 mm slot vent at the top of the 3 m tall wall.

The ventilation flow versus pressure relationship is calculated for each wall assembly and is summarized in Figure 2-28.

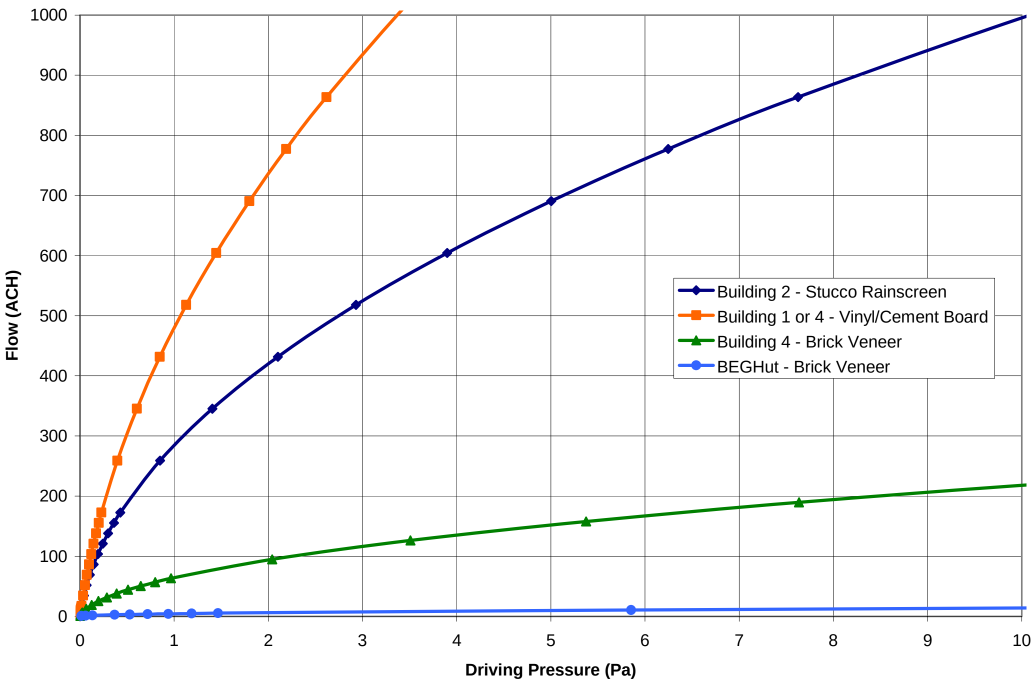


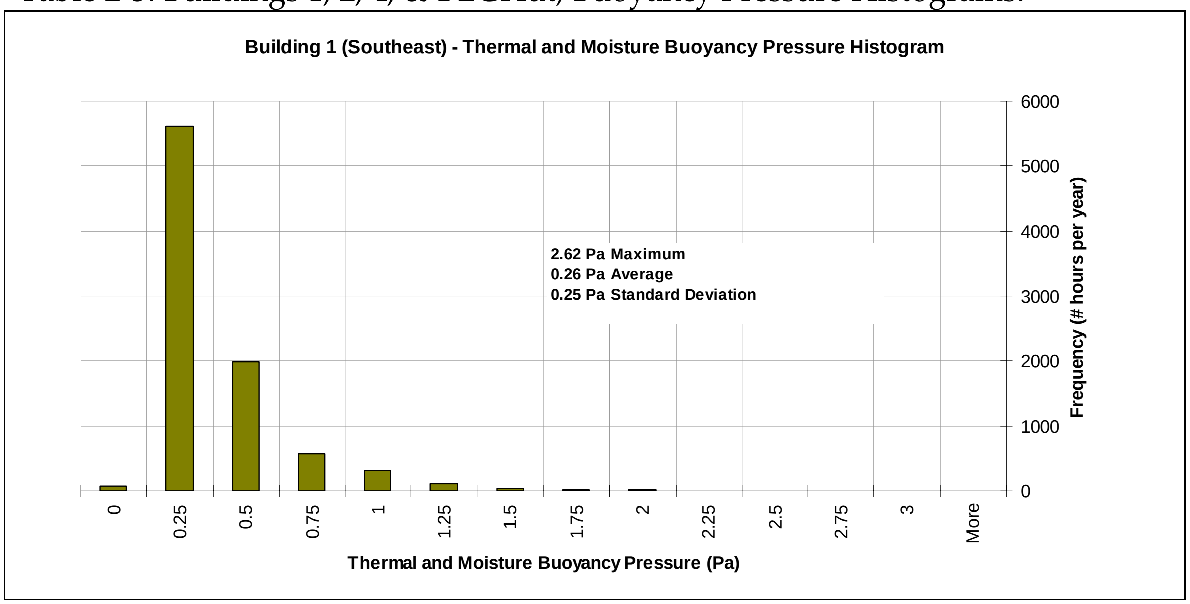
Figure 2-28: Flow versus Pressure Relationships for Building 1, 2, 4 & BEGHut

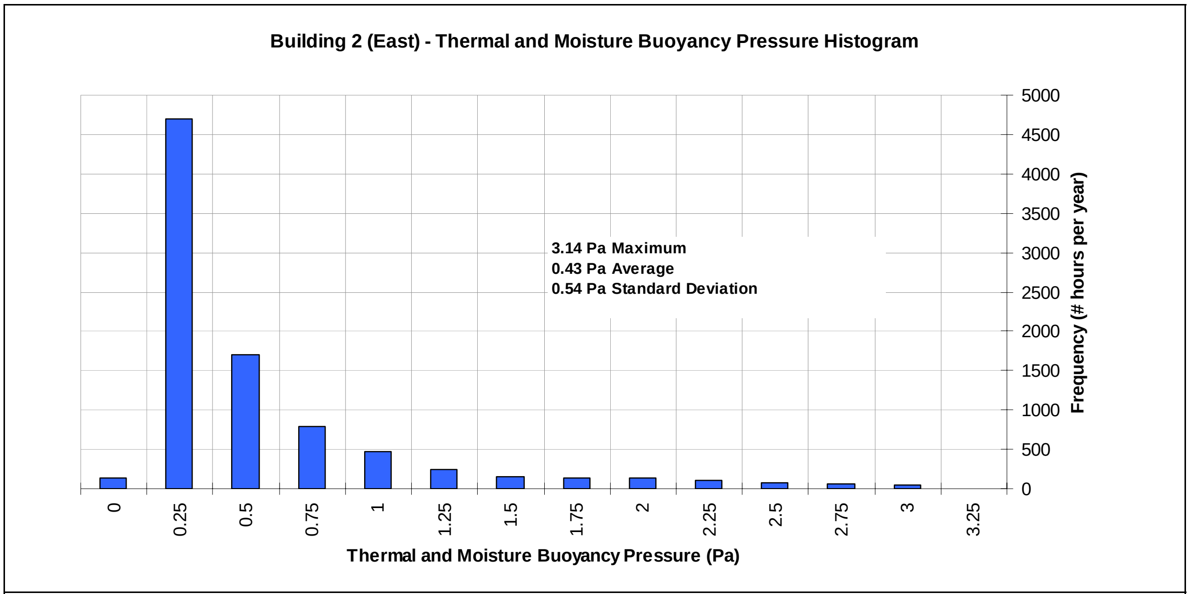
Hourly wind ventilation pressures were calculated for the BEGHut brick veneer walls from Equations 4, 5, & 6 in addition to previously developed wind directional ventilation pressure coefficients from Straube (1998) (ie. same building, wall type, and vent arrangement as previously studied). Total driving pressures were compared before and after the addition of the wind pressures and while significant as a percentage, had only a small impact on the overall ventilation rates. Wind pressures increased the average annual ventilation rate from 1.6 ACH to 2.1 ACH on the north to 2.2 to 2.3 ACH on the south, the baseline being thermal and moisture buoyancy pressures only.

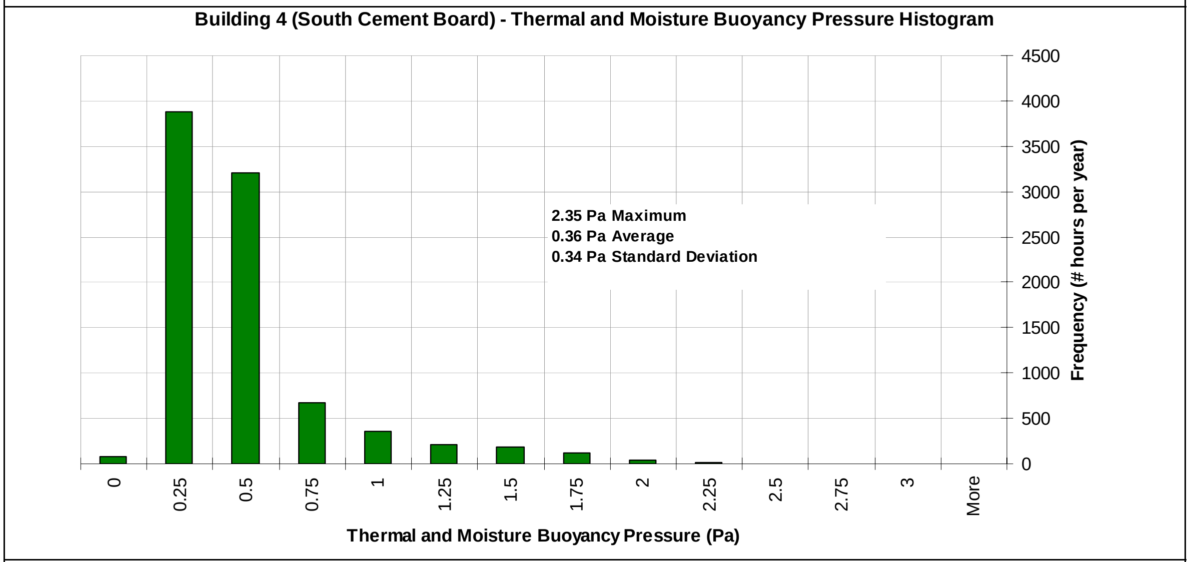
For the three Vancouver buildings presented, wind direction and ventilation pressure coefficients cannot easily be determined as the buildings are a different shape and height and have a different vent configuration than the BEGHut. Therefore cladding ventilation as a result of wind pressure was excluded from the analysis of these walls. However it will be shown later that the additional effect of wind driven ventilation may only have a minor impact on the results as high ventilation rates are already observed from thermal and moisture buoyancy alone. Although wind will significantly improve ventilation behind the claddings of these buildings, it will be shown that buoyancy pressures alone can generate high ventilation flows. Once high ventilation flows are reached, the additional impact of wind-induced ventilation will have little impact on the performance of these wall assemblies.

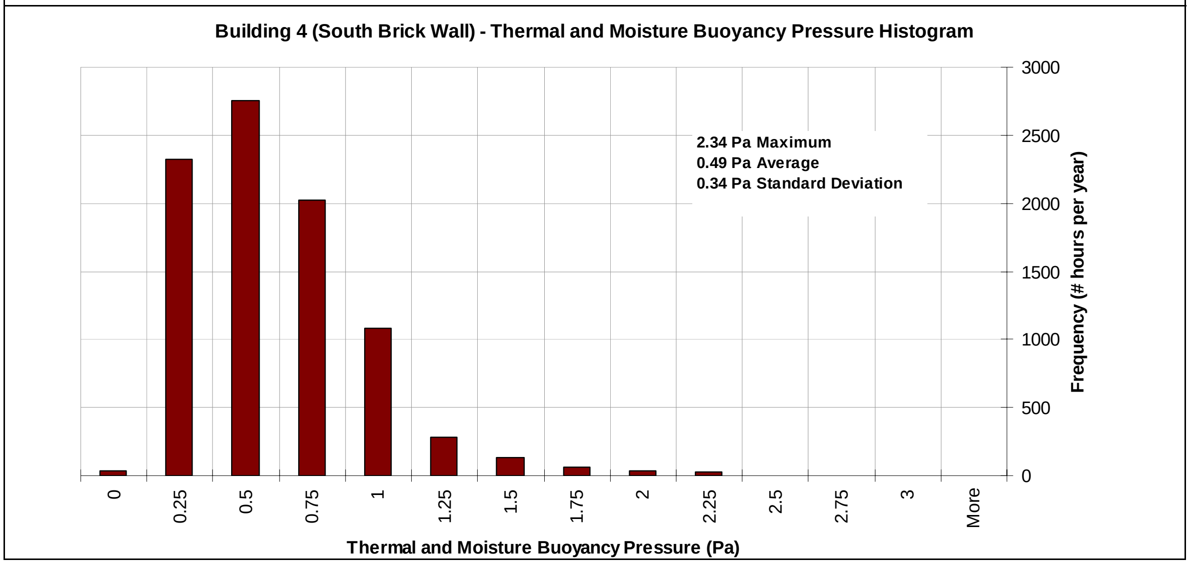
Applying the pressure-ventilation relationships, an annual histogram of the hourly calculated buoyancy pressures is presented in Table 2-3 and subsequent ventilation rates for the four buildings in Table 2-4. One wall location was chosen to be representative each building and an entire year of data is presented. Small differences were observed between wall locations (based on orientation) however were consistent with those presented here.

Table 2-3: Buildings 1, 2, 4, & BEGHut, Buoyancy Pressure Histograms.




Building 2 (East) - Thermal and Moisture Buoyancy Pressure Histogram
3.14 Pa Maximum
0.43 Pa Average
0.54 Pa Standard Deviation
Frequency (# hours per year)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
3.25
Thermal and Moisture Buoyancy Pressure (Pa)


Building 4 (South Cement Board) - Thermal and Moisture Buoyancy Pressure Histogram
2.35 Pa Maximum
0.36 Pa Average
0.34 Pa Standard Deviation
Frequency (# hours per year)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
More
Thermal and Moisture Buoyancy Pressure (Pa)


Building 4 (South Brick Wall) - Thermal and Moisture Buoyancy Pressure Histogram
2.34 Pa Maximum
0.49 Pa Average
0.34 Pa Standard Deviation
Frequency (# hours per year)
3000
2500
2000
1500
1000
500
0
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
More
Thermal and Moisture Buoyancy Pressure (Pa)

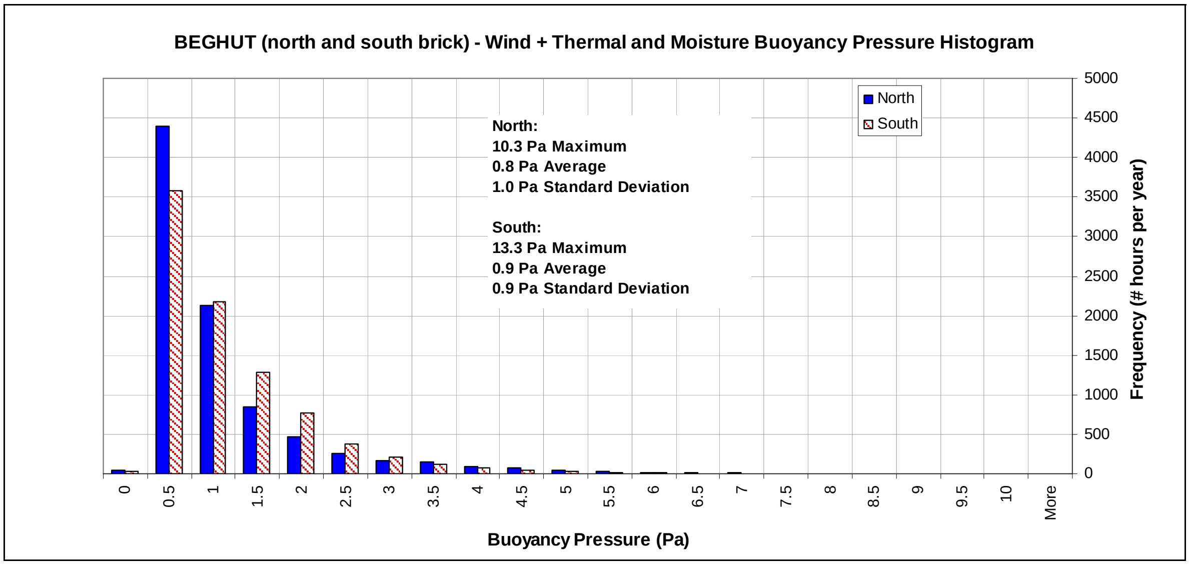
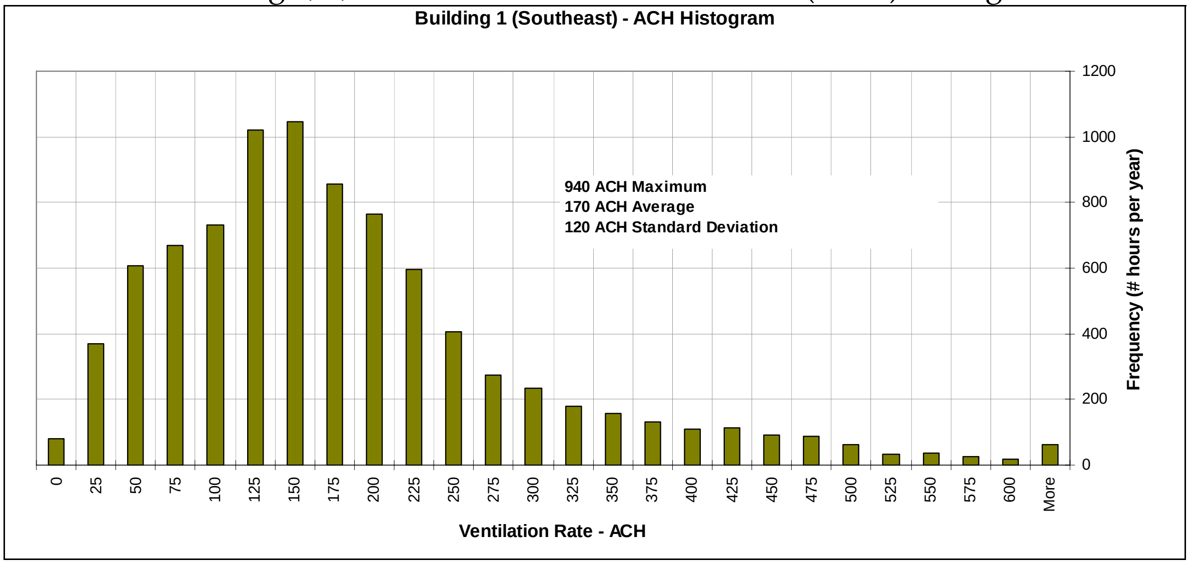
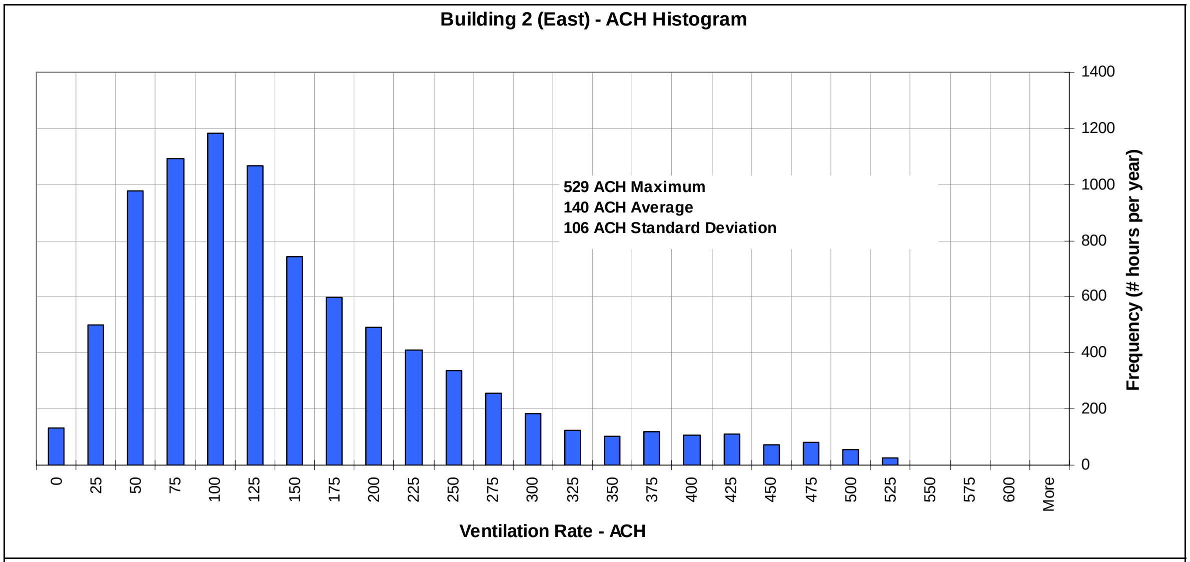
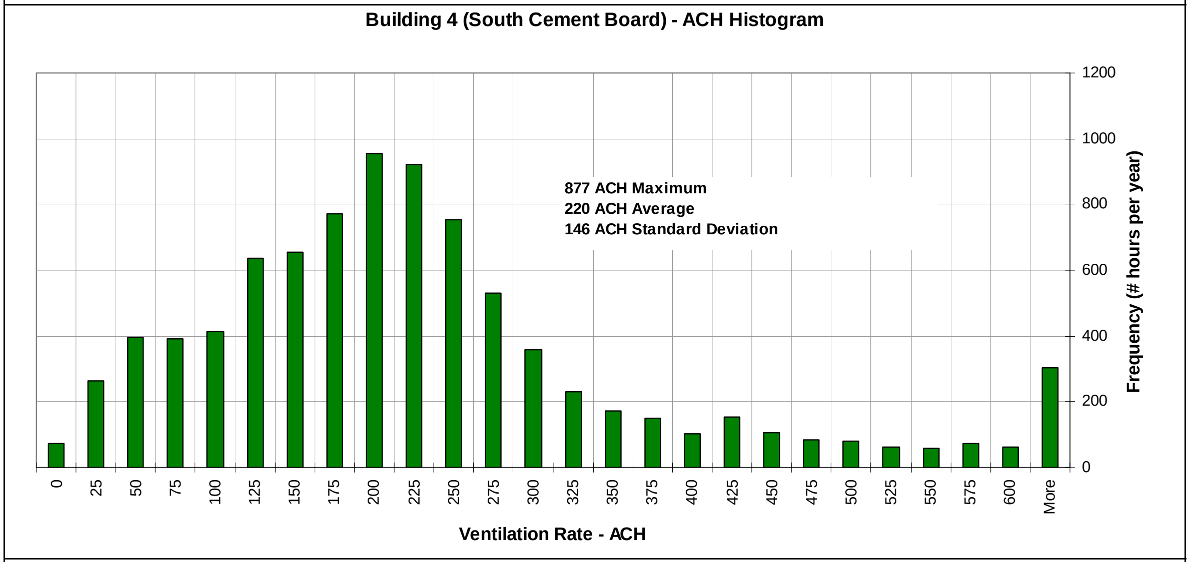
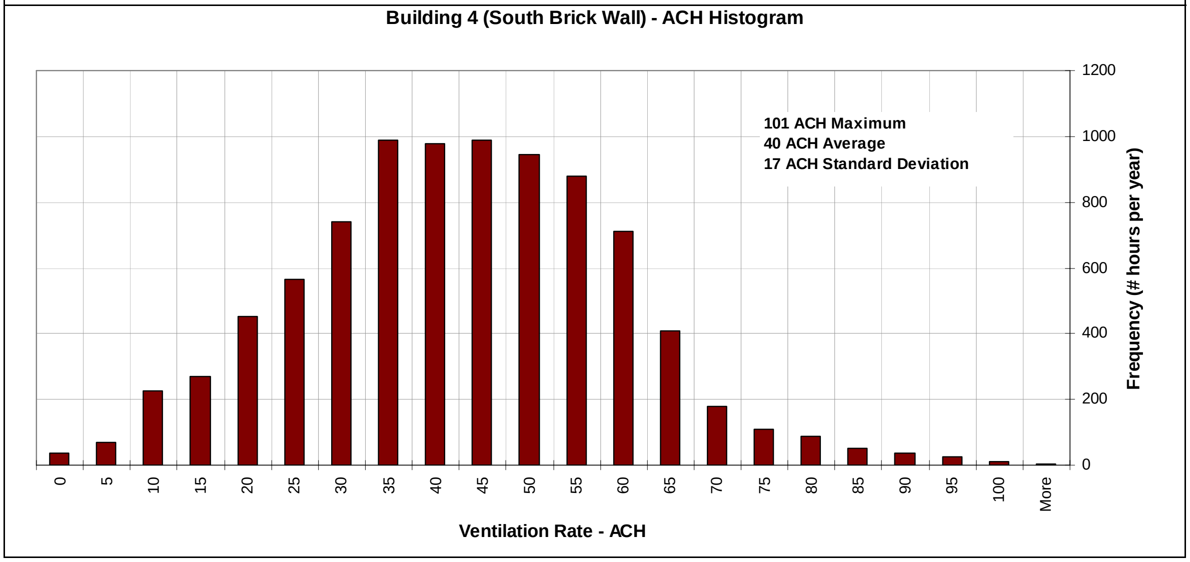


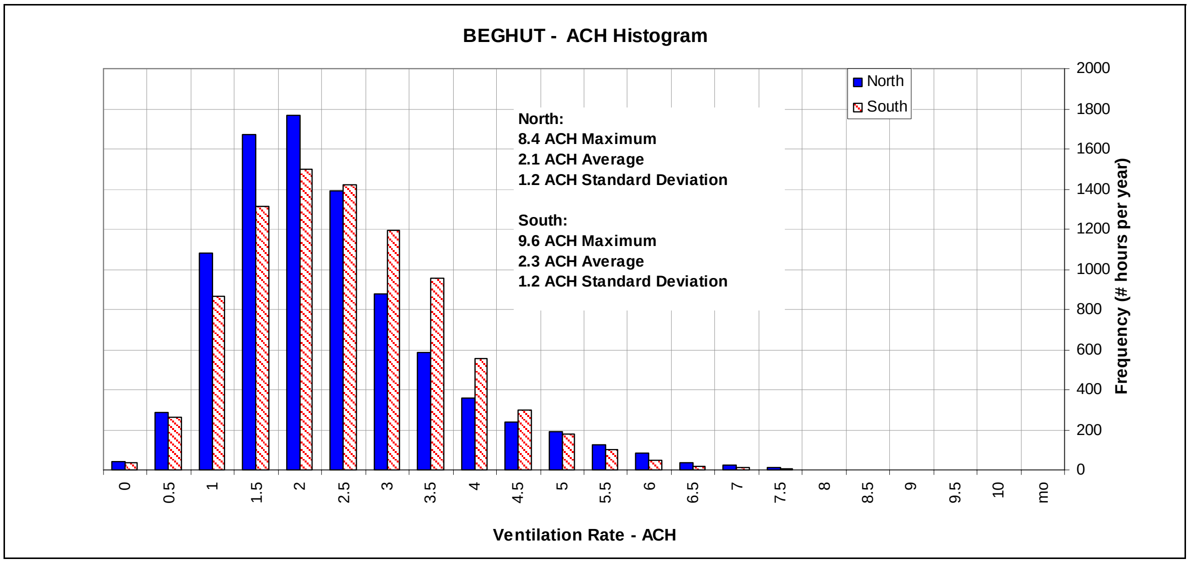
Table 2-4: Building 1, 2, 4 & BEGHut –Ventilation Flow (ACH) Histogram




Building 2 (East) - ACH Histogram
529 ACH Maximum
140 ACH Average
106 ACH Standard Deviation
Frequency (# hours per year)
Ventilation Rate - ACH


Building 4 (South Cement Board) - ACH Histogram
877 ACH Maximum
220 ACH Average
146 ACH Standard Deviation
Frequency (# hours per year)
Ventilation Rate - ACH


Building 4 (South Brick Wall) - ACH Histogram
101 ACH Maximum
40 ACH Average
17 ACH Standard Deviation
Frequency (# hours per year)
Ventilation Rate - ACH



The calculated ventilation rates for the three Vancouver buildings are similar to that measured by Bassett and McNeil (2006) in Figure 2-20. Bassett and McNeil measured ventilation rates of 0.5 to 10 L/s/m for similar type walls which equates to 40 to 800 ACH, similar to the distribution of rates shown above. The brick veneer wall at Building 4 saw the lower ventilation flows due to the smaller top and bottom brick vent openings. The BEGHut saw the lowest calculated ventilation rates and are consistent with previously reported values (Straube 1998), accounting for the flow reduction from the plastic bug-screen brick vent inserts.

While the annual average ventilation rate has been shown, it tells little about the hourly or daily ventilation rates. Figure 2-29 shows the hourly calculated ventilation rate over two days during March 2002 for Building 2 (stucco rainscreen), which compares the cavity and exterior temperature air temperatures and the impact of solar radiation on the east wall surface.

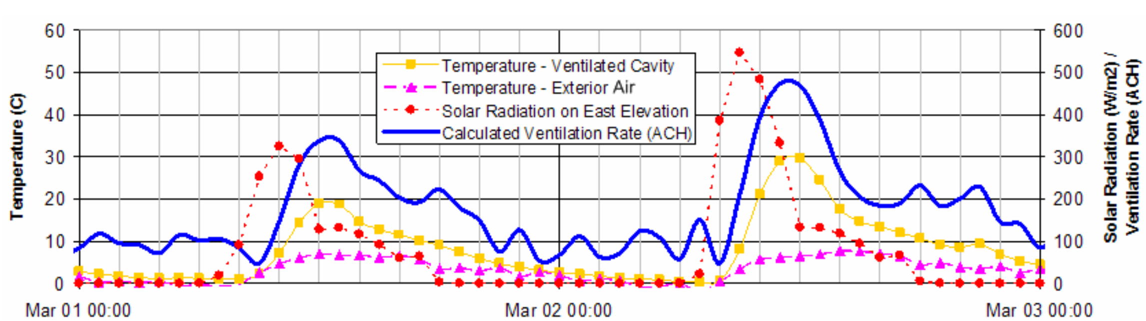


Figure 2-29: Building 2 - Calculated ACH versus Measured Temperatures and Solar Radiation

The impact of solar radiation and cavity temperature can be seen. March 1st was a cloudy day and had low solar radiation, and a reduced ventilation rate. March 2nd was a clear day and solar radiation increased the cavity temperature 20°C above the ambient exterior air temperature. The temperature differential between the cavity and exterior acted strongly to drive the large ventilation rates during the day when the sun is out. Hence the role of solar radiation is important and cannot be excluded from the analysis of cladding ventilation rates. Similar trends were observed across all buildings.

In the conclusion the impact of cladding ventilation on drying and reduced wetting of wall assemblies has been shown by previous work.

2.6 DAMAGE MECHANISMS

Materials can be damaged when the moisture content of the material is at levels high enough to cause microbial growth, decay, corrode, or be structurally weakened. High relative humidity levels not only increase the moisture content of surrounding materials, but can cause damage to surfaces. High RH levels may also sustain and promote microbial growth.

Mould & Decay Fungi

Mould growth is important because it defaces finishing materials, reduces the strength of many organic materials, and can have health consequences for occupants if the mycotoxins and spores enter the interior air.

Figure 2-30: Mould growth on Gypsum Drywall

Mould growth requires oxygen, spores, nutrients on a substrate, moisture and a specific temperature range. Oxygen and spores are available almost everywhere, nutrients depending on material (glass versus processed organic material such as wood fiberboard or paper). Each species of mould thrives over a different relative humidity and temperature range. For one type of typical mould spore, *aspergillus*, the germination time at different relative humidity levels is shown (Figure 2-31).

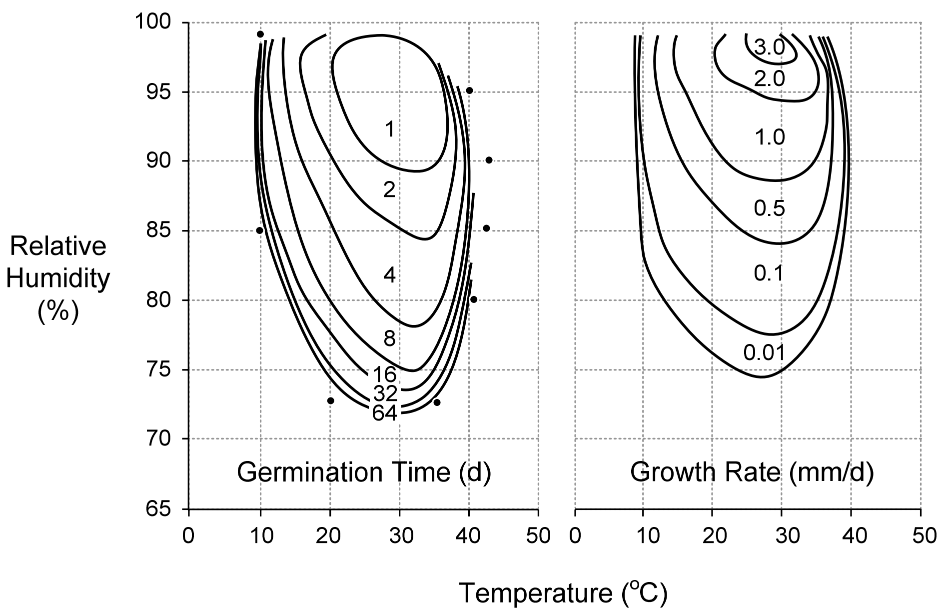


Figure 2-31: Relationship between RH, Temperature, Germination Time and Growth Rate for Aspergillus Mould Spore (Sedlbauer 2001)

Mould fungi do not cause much structural damage, but decay fungi can. Decay fungi begin to flourish at high levels of mould fungi for longer periods of time (months). Decay is a natural cycle that occurs to all dead organisms, however one which would like to be avoided within buildings. Figure 2-32 shows two examples of decay fungi which were observed after removing the cladding of moisture damaged buildings in Vancouver, BC.

Figure 2-32: Decay of Wood Lumber and Sheathing as a Result of Decay Fungi

Typically 80% RH has been suggested as a limit to prevent mould growth from occurring. Recent research however, has clearly shown that wetting conditions (i.e. condensation) are necessary to have significant mould growth in time periods of less than a few months (Doll 2002, Black 2006)

For decay fungi however, it is generally accepted that the fiber saturation of wood is required for fungi to develop. Fiber saturation is only achieved with liquid water contact (prolonged condensation rain-water leaks).

Corrosion

Corrosion is of concern for the for wall systems because of masonry ties, pre-cast concrete anchors, screw fasteners, and light-gauge steel studs are all susceptible to corrosion and critical to safe performance. All ferrous metals including those coasted with zinc, are susceptible to corrosion. The zinc coating is a sacrificial layer which corrodes more slowly than steel, however once the zinc coating is corroded away, the corrosion process continues on the base metal. Severe corrosion resulting in the failure of a face-seal wall assembly is shown in Figure 2-33.

Figure 2-33: Severe Corrosion of Steel Studs in a High-rise Building, Vancouver

In corrosion which occurred within a decade, the sacrificial zinc coating first corroded and exposed the base steel which continued to corrode the structural studs. Steel studs are especially prone to corrosion damage because of their thinness, and because they are in contact with gypsum which becomes acidic when wet and accelerates the corrosion process.

The two factors that have the largest affect on corrosion rate are the temperature and relative humidity at the surface of the metal component. Corrosion rate depends on the relative humidity and becomes significant above 75%. Temperature also plays as role as it provides the energy required to activate chemical reactions. Corrosion will not occur below freezing temperatures and the corrosion rate increases with temperature.

Corrosion can also be affected by acids and salts. The acidic reaction of gypsum sheathing is one, acid rain being another. Buildings exposed to salt-spray from the ocean of de-icing salts often report steel corrosion issues.

Structural Degradation of Gypsum Sheathing

Recent work by Levelton Engineering Ltd., sponsored by CMHC tested the structural strength of a number of gypsum board products at varying moisture contents, and showed a significant strength loss (flexural strength, pullout resistance and adhesion with elevated moisture contents, as low as 1% MC (Levelton 2005). Published sorption isotherms for gypsum sheathing indicate that when exposed to relative humidity levels between 85% and 90% an equilibrium moisture content of 1% is attained. Prolonged exposure to 100% RH can lead to much higher moisture contents and at a fast rate.

Further discussion regarding the strength loss of gypsum sheathing at elevated moisture levels is found in *Appendix A: Exterior Gypsum Sheathing – Electrical Resistance and Humidified Properties.*

Current Moisture Control Guidelines

Moisture performance evaluation criterion is outlined in ASHRAE Standard 160P and is presented here as it summarizes much of the industries current understanding on damage mechanisms.

To prevent problems associate with mould growth on the surfaces of components of building enclosure assemblies, the following conditions should be met (ASHRAE 2006):

- Surface RH (30-day average) below 80% when the average 30 day temperature is between 5°C and 40°C
- Surface RH (7-day average) below 98% when the average 7 day temperature is between 5°C and 40°C
- Surface RH (24-hour average) below 100% when the average 24-hour temperature is between 5°C and 40°C

There has be much debate about the 80% design threshold and its relevance to mould growth, however it remains good practice to keep the RH below 80% regardless, potentially if not for mould growth, but to act as a factor of safety in calculations.

Corrosion prevention is dependent on the material properties of the metals under analysis, however in absence of such information it is suggested that the 30-day average RH be kept below 80%. Therefore steel-studs cavities should be drier than 80% RH.

To avoid structural degradation for wood and wood products moisture contents above the fiber saturation point for longer than one week should be avoided. Condensation on windows should also be avoided for periods longer than 24-hours or more.

All of these thresholds are guidelines to designers to assist with analysis in determining safe or dangerous wall assemblies.

2.7 CONCLUSIONS

The fundamental function of the building enclosure is to separate the exterior and interior environments while maintaining healthy and safe indoor conditions for the occupants. The building enclosure will weather and gradually deteriorate over time and require ongoing work to maintain the appearance, performance, and efficiency.

Moisture in all its physical forms is regarded as the single greatest threat to the durability and long-term performance of a building and will accelerate the deterioration process. Excessive moisture cannot only cause significant damage to many building materials and components, but can lead to unhealthy indoor environments.

The balance between wetting, drying, and safe storage is critical to the long term performance of building enclosures. Where wetting cannot be controlled to acceptable levels, safe storage within materials and drying become critical. Many common building materials have little safe storage capacity, that is, they cannot be exposed to high levels of moisture for long periods of time, particularly when at above-freezing temperatures. Wall "performance" is hinged upon this balance. A wall is said to have good performance when it is typically dry (safe storage and drying exceed wetting) and poor performance when wetting exceeds the drying rate and safe storage of the material. A failed wall is one where damage mechanisms become present; including mould growth, metal corrosion, or loss of structural integrity.

Recent building enclosure failures have shown that the drying potential of some wall assemblies in certain climates may be insufficient when exposed to accidental wetting or leaks. As a response to these failures, drained and screened walls have been widely recommended to deal with rainwater penetration. However, cladding ventilation may be needed or useful to increase drying for some wall assemblies in some climates. Ventilated claddings can also control wetting due to inward driven vapour from rain wetted absorbent claddings. The use of large ventilated and drained cavity has already been mandated by some building codes.

While some previous research of ventilation drying shows conflicting results, the consensus in recent years is that cladding ventilation has the potential to increase the drying potential of a wall and reduce wetting from absorptive claddings and sun-driven moisture. Higher ventilation rates are shown to result in faster drying rates of wood sheathings. Measured ventilation rates in the field and laboratory show good agreement with the predicted rates calculated from fluid flow mechanics theory. The probable range of ventilation rates depend on the cladding type, cavity dimensions, and venting arrangement, and are driven by thermal and moisture buoyancy and wind pressures.

Cladding ventilation rates were calculated for the buildings in the monitoring study to further understand the impact of cladding ventilation on wall performance and are later used in the hygrothermal modeling programs. The average hourly ventilation rate was 40 ACH for the brick veneer and 220 ACH at the cement board on the south elevation of Building 4, 140 ACH for the east on stucco clad Building 2, and 170 ACH for the southeast vinyl clad Building 1. Ventilation rates were calculated based on thermal and moisture buoyancy pressures.

Building enclosure failures can be prevented. Failures can occur from accidents or acts-of-god, but all too often are as a result of improper design, poor construction, and insufficient maintenance. By understanding and applying the principles of building science in design, and a performing ongoing maintenance, most building enclosure problems can be avoided. The design requires knowledge of the exterior and interior environmental loads; heat, air, and moisture transport mechanisms; and the properties and limitations of the materials and assemblies used.

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3 THROUGH PROGRESS AND FAILURE – A HISTORICAL DEVELOPMENT OF THE WOOD FRAME WALL IN CANADA

This chapter discusses the history of the wood frame wall in Canada, eventually leading to the development of the rainscreen clad wall in Vancouver, British Columbia, mandated after the systemic failure of thousands of wood and steel stud framed walls constructed during the 1980's and early 1990's. Vancouver is located in the Pacific Northwest, a temperate climatic zone of coastal British Columbia and north-western USA (Washington and Oregon States). Some aspects of this climate are similar to much of northern Europe and Scandinavia.

The term "leaky Condo Crisis" has been applied to the failure of thousands of framed walls constructed in the 1980's and 1990's. Most believe these failures were largely failed due to rain penetration through deficient details. The moisture that penetrated remained trapped within the walls and lead to extensive deterioration of the sheathing and studs in less than a decade. Why this happened to walls constructed during this period, primarily in Vancouver, and not before will be discussed through the history presented in this chapter. Lessons one can learn from these failures, and those in other locations, will be sought.

To understand why we build the way we do, it is important to recognize how our construction technologies have evolved and from what. It is also useful to understand which mistakes were made, and why mistakes were made so we can avoid repeating them. Therefore this chapter provides a detailed review of the development of wood frame walls, changes in materials and practice, and a discussion of significant failures that have all lead to the technology used today. Failures are becoming more costly for all parties involved and are less and less acceptable to a society which strives for efficiency and good use of resources. Fortunately our understanding and the technology available has improved over time and we now have the capability to test new systems and materials in the lab, or even virtually using computer simulations.

3.1 INTRODUCTION

The 2005 National Building Code of Canada (NBCC 2005) requires that all dwellings, including single family homes, built in all "wet regions" of Canada to be constructed using rainscreen walls. What a rainscreen wall is, where the technology came from, and how we ended up mandating this technology after all these years, can be answered by looking at the historical development of the wood frame wall in North America.

The way we construct buildings in North America is perhaps best summarized by Joseph Lstiburek in the following quote:

> ''North American houses are not designed. They are built. While building them, we follow tradition more than science. Unless, of course, we try minute alterations. We modify materials, workmanship, construction details, or other seemingly unimportant elements of construction process. Then, the cost of repairs following these minute changes makes us believe that these details were important. In addition, this happens each time when we analyze only the detail itself and forget about its interaction with the other elements of the system. In other words, we fail when we loose track of the holistic approach.'' (Lstiburek 1995 p. 149)

Although true today it was also true when the first settlers arrived here over 400 years ago. European influences helped shape some of the early buildings; however our own techniques quickly evolved to suit the materials readily available in North America, largely wood. The wood frame technology seen today was first developed in the United States in the mid 1800's. The fundamentals today are similar, with improvements made based on experience, different needs, and newly developed materials. Successful details and building materials were passed on through generations of skilled tradesmen unhindered by government regulations or manufacturers' limitations. Builders learned from their mistakes and developed construction details that worked where they built. Local climate, exposure, and available materials informed what was built and how.

In the early part of the 20th century, a number of new construction materials were introduced to the market including thermal insulation and vapour barriers. Government institutions began researching and regulating building practice in the 1940's with successes and failures. However the science was new and not wholly understood, yet we continued to build. The understanding of the emerging science of buildings, referred to as "building science" or "building physics" was undertaking a revolution similar to that by structural engineering a century previous. As a result of building science research in the past century, and through technological advances in the science, materials, manufacturing, and practice, we have developed a better understanding of how and why buildings perform the way they do.

Recent building code requirements mandating the use of rainscreen clad walls are just one of the latest changes to building construction in Canada. The practice of using a screen cladding to keep the rain out of the wall is by no means new, (it was used several centuries ago), but the labelling of such technology did not come until the mid twentieth century.

The historical development of the wood frame wall is presented from the early influences in Europe to the 17th century settlements of Canada and the Unites States to the present day. The technologies, details, available materials and the influences are discussed through the historical development. Specifics of wall designs commonly used in Vancouver which failed in the 1980's and 1990's are discussed in more detail.

The information referenced prior to the 1940's is largely from architectural and history books on wood frame construction. Starting in the 1940's when building science research was found to be beneficial and commonplace; the later references in this chapter are primarily from the government and private research community (journal and conference papers) and provide a more critical assessment of practices and technology.

3.2 <u>EARLY INFLUENCES</u>

A brief history of post and beam timber framing is presented from its primitive development to medieval European times.

One of the basic human needs is shelter. Basic shelter provides protection from the sun, wind, rain, heat, and cold, and maintains conditions required for living. Natural rock shelters and caves were the first form of human shelter and the first attempts to build our own shelter consisted of crude and simple huts built of available materials such as branches and twigs or piled stones. At some point we developed the tools to cut and work standing trees and stones into simple framework for shelter, eventually leading to post and lintel type structures.

Wood has always been a useful building material, easily shaped by hand, and with its desirable strength properties has been the material of choice for a complete structural system, from the roof rafters, to the floor beams and supporting columns. The trabeated system refers to the use of post and lintel construction, originating in timber construction and is the fundamental principle of Ancient Greek, Ancient Egyptian, Persian, Chinese, and Japanese architectural styles (Summerson 1963).

In hot dry areas of the Mediterranean and Middle East, wood in quantities required for building has at times been scarce, and historically the primary building material has being concrete, stone, or clay brick. Some indigenous trees suitable for building were available, but provided only light timbers for building.

Historically, the Greeks were known at first to use timber construction. The language of classical Greek architecture was based on the aesthetic of trabeated timber construction, although later constructed of marble or stone for a number of reasons including dwindling timber resources. Later, during Roman times, the majority of buildings were constructed used newly invented arcuated construction techniques. Structurally they used the materials available to them being stone, brick or concrete for domed roofs and arches to span long distances, instead of using wood beams as with the trabeated style. The Roman buildings were typically constructed of concrete infill, with stone or brick facing for a number of reasons including the fact that timber was not readily available.

When the Roman Empire had expanded to what is today the United Kingdom, timber became available as a building material. Some evidence of Roman carpentry that was preserved in clay at Romano-British sites demonstrates that the Romans had the necessary techniques for half-timbered construction (Bowyer 1968), which may have been passed down to builders in Europe after the fall of the Roman Empire. In addition, the ancient technique of wattle and daub construction for infilling exterior walls was adapted at Roman-British sites. Wattle and daub construction consists of is a woven latticework of wood stakes and branches covered with clay or lime plaster to form a solid wall and is shown in Figure 3-1 infilled between the timber frame.

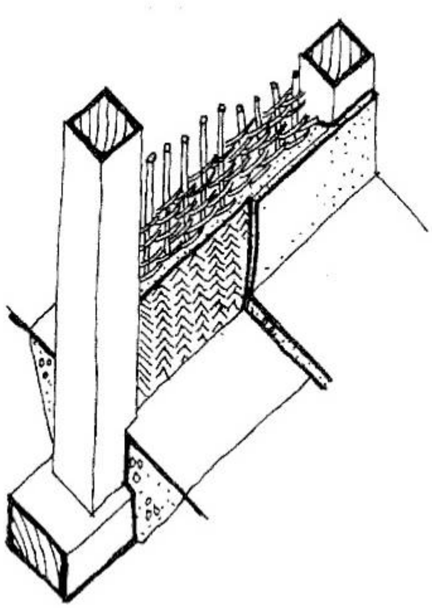

Figure 3-1: Roman-British wattle and daub wall construction (Bowyer 1968)

Timber framing, traditionally known as half-timbered construction, where large wood timbers provide the visible structural frame is characteristic of medieval and early modern England, Germany and France. This method of construction was typically used in localities where timber was in good supply. Timber frames were constructed by the hands of master craftsmen, with intricate mortise and tenon joints holding the components together. While the structural frame was timber, the exterior walls of the timber frames were typically infilled with stone masonry (noggin) or reinforced clay and mud (wattle and daub). The components of medieval timber framing are shown in detail in Figure 3-2.

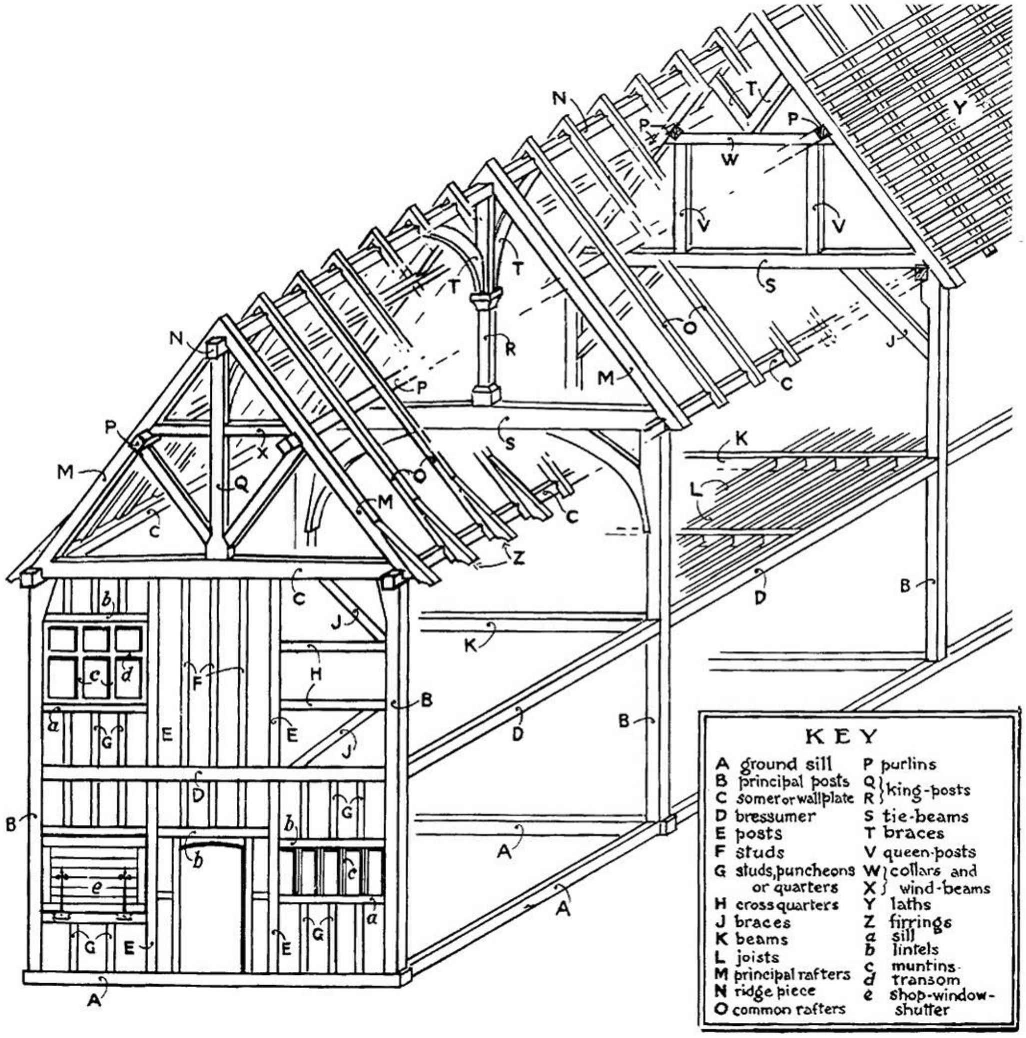

Figure 3-2: Medieval Timber Framing (Salzman 1952)

3.3 EUROPE IN THE EARLY 1600'S

By the 17th century, small refinements to the medieval timber frame structure had been made, and had developed into a distinct architectural building style. The construction techniques that existed in Europe in the early 17th century are discussed to understand how the English and French built and what technology they had to bring with them to North America.

3.3.1 England

At the beginning of the 17th century and prior to the first settlements in North America, the majority of dwellings in England and some other parts of Europe were of timber frame construction, also known as half-timbered construction.

Solid timber walls were constructed however it was found to be more economical to fill this void with another material. The post and beam frame structure walls were often infilled with clay wattle and daub as previously discussed. Figure 3-3, Figure 3-4, and Figure 3-5 show examples of a number of half-timbered buildings constructed prior to the 17th century which are still standing today. These buildings were fortunately spared from the numerous fires that have destroyed much of other historical timber buildings in Europe.

Figure 3-3: House in Wales (1380) with wattle and daub shown (J. Straube 2006)

Figure 3-4: Timber Framing, Court House in Wales, 1401 (J. Straube 2006)


Figure 3-5: Timber Framing, Warwick, England Prior to 1694 (Wikipedia 2006)

The row of houses with the distinct exposed timber frame and infilled whitewashed walls. Note the rainwater management adapted to the wet England climate; sloped shingle roofs with moderate overhangs with eaves-troughs and downspouts. Windows were of moderate size, and initially used for lighting, the small panes of glass formed by hand and soldered together with lead to create larger windows.

Forests in England were primarily hardwood, with oak being the building material of choice for timber frames for its hard and durable properties. Trees were fell and worked using hand-tools by sawyers, typically using pit-sawing techniques.

Prior to around 1550 timber was abundant in England, however as readily available wood became used up for ship construction, less timber became available for buildings. As a result, timber in buildings was used more efficiently and widely spaced, as increasing the spacing wasn't possible in the hull of a boat! This also meant that the walls could no longer be filled in with wood, which was sometimes customary, and other techniques became more popular including wattle and daub.

Wood lath was continued to be used at wattle, and the clay daub was finished with lime plaster and a white or colour wash. The differences made to construction are illustrated by Bowyer in Figure 3-6 with close-timbered framework on the left (prior to around 1550) and square-panelled framework on the right (1600's).

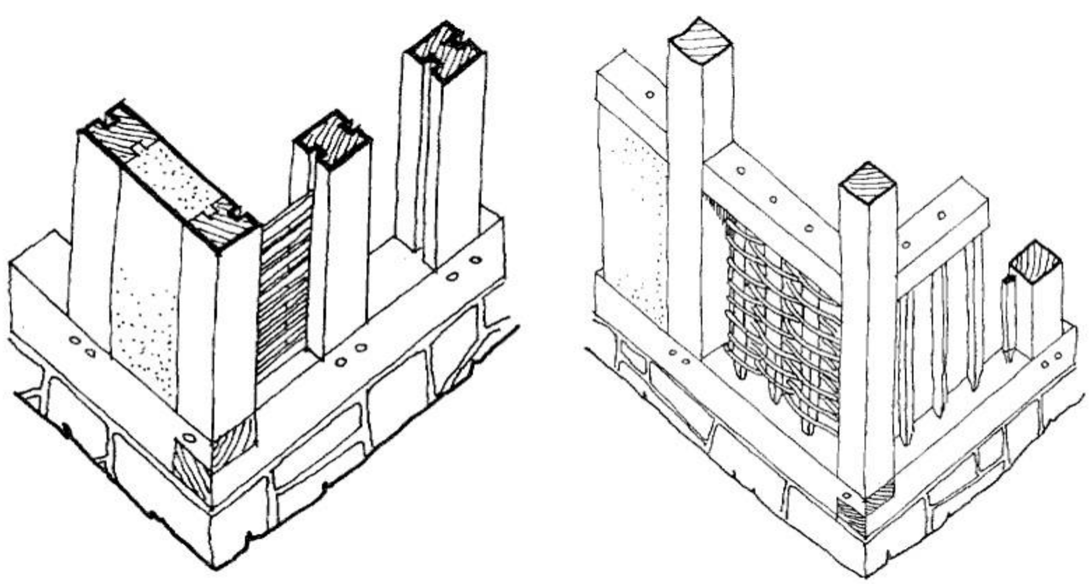

Figure 3-6: Timber Framing in Europe in the 17th century (Bowyer 1968)

Wattle and daub was gradually replaced by more durable stone masonry or clay brick noggin, as brick became more commonly used in building. Later, after the 17th century, many of the framed structures were clad with hung tiles or horizontal wood clapboards.

Buildings in much of Europe were heated with wood burning fireplaces, with a chimney constructed of stone or brick, although in the temperate climate, heating only required for part of the year.

A significant number of the timber framed buildings of the period were destroyed by fire, especially in the cities (eg. Great Fire of London in 1666), however today some of these original timber framed houses can still be found in rural areas. The majority of buildings in London prior to the fire were constructed of timber frame, far different than the stone buildings seen still standing today.

3.3.2 Scandinavia

Dwellings in the Scandinavian countries were also constructed primarily of wood, where there was also an abundance of timber, mainly softwoods such as pine and firs, which were readily worked. The building style differed than that in much of Europe, and the log cabin which we are familiar with today originated thousands of years ago in the Scandinavian countries. The log cabin style of building was brought to North America by the Swedish and later the Germans. But for some time in the early part of this century, there existed a myth that the log cabin was actually invented in America (Shurtleff 1939).

3.4 NEW WORLD SETTLEMENT – 1600'S

The history of the North American wood frame wall began with the first settlers in the early 17th century and was subsequently shaped by the cultures that emigrated there over many generations. The technology that the Europeans brought to North America is discussed for both the American and Canadian settlements. As both America and Canada were for all purposes empty and devoid of shelter, except for few Indian settlements, building construction influences were largely brought from Europe.

The writings of (Fitch 1947, Ritchie 1967, Condit 1968, Bowyer 1968) provided informative accounts for the period and are suggested for further reading. Much of the information herein is referenced from those sources, particularly on accounts of the wood frame construction techniques and the exterior wall.

3.4.1 America

Building Techniques and the technological development are discussed for America (later becoming the United States of America).

3.4.1.1 Building Techniques

The first settlers to America arrived in the early 1600's as part of commercial planned expeditions from England; landing on the coast of what was later known as New England. Largely unprepared for the new world, partially due to the inaccurate and embellished accounts of the first explorers, the very first settlers lacked the necessary skills for building or the tools required to do so. However, within years, craftsmen, carpenters, masons, sawyers and were among the settlers, bringing with them the necessary building tools from England. The trained carpenters brought with them centuries old traditions of timber-framing and construction techniques. Carpenters tools at the time were medieval in origin and included: axes, saws, plane and chisel for cutting; hammer, drill, awl for punching and driving; and square, compass, plumb line for squaring and fitting.

The first dwellings were out of absolute necessity and were primitive. Shelters consisted of holes dug into the ground, lean-tos, and simple huts built out of whatever materials were on hand. However within a few years they were building more suitable and permanent dwellings.

The Native Indian dwellings which the settlers encountered in New England were simple and consisted of small log framed structures covered with bark or structures of closely placed logs driven into the ground with the interstices filled with mud. However the English settlers found these indigenous dwellings as unsuitable and used traditions brought with them from home.

Wood was abundant in North America with a seemingly unlimited supply of quality first growth timber at the settler's disposal. By 1611, with adequate tools, the settlers were able to fall trees and work into square hewn timbers and build into medieval timber frames with mortise and tenon joints, based on practices in Europe.

Initially, the early settlers resorted to pit-sawing to shape timbers, but soon found it too slow for their needs and resorted to a mechanised process. One of the most significant impacts to timber framing construction was the invention of the power-driven sawmill. The first of its kind in North America was located in Jamestown in 1625, and greatly increased the output of squared framing timbers for building. A basic timber frame structure used by the North American settlers, for a small home is shown in Figure 3-7.

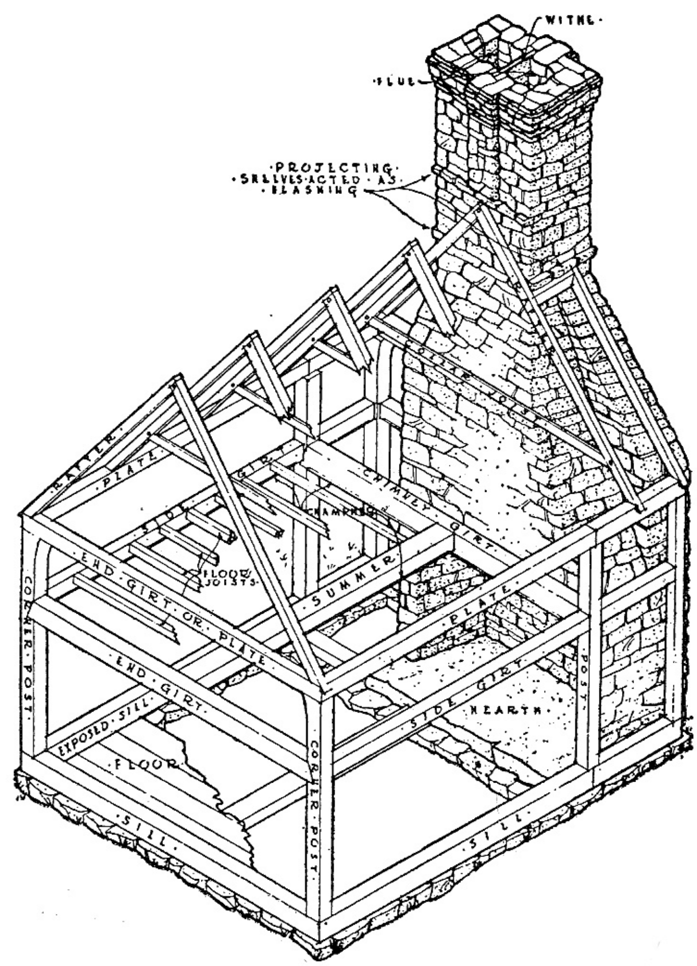

Figure 3-7: Colonial Post and Beam Framing (Shurtleff 1939)

A large fireplace and chimney was a necessity for survival in the new world and served for both cooking and heating. The wood burning fireplaces were not very efficient, but the mass of the masonry chimney absorbed the heat of the flue gases and radiated it back into the house. The climate was much different than the temperate climate they left in England. New England winters were much colder than in England, with long winters with temperature well below freezing which the English were not accustomed to.

The fireplace and chimney were typically constructed of rubble masonry, of stones collected from the land when it was cleared for building. Clay was initially used as mortar to hold the rubber together until lime; the key component in mortar was located and processed. Oyster shell lime was first used on the coast, before limestone quarries were developed.

The open spaces between timber framing members were typically filled with wattle and daub (clay and mud reinforced with straw or sticks) or masonry noggin of English origin. However in the colder climate of New England, with more extreme changes in temperature, it was found that thermal movement of the wood frame and stone/clay infill lead to cracks which allowed airflow through the walls, damaged the structure, and was uncomfortable.

Builders found it necessary to cover the structural timber frame and infill walls with horizontal clapboard siding, also of English origin. The entire structural frame protected from the weather by shingles and clapboards which shed water and reduced air draughts through the wall. The wood clapboard was held in place using wood pegs, but also hand-wrought iron nails were sometimes used, imported from England by the settlers until local nails were produced.

Eventually the infill noggin or wattle and daub was removed entirely and replaced with a plaster and wood lath, further reducing the air draughts through the walls. These changes occurred gradually and resulted in the new North American system of wood frame construction. The use of clapboard siding is still today widely used homes, and part the ubiquitous New England architectural style. Many of the original dwellings are still standing today, and Figure 3-8 shows a house constructed around 1675 in Salem, Massachusetts with clapboard siding over timber frame structure.

Figure 3-8: Clapboard Siding, 1675, Salem, Massachusetts (Pryce 2005)

The windows of the house are constructed of glass, which would have been imported from Europe, and also would have been quite expensive at the time, hence the small relative size of the windows, compared to what would be common today. The roof steeply sloped to shed snow, and note the use of the central fireplace used to heat the home.

As an alternative to wood clapboards, which required more labour to saw the timber, shingles were also used during the period. The Dutch introduced wood shingle covering for walls around 1650 on Long Island, which was quickly picked up by the New Englanders in their design. An example of this is shown in Figure 3-9, constructed in 1665 in Cape Cod, Massachusetts with a 'salt-box' profile and shingle siding.

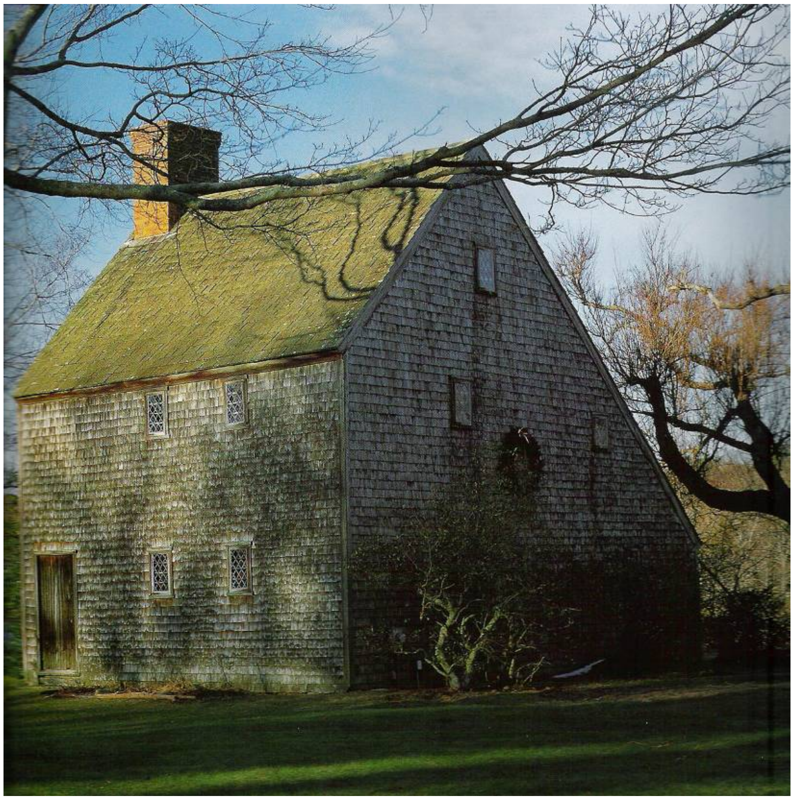

Figure 3-9: Shingle Siding, 1665, Cape Cod, Massachusetts (Pryce 2005)

Another type of construction used as early as 1627 in New England, was the plank house. The exterior walls and interior partitions were solid bearing structures consisted of vertical timbers planks butted together. The planks ranged in thickness from 1" to 3" thick and were covered on the exterior with wood cladding, either shingles or horizontal clapboard siding. The structure was very durable and rigid, and also offered some insulation against heat loss; however it was an inefficient use of wood.

The most common bearing wall construction however was the log house. Log houses built up of horizontally stacked logs were a medieval invention of the Scandinavian people and common to their homeland. The Swedish brought the log house to North America in 1638 in the newly established colony of New Sweden. There are three types of log houses with round, squared, or split logs. The interstices between logs are filled with mud or clay or with a chinking of wood chips and clay, resulting in a relatively air tight and well insulated construction method.

The Germans who came to Pennsylvania in the 18^{th} and 19^{th} centuries further spread the use of log houses, their variant being of square hewn timbers. Log houses provided superior thermal resistance to the English clapboard sided framed houses and became very popular with the settlers as they moved west across the country.

As the local economies grew, brick became a more popular building material, and was produced locally. The Dutch who were skilful brick masons in Europe brought brick construction techniques to North America, with brick kilns in New Amsterdam in 1628 and Salem in 1629. Brick buildings were typically constructed of solid brick masonry bearing walls with joints of lime mortar. Of interest, Dutch bricks were usually narrower 1 ½" versus the 2 ½" thick English bricks, which are the standard today.

Brick construction flourished in the southern colonies, especially Virginia where aristocratic taste and wealth desired the construction of brick masonry buildings. The settlers in Virginia were also from areas of England where brick construction was common, whereas the New Englanders came from the eastern and south-eastern counties where it was rare (Condit 1968).

Where timber was scarce, in such areas New Mexico, the Spanish settlers who arrived prior to the English or French used adobe, a method of construction the Spanish learned from the indigenous people. Adobe construction consists of sun-dried clay bricks and blocks stacked into bearing walls, which is then finished with a clay-gypsum adobe plaster. The roof is sloped and constructed of closely spaced wood beams, sticks, or branches where wood was available or reeds placed in a dense mat and covered with clay. Because of susceptibility to moisture, adobe structures were typically only used in hot arid areas of the southwest.

3.4.1.2 Technological Development

Building construction was typically performed by skilled craftsmen, with knowledge passed down by apprenticeships and word of mouth through generations of builders. However, in 1684 William Penn (founder of Pennsylvania) prepared a building guide which contained complete descriptions of framing systems and members and information on the manufacture of iron nails and the cost for carpentry work (Condit 1968).

By the 18th century, builders had adopted the practice of using wood board sheathing on the exterior of the timber frames, as the nailing base for the wood cladding, with the clay or brick noggin being abandoned around this time. This required the addition of wood studs to the wall frame, which were light boards framed vertically between the sills and girts to provide support for the wall sheathing. On the interior, lime and sand plaster over wood lath was used as a finish.

Fitch noted that in 1792, Thomas Jefferson recognized the deficiencies of traditional frame construction which offered an inefficient and often air leaky barrier to heat flow than either log or masonry construction. Jefferson also understood the phenomenon of water vapour condensation on the cold walls of masonry buildings, and outlined measures to prevent or minimize its occurrence. The myth, which some colonists believed at the time, was that this "weeping" of the walls was harmful and "that disease and death was caused by the malignant vapours" (Fitch 1947).

The wood fireplace was replaced in the home after Benjamin Franklin developed the mass-produced cast-iron stove in 1744, which had huge advantages in efficiency and size over the common fireplace for heating and cooking.

3.4.2 Canada

During the early 16th century, the waters off the coast of Newfoundland attracted fishermen from Europe, fishing during the summer but returning back home in the winter. Few people stayed over the winter months; however the shelters were crude and temporary. It wouldn't be until the following century that the first permanent settlers would arrive from Europe.

Around the same time as the English arrived in New England in the early 17th century the first settlers from France arrived in Quebec. Both wood and stone were abundant and used for construction of dwellings in Quebec. The first dwellings resembled French buildings of the period, but the North American climate forced the settlers to adopt new techniques and material use.

The French settlers initially constructed their dwellings with thick walls of uncut rubble stone, with mortared joints. However they soon found that these walls were not thick enough to shield them from the cold and brutal winters of Quebec. Possibly the first use of a screen cladding in Canada, builders began to use wood boards and shingles over their stone masonry buildings especially on the exposed eastern sides where the wind and rains came from.

Figure 3-10 shows such a screen clad house in Quebec, still standing today with the vertical wood cladding over the rubble stone masonry structure on the eastern elevation. At some later point, an owner applied aluminium siding above the first storey for the same purpose (Ritchie 1967).

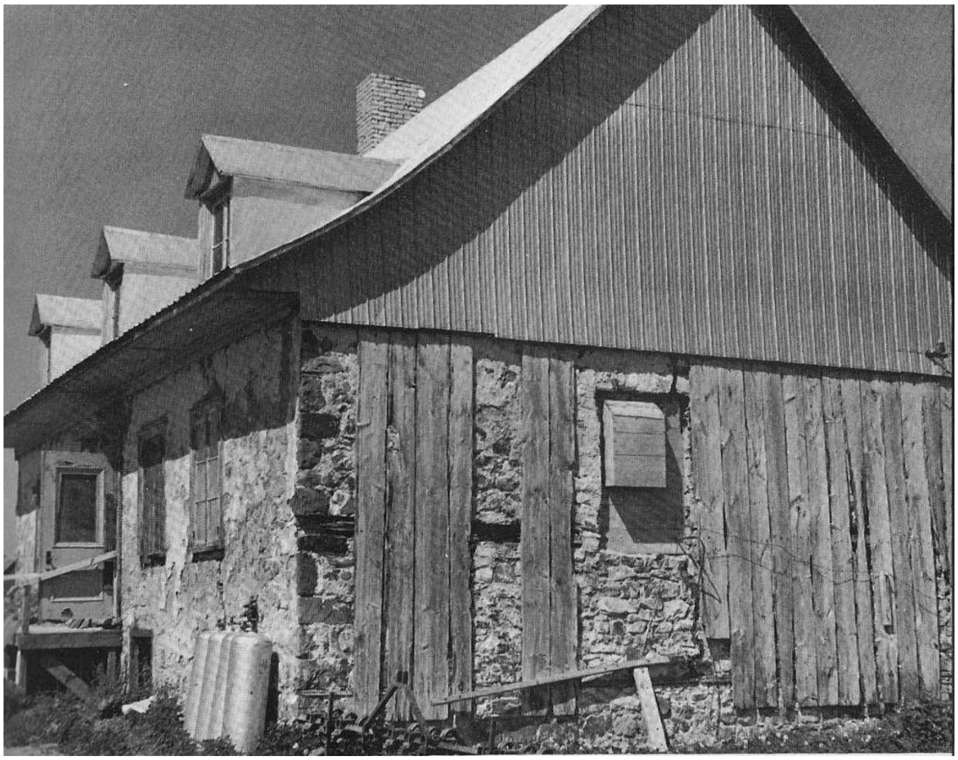

Figure 3-10: House on the island of Ile d'Orleans, Quebec with Wood Screen Cladding over Masonry Structure (Ritchie 1967)

In addition to stone houses, post and beam timber framed houses were constructed during the period, and clad with horizontal wood clapboards or shingles. The voids in the exterior walls between timber framing of houses were filled with brick and stone masonry (a technique known to the French as *colombage pierrote*) and sometimes short pieces of wood. This is similar to the English practice of brick or stone masonry noggin.

Not all building designs were as successful. Initially some French builders tried a building technique known as *poteaux-en-terre* (posts in the earth), possibly derived from the Native Indians who had used the method in some temporary buildings. The building structure consisted of logs hammered into the ground with interstices between the logs filled with a mixture of clay and grass or moss. The French found that wood decayed quickly when in contact with soil, and the builders developed a more durable version called *poteaux-sur-sole* (posts on a sill) whereby the vertical posts were placed into a timber sill, which in turn rested on a stone foundation above the soil. Incidentally, these same techniques were tried simultaneously with similar wood rot failures by other French settlers in colonial settlements of Louisiana.

Most of the earliest buildings could only withstand the harsh Canadian winters for a few decades as they were damaged by material degradation and thermal movements. Continual repairs were found necessary in this severe climate regardless of the material used. Builders quickly learned about frost heave as buildings on shallow foundations were damaged, and also of freeze-thaw damage which cracked wet brick and stone masonry walls and degraded mortar. By experience, builders learned to build on deep foundations below the frost line, and to cover stone walls with screen claddings such as clapboards or shingles to keep them dry and somewhat warmer.

In addition to the French in Quebec, Scottish and British settlers in the Maritimes also brought with them traditions from home, being half-timbered construction and rubble stone masonry as discussed.

While it could be argued that the European technology completely influenced building construction in Canada, in BC it is worth noting the construction practices of the indigenous people prior to European settlement. While the Native Indians did not have the same technology the Europeans had, their buildings were well adapted to this wet and temperate coastal climate.

When Simon Fraser explored the coast of what would become British Columbia in 1808, he wrote about the accounts with the buildings of the Coast Salish Indians. The indigenous buildings in this wet and temperate climate were massive and constructed almost entirely of wood, constructed with massive vertical posts embedded into the ground, with heavy beams laid on top of the posts to complete the structural frame. The exterior walls were enclosed with large planks laid horizontally and overlapped, like traditional clapboards.

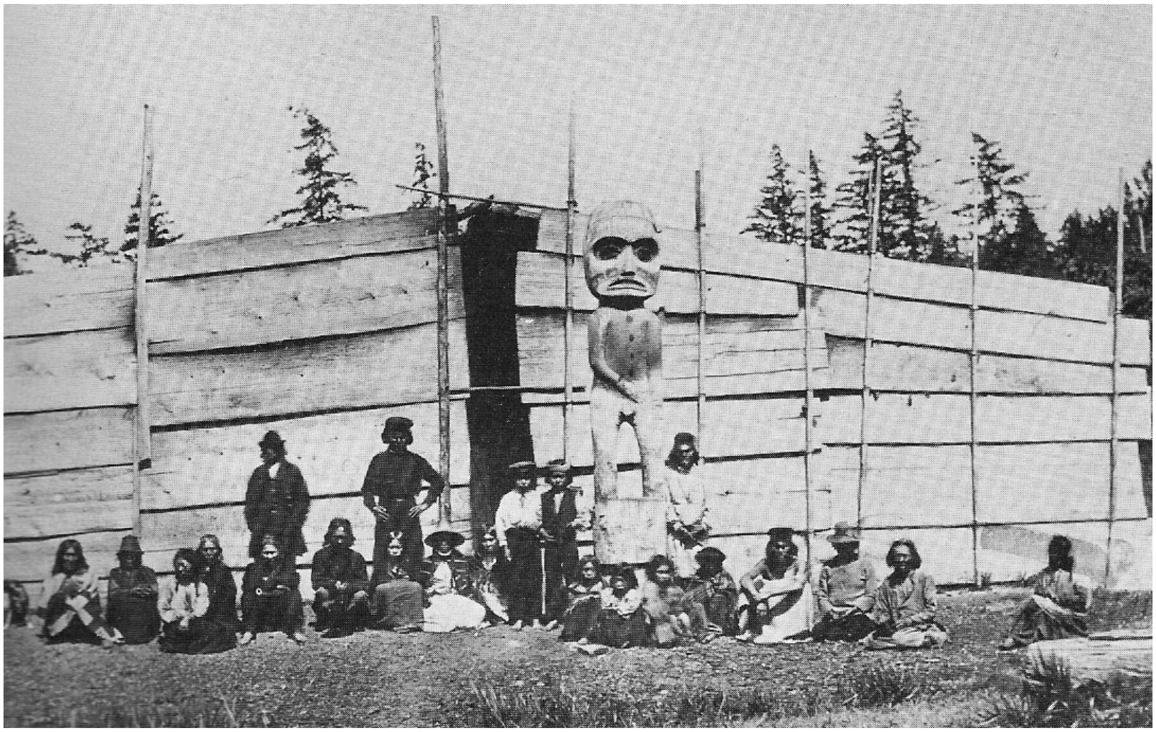

Figure 3-11: Coast Salish Long House, British Columbia (Ritchie 1967)

The large planks were lashed with cedar withes between sets of structural poles, with a gap left for doors or windows. The buildings were heated with a central fire pit, and roof constructed such that the smoke could escape through the joints of the lapped boards. The Indians used western red cedar almost exclusively as a building material as it is relatively light, durable, relatively rot resistant, and easily split along the grain. The only tools the Indians had were primitive and consisted of adzes, chisels and wedges constructed of stone, shell, or antler, and all lifting was done using human power (Ritchie 1967).

While more primitive of dwellings than the Europeans at the time, the indigenous people showed good use of durable materials, with details to shed rainwater from the roof and walls, and dealt with smoke from indoor fires.

3.5 NORTH AMERICAN BY DESIGN – 1800'S

Technological advances early in the 19th century played a significant role in the development of new construction techniques later that century. Mass produced nails and board lumber paved the way for a new revolutionary structural system to be developed, which fundamentals are still in use today.

One thing North America had was a seemingly unlimited and cheap supply of resources such as wood. Labour was however costly in contrast to Europe, therefore mechanisation and techniques that improved labour efficiency were readily accepted into common North American practice.

During the period from 1790 to 1830, the hand-wrought iron nail used for centuries was replaced by mass produced machine cut wire nails. The first nail cutting mills were operated by hand-power followed by water mills and later steam. The introduction of the power-driven circular saw in 1814 in the United States was another factor that greatly increased the output of board lumber.

The post and beam timber frame structure worked well for large buildings such as barns, mills and churches, however for houses it was heavy, and could be argued an inefficient use of material. It also required specialized skills to construct the joinery and erect the heavy columns and beams. With readily available cheap nails, and board cut lumber available, it was only a matter of time before more efficient structural systems were developed.

With the technological advances in nails and lumber, in 1833 Augustine D. Taylor of Hartford, Connecticut built with help of some unskilled labour the first balloon frame structure, St. Mary's Church in Chicago (Condit 1968, Wikipedia 2006). Taylor's design had removed the standard post and beam timber framework and replaced it with a light structure of evenly spaced joists and studs (typically 16" o.c.), with the members sharing the structural loads imposed. Standard framing lumber sizes (2x4, 2x6, 2x8, etc) were commonly used and the structure could quickly be constructed using unskilled labour with only a handsaw, hammer, and some nails.

Because of the significant advantages in economy and ease of construction, balloon frame construction quickly spread across the United States and Canada and became the standard construction method for homes and small buildings. Post and beam timber frame remained in use for larger buildings, however with the advent of steel framing and trusses, most industrial buildings became constructed of steel.

A modern example of balloon frame construction from 1932 is shown in Figure 3-12 which shows the structural members, representative of the basic details used first in the 1830's.

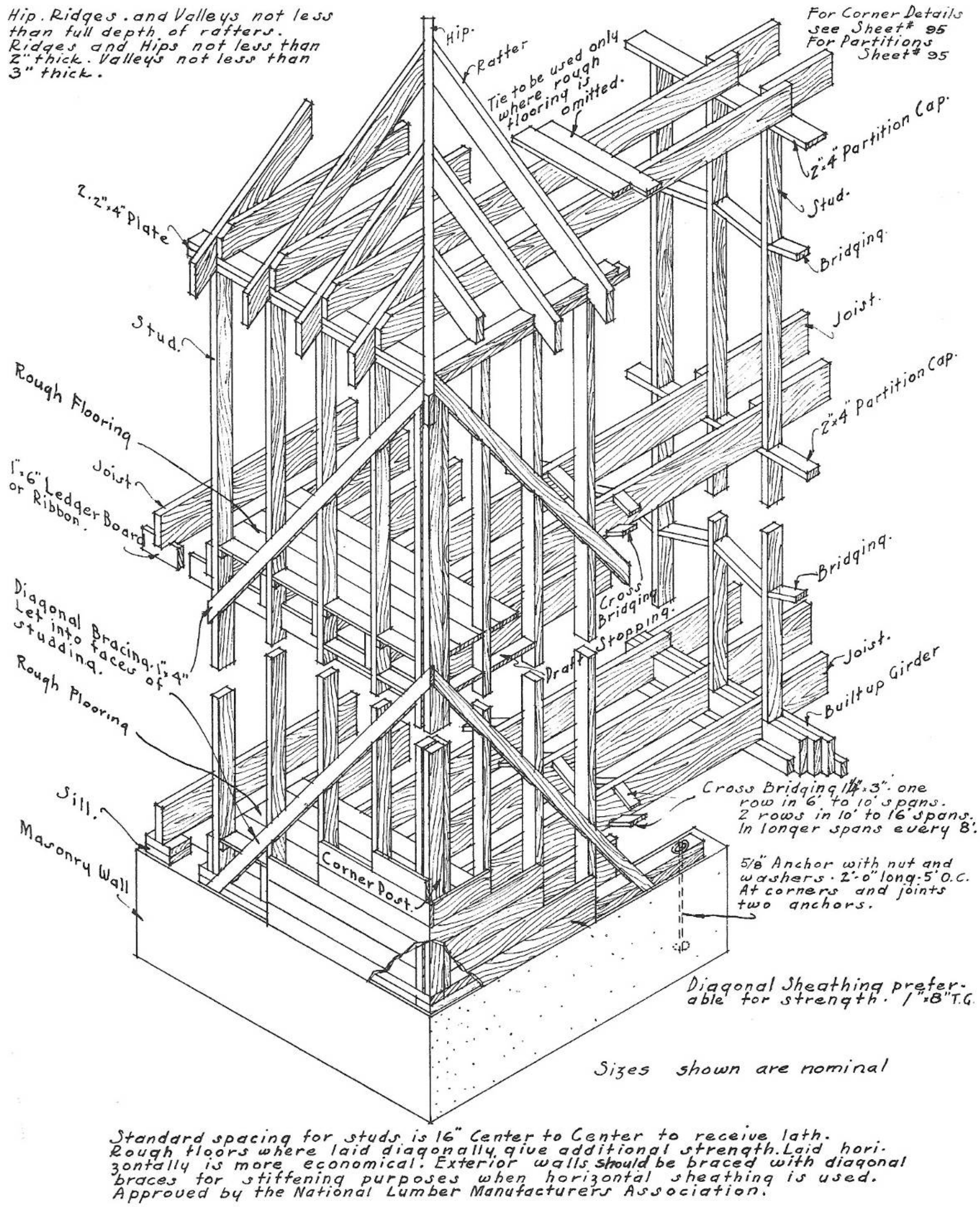

Figure 3-12: Balloon Framing (Ramsey and Sleeper 1932)

The exterior walls were covered with sheathing boards (typically 1" thick) nailed directly to the studs (horizontally or diagonally preferred for strength) and clad with wood clapboards or shingles for weather tightness.

The balloon-frame came just in time, and helped quickly build dwellings during boom periods in the several North American gold rush cities, notably 1848 in San Francisco, and through 1850's and 1860's in British Columbia where ample sawn lumber was available from the growing lumber economy. Ships arriving in BC during the 1860's arrived with mining supplies and exported timber as a return cargo, thus beginning the export trade of lumber from BC.

Balloon framing was also extensively used in the rebuilding of dwellings after the Great Chicago Fire of 1871.

The population of Eastern Canada was also increasing with immigration from Europe in the late 1880's particularly in the cities, requiring the need for additional housing units. Row houses and multi-story apartments became common as a quick and cheap housing option for new immigrants. The Canadian Pacific Railway (CPR) brought population west across the country, requiring housing along the way. By 1886 the railway stretched from coast to coast, and a wave of new immigrants poured into the country until the First World War (See Figure 3-47 in Section 3.8). With them, each culture bringing their homeland building traditions to Canada.

Many of the homes built in eastern Canada used balloon framing; however solid stone masonry and brick construction were quite common as well, with a number of available quarries and brick manufacturers.

It was in the settlements in western Canada including Vancouver where balloon-framing first came into common use, with abundant timber supplies and sawmills at the ready. In 1886 when the first train arrived in what was soon to be Vancouver, the area was largely covered in forest, except for the two small villages of Moodyville and Hastings, each with its own sawmill. The city of Vancouver was a planned city, and constructed from scratch with a deep-sea port linked to the railway with ocean trade to Asia. The resource based economy of Vancouver was based on logging, mining and fishing. The village of Granville in 1884 is shown in Figure 3-13, showing the typical wood frame dwellings along the shore. The area later destroyed in the Great Fire of 1886 and is now the area of Granville Island (Ritchie 1967).

Figure 3-13: Granville Island Area in 1884 (Ritchie 1967)

In the late 1800's one could buy all the lumber required to build a house, pre-cut and numbered for easily assembly from the British Columbia Mills Timber and Trading Company. A simple 12'x12' house was sold for $100 and included all the lumber, two windows, door, flooring and roof materials. Several other versions were available for up to $840 for a two storey house. Three of the designs produced by the company are shown in Figure 3-14.

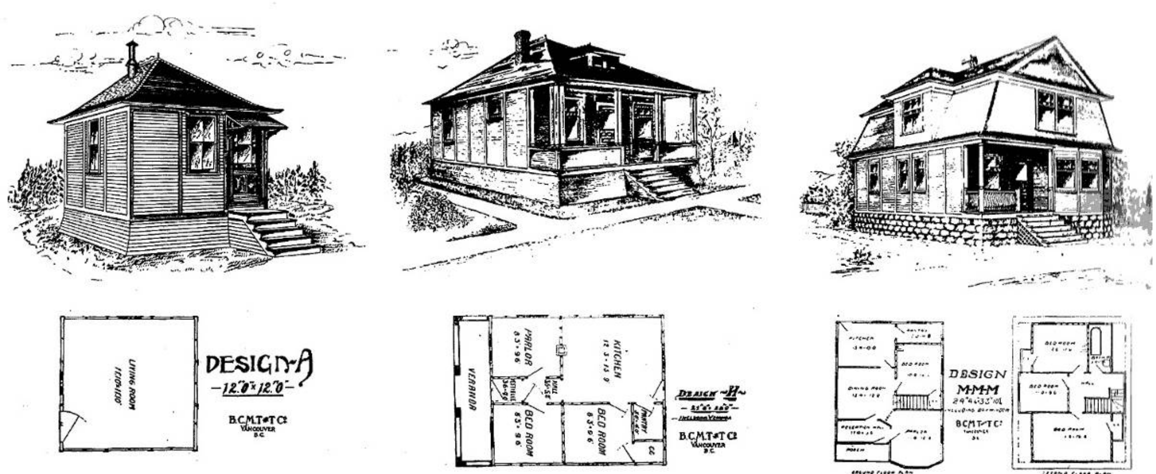

Figure 3-14: BC Mills Timber Trading Company "Kit-houses" (Ritchie 1967)

These houses were constructed using balloon-frame stud and joist construction and typically clad with horizontal wood lap siding.

While the structural components of houses were developing, some improvements were made towards making buildings more comfortable by insulating the exterior walls. Builders had earlier discovered that the spaces between the timber frames should be filled in to reduce air draughts and provide some thermal resistance. As previously discussed, this was commonly done using clay wattle and daub, or brick or stone masonry noggin. Some builders also filled the spaces with wood (solid, shavings, or sawdust) and in coastal areas of Nova Scotia, dried seaweed and eelgrass was used in instances. In addition, the interior of the framed walls were typically finished with plaster over wood lath, which provided resistance to airflow and had some thermal resistance.

One of the first documented uses of thermal insulation in Canada was a schoolhouse built in 1881 in Edmonton, Alberta. The building planners well aware of the harsh prairie winters required the walls "to be filled with sawdust well rammed down" (Ritchie 1967). Sawdust and wood shavings have relatively good thermal properties and were some of the most thermally efficient materials available at the time.

By 1873, mineral wool insulation was developed in the United States by glass manufacturers. It consisted of spun glass fiber, which could be stuffed into wall spaces and provide some resistance to heat flow. Manufacturers also found they could make it from certain rocks (rock wool) and blast furnace slag (slag wool). It was claimed that mineral wool "conducts neither cold nor heat nor sound" and the use of it in buildings would hinder burning if a building was on fire. Mineral wool insulation wasn't commonly used in home construction until early in the 1900's, and wasn't manufactured in Canada until the 1920's

Plywood was another development from the United States developed in the 1860's after the invention of the rotary lathe which allowed thin sheets of veneer to be peeled from large logs. Originally used for making furniture, it didn't see much use in building construction as a replacement for plank sheathing until the mid 20th century. Incidentally, Plywood was actually first invented in Egypt around 3500 BC, had subsequently fallen out of use, forgotten about, and has since been "re-invented" several other times through history by others.

Solid brick masonry construction continued to be used through the 19th century however, with the development of the balloon frame; brick veneer became commonly used as a cladding over wood frame buildings, for those who still wanted the appearance of a solid brick house. Ritchie describes a brick veneer wall from Ottawa, constructed in the late 19th century which was demolished in the 1960's and is shown in Figure 3-15.

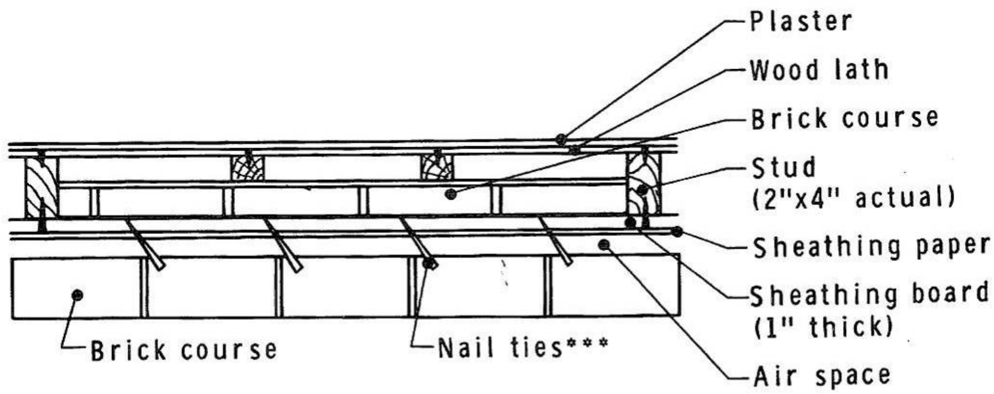

Figure 3-15: Brick Veneer Wood Frame Wall from the Late 1800's, Ottawa (Ritchie 1967)

What is interesting about this wall from the late 1800's, is the use of sheathing paper and the intentional air space between the brick veneer and sheathing. Asphalt sheathing paper was used extensively in homes after the Great Chicago Fire in 1871, manufactured by a number of paper companies. Asphalt was used to impregnate the paper, providing water resistance, using as roof underlayment and over sheathing in walls. The airspace prevented capillary water transport from the brick into the wood sheathing and possibly allowed for drainage at the bottom and perhaps venting of the wall sheathing. This century year old wall assembly is similar to that still used today, with some obvious differences with insulation and vapour control, changes made during developments in the 20th century.

3.6 TECHNOLOGICAL ADVANCE – EARLY 1900'S

Wood framing details used during the century are discussed as well as developments of insulation and vapour barriers prior to the 1940's. Some of the problems associated with buildings after the Second World War building boom are discussed as well as the impacts of the energy crisis in the 1970's and changes to the exterior wall made in the 1980's and 1990's. Details into some of the moisture failures that occurred in exterior walls in North America leading up to the "leaky condo" crisis in coastal British Columbia are also discussed.

3.6.1 Wood Framing Details

By the early 1900's wood framing details were well developed and began to be commercially published and widely distributed to practitioners. Typical architectural details for buildings constructed in the 20th century can be found in the "Architectural Graphic Standards" by Ramsey and Sleeper (1932, 1936, 1951, 1956, 1981, and 1991). First published in 1932 and revised every 5 years to 10 years until the present day, it provides an extensive historical documentation of common architectural practice including the details, materials, and understanding of the science at the time of publication.

Balloon framing had a number of drawbacks which were realized by the early 20th century, and adaptations were made which resulted in what was called platform framing (or western framing), and still in common use today. The main difference between the two framing methods is at the floor line (See differences between Figure 3-12 for balloon framing and Figure 3-16 for platform framing). With balloon framing, the wall studs extend from the sill to the top plate of the second storey (16 to 20′ long), whereas in platform framing, the studs only extend to each floor (8′ to 10′ long).

Platform framing has a number of advantages over balloon framing which are discussed in some detail.

- First, with platform framing, the construction process is simpler, shorter walls are put up faster, and a working platform is created immediately by the second floor placed on top of the first storey walls. The floor allows access to work on the upper level, whereas with balloon framing the second floor was more difficult to build, framed into the sides of the joists, and could not be constructed until after the wall studs were in place, which typically required the use of scaffolding to access the upper levels.
- Second, the potential fire and smoke path from floor to floor between the studs is eliminated with platform framing, the reason for a number of building codes to ban balloon framing. With platform framing these gaps are eliminated by the floor joists and headers, reducing the potential for fire and smoke spread between floors.
- Finally it became difficult to obtain the long studs required (16′-20′) for balloon framing and the 8′ to 10′ stud lengths used in Platform framing were easier to obtain. In addition to construct taller three and four storey

wood frame buildings, platform framing was required, as studs were not produce in lengths long enough to use balloon framing.

Figure 3-16 shows the typical framing details for Platform framing, as typical by 1932, from the Architectural Graphic Standards.

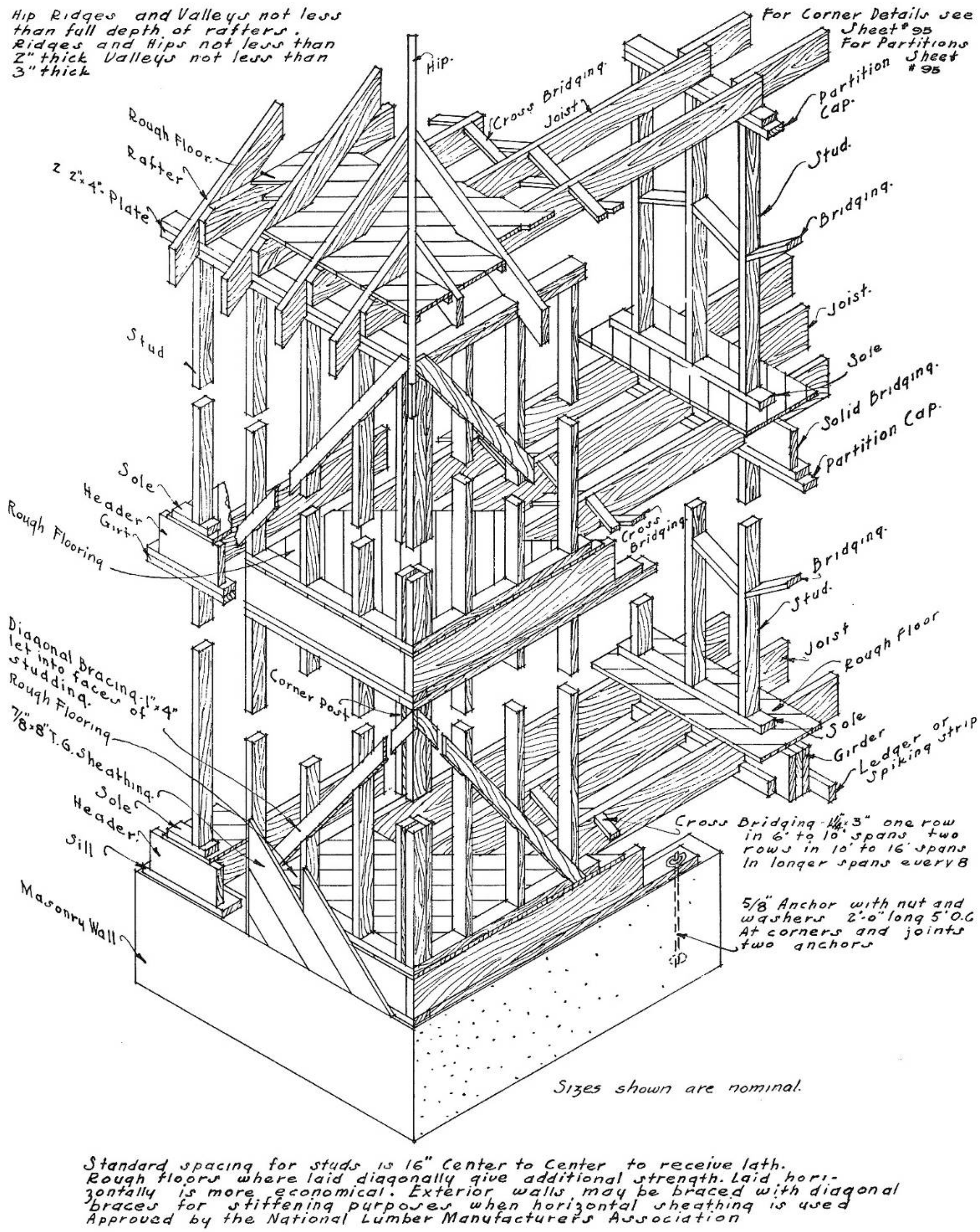

Figure 3-16: Platform Framing Details (Ramsey and Sleeper 1932)

Changes and improvements in efficiency were also seen in the cladding, sheathing and interior finish materials in the first half of the 20th century.

Wood cladding in use for several centuries consisted of horizontal wood siding, vertical board and batten, or shingles. Of these several different types of horizontal wood siding were commonly used by the 20th century including: drop siding, tongue and groove, ship lapped, dressed and matched, and bevel. The importance of back-priming and protecting the surfaces from moisture was also addressed in the early 20th century with wood sidings. Wood sidings were commonly stained or painted with oil based paints in a range of available colours. Cedar, redwood and pine were the most commonly used siding materials.

It wasn't until later in the 20th century when engineered siding materials such as plywood, hardboard, particle board, or cement asbestos boards were commonly used. These materials often textured and grooved to give the appearance of real wood siding, unfortunately often without the durability and performance of real wood.

Stucco was also commonly used as an exterior cladding, and construction details are of interest, especially for Vancouver. Stucco traditionally was made of lime, sand, and water; however as lime stucco was slow hardening, the use of Portland cement stucco became more common by the 20th century. Stucco typically consisted of a mix of Portland cement for strength and lime for workability mixed with sand and water. Using white Portland cement and lime, a wide range of colours were possible when mixed with coloured sands or pigments. It was also common to press coloured stone chips into the finish coat of the stucco before it hardened, known as a "rock-dash" or "stone-dash" stucco finish.

Unfortunately lime was sometimes removed from the mix, and builders in the 1980's and 1990's were found to be using surfactants such as laundry soap to increase the workability, with reduced strength and performance.

The quantity of lime in cement-lime stucco mix also has a significant impact on the vapour permeance. Straube (2000) showed that pure cement-sand stuccos have low vapour permeability, meeting the requirements for vapour barriers in some cases. Figure 3-16 plots the difference between stuccos with varying lime content.

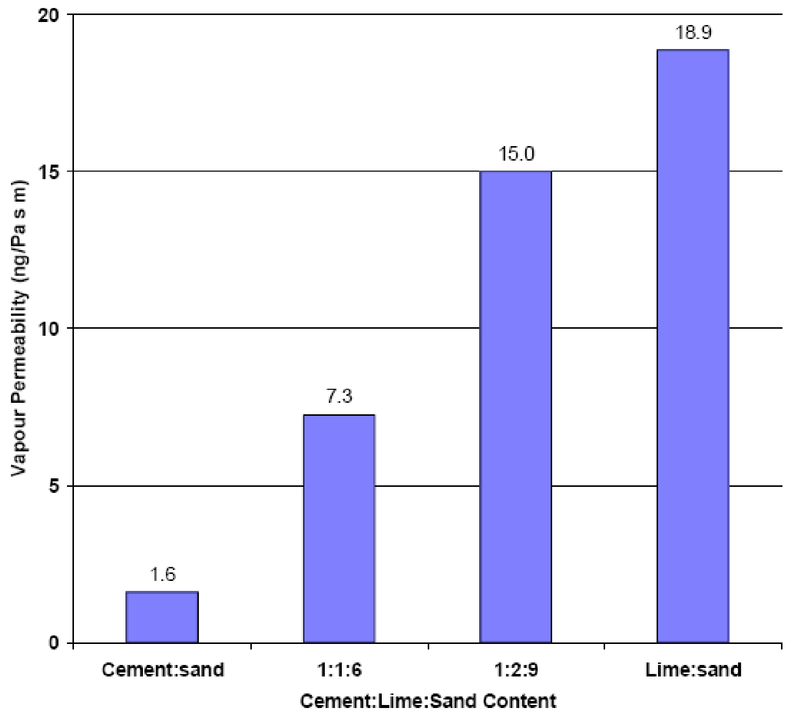

Figure 3-17: Lime Content and Vapour Permeability (Straube 2000)

Stucco is typically placed in 3 coats over expanded or woven self furring wire lath reinforcing; however note the use of the 3/8"horizontal wood furring behind the 7/8" stucco cladding, shown in detail in Figure 3-18 from 1932. This in practice would have left a gap between the stucco lath and building paper possibly allowing for some drainage and ventilation behind this wall system, and importantly a capillary break between the stucco and the building paper and wood sheathing. As discussed later, had this gap been in place in the buildings constructed in the 1980's and 1990's, some of the moisture problems may have been reduced or eliminated.

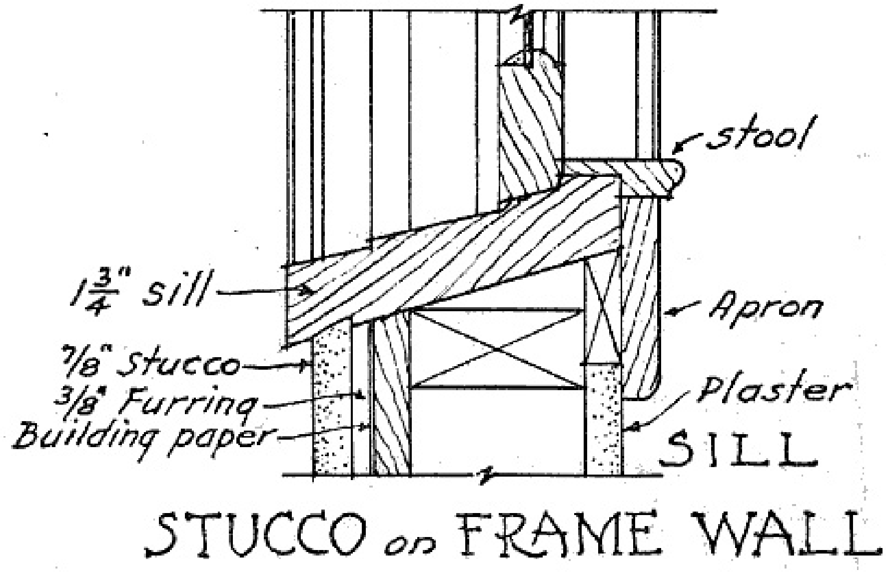

Figure 3-18: Wood Frame Window Sill, Stucco Wall (Ramsey and Sleeper 1932)

In 1974, from Dietz writing about typical construction practices during the mid 20th century, he had the following guidelines for stucco installation: "On sheathed walls, wood walls must first be covered with heavy asphalt impregnated waterproof building paper, lapped 3" horizontally and 6" vertically. For furring on wood walls, self furring lath, furring nails, or furring strips are employed. Furring must allow at least ¼" between the surface of the wall and the under surface of the lath". Common building practice at the time the importance of the capillary break between the absorptive stucco and moisture sensitive wood sheathing was understood.

Another change to stucco construction during the 20th century was the type of wire lath used. During the first half of the century, woven and expanded wire laths were used, which were self furring and had relatively small gaps between the wires(1/2" to 1"). Thus, when stucco was applied in the scratch coat, small gaps would be left between the sheathing paper and wire. Where wood strapping was used, an even larger gap was left. When galvanized welded wire mesh was introduced the gaps between the wires were larger (1-2"), and when the stucco was applied, it came into direct contact with the sheathing paper, thus allowing capillary transport of moisture between, and reduction or removal of the drainage plane and ventilation. The older stucco walls could be considered a drained and possibly ventilated (when strapping used) concealed barrier system, while the new stucco system largely eliminated the drainage layer behind, as thus could be considered a face-sealed system, relying on the surface and joints to resist moisture penetration. These small changes were made gradually, and for stucco walls were likely a contributor in the difference in performance between the new and old walls, as discussed later.

Brick veneer is also popular a popular cladding; however in the early 20th century was debated whether the space between the veneer and sheathing should be filled solidly with mortar or left open. The use of heavy grade waterproof paper was commonly used behind brick veneer, as the mortar joints were found to not be very watertight. By the early 1900's it was realized that drainage weeps at the bottom of brick cavity walls were necessary, although not commonly used at the time (Chown et al 1997).

Asphalt coated building paper was commonly used in construction on the exterior of the sheathing behind the cladding layer, and provided resistance against air draughts and water penetration. It was also sometimes used on the interior of the wall, on its own in a few layers, or behind the plaster, in an effort to reduce air draughts through the wall.

Exterior wall sheathing commonly consisted of 1" x 8" tongue and groove boards (typically 7/8" thick), placed horizontally or diagonally (which was preferable for strength). However, by the 1950's, the benefits of using plywood sheathing were realized and replaced board sheathing as the exterior sheathing of choice. Plywood was available in 4'x8' sheets in thicknesses of 3/8" to 1/2" and nailed up to the studs was rigid with comparable strength to diagonal sheathing boards, and superior to horizontal sheathing. Both plywood and 1x8 board sheathing are shown on the drawings of the 1951 and 1956 Architectural Graphic Standards, likely at a transition point when plywood started to become more popular in use after the Second World War.

Insulating fiberboard made of vegetable, sugar cane, or wood fiber was also used as exterior sheathing in some parts of the country, however did not provide the rigidity and strength that some buildings required, where 1x4 braces, let into the exterior of the studs were used instead. The insulating value of 1/2" fiberboard was not significant, and typically equally to the thicker 7/8" to 1" wood sheathing which it replaced.

As early as 1905, gypsum plaster boards (32" x 36", in thicknesses of 3/8" and 1/2") were being produced as an alternative to traditional wood or metal lath. The boards were nailed or screwed to the studs and finished with a coat of plaster. The gypsum lath came in both plain and perforated, the later providing a mechanical key in addition to the adhesion of the plaster to the surface. Both gypsum and wood or wire lath systems were used up until the invention and widespread use of gypsum wallboard.

Plaster was made from gypsum and lime mixed with clean sand. Similar to stucco it was typically applied in three coasts, a scratch, brown, and finish coat. Plaster ranged in thickness, usually 1/2" over gypsum lath or other board backer to 5/8" over brick and masonry and 3/4" over metal lath. Perlite and Vermiculite aggregates were sometimes used to lighten the plaster and improve the fire resistance of the plaster coat.

Typical wall construction, shown for the period up to 1932 is shown in Figure 3-19 from the 1932 Architectural Graphic Standards. Four different interior finishes, and different claddings are shown, which were used at the time. Only one of the wall sections at the time shows the use of insulation, a thin quilted batt stapled to the studs at mid-depth of the stud wall, relying partially on the insulating benefits of two airspaces instead of one.

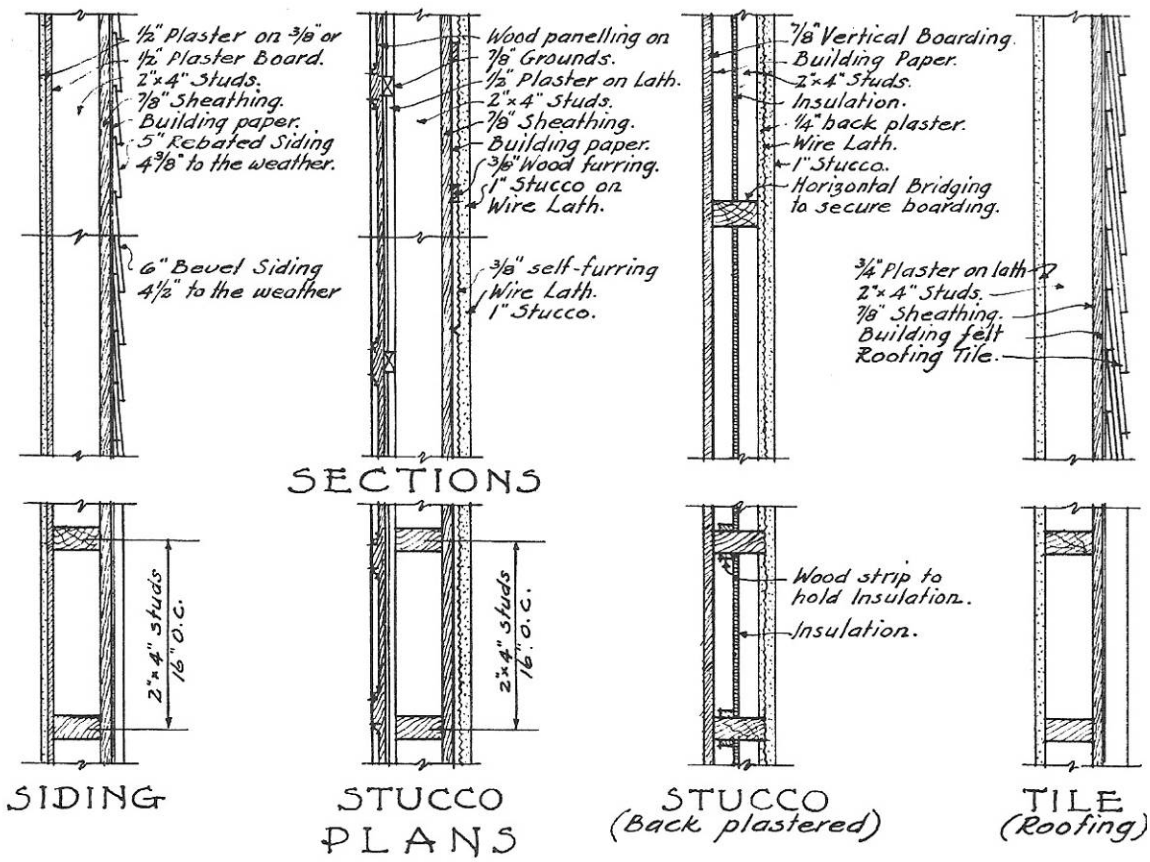

Figure 3-19: Typical Wood Frame Walls, Period Pre-1932 (Ramsey and Sleeper, 1932)

Window details also showed a level of sophistication during the early 20th century, with clearly drawn details of well sloped sills and head and sill flashings. Similar details which were sometimes omitted by architects and builders in Vancouver during the 1980's and 1990's.

Two such details for wood framed windows from the 1932 edition of the Architectural Graphic Standards are reproduced in Figure 3-20.

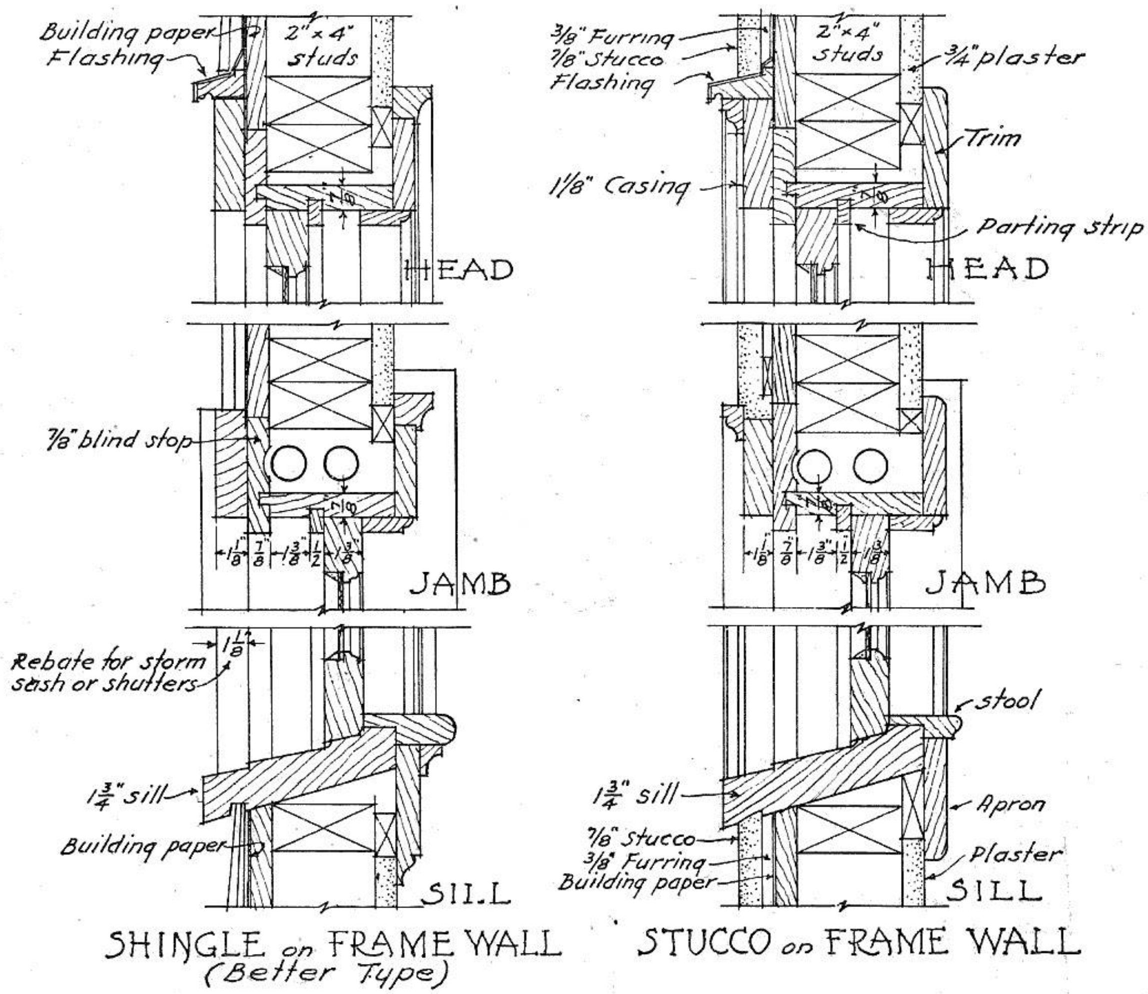

Figure 3-20: Wood Frame Windows (Ramsey and Sleeper 1932)

Later from the 1956 edition of the Architectural Graphic Standards, the window head and sill are shown in more detail than the 1932 edition. The details highlight the use of flashings lapped correctly by the building paper, and drip edges at wood frame window details, to properly shed rainwater and drain the cavity between the cladding and sheathing should water penetration occur.

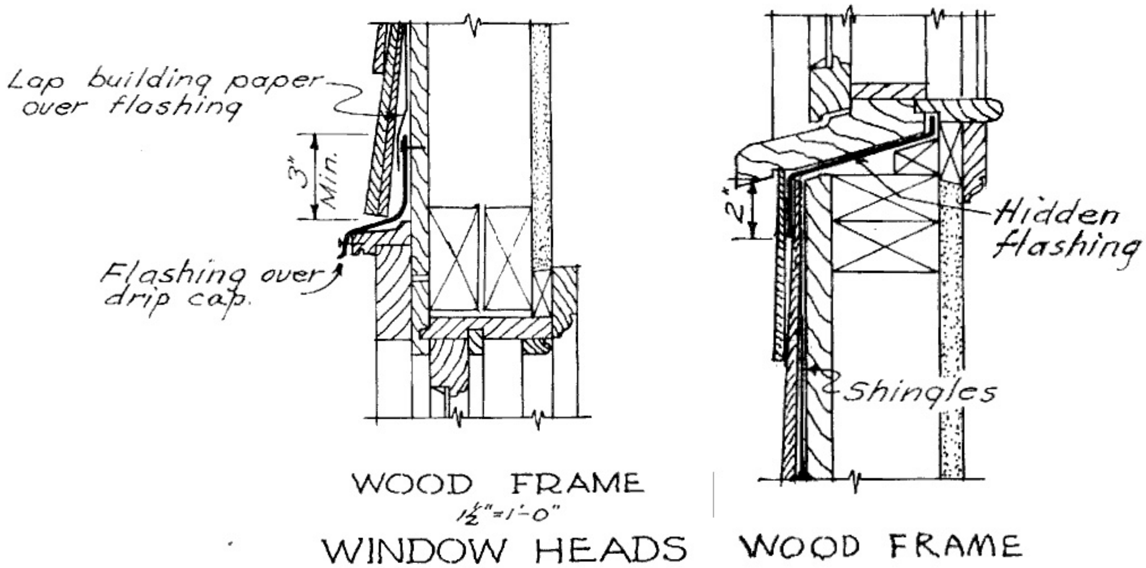

Figure 3-21: Wood Frame Window Flashing Details (Ramsey and Sleeper 1956)

Flashings were usually constructed of tin and other malleable metals (copper, aluminium or galvanized sheet steel). Vapour barrier and insulation, commonly used by 1956 were not shown in these details for clarity.

3.6.2 <u>Insulation – 1900's to 1930's</u>

With the advent of the balloon frame, the exterior walls became thinner, and had a reduced thermal mass compared to the predecessor infill heavy timber frame walls. The result was usually a less comfortable home in the winter, which required more fuel to heat. In rural areas people would cut down as much firewood as they needed for fuel. However in the cities, where fuel had to be bought, whether wood, coal, or oil, the economics of insulating to reduce heat loss in homes was beginning to make sense. In addition, governments began to promote the use of insulation as a means to reducing fuel costs and increasing comfort.

Some insulating materials were experimented with late in the 19th century as previously discussed, however by the early 20th century the use of materials marketed as thermal insulation to control heat loss from buildings began to be appreciated in North America.

Insulation was first used in humid manufacturing facilities, often constructed of steel as it was found that when placed over the exterior walls it would prevent condensation from interfering with the manufacturing process. Cork was typically used for this application in board form.

In the 1920's, Greig at the University of Saskatchewan was testing and demonstrating the value of various insulation materials incorporated in frame wall construction using full scale test huts (Greig 1922). At the University of Trondheim in Norway, Bugge was also doing the same thing (Hutcheon 1955).

Available insulating materials in the 1920's included sawdust, wood shavings, cellulose fiber, cork, seaweed or straw blankets, light boards of pressed wood or sugar cane fiber, and mineral wool batts or blankets. Bulk wood shavings and mineral wool blankets were the most popular insulation materials at the time and provided significant improvement over uninsulated walls.

"Porous gypsum" was also created in the 1920's where foaming chemicals were mixed with gypsum and water, creating small bubbles of gas and reducing the thermal conductivity when the compound hardened in the wall cavity. Its use was limited, and may have had issues with installation, but was used successfully in a few wood frame buildings.

By the 1930's expanded mineral insulations including perlite and vermiculite were in use, typically as fill materials in wall cavities. Perlite and vermiculite are minerals that when heated expand to many times their original size, resulting in a low density product, with decent insulating properties for a natural material.

It would be later found that one vermiculite product, known as Zonolite, mined in Libby, Montana (where approximately 70% of vermiculite was mined in the world) was found to be contaminated with tremolite amphibole asbestos. Amphibole asbestos is potentially 10 times as carcinogenic as the more prevalent chrysotile asbestos and poses a significant carcinogenic health hazard if disturbed (eg. during installation or renovation). Zonolite was quite popular in the 1950's through 1970's used in the attic and walls of thousands of homes and was not taken off the market until the 1980's (Health Canada 2005). Unfortunately Zonolite was just one of the many other insulation products introduced but later found to be a health hazard or other significant risk.

In addition to insulating the exterior walls, loose fill mineral wool, expanded mineral, or blown cellulose fiber was used in the attic spaces of houses where insulation could easily be added in new and retrofit situations.

In 1938, Tyler Rogers a trained architect from the United States published the book "Plan Your House to Suite Yourself" in which he described the many benefits of insulating a house (Rogers 1938a). Largely geared towards the home buyer but talked about the benefits of insulation, and notable for the time of basement walls, to protect against dampness. He suggested methods to avoid moisture problems of insulated basement walls using a small gap behind the insulation to allow condensation to drain to a gutter along the base of the wall, and stressed importance of keeping insulation away from contact with the wall, presumably to drain the condensation that occurred. Vapour barriers were not commonly used at the time of writing the book, but does mention them later as being recently invented "by scientists and insulation engineers."

He discussed some of the issues with interior humidity, and issues with condensation on windows and walls. He suggested using storm windows, of double glazed units to overcome the condition, but also suggested reducing the interior relative humidity, which "according to the experts the theoretical ideal for comfort and good physical condition is to maintain RH from 45% to 65%, but as low as 35% in the winter". Wintertime humidification was harmful, and that relative humidity should be maintained such at that excessive condensation does not occur.

On insulation he is quoted to say "Of all the dollars you invest in a house, those that you spend for proper insulation will pay the greatest dividends" (Rogers 1938a, p. 223). He stressed the importance of insulating both the walls and roof with equal effectiveness. The walls and roof for the winter, but in the summer, the roof insulation kept the house cooler.

He also recognized that for different climates, different insulation amounts should be used, ranging from R-17 in very cold or hot climates to R-3 for minimum protection in temperate regions. An uninsulated wood frame wall with wood cladding, sheathing and plaster interior would have U-value of 0.25 (R-4.0).

	Superior Protection	*Average Protection*	*Minimum Protection*
In very cold and very hot localities	.06 to .08	.08 to .12	.12 to .20
In moderately cold or hot localities	.08 to .12	.12 to .18	.18 to .25
In temperate regions—no extremes	.15 to .20	.20 to .25	.25 to .35

Figure 3-22: Recommended Insulation U-values (Rogers 1938a).

In regards to moisture problems, he recognized that during the 1930's, insulated houses were experiencing moisture problems as a result of condensation within the cold exterior walls, just as it occurs on the windows. The moisture source either "winter air conditioning" or humidification from daily activities including cooking and washing.

While vapour barriers had just been invented (more on this in the next section) by 1937, they were not in common use by 1938, however Rogers was very informed on the upcoming technology. Materials for vapour barriers could include: waterproofed building paper, metal foil, oil or aluminium paints, and he stated that "these should be used between the insulation and warm humidified air".

An important note that may have been overlooked by the development of the vapour barrier was that Rogers recognized that if the vapour was allowed to flow right through the wall, and was not impeded by heavy waterproof or vapour-sealing building papers on the exterior, the insulation would remain "bone-dry".

Interestingly, Rogers also had the information to mention that "new techniques for the installation of several forms of insulation are developing rapidly in consequence of research completed in late 1937 to solve the problems imposed by winter air conditioning (heating plus humidification) and modern "air-tight" construction" (Rogers 1938a, p. 229). Presumably he was referring to upcoming mineral wool insulations with integrated vapour barrier facers and flanges for easy installation in wall cavities. Rogers may not have had the technical background as some of the researchers at the time, who were developing regulations for the vapour barrier, but he was one of the few bringing the technology to the architects and consumers.

In 1946, Babbitt at the National Research Council (NRC) published a paper on the insulation of houses which summarized some of his previous work at NRC. Previously in 1939 and 1940 he published several other papers including one on the value of insulation, and another on the diffusion of water vapour through materials, one of the first in North America to do so.

In the 1946 paper he showed the many benefits of insulating houses to maintain comfortable and healthy living conditions throughout the year (both winter heating and summer comfort), but also the economical benefits of reduced fuel consumption. He even went as far as to state "There is in fact, everything to be said in favour of insulation, and nothing to be said against it" (Babbitt 1946, p.15).

He was aware that a considerable amount of heat was lost through the building enclosure, mainly the walls, roof, floors, windows and doors, but also air infiltration. He also realized that with reduced heat losses from insulation, a smaller furnace and heating system could be used.

Air infiltration he later describes as through the materials in the exterior walls, but also around doors and windows without weather-stripping. However he did not discuss air exfiltration and the possible effects it had on the wall assembly, but later separately discusses vapour diffusion.

He stated that in good construction, building paper is used behind the exterior cladding, to limit air infiltration but also as a barrier against wind-driven rain. Like Rogers, he stressed the importance that the building paper be vapour permeable, in order to allow the wall to dry to the exterior.

Referencing data from S. Konzo in 1936 from the University of Illinois, Konzo studied 200 uninsulated wood frame homes, and found that 16% of heat loss was through the roof, 27% through walls, 25.8% through the glass, 24.6% by air infiltration, 4.3% door and 2.1% floor and other. Storm windows reduced heat loss by 31.3% overall, and when walls were insulated with 2" of mineral wool, the heat loss was reduced by 17.4% overall. The total reduction of 2" mineral wool and storm windows was a savings of 62% overall, and a reduction in fuel from 10 to 4 tons of coal per year (Konzo 1936). Konzo incidentally was one of the pioneering researchers in the 1930's on air conditioning in the United States.

Babbitt concluded that depending on the location in Canada; an insulation thickness between 2" to 4" (51 to 102 mm) of insulation was most economical, based on the price of insulation and fuel at the time. In addition, insulated walls would also reduce possibility of surface condensation and thermal dusting.

In an example energy savings calculation for a house in Ottawa (8681 Heating Degree Days, Fahrenheit) he found a reduction of 50% in the energy requirement (13.5 to 6.8 tons of coal) by using 2" of Rockwool insulation in the walls and ceiling. With mineral wool insulation costing $0.12/sq.ft, and over a 20 year life cycle, the resulting annual fuel cost of coal was approximately $106, from $195 without insulation.

By the 1950's the use of thermal insulation and its benefits were well known and numerous products with varying properties were available on the market. Thermal transmittances (U-values) are commonly used to compare different insulations, and several products are compared in Figure 3-23 from the 1951 Architectural Graphic Standards, listing the percent improvement over an uninsulated stud wall (right side of figure), and the U-value (Btu/ft^2 hr F) (left side of figure).

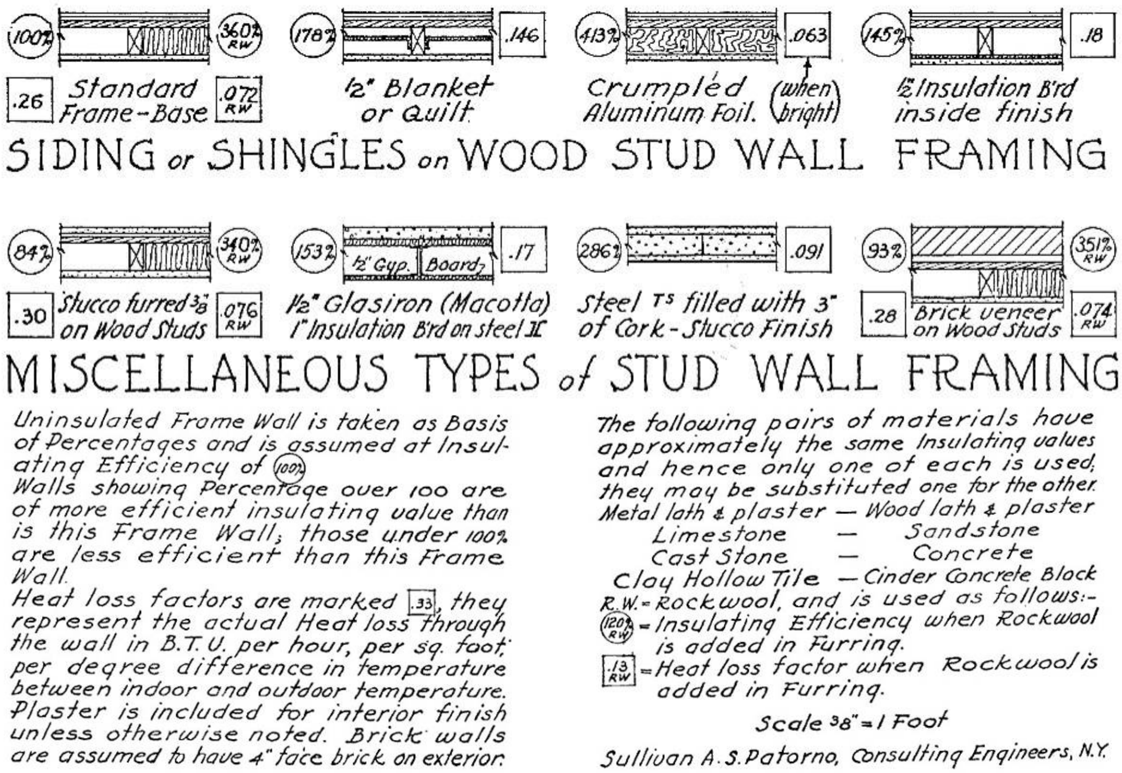

Figure 3-23: U-Values for Different Insulation Types, 1951 (Ramsey and Sleeper, 1991)

Several other available batt and blanket insulating materials are shown in Figure 3-24, which highlight the variety of products available to the builder at this time. These particular insulation products manufactured with integrated asphalt paper vapour barriers or reflective coated surfaces.

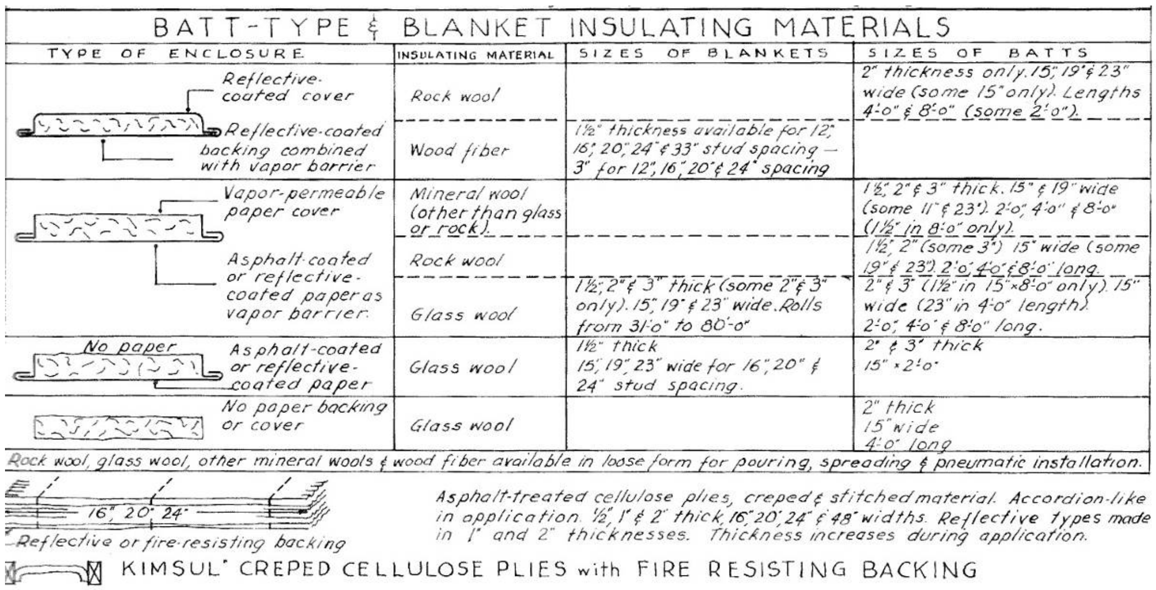

Figure 3-24: Faced Batt and Blanket Insulating Materials (Ramsey and Sleeper 1956)

Also quite popular during the mid 20th century were reflective foil insulations and as shown in Figure 3-25 came in a number of different configurations, with manufacturers trying to maximize the airspaces contained by the reflective foils and thus insulating value.

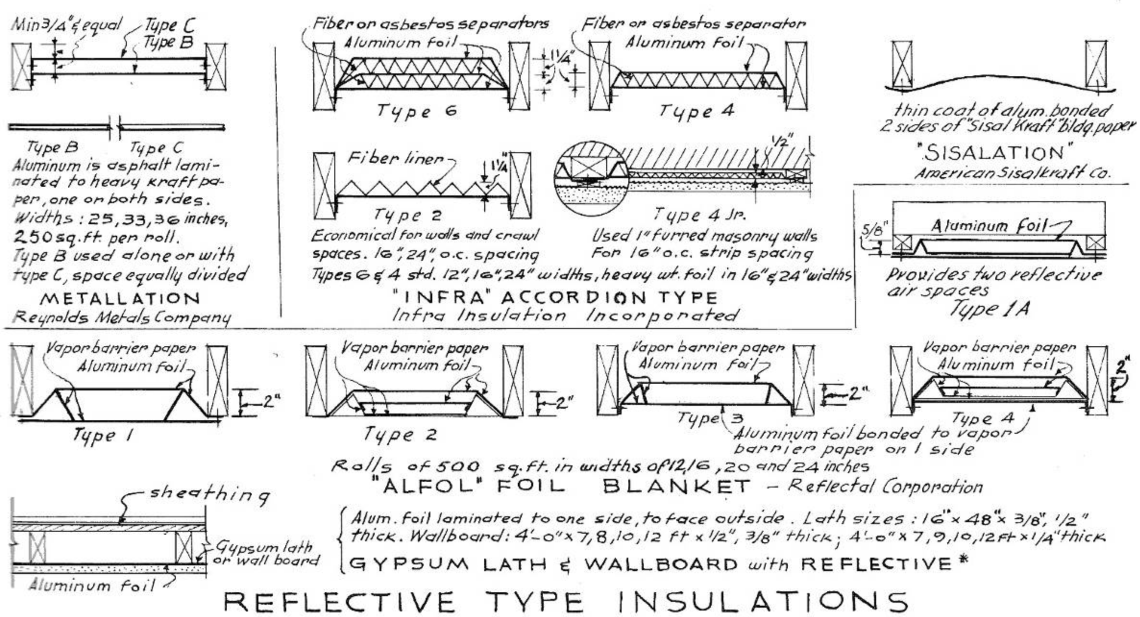

Figure 3-25: Reflective Type Insulations (Ramsey and Sleeper 1956)

Often manufacturers of reflective type insulations overstated the thermal resistance values of their products, as the installed performance was not quite as expected. Nevertheless the following values were published in the 1956 Architectural Graphic Standards. U-Values of 0.11 Btu/ft^2 hr F (R-9) could be attained with 2" batt or roll type insulation, or a few blanket reflective insulation products, or 2" reflective accordion type insulations. A further increase to U-value of 0.09 Btu/ft^2 hr F (R-11) was possible with either 3" batt or roll type insulation, or a number of other foil accordion type insulations, or blanket reflective insulations.

Reflective insulations were commonly used in some parts of the country; however the thermal resistance advertised was strongly dependent on the quality of installation. Figure 3-26, from 1964 shows a stud wall with reflective accordion type insulation in the left stud bay, and a fiberglass batt blanket reflective insulation on the right (vapour barrier installed on wrong side). Both were observed as installed in the stud wall of this house, highlighting some of the installation difficulties/mistakes with both these types of insulation.

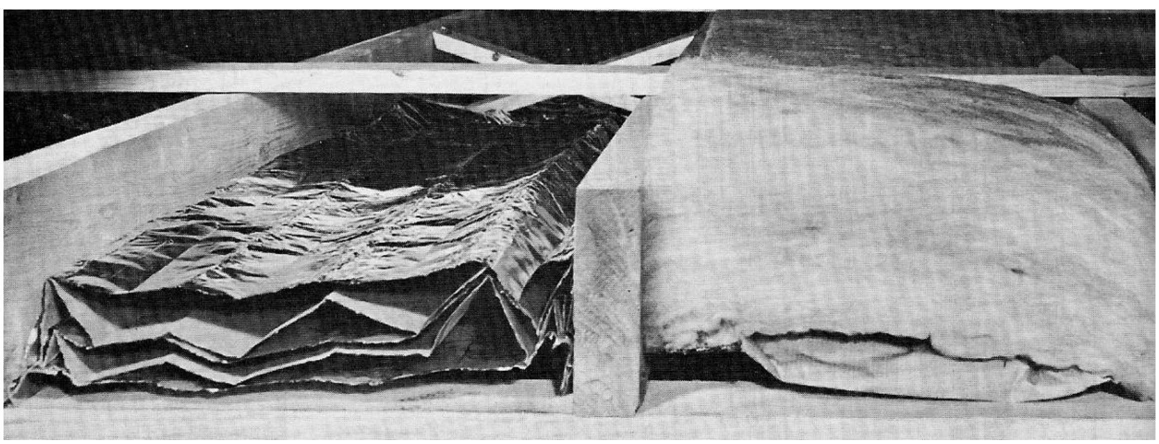

Figure 3-26: Reflective Accordion Type and Reflective Faced Batt Insulation (Rogers 1964)

The accordion foil system relies on airspaces trapped between the reflective foils, however as installed above the full advertised thermal resistance would not be achieved. One thing to note was that these reflective foil insulations were completely impermeable to water vapour, and also likely reduced air leakage through exterior walls if installed properly as compared other air permeable insulations.

3.6.3 Vapour Barriers – 1930's and 1940's

During the 1930's reports of moisture problems in insulated buildings began to be reported. Complaints of wood decay, peeling siding paint, and ice formation within the walls were common complaints from insulated houses in cold areas of the North America.

Before getting too far, it makes sense to define a *vapour barrier* at this point. A *barrier* implies that no vapour will get though the material, where as in practice some vapour will, and should be correctly termed a vapour *retarder* as it only slows the flow significantly. However, the difference between the two is important, and therefore vapour *barrier* will be referred to as a material with a vapour permeance of less than 1 US perm (57.4 ng/Pa·m^2·s) and vapour *retarder* anything higher than 1 US perm that purposely controls vapour flow. Vapour *permeable* materials such as gypsum plaster, building paper, and fibrous insulations have permeances much greater than around 10-20 US perms (574 – 1148 ng/Pa·m^2·s). *Vapour control* refers to using a vapour retarder or barrier to reduce vapour flow, or using vapour permeable materials to allow vapour to flow through intentionally

The use of the term *vapour retarder* wasn't used in normal nomenclature until after the 1970's following an ASTM recommendation and court case which argued against the ASHRAE 1961 definition of *vapour barrier* (Rose 2005).

While the consensus by the 1930's was that thermal insulation was beneficial, it undisputedly changed the temperature profile of the wall assembly, keeping moisture sensitive wood sheathing and cladding colder and susceptible to condensation from interior air and water vapour. Insulation was blamed for the problems, and prompted by insulation manufacturers; research into the wetting mechanism of vapour diffusion and its control was performed in the United States and Canada between 1937 and 1942. The results of this research lead to recommendations for vapour barriers in walls and ceilings and ventilation for attics and crawlspaces. While thermal insulation was the cause of the problem it had obvious benefits and suggestions to remove it entirely from buildings was never seriously proposed.

William Rose has spent considerable time researching the history of vapour barriers in the United States and has produced some very informative reading on the topic (Rose 1997, Rose 2005). A brief history of the development from with

American references from Rose's work and additional research from Canada performed concurrently is presented here.

Peeling paint was one of the initial signs of moisture problems within the walls with some painters even refusing to paint insulated houses (BRAB 1952). Work at the U.S. Forest Products Laboratory (FPL) by Browne in the early 1930's was one of the first attempted efforts to solve the problem. It was known that paint could peel on wet wood; however how the wood became abnormally wet was the problem. Browne found two conditions which lead to paint peeling. The first being rainwater leaking through joints in poor design. The second being moisture which originated within the building carried by air circulation through the outside walls, and condensing on cold surfaces (Browne 1933). While no solutions were recommended, he did however suggest two plausible wetting mechanisms. The first which could be addressed by better details, and second which required further research.

Larry Teesdale at the FPL carried on this further research and in 1937, published the report "Condensation within walls and attics", which explained how the use thermal insulation sufficiently cooled the exterior sheathing to a point where condensation would occur, and moisture accumulate. Teesdale further went on to recommend vapour barriers, attic ventilation, maximum wintertime RH of 30%, and removal of intentional moisture sources should water damage appear. (Teesdale 1937). The recommendations based upon cold climate (Wisconsin) observations and data.

Frank Rowley, at the University of Minnesota during the 1930's was also studying conductive heat flow through insulation and was developing a theory of vapour diffusion through solid materials (Rowley 1938). He showed that vapour flow was analogous to vapour flow, and the vapour flowed from high to low vapour pressure.

He showed how an insulated wall would reach vapour pressure saturation at the sheathing without a vapour barrier, while the uninsulated wall would not as shown in Figure 3-27. He showed how vapour retarder would reduce the vapour pressure and prevent condensation. He concluded his paper with recommendations for vapour barriers as well as attic ventilation

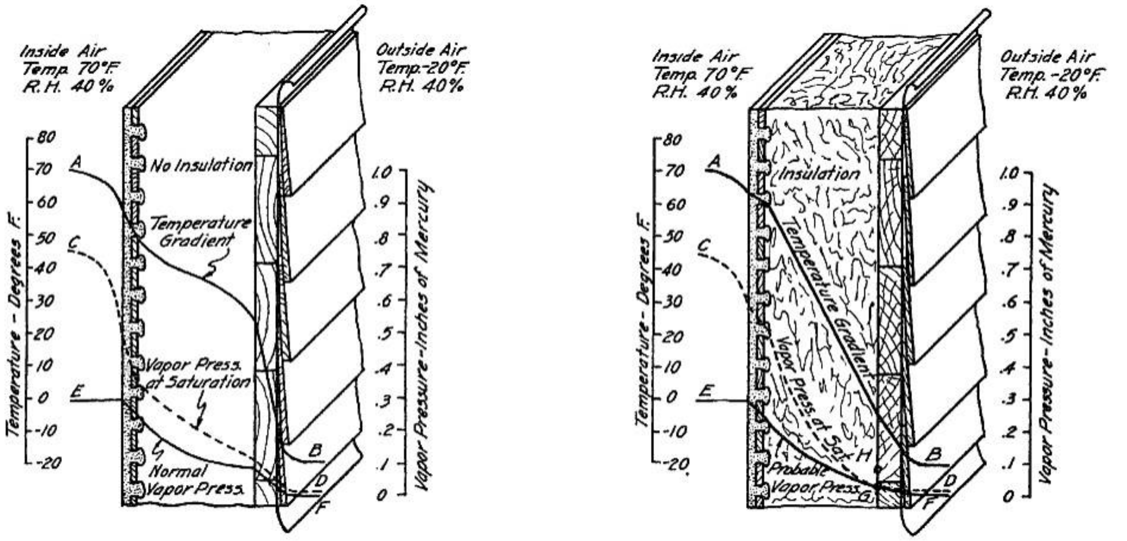

Figure 3-27: Vapour Pressure and Temperature Gradients for Insulated and Uninsulated Walls (Rowley 1938)

By 1938, Tyler Rogers had published his book "Plan Your House to Suit Yourself" (1938a) as previously discussed and published an article in the Architectural Record "Preventing Condensation in Insulated Structures" (1938b), where some of his ideas from his book were presented to a wider audience.

He was well aware of the moisture problems in the walls and attics of insulated buildings. To mitigate, he suggested reducing the wintertime interior relative humidity, the use of vapour permeable sheathing papers to allow any vapour to flow right through the wall, and the use of impermeable vapour barriers on the interior between the insulation and interior (Rogers 1938a & 1938b). The vapour barrier materials he recommended from the roofing and plastic packaging industries.

In his article in the Architectural Record he presented one of the first demonstrations comparing vapour pressure and temperature profiles for walls with a without vapour barriers as reproduced in Figure 3-28.

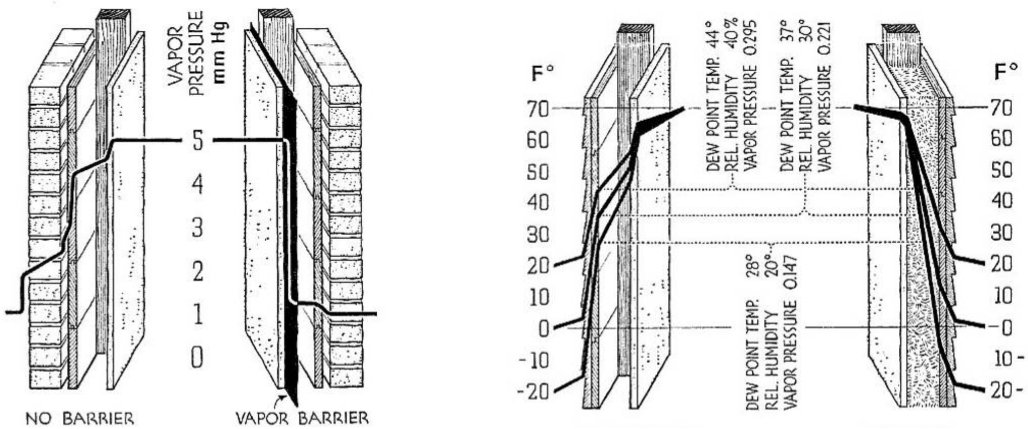

Figure 3-28: Comparing Temperature and Vapour Pressure in Insulated and Uninsulated Walls (Rogers 1938b)

A strong supporter of insulation in buildings, Rogers in 1939 went on to be director of technical publications for the newly formed Owens Corning Corporation, a partnership in 1938 between two major American glassworks, Corning Glass Works and Owens-Illinois (Rose 2005, Wikipedia 2006).

Simultaneously, at the National Research Council in Canada, Babbitt was testing the water vapour permeance of several building materials, in particular related to his research of insulation materials. Like Rowley and Rogers in the United States, Babbitt demonstrated that vapour was diffusing through insulated wall from the interior and condensing on the cold sheathing surface. (Babbitt 1939).

On condensation, Babbitt suggested three methods to prevent it from occurring during the wintertime. The first was to reduce the relative humidity within the house, second to use a vapour barrier on the warm side of the insulation, third to provide ventilation to the exterior and use permeable exterior materials. Finally he stated that all walls "must be weatherproof, impermeable to wind and wind-driven rain", with building paper installed beneath the cladding for this function (Babbitt 1946).

Much of the work on vapour barriers was performed during the Second World War, and the governments were largely preoccupied with war matters. However, based on the work described in Canada and the United States, regulations were put forth by the governments during the early 1940's.

In Canada, basic provisions for vapour barriers were in the 1st edition 1941 National Building Code, which called for a vapour barrier material (<0.76 US perms) to be used between the interior of studs and interior face of wall whenever the building paper or sheathing material is highly resistant to the transmission of water vapour (<3 US Perms). No mention of insulated walls, however the minimum R-value for exterior walls of habitable rooms was R-4, which corresponds to an uninsulated wood stud wall, for brick or stone, insulation would therefore be required.

In the United States in 1942 the Federal Housing Administration (FHA revised guidelines in the "Property Standards and Minimum Construction Requirements for Dwellings" and contained the following prescriptive requirements (from Rose 2005).

1. Vapour Barriers - in walls and ceilings with "a minimum of 1.25 grains/ft^2 hr in-Hg"
2. Crawlspaces and "Basement-less Spaces" – "sufficient foundation all vents to assure a total ventilating area"
3. Attics – prove ventilation of "not less than 1 square foot for 300 square feet of horizontally projected roof area" – the 1/300 rule still a requirement today.

In Canada, supplemental standards published in 1950, which later became mandatory as part of the 1953 NBCC (2nd edition) explicitly required vapour barriers in insulated walls, which created a gradient in water pressure. In the standard, vapour barriers were required on the interior warm side of the wall with a vapour permeance of less than 0.75 perms (45 ng/Pa·m^2·s) of an aged product. 1 perm was initially agreed on in both Canada and the United States, but for a non-aged product. In addition standards for building paper were established, and required the product to have a permeance greater than 3-5 perms (172 to 287 ng/Pa·m^2·s) (Bomberg and Onysko 2002).

Incidentally, neither the Canadian or American requirements made provision for climate; it was a widespread requirement, which research was based on largely cold climate requirements. Provisions for temperate and hot climates were not initially made, other than the vapour barrier should be placed on the warm side of the insulation.

Thus, by the late 1940's, at the time of the post-war building boom in North American cities, as a result of these regulations, both insulation and vapour barriers were widely used in the construction of these new homes. The most common insulation being 2" (50 mm) of mineral wool with integrated asphalt coated kraft paper vapour barrier.

During the early 1950's heavy promotion and marketing (even what could be considered today "fear mongering") was performed by the National Paint and Varnish Association (NPVA) to promote the use of vapour barriers as a method to "curb paint peeling in insulated buildings" (Rose 2005). The marketing campaign was known as "the war against water" and Rose has dug up some of the original marketing posters in his book, which are quite humorous today.

Also recommended by the NPVA to prevent paint peeling, was ventilation of the backside of wood cladding and reducing interior humidity levels. However no evidence on a large scale was shown that the last two were readily accepted into common practice, such as vapour barriers were.

In summary, both old and new construction methods, representing a turnaround in the 1930's and 1940's as reproduced in Rose (1997) from Kent (1950) is shown graphically in Figure 3-29.

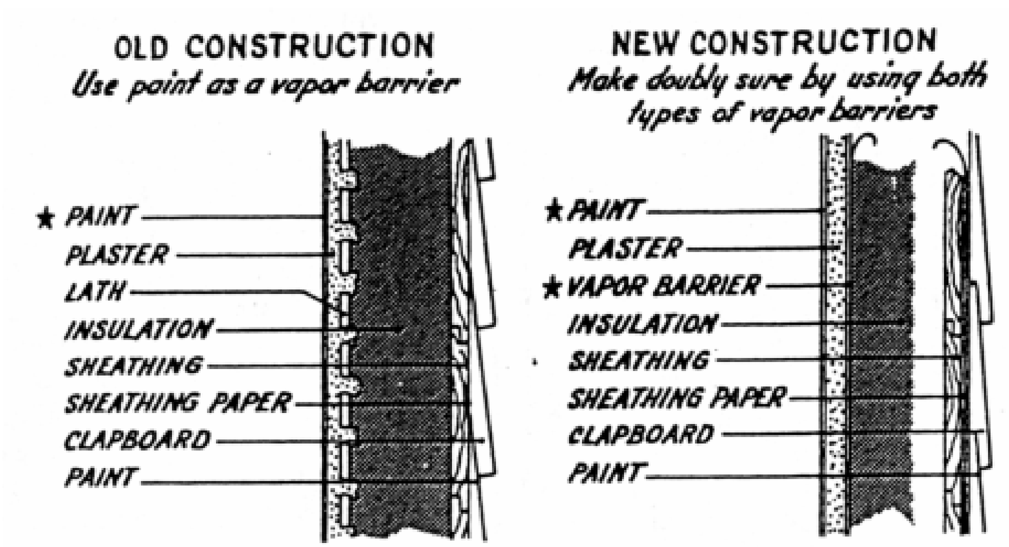

Figure 3-29: Old Versus New Construction Method after 1930 (Kent 1950)

Here the pre 1940's construction methods are shown on the left; with paint recognized as a "vapour barrier" (oil paint typically has a permeance of approximately 0.5 to 2 US perms (~30 to 120 ng/Pa s m^2, and more correctly a vapour retarder). Insulation as drawn completely filled the cavity, as loose fill insulations such as wood shavings or dust, or loose fill mineral wool, and expanded mineral fills were commonly used prior to vapour barrier faced mineral wool and fiberglass batts.

After the definition of the vapour barrier in the 1940's, mineral wool insulation was typically integrated with an asphalt coated kraft paper as shown earlier for ease of insulation. These faced mineral wool (and fiberglass) insulations did not completely fill the stud cavity, as typically 2" (50 mm) deep was common, stapled to the inside face of the vertical wood studs. The 2" (50 mm) airspace that remained between the sheathing and insulation, while thermally inefficient, could have allowed for redistribution of moisture leaks and potentially drying of the sheathing.

Requirements for vapour barriers were first added to the 1951 version of the Architectural Graphic Standards (Ramsey and Sleeper 1951). Guidelines on pg. 495 from the 1956 edition were as follows: "Vapour barriers are desirable in air conditioned buildings to reduce latent heat load and in all heated buildings to control or prevent condensation. In all cases place insulation on the warm-in-winter side of wall as near as possible."

Vapour barriers were also clearly shown on drawings throughout the 1956 edition as ground covering in ventilated crawlspaces. In regards to the use of vapour barriers in ceilings of ventilated attics, the following guidelines, by geographical area in the United States was provided, reproduced in Figure 3-30. The guidelines were not developed by Ramsey and Sleeper, but were referenced from the United Stated Housing and Home Financing Agency, "Condensation Control in Dwelling Construction".

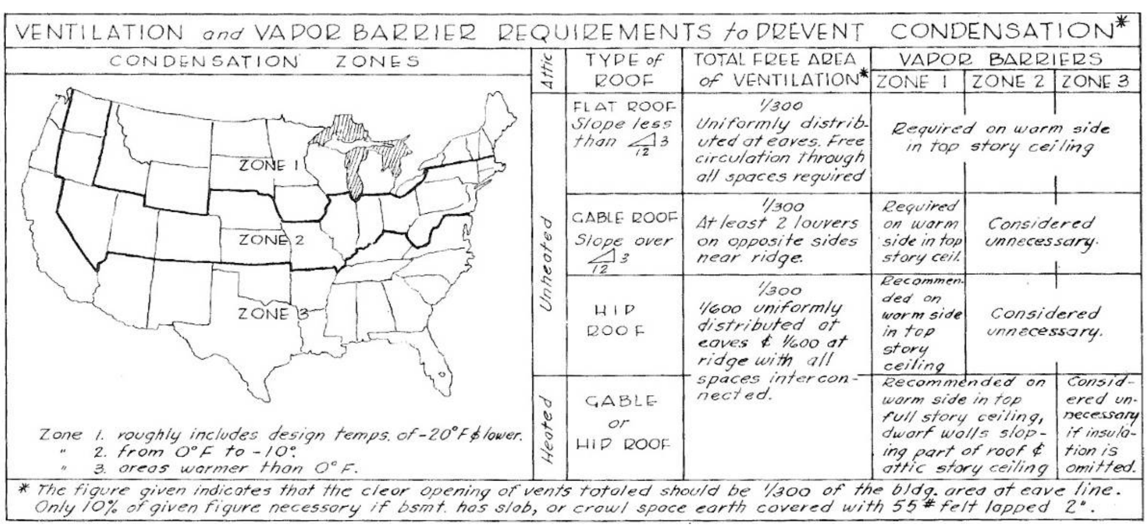

Figure 3-30: Vapour Barrier Requirements for Ventilated Attics (Ramsey and Sleeper 1956)

No such provisions as to climatic region appear to be given for vapour barriers in the exterior wall as they were for the ceiling.

As some point, between the initial widespread vapour barrier requirements in 1942 and 1956, provisions were made for the attic ventilation and ceiling vapour barrier requirements in different climatic zones based on geographical states. However by state, this meant that the same provisions would apply for beachside villa at Long Beach, California, as they would for a mountainside snow covered chalet at Mammoth Mountain, California. Two obviously different climates within the same geographical region, however both had the same prescriptive requirements.

In Canada, vapour barriers were required at the ceiling of all dwellings with unheated attics (same as Zone 1 for the United States); however it is interesting to note that Zone 3 or even Zone 2 covering Seattle, Washington could be extrapolated up to Vancouver and Coastal British Columbia, which are in the same Temperate Marine climate zone classified today (Lstiburek 2004). However no such options were made available in Canada.

As for the definition of climate zones, neither readily available weather data, nor the computer processing power was available in the 1950's to compare climatic regions, and the state by state separation was a reasonable approximate. However the consideration of all of Canada as a "cold climate" may not have been a reasonable estimate at the time, especially when one compares the climate of Coastal British Columbia to that in say Ottawa or Saskatchewan where much of the government field research at the time was performed.

In summary, the research into the problems of wet exterior walls and paint peeling of insulated houses, led to the prescriptive requirements for vapour barriers in insulated walls and ceilings and ventilation of attics and crawlspaces, regardless of climate. The solution was a new material to prevent wetting from indoor moisture sources, however did not address other potential wetting mechanisms such as rainwater penetration from poor detailing, or air leakage, both of which are in orders of magnitude greater moisture sources. It appears that the main focus of research was on perhaps the most insignificant wetting source available. William Rose calls this the "Diffusion Paradigm" because the central focus to design is that moisture moves through building envelopes by diffusion, which does so slowly, at rate exceeded by orders of magnitude by other mechanisms (Rose 2005).

3.6.4 Progress and Failure - 1940's through 1960's

While the addition of the vapour barrier to the typical wood frame wall resolved the problem with winter-time vapour diffusion condensation, moisture problems continued to persist in buildings. Problems with post-war housing created the need for research and recognition into the performance and requirements of walls (Hutcheon 1953).

The need for building research was recognized by the Canadian Government, and in 1946, the Central Mortgage and Housing Corporation (CMHC) now Canadian Mortgage and Housing Corporation was established. The CMHC was established to implement government housing policy, supply mortgage financing, and responsible for improving the quality of housing. CMHC also implemented many federal-provincial subsidized and social housing projects bringing more affordable housing to all Canadians (CMHC 2006).

Soon after in 1947, the Division of Building Research (DBR) was established under the National Research Council (NRC). The responsibility of the DBR was to provide technical support to CMHC and periodically revise the National Building Code. Previously, the work of Babbitt in the late 1930's and early 1940's at the NRC was performed under the Division of Physics and Electrical Engineering.

3.6.4.1 Neil Hutcheon – NRC/DBR

From the DBR, Hutcheon in 1953 presented his landmark paper "Fundamental Considerations in the Design of Exterior Walls for Buildings", which really brought the science into exterior wall design and outlined nine design considerations for Canadian conditions (Hutcheon 1953 p.3):

1. Strength and rigidity
2. Control of heat flow
3. Control of air flow
4. Control of water vapour flow
5. Control of liquid water movement
6. Stability and durability of materials
7. Fire
8. Aesthetic considerations

9. Cost

The separate items listed which were all to be considered when designing the exterior wall. His ideas were revolutionary for the time and he was one of the first to suggest insulating the exterior of walls to reduce temperature gradients in the building structure. Up until this time, insulation was placed primarily between the studs. By the end of the Second World War, however insulation materials in board form (particularly foamed plastic insulations) were available which could suit this purpose.

When discussing the use of vapour barriers, he noted that that the while the use of vapour control in wood frame walls was well established, it was "not yet conclusively shown that this is entirely satisfactory for insulated masonry construction (p.20)". Citing that in winter the total vapour flow into an outer 4" brick with an interior vapour barrier would result in a 0.25% increase in the moisture content, while "several times this amount of moisture may readily be added in a single rain (p.20)." When a vapour barrier is used, the wall can only lose moisture to the outside, and that in the summer, "hot sun following a rain drives moisture as vapour to the inside of the wall, and condensation behind the vapour barrier can occur (p.21)". Hutcheon realizing that a vapour barrier was not beneficial in all seasons, and that absorptive claddings such as brick could act as a reservoir for moisture, driving vapour inwards under solar heating.

To overcome these problems with brick cavity walls, he recommended that "the cavities should be ventilated to outside, by air passages through the outer withe. If placed at different elevations, these would promote air circulation to carry off vapour to the outside, under wet-hot summer conditions of the outer withe (p. 21)". He also cautioned against the use of water proof membranes or sprays over or in masonry construction which could prevent drying and potentially lead to problems, including freeze-thaw damage.

He also set out two fundamental principles for moisture control (Hutcheon 1953, p. 21):

1. Vapour flow from inside the wall in winter must be restricted by vapour barriers or otherwise, at a plane sufficiently warm to prevent condensation on the warm side of the barrier
2. Walls must be capable of limiting the entry of water from outside into capillary material in the main part of the wall, while permitting the flow of water vapour to the outside under winter conditions.

In addition he also suggested on the same page:

> "Require a minimum of potential storage capacity on the outside of the wall, or is such potential capacity exists, to separate it capillary wise from the inner portions of the wall, and to minimize by venting the transfer of vapour to the inside under summer conditions". (Hutcheon 1953, p. 21)

In relevance especially for Vancouver, and this thesis, later in the paper Hutcheon was the first to present the idea of the "rainscreen wall" to Canada, an idea translated from 1946 Johansson's Swedish paper in which he described the concept.

> "However, it is clearly unwise to allow it is clearly unwise to allow walls, whether of brick or porous cement, to be exposed to heavy rain. They absorb water like a blotting paper, and it would therefore be a great step forward if an outer, water repelling screen could be fitted to brick walls, with satisfactory characteristics from the point of view of appearance, mechanical strength and cost."

> "This screen could be applied so that water vapour coming from within is automatically removed by ventilation of the space between wall and screen."

> "If a **rain screen** of this type is used, the thermal resistance of the wall can be considerably increased for only a slight increase of expense, by employing one of the highly porous, thermally isolating materials now obtainable. With a highly porous layer between the actual wall and the rain screen, the house would retain its good characteristics as regards heat capacity, sound isolation and fire risk. At the same time it would be guaranteed free from moisture, even in the worst weather, and moreover be extraordinarily well isolated thermally". (Johansson 1946, translated by Hutcheon 1953, p. 22)

Hutcheon went on to comment, "The approach to wall design as presented by Johansson is perhaps an idealized one, to be modified to conform to many practical considerations. It is perhaps not the only idealized approach possible, but so far as can be predicted, it can be made to satisfy simultaneously all the various requirements, and it is possible of achievement. It permits a wider selection of materials, since the number of properties which any material or element must provide can be reduced" (Hutcheon 1953, p22).

In summary, Hutcheon suggested that vapour barriers could be used in a position (not always the interior surface) within the wall warm enough to prevent condensation. He suggested that the insulation and vapour barrier be placed outside of the structural wall, in order to maintain a relatively constant environment. Finally, the wall should be capable of limiting water entry from the outside through capillary or vapour flow to the inner wall, and for that he recommended a ventilation space behind porous claddings. The rainscreen idea was Johansson's in 1946, however Hutcheon practically applied the principles, whereby the "weather screen" cladding could be of any material, separated by a ventilated and drained airspace, rigid insulation and a vapour barrier applied to the exterior of the structure.

Later it was stated, that this approach of insulating on the outside of the structure suggested by Hutcheon initiated a gradual but significant change in construction practices in Canada (Handegord 1982).

On the research front, by 1960 the Canadian Building Digest (CBD) series began publication, which presented research from the NRC/DBR on building envelope issues. The first edition published by Hutcheon himself on Humidity in Buildings, but more on that later.

3.6.4.2 Material Development

After the Second World War, the use of oil replaced coal as a furnace fuel, due to its cleanness and ease of distribution and handling. By the 1960's electricity was also became popular as a heating method for homes, but only after houses were well insulated could it be economical.

Paper faced gypsum drywall was becoming more popular in the 1950's for its ease of installation and finishing, replacing plaster with gypsum or wood lath as an interior finish. Foil backed drywall was also available which utilized aluminium foil as an integrated vapour barrier.

Aluminium siding was introduced after the Second World War, as a durable and maintenance free alternative to wood. While aluminium is its self impermeable to water vapour, provisions were usually made for ventilation by openings along the lower edge. For rigidity, aluminium siding was often backed with fiberboard or foam insulation. Cement asbestos shingles and hardboard sidings were also common replacements for wood cladding.

Some not so successful claddings were also introduced on the market. In the 1940's through 1960's several "insulating" cladding materials comprised of wood fiber and asphalt were put on the market commonly known as "Insul-Brick", similar to roofing shingles. The material was patterned to look like stone or brick cladding and was applied over the cladding of existing homes and as the cladding in new low-cost construction. When installed it provided an impermeable vapour and air tight seal on the exterior of the building (the "wrong side" in cold climates), which was later found to be responsible for the deterioration and rotting of wood framed walls.


Figure 3-31: "Insul-Brick" Cladding (J. Murden 2006)

The wall shown here with "Insul-Brick", while spalled and past its useful service life, appears to have a strapped cavity behind (exposed closely spaced vertical wood strapping). It was likely realized that installing the impermeable cladding in contact with the sheathing would have lead to deterioration.

Various new types of insulation were introduced after the Second World War, mainly foamed plastics including polyurethane foam, polystyrene, sprayed asbestos and aluminium foils.

Of these new insulation products, Urea-formaldehyde foam (UFFI) was introduced into Canada in the 1960's. UFFI was developed in Europe in the 1950's, a spray-foamed insulation formed by mixing urea and formaldehyde, producing insulation with an R-value of R-4 to R-4.6 per inch. It became a common replacement for mineral wool insulation within stud spaces for its ease of application and good thermal resistance. Unfortunately it was later found that it released toxic formaldehyde gas over time (higher initial rate), resulting in debated problems of indoor air quality and health concerns, and leading to several lawsuits. UFFI was not banned until the early 1980's when the ill-effects of its off gassing were fully realized.

By the late 1960's, the effect of fiberglass batt location and fit between studs on heat flow and wall surface temperatures was recognized, which lead to the development and use of "friction-fit" batt insulations of mineral wool and fiberglass. By 1967, CMHC recommended 2 to 3" (51 to 76 mm) of insulation in walls, and 3" (76 mm) in ceilings. However for electrically heated houses, 4" (102 mm) in the walls and 6" (152 mm) in the ceilings was usually provided (CMHC 1967).

Problems with cold spots and dust marking due of walls insulated with reflective foils, popular in the 1940's and 1950's were also realized during the 1960's. It was shown that convective loops within connected airspaces were reducing the effectiveness of the insulation, and leading to reduced thermal performance and cold spots.

3.6.4.3 Vapour Control

By the late 1960's, papers coated or laminated with bitumen, wax-coated papers, aluminium foil and polyethylene film were typically used as vapour barriers in wood frame construction (CMHC 1967).

As for vapour barrier technology, practitioners were primarily concerned with the careful installation of the material, as to ensure the seams, holes, rips, or tears were well sealed. The general understanding at the time was that vapour would diffuse around corners and or "escape" at joints or holes. Even the Building Codes and builders handbooks outlined prescriptive requirements for well sealed vapour barriers, with lapped edges and seals. From the 1967, CMHC Builder's Handbook:

> "The effectiveness of a vapour barrier depends to a large degree on how carefully it is installed. To ensure a good vapour seal, all joints in the barrier should be lapped by at least 1 inch, and joists made over a solid surface and stapled. When the interior finish is later nailed to the same members this helps ensure that the vapour barrier joints are pressed together to make a good seal" (CHMC 1967).

This essentially meant that vapour barrier was acting somewhat as an air barrier, however not explicitly understood. What the majority of practitioners didn't understand was that vapour diffusion was not the primary mechanism transferring moisture (as vapour flow occurs from a high to low potential, not around corners, nor knows of a hole), but rather air movement was transporting water vapour, in quantities far greater than vapour diffusion could at these locations.

It may have been anecdotal evidence and recommendations by builders to seal the vapour barrier during installation as moisture problems persisted in buildings. This practice to properly seal the vapour barrier was in effect the beginnings of the air barrier, and while the materials (largely paper) were not always suitable to be an air barrier, the sealing practices likely improved the performance of the wall.

In 1964 Tyler Rogers, published the book "Thermal Design of Buildings" in which he summarized the general understanding of vapour barriers and control of condensation at the time. In addition to use of vapour barriers avoid condensation he stated six rules to follow which are still applicable today (Rogers 1964):

1. Get rid of excess moisture in the home.
2. Keep moist air away from cold surfaces.
3. Keep critical surfaces warmed than the dewpoint temperature.
4. Allow water vapour within the construction to escape through the cold side.
5. Avoid dual vapour barriers (vapour traps).
6. Use absorbent materials that can hold transient condensation harmlessly.

At the time, vapour barriers were required by the Federal Housing Act to be less than 1 US perm (57.4 ng/Pa s m^2). Possible vapour barrier materials included (with vapour permeances in US Perms):

- Paints – oil (1-3 perms), asphalt (0.4 perms), aluminum(0.4), enamels(1.0 perms), white lead and oil on wood siding (0.3 – 1.0 perms), white lead-zinc oxide linseed oil on wood (0.9 perms)
- Plastic films, 2 and 4 mil polyethylene (0.16 and 0.08 perms)
- Aluminum foil, asphalt laminated (0.002 perms) (only for cold storage)
- Kraft and asphalt laminated paper, reinforced (0.3 perms)
- Insulation back-up paper, asphalt saturated (0.4 perms)

Recognizing that oil painted wood siding was a vapour barrier, and in contradiction to rule #5, he recommended ventilation behind the cladding to prevent paint blistering and moisture damage. Other impervious materials such as aluminium siding, imitation brick-faced sidings (Insul-Brick), glazed face brick and metal curtain walls also required ventilation.

Rogers also recommended the 1:5 ratio rule, where the warm side vapour barrier "should have a permeance lower than that of any colder component, in the ratio of 1 to 5 or more, unless adequate cold side venting can be provided." For venting he suggested air channels aided by natural stack effect and ventilation. He also suggested that ventilation also had the effect of "air-cooling" the walls resulting in a reduction of the solar heat gain through the wall.

3.6.4.4 Air Leakage Research

By the early 1960's the concept of air infiltration, particularly around non-weather stripped windows and doors was realized in energy gain/loss calculations, however its effect on exterior walls was not fully realized. Vapour diffusion was traditionally the only moisture source considered.

Research by Grant Wilson at the DBR/NRC, into air leakage and condensation between double windows recognized that air leakage was more significant at transporting moisture than by vapour diffusion (Wilson 1960). He noted that stack effect pressures resulted in condensation due to air exfiltration on upper levels, but not lower levels, as observed in actual buildings. Condensation he noted was also more prevalent on the leeward side of buildings due to air exfiltration.

In Canadian Building Digest 23 "Air Leakage in Buildings", Wilson noted that "Condensation can also occur in hidden parts of walls or roofs as a result of air exfiltration through cracks, openings and porous construction. The extent of such condensation in heated buildings depends primarily on indoor humidity, outdoor temperature and on the rate and duration of air flow (Wilson 1961 p.4)." Further he noted several cases of "severe wall deterioration caused by air exfiltration in multi-storey buildings" (Wilson 1961 p.5).

The term "air barrier" wasn't in common usage prior to this paper, however when discussing cold-storage buildings and cold rooms in heated buildings, Wilson stated the following "The need to preserve air-tightness in such buildings by an unbroken vapour and *air barrier* completely enveloping the structure cannot be over-emphasized" (Wilson 1961 p.5).

In conclusion Wilson had the following recommendations:

> "To overcome condensation problems resulting from exfiltration, cracks and porous construction must be eliminated on the warm side of the structure. It may be desirable, sometimes, to provide venting around the outer cladding so that moisture entering the construction from inside will be more readily dissipated to the outside. The air-tightness of the inner part of the enclosure must always be many times greater than that of the outer cladding. This is especially important in buildings that are humidified. In multi-story buildings air flow between floors should be restricted to reduce pressure differences resulting from chimney action." (Wilson 1961 p.6)

Later work by Wilson, Garden, Brown and Tamura at the DBR/NRC all stressed the importance of air-flow control to prevent interstitial condensation (Wilson and Brown 1964, Wilson and Garden 1965, Tamura and Wilson 1963).

By the 1965 NBCC, provisions for a continuous vapour and air barrier on the high pressure side of the major thermal resistance were made to part 4 but not part 9 of the code, applying some of the research from the early 1960's at the NRC. Part 4 buildings typically larger, taller and more exposed than Part 9 buildings.

Despite the research and recommendations by the DBR/NRC, during the 1960's building practitioners largely ignored the measures to improve air-tightness, and were preoccupied with the wetting of vapour diffusion alone (Bomberg and Onysko 2002).

3.6.4.5 Rain Penetration Technology

Canadian Building Digest No. 6, June 1960, by Tom Ritchie discussed "Rain Penetration of Walls of Unit Masonry" in which he suggested ways to construct walls which were more tolerant of rain. He suggested that as early as 1920, as a result of changes in methods of construction and materials, rain penetration of masonry walls has more common of a problem. Research in other countries including United States, Great Britain, France and the Scandinavian countries, indicated it was a significant and widespread issue, not just to Canada.

To address moisture problems, due to wind-driven rain, Ritchie suggested improvements to mortar and joints, but also to the use of cavity wall construction, which was commonly used in Great Britain at the time. The cavity wall he referred to consisting of the structural masonry wall split in two, with a continuous vertical airspace between, connected laterally using metal ties. The outer brickwork was therefore not relied upon solely to prevent moisture penetration. He also noted "that properly designed flashings over wall openings must also be provided, as well as vertical diverter strips in the cavity at door and window jambs" (Ritchie 1960). He also emphasized the importance of sealing cracks and openings, particularly around windows, and repair of faulty flashings.

Canadian Building Digest No. 30, June 1962, by Ken Latta discussed some of the known deterioration mechanisms caused by water in walls, including corrosion, decay, blistering, efflorescence, leaching, freezing and aesthetics.

Canadian Building Digest No. 40 by Kerby Garden (a former student of Hutcheon's) in 1963 introduced the "open rain screen" approach, largely following Hutcheon's 1953 recommendations, but also utilizing pressure equalization of the cavity space to reduce water infiltration. He stated that wide overhangs and cornices while successful in preventing wetting of low buildings but were incapable of protecting tall buildings, or buildings exposed to high winds.

Recognizing the forces of rain penetration through cladding of capillary, gravity, and pressure he suggested a rainscreen wall, but with open joints to allow the wind pressure to maintain equalization. He concluded that without an air pressure difference, water could not move inwards. Recognizing that the air pressure in this cavity would now longer be taken by the cladding, a specified air barrier was required, to be installed inward of this pressure equalized air space (Garden 1963). He presented this idea for a wood frame, cavity brick and brick veneer wall as shown in Figure 3-32.

The definition of a pressure equalized rainscreen versus a normal rainscreen could therefore be the difference between a sealed air barrier on the exterior of the sheathing, both with claddings separated by an air space and allowing drainage of moisture through the cavity and out the bottom.

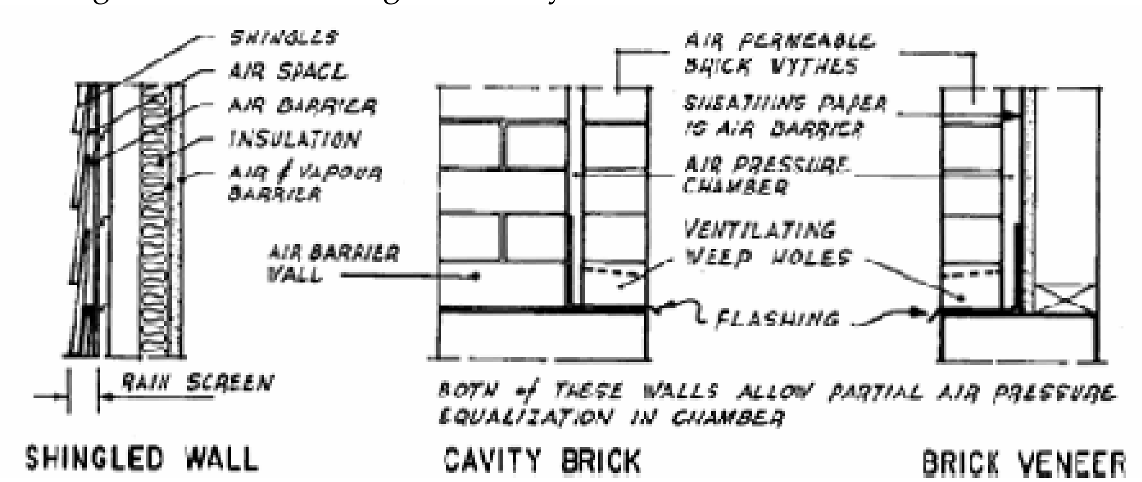

Figure 3-32: Walls to Resist Rain Penetration (Garden 1963)

In the wood framed shingled wall (left), Garden recognizes that the vapour barrier could also be an air barrier, but also that a secondary air barrier was to be installed outside of the sheathing, where the sheathing paper was located. Thus the sheathing or sheathing paper could form a secondary barrier if well sealed.

Some pressure equalization techniques were suggested by creating separate chambers behind the cladding, with compartments being smaller near the extremities of the walls where wind pressures would be highest.

Despite the strong recommendations for cavity, ventilated, and open rainscreen walls, the techniques were not commonly adapted to wood frame construction, with wood, stucco or other claddings, aside from brick veneer. Brick veneer is porous to water penetration that not providing the air space for capillary break alone would have resulted in failure.

3.6.4.6 CMHC Builder's Guidelines

In 1967 CMHC published the first Canadian Builder's Handbook in which it provided guidelines as to the best construction practice and details at the time. It provided information about available materials and typical design details to construct an entire house. A typical wall section at the time is shown in Figure 3-33. Note the placement of the 2″ (50 mm) mineral wool insulation towards the interior, half filling the stud cavity.

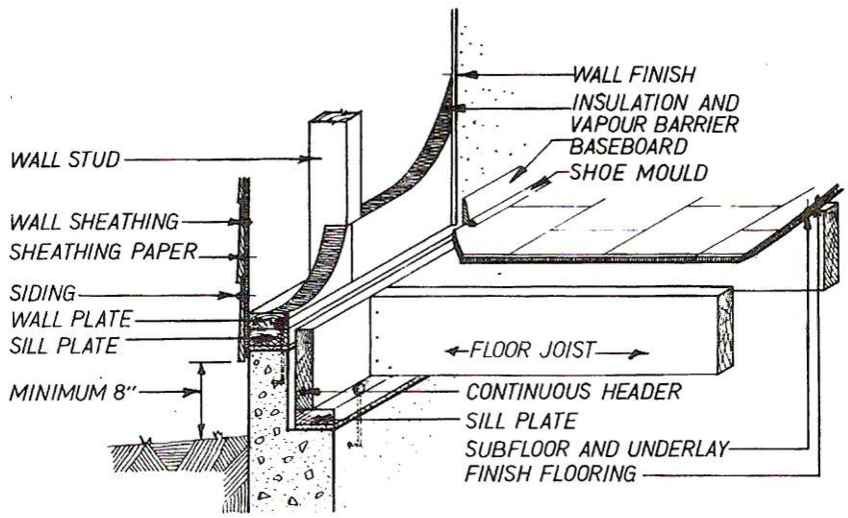

Figure 3-33: Typical Wood Frame Construction (CMHC 1967)

On recommendations for stucco siding, it appears that construction practices had changed from those presented in the 1930's through 1950's. CMHC recommended that stucco be applied in three coats, as before, however over reinforcing of self-furring welded or woven mesh applied over asphalt sheathing paper (CMHC 1967). The use of woven mesh was considered equal to welded mesh, however as discussed previously had different performance.

For whatever reason, likely for cost and ease of construction the 3/8″ horizontal wood strapping as shown in the 1932 through 1956 Architectural Graphic Standards was omitted from common practice at this time or by CMHC in the guide. This would have had the result of placing the stucco in direct contact with the building paper as it pressed through the self-furring woven or welded metal lath. As a result air cavity behind the stucco was largely eliminated, and capillary flow could now transport moisture through the stucco and into the rest of the wall.

In the builder's guide it was also recognized that framing lumber should not be installed with a moisture content exceeding 19%, as to prevent entrapping moisture in the wall.

3.6.5 <u>Energy Shortage and Wall Modifications – 1970's</u>

The 1973 Oil Crisis, spurred by conflicting tensions in the Middle East, temporarily resulted in an oil shortage and in the long term drastically increased in the price of oil, and thus energy in North America in Europe. Again in 1979, the second oil crisis further drove up oil and subsequently energy prices. It was a decade of attempts to conserve energy as the governments widely promoted the use of additional insulation in buildings through government retrofit grants and increased building code insulation requirements for all new buildings. At the same time, air tightness was being realized as important, and new less vapour permeable plastic materials were being introduced to the market as replacement for older more permeable ones.

Insulation levels were not increased dramatically in homes by the oil crisis, prior to 1973, "Owens Corning Fiberglass recommended R-11, 3.5" (89 mm) in walls and R-19 5.5" (140 mm) in ceilings" (Wass 1973). Albeit advice from an insulation manufacturer, in whose best interests it was to use as much insulation as possible, the recommended insulation levels correspond with full cavity friction fit batts which were becoming more popular by the end of the 1960's.

Both friction fit, and kraft paper faced fiberglass and mineral wool insulations were available in the 1970's. Where friction fit batts were used, a separate vapour barrier such as kraft paper or newly popular clear polyethylene film was used. Polyethylene had some advantages for the builder, was cheap and allowed for easy inspection of the wall cavities which also suited the building inspectors. Figure 3-34 shows typical installation practice during the 1970's for friction fit insulation with polyethylene and stapled kraft faced batts.

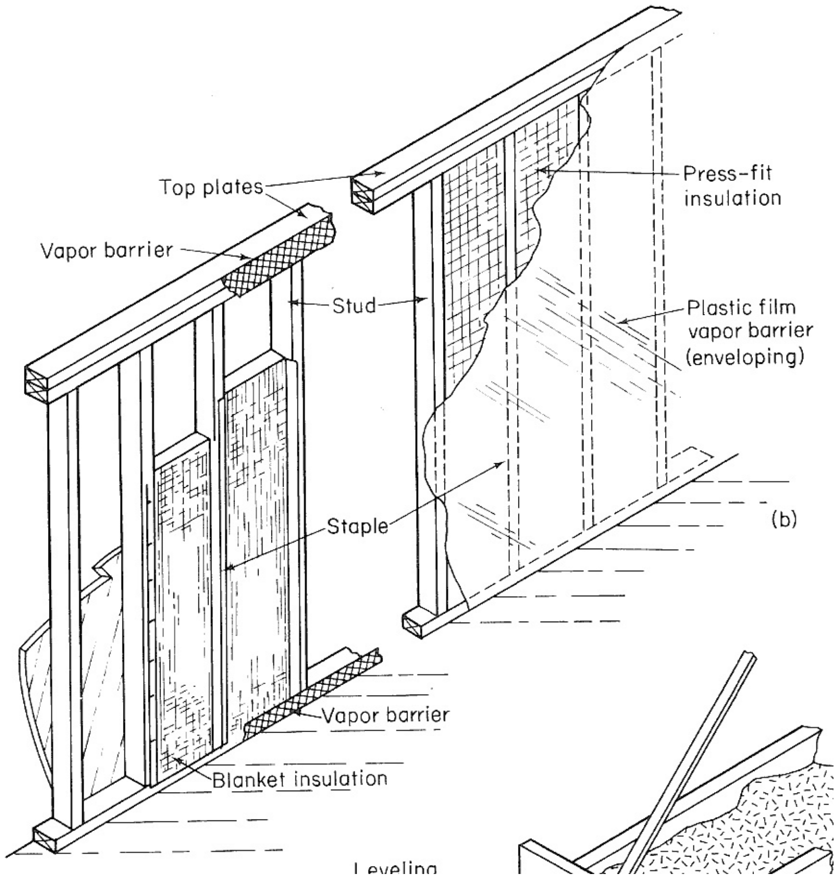

Figure 3-34: Typical Insulation and Vapour Barrier Installation early 1970's (Wass 1973)

As a result of the oil crisis the exterior walls gradually became thicker to accommodate the additional insulation required. Walls constructed of 2x4 studs became 2x6 studs (where good supplies of timber existed) to accommodate the increased insulation thickness to attain the required thermal resistance. This suited the insulation manufacturers well, in particular the fiberglass batt insulation manufacturers. Fiberglass batt was by far the cheapest material, and it was convenient to increase the insulation thickness to reach the required thermal resistance using larger studs instead of modifying the wall assembly.

Attics spaces at the roof trusses were easily insulated using blown in and loose fill materials such as fiberglass and cellulose fiber. Large quantities and high thermal resistances were easily installed, especially in retrofit situations. It was however not common to increase the air tightness at the ceiling level during the insulation upgrades, which lead to an increase in the number of condensation and moisture problems in attics which were now much colder from the reduced heat flow.

Alternatives to increasing the wall thickness were available using foam board insulation products. With the introduction of several new board products, insulation could easily be placed to the exterior of the stud cavity as suggested previously by Hutcheon (1953).

A new insulation type was introduced to the housing industry in the early 1970's by Dow Chemical, known as extruded polystyrene (XPS) board or by trade name as Styrofoam™ SM, TG, or RM. Like a new wonder material, Dow marketed it as "eliminating the need for vapour barrier and batt insulation as an insulating sheathing material, a replacement for plywood" (Wass 1973). It was also advertised "as its own vapour barrier", and had "unusual resistance to moisture, rot and mildew" and would "never lose its insulating effectiveness and would remain fully insulated for a lifetime". As it was nailed to the exterior of the studs, the manufacturers suggested, no additional insulation between the studs was required. As the foam sheathing was non-structural, lateral bracing was provided by 1x4 braces let in to the outside of the wood studs. Wood frame construction methods using Styrofoam™ sheathing are shown in Figure 3-35.

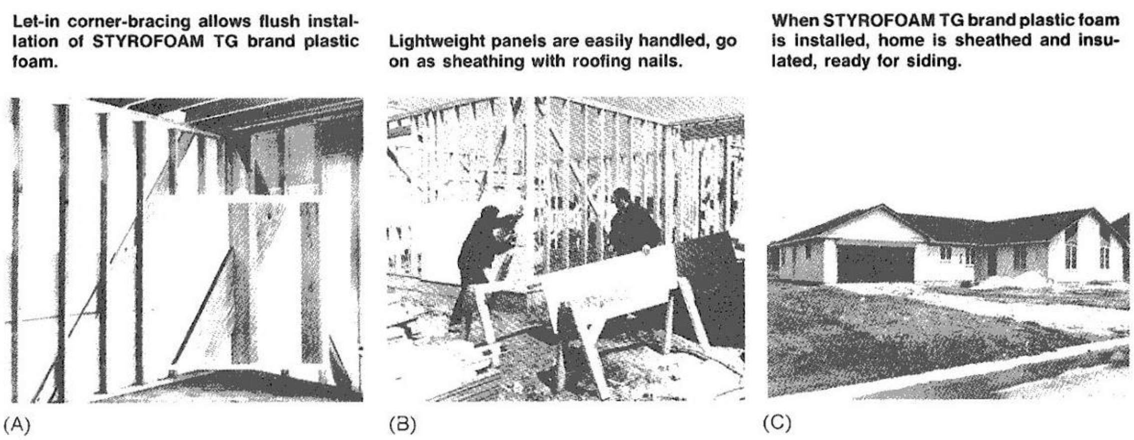

Figure 3-35: Dow Styrofoam™ TG Installation (Wass 1973).

Extruded polystyrene also became popular in applications to increase the overall thermal resistance, where it was placed on the exterior of a fiberglass insulated 2x4 walls. 1" (25 mm) of foam sheathing provided a thermal resistance of R-5, and 2" (50 mm) could provide almost as much as the 3.5" (89 mm) fiberglass which offered R-11.

Another insulating product, rigid phenolic foam board was also introduced to the market in the late 1970's and early 1980's. It immediately became popular in roofing applications, for commercial and industrial buildings with its high thermal resistance value (up to R 7-8 per inch), fire resistance, and relatively low cost. It was not commonly used in exterior walls in Canada, however within a few years of introduction, several roofing failures were noted as it was found that moisture (either condensation or water leaks) reacted with the foam and released sulfonic acids, which readily corroded steel roofing decks. Several class action law-suits were filed and the product was pulled from the North American market by the early 1990's. However, in Europe it is still commonly used today, primarily as cavity insulation in walls because of its excellent thermal resistance and fire resistance, produced by several insulation manufacturers. The potential problems with moisture and corrosion are recognized the manufacturers but have not been a significant issue in this usage, provide the insulation remains dry.

Semi-rigid fiberglass boards were also introduced to the market by the late 1970's in response by fiberglass manufacturers to develop a board product to compete with other rigid foam boards (Jansen 1980). Jansen with Fiberglas Canada showed the economic benefits of using 2" (50 mm) fiberglass sheathing instead of 2x6 studs with infill fiberglass batt insulations and showed construction details for using the semi-rigid non-structural sheathing. He also mentioned the upcoming development of semi-rigid fiberglass faced with a spun bonded polyolefin air barrier.

Expanded polystyrene (EPS) or beadboard also became popularly used as an exterior insulation used in Exterior Insulated Finish System (EIFS) which was introduced in the early 1970's. EIFS, as the name implies consists of a finish (typically thin acrylic-cement stucco) over insulation applied over the exterior of the wall structure. It became popular with commercial and high-rise construction, and wasn't used in the residential market until the 1980's.

By the early 1970's light gauge steel studs were introduced on the market as a replacement for wood. However the thermal performance of the light gauge steel was not equal to wood, in addition thermal dusting and mould problems on the now colder interior gypsum surfaces were commonly observed in cold climates. The abundance of wood and thermal issues with steel prevented its widespread acceptance in single family dwellings. However, where the building code required non-combustible construction as in larger multi-storey buildings, steel studs and gypsum sheathing became commonly used as a cheap alternative to the more durable concrete masonry block construction.

3.6.5.1 Canadian Research

To summarize the research completed by the DBR/NRC by the mid-1970's, Ken Latta from the DBR/NRC published the book "Walls, Windows and Roofs for the Canadian Climate" in 1973 which summarized much of the information from the Canadian building digests. In it, he discussed the need for control of heat and water, including a section of movement on water vapour by air currents, and described the purpose and some of the requirements for air barriers (Latta 1973).

3.6.5.2 Air Leakage

It was perhaps the trend towards electrical baseboard heating in the 1960's that lead to the widespread realization of the importance of air leakage (Bomberg and Onysko 2002). Electric heating became popular to builders as it eliminated ductwork associated with air heating systems, and the baseboard units were cheap and easy to install. Increased insulation levels were required for homes with electrical heating to make it economically feasible, as electricity was provided at additional cost than gas. Increased insulation levels meant that outer surfaces of the walls were colder and thus more prone to wetting from condensation and had a reduced drying potential.

In addition, the advent of the electrical baseboard heater significantly changed the air pressure and ventilation characteristics of the home. Furnaces or fireplaces by virtue of the combustion process draw large quantities of air from the home for, typically infiltrating through the walls and exfiltrating through the chimney, resulting in high ventilation rates. In electrically heated homes, the passive ventilation flow is dominated by stack effect pressures, infiltrating at the lower levels, and exfiltrating above the neutral pressure plane, and into the unheated attic space. In a single or two-storey home the stack effect pressures are also relatively small, particularly in temperate climates, resulting in low air exchanges. The air pressure and flow differences between houses heated with a combustion appliance and electric baseboard are compared in Figure 3-36.

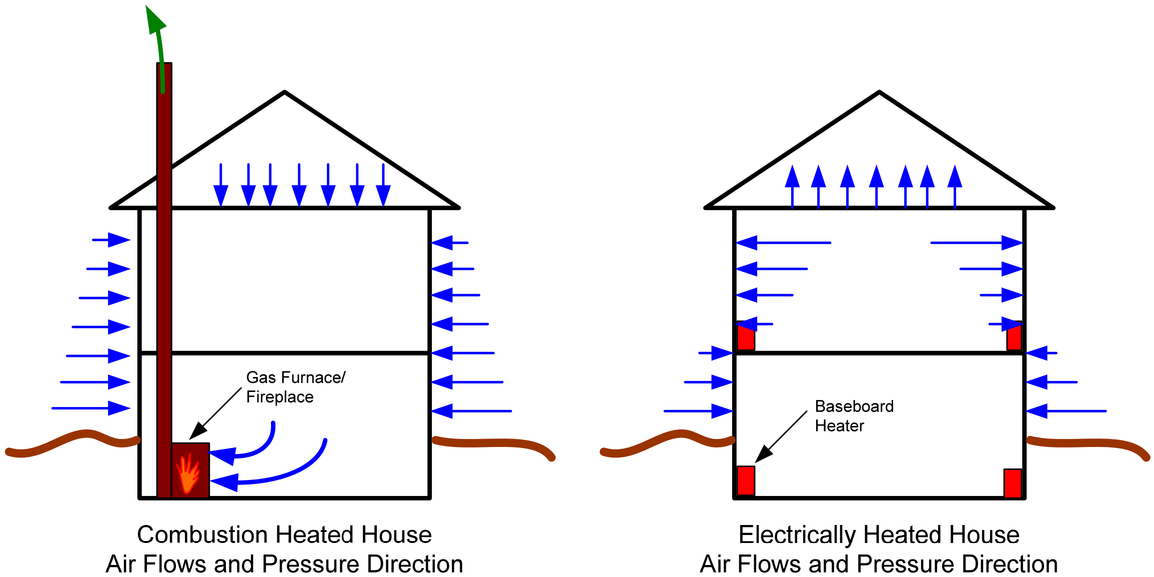

Figure 3-36: Air Pressures and Flows for Combustion Appliance versus Electrically Heated House

Air leakage testing in the mid 1970's found that condensation problems in attics became frequent as a result of air leakage from poorly ventilated interiors (Stricker 1975). Further research into walls and flat roofs by Tamura et al (1974) and Orr (1974) found the situation to be much worse in colder regions of the country.

3.6.5.3 Hardboard Siding Problems – Late 1970's

In the Morrison Hershfield/CMHC report "Moisture in Canadian Wood-Frame Construction: Problems, Research and Practice from 1975 to 1991" some background information on siding moisture problems during the 1970's is provided and summarized below as it is relevant to the problems encountered in the 1980's and 1990's (Morrison Hershfield 1992).

Starting around 1976, the number of moisture related problems were reported with wood sidings, in particular hardboard sidings in Atlantic and eastern Canada produced by Masonite Canada. Hardboard sidings consist of pressurized wood fiberboards, and are relatively durable provided they remain somewhat dry.

Significant R&D was performed by Masonite with help of Scanada to determine the cause of the problems. Customary for retrofits, Masonite's installation instructions since 1962 required the use of strapping under the hardboard cladding (as older houses were less likely to have a deficient air and vapour barrier). In Quebec, it had been customary since about 1970 to install Colorlok siding on strapping (which the French call *forrins*). Authors note, this practice is not revolutionary, however was not common in the rest of the country at the time. In Quebec they were following the code requirements providing ventilation of the cold side of the insulation when a vapour impermeable cladding was used, which oil painted hardboard siding is.

However for new construction, strapping behind the Masonite siding was not required. Therefore use of strapping to therefore address moisture problems in new construction was an obvious solution to the problems. To further prove this system Masonite had 8 houses built with siding installed on strapping, a test hut built, and test walls in field and laboratory conditions. Masonite concluded that furring was beneficial, confirming common sense assumptions. They found it necessary to have both the top and bottom of the cavity open as well, and that a ¼″ cavity was as effective as a ¾″ one. The results were published and with CMHC attempt to specify the requirement of strapping for all horizontal lap sidings in Newfoundland, leading eventually to CMHC Builders Bulletin T-4.

However it was quickly observed that Masonite sidings were not only products failing, and evidence of moisture problems of observed lead to further research in the early 1980’s by CMHC.

3.6.6 Wall Failures, Air Leakage and Modifications – 1980’s

The 1980’s brought about further changes to the wood frame wall. The concept of an air barrier as a separate function was introduced and higher levels of insulation in exterior walls and attics were commonly used.

It was also a decade of realization that some of the materials and technologies built in the 1960’s and 1970’s were not performing well in the long term. Several insulation materials were pulled from the market including UFFI, phenolic foam, sprayed asbestos, and Zonolite (vermiculite) citing health and safety risks as previously discussed. In addition moisture problems were still prevalent in insulated walls, despite the advances in research with vapour barriers, and recognition of the importance of the air barrier.

Much of the building science research up to 1983 can be found in Hutcheon and Handegord's "Building Science for a Cold Climate" summarizing much of the information from the 200+ Canadian Building Digests published at the time.

3.6.6.1 NHA Housing Problems

To determine the extent of moisture problems in Canadian Housing, CMHC sponsored a number field studies in the early 1980's (Scanada 1980, Scanada 1981, Marshall 1983). Scanada found a number of moisture problems, particularly in Newfoundland and Atlantic Canada. Numerous other problems with indoor air quality, moisture damaged claddings, and interior condensation and mould were also observed in many of the homes. Comparing reports of condensation on windows (an indicator of ventilation and moisture within the homes), Scanada found condensation occurred on windows in 5-10% of houses in all regions, but 20-30% in electrically heated homes in Atlantic Canada. The link between electrically heated houses and moisture problems was apparent.

Marshall Macklin Monaghan with assistance from CMHC produced a three part report on "Moisture Induced Problems in National Housing Act (NHA) Housing" (Marshall 1983). Part 1 consisted of the analysis of results and projections of future problems. Part 2 consisted of literature review performed by J. Timusk at the University of Toronto, and part 3, consisted of an analysis of passive ventilation techniques. In 1984 a summary report was published compiling the results and recommendations from the 3 previous reports (Marshall 1984).

It is felt that these studies are an integral part in the history of the wood frame wall in Canada. Small changes made to materials and building practice in the decades previous were eventually realized by failure of a percentage of the Canadian housing stock. The study addresses the observed moisture problems, and recommends a number of solutions, some of which were eventually used in practice. One of the most relevant solutions proposed the use of furring strips to create a ventilated and drained cavity behind the sheathing (rainscreen principle), however was rejected initially by builders based on cost. In the writer's opinion, poorly conceived and limited field studies lead to inconclusive results of whether the rainscreen cladding was beneficial to drying and reduced wetting. This study alone had the potential to recommend changes to walls in coastal and temperature climates such as coastal BC. This could have changed the way walls were constructed in Vancouver and thus an impact on the failure of thousands of face-sealed buildings in Vancouver in the mid-1990s. Therefore an extensive look at the observations and recommendations including further work is performed.

A total of 201 moisture damaged National Housing Act (NHA) financed units were field investigated across Canada, of a total of 3400 with reported problems. The majority of the problems observed in NHA housing were located in Newfoundland. CMHC owned the NHA housing units or had provided insured mortgages to the owners, and thus had a significant financial stake in resolving the problems.

A summary of the observations made from the three reports is compiled below (Marshall 1983):

<u>Severity of the Problem</u>

- 3400 moisture NHA housing units with moisture problems reported in Canada
- Moisture problems expected in NHA housing stock (constructed between 1973 and 1981) based on survey results, 27.5% of units in Newfoundland, 1.5% Canada wide, and slightly higher than the average at 3.0% in BC.
- Row and attached units had higher instance of problems, as they had a reduced exterior wall area, and reduced air exchange rates.
- The majority of problem houses were constructed after 1973.
- Construction boom during the mid-1970's resulting in large number of units to be constructed during this period (See Section 3.8).

<u>Air Leakage</u>

- The switch from kraft paper faced batts to continuous polyethylene sheets in the 1970's concentrated air leakage at holes, penetrations and partition walls.
- Extent of sheathing damage was usually isolated at holes in the air/vapour barrier, and not widespread.

<u>Ventilation and Interior Conditions</u>

- The moisture damaged homes had an average household size of 4.1 people versus the Canadian average of 2.9. The average interior RH was also 50% in the problem homes, versus 35% versus the Canadian average (however no discussion is made for more humid coastal climates versus colder drier interior climates).

- 81% of problem units were electrically heated, however a number of the remaining units were heated with sealed combustion wood stoves, drawing air directly from the exterior for combustion, and having similar impact to the interior ventilation rate as electrical baseboard heaters.
- The switch to electrically heated homes influenced the indoor relative humidity as natural ventilation and removal of excess moisture was decreased.
- Air tightness was also a contributor to interior moisture problems, but only as sufficient makeup air ventilation was not provided.
- Interior condensation on cold surfaces (closets, corners, behind furniture, windows) occurred as a result of high interior RH.
- Mould and mildew was observed on interior surfaces as a result of high interior RH.

Attics

- Moisture damage was observed in attics where no or insufficient ventilation was provided. High interior RH exacerbated the problems observed.
- Row houses had higher instance of attic problems as they typically have a reduced number of ventilation openings or only openings on two elevations.

Materials

- Increased insulation levels, resulted in colder sheathing temperatures, and higher potential of condensation, and in addition reduced drying rates.
- Non-vented plywood sheathing resulted in buckling and warping of wood siding.
- Low cost claddings with low permeability ("Insul-Brick" and asphalt shingle type materials) were noted to cause moisture problems in sheathing.

Climate Specific

- Siding and sheathing moisture content are climate related. Higher instance of moisture problems in exposed locations, as result of driving rain and wind. Low solar gain also significant in locations like Newfoundland resulting in low drying.

- Strong winds correlated with indoor mildew problems as a result of wind washing of the insulation, resulting in colder indoor surface temperatures.

Based on the observations, literature review, and industry practice at the time, the following recommendations were made (Marshall 1983):

- One of the most important recommendations was to separate the wood siding from the sheathing paper and rest of the wall using furring strips, creating a ventilated cavity top and bottom – essentially an open rainscreen wall. This would allow the wood sheathing and siding to dry out sufficiently to avoid moisture problems.
    - Recommended furring strips 7-8 mm, but be kept to a minimum to reduce unnecessary loss of solar heat gain. Further research required was recommended to determine optimum furring gap.
    - Self-furring fastener clips for horizontal siding prevent board to board contact were recommended.
    - Wood sidings should be stained with vapour permeable stains or painted with low permeance oil based paints instead of impermeable oil paints traditionally used.
- Raise temperature of potential condensing surface using 2x4 studs and insulated sheathing instead of 2x6 studs with infill batt insulation.
    - Use semi-rigid fiberglass or mineral wool insulating sheathing.
    - XPS not recommended due to low vapour permeance, EPS not because of high water absorption and low vapour permeance.
    - If 2x6 studs used instead without exterior insulation, then conditions are worse than 2x4
- Improvements to interior air barrier including sealing at penetrations (foam gaskets, caulking).
- Use an exterior applied air barrier in new construction, vapour permeable such as spun bonded polyolefin (such as Tyvek)
- Increasing the attic ventilation rate in humid climates such as Newfoundland or coastal British Columbia may not solve attic problems as the ventilation air cannot remove much moisture
    - Air barrier at ceiling critical to preventing attic moisture problems. No holes or unsealed penetrations, sealed hatch. In retrofit situations use a sealed drywall approach.

- Back-priming wood siding to reduce moisture uptake resulting in buckling, paint peeling and decay. Use of vapour permeable oil stains instead of paints
- Providing minimum mechanical ventilation (0.5 ACH) in all units. Passive ventilation alone may not be a practical solution.
    - Passive ventilation options included vent stacks (to raise neutral pressure plane) with wind driven turbines to increase air flow.
    - Lifestyle and climate contributors to high interior RH, education could alter lifestyle choices, however exterior climate most critical.
    - 0.5 ACH not enough for coastal Newfoundland and other parts of the country, recommended using heat recovery ventilators (HRV) in those locations.
    - Design solutions that do not rely on mechanical equipment are however preferred.
- Local weather had an impact on the wall performance and recommended code changes based on local climate, not Canada wide provisions as before.
- In BC, 2200 of 71,300 NHA housing units (3.0%) were considered problem units; however proportionally 8.0% of all apartment buildings were affected. Of these, 42% had problems with the walls, 88% with roof or ceiling and 8% with the windows.

Marshall further warned if immediate changes not made in construction practice then obviously additional problems could be expected beyond their initial estimates.

Based on the previous work by Masonite, and the NHA study, in 1982 regulations were put into place by CMHC (Builders Bulletin T-4), mandating the use furring strips under exterior siding (wood, plastic or metal) in Newfoundland only. This essentially created a ventilated cavity behind the siding, or a rainscreen wall approach. In 1984, CMHC (Builders Bulletin T-6) was issued requiring furring strips under siding in all Atlantic Provinces. However, the Canadian House Builders Association (CHBA) and local builders were concerned about unnecessary construction cost and were successful in preventing the ventilated cladding (rainscreen wall) requirements (T-6) from being implemented. They also argued that the need for furring strips had not been demonstrated (Morrison Hershfield 1992).

A joint CMHC/CHBA task force was formed in 1985 to investigate causes and solutions of moisture damage in Atlantic Canada and to perform further testing to determine the impact of proving a ventilated space behind wood cladding, creating in practice a rainscreen wall.

The task force reviewed moisture damaged houses in Atlantic Canada (PEI, Nova Scotia, New Brunswick) and found moisture damage as a result of water entry into walls due to poor detailing, installation, lack of flashings and lack of maintenance. Many of the houses also experienced indoor moisture problems including condensation and mould. Although the incidence of moisture damage in Nova Scotia, New Brunswick and PEI was found to be lower than Newfoundland (CMHC 1988).

To test the efficiency for furring strips behind the cladding, identical test huts were constructed in three different locations in Atlantic Canada 1986 (CMHC 1988). Vinyl siding was used instead of wood, and installed with and without furring strips. The ventilation cavity was open at the bottom but closed at the top (to prevent humid ventilation air from transferring to the soffit), and in effect they had created a vented system. Vinyl siding with a relatively small integral venting area was used. The walls were typically constructed, with different wood and insulating sheathing materials and stud cavity insulation of fiberglass batt or cellulose fiber and interior 4 mil polyethylene vapour barrier.

The framing members started at high moisture contents (25-30%) and the drying was observed. The results were inconclusive that strapping had a significant impact on the results, and the test panels with the more permeable sheathings dried the quickest. Some speculation was made however as some evidence was shown that the walls with furring strips usually dried faster than those without (Morrison Hershfield 1992).

Recently it has been shown that vinyl-siding, which was used in the test-huts without integral ventilation holes tends to be quite leaky at the horizontal and vertical joints (Van Straaten and Straube 2004). Therefore the choice of using vinyl siding could have impacted results from the study, as the differences between strapping and un-strapped walls may not have been apparent. The differences in air leakage through the cladding may have been sufficient enough for drying even with the un-strapped walls.

In addition, the study only looked at drying from an initially saturated state, in which they had intended on pre-wetting the samples, however it was found that the samples came from the mill between 25-30% moisture content (MC), much higher than the 19% MC recommended.

A further study looked at the moisture content of framing lumber supplied by the lumber mills in Atlantic Canada and built into homes. CMHC found 90% of the lumber was in excess of 19% and 54% beyond fiber saturation (CMHC 1989). This lead to the conclusion that wet framing lumber built into the walls was a significant contributor to the moisture load to walls in Atlantic Canada.

The research in Atlantic Canada brought about some insight into the moisture problems with housing in temperate maritime climates. While the problems in Atlantic Canada were recognized to be from indoor moisture sources, the effects of wind-driven rain should not be ignored. The high instance of driven rain in Newfoundland on the east elevation largely correlated with the observed moisture problems. While rain penetration may not have been largely observed (no destructive testing was performed or cladding removed) the rain wetted claddings would have reduced the drying potential on the exposed elevations (Morrison Hershfield 1992).

3.6.6.2 Moisture Problems in Housing – Pacific Northwest

In the Pacific Northwest of the United States, George Tsongas and others were researching moisture problems in American Building stock in the early 1980’s (Tsongas 1994). Tsongas a mechanical engineering professor from Portland State University investigated thousands of buildings with and without moisture problems in the Washington and Oregon, a temperate climatic region similar to coastal British Columbia (see Figure 3-59 later). The problems observed in the 1980’s in Oregon and Seattle is presented as little documentation or research is published from coastal British Columbia for the period.

Tsongas (1994) summarized some of his previous studies (early 1980’s) pertaining to interior moisture problems. In a Portland Oregon study of older homes (pre 1979) he found he found interior mould problems in approximately one-third of 102 the homes. The Portland homes were found to be quite air-leaky, with an average ACH of 16.9 at 50 Pa ruling out home air-tightness as a cause of the problems. In a Spokane, Washington study of older homes (pre 1982), mould and mildew was found in 38% of the 96 homes investigated. In both studies, interior moisture problems were prevalent (similar to the Newfoundland and Atlantic Canada studies). The interior problems in Portland and Spokane were in part found to be caused by insufficient (or lack thereof) indoor moisture control.

High relative humidity levels were found in the homes observed 56% for the Portland homes and 47% for the Spokane homes with many above 70%.

The field studies also looked at the impact of retrofitting wall insulation in the older homes and concluded the following:

> "The major conclusion of the two field studies was that retrofitting wall insulation in older, leaky homes in climates like those of Portland and Spokane does not create or accelerate moisture damage. **Any moisture damage within the wall cavities was always caused by leaks**. Furthermore, because there are no associated wall moisture problems, there is no need to add a vapor barrier when retrofitting wall insulation in older existing homes." (Tsongas 1994 pg. 14)

In this temperate coastal climate, vapour diffusion or air leakage was not found to be contributing to problems in insulated homes, but rather rainwater leaks from the exterior. Tsongas also went on to state the probably causes for the lack of moisture damage and some observations regarding the type of sheathing used and its impact on moisture problems.

> "The walls of older homes stay dry because even though moisture enters the wall cavities from inside the house, the moisture dries out due to the relatively leaky exterior portion of the walls. Recall that most of the wall sheathing in the Portland and Spokane studies was board-type wood with substantial air leakage rather than more airtight plywood panels. The results might have been different if the homes had plywood sheathing. In fact, we of the Spokane homes had plywood sheathing, and their walls had among the highest moisture contents. However, there was no moisture-related damage." (Tsongas 1994 pg. 14)

The problems in the Washington, Oregon and Atlantic Canada shared the common conclusion that humid interiors were contributing to interior moisture problems including mildew and mould. In the Atlantic Canada (colder climate) air leakage was found to be a more significant problem. Rainwater leaks were found to be problematic in both locations, however in neither study was the primary focus.

3.6.6.3 Air Tightness and Ventilation

The increased construction of electrically heated homes and use of higher insulation levels (as they were electrically heated) lead to a lower natural ventilation rate and subsequently a growing number of complaints about indoor air quality. Recognizing the need for mechanical ventilation by 1980, the NBCC required that all dwellings had a ventilation system capable of providing 0.5 ACH. However was reduced to 0.3 ACH in 1990 based on experience from builders and occupants that this resulted in too dry of conditions in the colder drier areas of the country (prairies and Ontario/Quebec) (Bomberg and Onysko 2002). These ventilation requirements were typically met by using a cheap and noisy 24 L/s (50 cfm) bathroom fan manually controlled by a humidistat, something which most occupants don't know how to operate, or simply turn off. Whether these ventilation requirements are met by this method even today is a topic of discussion later in this thesis.

An idea of how tight the houses were becoming by decade was shown by Dumont et al (1981). Dumont found that houses constructed in Saskatoon based on age was shown to decrease from an average of 10.45 ACH for pre-1945 housing, to 4.55 for 1946—1960 housing, to 3.57 for 1961-1980 housing giving an idea of the impact of changing construction practices.

3.6.6.4 Air and Vapour Barriers

The concept of the combined air/vapour barrier was introduced in the mid 1980's; recognizing the dual role interior polyethylene had in walls (Quirouette 1985, Quirouette 1986). The simplicity of a combined air-vapour barrier and ease which it could be specified and installed had resulted in its widespread residential application; however the understanding of both functions was sometimes confused. The confusion between an air and vapour barrier also existed in the 1981 Edition of the Architectural Graphic Standards, stating:

> "Vapour barriers must be properly located in the wall section and carefully placed to fully cover all areas. Edges should be sealed and joints overlapped. Attachment by gluing instead of stapling should be practiced if possible because the effectiveness of vapour barriers may be greatly reduced if openings, even very small ones, exist in the barrier." (Ramsey and Sleeper 1981)

The 1985 NBCC had sorted out some of the confusion and outlined separate provisions for an Air Barrier as distinct from a Vapour Barrier. The code required that the air barrier be continuous air tight which meant that all polyethylene joints be lapped and sealed, further air tightening the wall. The vapour barrier only had to be continuous and in a location that would prevent condensation within the assembly.

Polyethylene as an air barrier was also applied to commercial and high-rise walls, much to concern of some knowledgeable contractors who questioned its suitability as an air barrier, particularly structurally against wind loads during construction but also over the service life of the building (Shaw 1985, Quirouette 1985).

The long-term durability of the polyethylene sheet material was also questioned as failures were observed where the polyethylene had degraded and no longer provided a proper air, let alone vapour seal. Typical industry standard was to manufacturer the sheet in thicknesses as low as 0.035 mm (1.4 mils), to 0.045 mm (1.8 mils). It was found that the use of recycled materials to manufacturer the product lead to durability problems and readily deteriorated. As a result polyethylene became manufactured from virgin material only, and to a typical thickness of 0.15 mm (6 mil) with a vapour permeance of 2 $ng/Pa{\cdot}s{\cdot}m^2$ (Plastechnics 1985).

The changes marked an improvement in the quality of polyethylene sheet, however at reduction in the vapour permeance. Intended or not, the improved vapour tightness, combined with 1985 NBCC code changes to provide a continuous air barrier (often using polyethylene) meant that walls no longer had the ability to dry to the interior.

The building code has never explicitly required the use of polyethylene as a vapour or air barrier, several other materials used which satisfied the requirements for a vapour barrier, however when the requirements for a continuous air barrier came into effect, polyethylene was the "easiest" material to use, and at no additional cost to the builder (as already used as vapour control), thus leading to its widespread use in Canada. Several people continued to raise concerns about the suitability of polyethylene film as the primary air barrier, citing structural strength and detailing of sealed penetrations however.

Using other materials as the air barrier also came to be realized during the mid-1980's. Lstiburek and Lischkoff (1984) introduced the Air Tight Drywall approach (ADA) which used gaskets and sealing penetrations in the drywall sheets to achieve air-tightness without polyethylene. For vapour control they painted the gypsum drywall. Another approach was to use the exterior sheathing as the air barrier, as it provided a continuous surface on the exterior of the wall. Sheathing materials were taped and sealed and the method has been coined EASE by some (Bomberg and Onysko 2002). Despite the promising technology presented, ADA and EASE did not come into common practice with builders, as polyethylene remained in common use.

As for vapour retarders/barriers, during the 1980's the use of paint as a suitable replacement for polyethylene was realized. Lstiburek who introduced the airtight drywall approach recommended paint as a vapour diffusion control layer for most climates (Lstiburek and Carmody 1990). However where paint is used, the performance is more sensitive to interior relative humidity which must be controlled to "safe" levels.

Studies by the Alberta Research Council found that oil based paints over gypsum were suitable vapour barriers but that common latex paint was not (Cutter 1989). However the research was looking at the prescriptive building code requirements for a vapour barrier which required a Type 2 vapour retarder to have a permeance of less than 60 $ng/Pa \cdot m^2 \cdot s$ (CAN2-51-33-M80 Standard).

As earlier discussed, Tsongas during field reviews in the early 1980's found virtually no problems in retrofit insulated homes without an intended vapour retarder (polyethylene or kraft paper) in the temperate climate of the Pacific Northwest (1994).

As a result of the research and field performance presented in the mid to late 1980's, the use of vapour barriers, especially polyethylene was beginning to be seriously questioned by some designers and builders. However the incentives to change were small and building codes had prescriptive requirements for air and vapour control, and for builders were easier to meet using materials such as polyethylene.

3.6.6.5 R-2000 Program

As a result of the energy supply crisis during the 1970's the R-2000 program was developed in Canada during the early 1980's for energy efficient home construction. It is a systems approach to housing design involving the building industry, researchers and material manufacturers outlining the technical requirements. The R-2000 program was developed to show that energy efficient homes can be produced which take into account the moisture problems often associated with increased insulation and air tightness. The program used mechanical ventilation to provide control of indoor ventilation for air quality, and set up requirements for an air barrier system. Air tightness testing was also performed to ensure air leakage of the house was within conformance. It also showed other approaches for improving wall thermal resistance other than changing the wall studs from 2x4 to 2x6 using insulating sheathings such as extruded polystyrene and semi-rigid fiberglass as previously introduced.

3.6.6.6 Materials

Vinyl siding was introduced in the early 1980's, and quickly became a popular lost cost, no maintenance alternative to wood siding. By virtue of its installation it is usually self-ventilated, and some manufacturers also provide perforations or holes at the bottom of the tracks to drain any trapped moisture. Vinyl as a material is impermeable to water vapour and without ventilation would trap moisture within the wall.

Stucco cladding was still used, however only where the plastering trade had survived. With the widespread use of interior gypsum board, fewer plasterers were needed and the trade gradually disappeared in areas. In places like Vancouver however, stucco has remained widely used as seen by the number of stucco buildings still being constructed.

Oriented strand board (OSB) was introduced in the 1960's however didn't gain popular until the 1980's when it became a cheap replacement for plywood. OSB is an engineered wood sheathing consisting of wood chips and fibers mixed with an adhesive (typically urea formaldehyde) and pressed into board form. It utilizes waste wood and smaller trees which are unsuitable for plywood. OSB is often treated with a wax or other hydrophobic material to improve water resistance, as when it gets wet it tends to swell.

In much of the country during the 1950's, plywood replaced 1x8 board sheathing because of cost and ease of construction, and in the 1980's OSB began to replace plywood in some applications because of cost and availability. Because of the joints in the initial 1x8 board sheathing, it was relatively permeable to water vapour, and air flow at the joints would have enhanced drying. Plywood is only slightly less vapour permeable than board sheathing due to the adhesives used in plywood. On the other hand, OSB is much less vapour permeable plywood due to the quantities of adhesive required and hydrophobic materials used in production. The different hygroscopic behaviour for OSB compared to plywood is shown in Figure 3-37 comparing the vapour permeance versus relative humidity.

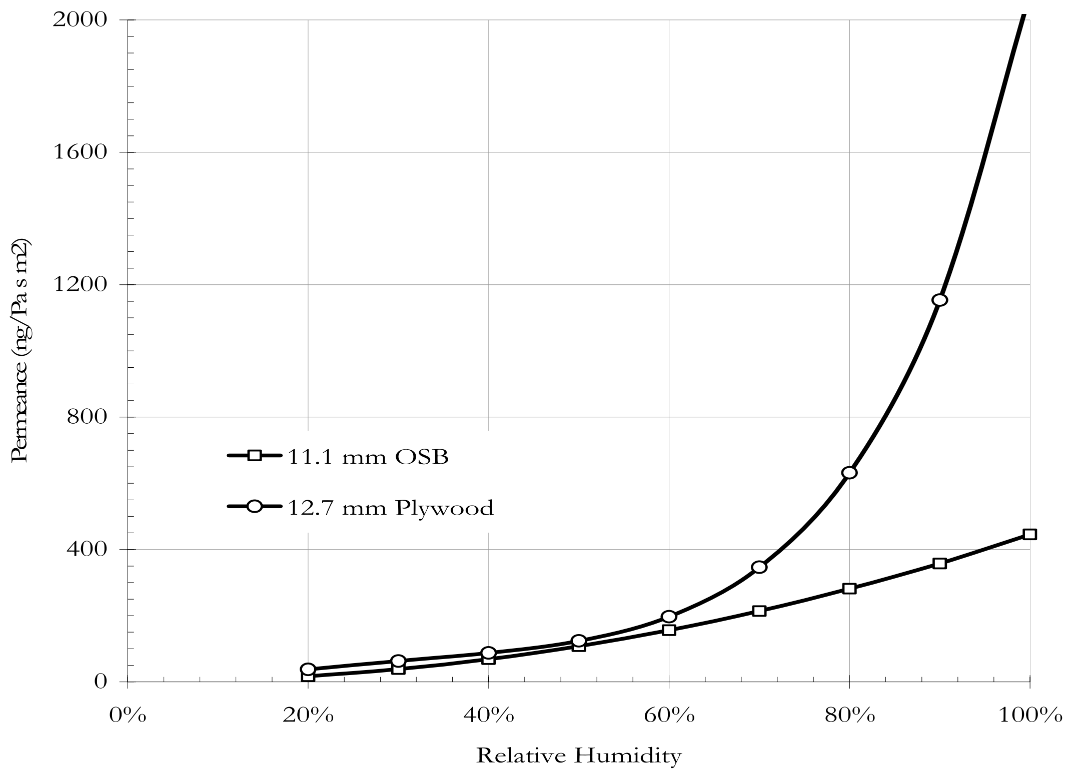

Figure 3-37: Vapour Permeance of Plywood and OSB with Relative Humidity (Kumaran et al. 2002)

Normal relative humidity levels for exposure in a frame wall could potentially range from 50% to 90% based on climate and season. At 80% RH, the plywood is approximately 2 times a permeable, and at 100% RH, or when saturated, plywood is approximately 4 times as permeable. Thus the rate of drying through a wall with plywood sheathing would be faster than that with OSB under normal, but especially under saturated conditions. Neither of which should be termed a "vapour barrier", as some have suggested however both could be considered vapour retarders at low relative humidity levels.

3.7 RAIN, ROT, AND MOULD – 1990'S

In Hutcheon and Handegord's 1980 paper "Evolution of the Insulated Wood-Frame Wall in Canada" they stated:

> "Rain penetration has NOT been a serious problem with wood-frame walls in Canada, but the severe winter climate has made the thermal and moisture problems more critical so that much effort has been devoted to understanding and resolving them" (Hutcheon and Handegord 1980 p. 436).

What hadn't been seen, nor predicted was the high proportion of failures caused by rain penetration in coastal British Columbia during the mid 1980's to late 1990's.

The wood frame wall had evolved significantly over the past century, first based on recommendations in the 1930's and 1940's for vapour control and later in the 1960's and 1970's for air flow control, both mechanisms focused on preventing wetting from interior sources. It was typically assumed that wall designs and details would be largely effective at preventing rainwater penetration, and for the most part they were.

Over the past century, while controlling interior moisture sources, the compounding effect of small changes made to wall construction and materials over the decades eventually pushed walls past a safety threshold to failure resulting from a reduction in drying, and exterior moisture sources. The consequences and importance of rain penetration control were again realized, particularly in coastal climates. As a result, details were largely improved and recommendations which were made since the 1950's for ventilated cavities behind light claddings to improve drying and reduce wetting were finally realized and put into practice.

3.7.1 Vancouver's Leaky Condo Problem

In the early to mid 1990's a problem with the housing stock began to be realized in coastal British Columbia. In particular, those buildings affected were the recently popular three and four storey wood-frame condominiums. Construction booms throughout the 1980's and 1990's in Vancouver (See Section 3.8) brought population growth and a large demand for housing. As land prices rose, developers found it more economical to build denser multi-unit buildings and scrambled to meet demand.

Platform wood frame construction which was originally developed for one and two storey dwellings was adapted to larger buildings up to four stories (maximum allowed for wood-frame building by Building Code). In addition, Architectural style popular at the time was largely influenced by "Mediterranean" and "Californian" styles which included large exposed balconies, access by exterior walkways, and architectural details which sometimes complicated the building form. Roof overhangs, commonly used on one and two storey dwellings were often omitted citing the architectural style or set-back restrictions on the already packed city lots. The buildings were often clad in face sealed cement stucco over building paper/polyolefin house-wrap over OSB/plywood and a fiberglass insulated wood frame with interior polyethylene vapour barrier. Other claddings such as vinyl siding and cedar siding were also used, however stucco cladding was very commonly used during the period.

It soon became evident that there were problems with some of these wood-framed condominiums. Staining and mildew growth on the exterior façade was observed, particularly at details including balconies and windows. Interior problems including mould growth and water leaks also became apparent shortly after completion of some buildings. After a few years the wood-frame walls in a number of the buildings were found to be severely decayed and structurally deteriorated. In cases the wood studs and sheathing was so badly deteriorated that it lacked structural integrity and could be torn apart by hand.

As builders and consultants who were called in by the owners probed further, the full extent of the deterioration was finally realized. The problems were so widely spread and systemic that they could not be blamed just on poor construction of a few buildings. A wide-scale crisis was emerging with much of the recently constructed housing stock in coastal British Columbia.

Photographs showing some typical exterior signs of damage (Figure 3-38) and deterioration uncovered beneath the cladding (Figure 3-39 and Figure 3-40).

Figure 3-38: Typical Water Staining and Algae Growth of Early 1990's Stucco Clad Condominium (RDH Building Engineering)

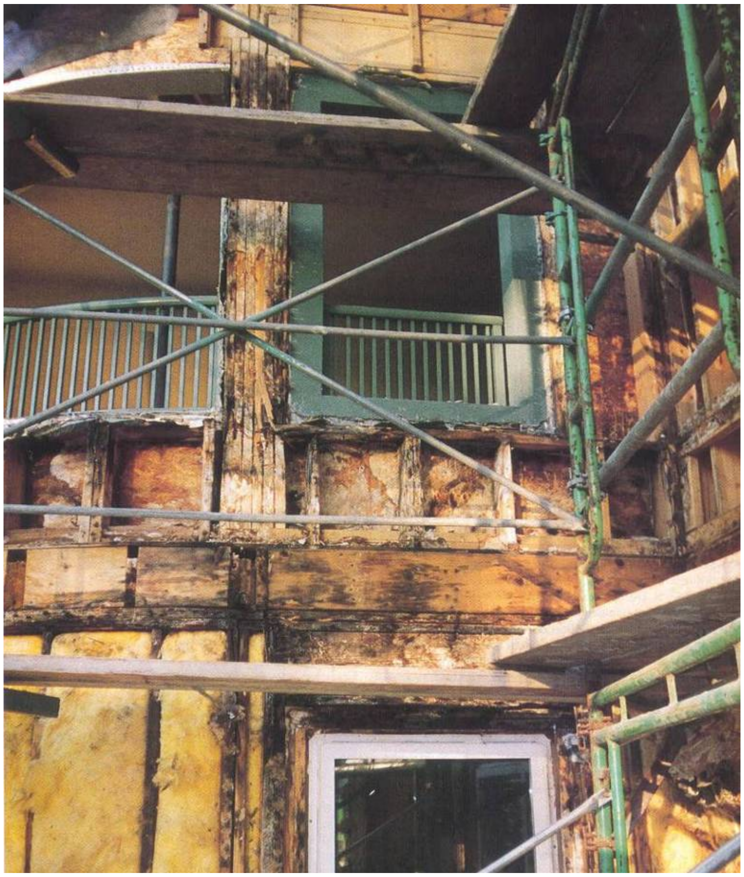

Figure 3-39: Typical Deterioration of the Wood-Frame Structure after Cladding and Sheathing is Removed (RDH Building Engineering).

Figure 3-40: Severe Deterioration of Wood Framing at a Vent Opening (RDH Building Engineering)

Moisture damaged buildings continue to be repaired today, with the total repair cost exceeding almost $2-billion to date (BCDEX 2006). Named the "leaky condo crisis" by the media and as its name so implies, was because a large percentage of condominiums buildings were initially affected. Media attention fuelled by some very outspoken and angry condo-owners brought about a nationwide recognition of the problem.

Failures were reported in all types of buildings, however less publicized than the condominiums and included single-family homes, townhouses, high-rises, schools, and commercial buildings all built during the same period. The damage to some of these smaller and rain sheltered buildings usually localized and taking longer to manifest. As the construction boom continued right up until the full realization of the problem, thousands of units were constructed in the late 1990's without construction improvements and are just seeing problems now.

Some of the possible clauses postulated at the time included: poor construction practice, poor details, lack of details, unskilled labour, rain, wind, lack of overhangs, increased insulation, OSB, stucco, house wraps, polyethylene, architectural style (mainly Mediterranean of Californian styles) and so on the list continues. Everyone was looking for a singular problem when in fact it turned out to be a combination of different construction practices (Morrison Hershfield 1996, Barrett 1998, Barrett 2000, UDI 2000). Whatever combination of changes had been made during the 1970's and 1980's, it could be safely stated that in the fight between wetting and drying, wetting had won.

3.7.2 <u>1996 Survey of Building Envelope Failures – Lower Mainland of BC</u>

In 1996, CMHC funded a study to determine the causal factors into the high incidence of moisture related failures in British Columbia (Morrison Hershfield 1996). A total of 46 buildings were studied, 37 with problems and 9 which had not experienced problems. All buildings were three and four storey wood frame residential buildings located in the BC lower mainland and Vancouver Island within 30 km of the coast of the Strait of Georgia. While the sample size was not statistically significant to the entire population and not necessarily applicable to the entire building stock, the study found some very important observations and conclusions.

The buildings in the study were clad with stucco, vinyl or wood and a range of sheathing papers, sheathing, insulation and wood framing members were used in different configurations, providing some variables which to compare different materials and the effect they had on the wall performance.

The survey results also provided an idea of the typical construction materials used in Vancouver during the period from 1985 to 1991. OSB was more commonly used than plywood, and building paper was more commonly used that plastic house-wraps. Stucco cladding was more common that wood or vinyl.

The following observations and conclusions were made in the report (Morrison Hershfield 1996):

- The most significant conclusion was that exterior water sources (wind-driven rain) lead to the performance problems. Interior moisture sources (diffusion and air leakage) and construction moisture were found to be insignificant.
- 90% of the problems were related to interface details between wall components or at penetrations, only 10% of the problems could be directly related to the wall assembly in the field of the wall. Thus water entered the wall at the details and over time led to the deterioration observed.
- Water penetration at window frames was a significant issue. Primarily non-thermally broken aluminium frames were used at the time. Typically the corner mitre joints were unsealed and leaked. Water could also collect in the open sills (sliding windows) continually adding to the moisture load. Flashings at windows were not commonly used, and interface details were generally poor allowing water to penetrate easily into the walls.

> It should be noted that the problem with rainwater leakage at window frames was not new, as it had been noted as a significant issue as early as 1984 in the Lower Mainland of British Columbia by Ted Blackall and Max Baker from the NRC. (Blackall and Baker 1984).
>
> Not from the Morrison Hershfield (MH) study, but interestingly from the 1997 CMHC Builder's guide, a typical early 1990's window detail is shown in Figure 3-41. The detail is representative of construction practices for the time for wood frame windows however showing some of the faults noted in construction details from the MH study.

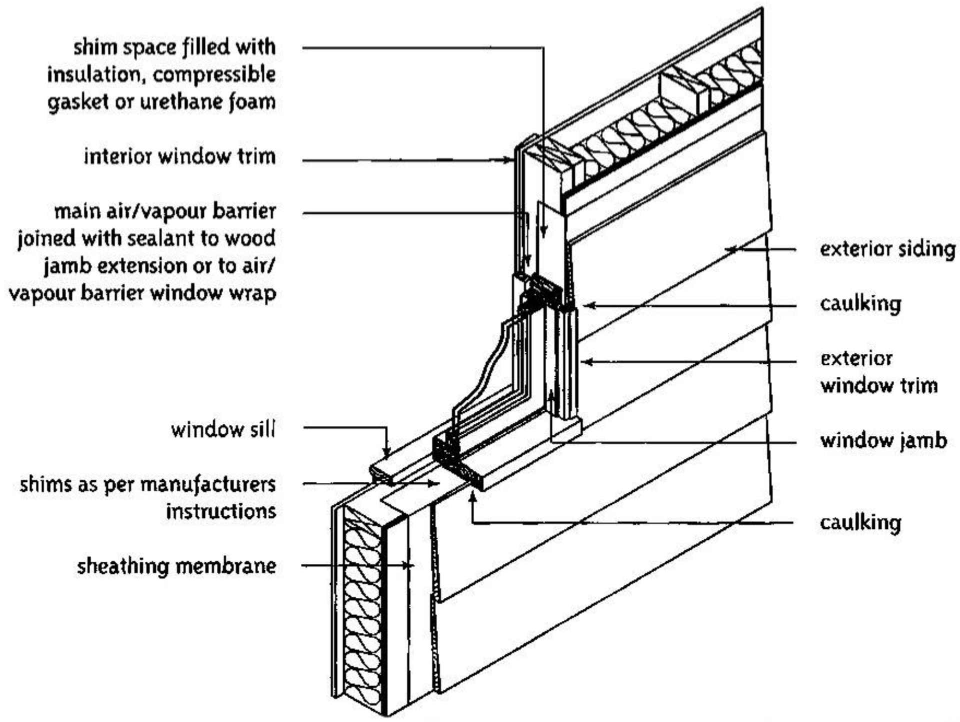

Figure 3-41: Typical Window Frame Installation (CMHC 1997)

Note that the sheathing membrane wraps up onto the flat sloped wood framing. Flashings to drain water that does incidentally penetrate the window frame were not provided below or above (not shown here) the window.

- Stucco buildings were more common in the study, and a higher proportion of problems were found with stucco buildings. Window problems in stucco buildings were also more prevalent, indicating an issue with window interface details with this type of cladding.
- Water penetration at decks, balconies and exposed walkways are an issue.
- Lack of details on drawings or poor details are a significant contributor to the as-constructed details
- Architectural details on the problem buildings were also found to contribute to problems. The control buildings (without water penetration problems) had fewer details, and typically the penetrations were flashed.
- While the proportion of OSB sheathed walls experienced problems than plywood walls, there was no correlation between OSB sheathing and the size or cause of the problems.
- Problems on wind-driven rain exposed east and south elevations were higher than other elevations.

- Insufficient data to establish differences prevalence of moisture problems with buildings between plastic house wraps or building paper. It was also reported in the study that most house wraps had a much lower vapour diffusion resistance than building paper at the time, 10-20 times less.
- Problems with 2x4 walls were actually found to be worse than 2x6 walls, citing possible moisture storage capacity within the 2x6 walls, even though more insulated.

  The minimum insulation requirements from Coastal British Columbia were increased from RSI 1.9 to RSI 2.5 (R-11 to R14) in the 1990 NBCC and 1992 BCBC, the first separate provincial building code for British Columbia. To achieve R-14, some builders switched to using 2x6 studs filled with R-19 or R-20 fiberglass batt insulation, hence why in the study both 2x4 and 2x6 walls were observed.

Perhaps one of the most widely referenced pieces of information from the study shown in Figure 3-42 plots the width of overhang versus the percent of walls with problems. The link between a wider overhang and reduced wetting of the walls and thus moisture problems is apparent for the low-rise condominium buildings. Most of the control buildings it was stated had wider overhangs than the problem buildings.

Overhangs are typically a function of architectural style, and there certainly were a lot of buildings constructed with flat roofs and parapets without overhangs during this period when this was architecturally in fashion.

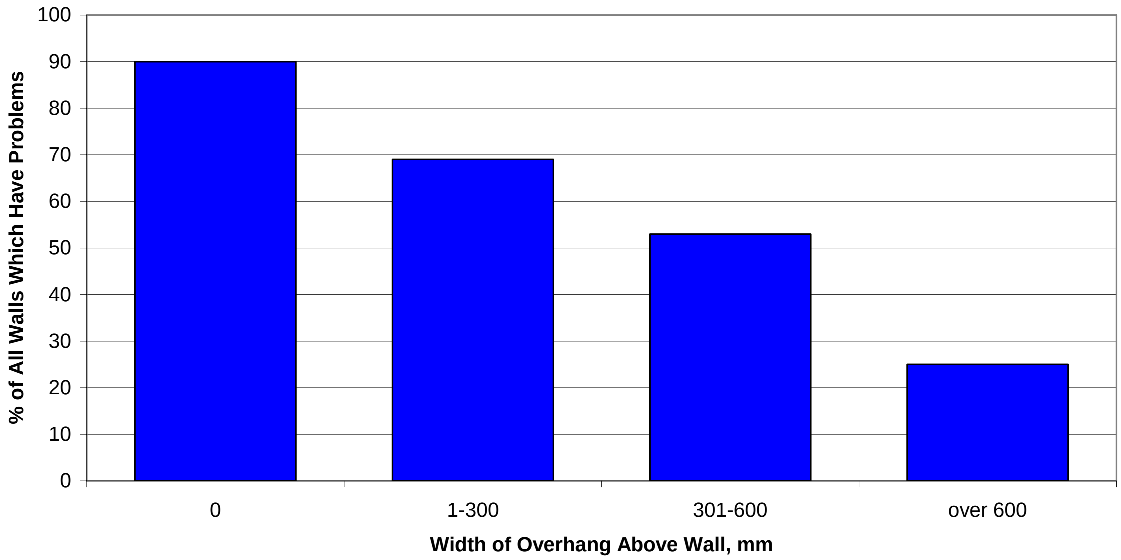

Figure 3-42: Effect of Overhangs on Wall Performance (Morrison Hershfield 1996)

The study also discussed the recognized need for walls to effectively balance water management principles. Control of moisture ingress, drying and drainage were discussed. The control of moisture ingress was an apparent problem with the details, so the drainage and drying functions were further reviewed.

Typically in Vancouver, and most of Canada during the 1980's and early 1990's the exterior walls clad with stucco, wood, or vinyl siding could be considered either a face-seal or slightly improved concealed barrier approach to rain water management. Rainscreen (vented, drained or ventilated) the third approach was not commonly used for light claddings, however brick veneer with an air space could be considered a form of this approach.

Stucco walls were traditionally face-sealed, while wood and vinyl sidings behaving more like the concealed barrier approach by virtue of the material installation and small gaps behind the siding. Stucco as discussed earlier was placed on self-furring metal lath, with the stucco adhering to the building paper unless furred out sufficiently. By the 1980's the use of welded wire mesh was common, resulting in the stucco being directly in contact with the building paper.

A face-seal approach relies on the exterior surface of the cladding and sealed joints to resist the penetration of water into the exterior walls. The air and weather barrier is the exterior surface, also used for drainage. Any cracks, imperfections, or unsealed joints that allow water to penetrate past the cladding are potentially damaging, as the water cannot easily dry out. Typically flashings are not used, and the sheathing paper is only somewhat of a capillary break between the cladding and sheathing, not for drainage. With stucco, the sheathing paper or wrap is usually adhered to the backside, preventing any drainage between the stucco and building paper from occurring.

A concealed-barrier approach is a slightly improved face-seal wall. The exterior surface is still largely the weather barrier and sealed, however if water does penetrate past the cladding, the sheathing paper provides some minimal drainage, and flashings are often utilized. The cavity behind the cladding, especially stucco can be improved using two layers of building paper, or textured/crinkled house wrap.

The authors stated that it was not clear when reviewing the buildings in the study whether concealed barrier or face seal was intended. By virtue of design, both concealed barrier and face seal walls tend limit the drying. Diffusion is only mechanism for drying in these systems, but with wet cladding is reduced, thus no drying in winter, and significant wetting by capillarity through the cladding and rainwater leaks.

The concept of a rainscreen wall also discussed. The main difference between a concealed barrier and a rainscreen is the addition of an air space. The air space provides drainage and ventilation, and also some pressure moderation to limit rainwater penetration. Improved flashings and details also required for the rainscreen wall system to work. Rainscreen systems theoretically provide the best opportunity to achieve acceptable performance as they are more forgiving in the balance of water management.

The authors also went on to conclude that it is not possible to achieve acceptable performance with concealed barrier or face sealed systems in the Lower Mainland due to the moisture sensitivity of these wall systems. Interface details also had to be improved to achieve acceptable performance.

The survey also produced some recommendations for practice:

- Development of a best practices guide for builders and architects for wood frame buildings in British Columbia. This was later published in 1999 by CMHC.

- Improved drawing and construction of details at penetrations (windows, balconies, roof-wall interfaces, vents etc). To be constructed of better quality and drawn at a larger scale to show detail.
- Use of shop drawings specifically for windows to show wall interface details and material construction.
- Improved sequencing of trades on site to ensure correct material sequencing and application.
- Construction of site mock-ups by contractors prior to full scale implementation of a detail on a building.
- Move from face-seal and concealed barrier to rainscreen walls using cladding that traditionally have not been used in this application. For example a stucco rainscreen would require a backer-board type material to place over the strapping/furring.
- Further research into drying of walls (later by Morrison Hershfield 1999 and Forintek 2001)
- Improved window standards (revised CSA A440).
- Improved maintenance and guidelines for building owners.

3.7.3 <u>Reaction in Vancouver – Rainscreen Walls</u>

In July 1996, the City of Vancouver passed building Bulletin 96-02, which effectively mandated the use of rainscreen type claddings on new (or retrofit) buildings as of September 1, 1996. City of Vancouver Bylaw #7623 passed on September 24th, added the local amendments to Part 5 of the National Building Code (Not Part 9). Incidentally, the bylaw was passed prior to final CMHC publication of the Morrison Hershfield's "Survey" in late November.

The bylaw was only directly applicable to buildings constructed in the City of Vancouver, however much of the region followed the recommendations. The bylaw specified that any stucco wall systems be constructed with "a vertically-strapped drainage cavity" or "self furring, non-wicking drainage medium" or "other acceptable means of creating a cavity." Provisions for drainage outside at each floor level, and requirements for flashings were also included in the bylaw (Vancouver 1996, Lawton 1999).

Improved details are shown for a rainscreen strapped wall and window frame including strapping, flashings and properly lapped membranes and water resistant sheathing membrane (Figure 3-43). The details produced by RDH

Building Engineering, three-dimensional renderings of details from the 1999 CMCH Best Practice Guide.

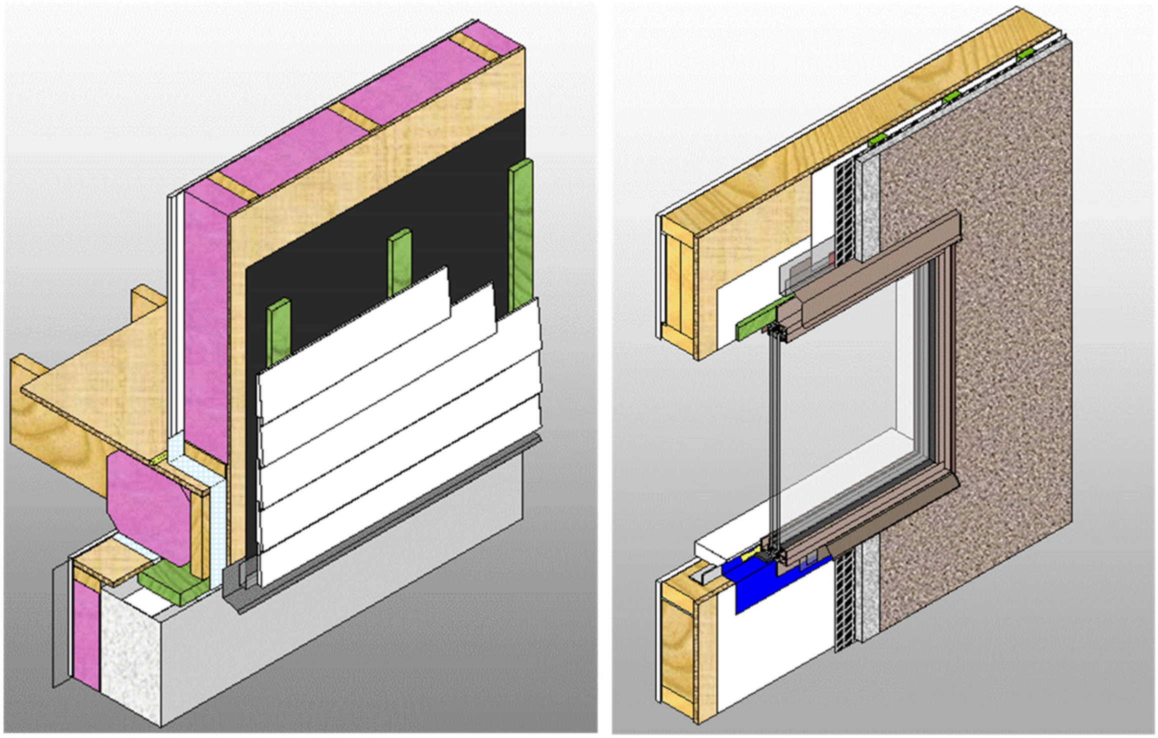

Figure 3-43: Improved Rainscreen Wall Details (RDH Building Engineering)

Note the use of pressure treated strapping, flashings and improved details at the window frame (sub-sill flashing, well lapped membranes, and head and sill flashings) as compared previously to Figure 3-41.

3.7.4 <u>Further Investigation – British Columbia</u>

In 1998, the former Premier of British Columbia Dave Barrett launched a commission and two public inquiries into the failure of hundreds of wood-frame condominiums (Barrett 1998, Barrett 2000). In addition to the hundreds of angry condo owners, dozens of experts provided their input into the problem and solutions.

The Barrett Commission brought forward many of the building code changes and issues, government politics, and re-iterated many of the conclusions from the 1996 Morrison Hershfield-CMHC survey. Mainly the walls got wet and couldn't dry out in this climate which leads to the problems including decay. While it is not the intent of this thesis to cover the political or building code changes during the period, much of the relevant technical information has been provided throughout this chapter. For further reading, pertinent National and Provincial Building Code changes are well summarized by the Barrett Commission (1998, 2000) and others (UDI 2000 and McCreery 2004).

As a result of the Barrett Commission, recommendations for building code changes, technical training, and further research and testing were made. As a direct result of recommendations by the Commission, the Homeowner Protection Office (HPO) was established in 1998 to provide assistance and education to homeowners affected by the moisture damaged buildings. The HPO also licenses residential builders and monitors the provision of third-party home warranty insurance for entire province.

The Barrett Commission presented a number of scenarios and it was estimated to repair the moisture damaged buildings constructed between 1983 and 1997 it would cost between $650 million and $1 billion, provided that repairs remained at $15,000 per unit for low-rises and $10,000 for high rises (Barrett 1998 Appendix 3). Today that figure is much higher, projected up to $2 billion with significantly higher repair costs per unit.

From the evidence, it appears that the technology and materials existed to construct more durable walls at the time; however the builders found it uneconomical to do so, who were in turn building for buyers who wanted the most economical option. Arguably today, those original builders and buyers would have found it in their best interest to spend the couple of extra dollars per square foot for a better system originally (improved detailing and rainscreen technology).

The cost for building repairs has increased significantly from the rehabilitation projects over a decade ago. Costs initially at a few thousands of dollars per unit have risen to tens of thousands of dollars even as high as one or two hundred thousand dollars per unit in the past decade. The rehabilitation costs have increased due to inflation in labour and materials but also the problems within the buildings have only gotten worse and further deteriorated over time, leading to a more widespread problem. Had localized repairs been made initially, the entire stripping and re-cladding now required in most cases may have been avoided. Today the rehabilitation costs for affected buildings in particular high-rises can often exceed the original purchase price of the units. In one recent case, a large condominium development that cost $29 million to build in 1994 is estimated at a total of $40 million to repair (Vancouver Sun 2006).

3.7.5 Wood-Frame Research - Drying

Two research projects were founded as a result of the Barrett Commission recommendations. While wetting was understood to be a causal factor in the leaky condo problems, the impact of drying while important was not fully understood. The first study was completed by Morrison Hershfield and CMHC in 1999 to address the drying characteristics of both stucco-clad face-sealed and drained (rainscreen) walls and also looked at alternate materials to strapping to achieve a ventilated or vented cavity (Morrison Hershfield 1999). The second study completed by Forintek and CMHC in 2001 evaluated the relative drying rates of various wall configurations, exposed to simulated field conditions (Forintek 2001).

3.7.5.1 Morrison Hershfield – Stucco Clad Drying Experiment

In the Morrison Hershfield study and small environmental chamber was built and five wood frame walls were simultaneously tested to observe drying rates (Morrison Hershfield 1999). The walls were initially wet with a known quantity of water and monitored for 5½ months while subjected to a small temperature and vapour pressure gradient. Both wood frame (plywood sheathing) and steel stud frame (gypsum sheathing) walls were tested. Unfortunately, solar radiation and wind effects were not simulated in this study, limiting the application and validity of the results to buildings in the field. Regardless the results show the relative comparison of drying of different walls, under unfavourable conditions. The following conclusions were made in the report:

- Drying was very slow for all wall types and there was no significant difference between the face-sealed or ventilated rainscreen stucco cladding
- The drying rate was not affected by cladding design, either face seal or rainscreen. It was also stated that drying would not be improved with other cladding types (however no other claddings were tested)
- The injected water flowed from the top to the base of the wall panels and was absorbed into the bottom plate and lower portions of studs and sheathing. The moisture stayed where it was absorbed and did not redistribute throughout the remainder of the wall. Therefore a small leak into the insulated cavity could lead to a localized problem, and that overall drying of the wall may not avoid this.

- The presence of the rain screen cladding does not appear to increase the drying potential, and while much of the problems in Vancouver were associated with leaks that bypass the rainscreen cladding (windows, penetrations etc), highlighting that the details to eliminate water entry are critical.

3.7.5.2 Forintek – Envelope Drying Rates Experiment

The second drying study was performed in Forintek Canada's western lab in Vancouver (Forintek 2001, and summarized in Hazleden and Morris 2002). The research program consisted of 12 wall panels of different configurations. Ten stucco-clad and two wood-clad wall panels were tested. Nine used OSB sheathing, and three used plywood sheathing. Building paper and Spun Bonded Polyolefin (SBPO) house wrap were compared. Different cladding arrangements including vented (vents bottom only), ventilated (vents top and bottom), and the impact of the cavity depth were tested.

The boundary condition temperature/relative humidity during the test was kept relatively constant at 21°C/40% RH indoors and 5°C/70% RH outdoors, representative of average winter conditions in Vancouver. Solar radiation was simulated using heat lamps at intensities consistent with a north-east oriented wall during January. The testing was not intended to simulate drying in the field.

The entire panels were initially loaded with moisture in excess of 30% MC by weight and the relative drying rates were compared, considering 16% MC as dry. Phase 1 testing ran for 1500 hours without simulated solar radiation and Phase 2 ran for 2000 hours with simulated solar radiation.

The following observations and conclusions were made in the report:

- Relative drying occurred in all wall panels at the end of each phase; however was not uniform over all components. There were some areas in each of the panels which remained above 19% MC at the end of the test, typically at the sheathing or sill.
- The studs dried faster than the sheathing (OSB or plywood). On average the studs dried below 19% in less than 500 hours, however portions of the studs (within 20 mm) of the sheathing were also found to remain above

20% at the end of the tests. The OSB and plywood sheathing was generally above 19% MC by the end of the tests.

- No decay was found at the end of the 3500 hours (almost 5 months) of testing.
- Walls with cavities (vented and ventilated) dried faster than comparable panels without cavities (face-sealed). There was a substantial range in the drying rates and up to a factor of 3 higher for comparable walls with a ventilated cavity than for those without.
- Ventilation (top and bottom vents) resulted in marginally faster drying than vented (bottom vents) walls. The width of cavity was also important, and those walls with cavities of 19 mm dried faster than 10 mm.
- Walls with plywood dried faster than comparable walls with OSB sheathing.
- There was no substantial difference in drying between building paper and SBPO house wraps.
- In phase 1 (no solar) the walls with wood siding dried faster than comparable stucco walls. However in phase 2 (solar) the trend was reversed.
- Solar radiation effects were found to be significant in the drying and moisture content of the OSB and plywood sheathing. Ventilation reduced the moisture content of the plywood more than it did the OSB sheathing in the observed cases.

The drying rates were also compared in terms of an effective vapour permeance, those walls with ventilation or venting had a significantly higher effective vapour permeance up to 3.6 times higher (for the whole wall) than without ventilation.

Unlike the Morrison Hershfield study, Forintek found drying to occur at a reasonable rate and potentially be beneficial to wood-frame walls, in particular with ventilated rainscreen cladding. However as both reports concluded the amount of drying (albeit under laboratory conditions) was perhaps insufficient to reduce the sheathing moisture content to safe levels in a reasonable time. Both reports highlighted the importance of preventing wetting, as the amount of drying was limited, even when ventilated rainscreen claddings were employed.

Under field conditions, walls exposed to wind, solar radiation, and temperature effects, especially during the spring and summer would likely have improved drying rates from the laboratory results. The amount of moisture that leaks into the wall may also be important as both tests only tested high initial moisture loadings. The effect of a persistent leak associated with driving rain events may have a different effect on the wall performance which could only be addressed by field studies. Discussed later in this thesis, the physics and impacts of ventilation in the field are covered (Straube 1998, ASHRAE 2004).

As part of the Forintek study, the effectiveness of "vapour-diffusion ports" were also tested on the improvement they had on drying of OSB and plywood sheathed walls. An example of "vapour-diffusion ports" which are essentially 3" (75 mm) diameter holes cut into the top and bottom of the sheathing as shown in Figure 3-44.

Figure 3-44: Vapour Diffusion Ports (Forintek/CMHC 2003)

It was found that the "vapour diffusion ports" did not significantly increase the drying rate for plywood sheathed walls; however slightly increased the drying rate by 10% for OSB sheathed walls. Only a few builders and consultants have adopted the practice in Vancouver as the field effectiveness is questionable and possibly detrimental (as a water leak at the sheathing can now directly penetrate through the hole into the wall cavity). Incorrectly coined "vapour diffusion" ports they should have rather be called "air leakage" ports, as water vapour would be removed by the mechanism of convective air currents, not vapour diffusion (which only occurs from high to low vapour pressures), not around the sheathing and through small openings as suggested.

3.7.6 Gypsum and Steel Stud Framed Walls

In addition to the wood-frame buildings, non-combustible buildings constructed with steel stud and gypsum sheathing constructed during the 1980's and 1990's also experienced moisture problems similar to the wood frame buildings. Non-combustible steel-stud and gypsum sheathed walls are largely used in mid-rise and high-rise applications where required by Building Code.

In these buildings the exterior walls were typically constructed of stucco, brick or other non-combustible cladding over sheathing paper, exterior grade gypsum board, and an insulated steel stud cavity with polyethylene vapour barrier and gypsum drywall. Like wood frame walls, but more exposed, significant problems were observed in these walls as well, leading to extensive corrosion of the steel studs and deterioration and mould growth on the gypsum sheathing.

By nature of construction, steel stud and gypsum insulated walls have less storage capacity in the event of a leak (approximately $1/10^{th}$ of that of wood), and the physical properties of gypsum sheathing are strongly affected by moisture content, so the potential for catastrophic structural failure is arguably more critical. In addition, high humidity and water leaks combined with gypsum, chemically releases an acid, which further accelerates the corrosion of steel studs and fasteners. See *Appendix A: Exterior Gypsum Sheathing – Electrical Resistance and Humidified Properties* for further discussion about the moisture content and strength relationships of gypsum sheathing.

Investigations often revealed extensive moisture damage including mould growth on the paper-faced exterior gypsum sheathing, and moderate to severe corrosion of the steel studs. During rehabilitation, when the cladding was removed from some of these buildings, the steel studs supporting the cladding were found to be corroded through with a fraction of the original structural load carrying capacity in less than a decade (Figure 3-45).

Figure 3-45: Corroded Steel Studs from the Exterior Wall of a high-rise under Rehabilitation (RDH Building Engineering)

When the interior gypsum was stripped off, and insulation removed, mould growth was also commonly observed on the exterior sheathing (Figure 3-46).

Figure 3-46: Mould Growth and Water Staining on Backside of Paper Faced Gypsum (Lawton, 2004)

The photograph shown here is from Building 3 of the study taken during a condition assessment in 1999 prior to rehabilitation of the exterior walls. The investigation found extensive moisture damage of the exterior walls from rainwater, but also moisture damage and mould growth on the interior drywall surfaces from humid interiors.

Like the failures of the wood-frame buildings, the gypsum and steel stud buildings were largely as a result of water penetration at windows and details and the inability of the walls to dry.

In 2001, RDH Building Engineering published a study with CMHC to identify causal relationships resulting in problems in non-combustible high-rise buildings in coastal BC (RDH 2001). Similar to the 1996 Morrison Hershfield survey which documented three and four storey wood frame buildings, the RDH study looked at moisture problems with residential mid and high-rise buildings between five and twenty-eight storeys and constructed after 1981. Thirty-five buildings were studied with eight types of cladding; however the majority of the buildings clad with face-sealed stucco or EIFS.

Like the previous studies, exterior moisture penetration at interfaces between assemblies and details were the dominant cause of moisture problems in the high-rise buildings. Windows were also a significant issue, as observed in the wood-frame study. The deterioration issues were as a result of corroded steel studs, fasteners, and moisture damage of the paper faced gypsum sheathing. Those walls with fiberglass faced gypsum board showed lower extent and severity of damage.

A few of the older buildings in the study had incorporated drainage cavities behind the cladding (similar to rainscreen), of which none of these walls were found to experience moisture problems.

Another issue noted was the general inadequacy of the mechanical ventilation provisions in high-rise buildings resulting in high interior relative humidity conditions.

Recommendations called for rainscreen claddings on high rise buildings and improved detailing at interfaces and windows. The use of fiberglass faced gypsum sheathing products were also recommended as paper faced gypsum was found to be unsuitable. Improvements to deficient mechanical systems were also suggested.

3.7.7 Moisture Related Failures Outside Coastal British Columbia

During the 1990's other large-scale wall moisture problems were observed in other parts of North America. EIFS clad wood-frame wall failures in North Carolina, Stucco clad wood-frame wall failures in Minnesota are discussed in some detail with similarities to coastal British Columbia problems.

3.7.7.1 EIFS – North Carolina

Around the same time as leaky condos were being discovered in Vancouver, BC, moisture problems in EIFS clad housing in Wilmington, North Carolina were being investigated. Wilmington, North Carolina is considered a warm, wet climate on the Atlantic coast and annually on average receives more rain than Vancouver (1406 versus 1058 mm), and also high instance of wind-driven rain. The moisture index, a measure of the wetting potential of the climate as determined by the NRC is 1.13 for Wilmington, compared to 1.09 for Vancouver, both high values (NRC 2002, NRC 2003).

Initially the moisture problems were thought to have been as a result of the active 1994-1995 hurricane season when 4 hurricanes hit the area. However upon further investigation the problems were found to be largely isolated to EIFS clad houses under a decade old. An investigation by the American Institute of Architects surveyed over two-hundred EIFS clad houses and found moisture contents above 19% in over 90% of the houses. The houses were located in several different sub-divisions, constructed by different builders, EIFS installers and manufacturers, which prevented of a specific system or builder from being isolated as the cause. Problems were found to be as a result of moisture penetration at joints of the EIFS panels (windows, doors, penetrations, decks, fireplaces etc), and once the moisture had got into the walls it could not dry out, and over time lead to extensive decay.

Further investigations to determine the extent of the damage sampled 300 of 3,200 EIFS houses constructed during the period and found moisture problems in 98%.

United States Gypsum Corporation (USG) contracted with the National Research Council of Canada (NRC) to perform addition research and modeling of the failures. Much of the modeling and results are presented in the MEWS taskforce reports, specifically Task 8 (NRC 2002). Two-dimensional hygrothermal modeling using HygIRC 2D validated with laboratory testing showed that rainwater leaks into face-sealed EIFS wall assemblies had the potential to cause the deterioration widely observed. The warm and wet climate of Wilmington, North Carolina was also a contributing factor to the extensive and rapid failures observed. Recommendations for drained and ventilated EIFS systems but most importantly improved water shedding details at windows and penetrations.

3.7.7.2 Stucco - Minnesota

In 1999, a problem became apparent in Minneapolis and other cities in Minnesota that stucco clad homes constructed after 1990 were experiencing moisture related problems. Minneapolis, Minnesota receives less rain that Vancouver or Wilmington, and a colder climate, however many of the problems

Moisture damage again was attributed to water leakage from the exterior, particularly at windows, but in this colder climate, air leakage condensation from humid interiors exacerbated the problems in some cases. A high proportion of the problems were associated with stucco buildings, however other sidings were also affected. Recommendations to improve penetration details were made, and the use of stucco as a cladding fell out of favour by builders. Repairs were made to address structural damage and mould remediation, with many houses costing $150,000 US or more (Woodbury 2005).

3.7.7.3 Vancouver's Twin - Seattle

Similar to Vancouver, pervasive moisture problems with three and four storey wood-frame condominiums were observed in Seattle, constructed during the same period (1984-1997). Seattle and Vancouver are within the same temperate coastal climate, experiencing much of the annual precipitation during the winter months. Seattle, like Vancouver experienced a building boom during the 1980's and early 1990's bringing with it many new buildings constructed with moisture problems.

Similar problems were observed in Seattle to be contributing to the moisture related damage, and the rehabilitation costs were just as high. By 2002, 52 multifamily projects constructed between 1984 and 1998 were rehabilitated at a cost of almost $100 million US (Brock 2005, from City of Seattle Report "Summary of Wood-Framed Exterior Wall Performance Study).

A survey conducted by Seattle's Construction Codes Advisory Board looked at 53 buildings constructed after 1984 which reported leaks. 70% of the structures were wood frame and 19% had steel stud/gypsum and concrete frame. EIFS was most widely used cladding (26%) with wood siding (23%) and stucco (20%). The source of the problems correlated with the findings of deficiencies noted in the 1996 MH survey (Brock 2005).

CMHC and Morrison Hershfield performed a study in 1999 to compare residential construction in Seattle and Vancouver to potentially identify similar causal factors where the construction practices were slightly different (Morrison Hershfield 1999b). Only four buildings were studied, and differences in construction were noted, however the materials used did not appear to be causal factors in the moisture failures. They found like other studies that the failure mechanism in both locations was exterior moisture (rain) and that water was able to bypass the weather-barrier at wall penetrations. Again face-sealed walls were found to be too sensitive to climate and exposure and recommended rainscreen wall assemblies.

3.7.7.4 Additional Moisture Problems

By end of the 1990's further investigations and research had uncovered further moisture problems in Atlantic Canada (Chouinard and Lawton 2001) and parts of Alberta (Vlooswyk et al. 1999). In 2003 further cases studies of damage as a result of water penetration at details and interfaces were presented for Ontario and Quebec in addition to Alberta, BC, and Atlantic Canada (Brown et al 2003). Consistent with the previous studies, moisture damage was largely occurring in buildings as a result of water infiltration at windows and other wall penetrations. Deficient or missing details often the blame. All of these cases further broadening the scope of the moisture problems with North American housing stock and susceptibility to rain-water intrusion and damage.

To answer some of the questions regarding the impact of such variables including: materials (stucco, OSB/plywood, building paper/house wraps, polyethylene), rainwater leaks, air leakage etc, several hygrothermal modeling studies were performed. Some of the more encompassing published studies include those by Achilles Karagiozis at Oak Ridge National Laboratory for Seattle (Karagiozis 2002), Louise Goldberg at the University of Minnesota for Minnesota (Goldberg 2006) and at the National Research Council, MEWS Task Force for North Carolina (NRC 2002, NRC 2003). The results of the modeling studies help to understand the failures in the field and impact of material choices and have been used to implement changes to construction practice. Hygrothermal modeling is further discussed and validated for the buildings discussed in this thesis in *Appendix B: Hygrothermal Modeling* with results presented throughout.

3.7.8 Conclusions

The moisture related failures during the 1990's brought about new research and understanding of building science issues. Catastrophic failures of wood and steel stud/gypsum frame buildings brought the issue of rain control back into focus. As a result of small incremental changes made to construction practice during the 1970's and 1980's in details and new materials, wall systems in wet climates became prone to failure.

The relatively air-tight, highly insulated homes of the 1990's were unforgiving. The interior was typically finished with drywall over 6 mil polyethylene taped and sealed at the joints, resulting in a near perfect barrier to vapour. High levels of insulation in the stud space meant the sheathing was close to the exterior temperature and vapour pressures. New materials including OSB sheathing was less moisture tolerant and vapour permeable than the plywood it replaced. Paper faced gypsum and steel stud framing, a low-cost alternative to concrete masonry block were inherently less moisture tolerant, and more prone to deterioration under wet conditions.

Window technology largely carried over the 1970's and 1980's in terms of interface details and often found to leak, particularly at frames. Waterproofing and flashing details were often left up to the tradesmen on site, with little or no guidance from the architect or engineer, and possibly little experience. As a result water shedding details around windows and penetrations were generally poorly constructed and allowed the intrusion of large amounts of water into the wall cavities.

With a vapour and air tight interior the only way for moisture that got into the wall to dry was outwards, which for times of the year was difficult. The stucco or other claddings were applied directly to the building paper, and were constantly wetted by rain during the winter months, thus, the moisture couldn't very well dry out through the cladding either. Cement stucco and EIFS, relatively new products were less permeable to water vapour, and when used as cladding also significantly reduced drying. The lack of a drying potential combined with high instance of wetting resulted in moisture accumulation over time leading to the extensive and catastrophic deterioration of many wood frame and steel stud and gypsum buildings.

Drainage was found to be critical at removing bulk water such as due to a rainwater leak and studies found that drying was important to the remove any additional moisture. It was found that the drying rate could be increased by use of ventilated or vented air spaces behind claddings (rainscreen walls). However it was also found that there is a maximum amount of moisture that can be dried through walls to avoid damage. In most cases in British Columbia, North Carolina, and Minnesota that the amount of water that penetrated the walls could not be removed by vapour diffusion drying or even air convection alone. It therefore cannot be stressed enough, that wetting must be controlled by use of good detailing at penetrations, cladding drainage, and in some cases venting or ventilation (rainscreen claddings).

The failures in coastal British Columbia lead to the mandated use of rainscreen walls constructed of light claddings over wood strapping and improved rainwater shedding details and flashings. Thus the widespread execution of recommendations which had been suggested by numerous researchers and practitioners over the past 50 years including Johansson (1946), Hutcheon (1953), Ritchie (1960), Garden (1963), Marshall (1983), Morrison Hershfield (1992) and several others.

Later, this thesis reports on the performance of five buildings constructed with rainscreen clad walls constructed after 2000, as an indicator of how wall improvements made in the mid to late 1990's are performing.

3.8 POPULATION GROWTH AND HOUSING STARTS

The impact of population growth largely from immigration and the number of housing starts in Canada, and specifically Vancouver is discussed.

3.8.1 Population Growth

Population growth and immigration in Canada is further analyzed as it applies to the building industry. Canadians (aside from the indigenous population) originally emigrated here from other countries around the world, and have continued to do so since Canada was founded. We have been continually building to provide housing to new Canadians. There isn't a large surplus of vacant dwellings on hand, and the first thing people need when they arrive in Canada is shelter.

This is shown for reference to support the other underlying development of the wood frame wall, and give an idea of the amount of construction which was occurring at the time, applying the principals and materials discussed in the previous sections. Housing starts or completions are another indicator, however only readily available from the 1940's, and presented in some detail later. Peaks and lows in immigration tend to coincide with building boom and bust periods, providing a reasonable indicator of the construction economy and how many units were built during those periods.

For example, periods during the First World War, Economic Depression of the 1930's, Second World War, and boom and bust economic periods of the 1970's through 1990's are indicated by the immigration to this country. The total immigration to Canada is shown in Figure 3-47 from 1861 to 1998, and Canada's total population from 1861 to 2001 is shown in Figure 3-48.

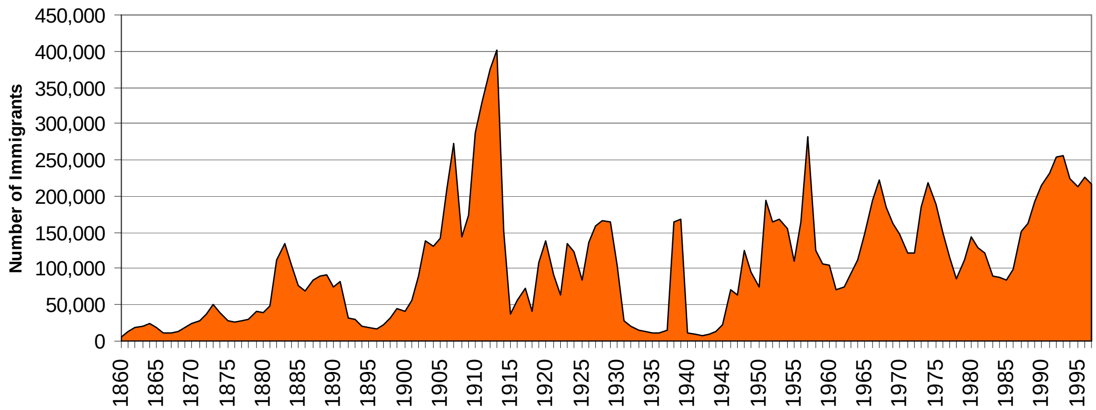

Figure 3-47: Immigration to Canada 1860-2000 (Source Statistics Canada 2005)

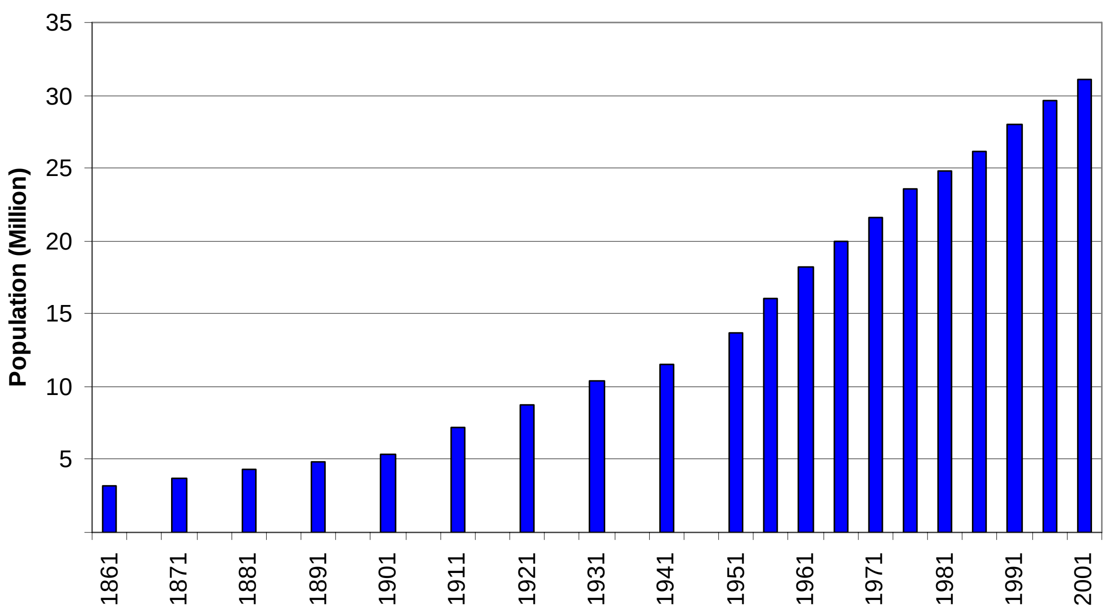

Figure 3-48: Canada's Population 1861 to 2001 (Source Statistics Canada 2005)

3.8.2 Canadian Housing Starts

It has been found that the majority of "leaky condos" in British Columbia were constructed in the period between 1983 and 1997. Obviously buildings constructed outside of this period were not immune to failure; however the incidence of total wall failure was lower for those buildings. The period from 1983 to 1997 also coincides with two building booms. By 1997, several changes to building practice in Vancouver were made to improve the quality of construction, which for the most part have reduced the instance of moisture related failures.

The total number of housing starts in Canada is compared to Vancouver, BC and Victoria, BC in Figure 3-49.

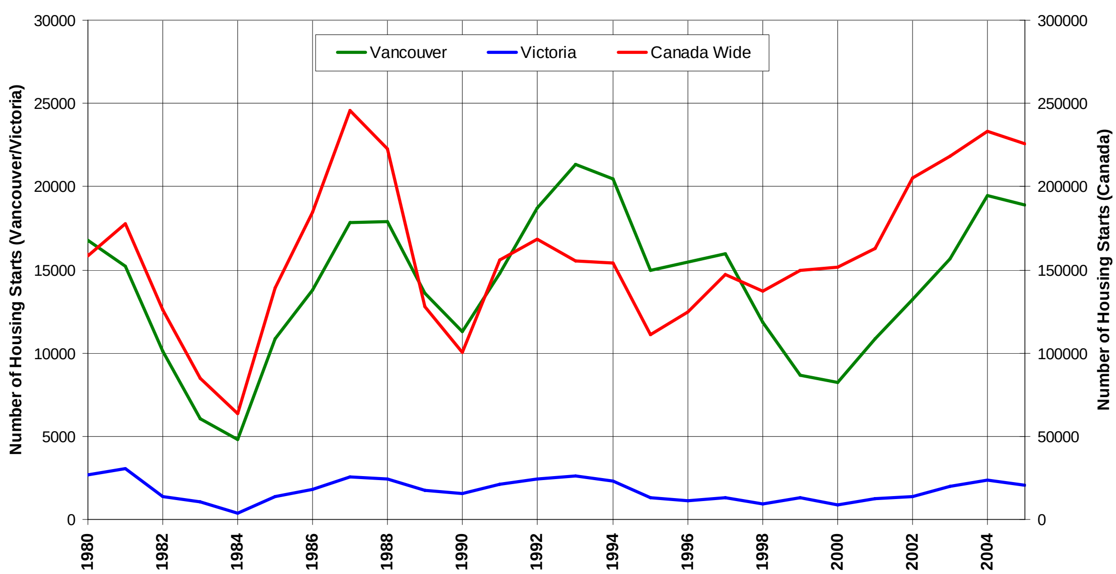

Figure 3-49: Housing Starts in Canada compared to Vancouver and Victoria (Source CMHC 2005)

Vancouver and Victoria like the rest of Canada experienced a construction boom starting in 1984, after the early 1980's economic recession. As immigration and population growth had continued during the recession period, a construction boom occurred in the years following. The number of housing unit starts per year increased almost four fold in Vancouver from a low of approximately 5,000 in 1984 to 18,000 in 1987.

Another smaller economic recession occurred in the late 1980's, slowing construction at that time to approximately 10,000 units per year in Vancouver. However, again by 1992-1994, the number of housing starts rose to high levels previously unseen of approximately 21,000 units per year.

The total housing starts is further broken down by unit type (single detached, semi-detached, apartment (including condominiums), and row houses). The total number of housing starts for Canada is shown in Figure 3-50 and specifically for Vancouver in Figure 3-51. While the majority of housing starts in Canada are single detached single family homes, in Vancouver it is shown that number of apartment and condo units was steadily increasing from about 1983 to 1994, surpassing the number of single detached units at this time. Increasing land prices at this time resulted in denser urban apartments and condos becoming more popular and affordable to new Canadians.

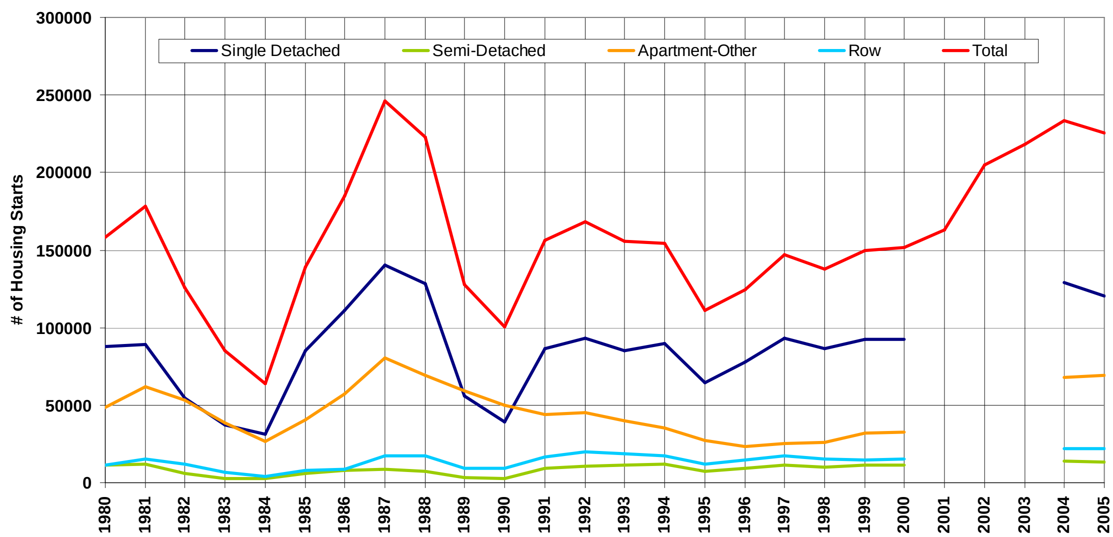

Figure 3-50: Housing Starts in Canada by Type (Source CMHC 2005)

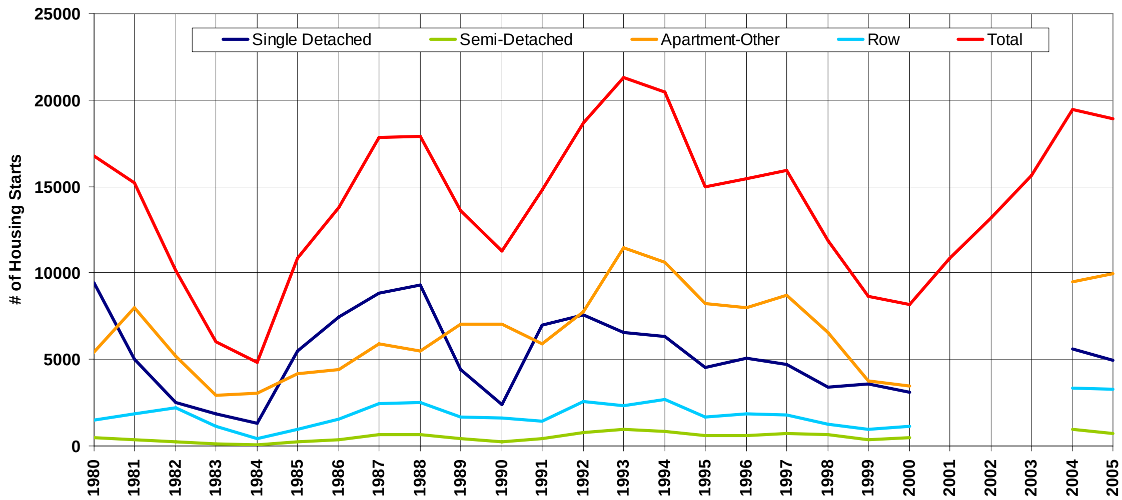

Figure 3-51: Housing Starts in Vancouver by Type (Source CMHC 2005)

As shown, the number of apartment units (including condominium units) increased steadily from 1984, reaching a peak in 1993-1994. At the widespread discovery of the leaky condo issue by 1995-1997, the total number of housing starts dropped off, potentially as home buyers were apprehensive of buying into problematic condominium buildings. This trend was not seen in the rest of the country as the total number of Canadian housing starts steady increased. The construction industry in Vancouver rebounded by 2000, and the number of housing starts has increased since, marking another construction boom until the present.

A few final statistics to look at are presented by CMHC in 1997. The number of housing starts compared to the average house size, selling price, construction time and carpenters wage are shown in Figure 3-52.

Canadian wood-frame house construction statistics.*

Year	1943	1956	1965	1975	1985	1995
Housing Starts	59,900	115,420	155,128	180,952	180,000	110,993
Average Size	800 ft^2	1,080 ft^2	1,200 ft^2	1,080 ft^2	1,230 ft^2	1225 ft^2**
Average Selling Price	$5,500	$13,000	$17,400	$35,500	$80,500	$103,000
Hourly Wage Carpenter	$1.05	$2.30	$3.46	$8.30	$18.37	$26.20
Minimum Construction Time	30 weeks	20 weeks	10 weeks	9 weeks	8 weeks	8 weeks

* These statistics have been gathered from a number of sources. They are indicative of era statistics and should not be treated as definitive.
** Based on 1990 data

Figure 3-52: Canadian Wood-Frame House Construction Statistics (CMHC 1997)

The most interesting point shown is the minimum construction time to complete a house from 1943 to 1995 a reduction of 22 weeks, this reduction a result from changes in construction practice, largely the shift from single home builders to large scale builders utilizing large crews who construct dozens to hundreds of homes at one time. While the time to construct a home has been significantly reduced, it leaves us the question, how has the quality of construction fared, and what influence might this have?

3.9 HYGROTHERMAL SIMULATION

In an effort to quantitatively determine how changes in building practice impacted the performance of the exterior wall, a few models are presented to show the impact of changing materials. The drying potential, by vapour diffusion is compared, as well as the moisture performance of several walls modeled using WUFI 4.1.

3.9.1 Maximum Drying Potential

The first model looks at the maximum drying potential differences for a saturated sheathing material located within a wall. A simple model was produced which uses hourly CWEC weather data to determine the hourly vapour pressure through the wall. From the vapour pressure differences, the net drives (wetting and drying) are determined. The maximum drying potential is used for comparison, and is calculated based on a sheathing material that is at saturation for the entire year. In practice the drying potential would be reduced as this material dries however say down to 80% RH however is used as a relative indicator of the wall performance. It is however representative of how much moisture could be dried if the wall was constantly wetted by leak or otherwise. See *Appendix C: Maximum Drying Potential Model* for further information about the model which was developed.

The sheathing saturation vapour pressure is calculated from the temperature of the sheathing which is based on the thermal resistances of the materials within the wall. The net vapour pressure difference and drying potential is therefore the sum of the hourly values for a specified time interval as presented.

Typical wood frame walls for each decade are discussed are presented further in the Appendix which and based on materials commonly used at the time as previously discussed in the past chapter.

For all cases in the simulation, exterior vapour pressure was calculated from Vancouver CWEC data and the interior assumed varied cyclically with season from 20°C and 40% RH on January 1st to 22 and 60% on August 1st year round for simplicity. As the exterior and interior vapour pressure is similar for each of the cases, the only variables between cases are the thermal resistance of the wall components and vapour permeances of the materials used.

Air leakage is not accounted for, however as older walls were typically more air leaky, and new walls more air tight, the newer walls (1980s and 1990s) would be relatively accurate, while the older walls would actually have an increased drying potential. Air leakage while causing wetting, also contributes to drying, especially in the warm months.

Results for Vancouver are presented seasonally in Figure 3-53 and annually in Figure 3-54.

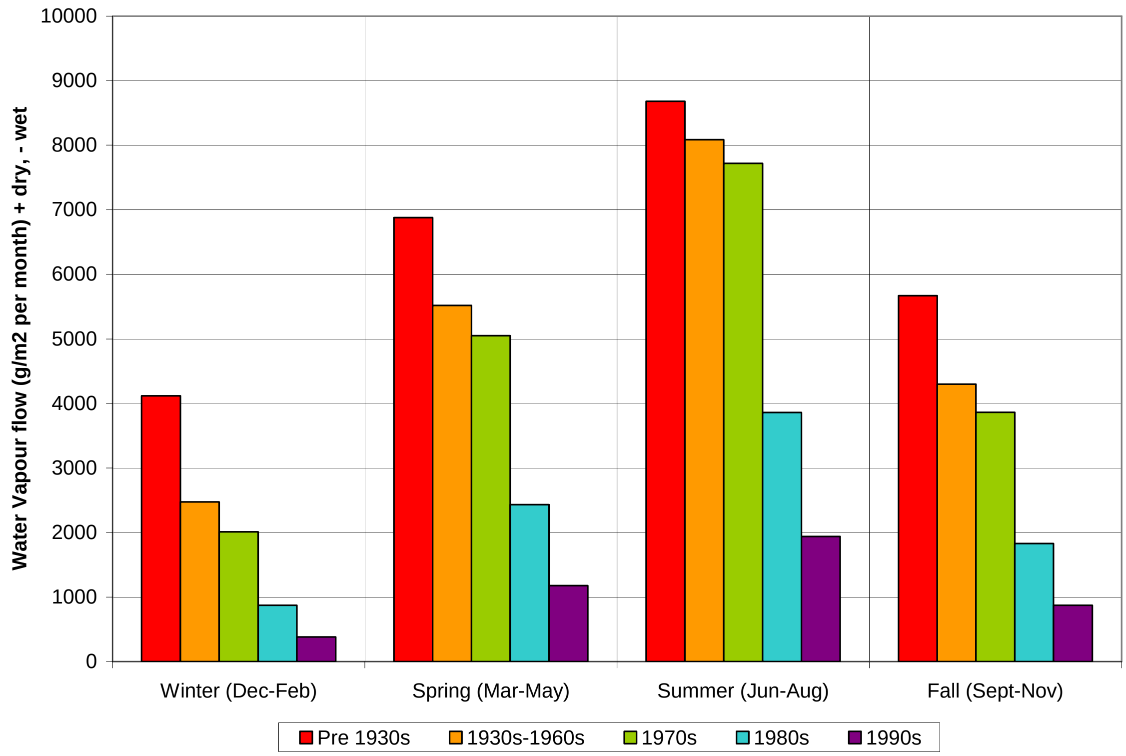

Figure 3-53: Vancouver Historical Walls, Maximum Seasonal Drying Potential.

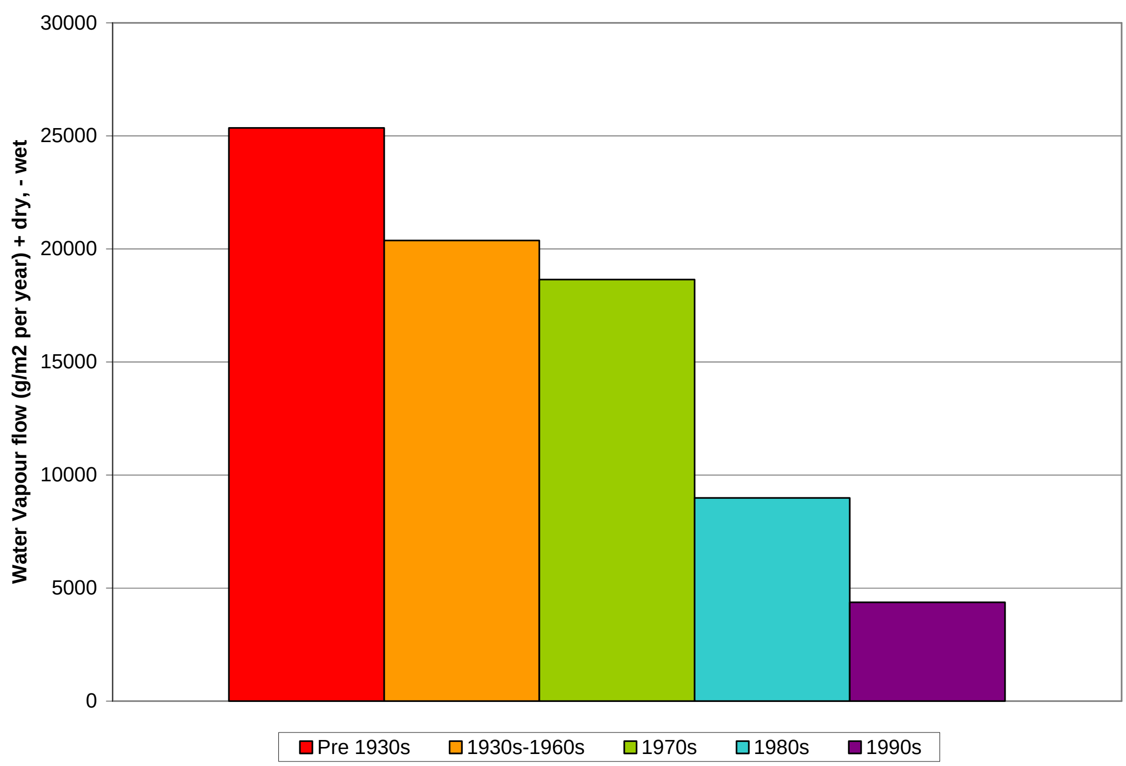

Figure 3-54: Vancouver Historical Walls, Maximum Annual Drying Potential

The difference between the maximum drying potential of the walls constructed in the 1990's and 1980's compared to older pre-1970's walls (less permeable materials and less insulation) is shown to be very significant. A difference of more than 5 times the drying potential between an uninsulated pre-1930's wall and the 1990's.

While vapour barriers were added in the 1940's (1930's to 1960's wall), they had only a small impact on the maximum drying potential, as much moisture in this climate could dry to the exterior. The most significant impact however is the addition of insulation in the stud space, which reduces the temperature at the sheathing, and later use of lower permeance materials both on interior and of the sheathing (OSB versus board sheathing).

It should be noted that as the maximum drying potential (ie. 100% RH at sheathing) is shown, if the sheathing were at 50% RH during the winter, the net vapour flow particularly during the winter months would be negative or wetting as expected as vapour pressure differences typically result in drives to the exterior during the winter.

The effect of the insulation ratio (inside the stud space to out) is shown. A highly insulated wall entirely on the exterior would have an insulation ratio of 1:10 to 1:5, where as a typical R-20 batt insulated wall would have an insulation ratio between 10:1 and 20:1 depending on other materials in the wall.

The seasonal maximum drying potential for a wall in the climate of Vancouver is shown in Figure 3-55. Further discussion and comparisons to other climates are shown in Appendix C.

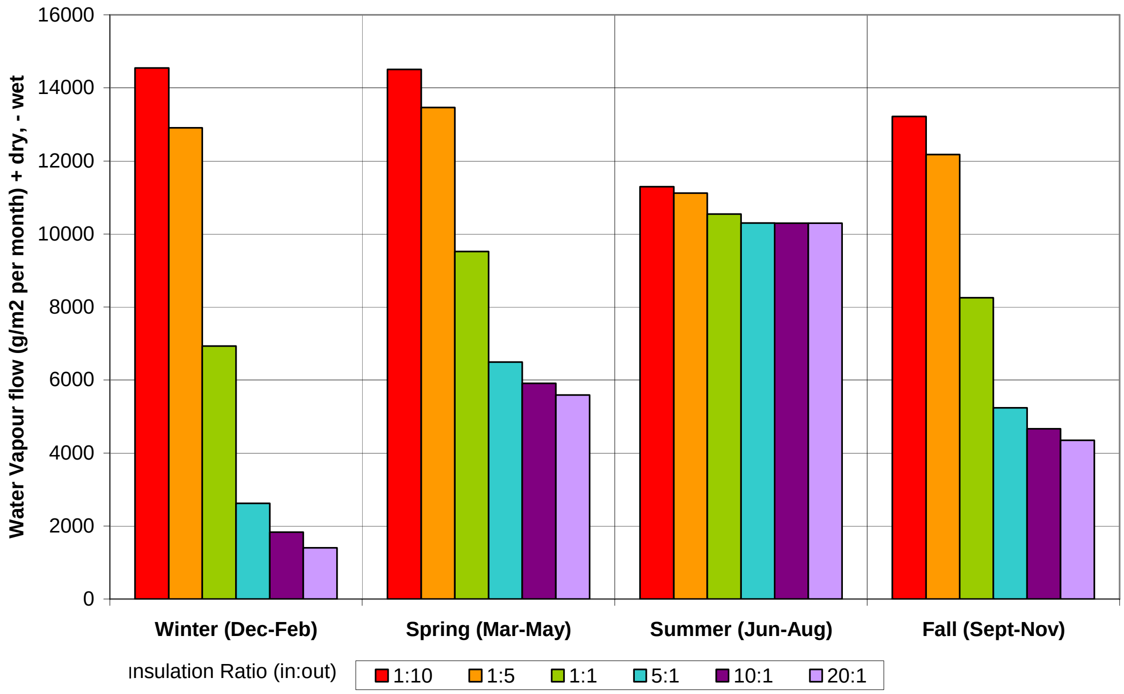

Figure 3-55: Vancouver Maximum Drying Potential based on Insulation Ratio

While all walls have similar drying potentials in the summer (sheathing is at higher temperatures), the difference in winter-time drying is very different depending on the insulation ratio. By exterior insulating (1:10 and 1:5 ratios) the sheathing is kept at interior conditions for much of the year resulting in a constant drying potential. Drying is required during the wet winter months, particularly in Vancouver, and is best achieved using exterior insulated walls. Balancing the maximum drying with potential wetting will determine

3.9.2 <u>Hygrothermal Simulation</u>

WUFI 4.1 was used to compare the changes made to stucco clad wood frame walls from the pre 1930's to the 1990's. For field validation and further information on the WUFI 4.1 hygrothermal model refer to *Appendix B: Hygrothermal Modeling*. Incremental changes in materials as discussed in this chapter are modeled to show the impact of common wall designs over the past century. The materials used in the modeled walls are summarized in Table 3-1.

Table 3-1: Hygrothermal Model Cases – Impact of Construction Practices

Period	Significant Change	Construction
Pre 1930's	-	Lime Stucco, slightly vented 8 mm gap (8 mm horizontal furring), 30 min building paper, 20 mm board sheathing, 100 mm air space (uninsulated stud cavity), 19 mm gypsum plaster, paint
1930's	Insulation (R-6 mineral wool)	Lime Stucco, slightly vented 8 mm gap (8 mm horizontal furring), 30 min building paper, 20 mm board sheathing, 50 mm air space, 50 mm mineral wool insulation (R-6), 19 mm gypsum plaster, paint
1940's	Kraft Paper (vapour retarder)	Lime Stucco, slightly vented 8 mm gap (8 mm horizontal furring), 30 min building paper, 20 mm board sheathing, 50 mm air space, 50 mm mineral wool insulation (R-6), asphalt coated kraft paper vapour retarder, 19 mm gypsum plaster, paint
1950's	Plywood Sheathing	Lime Stucco, slightly vented 8 mm gap (8 mm horizontal furring), 30 min building paper, 12 mm plywood sheathing, 50 mm air space, 50 mm mineral wool insulation (R-6), asphalt coated kraft paper vapour retarder, 19 mm gypsum plaster, paint
1960's	R-12 friction fit batt insulation	Lime Stucco, slightly vented 8 mm gap (8 mm horizontal furring), 30 min building paper, 12 mm plywood sheathing, 89 mm friction fit mineral wool insulation (R-12), asphalt coated kraft paper vapour retarder, 13 mm gypsum drywall, paint
1970's	Polyethylene vapour retarder	Lime Stucco, minimal vented 1 mm gap, 30 min building paper, 12 mm plywood sheathing, 89 mm mineral wool insulation (R-12), 4 mil polyethylene vapour retarder, 13 mm gypsum drywall, paint
1980's	Direct applied stucco	Lime - Cement Stucco, 30 min building paper, 12 mm plywood sheathing, 89 mm mineral wool insulation (R-12), 4 mil polyethylene vapour retarder, 13 mm gypsum drywall, paint
1990's	Painted Stucco, R20 insulation, OSB	Lime - Cement Stucco (acrylic painted), 30 min building paper, 12 mm OSB sheathing, 140 mm mineral wool insulation (R-20), 6 mil polyethylene vapour retarder, 13 mm gypsum drywall, paint

Parametric simulations were performed on the impact of the 8 mm slightly ventilated air space behind the stucco cladding perhaps evident in older construction; however it was found that it had only minor impact on the results when lime stucco was used. Less favourable impact was observed when cement stucco was used (less vapour permeable), and thus the ventilation was significant in removing moisture from behind the cladding. Hence the properties of the stucco are important in this type of analysis. Documentation of the type of stucco used, and cement to lime ratios is not well recorded, nor is similar in each locality. It is however known that the use of Portland cement stucco has become more popular in the last 20 years with lime less frequently used.

The most significant changes were observed during the 1980's and 1990's, and are strongly impacted by the stucco properties (permeability) and less by the changes in insulation and vapour control layers. Figure 3-56 compares the results from the hygrothermal analysis for the eight cases documenting small changes in construction.

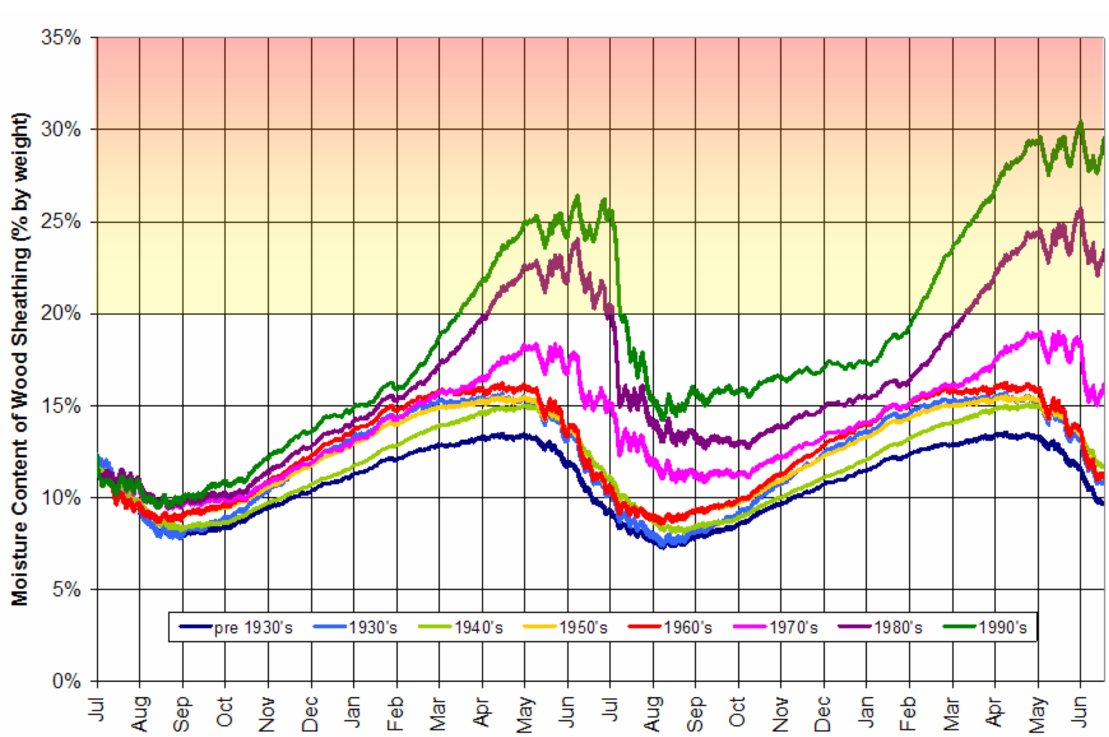

Figure 3-56: Impact of Construction on Stucco Clad Wood-frame Walls.

As shown the driest wall was the uninsulated, pre-1930's wall, and the wettest walls from the 1980's and 1990's. The impact of cement versus lime stucco is compared in Figure 3-57 and Figure 3-58 for a pre-1930's uninsulated wall to a

1990's wall, highlighting the increased sensitivity of the 1990's wall to the material changes made post-1930.

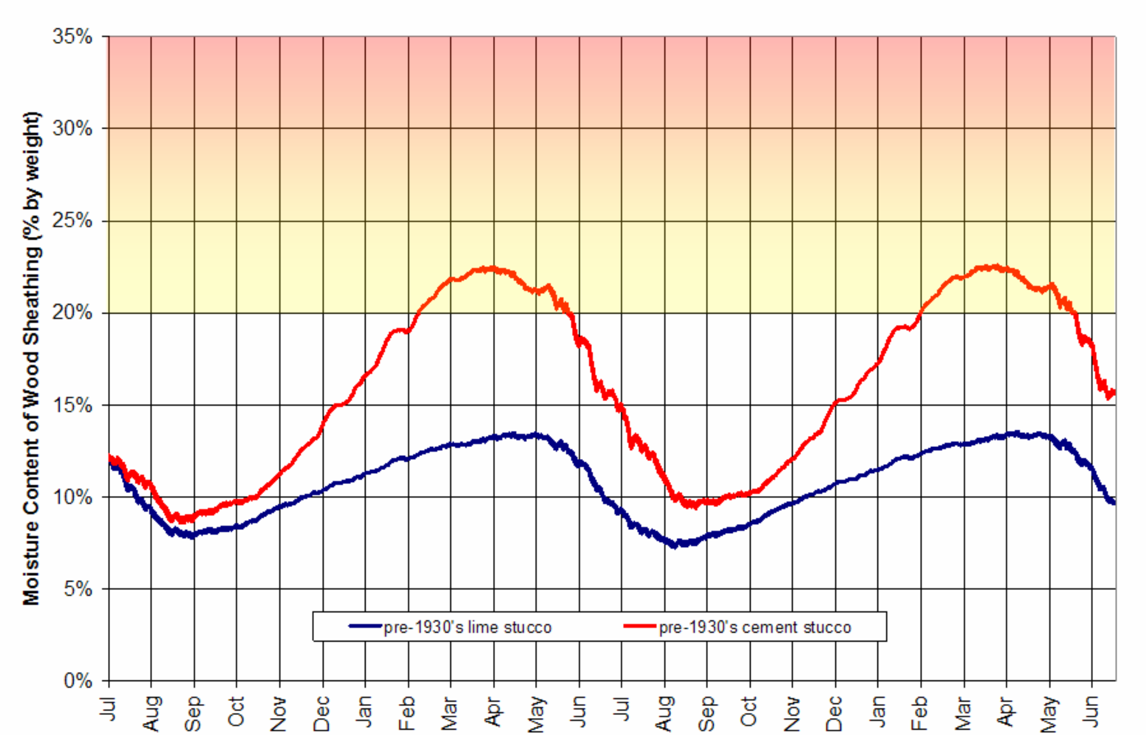

Figure 3-57: Impact of Cement and Lime Stucco on 1930's Wall

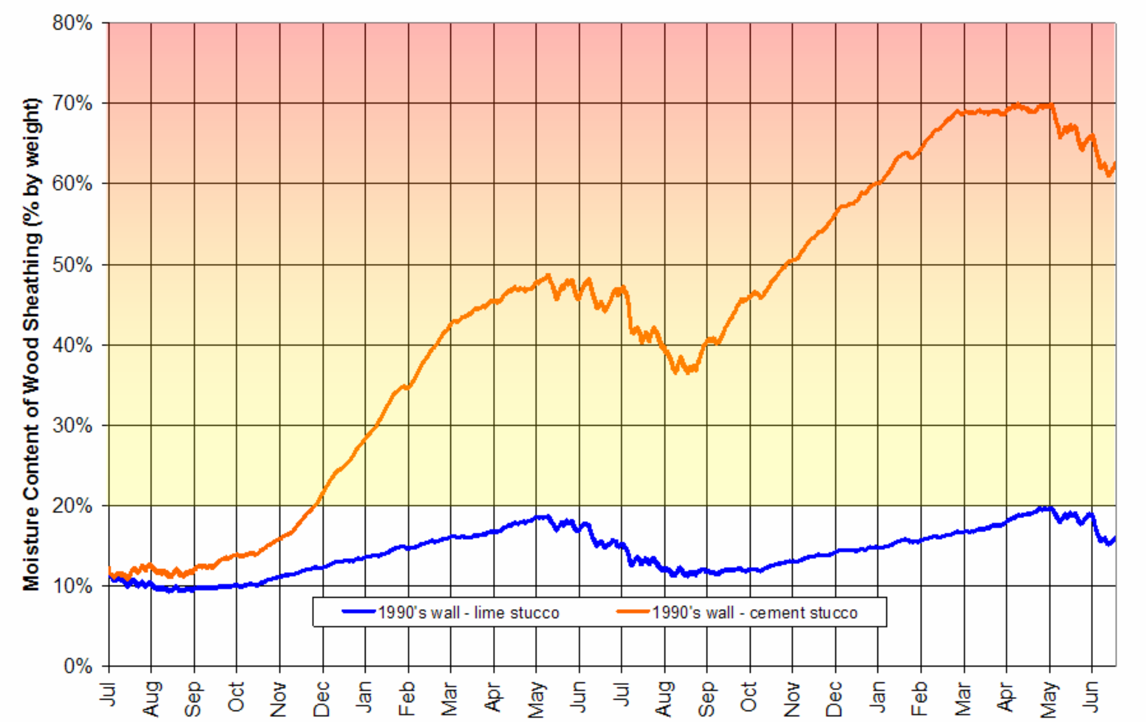

Figure 3-58: Impact of Cement and Lime Stucco on 1990's Wall

3.10 PRESENT TECHNOLOGY AND PERFORMANCE

Current design thought, including climatic recommendations for design are discussed as well as a discussion of the performance of current rainscreen wall systems in Vancouver, BC.

3.10.1 Design and Climate

Some good recommendations made in the 1930's through 1950's to deal with condensation and reduce moisture accumulation in walls, aside from vapour barriers were to ventilate the cladding (to reduce paint peeling), or allow the vapour to flow right through the wall (by use of vapour open sheathing papers (Rogers 1938a). The simplicity of these recommendations were for the most part overlooked, and the simple solution, and the only solution in some peoples minds at time being the vapour barrier, and for some climates they were correct. As a result vapour barriers were instituted and for all climatic zones were required to have the same material properties.

When the importance of air flow control was realized in the 1960's and 1970's, the materials originally intended to control vapour diffusion were modified and largely sealed to control air flow. When air leakage control was realized as the dominant moisture transport mechanism, an order of magnitude higher than vapour diffusion, regulations governing vapour barriers were not modified. The prescriptive vapour control regulations made in the 1940's based on cold climate conditions have remained largely unchanged for vapour barrier materials, attic and crawlspace ventilation, however much research has shown the regulations are unnecessary and often detrimental in some climates (Lstiburek 2004).

The use of alternate vapour control layers, apart from impermeable vapour barrier materials such as polyethylene are again being re-considered. Paint as a vapour control layer has been suggested in the past (Lstiburek and Carmody 1990, Cutter 1989) and revisited again in field studies (Finch and Straube 2007, Wilkinson et al 2007) as an alternate to the standard polyethylene vapour barrier. However, the key to successful building is not removal of a singular material, it is an understanding of the building as a system, designed and built to a specific climate. Removal of polyethylene, against much tradition only allows the designer the ability to tailor the wall to certain climates. The use of other materials to control vapour is still required, as are alternate materials to control air flow. The vapour resistance of polyethylene may actually be required in some very cold climates or buildings with high humidity. The problem is that codes and tradition has largely limited the designer's choice of materials.

Joe Lstiburek perhaps summarizes the philosophy best in the following quote:

> "Houses should be designed to suit their environments. In the home-building industry, we have accepted that design and construction must be responsive to varying seismic risks, wind loads and snow loads. We also consider soil conditions, frost depth, orientation and solar radiation. Yet we typically ignore the variances in temperature, rainfall, exterior and interior humidity and their interaction." (Lstiburek 2006 pg. 3)

Climate zones are now better defined, and provide useful guidelines for engineers and builders to build better performing buildings. Lstiburek has categorized eight climatic zones in North America (Figure 3-59), with different design recommendations based on climate. These climate zones are align with the International Energy Conservation Code (IECC) Climate Zones as developed by the US Department of Energy, which uses an eight numbered system to categorize the climatic zones.

Figure 3-59: North American Climate Zones (Lstiburek 2004)

In addition to the eight climatic zones, a map of annual rainfall in four zones is provided in Figure 3-60. Here four zones are shaded with recommendations for cladding type being either rainscreen, (vented, or ventilated), drained, or face-sealed wall assemblies based on rain exposure.

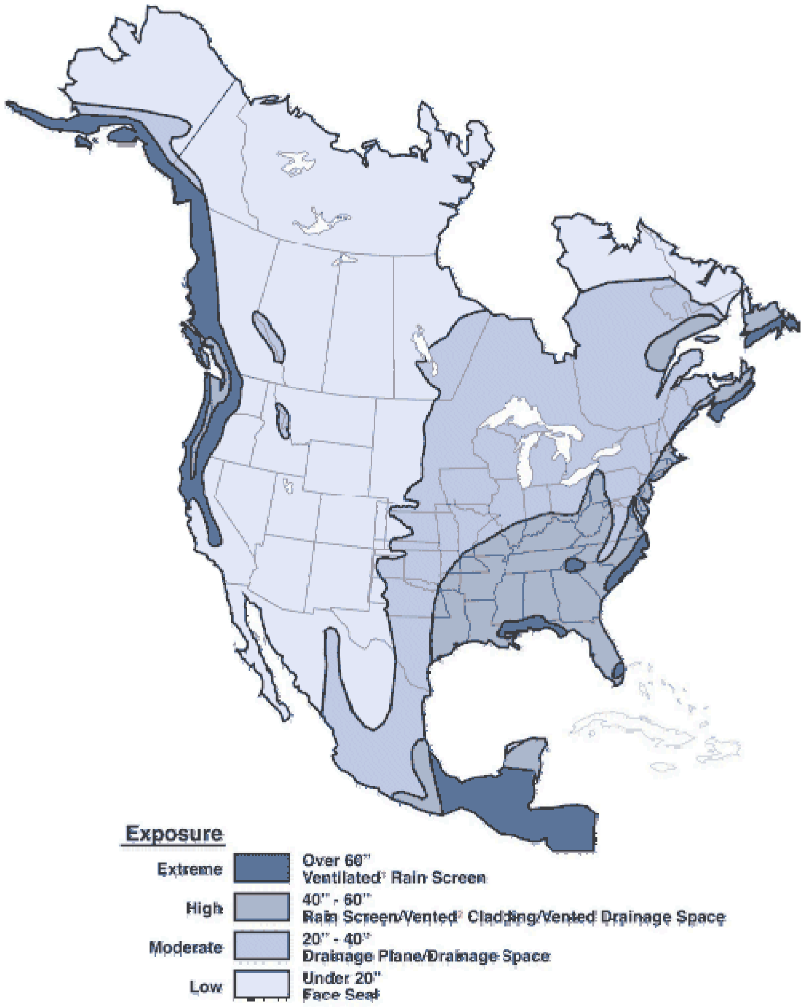

Figure 3-60: North America Rainfall Map (Lstiburek 2004)

In conjunction to those climatic zones by the IECC and Lstiburek, the National Research of Council of Canada (NRC) has developed five zones based on different criteria. The NRC zones are based on the calculated Moisture Index (MI) which is determined from a Wetting Index (WI) and Drying Index (DI). Using climatic data, the Wetting Index is determined from annual rainfall and annual wind-driven rain. The Drying Index is calculated based on climatic conditions and the potential for evaporation and drying once a wall gets wet. The NRC zones are shown in Figure 3-61, and are not directly comparable to those from Lstiburek in Figure 3-59 or Figure 3-60.

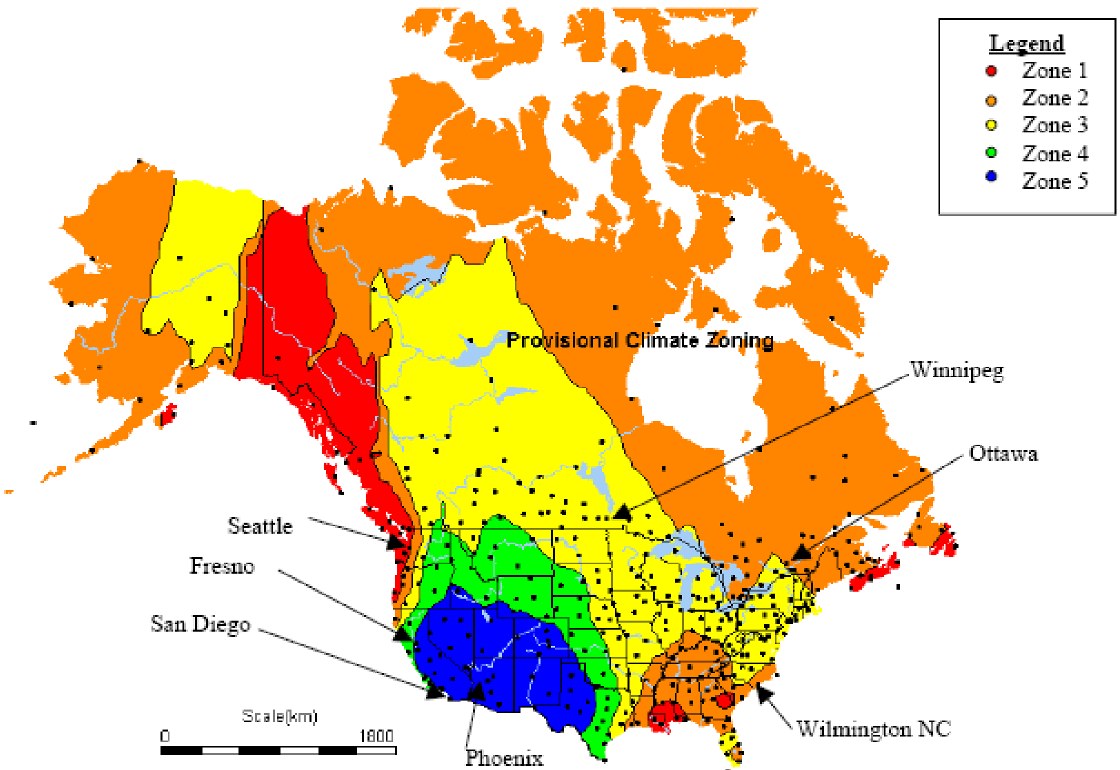

Figure 3-61: North American Climate Map based on Moisture Index (NRC 2002)

While all climatic zones are based on historical data from weather stations (typically at airports) it is up to the designer to apply the appropriate recommendations for the local climate or even building microclimate. Climatic conditions will also vary within cities (discussed later in this thesis for Vancouver), where annual rainfall amounts or wind-speeds can literally double only kilometres from the airport.

A sheltered building in the downtown core would obviously see different conditions than that of an urban farmhouse on the top of an exposed wind-swept hill. For assistance, the National Building Code of Canada (2005) provides factors for wind speed and pressures that can be applied, but also good engineering judgement must be used with design.

3.10.2 <u>Rainscreen Wall Performance in Vancouver – Current Knowledge</u>

As previously introduced, this thesis analyzes the hygrothermal data from five rainscreen clad buildings, constructed or rehabilitated in Vancouver, BC between 2000 and 2003. The monitoring study was implemented by RDH Building

Engineering (RDH), CMHC, Homeowner Protection Office (HPO), and British Columbia Housing Management Commission (BCHMC) to understand the field performance of rainscreen clad walls in this climate. A summary of the data has been presented by RDH (2007) which generally shows the performance of rainscreen walls under normal conditions to be satisfactory, with the exception of moisture problems observed in Building 3. However, in this building the moisture problems were a result of the sensitivity of the wall assembly to humid interior conditions, and insufficient suite ventilation (Finch et al. 2006) and discussed further in this thesis. The RDH summary of results will be covered in further detail throughout the thesis.

From field observations and reports of isolated moisture problems required further repair in some rainscreen clad buildings, it appears that rain water leaks still have a significant impact on the performance of ventilated rainscreen walls. As shown earlier, if the wetting is too high, ventilation and diffusion drying may be insufficient to maintain acceptable performance even with rainscreen claddings, hence the details like with the previous failures are still important.

In the monitoring study, only five to eight locations were installed with sensors on each building, therefore the likelihood of observing the impact of a rainwater leak was small. However at one location, discussed later in this thesis, a small rainwater leak at an exhaust vent hood resulted in elevated moisture levels in the plywood sheathing until it was repaired. As a result of the limited and uncontrolled data (how big was the leak), the impact of leaks in rainscreen walls cannot fully be concluded from this study, and must draw on other studies.

Reports of rainscreen clad walls experiencing rain water leaks and moisture damage have been reported by Detec Systems, who specialize in the permanent moisture modeling of buildings. Using moisture pins placed at critical locations throughout the exterior walls, moisture intrusion can be located and repairs potentially be made before deterioration occurs. The continuous monitoring system also provides a unique monitoring opportunity to observe seasonal wetting and drying trends of entire rainscreen clad walls in coastal British Columbia.

Figure 3-62 presents results from January to March 2005 of the east elevation for a four-storey wood-frame condominium in Victoria, BC constructed in 2005 with ventilated rainscreen wood siding. Details were constructed by a reputable contractor, and a local Building Envelope Consultant oversaw the work.

The data indicates that some of the windows details are allowing water penetration resulting in wetting of the exterior sheathing to cautionary (19-28% MC) and dangerous moisture levels (>28%) during the wet winter months. Wind-driven rain has a significant impact, as the increased moisture contents correlate with rainfall events. All locations show that drying of the wood sheathing occurs during the spring; however some locations stay within the cautionary zone until early summer (Detec 2006).

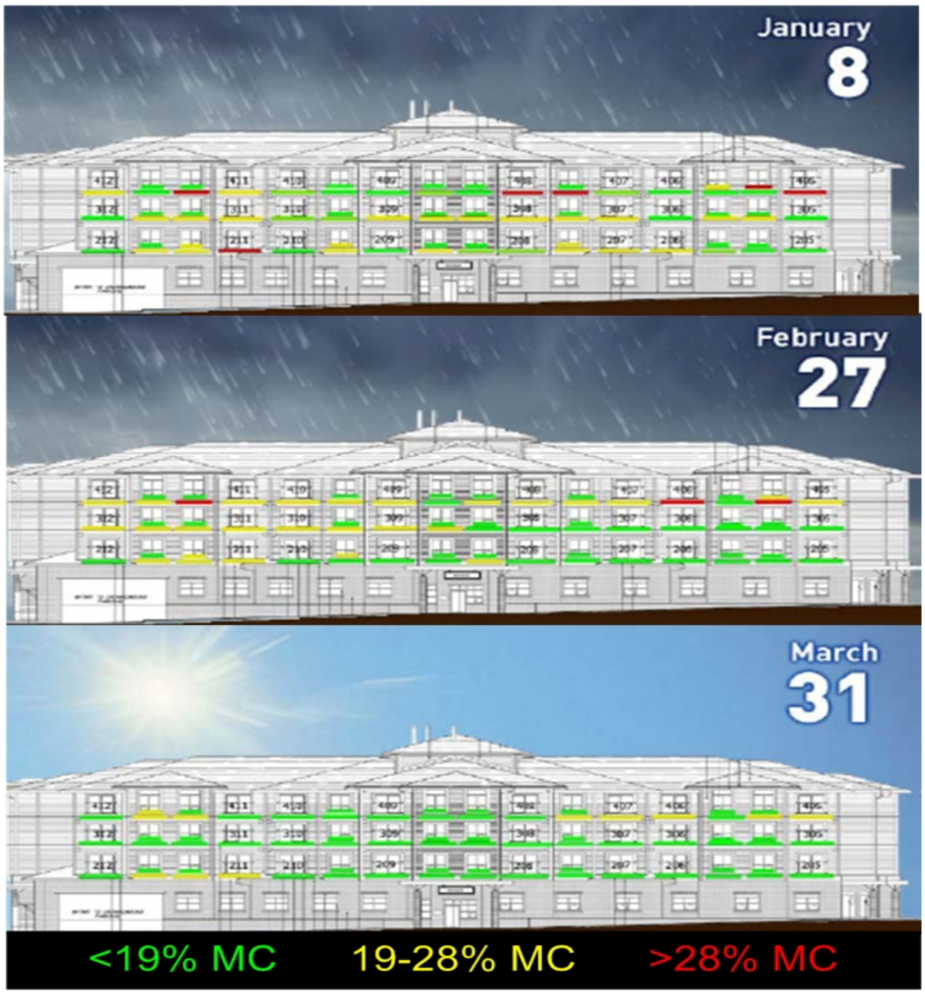

Figure 3-62: Rainscreen Clad Wall – Sheathing Moisture Contents, February and March 2005 (Detec 2006)

Several other case-studies are presented by Detec Systems which highlight typical construction deficiencies (missing or incorrectly placed flashings) resulting in leaks and the potential for moisture damage.

A case stud is presented for a three-storey townhouse which was rehabilitated in 1997 and 2000 by unnamed consultants, however continued to see moisture problems after repairs were made. RDH Building Engineering was called in to perform an assessment in 2003 and observations here are made from that report highlighting the importance of interface detailing.

During the second building rehabilitation in 2000, the windows were replaced, however flashing details were found to be poor at shedding water from the walls. Peel-and-stick membrane was used around the window opening, correctly lapped over the building paper, however water was still able to penetrated the walls at some of the window openings. In addition the vinyl siding J-trim was found to be depositing large quantities of water into the cavity onto the building paper. The walls while not rainscreen, however consisted of vinyl cladding (drained, with some ventilation through perforated and loose jointed siding, however no vertical strapping was used). Typical damage as observed during test openings is shown in Figure 3-63.

Figure 3-63: OSB Sheathing Damage below a Rehabilitated Window with Poor Water Shedding Details (RDH Building Engineering)

Again, and it cannot be overstated, the use of appropriate water shedding details for the climate and exposure are required.

The existing research and monitoring indicates that ventilated or even vented rainscreen walls are performing better than the face-sealed and concealed barrier counterparts commonly used in the 1980's and 1990's. However in the coastal climate of British Columbia and many other locations, rainwater leaks still have the potential to raise sheathing and stud moisture contents above 19% and even 30% in cases for prolonged periods leading to a high risk for damage. Depending on the severity and frequency, isolated moisture damage may occur over time.

Drainage is one benefit of the rainscreen clad design, however can only occur only if the water ends up on the exterior side (cold side) of the sheathing membrane, leaks that penetrate past the sheathing and sheathing membrane (warm side) can enter the stud cavity and then only be removed by vapour diffusion drying. Air leakage through walls may have been a benefit to the moisture performance of exterior walls in the past, however with energy conservative and air-tight homes of today, can no longer be relied upon as a drying mechanism.

Vapour diffusion drying as shown by testing (Morrison Hershfield 1999, Forintek 2001) can be a relatively slow process, and depending on the size and frequency of the rainwater leak may be insufficient at removing all of the moisture. Cladding ventilation has the potential to improve drying in rainscreen walls (Forintek 2001, Straube 1998, ASHRAE 2004) however may be insufficient if the leak is too large.

For example, the impact of leaks on ventilated claddings can be simulated using WUFI 4.1, and results for a typical stucco clad rainscreen wall with plywood sheathing in Vancouver, BC are summarized in Figure 3-64. The impacts of rainwater leaks and ventilation are fully discussed later in this thesis, and modeling of WUFI in *Appendix B: Hygrothermal Modeling*. However here it is shown that there may be a practical size of leak which can be handled by some walls, and that some material choices and wall assemblies may provide an increased tolerance to accidental wetting.

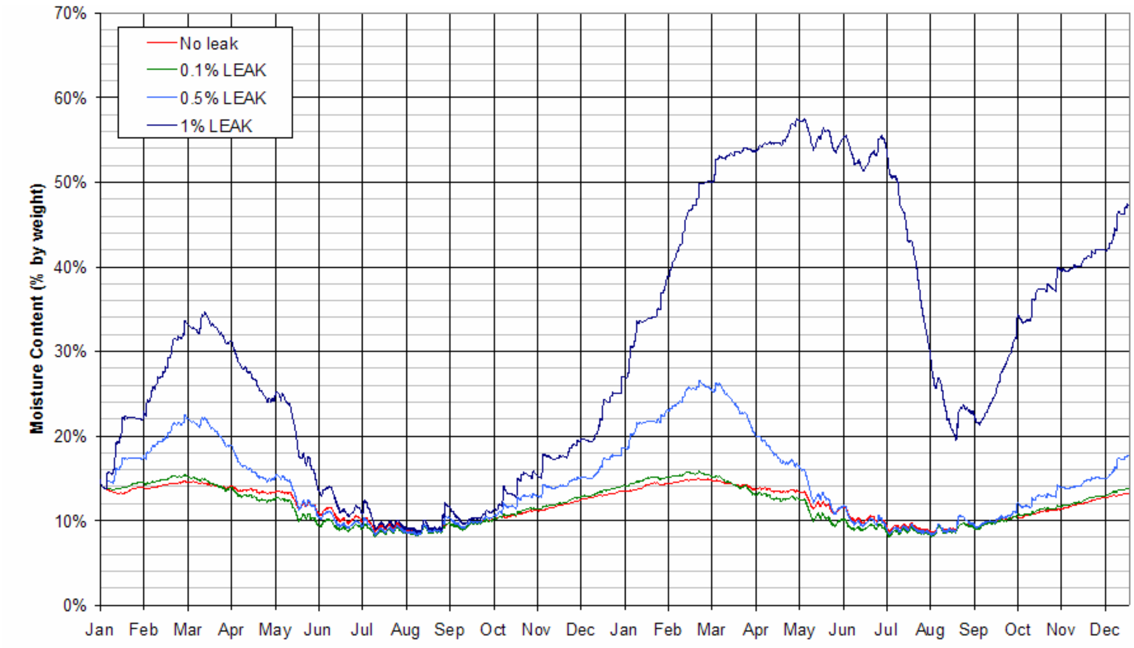

Figure 3-64: Impact of Rainwater Leak on Ventilated Rainscreen Wall

Improvements to improve drying potential in rainscreen clad walls are presented later, as well as recommendations to improve performance. It should also be recommended that details which could allow water penetration be properly inspected or tested during construction. Quality control is very important when building with moisture sensitive materials in wet climates and it seems reasonable to fully inspect ALL of the water shedding details on a building prior to installation of cladding, as one poor detail can continue to cause moisture problems.

3.11 CONCLUSIONS

One of the basic needs of humans is shelter, and soon after we came out of our caves and natural shelters we had found, we started building our own. The built shelters were crude and simple at first, however over thousands of years developed into the simple structural technique known as post and beam construction. We built with the materials we had available to us at the time. In the Middle East where the first civilizations grew, wood was initially used, however when it quickly ran out, stone and eventually brick construction methods were developed. During the Middle-Ages, post and beam half-timbered construction evolved suiting the climate of much of northern Europe.

Post and beam timber framing was brought to North America by European settlers over 400 years ago, however changes were made to designs to accommodate the new harsher climate. Walls previously filled-in with clay or rubble stone no longer provided sufficient protection from the elements, so the builders added wood siding as a screen from the wind and rain. Other details and building techniques were modified to accommodate the new climatic conditions. Eventually the clay and rubble stone infill was removed, and the frame filled in with lighter timbers to support the cladding.

Technological advances which mechanized nail and timber cutting lead to the development of an entirely new more efficient wood frame, known as balloon framing. The advent of balloon framing meant that more people could build their own houses using readily available materials, and quickly. Gold rushes and immigration throughout the 1800's both lead to the widespread use of balloon framing in North America. To deal with wind and rain in these new light-framed buildings sheathing paper was added to the walls for protection. But since we had reduced the wall thickness and thermal mass of our older designs, we began to get cold in this harsh climate again, and found it difficult to heat our homes and maintain wintertime comfort.

Initially more efficient stoves and heating methods were developed to address the effect; however we then approached the cause. We began experimenting with low density materials, filling the open stud spaces with a new invention called insulation. At first we experimented with scrap and waste materials such as wood shavings, rubble stone, or seaweed and in the late 1800's invented mineral wool insulation. As soon as the benefits of insulation were realized, manufacturers developed dozens of new products, all hoping to capitalize on this new market. By the 1930's insulation was commonly used in homes to reduce heating and increase thermal comfort.

We then began to see moisture problems in the walls, and the cladding started to deteriorate from moisture. In the 1940's we introduced vapour barriers, based on research largely in the colder areas of Canada and the United States as a solution to all of the countries moisture problems. Unfortunately these regulations were applied even in the warmer or more temperate areas that weren't experiencing problems. After the Second World War we built a lot of homes for a new wave of immigrants fleeing from war and economically depressed Europe. Manufacturers that developed materials for the war-effort modified the materials to the new building market. Of these, several new insulation products were introduced to the market, advertising significant improvements over the old and dependable ones. Many of these new insulation products were doomed to fail without proper testing and consideration of health the compatibility effects, and did so at some time later.

With all of these seemingly small improvements we were still seeing moisture problems in homes, somewhat worse than before. In the 1960's it was realized that air leakage condensation was causing the majority of our moisture problems, eclipsing that could be caused by vapour diffusion. By the 1970's we had tried to seal up the vapour barrier in hopes that it would resolve the issue. The energy crises of 1973 and 1979 made us realize our dependence on the supply and price of oil. So we developed electrical heat and increased insulation amounts to reduce our oil dependence and to conserve energy.

Still we continued to see more wall failures, this time with health side-effects blamed on damp and mouldy interior environments, particularly in the temperate coastal climate of Atlantic Canada. This time we blamed the problems on the reduced ventilation and air exchange when switching from combustion furnaces with flue to electrical heat. These overcrowded and humid houses exacerbated air leakage and diffusion problems causing deterioration of moisture sensitive materials in the exterior walls. As a result we added minimum mechanical ventilation requirements and continued to further tighten up the air-barrier. In the rest of the country we watched and postulated on whether problems could occur in our homes, so we too applied recommendations to improve air-tightness and mechanically ventilate.

In the 1980's and early 1990's we saw a decade of boom building conditions in Canada and the United States fuelled by immigration from Europe and Asia. We built as fast as we could with the technology we had been fine-tuning for years, however found it difficult to keep up with the demand. Single family dwellings were displaced in our cities by multi-unit residences, and the condominium building became the norm.

But in the mid-1990's thousands buildings began to experience severe and wide-spread moisture issues in coastal BC and other parts of the North America including Minnesota and North Carolina. In Vancouver this became known as the leaky condo crisis, a term coined by the media for the extensive moisture problems experienced primarily in 3-4 storey wood-frame condos. At first we first blamed the new materials, or the rapid construction practices, and then slowly realized some of the impacts of changes we had been making for several decades. While designing to absolutely negate wetting from interior moisture sources, rain turned out to be our worst enemy. Health and safety issues were prevalent, mould became a litigious problem. More than just condos were affected by the issues; the whole building industry was on its heels.

If anything good came out of the failures, some significant changes to construction practice were made across the country. Improved water shedding details and rainscreen wall designs with ventilated cavities were instituted in coastal BC, addressing the largest potential moisture source of all, Rain. But hadn't we figured out rain hundreds of years ago? We had, but the details and materials had evolved, with moisture tolerant materials gradually replaced by cheaper and more moisture sensitive and less forgiving ones. Finally a threshold was reached, and the balance of wetting, drying, and safe storage was tipped towards failure.

Today there is recognition that we need to build with more durable materials, however when we can't, we must protect the moisture sensitive ones from water. The consensus is leaning towards vapour open yet air tight construction, which prevent the trapping of moisture and allow accidental or seasonal moisture to dry-through the walls. Energy efficiency is also as important; if not more than it was in the 1970's. Use of increased insulation levels for energy efficiency but also correctly placed or distributed to protect moisture sensitive materials appears to be the answer. Indoor air quality and humidity should controlled by mechanical or well designed and tested passive means to prevent problems with air-tight building enclosures.

Air-tight building enclosures are not the problem; we however must approach the design of buildings holistically. Consideration for integration of all building components including the mechanical, electrical, structural, and enclosure systems must be made while conserving energy and maintaining safe and comfortable environments for the occupants. The approach is scientific; we now widely use laboratory and field testing and computer modeling to test new materials and walls in specific climates. Tailored wall design to climate and exposure is the future, and as long as designers build-in safety factors to designs we will reduce the instance of failures.

We have realized through our successes and failures through history that no singular design is appropriate for all climates. Buildings should be built to their local environment; national building codes that spread requirements over all climates are being phased out, replaced with guidelines and objective requirements based on local climate. Vitruvius knew this over 2000 years ago, yet for a while our society blindly forgot:

> “Firmness Commodity Delight” “These are properly designed, when due regard is had to the country and climate in which they are erected. For the method of building which is suited to Egypt would be very improper in Spain, and that in use in Pontus would be absurd at Rome: so in other parts of the world a style suitable to one climate, would be very unsuitable to another: for one part of the world is distant from it, and another, between the two is temperate” – Marcus Vitruvius Pollio

The wisdom of Vitruvius is still very applicable today in North America, and why shouldn’t it be. Today we now realize that a wall designed in Ottawa cannot expect the same performance in Miami, Vancouver, or Las Vegas, four very different climatic zones. In one of these climates it may even fail. Through our history of success and failure we have eventually come to realize this.

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4 FIELD MONITORING PROGRAM

An initial report by RDH Building Engineering (2007) summarized much of the primary data and results from the monitoring program. Further to the initial report, this thesis study further investigates several issues which could not be addressed in the initial report, incorporates additional testing, and expands on the results of the study with further recommendations to industry.

The field monitoring program as put together by RDH, Canadian Mortgage and Housing Corporation (CMHC), Homeowner Protection Office (HPO), British Columbia Housing Management Commission (BCHMC) in 2000 is discussed in this chapter. An introduction to the program, the experimental setup and data acquisition system are discussed and a full description of each of the monitored buildings is provided. A quick reference (wall section, monitor locations, overview image) for each building is provided in *Appendix I: Quick Reference*.

4.1 INTRODUCTION

To address the high incidence of rain penetration and deterioration of exterior wall assemblies of buildings in coastal British Columbia; CMHC, HPO, BCHMC, and RDH sponsored a field monitoring program in Vancouver, BC to monitor the performance of five residential buildings being constructed or rehabilitated with rainscreen wall assemblies. The primary goal was to assess whether these wall assemblies were suitable in this climate and if moisture problems observed in the past could be alleviated by using improved water-shedding details combined with strapped and ventilated rainscreen walls versus the traditional face-seal or concealed barrier approach to rainwater management.

The installation and field monitoring work was undertaken by RDH Building Engineering with financial assistance of CMHC, HPO, and BCHMC. The monitored buildings were selected from the local housing stock under construction, and are primarily social and low-income housing multi-family buildings. Buildings were selected based on location and cladding type to provide a sample of several different rainscreen wall constructions within Vancouver.

The field monitoring program began in 2000 and continues to this day. It is one of the largest and longest running field studies of its type and has collected data which provides some assurance new rainscreen wall assemblies are performing satisfactorily. It has also brought up several issues unforeseen at the onset of the program including the relative airtightness and ventilation strategies in multi-unit dwellings and the mechanical properties of moist gypsum sheathing which are discussed in the later chapters of this thesis.

The scope, objectives, and approach of the initial program are discussed including a review of the monitoring equipment and a description of each of the monitored buildings.

4.1.1 Scope of Monitoring Program

The five monitored buildings include three multi-unit wood frame residential projects (two new-construction and one rehabilitation), a concrete frame mid-rise residential rehabilitation project, and a new residential high-rise construction project. All buildings are located in the city of Vancouver within by a 5 km radius.

The original intent of the monitoring program was to simultaneously monitor all buildings for a period of 1 year. Due to construction delays, the commissioning of the monitoring systems was performed over a two year period and the buildings were eventually monitored for at least one year simultaneously (during 2003). The intent was to monitor each building for a total of five years, and longer if deemed necessary. The start and end dates for the five buildings of the monitoring program are shown on Table 4-1.

Table 4-1: Monitoring Dates – Buildings 1-5

Building	Monitoring Dates	Months
1	01 January 2001 to 30 June 2004	42
2	31 May 2001 to 30 June 2004	36
3	17 January 2002 to present (May 2007)	65+
4	26 March 2002 to present (May 2007)	62+
5	01 January 2003 to present (May 2007)	53+

Monitoring of Buildings 3, 4, and 5 continues to the present (May 2007) under supervision of the British Columbia Institute of Technology (BCIT). Reduced monitoring of buildings 1 and 2 has continued past June 30, 2004 with only daily moisture content readings recorded until the present.

The sensors used for the monitoring program, while durable and of high quality were not typically designed for field exposure longer than one year exposed to exterior conditions. Some sensors have in fact failed over the course of the monitoring however the majority remain operational. Attempts were not made during the course of the monitoring program to replace or troubleshoot broken sensors. The condition of the sensors within Building 3 were reviewed in some locations during field openings in January 2006 and found to be in good working order, as discussed in Chapter 9.

4.1.2 Objectives of Monitoring Program

The primary objective of the monitoring program was to provide data that could be used to assess the effectiveness of rainscreen wall assemblies in Vancouver's coastal climate. As a result of the "leaky condo" disaster (Barrett 1998), rainscreen wall assemblies were mandated in Vancouver and other coastal areas of British Columbia by the end of 1996. At the time very little field data on how these wall assemblies perform in the field was available, however as discussed in the last chapter, the idea of a rainscreen wall had been around for quite some time however not put into practice of such a scale. Fortunately the insight was to monitor a selection of these new wall assemblies albeit not until 2000, to provide assurance to builders, practitioners, and the general public to see that these new wall designs were in-fact working.

The focus of the monitoring program and initial summary and analysis by RDH was to obtain the raw data for analysis, and to identify significant anomalies, which fell outside the traditional assumptions for adequate performance. A summary report is presented and discusses some issues covered in further detail in the later chapters of this thesis.

4.1.3 Monitoring Program Approach

The monitoring program was designed to measure temperature, moisture content, relative humidity, local weather conditions including rainfall, driving rainfall, and pressure difference across the exterior walls. A continuous, automatic electronic system recorded measurements from all sensors every 15 minutes and could be downloaded on-site or remotely via modem.

Five to eight locations on each building were monitored, each location contained a minimum of 4 temperature, 4 moisture content, and 2 relative humidity sensors. On the non-combustible buildings (3 & 5), moisture content measurements on the steel studs were not applicable, therefore gold leaf wetness sensors were used to detect the presence of liquid water at these locations. The data acquisition and logging system was powered by a battery, which was charged by a solar panel; allowing the system to collect data during severe storms even if building power is interrupted.

The majority of the monitored locations were chosen to be representative of areas most likely to be wetted during severe weather, while a single location was located in the center of the wall, away from details, to act as a control. The monitored locations were generally chosen on the east and south elevations at key details such as vents, windows, balcony transitions, and saddle flashings where historically, high moisture levels have been observed.

4.2 EXPERIMENTAL SETUP AND DATA ACQUISITION SYSTEM

The sensors, monitoring equipment, and data loggers are discussed. While the majority of sensors output data in immediately usable format, the moisture content pins require calibration depending on the substrate, which is also discussed here.

4.2.1 Sensors, Monitoring Equipment, and Data Loggers

A summary of the sensors used within the five buildings for the monitoring project are summarized in Table 4-2.

Table 4-2: Monitoring Equipment and Sensor Information

Sensor Type	Description
Wood Moisture Content (Buildings 1, 2, & 4)	Two 9 mm (3/8”) brass screws installed 25 mm (1”) apart into the plywood sheathing, strapping, or sill plate
Gypsum Moisture Level (Buildings 3 & 5)	Two 19 mm (¾”) brass nails installed on a 45° angle, 25 mm (1”) apart into gypsum sheathing (exterior grade fiberglass faced gypsum board)
Temperature	Uni-Curve Thermistors (192-103LET-A01) by Fenwal Electronics (Honeywell)
Relative Humidity	Honeywell HIH 3610-002
Interior/Exterior Temperature/Relative Humidity	Hobo 8 Pro – 2 Channel T/RH Exterior data logger
Relative Wetness	Davis Leaf Wetness Sensor 6420
Differential Pressure	Setra Systems Model 265 – Differential Pressure Transducer
Rain Accumulation	**Vertical Rain**: Davis Rain Collector II **Driving Rain**: Davis Tipping Bucket Sensor in Custom Built driving rain collector, 1’ x 1’ opening for driving rain only
Wind Speed/Direction	Buildings 1 & 2: OMEGA WMS-22B, Wind Speed and Direction Module on 3 m (10’) pole on rooftop Buildings 3, 4 & 5: R.M. Young Company Wind Sensor, 05103-10A Wind Monitor on 3 m (10’) pole on rooftop
Data Logging System	Buildings 1 & 2 - Lakewood 8 Channel Chart Pac CP-X loggers Buildings 3, 4, & 5 – Campbell Scientific Inc. CR-10X Logger w AM16/32 Multiplexer and modem

Technical specifications for the equipment used is provided in *Appendix D: Monitoring Equipment and Sensor Information*

The moisture content, temperature, relative humidity, wetness, pressure sensors are installed within the exterior walls, hard-wired to a central weather-sealed control box on the roof. The driving rain, falling rain and wind station sensors are also wired to the control box. Sensors and monitoring equipment were installed by engineers at RDH at each of the five buildings with assistance in sequencing with the respective contractors on-site during construction. Within the weather-sealed control box the wires are connected to the multiplexers and/or dataloggers. Power is supplied to the unit via a 12 V battery within the box, which is continually recharged via an attached solar panel. No issues with power failures were reported at any of the buildings. A typical roof-top control box from Building 2 is shown in Figure 4-1.

Figure 4-1: Roof-top Control Box Housing for Datalogging Equipment

The following is a summary of the data which was collected for the monitoring project.

- Exterior weather data including: wind-speed, wind direction, falling rain, driving rain, temperature, and relative humidity.
- Interior data including: temperature and relative humidity
- Temperature and relative humidity at key interfaces through the wall assemblies (ventilated rainscreen cavity, sheathing, center of insulation, interior drywall)
- Moisture content of the sheathing, sill plate and strapping at details with the possibility for water leaks (windows, balconies, vents) and at the middle of the wall away from the potential influence of details.
- Relative wetness within the stud cavity/ventilated rainscreen cavity of the non-combustible frame buildings

- Differential pressure between the ventilated rainscreen cavity and the interior of the stud wall and/or interior of suite.

4.2.2 Moisture Content Calibration

Wood

The moisture content of wood species can be determined measuring the electrical resistance between two points in a sample, typically 25 mm (1") apart. The relationship between electrical resistance and moisture content of wood is well researched and documented.

Wood moisture content can accurately be measured and corrected for species and temperature using species coefficients and temperature correction. Moisture content for the wood products in this thesis (plywood sheathing, strapping, sill plates) were calculated using methods outlined by Straube et al. (2002).

The uncorrected moisture content (MCu) is determined from the electrical resistance in the relation developed by the US Forest Products Laboratory (1999).

$$\mathrm{Log}_{10}(\mathrm{MCu}) = 2.99 - 2.113\,(\log_{10}(\log_{10}(\mathrm{Rw}))) \qquad \text{(Equation 4-1)}$$

Where, Rw = the electrical resistance of the wood sample (ohms)

At Forintek Canada, following several studies during the 1970s through 1980s Garrahan et al. (1991) developed a correction equation for wood products for species and temperature.

$$\mathrm{MCc} = \frac{\left[\left(\dfrac{(\mathrm{MCu} + 0.567 - 0.0260 \cdot \mathrm{T} + 0.000051 \cdot \mathrm{T}^2)}{(0.881 \cdot (1.0056^{\mathrm{T}}))}\right) - b\right]}{\mathrm{a}} \qquad \text{(Equation 4-2)}$$

Where, MCu = the uncorrected moisture reading from Equation 4-1
MCc = the corrected moisture reading for temp/species
T = the temperature of the sample (°C)
a & *b* = constants for specific species (Table 4-3)

Table 4-3: Wood Species Coefficients a & b for Garrahan Eqn. (Evans et al. 2006)

Species or species group	*a*	*b*	Source
Eastern hemlock	0.904	−0.051	Pfaff, 1974
Sitka spruce	0.853	0.398	Salamon, 1971
Red pine	0.730	0.793	Pfaff, 1974
Eastern white pine	0.821	0.556	Pfaff, 1974
Western white pine	0.969	−0.391	Salamon, 1971
Ponderosa pine	0.849	0.233	Anonymous; Moore moisture meter
Western red cedar	1.019	−0.455	Salamon, 1971
Yellow Red Cedar	0.922	−0.751	Salamon, 1971
Trembling Aspen	0.91	2.75	Bramhall and Salamon, 1978
Western white spruce	0.828	−0.621	Salamon, 1971
Eastern white spruce	0.702	0.818	Pfaff, 1974
Lodgepole pine	0.835	−0.545	Salamon, 1971
Jack pine	0.749	0.467	Pfaff, 1974
Alpine Fir	1.07	−2.95	Bramhall and Salamon, 1978
Balsam Fir	0.900	0.35	Pfaff, 1974
Black spruce	0.820	−0.378	Cech and Pfaff, 1975
Red spruce	0.820	−0.378	Pfaff and Garrahan, 1984
Eastern White Cedar	0.812	0.171	Letter from Pfaff
Douglas-fir (coastal)	0.813	1.888	Letter from Pfaff
Douglas-fir (interior)	0.857	0.726	Letter from Pfaff
Douglas-fir	0.835	1.307	Average of Douglas fir (coast) and Douglas fir (interior)
Western larch	0.843	−0.534	Letter from Pfaff
Douglas Fir–Larch	0.838	0.693	Average of two Douglas firs and Western larch
Amabilis fir	0.882	−0.385	Letter from Pfaff
Western hemlock	0.822	0.202	Letter from Pfaff
Hem–Fir	0.852	−0.092	Average of Amabilis fir and Western Hemlock
Aspen	0.772	0.866	

For the three wood frame buildings, the plywood species used was typically found to be untreated Coastal Douglas-fir therefore *a* and *b* values of 0.813 and 1.888 were used in the calibration. For the studs, sill-plates, and strapping similar *a* and *b* values were used as the species were varied and unknown and the strapping was pressure treated. The range of error is shown in Figure 4-2 for wood species commonly used for construction in British Columbia where Douglas-fir falls in the mid-low range of plotted values, therefore may under-predict the moisture content by up to 2% say if the actual species had say been Western Larch at 15% MC.

Pressure treated wood may produce erroneous moisture content readings as some of the treatment minerals could impact the electrical resistance of the wood. However based on observations from this study, the pressure treated strapping moisture levels closely follows that of the plywood sheathing, exposed to the same exterior boundary conditions, therefore it is a reasonable assumption to say that the treatment used in the three wood frame buildings had negligible impact on the wood electrical resistance.

Treated plywood may have been called for on the drawings of a few of the buildings however did not end up being used in the field for any of the buildings.

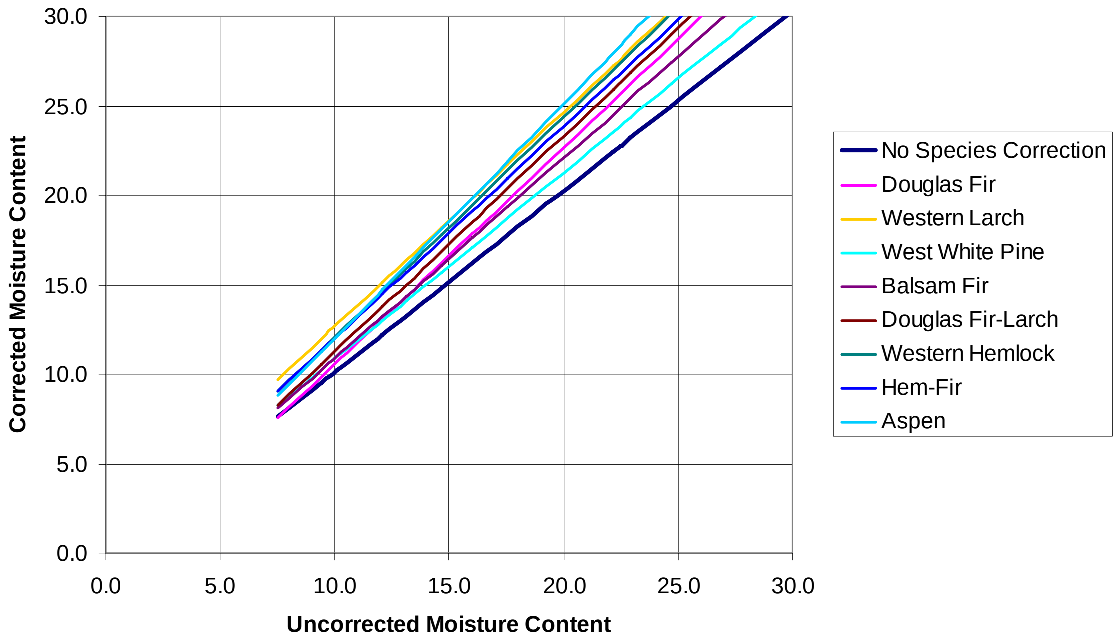


Figure 4-2: Uncorrected Versus Corrected MC for Wood Species

Using the Garrahan equation and species coefficients, the calculated moisture contents for wood are valid between 7-25% moisture content up to fiber saturation with a maximum error of up to ±2% (Straube et al. 2002). Above fiber saturation (approximately 28-30% moisture content) the moisture content relationships follow the same relationship but can become quite variable. Below 7% moisture content the wood resistance is too high to measure using conventional data logging equipment and is not required. In the study the moisture contents generally ranged from 8 to 25%.

Gypsum

While the relationship between wood moisture content and electrical resistance is well defined in past work, little research has been performed on gypsum products using similar methodology.

To overcome this shortcoming, the initial RDH report summarized gypsum moisture levels using a relative moisture level scale (0-100) which were calibrated to a Delmhorst BD-10 moisture meter. The gypsum electrical resistance readings measured by the dataloggers (in ohms) were converted to a relative gypsum moisture level using the following formula (RDH 2007):

$$ML = 56.056 \cdot \ln(MC) - 99.584 \qquad \text{(Equation 4-3)}$$

Where, MC = Calculated wood moisture content (uncorrected for species) as would be read on a Delmhorst moisture meter

The RDH method provided a useful measure, however the actual gravimetric moisture content of the gypsum was unknown. As the mechanical properties of gypsum are very sensitive to moisture content it was desirable to determine the actual moisture content of gypsum in the field. Following reports of significant strength loss in gypsum sheathing at moisture contents as low as 1% by mass (Levelton 2005) and high reported moisture levels (80-100 relative scale) within the walls of Building 3, further research was undertaken in the laboratory at the University of Waterloo in 2005-2006 to convert the resistance readings to an actual moisture content.

The full report is provided in the *Appendix A: Exterior Gypsum Sheathing – Electrical Resistance and Humidified Properties*, however in summary the gravimetric moisture content versus measured electrical resistance relationship was determined for fiberglass faced gypsum sheathing (same product as used in Buildings 3 and 5). Gypsum samples were subjected to varying moisture contents (in humidified chambers) and the electrical resistance between brass moisture pins was recorded. The material properties were also observed and found to deteriorate with increasing moisture content.

A relationship for the gravimetric moisture content versus electrical resistance of gypsum sheathing was determined using several different samples of the same exterior-grade fiberglass faced gypsum product and is shown in Figure 4-3.

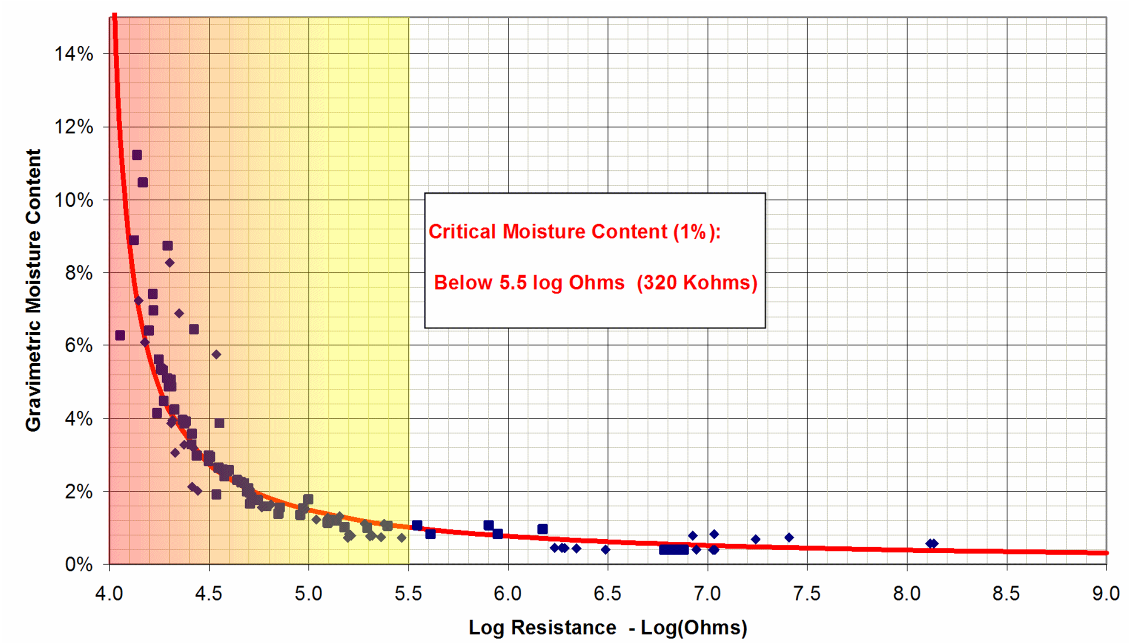


Figure 4-3: Moisture Content versus Resistance Relationship for Gypsum Sheathing

As shown the while the data shows some scatter, a definite relationship exists in the data. Further discussion can be found in Appendix A. The formula of the best-fit curve of the data set takes on the following form:

$$GypsumMC(\%) = 1/((62.0693 * (\log(\text{Resistance}))) - 243.0790) \qquad \text{(Equation 4-4)}$$

The relationship between gypsum moisture content and electrical resistance can be further applied to a wood-scale for use with any hand-held moisture meter. The equivalent wood moisture content, as would be read on a moisture meter (when measuring gypsum directly) can be converted to approximate gypsum moisture content using Figure 4-4. This method allows practitioners to use wood moisture meters to measure the approximate moisture content of gypsum products in the field by applying a quick conversion.

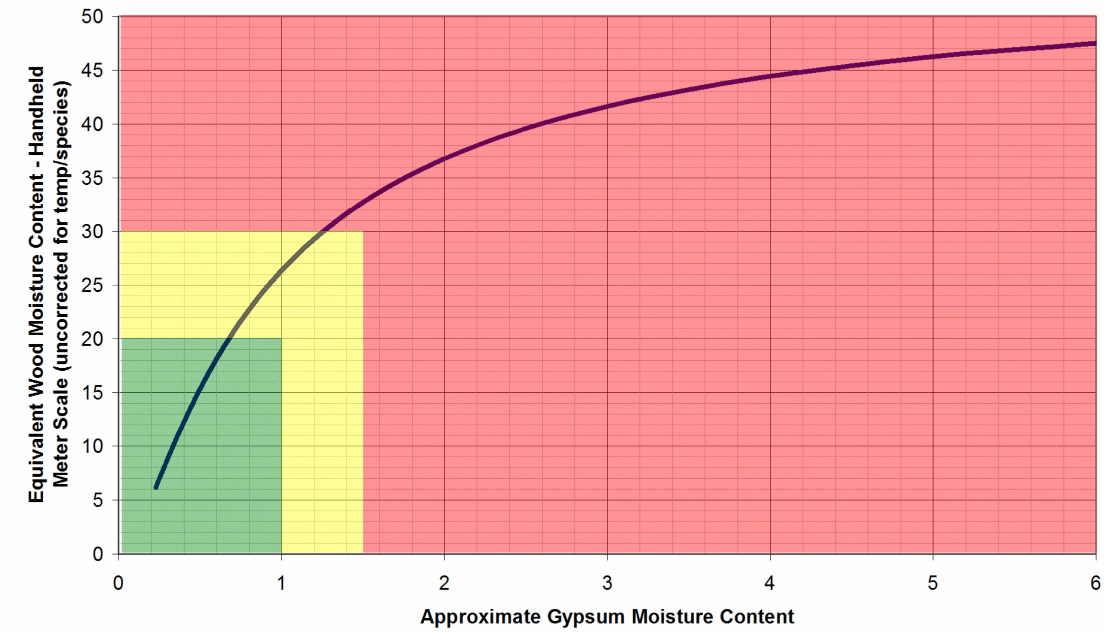


Figure 4-4: Equivalent Wood Moisture Content versus an Approximate Gypsum Moisture Content for use with Handheld Wood Meters.

4.2.3 Vancouver Airport – Supplemental Exterior Data

Hourly climatic data for Vancouver International Airport (YVR) is used where exterior data is missing from the buildings, and for comparison between buildings. Hourly data used includes: temperature (°C), relative humidity (%), wind speed (m/s), wind direction (degrees from North), and weather observations (including cloud cover and rain intensity).

4.2.4 University of British Columbia – Solar Radiation Data

Solar radiation data was not collected as part of the monitoring study however is useful in the determination of wall performance. Solar radiation data is required for certain hygrothermal modeling applications; therefore it was of interest to find data from a local source close to the buildings.

In the past, Environment Canada has collected solar radiation data as part of the climatic data it records at the Vancouver International Airport (YVR). However for recent years (including from 2000 onwards), hourly solar radiation data has not been collected at this location, therefore another local source was required.

Measured hourly solar radiation data for Vancouver was provided by Andrew Black at the University of British Columbia (UBC) Biometeorology and Soil Physics Group. The UBC Weather station records hourly solar radiation data (total radiation on horizontal - W/m^2) and is situated on average 10 km to the west of the five buildings (ranging from a minimum of 7 km to Building 2 and 16 km to Building 1) . See Figure 4-5 for the five building locations

The solar radiation data was provided at 15 or 30 minute intervals and was averaged to hourly measurements. The solar radiation data was checked against climate normals and also the hourly data was checked with temperature data against the YVR and the data from the five buildings and found to be in good agreement with the other measured data and climate normals. Data was provided for the four year period from January 1, 2000 to December 31, 2004.

4.3 MONITORED BUILDINGS

The buildings as referenced throughout this and previous reports are labelled 1 through 5 for anonymity. Sufficient information is provided to understand the building composition, location, and relation to surrounding buildings within the neighbourhood which may impact local wind and rain patterns. Figure 4-5 shows the location of the five buildings, UBC, and the airport (YVR).

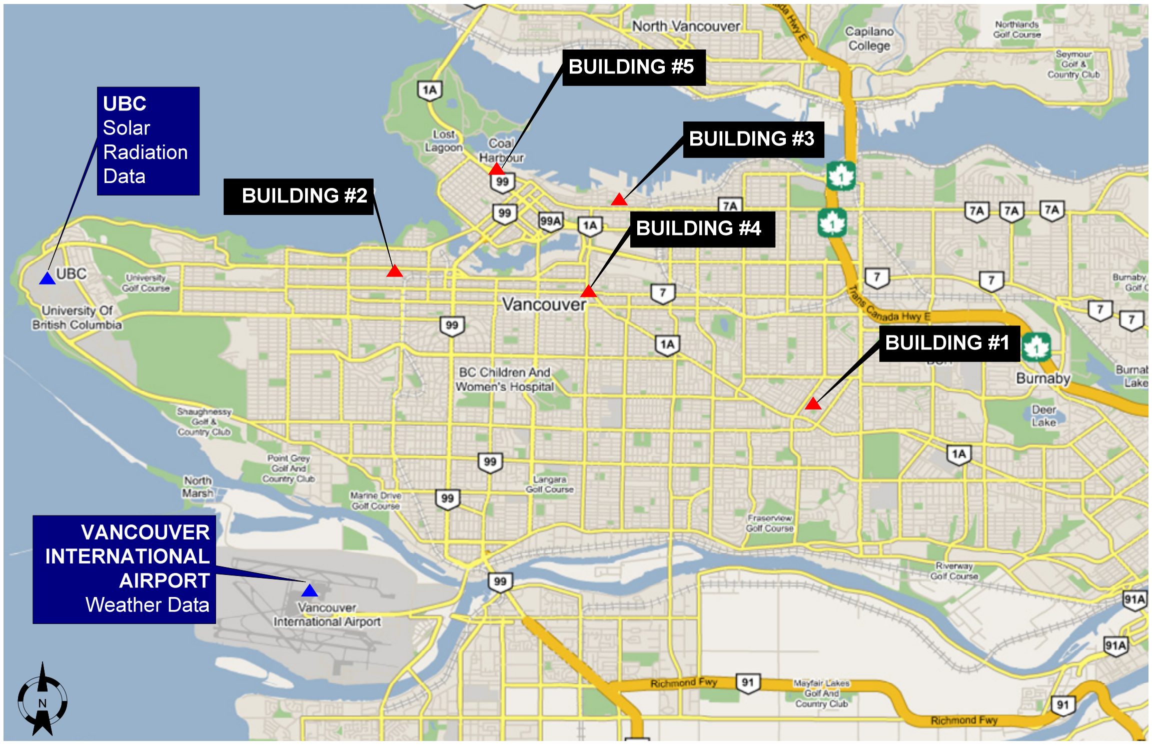


Figure 4-5: Five Monitored Buildings and Supplemental Data Locations (Google Maps 2006)

At each of the buildings a five to eight different wall locations were monitored for a total of 31 locations over the five buildings. These locations were chosen to understand wall performance but also potentially capture rain water leaks at key details such as vents, windows, balcony transitions, and saddle flashings where historically leaks occurred and lead to damage. The 31 monitored wall locations are summarized in Table 4-4 and shown on each building in the following sections. These locations were confirmed during site visits and original installation photographs or drawings.

Table 4-4: Summary of Monitored Wall Locations

Building	Wall Location#	Wall Orientation	Location/Detail
1	1	Southeast	At balcony-wall interface
1	2	Southeast	Below corner of window
1	3	Southeast	Away from details
1	4	Southeast	Away from details (electrical outlet at interior)
1	5	Southwest	Below bathroom exhaust vent
2	1	East	Below dryer exhaust vent
2	2	East	Away from details (electrical outlet at interior)
2	3	East	Away from details
2	4	East	Below corner of window

2	5	South	At balcony-wall interface
3	1	East	Below bathroom exhaust vent (3^{rd} floor)
3	2	East	Below balcony-wall interface (3^{rd} floor)
3	3	East	Below window corner (3^{rd} floor)
3	4	East	Corner of wall away from details (2^{nd} floor)
3	5	East	Below bathroom exhaust vent (5^{th} floor)
3	6	East	Corner of wall away from details (6^{th} floor)
3	7	East	At balcony-wall interface (6^{th} floor)
3	8	East	Below window corner (6^{th} floor)
4	1	North	Below window (3^{rd} floor)
4	2	North	Away from details (electrical outlet at interior) (3^{rd})
4	3	South	Away from details (electrical outlet at interior) (3^{rd})
4	4	South	Below window corner (3^{rd} floor)
4	5	South	Away from details (brick veneer at ground floor)
5	1	Southwest	Away from details (5^{th} floor stucco)
5	2	Southeast	Below exhaust vent (5^{th} floor stucco)
5	3	Southeast	Below window corner (5^{th} floor stucco)
5	4	Southeast	At balcony-wall interface (5^{th} floor stucco)
5	5	Southeast	Away from details (30^{th} floor stucco)
5	6	Southeast	Spandrel Panel (30^{th} floor window-wall)
5	7	Southeast	Spandrel Panel (30^{th} floor window-wall)
5	8	Southwest	Spandrel Panel (30^{th} floor window-wall)

4.3.1 Building 1

Building 1 is a four-storey multi-unit residential building which was constructed in 2000 (Figure 4-6). The building is the largest and tallest in the surrounding neighbourhood, which generally consists of one- and two-storey single family dwellings. A large two-storey town-house complex was also constructed in 2000, on the southwest side of the same lot. Two-lane local streets are located to the northeast and southeast of the building. The Vancouver sky-train line is located to the northwest, across the street. The building is relatively exposed to wind and rain on all elevations above the second floor. Figure 4-7 shows the building within the surrounding neighbourhood.

The building is of wood-frame construction and is clad with pre-finished vinyl siding (tan colour) and cement board (green colour) (strapped rainscreen assembly). The rainscreen wall cavities are flashed at each floor level (only at 2^{nd} on southeast corner where sensors located) and the windows/doors are flashed top and bottom, and all penetrations are flashed and well detailed. Vinyl J-trim is used around penetrations and flashings at the edge of the vinyl siding.

The windows consist of insulated double glazed units in vinyl frames. An asphalt-shingled sloped roof covers the building with an approximately 600 mm (24") over-hang. Construction details are consistent with best practice details outlined by CMHC (1999). A typical wall section showing the materials and placement of the sensors is provided in Figure 4-9 with the five monitored wall locations shown on the building in Figure 4-8.

The interior conditions (temperature and relative humidity) within the master bedroom and second bedroom of suite 206 were monitored for the duration of the program.

Further maps, photographs, aerial images and sensor install photos can be found in *Appendix E: Supplemental Building Information and Photographs*.

Figure 4-6: Northeast and Southeast (left) Orientations of Building 1

Figure 4-7: Building 1 in surrounding neighbourhood (Vanmap 2006)

Figure 4-8: Monitored Wall Locations for Building 1 at South Corner, Suite 206 to Interior of Sensors.

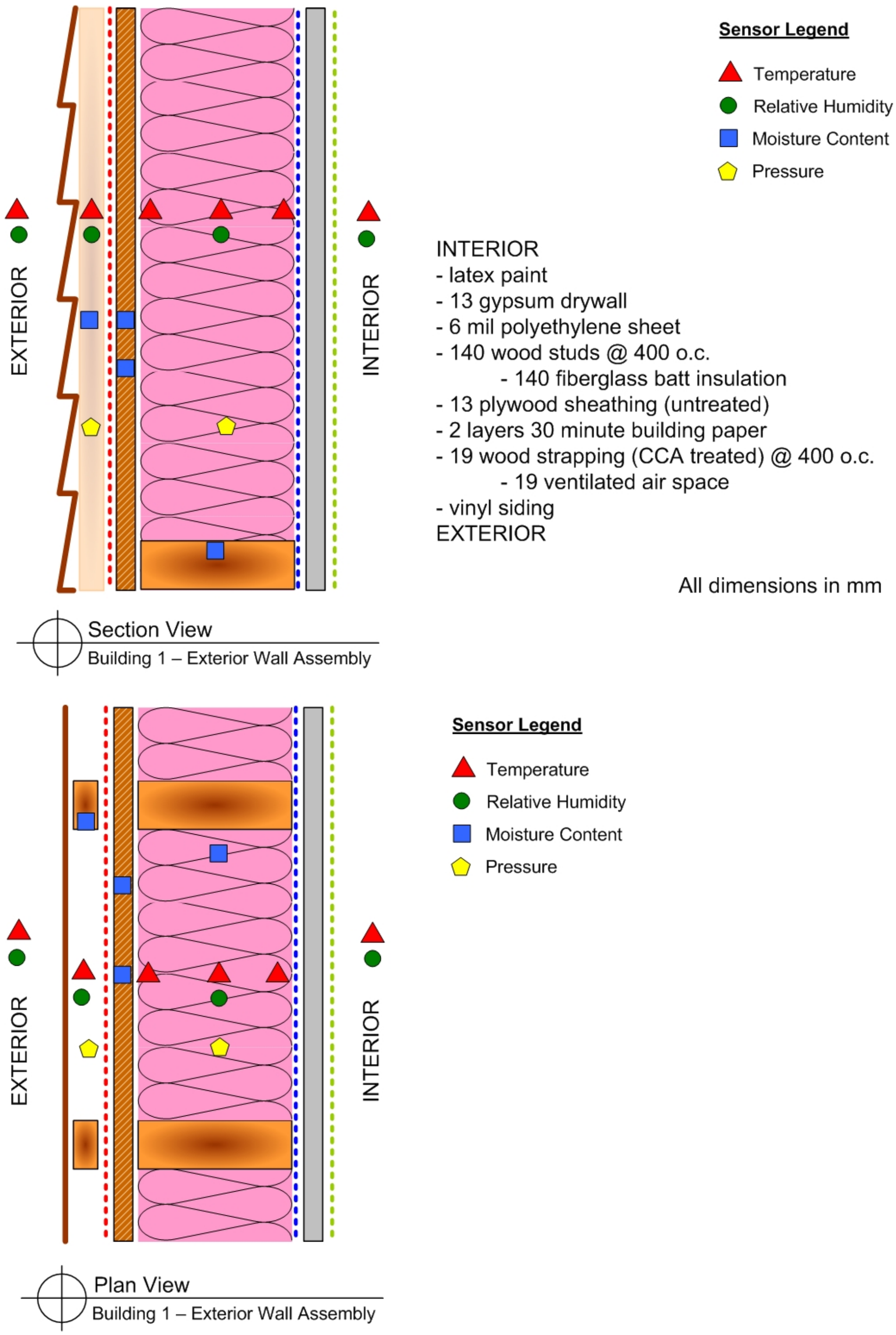


Figure 4-9: Wall Assembly and Sensor Layout for Building 1

4.3.2 Building 2

Building 2 is a four-storey multi-unit residential building which was constructed in 1987 and rehabilitated in 2000 (Figure 4-10). The building is generally the same height as the other multi-unit buildings in the surrounding neighbourhood. Two-lane local streets are located to the south and west of the building, and a single lane alley-way with the building parking garage access is located to the north. The building is relatively exposed to wind and rain on the north, south and west elevations, and exposed only above the third floor on the east, partially sheltered by an adjacent building (10 m to the east). Figure 4-11 shows the building within the surrounding neighbourhood.

The building was originally clad with a face seal stucco wall assembly. Reports indicate water infiltration led to the extensive deterioration of the exterior wall, roof and balcony assemblies (RDH 2005).

The building is of wood-frame construction and is clad with a light-grey colour stucco cladding (strapped rainscreen assembly) which was installed in 2000 when the exterior walls were rehabilitated. The rainscreen wall cavities are flashed at each floor level and the windows/doors are flashed top and bottom, and all penetrations are flashed and well detailed.

The windows consist of insulated double glazed units in aluminium frames which were replaced in 2000. A modified bitumen low-slope roof covers the building with an approximately 50 mm (2”) over-hang at the parapet flashing. Rehabilitation construction details are consistent with best practice details outlined by CMHC (1999). A typical wall section showing the materials and placement of the sensors is provided in Figure 4-12 with the five monitored wall locations shown on the building in Figure 4-13.

The interior conditions (temperature and relative humidity) within the bedroom of suite 401 were monitored for the duration of the program.

Further maps, photographs, aerial images and sensor install photos can be found in *Appendix E: Supplemental Building Information and Photographs*.

Figure 4-10: West and South (right) Orientations of Building 2

Figure 4-11: Building 2 in Surrounding Neighbourhood (Vanmap 2006)

Figure 4-12: Monitored Wall Locations for Building 2, South and East (right) Orientations, Suite 401 to Interior of Sensors

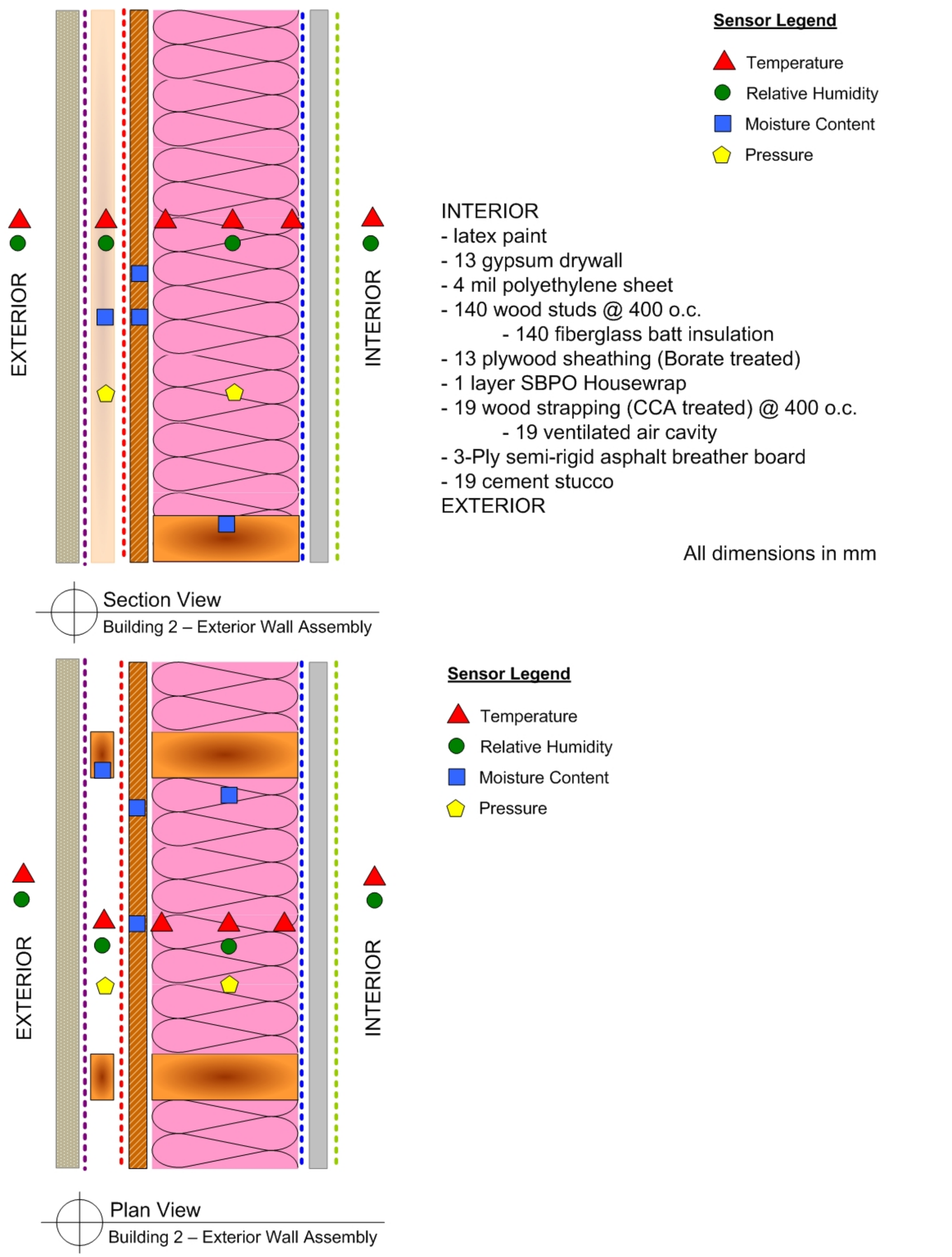


Figure 4-13: Wall Assembly and Sensor Layout for Building 2

Borate treated sheathing was specified in the original drawings where the sheathing was replaced, however could not be confirmed on site.

4.3.3 Building 3

Building 3 is a six-storey multi-unit residential building which was constructed in 1990 and rehabilitated in 2001 (Figure 4-14). The building is generally the same height as the other residential and commercial buildings in the surrounding neighbourhood. Two-lane local streets are located to the north and east of the building, and a single lane alley-way with the building parking garage access is located to the south. The building is relatively exposed to wind and rain on the north, east, and west elevations, and on the south at the alley-way, is sheltered by an adjacent building (10 m to the east). Figure 4-15 shows the building within the surrounding neighbourhood.

The building was originally clad with a face seal stucco wall assembly. Reports indicate water infiltration and high interior humidity conditions led to the deterioration of the exterior wall assembly which was rehabilitated (Lawton 2004).

The building is of concrete-frame construction infilled with steel-stud and gypsum sheathed walls. The exterior walls are clad with a light-yellow colour stucco cladding (rainscreen assembly) which was installed in 2001 when the exterior walls were rehabilitated. The rainscreen wall cavities are flashed at each floor level and the windows/doors are flashed top and bottom, and all penetrations are flashed and well detailed.

The windows consist of insulated double glazed units in aluminium frames which were replaced in 2001. A modified bitumen low-slope roof covers the building without an overhang at the parapet flashing. Rehabilitation construction details are consistent with best practice details outlined by CMHC (1999). A typical wall section showing the materials and placement of the sensors is provided in Figure 4-17 with the eight monitored wall locations shown on the building in Figure 4-16.

The interior conditions (temperature and relative humidity) within bedrooms of suites 311 and 611 were monitored for the duration of the program.

Further maps, photographs, aerial images and sensor install photos can be found in *Appendix E: Supplemental Building Information and Photographs*.

Figure 4-14: South and East (right) Orientations of Building 3

Figure 4-15: Building 3 in Surrounding Neighbourhood (Vanmap 2006)

Figure 4-16: Monitored Wall Locations for Building 3 on East Elevation. Suites 211, 311, 511 and 611 are to Interior of Sensors.

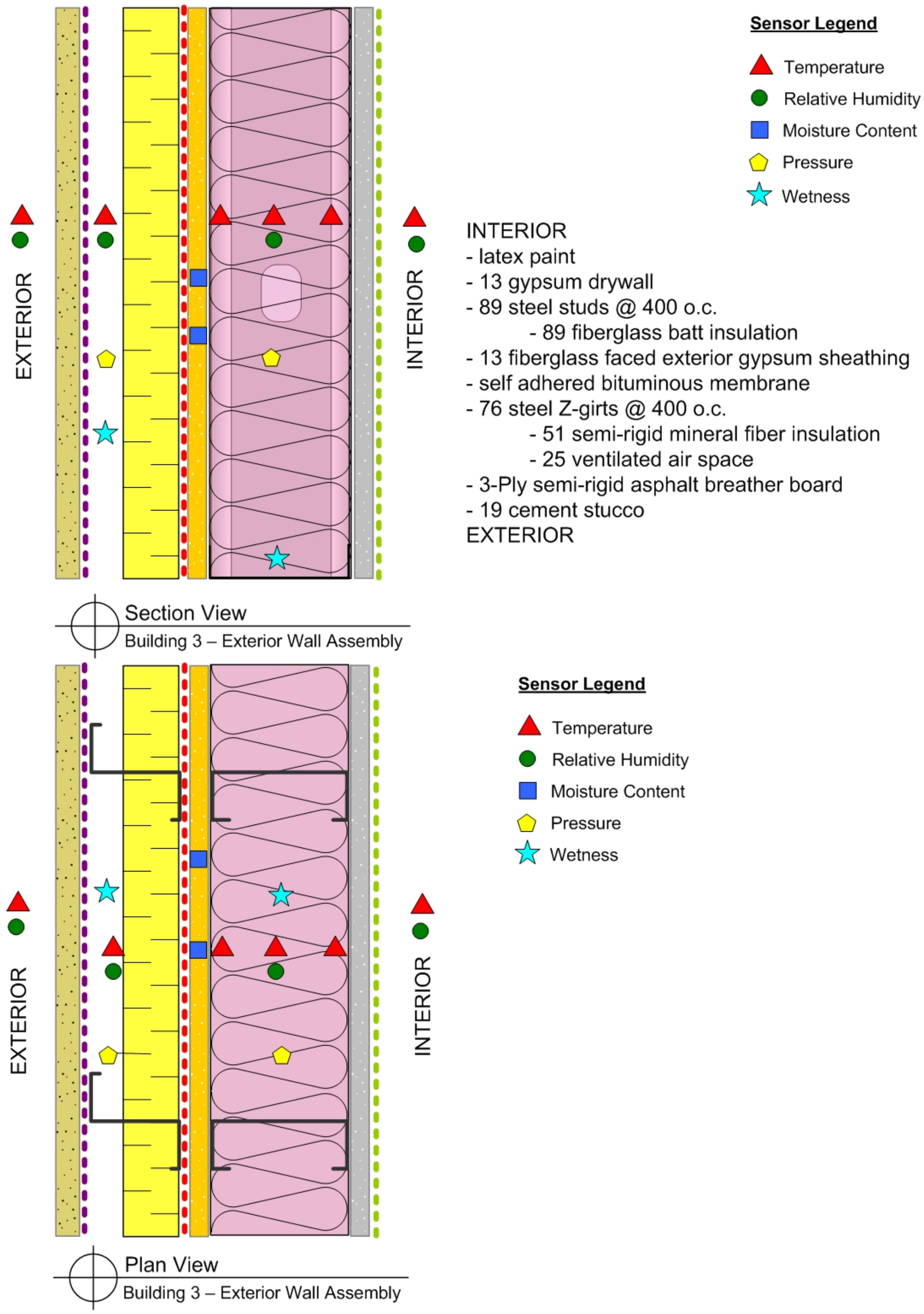


Figure 4-17: Wall Assembly and Sensor Layout for Building 3

4.3.4 Building 4

Building 4 is a four-storey multi-unit residential building which was constructed in 2001 (Figure 4-18). The building is generally the same height as the other buildings in the surrounding neighbourhood. Local streets are located to the north and west of the building, and an alley-way is located to the south. The building is relatively exposed to wind and rain on the north and west elevations, is relatively sheltered by a taller building to the south, and the east elevation consists of a concrete block fire-wall. Figure 4-19 shows the building within the surrounding neighbourhood.

The building is of wood-frame construction and is clad with pre-finished cement board siding (yellow colour) on floors 2 through 4 and red brick veneer at the ground floor. The cement board rainscreen wall cavities are flashed at each floor level and the windows/doors are flashed top and bottom, and all penetrations are flashed and well detailed. The brick veneer is separated by a 19 mm open cavity and is ventilated with brick head-joint vents at the bottom and a continuous open vent at the top.

The windows consist of insulated double glazed units in aluminium frames. A modified bitumen low-slope roof covers the building and overhangs the building by 1200 mm (4'), 600 mm (2') at the bay-windows. Construction details are consistent with best practice details outlined by CMHC (1999). A typical wall section showing the materials and placement of the sensors is provided in Figure 4-22 (cement board) and Figure 4-23 (brick veneer) with the five monitored wall locations shown on the building in Figure 4-20 (north) and Figure 4-21 (south).

The interior conditions (temperature and relative humidity) within bachelor suites 303 (south) and 309 (north) were monitored for the duration of the program.

Further maps, photographs, aerial images and sensor install photos can be found in *Appendix E: Supplemental Building Information and Photographs*.

Figure 4-18: North and West (right) Orientations of Building 4

Figure 4-19: Building 4 in Surrounding Neighbourhood (Vanmap 2006)

Figure 4-20: Building 4 – North Elevation, Monitored Wall Locations 1 & 2.

Figure 4-21: Building 4 – South Elevation, Monitored Wall Locations 3, 4, &5.

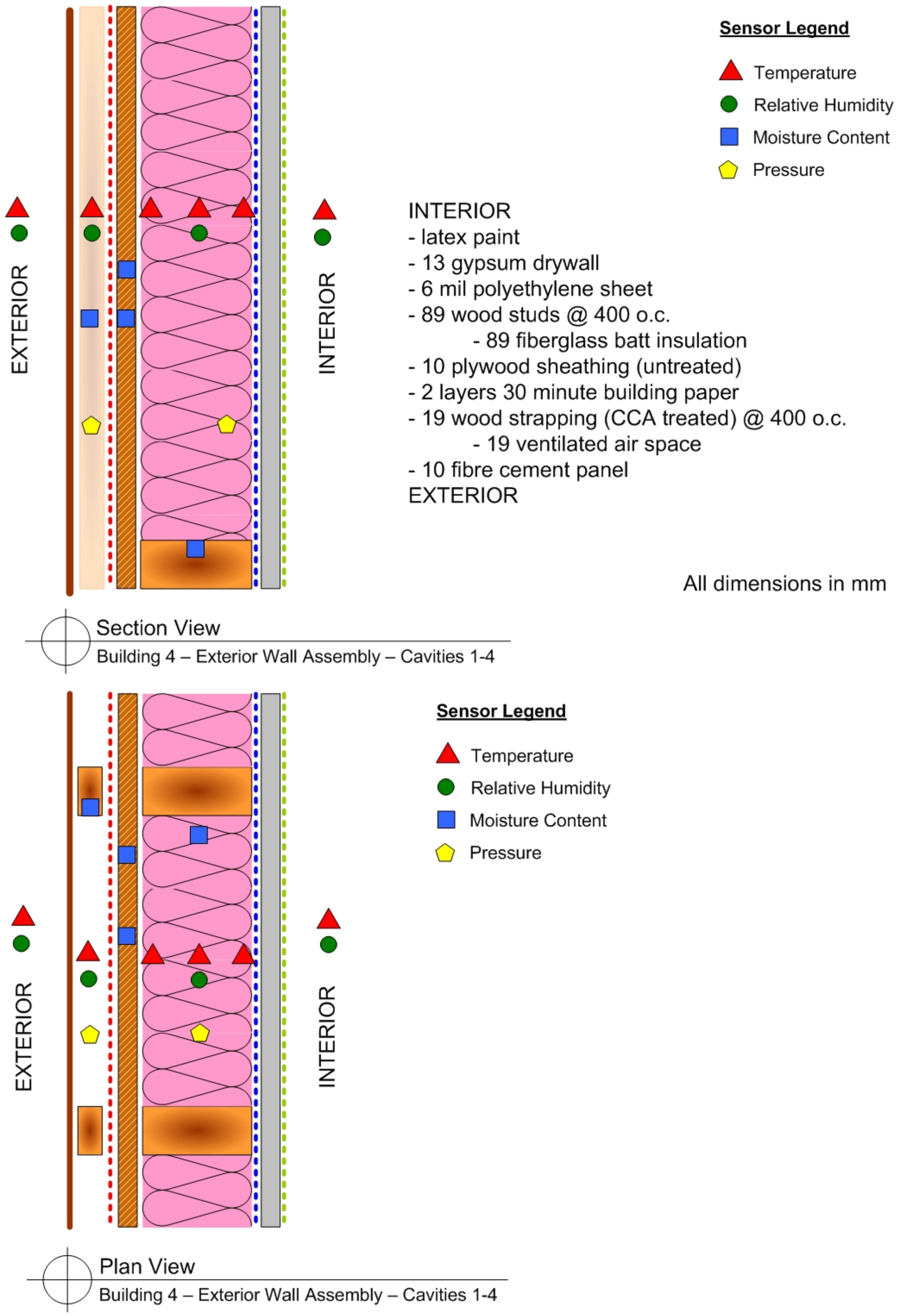


Figure 4-22: Wall Assembly and Sensor Layout for Building 4 – Monitored Locations 1 -4 at Cement Board Cladding

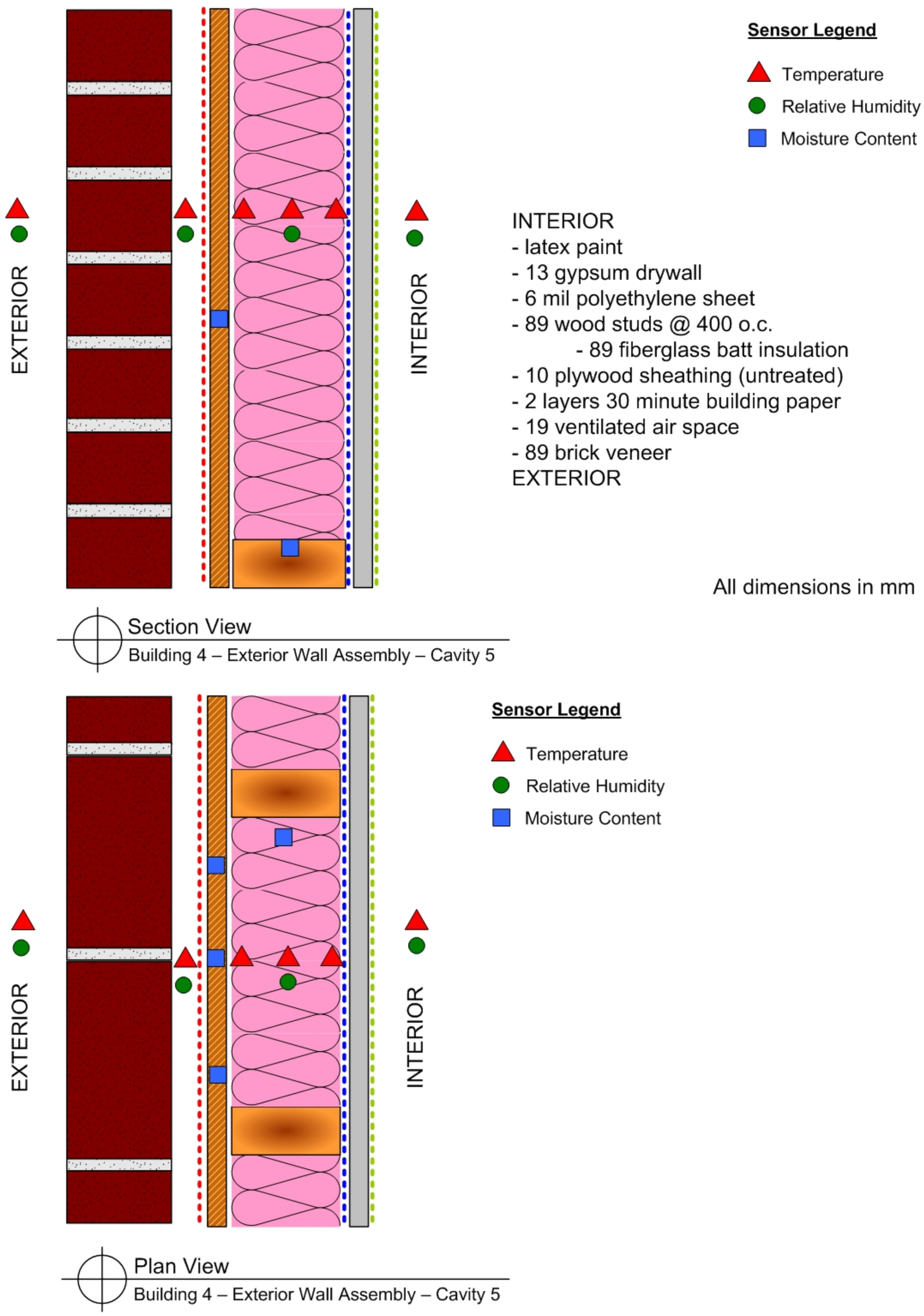


Figure 4-23: Wall Assembly and Sensor Layout for Building 4 – Monitored Location 5 at Brick Veneer

4.3.5 Building 5

Building 5 is a thirty-storey multi-unit residential building which was constructed in 2002 (Figure 4-24). The building is located in Coal Harbour at the north end of Vancouver's downtown core which full of other high-rise buildings. Local streets are located to the northwest, northeast, and southwest of the building, and a parking lot is located to the southeast. The building is relatively exposed to wind and rain from all directions; however some wind sheltering and/or tunnelling may occur due to other nearby buildings. A wind-tunnel effect was noted at this building during monitoring and is discussed in further detail in the next chapter. Figure 4-19 shows the building within the immediate neighbourhood.

The building structure consists of reinforced concrete frame construction. The exterior walls consist of infill steel-stud and gypsum clad with a rainscreen stucco assembly from floors 1 through 12 and a pre-finished window-wall assembly from floors 13 through 30. The stucco rainscreen wall cavities are flashed at each floor level and the punched windows/doors are flashed top and bottom, and all penetrations are flashed and well detailed. The window-wall assembly is constructed as a drained and vented assembly.

The punched windows and window-wall glazing units consist of insulated double glazed units in thermally broken aluminium frames. A modified bitumen low-slope roof covers the building without an overhang at the parapet wall. A typical wall section showing the materials and placement of the sensors is provided in Figure 4-22 (stucco rainscreen) and Figure 4-23 (window-wall) with the eight monitored wall locations shown on the building in Figure 4-20 (5^{th} floor) and Figure 4-21 (30^{th} floor).

The interior conditions (temperature and relative humidity) within the living area of suites 504 (5^{th} floor) and 3005 (30^{th} floor) were monitored for the duration of the program.

Further maps, photographs, aerial images, and sensor install photos can be found in *Appendix E: Supplemental Building Information and Photographs*.

Figure 4-24: Southwest and Southeast (right) Orientations of Building 5

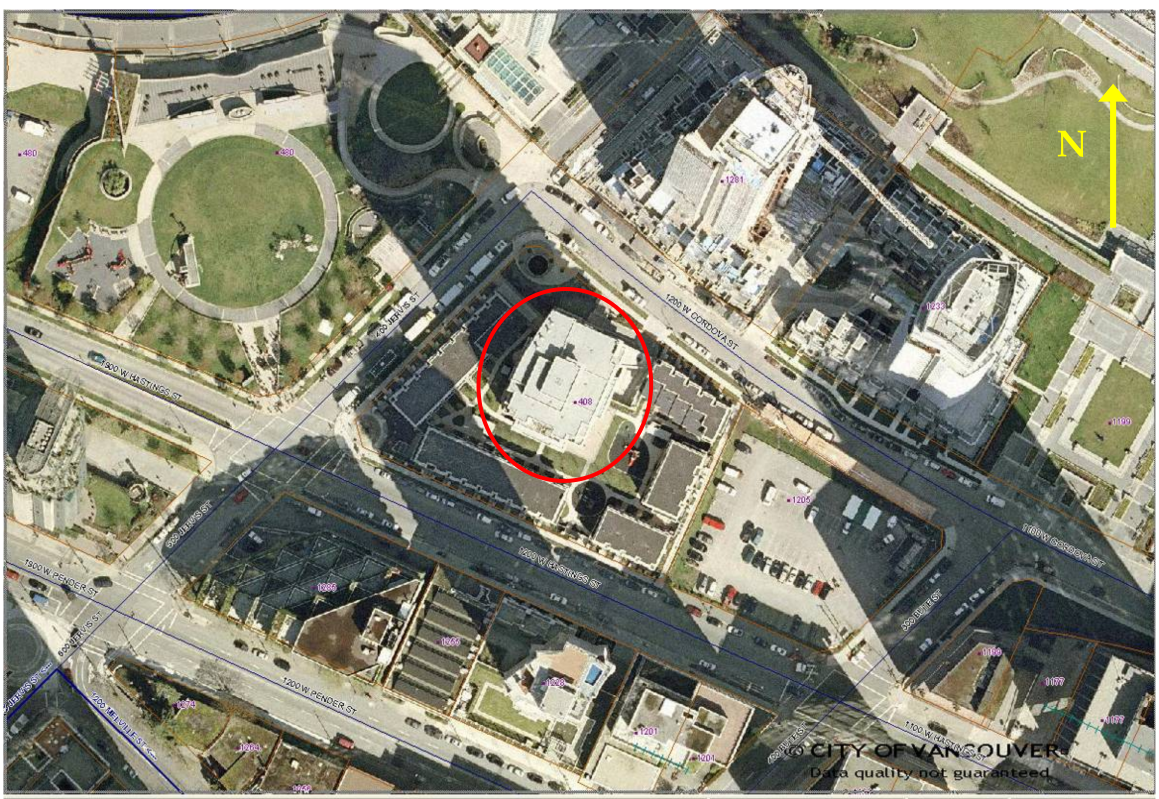
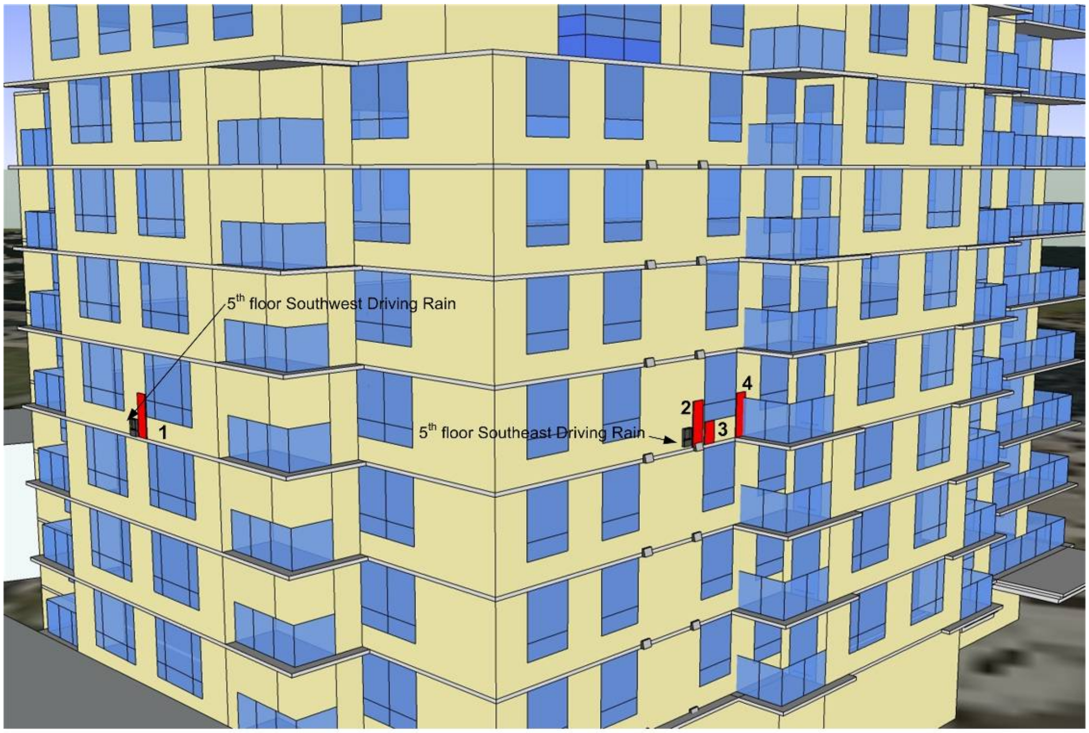
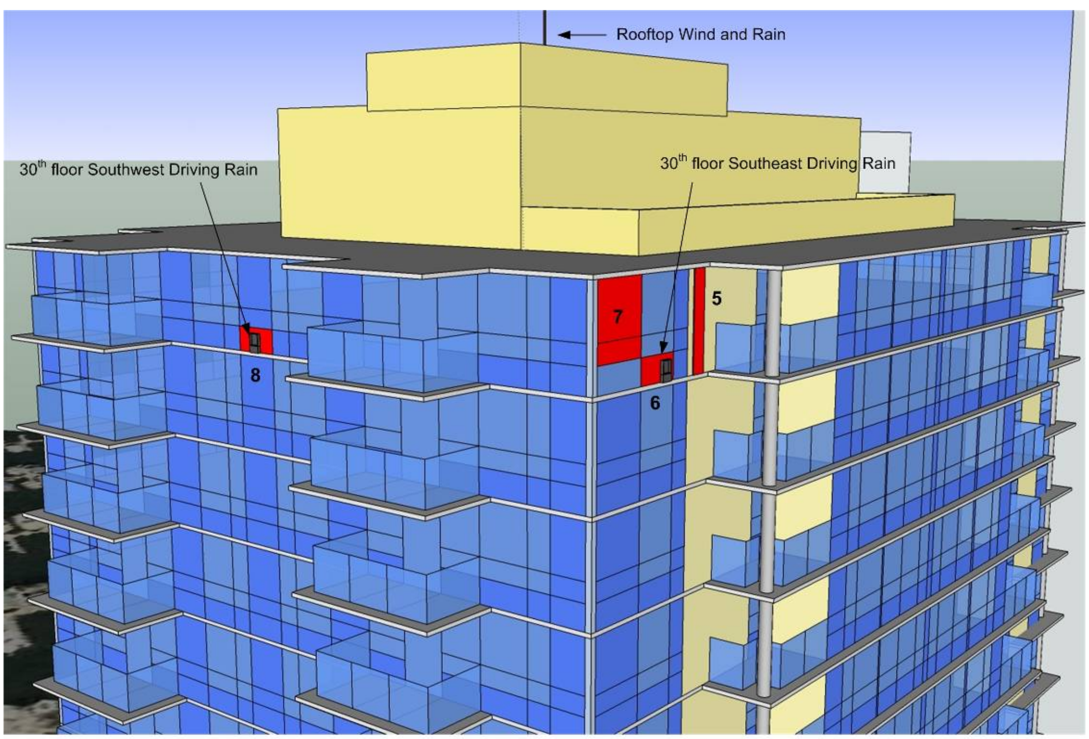


Figure 4-25: Building 5 in Surrounding Neighbourhood (Vanmap 2006)



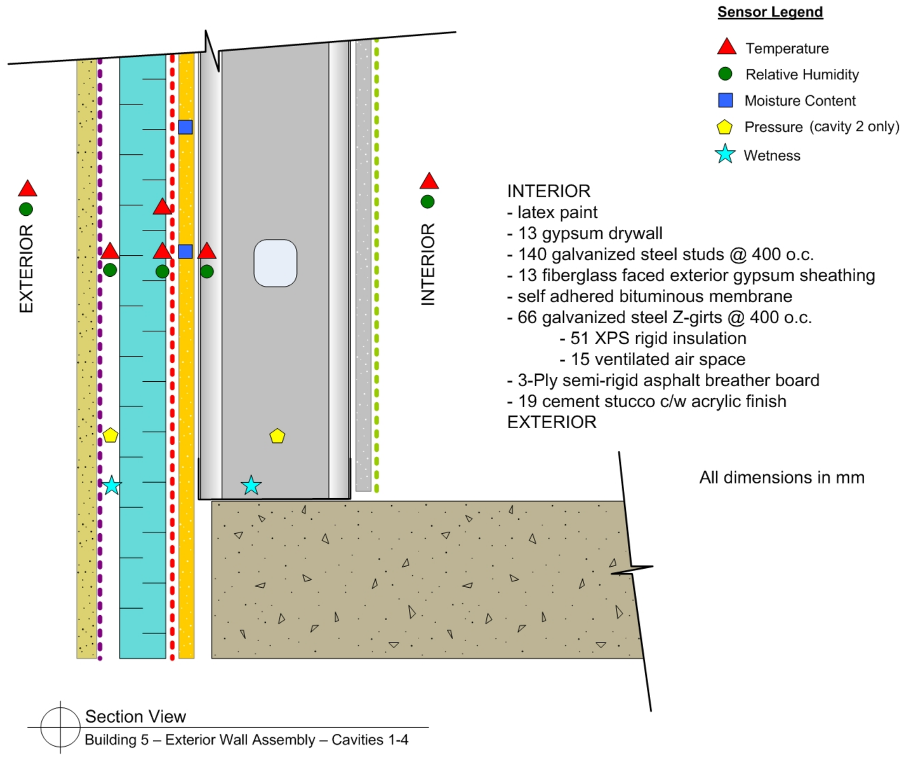
Building 5 – 5th Floor Wall Cavities – Southeast view

Figure 4-26: Building 5 – Location of 5th Floor Sensors



Building 5 – 30th Floor Wall Cavities – Southeast view

Figure 4-27: Building 5 – Location of 30th Floor Sensors



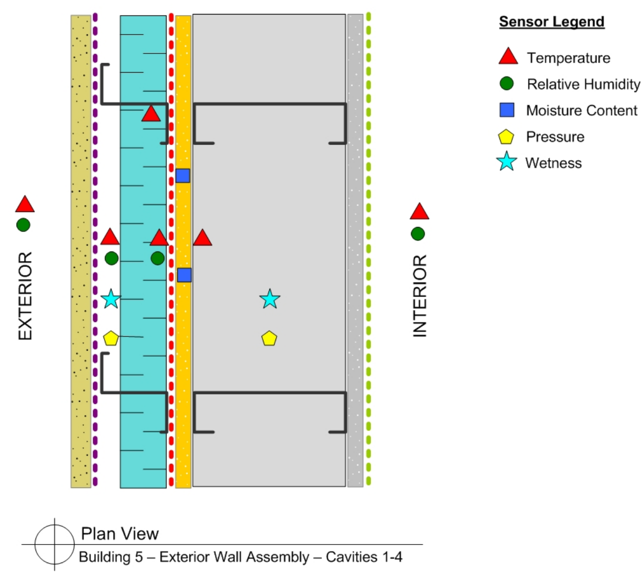
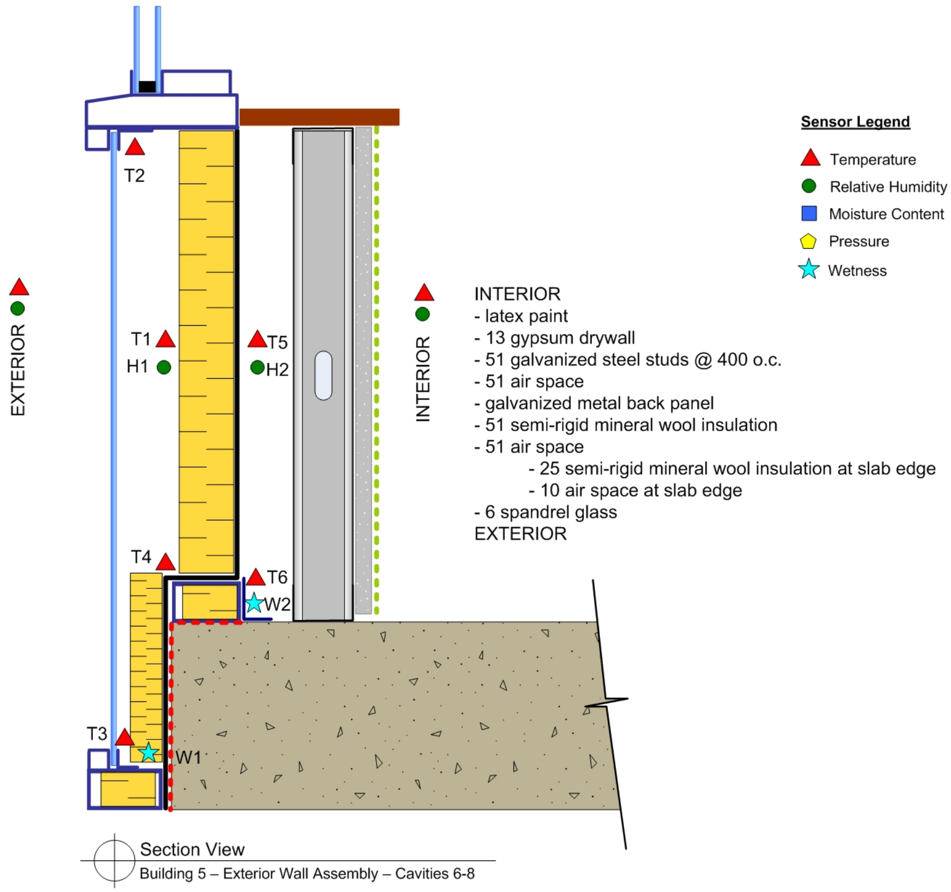


Figure 4-28: Wall Assembly and Sensor Layout for Building 5 – Monitored Locations 1-4 (5 similar – see Appendix) at Stucco Wall



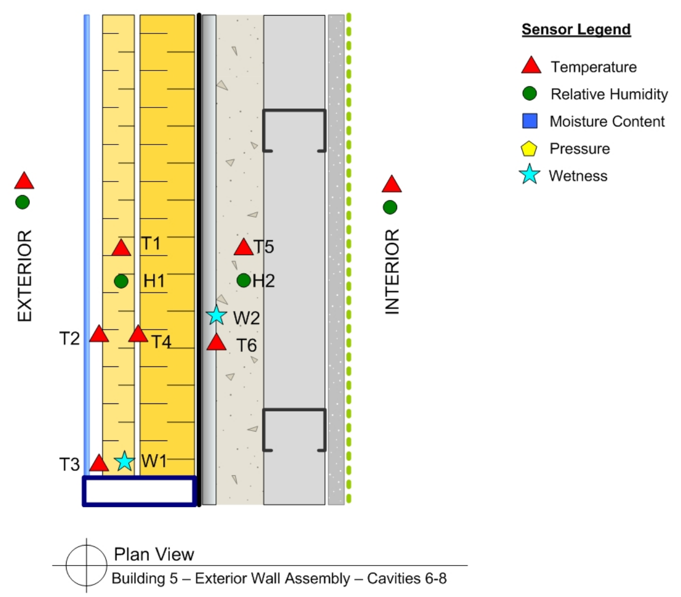


Figure 4-29: Wall Assembly and Sensor Layout for Building 5 – Monitored Locations 6-8 at Window-Wall Assembly

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5 EXTERIOR BOUNDARY CONDITIONS – THE CLIMATE OF VANCOUVER

In this chapter the climate of Vancouver, BC is discussed and measured exterior climate data from the five monitored buildings is presented and compared existing design data. The influence of local topography and microclimate (particularly on wind and rain) across the city is shown in comparison to typical airport data, which is often used for design and in hygrothermal modeling programs.

Measured driving rain data is presented for the five buildings and an attempt is made to correlate the observations with predictions made by empirical calculation methods. The influence of building geometry and details (ie. roof overhangs, balconies, or protrusions) impact wind flow and rain deposition patterns on buildings and are shown to affect the accuracy of simple empirical methods.

Solar radiation data for Vancouver is also discussed, and a calculation method is presented to convert measured horizontal solar radiation into diffuse and beam (direct) components for conversion onto vertical surfaces and for use with hygrothermal models.

Finally, the differences between climate data from several sources for Vancouver are discussed to assist practitioners with selecting appropriate climate data for design.

5.1 INTRODUCTION

The climate of the Greater Vancouver area is discussed to assist practitioners to better understand the local design conditions and highlight local differences across the city in rainfall, wind speed and direction, and temperature.

Exterior climate is the most significant loading on the building enclosure. The building enclosure separates our controlled interior spaces from constantly varying exterior conditions. We construct our buildings to exclude the unpredictable and sometimes severe exterior climate and expect all of our buildings to perform the same, regardless of location. This puts a strain on wall or roof assemblies to withstand and control the flow of heat, air, and moisture.

Rain water is often the most significant moisture load on a building and driving rain or wind-driven rain has a significant impact on the performance of exterior walls of buildings. The driving rain load is a very important design consideration for buildings located in Coastal British Columbia and has been shown in the past to result in the failures of poor water managed wall assemblies (Morrison Hershfield 1996).

The driving rain load on a building façade is influenced by the rain intensity and wind speed and direction. In addition, local topography, adjacent buildings, and building geometry and details (ie. overhang and/or protrusions) all impact driving rain deposition. Predicting driving rain loads on building facades is of interest to designers in selecting appropriate wall and window assemblies for a building, however to date there is only limited data of the driving rain load which buildings actually receive in the field.

Building codes are beginning to require water-managed rainscreen type walls for certain exposure and driving rain loads. Often these driving rain loads are calculated and provided for an exposed airport weather station, whereas a house in a protected and built-up neighbourhood would only see a small fraction of this load. Therefore being able to accurately predict the driving rain load on any building is of interest to practitioners to assist with design choices for water managed wall assemblies.

Despite the importance of driving rain to building performance, there is still a lack of quantitative data of rain deposition on buildings. Empirical and numerical methods have been developed to approximate driving rain loads for buildings, however these models have only been compared to a limited number of field measurements as such data is not typically measured beyond research applications. Numerical modeling using Computational Fluid Dynamics (CFD) has improved our understanding of wind-rain interactions with buildings in recent years. However, CFD models currently remain only useful as a research tool, beyond the grasp of most practitioners due to cost, computational time, and high complexity. The use of a simple method is also preferred for most applications if the accuracy is sufficient.

As part of the monitoring project, driving rain gauges were installed on the facades of the five buildings to measure actual loads and help further understand the relationships of wind, rain, and the building itself on real driving-rain loads. Driving rain measurements are presented for each building, and an attempt is made to correlate the annual measurements with a simple empirical calculation method. The use of CFD numerical models were not investigated as it is beyond the scope of this thesis.

The exterior temperature and relative humidity are discussed and compared between buildings. Measurements and the influence of solar radiation are also discussed as it is important to the drying of walls, but also potentially wetting from reverse solar-driven moisture from rain-wetted absorptive claddings such as brick, wood, or stucco.

Climate data is measured by numerous agencies at several locations within the city; with the main government weather station located at the Vancouver International Airport (YVR), located on a flat river plain in Richmond, just south of Vancouver. Vancouver climate data provided with hygrothermal simulation packages such as WUFI or hygIRC is represented by YVR data as this is the most reliable weather data source, collected for over the past 70 years. However it is shown that the local climate at the airport does not always reflect that in the rest of the city and practitioners should be aware of differences in local climate and the impacts it may have on design choices.

While a large amount of data from the five buildings is summarized in this chapter, further background data is provided in *Appendix F: Supplemental Measured Data.*

5.2 THE VARIED CLIMATE OF VANCOUVER

When people think of Vancouver, the first thought that comes to mind is often how much it rains. While it does rain in Vancouver like most of coastal British Columbia, typically in the winter months, the summer can be quite dry and warm. Like most places, the climate varies seasonally and cannot be fully described by a single number or a "climate classification". Instead, the climate of Vancouver here is described in terms of building design variables of temperature, relative humidity, solar radiation, rainfall, windspeed/direction, and finally driving-rain.

Vancouver is located on the west coast of the North American continent at 49° 10′ north and 123° 10′ west. The Strait of Georgia, which separates the mainland from Vancouver Island and the Pacific Ocean, is situated to the west. Figure 5-1 shows a map of the west coast of south-western British Columbia and north-western Washington, US often referred to as the Pacific Northwest.

The climate of Vancouver is considered to be temperate, without extreme summers or winters. The Köppen climate type classification for Vancouver is "Cfb" which is marine west coastal. The ASHRAE/DOE climate classification is "5C" also marine west coastal. "Marine west coastal" describes a climate with a warm summer, mild winter, rain all year, and at latitude of 35-60°N (ASHRAE 2005).

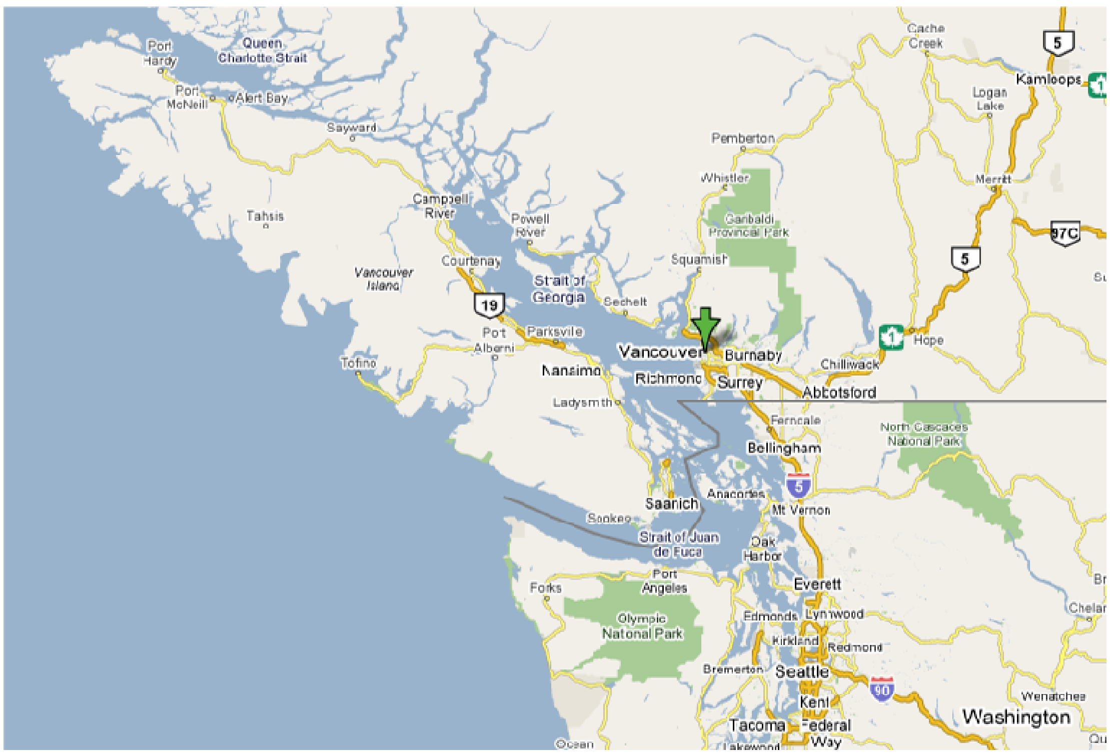


Figure 5-1: Map of the Coastal British Columbia and Washington, USA. (Google Maps 2006)

The average annual temperature in Vancouver is 9.7°C and the average relative humidity is 80%. The January daily average is 3°C and 90% RH while July is 18°C and 75% RH. Vancouver receives on average 1155 mm of rain at the airport, however varies by year as shown in Figure 5-4, where as little as 700 mm/yr to as high as almost 1600 mm/yr has been observed in the past 70 years.

The mean monthly temperature and relative humidity measured at YVR is shown from 1971-2000 and 2001-2005 in Figure 5-2. Data from 2001-2005 is presented for the five buildings throughout this thesis. These are the corresponding averages during that period. On average 2001-2005 was observed to be warmer and less humid than the 30 years previous from 1971-2000. Annual fluctuations and trends in mean temperature are shown in Figure 5-3.

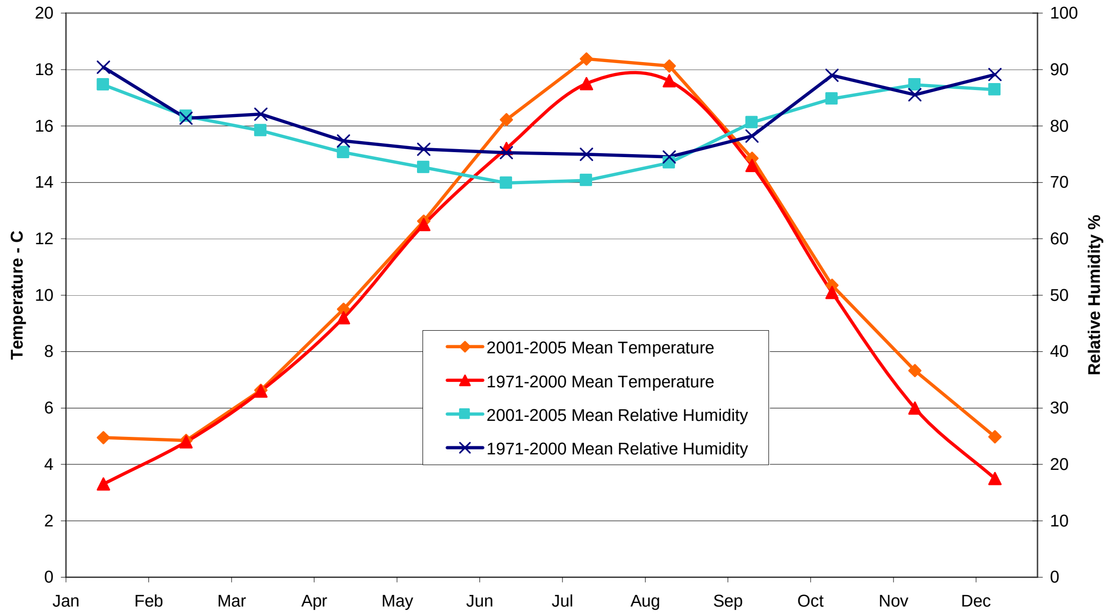


Figure 5-2: Vancouver Airport – Mean Monthly Temperature/RH

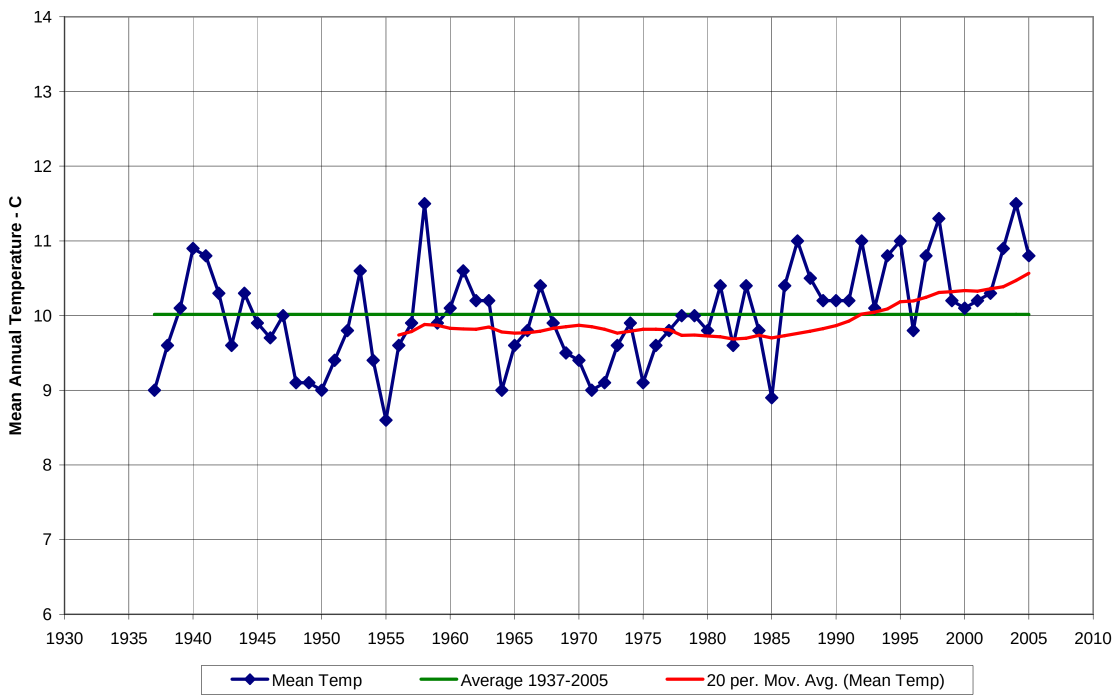


Figure 5-3: Mean Annual Temperature – Vancouver Airport 1937-2005

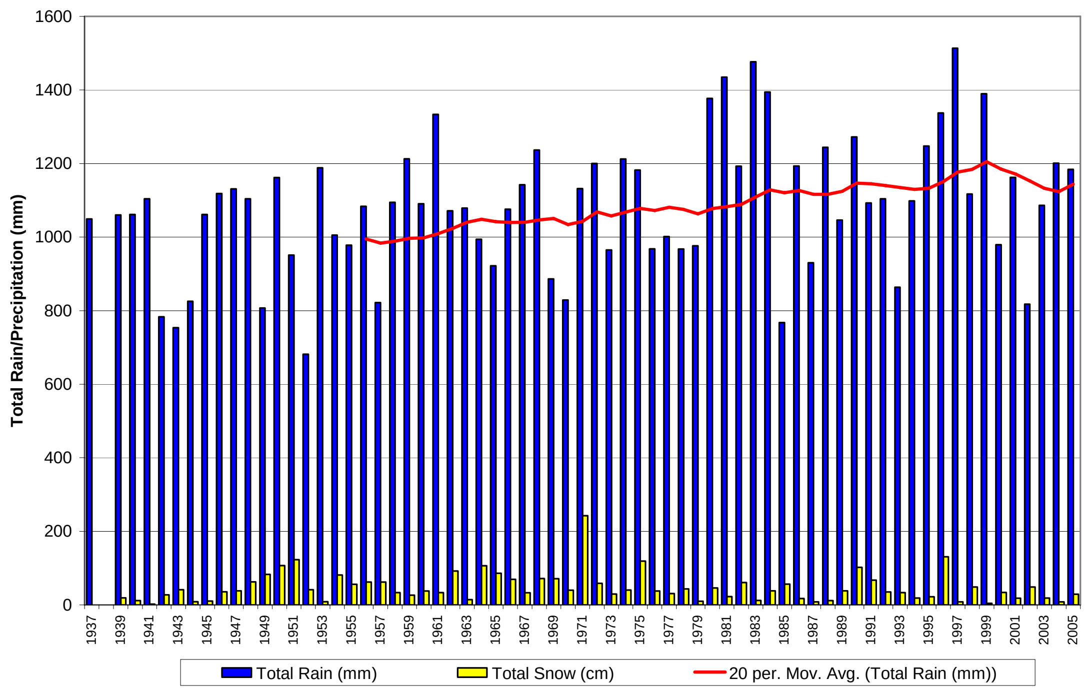


Figure 5-4: Total Annual Precipitation – Vancouver Airport 1937-2005

The majority of the total annual rainfall occurs during the late-fall, winter, and early spring months in Vancouver. Summer months can be quite dry and in some years almost no rainfall has been recorded in July or August. The monthly average rainfall amounts are shown in Figure 5-5 showing typical seasonal rainfall distribution.

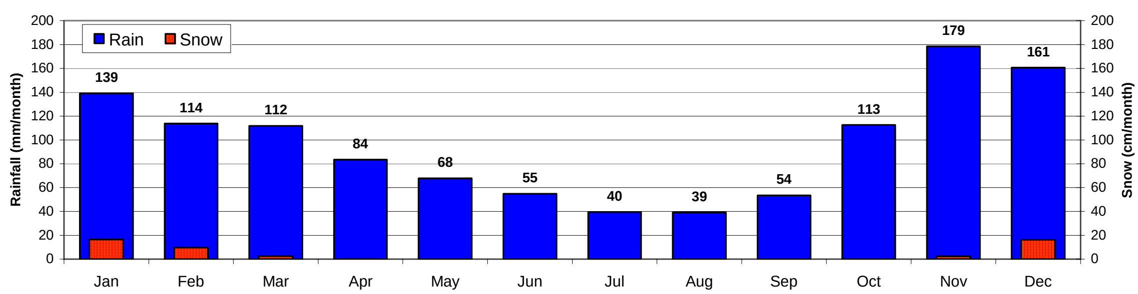


Figure 5-5: Monthly Average Precipitation – YVR, 1971-2000.

The discussion in the remainder of this section is focused on the diversity of the climate within the greater Vancouver area and how buildings may be affected by different microclimates across the city with variances in temperature, windspeed/direction, and rainfall as a result of the built environment and topography. It will be shown that applying general averages for one location in Vancouver may not always be representative of the conditions in all areas.

For practitioners in Vancouver, these differences in microclimate may only be partially understood and represented by a “number” in the building code; however the impact this microclimate has on a building may impact design and construction choices. For example, local wind sheltering within neighbourhoods is shown to significantly reduce the instance of wind-driven rain.

While only a summary of relevant data is presented here, an excellent climatology and discussion of the general weather mechanisms for Vancouver are presented by Timothy Oke and John Hay at the Geography Department of the University of British Columbia (1994). From their research, plots showing differences in temperature, rainfall and windspeed and direction across Vancouver are referenced here.

Mean annual temperature differences across Vancouver are shown in form of a temperature contour map in Figure 5-6. The air temperature increases from the coast into the city (<10 km) on average by up to 2°C. These temperature differences are influenced the cool ocean surface and by the contrasting urban heat island effect, further demonstrated in Figure 5-9. Air temperature measurements from 2001-2005 at the airport and the five buildings are presented in Figure 5-7 showing this temperature difference between the airport and city. Figure 5-8 further expands Figure 5-7 and presents measurements of temperature and relative humidity for 2003.

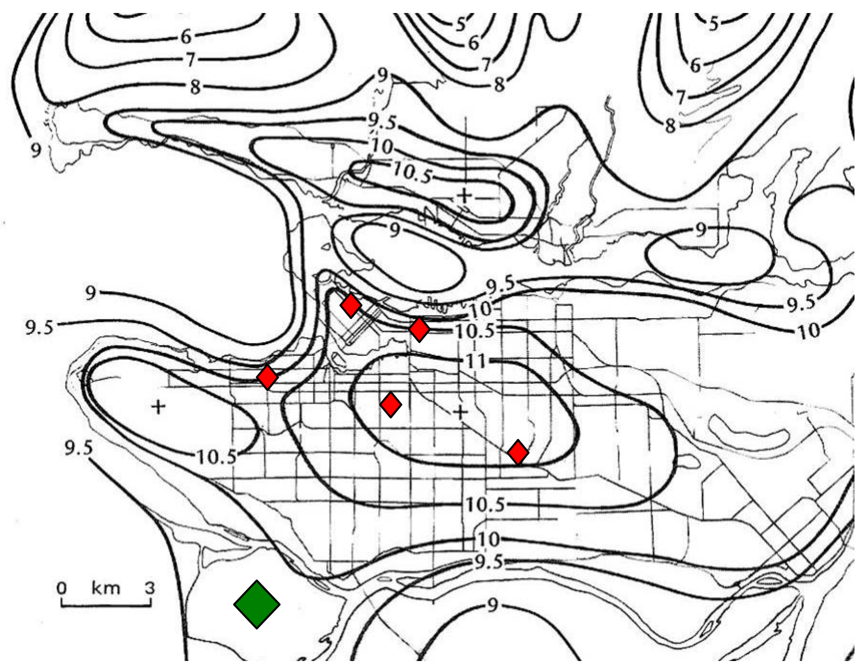


Figure 5-6: Mean Annual Temperature for Greater Vancouver (Oke & Hay 1994)

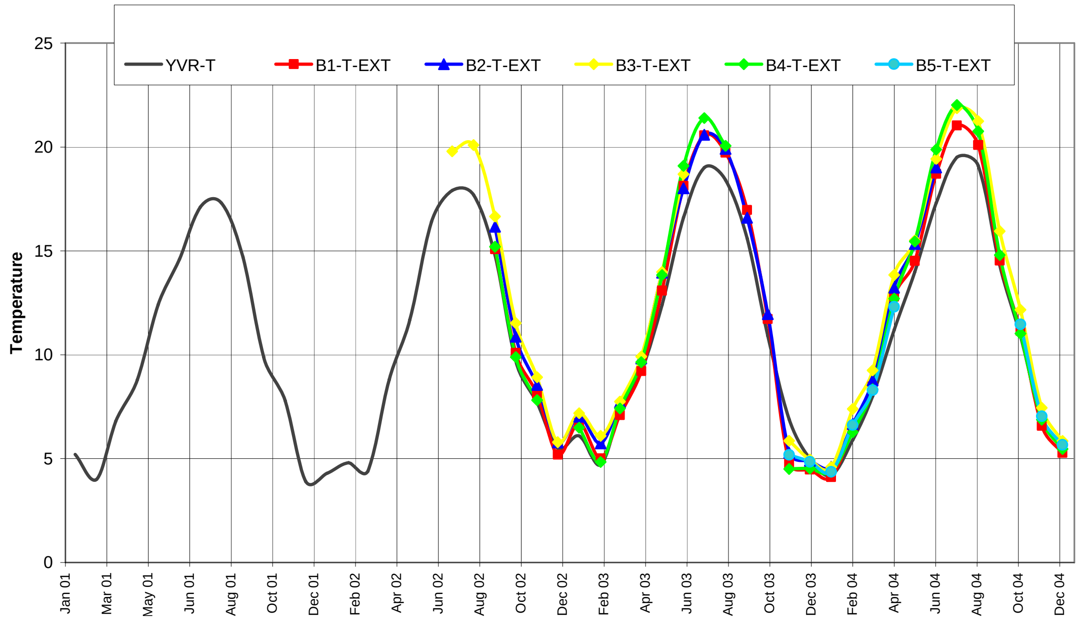


Figure 5-7: Average Monthly Temperature – Buildings 1-5 & YVR 2001-2004

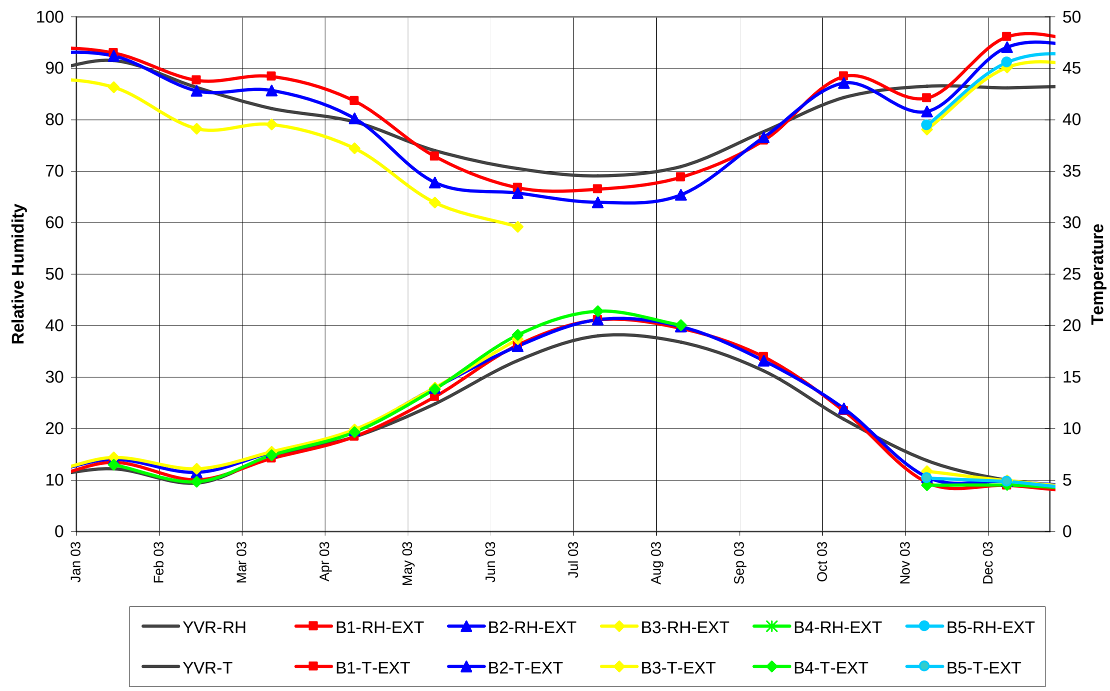


Figure 5-8: Vancouver 2003 – Mean Monthly Temperature/RH

The difference in temperature is largest during the summer months, when a 2-3°C difference is observed between the airport and the five building sites. The differences in the winter and spring/fall are smaller between 0-1°C. It is also noted that the average summer temperature over the past four years increased from 17.5° to almost 20°C at all locations.

Reviewing temperatures from 2003, the average annual temperature recorded at Building 1 was 11.5°C and at Building 2 was 11.8°C while the airport was at 11.2°C. In 2004 the annual average temperature at Building 3 was 12.9°C and Building 4 was 12.3°C while the airport was 11.4°C.

The urban heat island effect, a result of the built environment is shown by temperature potentials in Figure 5-9. Temperatures contours show the near surface (1.5 m above grade) temperature potentials above the local air temperature for a typical clear summer day.

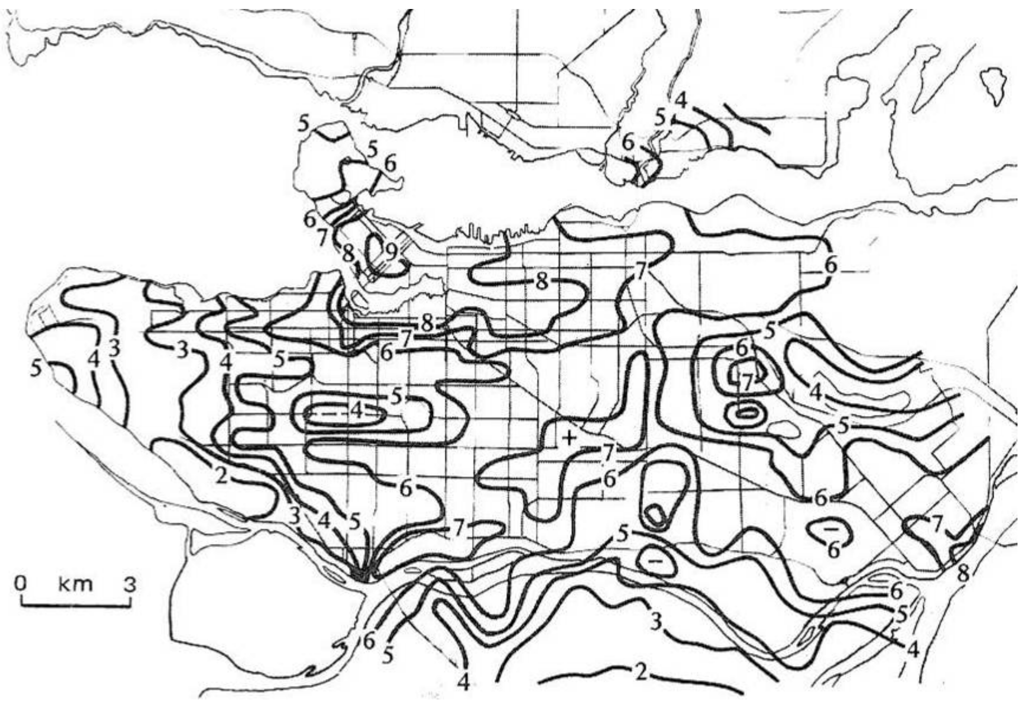


Figure 5-9: Urban Heat Island Effect in Greater Vancouver – Near Surface (1.5 m) temperature patterns (Oke & Hay 1994).

Here surface temperatures of up to 9°C were observed in the downtown core and between 5-8°C in other locations around the city. These surface temperatures have an impact and influence the air temperatures measured on the roofs of the five buildings.

Within 20 km from North Vancouver to Richmond, the total rainfall across greater Vancouver can almost double from 1070 mm/yr at the airport, to 1850 mm/yr on Burnaby Mountain, and 2000 mm/yr in North Vancouver (NBC 2005). These rainfall differences are further emphasized in Figure 5-10, showing a mean annual precipitation contour map for Greater Vancouver.

Finally, wind direction rosettes for several weather stations across greater Vancouver are shown in Figure 5-11, showing the predominant wind direction from the east and southeast. Corresponding wind direction measurements from the five buildings are presented in Section 5.4.

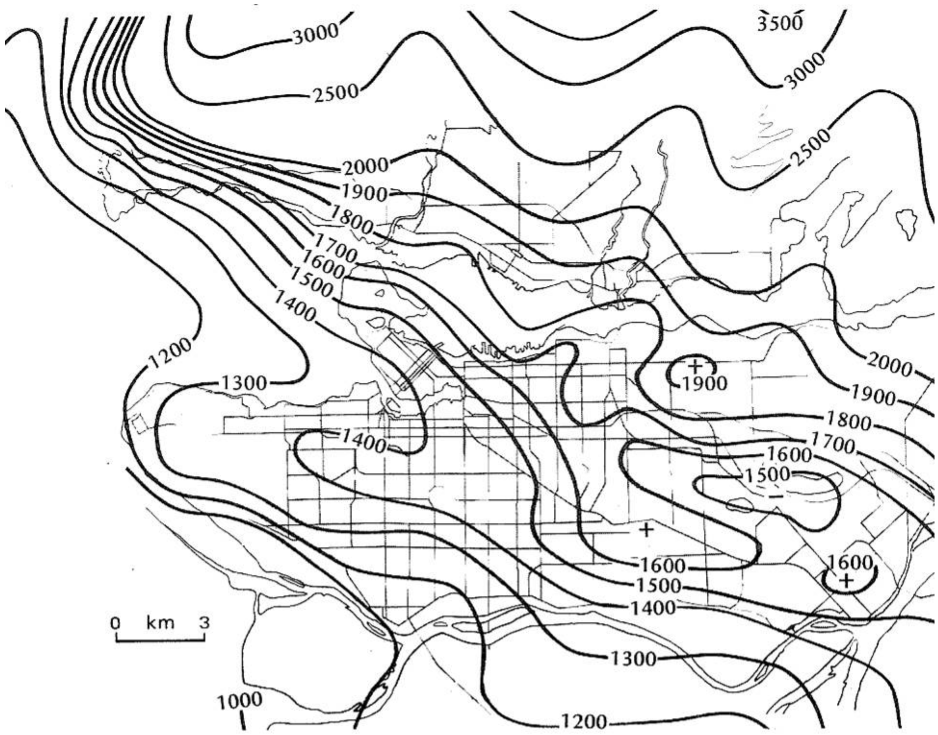


Figure 5-10: Greater Vancouver Mean Annual Precipitation Map (Oke & Hay 1994)

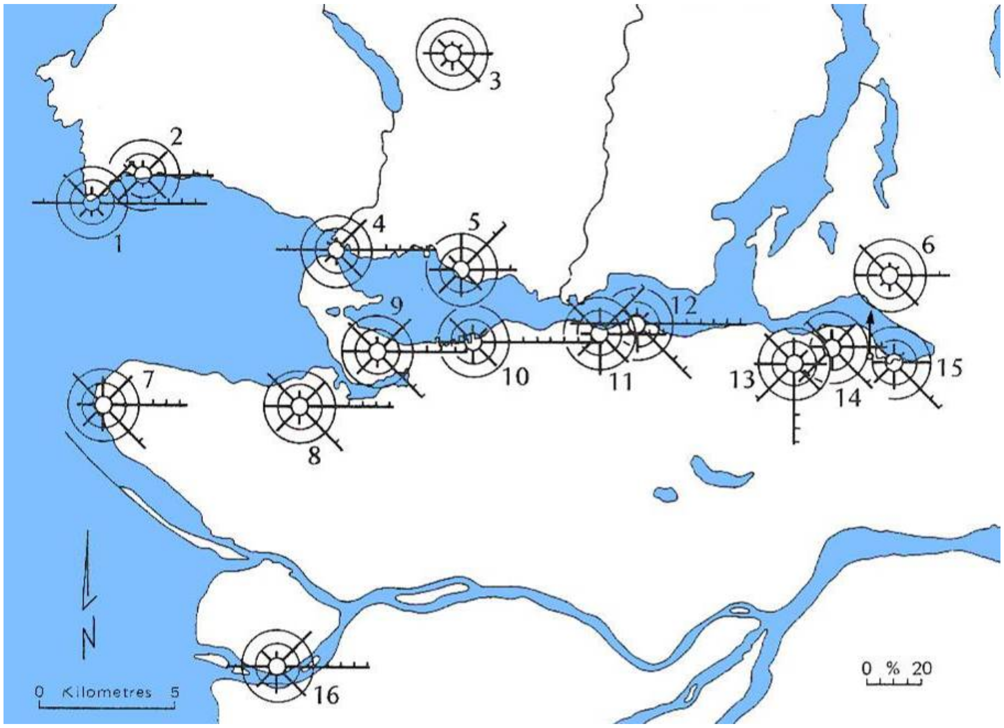


Figure 5-11: Annual Average Direction Rosettes (Oke & Hay 1994)

Wind flow patterns were investigated by Oke & Hay and are reproduced here to attempt to explain one of the anomalies in wind-direction data from the study. This plot shows the influence of the North Shore Mountains, in particular the potential for wind to blow from the north and north-east off the mountains into downtown as was consistently observed at Building 5. However for much of the city south of downtown, winds are primarily from the east as shown in the previous figure.

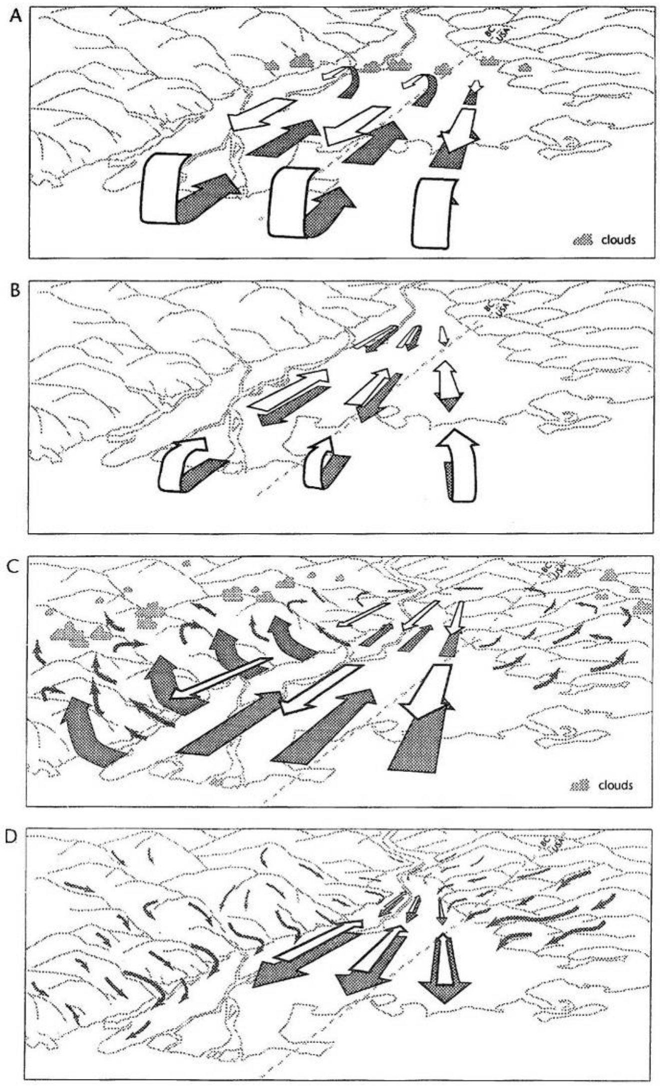


Figure 5-12: Schematic Diagram of Wind Flows Over Vancouver. Land/Sea Breeze (A) by day, and (B) by night. Mountain/valley winds (C) by day and (D) at night) (Oke & Hay 1994)

Levelton (2004) further researched the differences in wind and rain across Vancouver and parts of Coastal British Columbia. Data from eight weather stations in the lower mainland (Figure 5-13) and four from Vancouver Island were presented in the report.

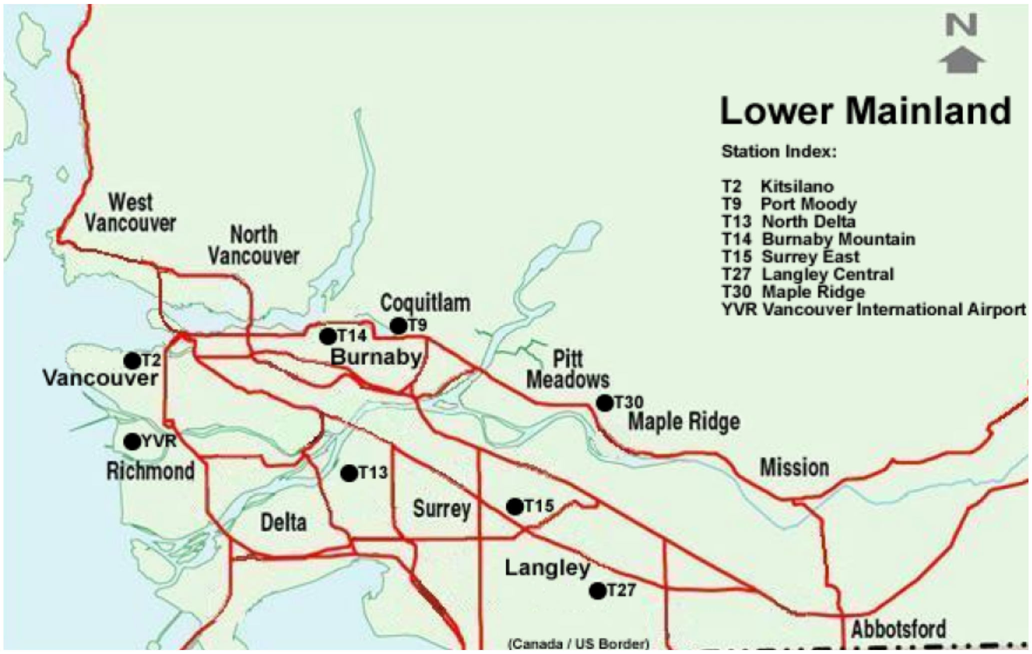


Figure 5-13: Eight Lower Mainland Weather Stations (Levelton 2004)

Differences in seasonal and annual rainfall are shown in Table 5-1 and windspeed in Table 5-2.

Table 5-1: Rain Measurements for 12 Coastal BC Stations (Levelton 2004)

Station[1]	Average Seasonal Rainfall Amounts (mm)				Average Annual Rainfall Amount (mm)
	Spring	Summer	Fall	Winter	
Port Hardy Airport	290	212	691	614	1,807
Comox Airport	204	125	340	421	1,089
Nanaimo Airport	205	107	304	421	1,037
Victoria Int'l Airport	159	88	275	340	861
Vancouver Int1 Airport	242	146	349	412	1,150
Kitsilano	277	140	366	510	1,293
Burnaby Mountain	420	241	511	685	1,858
North Delta	271	164	407	499	1,342
Port Moody	397	182	522	667	1,767
Surrey East	284	146	341	494	1,265
Maple Ridge	337	186	468	476	1,466
Langley Central	269	119	347	585	1,320

[1] Listed in geographical order from west to east.

Table 5-2: Wind Measurements for 12 Coastal BC Weather (Levelton 2004)

Station	Average Wind Speed (m/s) *(Standard Deviation of Wind Speed (m/s))*	
	All Hours	Wet Hours
Port Hardy Airport	3.1 *(2.7)*	4.0 *(3.1)*
Comox Airport	3.5 *(3.0)*	5.9 *(4.2)*
Nanaimo Airport	2.2 *(1.9)*	2.7 *(2.2)*
Victoria Int'l Airport	2.4 *(1.9)*	3.1 *(2.3)*
Vancouver Int1 Airport	3.3 *(2.3)*	4.3 *(2.2)*
Kitsilano	1.6 *(1.0)*	2.0 *(0.9)*
Burnaby Mountain	3.9 *(2.0)*	5.1 *(2.2)*
North Delta	2.1 *(1.1)*	2.7 *(1.2)*
Port Moody	1.4 *(0.9)*	1.4 *(0.8)*
Surrey East	1.7 *(1.0)*	2.1 *(1.2)*
Maple Ridge	1.5 *(0.9)*	1.7 *(1.0)*
Langley Central	2.0 *(1.4)*	2.7 *(1.8)*

The weather station in Kitsilano (data presented above, station T2 in Figure 5-13) is located within the city of Vancouver and is situated closer to the five buildings than the airport. Higher rainfall deposition is observed at Kitsilano than at the airport however significantly lower average windspeeds (approximately half) were observed. In contrast, higher windspeeds and rainfall amount were observed at a local high point on Burnaby Mountain (at the Simon Fraser University Campus).

The distribution of rainfall intensity for Kitsilano is compared to YVR in Figure 5-14 showing more hours of rainfall in Kitsilano. Similar plots are presented for the five building in Section 5.4 and referenced in the discussion on driving rain.

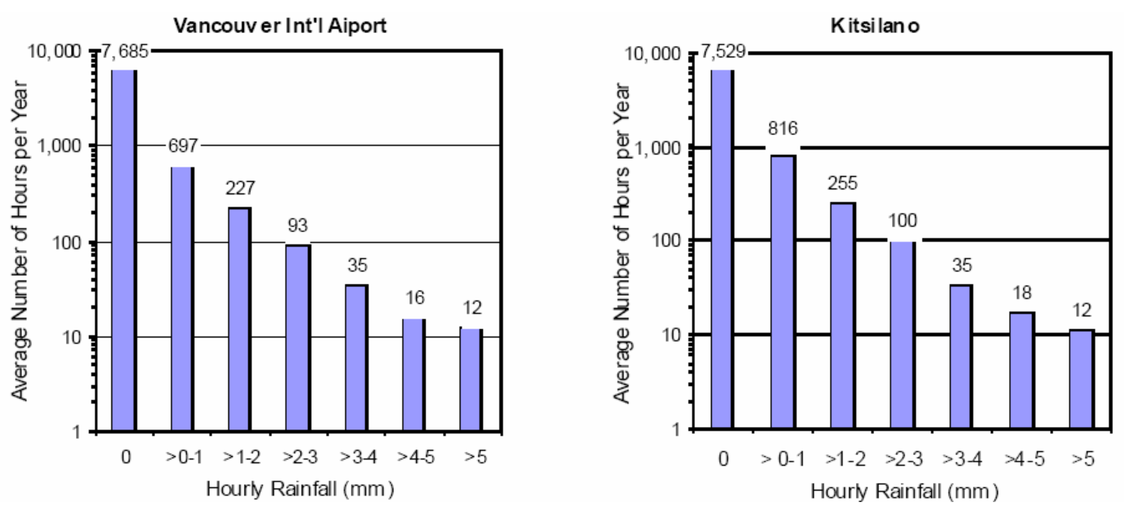


Figure 5-14: Rainfall Intensity for 2 Stations in Vancouver (Levelton 2004)

As shown the climate across Vancouver can be varied in surface and air temperature, windspeed and direction, and rainfall. These climatic differences have an impact on the design and performance of buildings across the city. Assuming the conditions measured at the airport when making design decisions may have a negative impact on design. As many hygrothermal simulation programs only provide data measured at the airport, appropriate correction factors should be made to represent conditions at the actual building site. This may be as simple as applying multiplication factors to account for additional rain or higher windspeeds and will be discussed later in this chapter.

5.3 SOLAR RADIATION

Solar radiation data was provided by the University of British Columbia (UBC) to supplement the collected weather measurements at each of the five buildings and the airport. While the data was not collected at the buildings (<10 km away), only small differences (due to localized cloud cover) would be observed in solar radiation intensity between UBC and the buildings. Solar radiation data is used with the measured weather data to perform hygrothermal simulations later in this thesis. Methodology to compile these annual climate files is discussed in *Appendix B: Hygrothermal Modeling*.

Solar radiation data was measured using a pyranometer, which measures the total solar radiation on a horizontal surface (W/m^2). To apply this horizontal measurement onto the vertical facade of the buildings, the components of direct and diffuse radiation must be determined from the single horizontal measurement using empirical methods. After direct and diffuse solar radiation components are determined, mathematical relationships for the sun's location and angle to the building are applied to calculate the solar radiation on a vertical surface for any given orientation. The calculation procedure and methodology is described in *Appendix H: Solar Radiation Measurements and Calculations* and results are used throughout the thesis.

The measured solar radiation data is compared to two independent sources: one from CWEC data for averages from 1971-2000 (Environment Canada 2005) and the second from WUFI 4.0 which provides "Hot-Year" and "Cold-year" weather file for Vancouver, BC. The solar radiation data was compared to these available sources to confirm the accuracy of the UBC measurements and conversion methodology. Solar radiation data was not collected by Environment Canada within Vancouver from 2000-2005 and could not be used for a validation of the actual hourly measurements.

The components of diffuse, beam (direct), and total solar radiation was extracted from the CWEC and WUFI data files and compared. While the methodology which was used to convert/measure the diffuse or direct radiation is unknown in these sources, it provides an industry recognized measurement of these values (where none other exists) for comparison of the measurements and methodology developed in this thesis.

It was found that the measured horizontal radiation from UBC (January 1st, 2001 to January 1st, 2005 provided) correlates well with total monthly averages (Figure 5-15). In addition, the calculated diffuse and direct radiation also correlate well (Figure 5-16) showing the relative accuracy of method described in *Appendix H: Solar Radiation Measurements and Calculations*. Monthly averages are for 24 hours per day for all days of the month and further hourly comparisons are shown in the Appendix.

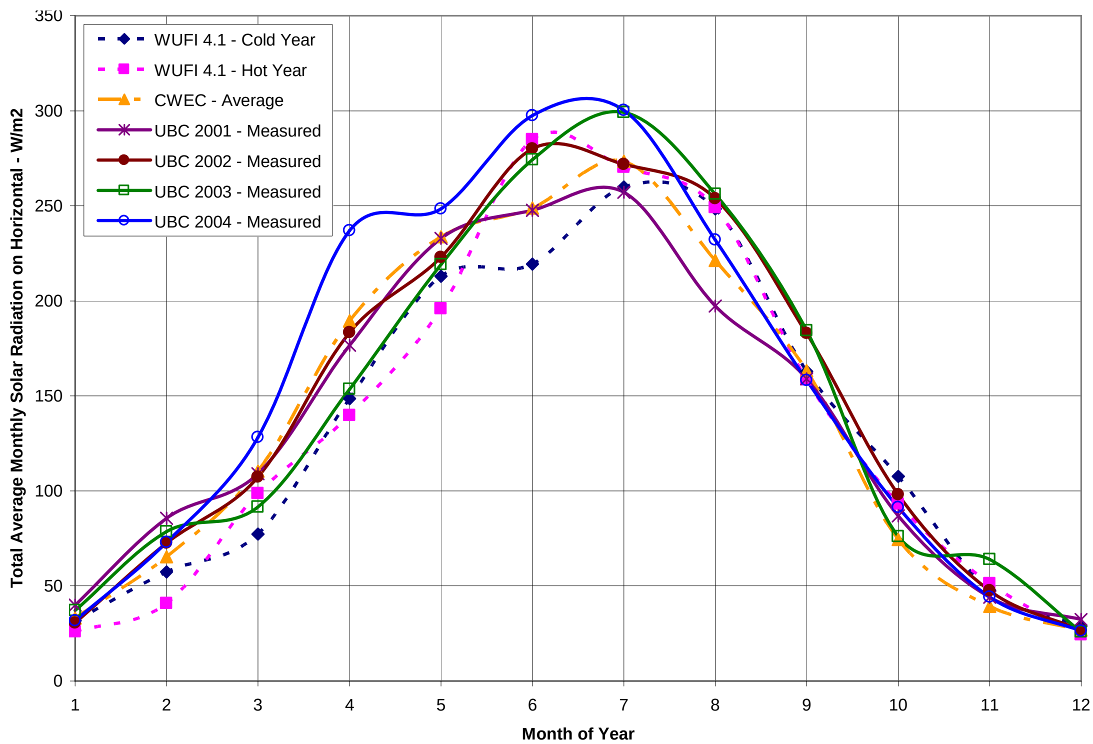


Figure 5-15: Monthly Average Total Solar Radiation on a Horizontal Surface for Vancouver, BC – Comparison of Data Sources

The total solar radiation (above) is equal to the components of diffuse and beam (direct) radiation on the horizontal surface. The calculated diffuse radiation is presented in Figure 5-16, with the beam (direct) component making up the differences between Figure 5-15 and Figure 5-16.

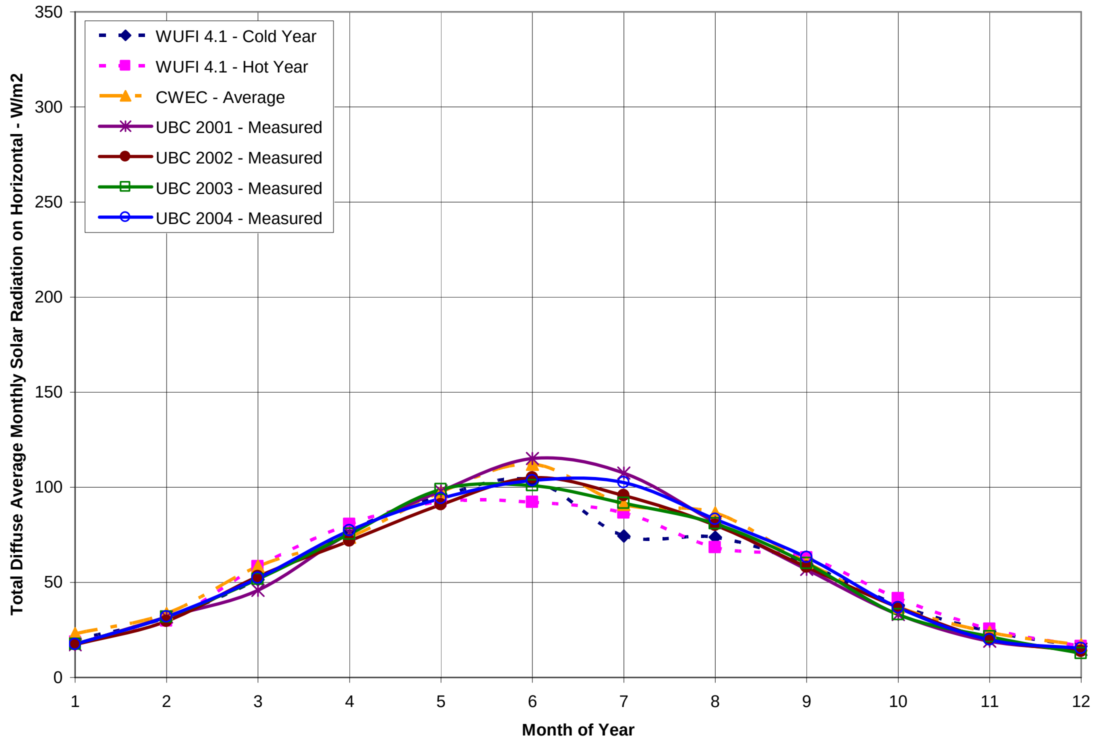


Figure 5-16: Monthly Average Diffuse Solar Radiation on a Horizontal Surface for Vancouver, BC – Comparison of Data Sources

As shown, during the winter months when the sun is low and days are shorter, solar radiation levels are quite low, on average less than 1/6th than in the summer months. The winter months are also the rainiest in Vancouver. The combined low solar radiation, short days, and high amounts of rain make for a relatively wet climate with a limited drying potential. The impact of Solar Radiation on the wetting and drying potential for walls is demonstrated in *Appendix C: Maximum Drying Potential Model*.

5.4 MEASURED RAIN & WIND

In this section measured rainfall and wind data is presented for the five buildings and is discussed with comparisons across sites and to the airport.

5.4.1 Rain

A summary of monthly rainfall measurements from 2001 to 2005 for Buildings 1 through 5 and the airport are provided in Table 5-3. Where cells are blank, data was missing (entire or part of month) or not yet recorded for that building. Monthly rainfall is summed annually and for the part years collected to compare differences across the six sites.

Table 5-3: Summary of Measured Rainfall on Horizontal – Buildings 1-5 & YVR

	YVR	**Building 1**	**Building 2**	**Building 3**	**Building 4**	**Building 5**
Jan 2001	130.3					
Feb 2001	25.8					
Mar 2001	120.2					
Apr 2001	107.7					
May 2001	47.6					
Jun 2001	60.4					
Jul 2001	39.3	48.8	36.4			
Aug 2001	88.4	93.4	90.4			
Sep 2001	43.6	39.2	47.2			
Oct 2001	146.1	173	150			
Nov 2001	141.9	141.8	142			
Dec 2001	211	203.6	205			
TOTAL Jul-Dec.	**670.3**	**699.8**	**671**			
TOTAL 2001	**1162.3**	**-**	**-**			
Jan 2002	133.4	154.8	142.4			
Feb 2002	103.3	110.2	102.6			
Mar 2002	55.6	86.8	86.6			
Apr 2002	82.3	83	77.6	99.2	89.4	
May 2002	51.5	42.2	56.8	71.4	67	
Jun 2002	30.8	33.4	33.2	36.2	36.6	
Jul 2002	15.2	15.4	26	23.6	16.8	
Aug 2002	5.8	13.6	2.6	7.8	6.2	
Sep 2002	34.6	51.4	44.6	54.8	53	
Oct 2002	18.3	16	17.4	17.2	16.4	
Nov 2002	147.7	197.6	186.4	228.6	212.6	
Dec 2002	139.5	109.6	128.2	140	130	
TOTAL Apr-Dec.	**525.7**	**562.2**	**572.8**	**678.8**	**628**	
TOTAL 2002	**818**	**914**	**904.4**	**-**	**-**	
Jan 2003	150.5	129.2	130	146.2	132.6	151.2
Feb 2003	27.1	37	30.8	33	32.8	40
Mar 2003	130	131.2	131	149.2	140.2	178.8
Apr 2003	139.6	110.8	120.4	112.6	123.2	146

	YVR	Building 1	Building 2	Building 3	Building 4	Building 5
May 2003	49.3	54.4	42.6	64.8	57	72.4
Jun 2003	12.8	16.2	12.6	14.4	14.4	16.6
Jul 2003	19.8	13.6	22.4	25.4	24	31.8
Aug 2003	4.1	5.6	4	5.8	5.4	7.6
Sep 2003	40.2	27.6	29.2	36.2	36.2	43
Oct 2003	248.2	232	234.6	258	252.2	
Nov 2003	167.4	193.8	187.2	217.2	203.6	
Dec 2003	97.2	78	122.6	124.2	114.8	134.8
TOTAL Jan-Sep	**573.4**	**525.6**	**523**	**587.6**	**565.8**	**687.4**
TOTAL 2003	**1086.2**	**1029.4**	**1067.4**	**1187**	**1136.4**	**-**
Jan 2004	151.6			165.6	171.4	148.2
Feb 2004	83.4			70	78.2	80
Mar 2004	101.2	137.6	108.6	126.4	130.6	118.6
Apr 2004	15	26	14.8	17	18.6	20
May 2004	60.8	92.8	79	81.2	94	98.8
Jun 2004	22.8	19.2	19.6	18.2	19.2	22.2
Jul 2004	16.6			12	16.2	12.4
Aug 2004	75			88.4	73	78.8
Sep 2004	169.4			91.6	97.6	99.6
Oct 2004	117.2			115.8	121.4	111.8
Nov 2004	199.6			188.6	210.2	169.4
Dec 2004	188.2			175.8	193	176.2
TOTAL Mar-Jun	**199.8**	**275.6**	**222**	**242.8**	**262.4**	**259.6**
TOTAL 2004	**1200.8**	**-**	**-**	**1150.6**	**1223.4**	**1136**

Data from 2003 is compared across the six sites in Figure 5-17 showing the measured differences in rainfall. Further plots of the data for 2001, 2002, and 2004 are provided in *Appendix F: Supplemental Measured Data.*

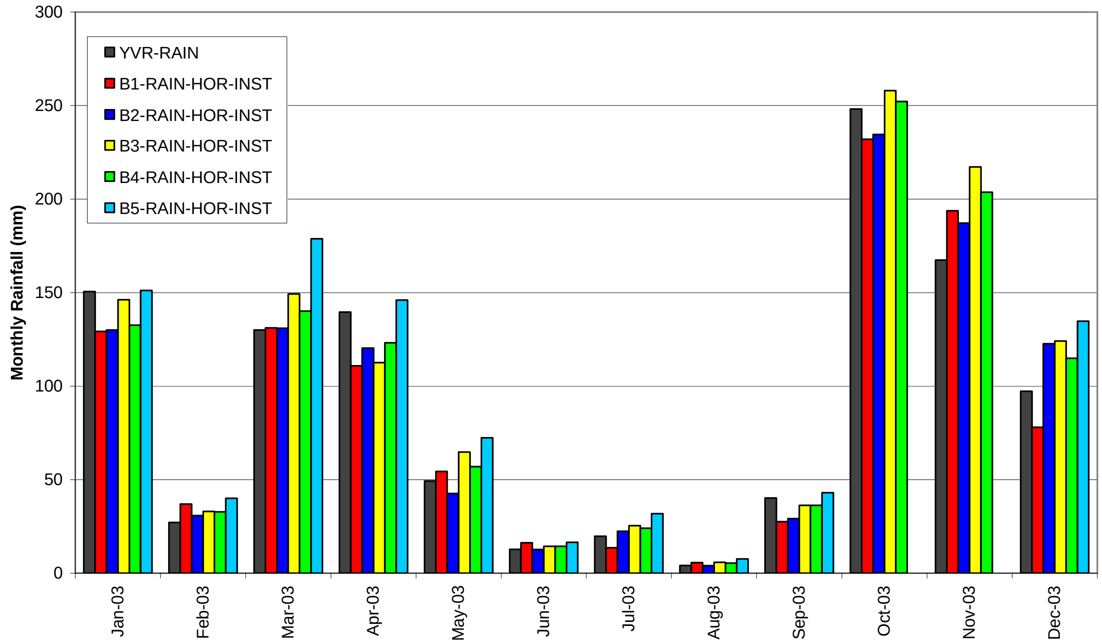


Figure 5-17: Comparison of Rainfall across Buildings & YVR - 2003

A difference in rainfall of up to approximately 50 mm (2") per month is observed between the airport and downtown at Building 5, however is not consistent over every month. On average, observations indicate lower rainfall accumulation at the airport compared to the five buildings within the city of Vancouver; however the differences may not be as large as suggested by the contour maps shown previously by Oke & Hay (1974).

5.4.2 Windspeed and Direction

The predominant wind direction in Vancouver is shown to be east to southeast. However this varies by month and the average wind direction shifts from east/southeast during the winter months to south/southwest during the summer months. Figure 5-18 presents measurements of wind direction and windspeed for the airport and the five buildings showing the relative differences between sites.

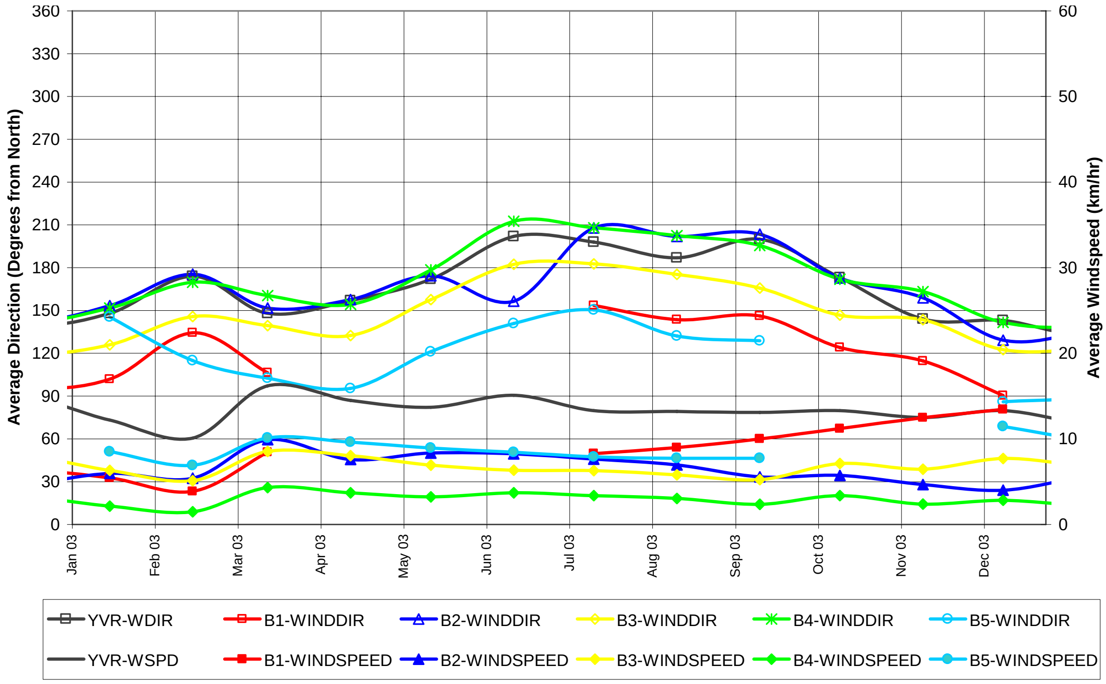
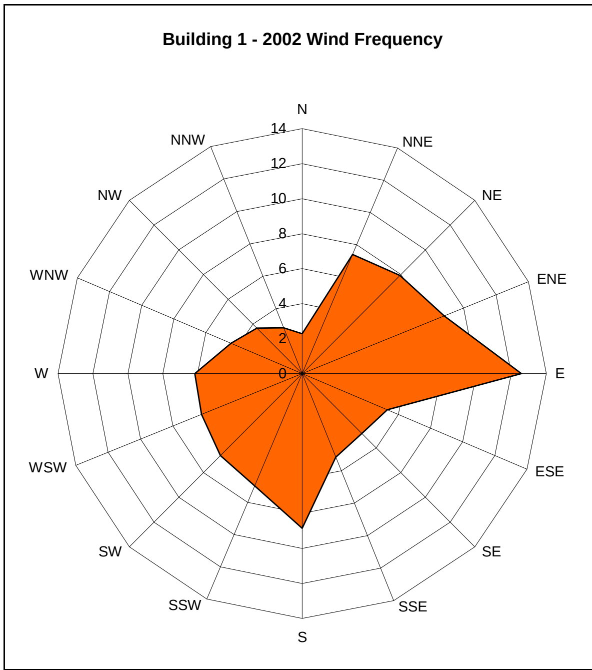


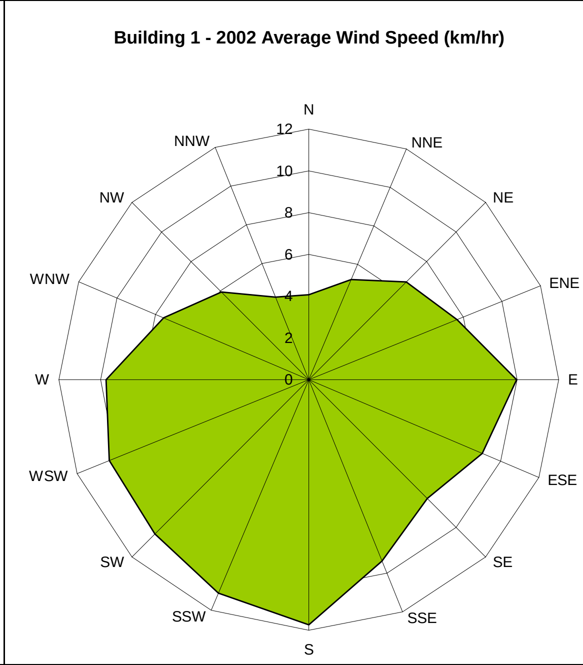
Figure 5-18: Comparison of Wind Speed/Direction - Buildings 1-5& YVR – 2003

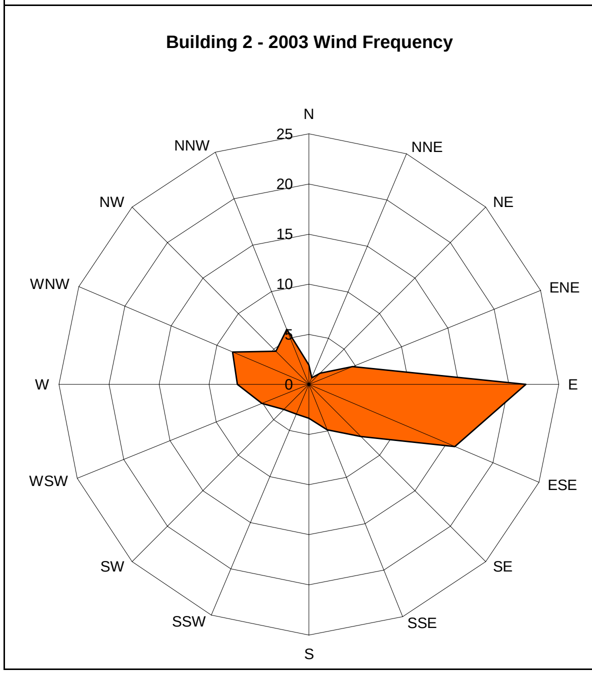
A similar trend is repeated annually for the fives years of data collected and is not an anomaly as shown for 2003. Wind speeds are highest at the airport and lowest at Building 4. Buildings 1, 2, and 3 also recorded low windspeeds, while Building 5, downtown had moderate levels. The difference in wind-direction at Building 5 is also highlighted as different from the other locations as discussed below. Further data plots are provided in *Appendix F: Supplemental Measured Data.*

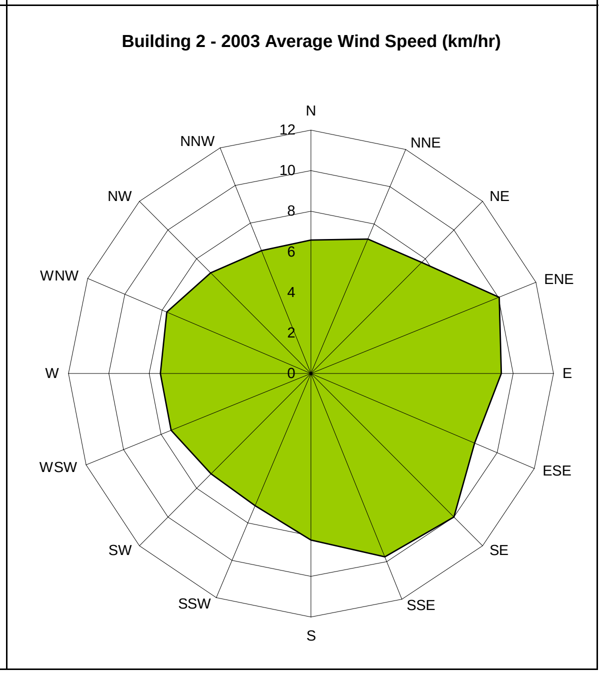
While Figure 5-18 provided average readings of windspeed and direction, average readings actually tell little about the predominant wind direction or windspeed from that direction. Instead, wind-roses were produced plotting wind frequency with direction and average wind speed with direction for each building and the airport. Table 5-4 presents a summary of the wind data from each of the five buildings and compared to the airport from CWEC data compiled by Straube & Schumacher (2006). Note that the vertical scale is not necessarily the same for all plots and the year is not the same (as a common year of continuous data was not collected across all buildings simultaneously). Years not shown here have similar relationships.

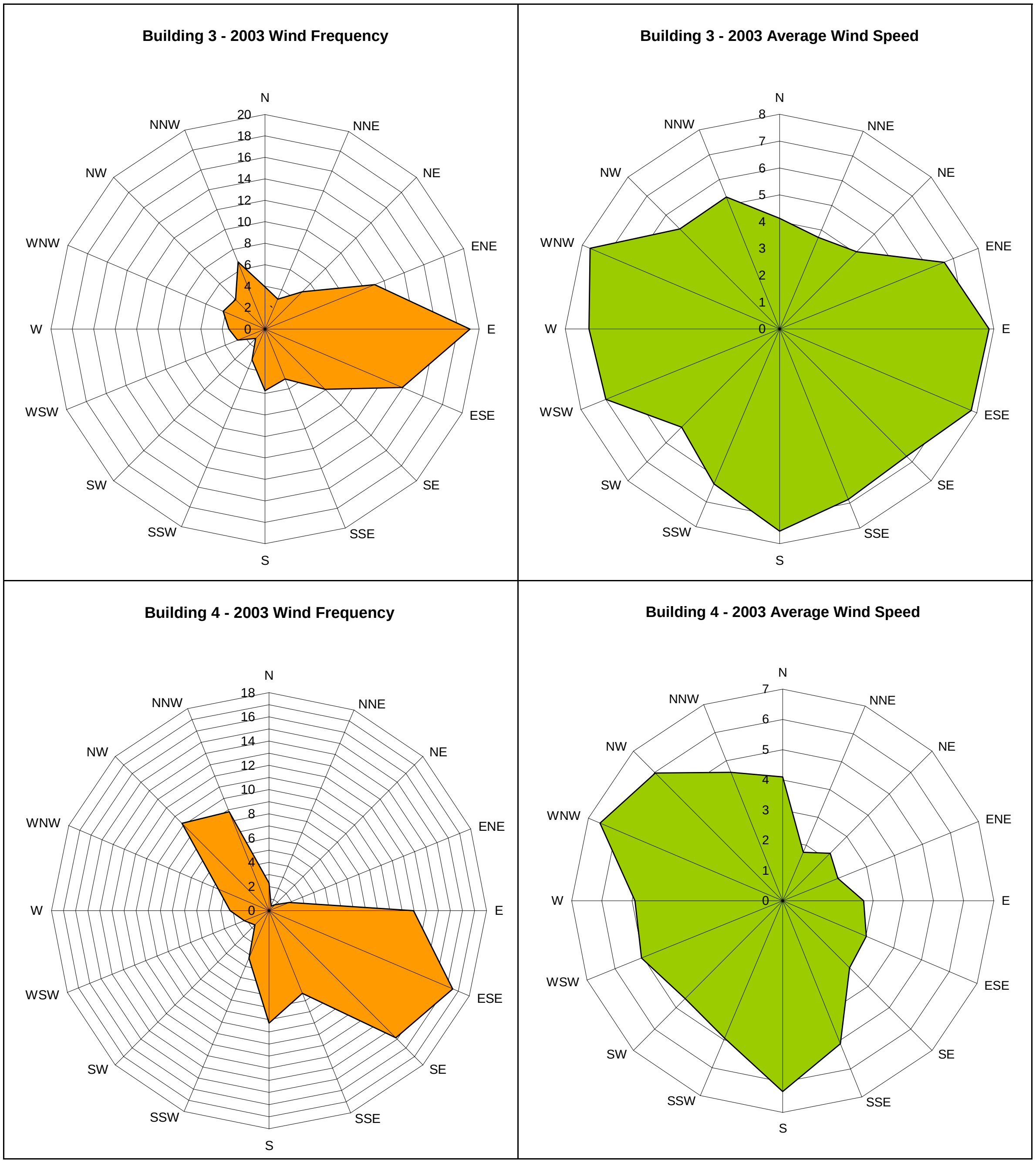
Table 5-4: Measured Wind Direction Frequency (%) and Windspeed (km/hr)

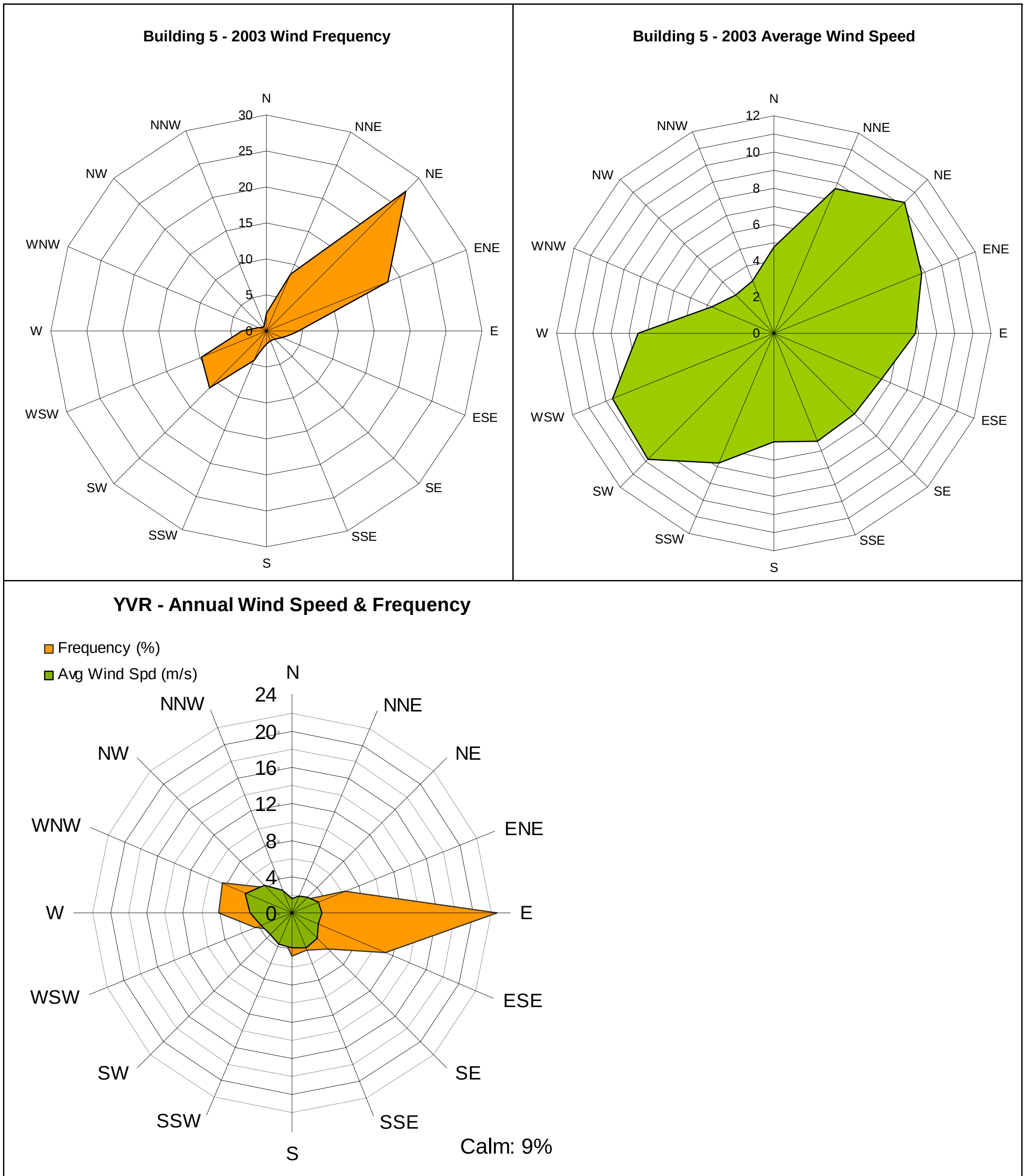









Building 3 - 2003 Wind Frequency
N
NNE
NE
ENE
E
ESE
SE
SSE
S
SSW
SW
WSW
W
WNW
NW
NNW
0
2
4
6
8
10
12
14
16
18
20
Building 3 - 2003 Average Wind Speed
0
1
2
3
4
5
6
7
8
Building 4 - 2003 Wind Frequency
18
Building 4 - 2003 Average Wind Speed



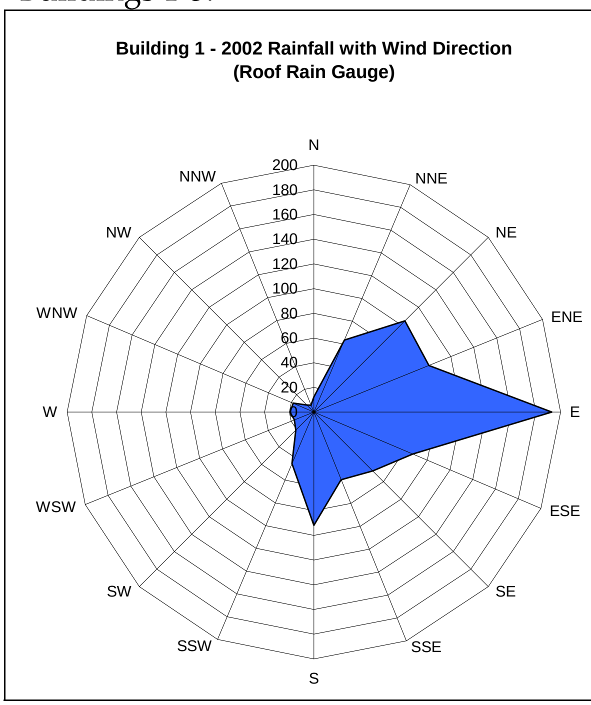
(YVR source CWEC weather files from: Straube & Schumacher 2005)

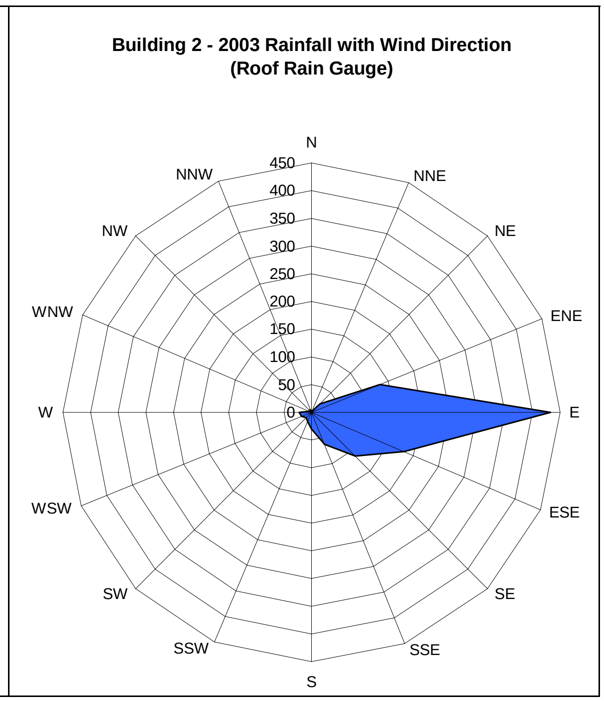
The differences in predominant wind direction and windspeed are shown across the five buildings. The influence of topography and local sheltering from surrounding buildings is also shown.

While the predominant wind direction at Buildings 1-4 and the airport is from the east to southeast, at Building 5 the predominant direction is from the northeast (27% of the time). Average windspeeds are also strongest at Building 5 from the northeast and southwest, showing sheltering at other directions. As discussed, winds from of the North Shore Mountains across the Burrard inlet appear to be predominantly from the northeast into downtown (Oke & Hay 1994). Wind sheltering and the impacts of other adjacent high-rises could also be influencing this anomaly as compared to the other buildings.

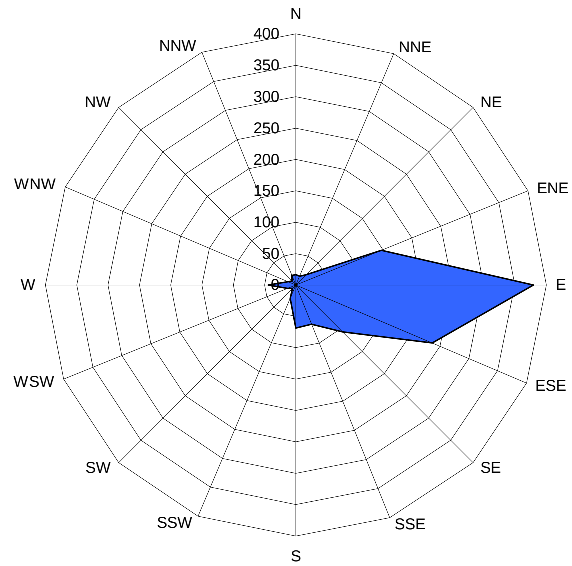
Further to the wind data, wind direction is correlated with horizontal rainfall measurements at the roof to determine the primary direction of driving rain at each building (Table 5-5). These plots are not the calculated driving rain on a surface but an indicator of the predominant wind direction during rain events. Note that the vertical scale is not necessarily the same for all plots and the year is not the same (as a common year of continuous data is not available for all buildings). Actual driving rain plots for each of the buildings are calculated and presented in the following section as these plots only show direction of wind during rain events.

Table 5-5: Wind Direction correlated with Rainfall on Horizontal (mm) for Buildings 1-5.

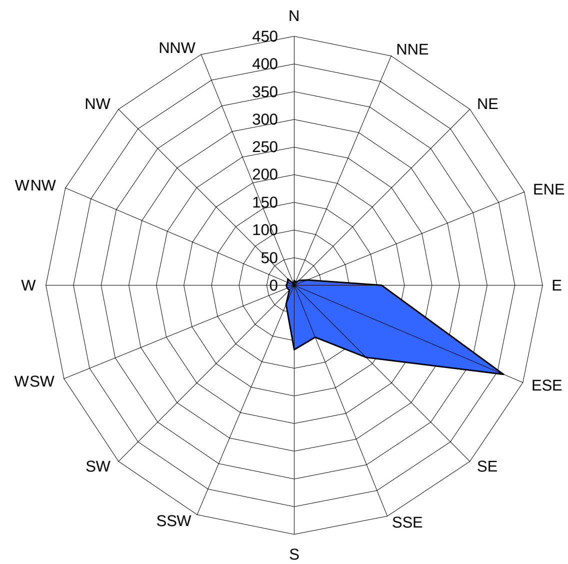




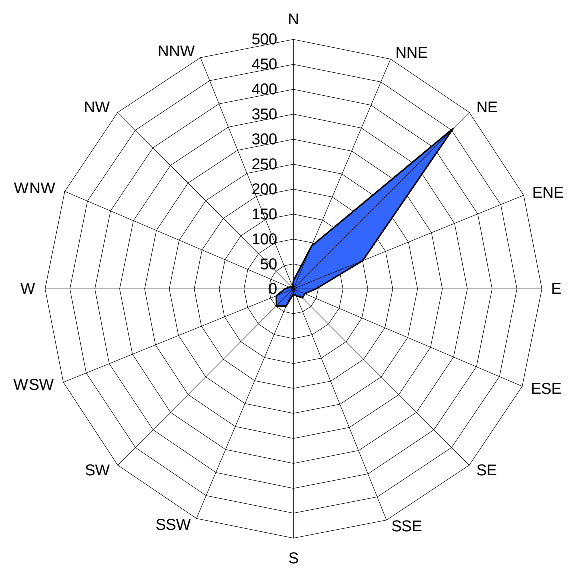
Building 3 - 2003 Rainfall with Wind Direction (Roof Vertical Rain Gauge)



Building 4 - 2003 Rainfall with Wind Direction (Roof Vertical Rain Gauge)



Building 5 - 2003 Rainfall with Wind Direction (Roof Vertical Rain Gauge)



The predominant direction for wind and rain is from the east for Buildings 1, 2, and 3; east-southeast for Building 4; and northeast for Building 5.

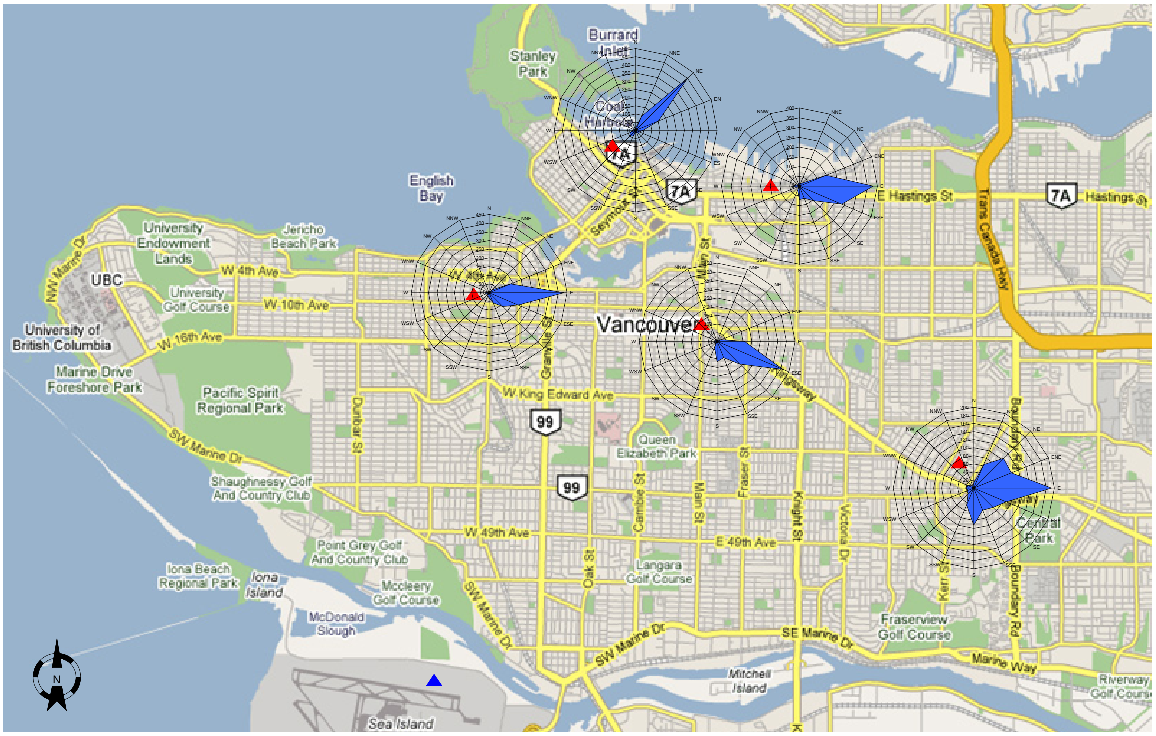
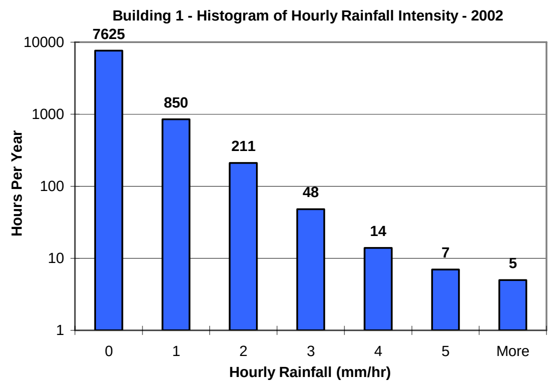


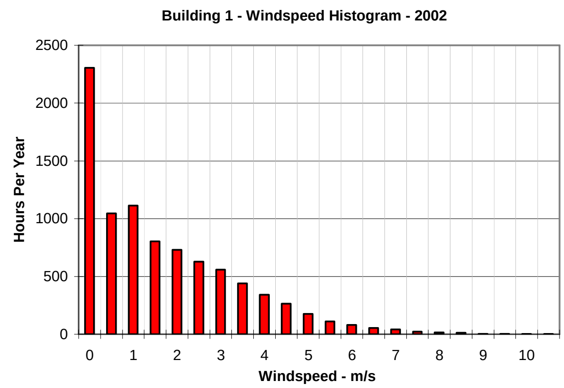
Figure 5-19: Summary of Wind Direction during Rain Events – Buildings 1-5 (underlay map: Google Maps 2006)

Rainfall intensity and windspeed histograms are also plotted for each building to understand the frequency distribution of wind and rain events (Table 5-6). The bins are represented by a single number on the x-axis which corresponds to a range from the number to the number on the left (ie. 1 mm/hr corresponds to 0-1 mm/hr and 2 mm/hr corresponds to 1-2 mm/hr. etc).

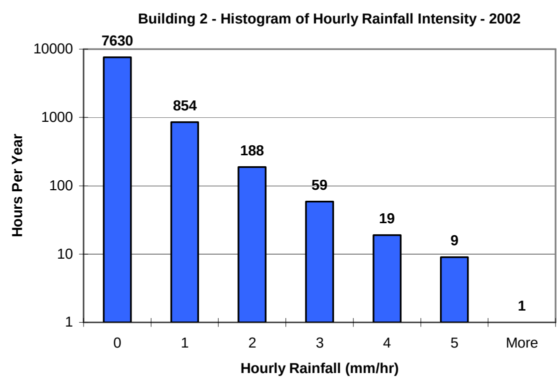
Windspeed bins are in 0.5 m/s increments from 0 to 10 m/s. Calm winds are represented by 0 m/s and make up a high percentage of the hours at low-rise Buildings 1, 2 and 4. However at mid and high-rise Buildings 3 and 5 zero calm hours were observed possibly as a result of the higher exposure at the rooftops of these buildings.

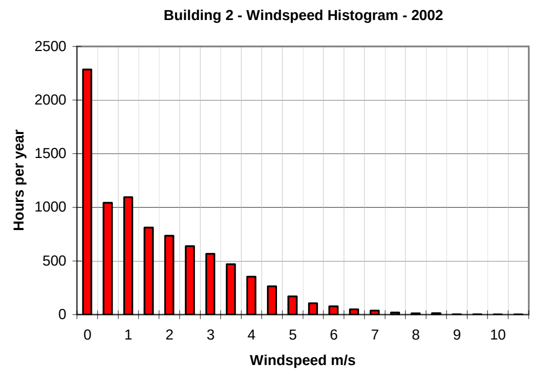
Table 5-6: Histograms of Hourly Rainfall Intensity and Windspeed, Buildings 1-5



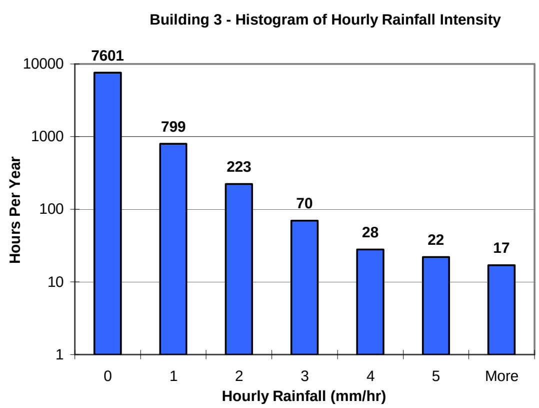


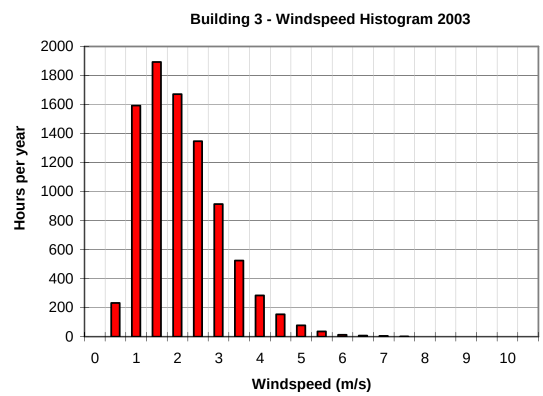
Building 1 – 2002 Data



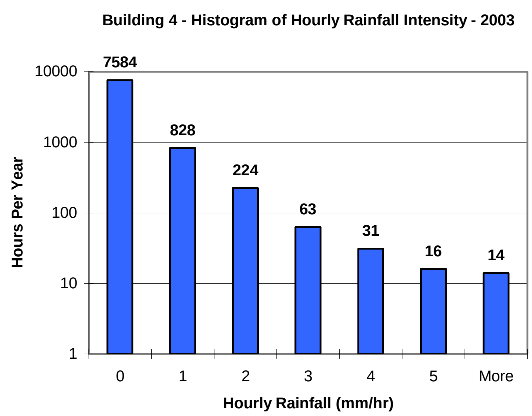


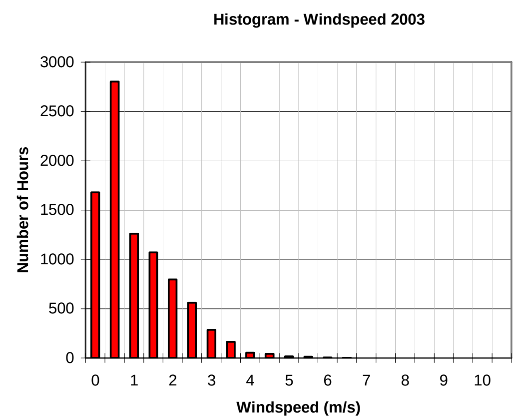
Building 2 – 2002 Data



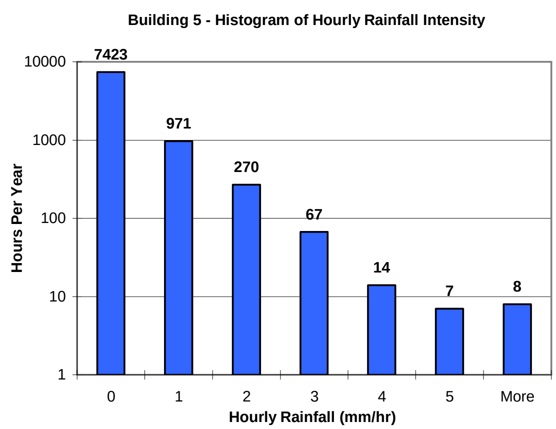


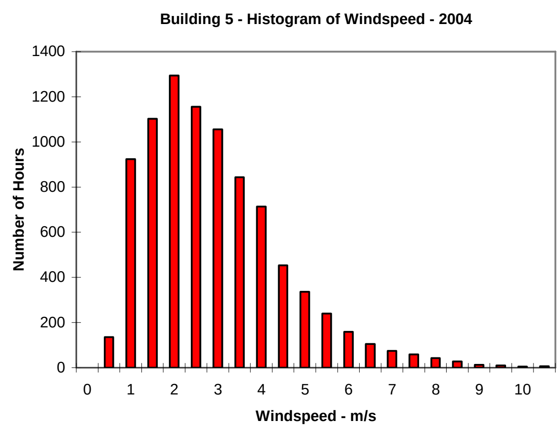
Building 3 – 2003 Data





Building 4 – 2003 Data





Building 5 – 2004 Data

Rainfall intensity plots are similar to those produced by Levelton (1994) showing the number of hours without rain, and the intensity of rainfall during wet hours.

Windspeed histograms show higher frequency of high wind events at exposed Building 5 as compared to the other buildings. The distribution of wind speed is compared to that from 25 years of data from the airport at Seattle, WA in Figure 5-20.

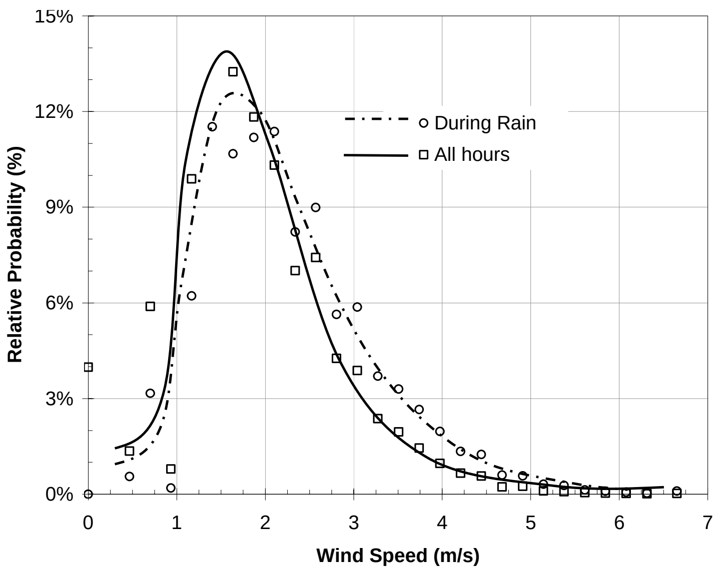


Figure 5-20: Relative probability distribution wind speed for Seattle, WA from 25 years or hourly data (Straube & Schumacher 2006)

The windspeed distribution from Seattle shows a similar distribution function as Buildings 3 and 5 (mid and high-rise), with the highest probability being between 1-2 m/s. The high frequency of zero readings at Buildings 1, 2, and 4 are potentially a result of sheltering at those sites (all low-rise), and unlikely an equipment issue (3 different windspeed monitors - 1 YM Young and 2 Omega as described in Chapter 4).

5.5 DRIVING RAIN

A brief background of driving rain theory is followed by a discussion of empirical calculation methods. Field observations and measurements of driving rain from the five buildings in the field study are then presented and compared to values predicted using an empirical model. Finally, the accuracy and limitations of using such empirical models to calculate driving rain loads are discussed for field applications.

5.5.1 Background

Driving rain, also referred to as wind-driven rain is the amount of rainwater that is deposited on a vertical wall surface under the influence of wind. It is a critical climatic load to consider when designing wall and window assemblies for buildings. Current best practice and some building codes provide guidelines for the design of wall assemblies based on exposure, which is function of the driving rain load. Unfortunately driving rain data is usually lacking, meaning that determination of an appropriate load is left up to professional judgement or experience of the designer. Therefore understanding and being able to predict driving rain loads at a specific location is of great interest to the building industry.

Driving rain is difficult to predict or quantify because the complex interactions between rain, wind, and the building itself. Driving rain is influenced by wind speed and direction, rain intensity and duration, local topography, surrounding buildings, building geometry, and building details such as overhangs, balconies or other protrusions.

Driving rain can be calculated on a building surface by one of three methods: field measurements, empirical calculations, or numerical methods using computer models. Measurements of driving rain on buildings are seldom recorded except in research applications; however some of these measurements have been correlated and applied to quantify driving rain measurements into empirical relationships. As a result, we are able to calculate the amount of rain in unobstructed wind flow with reasonable accuracy; however the interactions around a building add complexity to the calculations and often require the use of more advanced methods, which empirical models may not be able to accurately capture.

Numerical modeling using Computational Fluid Dynamics (CFD) has improved our understanding of wind-rain interactions with buildings in recent years. Some CFD models have been shown to be in relatively good agreement with measurements for simple buildings under influence of wind and rain in the field (Blocken and Carmeliet 2000 & 2006b, Blocken 2004, van Mook 2002). However, CFD models currently remain only useful as a research tool, beyond the grasp of most practitioners due to cost, computational time, and high complexity.

Empirical methods are still better suited for general applications because of their simplicity; however only if they are able accurately predict driving rain loads on buildings. As a minimum, empirical methods should be able to predict the worst case driving load for a building; which can be used for most design applications. In addition, due to scepticism by some, further correlation between field measurements and either empirical or numerical CFD models are required before widespread acceptance of either method is made.

Field measurements of driving rain loads in Vancouver have received limited research in the past with most studies focusing on relationships between wind, rain, and driving rain pressures, but not focusing on actual driving rain loads.

The relationships of wind and rain were studied across Canada by Surry et al. (1995), however as part of the criteria for the study, only looked only at the months from April to September across the country to avoid measurement issues with recording of snowfall. In addition, Victoria was selected to be representative of British Columbia. Two critical omissions to understanding driving rain in BC were made which were reflected in the results: referring to Table 5-1 and Figure 5-5, it is shown that Victoria on average receives less rainfall than Vancouver, and that BC's "dry-season" is from April to September. As shown in the previous section, the majority of precipitation in BC occurs during the winter months of October to April in form of rain while other Canadian locations see snow. In this study the driving rain relationships were severely under predicted for BC.

Improving on BC data from the 1995 study, relationships between wind and rain were summarized for several weather stations in coastal British Columbia by Levelton (2004) as presented in Section 5.2. Driving rain loads were not calculated but a correlation was made between wind direction and rainfall similar to that shown for the five Buildings in Table 5-5. In addition, the predominant directions of driving rain in different locations were presented and discussed. This was a step forward in determining worst case exposures and relative driving rain loads for buildings within the city, however actual driving rain loads on buildings were not determined.

Moving forward, Straube and Schumacher (2006) calculated driving rain loads for several cities across Canada using hourly weather data from CWEC files (representative of average conditions). Vancouver was found to have the highest annual average hours of rain (Figure 5-21), however slightly higher driving rain loads were calculated for other Atlantic coast cities of Sydney, NS, Saint John, NB, and St. Johns, NF (Figure 5-22). Significantly lower driving rain loads were calculated at inland Canadian cities (away from oceans) than those on the east and west coasts. Victoria, BC was also shown to have a significantly smaller driving rain load than Vancouver.

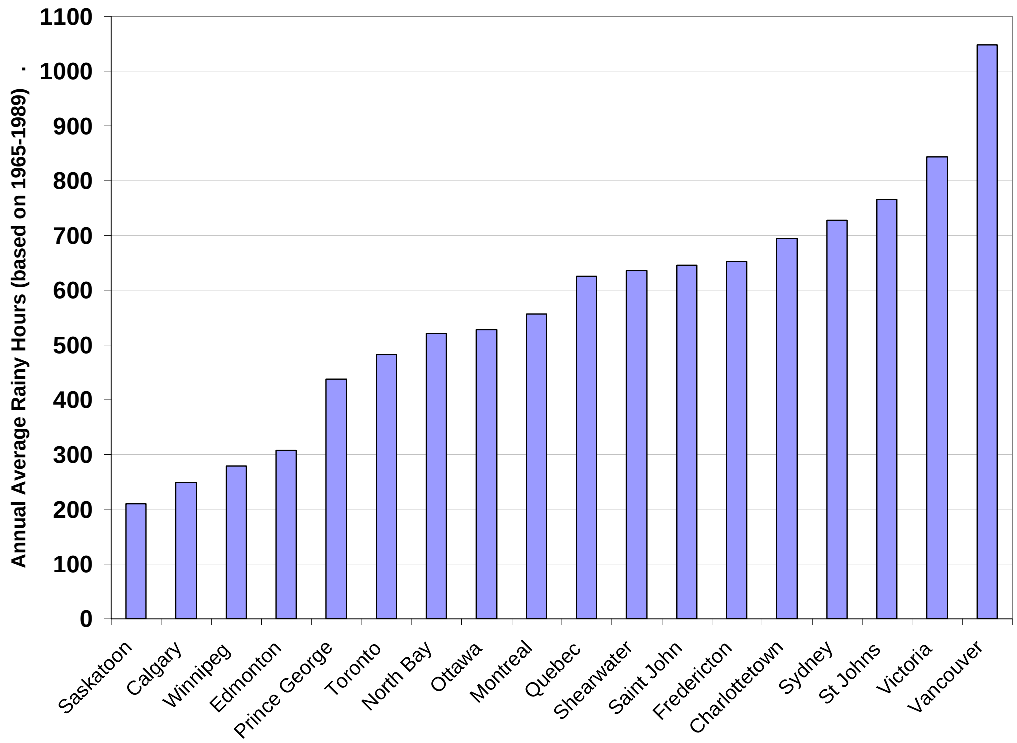


Figure 5-21: Annual Average Rainy Hours for Selected Cities across Canada (Straube & Schumacher 2006)

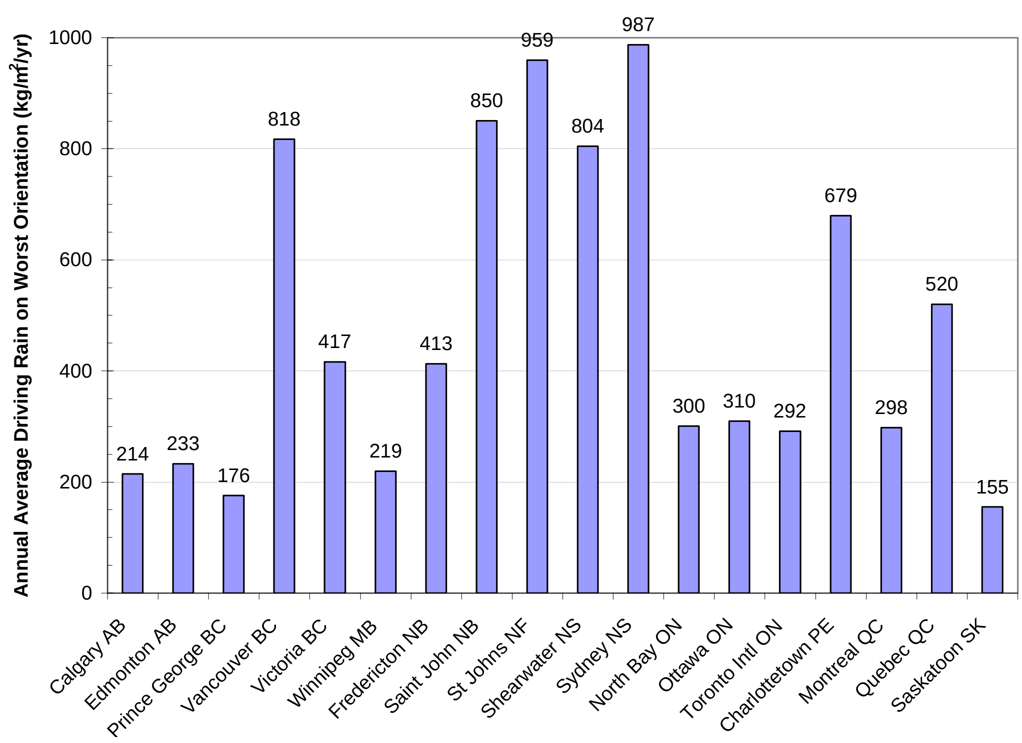


Figure 5-22: Annual Average Driving Rain on Worst Orientation for Selected Cities across Canada (Straube & Schumacher 2006)

Recently at the British Columbia Institute of Technology (BCIT), a research project measured driving rain on a low-rise building. Annual driving rain loads are not presented, however the spatial relationships of driving rain were investigated for several rainstorms during the winter. Preliminary results measured largest deposition at corners of the building and that a 130 mm overhang was found to reduce wetting of the wall surface below it by two to five times (Ge and Krpan 2007).

To improve the understanding of driving rain in Vancouver, measurements and observations are presented here for each of the five buildings in the study. The measurements are compared to calculated results from a simple empirical model and the accuracy of the model is discussed. The use of CFD models to correlate with the measured wind driven rain is beyond the scope of this thesis.

5.5.2 Calculating Driving Rain

Driving rain can be defined as the quantity of rain that passes through a vertical plane under the influence of wind. On buildings, this is the amount of rain that impinges on the vertical façade. Driving rain will either be absorbed by the cladding, run-down the face of the cladding, and/or in some circumstances penetrate into the wall assembly. Calculating the amount of driving rain that impinges on the vertical façade of a building at a particular location is of interest to many practitioners. With knowledge of the driving rain load, designers are able to assess the exposure and potential risk of selecting certain claddings and wall assemblies. For example, some upcoming standards such as ASHRAE 160P will require a percentage of the driving rain load on the cladding to be absorbed into the wall assembly without failure. Therefore understanding and predicting the correct load would be critical for this application.

Starting within the clouds, raindrops fall to the ground at their terminal velocity and are be blown sideways at the speed of the wind. Gravity pulls the raindrop to the ground and the wind carries the rain drop horizontally determining the resulting trajectory (Figure 5-23). A simple geometric relationship can then be used to determine the amount of rain passing through a vertical plane (driving rain). This simple assessment is complicated by the range of raindrop sizes during a storm, however a distribution function can be determined based on previous meteorological research.

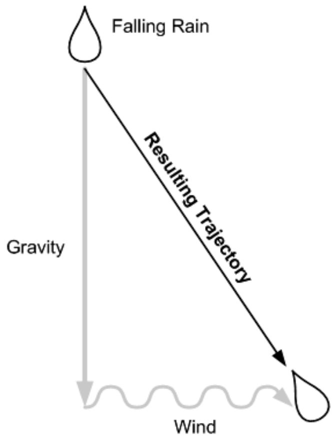


Figure 5-23: Wind Driven Rain (Straube and Schumacher 2006)

One of the first correlations between unobstructed wind flow and rainfall was developed by Lacy (1965) at the Building Research Establishment (BRE) in the United Kingdom (UK). The correlation was based on a mix of field measurements and calculations across the UK and at the research facility. Lacy proposed a simple equation relating windspeed and rainfall intensity to driving rain:

$$r_v = 0.208 \cdot V \cdot r_h \qquad \text{(Eqn. 1)}$$

Where, r_v is the rate of rain through a vertical plane – driving rain (mm/hr),
V is the average wind velocity (m/s), and
r_h is the average rainfall rate on ground, horizontal plane (mm/hr).

Based on subsequent theoretical work and field measurements, Lacy's equation can be generalized to the following (Straube & Burnett 1997):

$$r_v = DRF \cdot V(h) \cdot r_h \qquad \text{(Eqn. 2)}$$

Where, DRF is a driving rain factor, and
$V(h)$ is the wind speed at the height of interest.

The driving rain factor (DRF) is a proportionality constant of the ratio of driving rain to rain on the horizontal (falling rain) as defined by Straube & Burnett (1997). The DRF is a function of raindrop size, distribution, and terminal velocity and is found to range from 0.20 to 0.25 for average conditions, and hence why the 0.208 factor used by Lacy was so successful on average (Straube & Schumacher 2006).

The DRF varies with rainfall intensity, and ranges from 0.5 for light mist to 0.15 for heavy downpours. Using field measurements and theoretical analysis, Straube (1998) found the value of the driving rain factor to be the inverse of the raindrop terminal velocity.

To determine the terminal velocity and subsequently the DRF, Straube and Schumacher (2006) outline the procedure with reference to the original research described here.

First the distribution of raindrop sizes as a function of rainfall intensity is determined using the following relationship.

$$F(\phi) = 1 - \exp\left(-\left(\frac{\varnothing}{1.30 \cdot r_h^{0.232}}\right)^{2.245}\right) \qquad \text{(Eqn. 3)}$$

Where, $F(\phi)$ is the cumulative probability distribution of drop diameters for a given rainfall intensity,
ϕ is the equivalent spherical raindrop diameter (mm), and
r_h is the rainfall rate or intensity on a horizontal plane (mm/m^2/h).

This distribution can be further mathematically simplified to determine the equivalent raindrop diameter.

$$\phi = 1.1042 \cdot r_h^{0.232} \qquad \text{(Eqn. 4)}$$

Knowing the relative distribution and the equivalent raindrop size, the terminal velocity for the raindrop in still air can be determined.

$$V_t(\phi) = -0.166033 + 4.91844\phi - 0.888016\phi^2 + 0.054888\phi^3 \leq 9.20 \qquad \text{(Eqn. 5)}$$

Where, ϕ is the raindrop diameter from equation 4 (mm), and
$V_t(\phi)$ is the terminal velocity of a raindrop in still air (m/s).

Finally, the DRF factor is calculated as the inverse of the terminal velocity in m/s ($1/V_t$). The relationship between DRF and rainfall intensity is shown in Figure

5-24 showing a higher DRF for low intensity rain events, to a lower DRF for high intensity events.

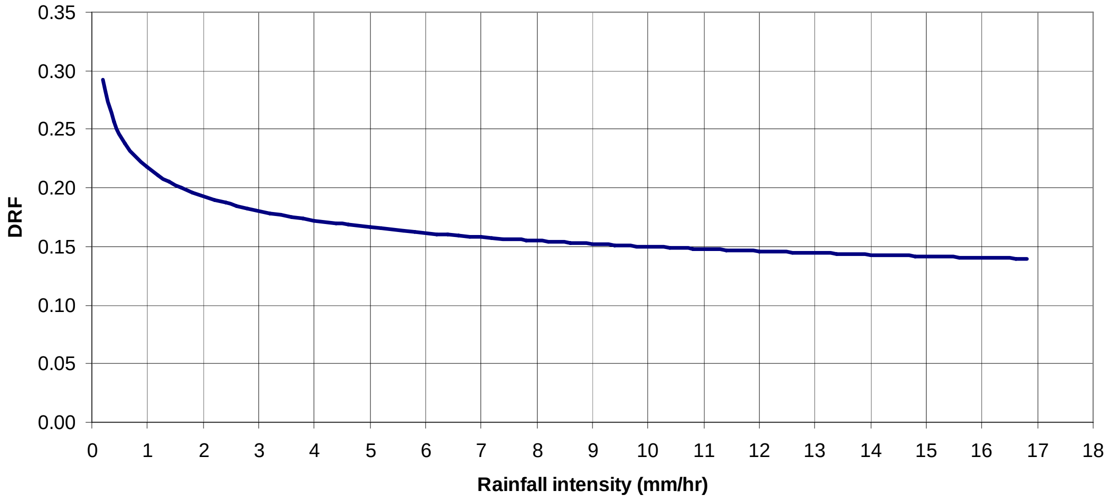


Figure 5-24: Calculated Driving Rain Factor (DRF) versus Rainfall Intensity

Appling this relationship to the hourly measured data, a histogram of the hourly calculated DRF factors is plotted in Figure 5-25 for Building 1 in 2002 and Building 5 in 2004. A similar distribution was observed at all five buildings over the four years from 2001-2005.

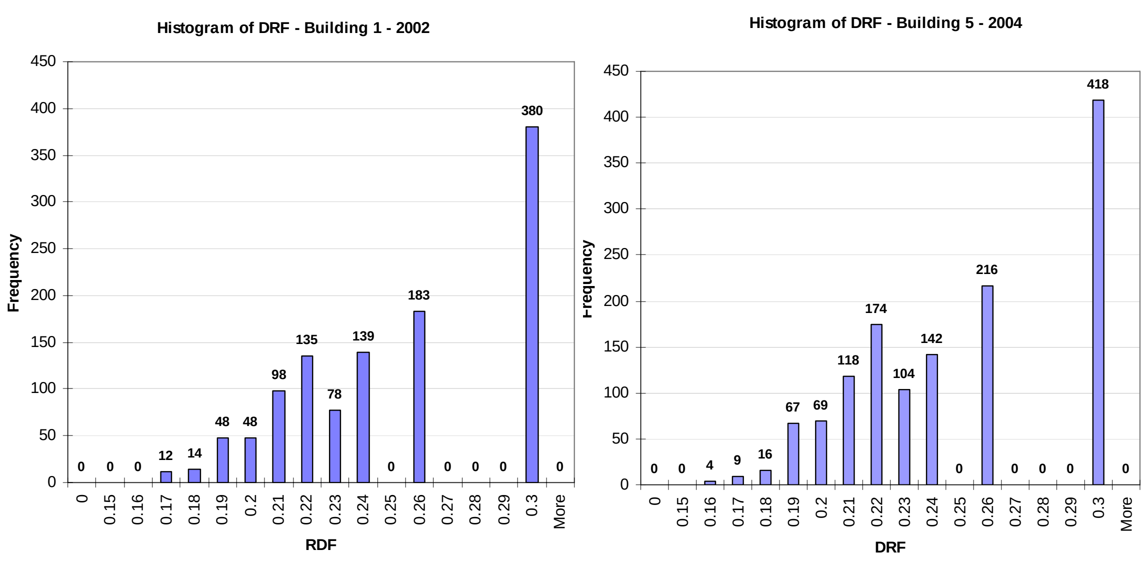


Figure 5-25: Histogram of Calculated Hourly DRF Factor for Buildings 1 and 5

Gaps in histogram data are due to the minimum 0.2 mm measuring resolution of the rooftop tipping rain gauge which is reflected in the calculation (ie there is a large gap difference in DRF between 0.2 and 0.4 mm which corresponds to a DRF of 0.3 and 0.26 respectively).

Considering all rain events, the annual average DRF factor for Building 1 in 2002 was 0.252 and Building 5 in 2004 was 0.255. RDF data collected from all five buildings in Vancouver from 2001-2005 resulted in an average DRF of 0.25 and ranged closely from 0.24 to 0.26. As the DRF is largely a function of the rainfall intensity, the observations in Table 5-6 (which showed similar rainfall intensities between buildings and over all years) is reflected in this calculated DRF.

Each city would have a different DRF factor depending on the characteristics of rain events in that climate. For example a climate with a lot of high-intensity thunderstorms would have a lower average DRF factor. Vancouver sees a high number of rainy hours, a large number of these with low intensity drizzle or light rain, thus resulting in a fairly high average DRF factor.

Once the DRF factor is determined, using hourly wind speed/direction and rainfall data, the driving rain deposition can be calculated for a given wind direction perpendicular to the building façade.

To calculate the total driving rain that would accumulate on the vertical surface of a building at a specific orientation a cosine projection is used to account for rain coming from the full 180° field of view for a wall plan as shown in Figure 5-26. Equation 2 is therefore modified to the following:

$$r_v = DRF \cdot V(h) \cdot r_h \cdot \cos(\Theta) \qquad \text{(Eqn. 6)}$$

Where Θ is the angle between the wind direction and normal to the wall.

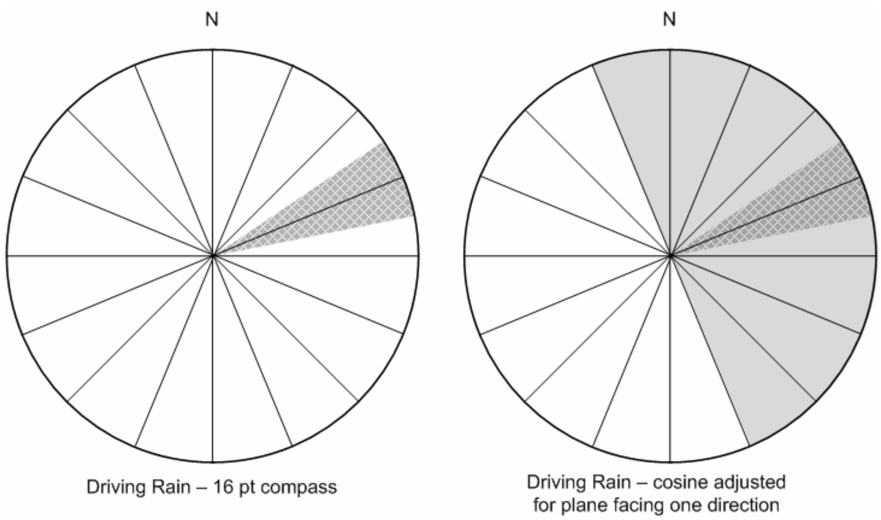


Figure 5-26: Cosine adjusted for plane facing one direction (Straube & Schumacher 2006)

All empirical methods use this cosine projection method to determine driving rain projected on a wall surface. The cosine project method assumes the full wind velocity acts at the angle to the surface and the rain deposition can be geometrically determined from this relationship. However, recent numerical modeling work by Blocken and Carmeliet (2006b) suggests that the cosine method may be inaccurate at predicting rain deposition for wind angles not perpendicular to the wall as a result of the complex wind-rain relationships with the façade. The errors were found to be large (up to 300%) when the wind was at large (>45° or even moderate 22.5°) angles to the perpendicular to the wall (ie. wind from southeast for an east facing wall).

No alternate methods to the cosine method could be suggested for use with empirical models and Blocken and Carmeliet suggest the use of numerical CFD models to overcome the issue. While the preliminary numerical research may prove to be true, without field testing and barring any other available empirical calculation method, the cosine method will continue to be used here. The field observations of this potential issue are discussed with the correlation of driving rain for each building in Section 5.5.4.

Applying hourly wind and rain measurements the driving rain load is calculated for Vancouver (at YVR) using CWEC data and is presented in Figure 5-27. The predominant driving rain direction is calculated to be east (as experience and previous research suggests) with a calculated driving rain load of 811 mm (kg/m^2) on that orientation. All wall orientations will potentially see some driving rain, however to determine the actual load on the wall of building, modification factors must first be applied.

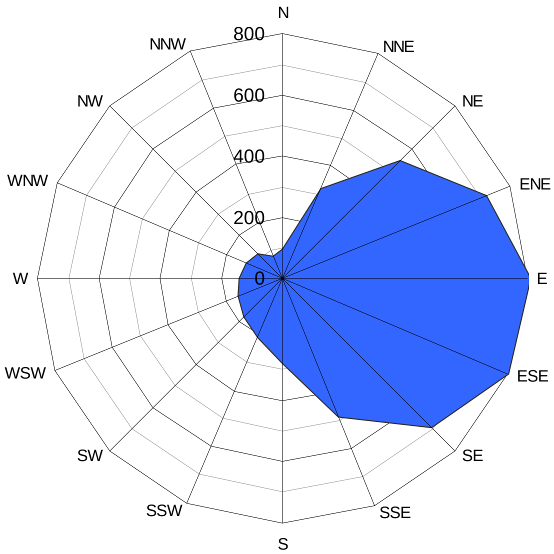


Figure 5-27: YVR Annual Driving Rain – (Straube and Schumacher 2006)

The driving rain calculations up to this point are a measure of the climate and are the driving rain calculated in the undisturbed wind stream. The loads calculated are not maximum driving rain loads as exposure corrections could be applied to increase the load further on a building. To convert the calculated driving rain onto a vertical building façade modification factors are applied.

The first modification, the rain deposition factor (RDF) is used to transform the rate of driving rain in the free wind (outside of the region disturbed by a building) to the rate of rain deposition on a particular building (Straube 1998). Therefore for a particular orientation and location on a building face the driving rain can be determined from:

$$r_{vb} = RDF \cdot DRF \cdot V(h) \cdot \cos(\Theta) \cdot rh \qquad \text{(Eqn. 7)}$$

Where, r_{vb} is the rain deposition rate on a vertical building surface (mm/hr),
Θ is the angle between the normal to the wall and the wind direction (degrees),
DRF is the driving rain factor which accounts for interaction of wind and rain in the undisturbed wind, and

RDF is the rain deposition factor which is the ratio of free wind to rain deposition on a building which accounts for the effect of building shape.

The rain deposition (RDF) factor is generally assumed to be independent of rainfall intensity, windspeed or wind direction. Based on past research (field and wind tunnel studies), suggested RDF are presented for three different types of buildings in Figure 5-28.

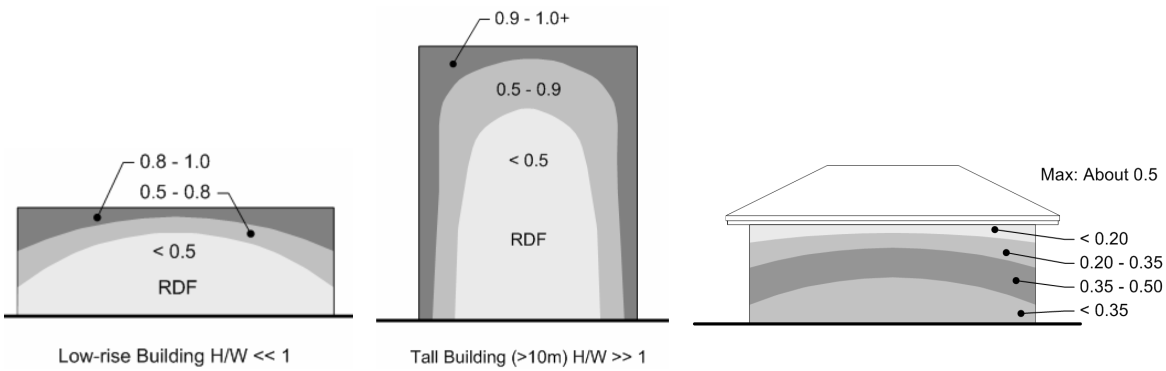


Figure 5-28: RDF Factors for Three Different Building Types (Straube & Schumacher 2006)

Peaked roofs and overhangs redirect airflow up and over the building at a distance from the façade (Figure 5-29) and can thereby have a significant effect on rain deposition (regardless of the building size). This has been shown at the one-storey UW BEGHut (Straube 1998), in wind tunnel studies of a high-rise building (Inculet and Surry 1995), and in field monitoring (Ge and Krpan 2007). Buildings with overhangs and/or sloped roofs will therefore have a smaller RDF than similar buildings without, particularly for low-rise buildings. This phenomenon is also shown in the results from the five buildings here as discussed in the following sections.

The size of roof overhang was also correlated with wall damage (primarily as a result of driving rain and subsequent water penetration) by Morrison Hershfield (1996) as shown in Chapter 3 which concluded that larger overhangs reduced the occurrence of moisture damaged walls.

To provide further assistance to practitioners, in the next section RDF factors are shown for the five buildings which were determined by correlating field measurements with driving rain calculations.

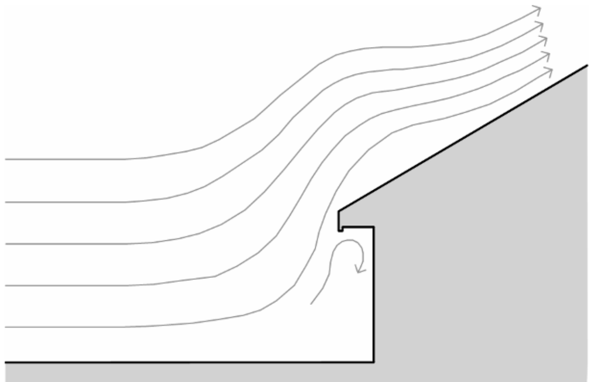


Figure 5-29: Influence of Overhangs on Buildings (Straube & Schumacher 2006)

A final correction is suggested to correct the wind velocity for height and sheltering also called an exposure height factor (EHF) which acts as a multiplier to increase or decrease driving the amount of driving rain predicted in Equation 6:

$$r_{vb} = EHF \cdot RDF \cdot DRF \cdot V(h) \cdot \cos(\Theta) \cdot rh \qquad \text{(Eqn. 7)}$$

Where, EHF is the exposure height factor to correct for wind speed at different exposures and height above grade.

Straube and Schumacher (2006) recommended EHF factors are 0.5 for sheltered buildings and 1.4 for exposed based on modified wind speed factors from the National Building Code of Canada (NBCC 1995).

Other similar empirical methods are available which follow the same fundamentals but use different nomenclature or slightly different methods to calculate the DRF/EHF factors (ASHRAE, British Standard BS-8104, 1992). This recent and practical approach presented here reflects current research and is the method preferred in this thesis.

5.5.3 Observations & Measurements

Driving rain measurements from driving rain gauges installed on two facades of each building are presented annually for each building. An overview and close-up figure showing the location of the rooftop and driving rain gauges is presented for each building. Dimensions and size of roof overhang are indicated on the figures and driving rain summaries are shown for one entire year (2002, 2003, or 2004 depending on available whole year data).

Annual predicted driving rain plots are provided for each building based on measured wind speed/direction and rainfall using the empirical method from the previous section (without correction or sheltering factors applied). This represents the total amount of driving rain for a given orientation based on the windspeed and rainfall intensities observed at the roof. Corrections for exposure and sheltering are further required to represent conditions on the façade of the building (RDF and EHF factors).

Using the empirical method discussed, the predicted driving rain load is calculated and presented in conjunction with the measured results. A rain deposition factor (RDF) and an exposure height factor (EHF) are used to correlate the predicted to measured results and are graphically presented for each location.

The procedure to correlate the measured driving rain (at the driving rain gauges) with the calculated predicted driving rain is as follows.

1. Calculate hourly driving rain at the orientation of driving rain gauge using measured wind and rain data and compare the annual sum of total calculated to the measured driving rain.
2. Apply a rain deposition factor (RDF) and exposure factor (EHF) to the calculated values to correlate with the measured sum.
    a. An exposure factor was used to account for local sheltering of adjacent buildings and typically assumed to be 0.5 for the five buildings. Therefore the only variable was the RDF and the product of the RDF*EHF is the ratio of deposition on a building to the total calculated driving rain. Obviously the EHF factor could be set to 1.0 and the RDF shown would be double.
3. The hourly data is plotted and compared to determine the accuracy of the calculation and chosen RDF/EHF factors.

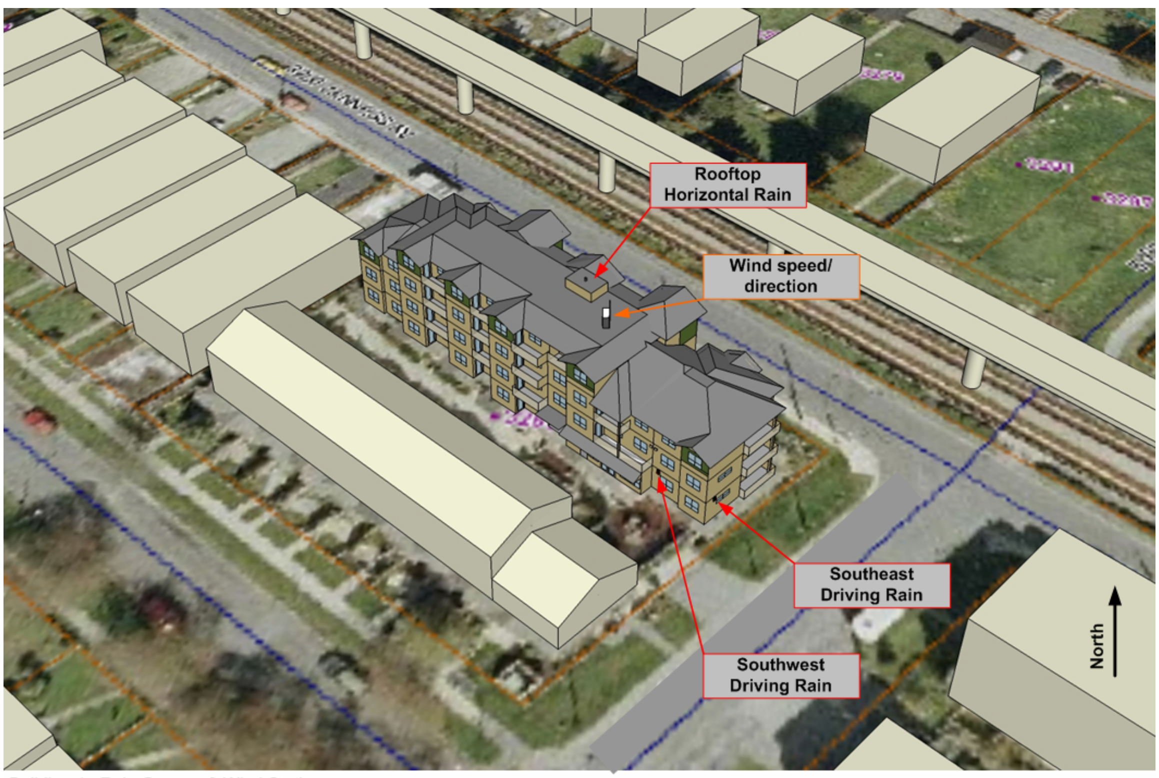
Data is presented for one entire year from January 1st to December 31st as indicated. Measurements from other years produced similar results at all buildings and are discussed where noted.

Results are shown in graphical form, for numerical results see *Appendix F: Supplemental Measured Data*.

5.5.3.1 Building 1

Data is presented for Building 1 from 2002. Driving rain gauges are located on the southeast and southwest elevations located above the first floor (8′ from grade). The gauges are relatively sheltered being close to the ground and protected by a roof overhang (17′ above) and therefore saw only a small percentage of the total driving rain load calculated at the roof.

An overview of the building and surrounding neighbourhood is shown in Figure 5-30, and a close-up of the gauges with driving rain data is shown in Figure 5-31. An annual calculated driving rain plot and an aerial view of the building showing the surrounding neighbourhood is shown in Figure 5-32.



Building 1 : Rain Gauges & Wind Station

Figure 5-30: Building 1 – Overview and Location of Rain Gauges

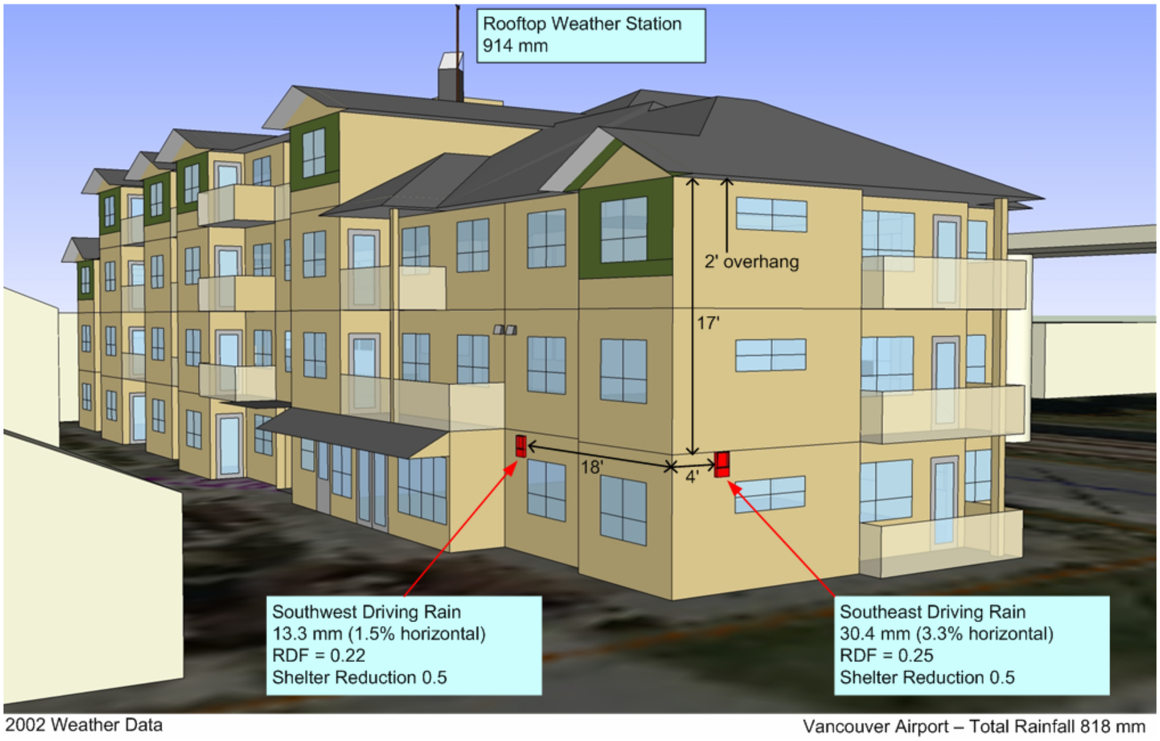


Figure 5-31: Building 1 – Driving Rain Gauge Location and Measurements

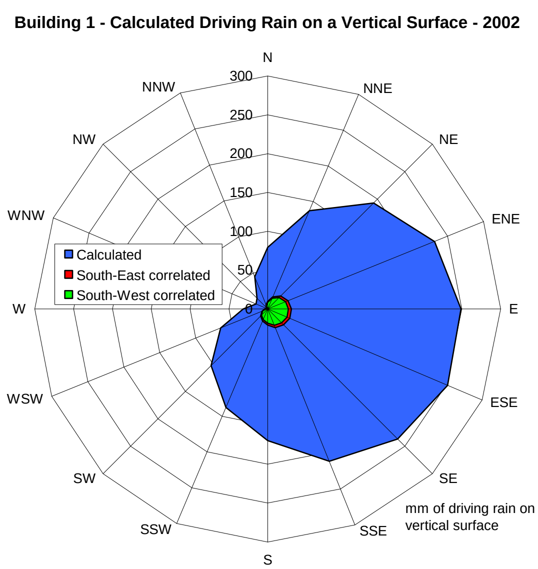


Figure 5-32: Building 1 - Calculated Driving Rain (Predicted Annual and Measured correlated with RDF/Shelter Factors) and Aerial Photo of Site.

Of the total predicted driving rain, approximately 11% was measured by the driving rain gauge on the southwest and 13% on the southeast. The building overhang, geometry and sheltering reduced the predicted driving rain on these elevations significantly. The calculated driving rain plot shows the potential for significantly higher driving rain loads on this building, however were not confirmed by measurements. The RDF factors determined for the two sheltered locations are consistent with those presented in the literature when an EHF factor of 0.5 is used.

The measured horizontal and driving rain is compared by month in Figure 5-33 showing that the majority of the driving rain occurred during November and December during large storm events. Note different scales between horizontal (left) and driving rain (right).

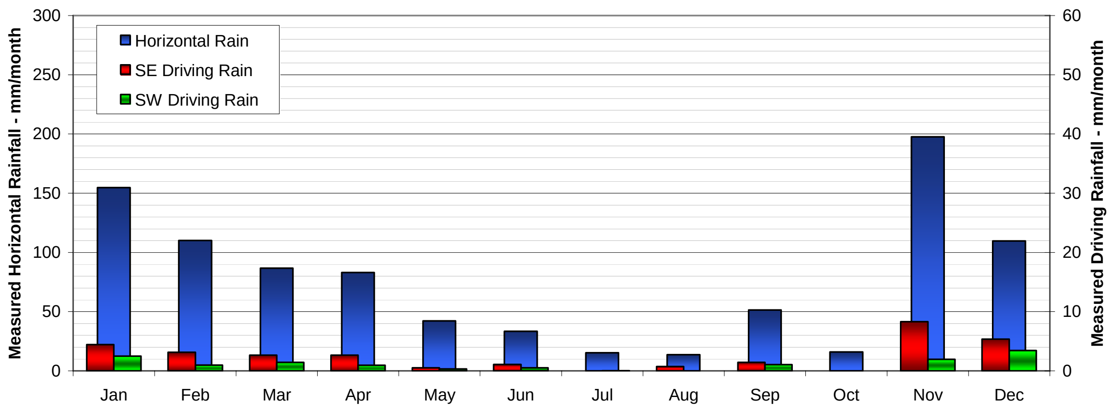


Figure 5-33: Building 1 – Measured Horizontal & Driving Rainfall 2002

5.5.3.2 Building 2

Data is presented from for Building 2 from 2002. Driving rain gauges are located on the east and south elevations located above the third and fourth storeys respectively. The gauges are relatively exposed close to the roof top and therefore saw a significant percentage of the total driving rain load calculated at the roof weather station.

An overview of the building and surrounding neighbourhood is shown in Figure 5-34, and a close-up of the gauges with driving rain data is shown in Figure 5-35. Figure 5-36 shows a photograph of the actual rain gauges as situated on the east and south orientations and size of overhangs. The annual calculated driving rain plot and an aerial view of the building is shown in Figure 5-37.

Figure 5-34: Building 2 – Overview and Location of Rain Gauges

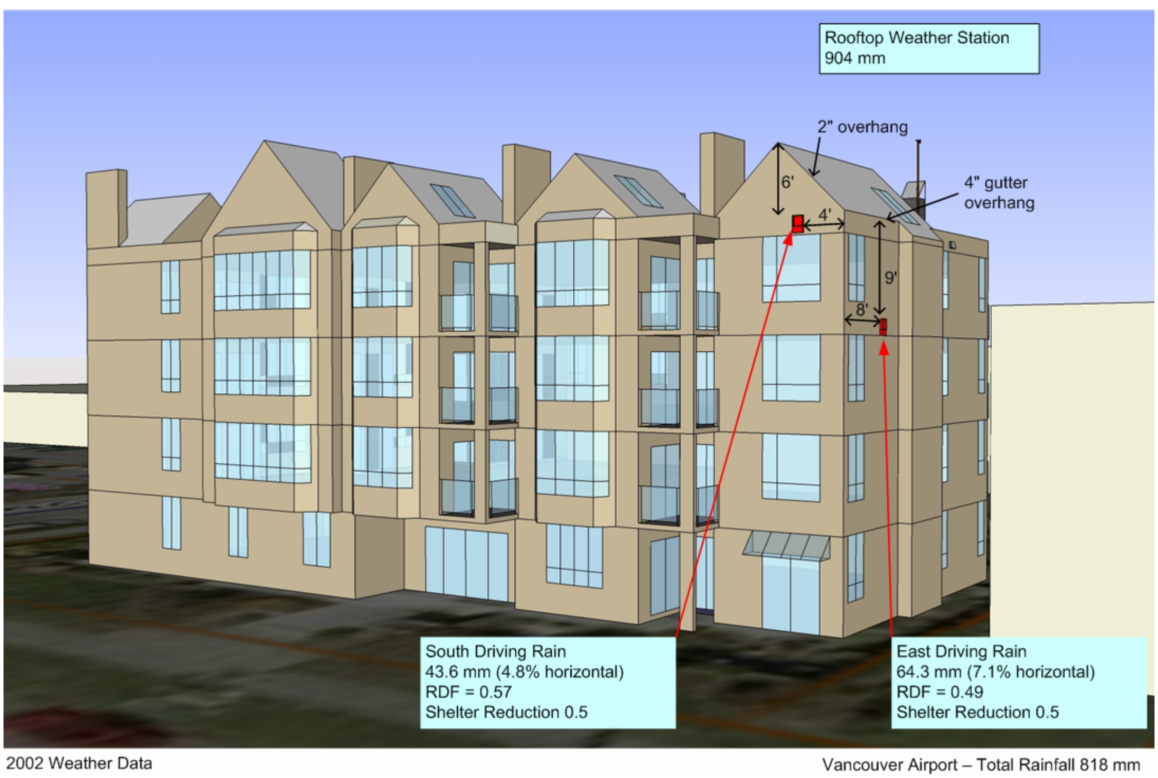


Figure 5-35: Building 2 – Driving Rain Gauge Location and Measurements

Figure 5-36: Building 2 – Driving Rain Gauge Locations

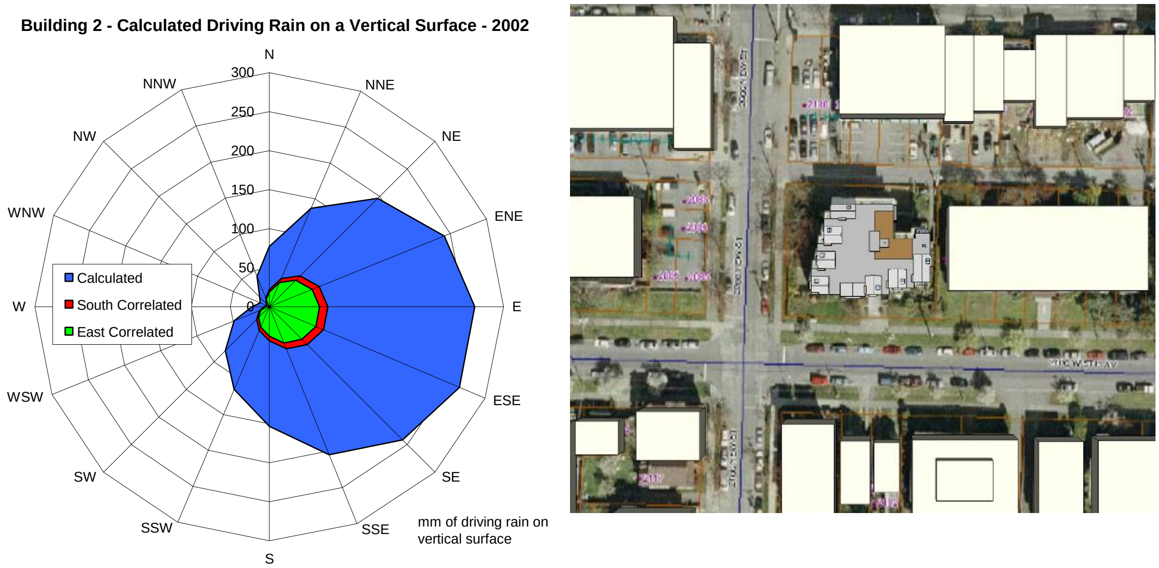


Figure 5-37: Building 2 - Calculated Driving Rain (Predicted Annual and Measured correlated with RDF/Shelter Factors) and Aerial Photo of Site.

Of the total predicted driving rain, approximately 25% was measured by the driving rain gauge on the east and 29% on the south. The building overhang, geometry, and sheltering from adjacent buildings reduced the total driving rain on these elevations.

The measured horizontal and driving rain is compared by month in Figure 5-38 showing that the east elevation typically received more driving rain than the south, except during November and December. Note the different scales between horizontal (left) and driving rain (right).

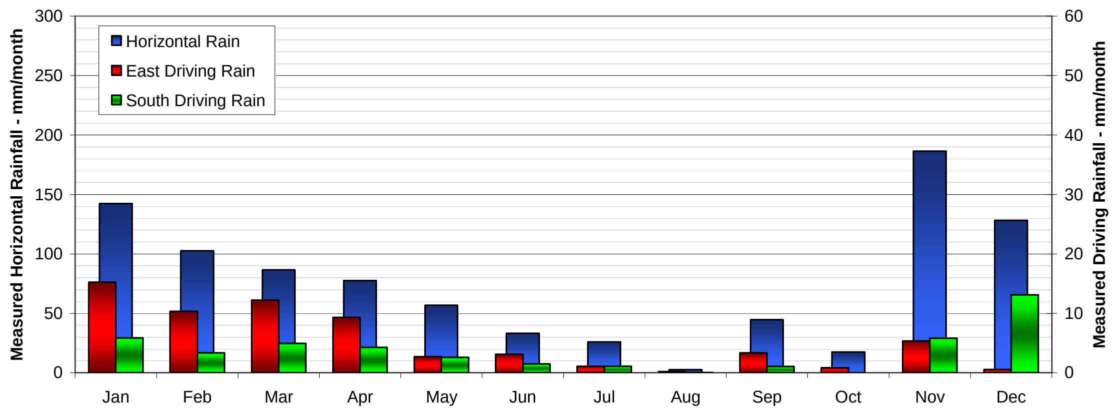


Figure 5-38: Building 2 – Measured Horizontal & Driving Rainfall 2002

5.5.3.3 Building 3

Data is presented for Building 3 from 2003. Driving rain gauges are located on the east elevation at the 3rd and 6th floor levels. The gauges are relatively exposed and therefore saw a large percentage of the total driving rain load as calculated at the rooftop weather station. Building 3 had the highest measured rain deposition of any of the five buildings in the study.

An overview of the building and surrounding neighbourhood is shown in Figure 5-39, and a close-up of the gauges with driving rain data is shown in Figure 5-40. The annual calculated driving rain plot and an aerial view of the building is shown in Figure 5-41.

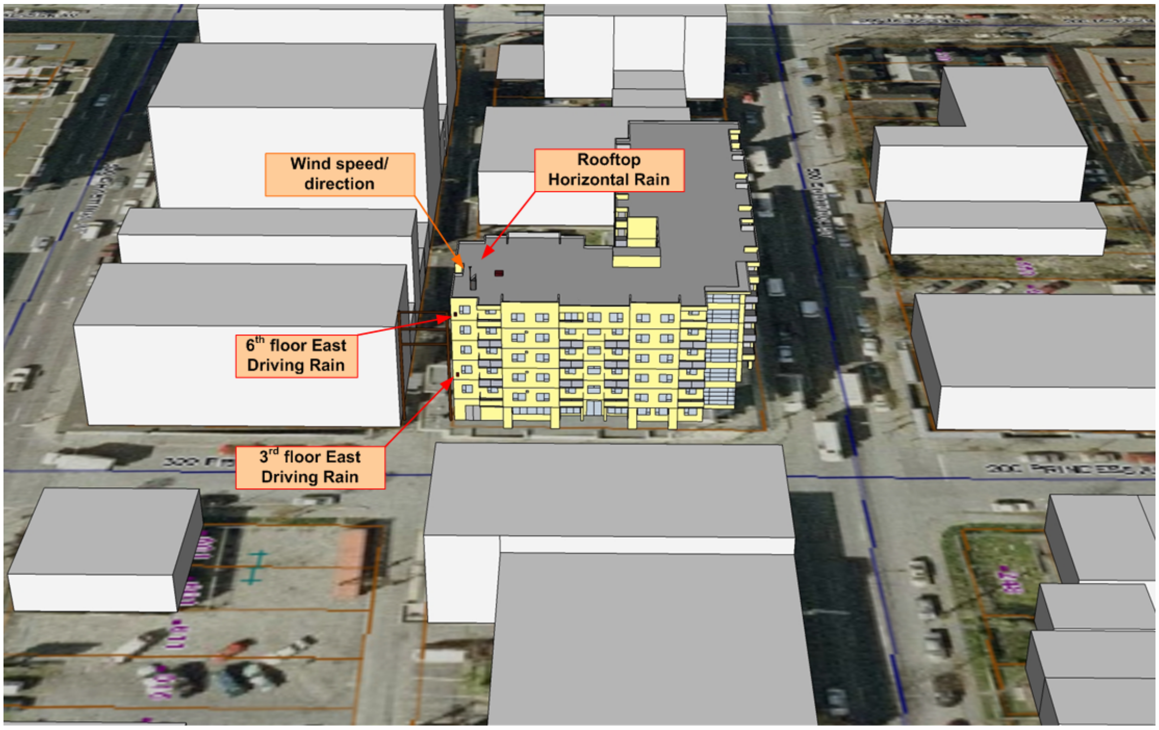


Figure 5-39: Building 3 – Overview and Location of Rain Gauges

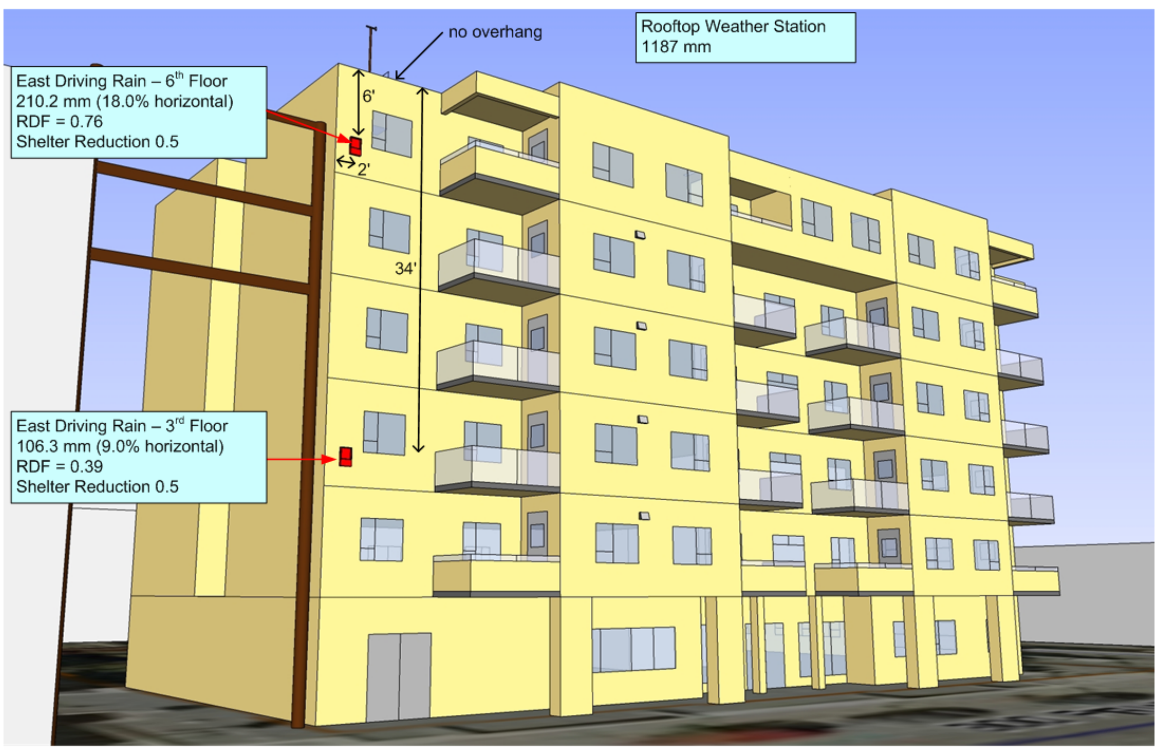


Figure 5-40: Building 3 – Driving Rain Gauge Location and Measurements

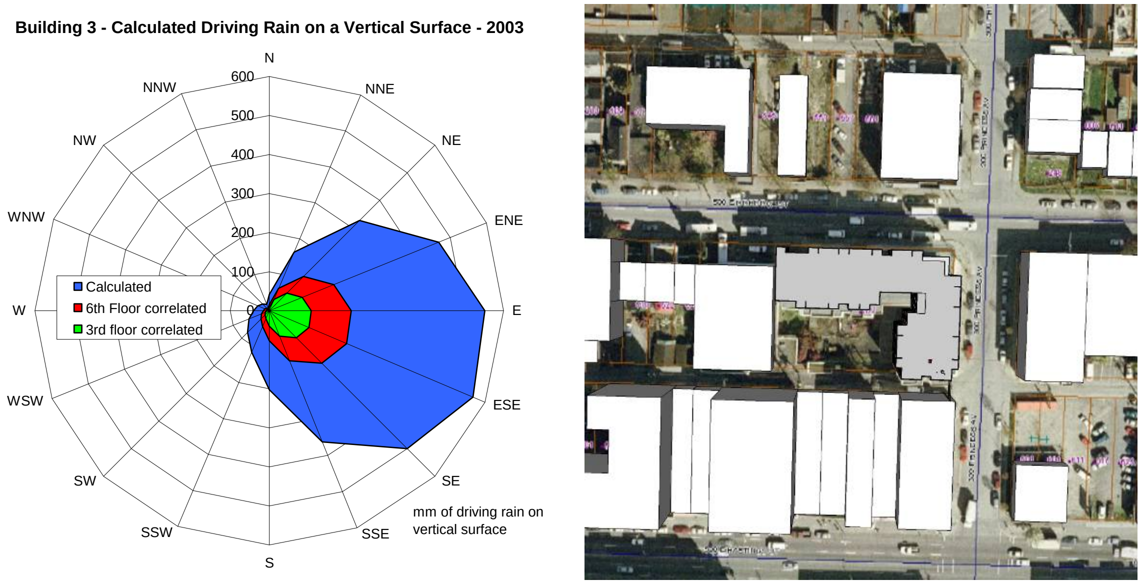


Figure 5-41: Building 3 - Calculated Driving Rain (Predicted Annual and Measured correlated with RDF/Shelter Factors) and Aerial Photo of Site.

Of the total predicted driving rain, approximately 38% was measured by the east driving rain gauge on the 6th floor and 20% on the 3rd floor. The building geometry and sheltering from adjacent buildings reduced the total driving rain on these elevations. The difference in rain deposition between the exposed 6th floor is apparent compared to the lower 3rd floor by a factor of approximately two.

The measured horizontal and driving rain is compared by month in Figure 5-42 showing the consistent difference in deposition between the 3rd and 6th floors. Note the different scales between horizontal (left) and driving rain (right).

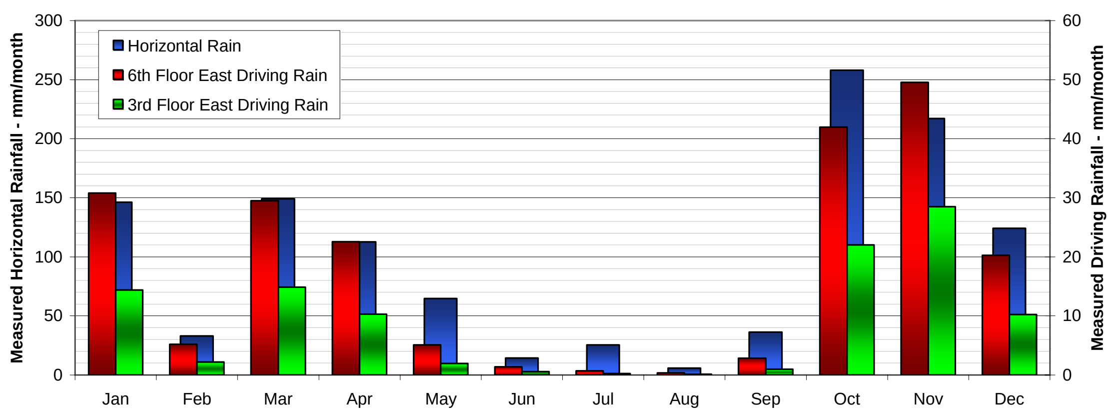


Figure 5-42: Building 3 – Measured Horizontal & Driving Rainfall 2003

5.5.3.4 Building 4

Data is presented for Building 4 from 2003. Driving rain gauges are located on the north and south elevations located at the third storey. The gauges are sheltered by very large roof overhangs (1200 mm at walls and 600 mm at bay windows) and surrounding buildings and therefore saw a minimal amount of the total driving rain load calculated at the roof.

An overview of the building and surrounding neighbourhood is shown in Figure 5-43, and a close-up of the gauges with driving rain data is shown in Figure 5-44. Figure 5-45 shows a photograph of the actual rain gauges as situated on the east and south. The annual calculated driving rain plot and an aerial view of the building is shown in Figure 5-46.

Building 4 : Rain Gauges & Wind Station

Figure 5-43: Building 4 – Overview and Location of Rain Gauges

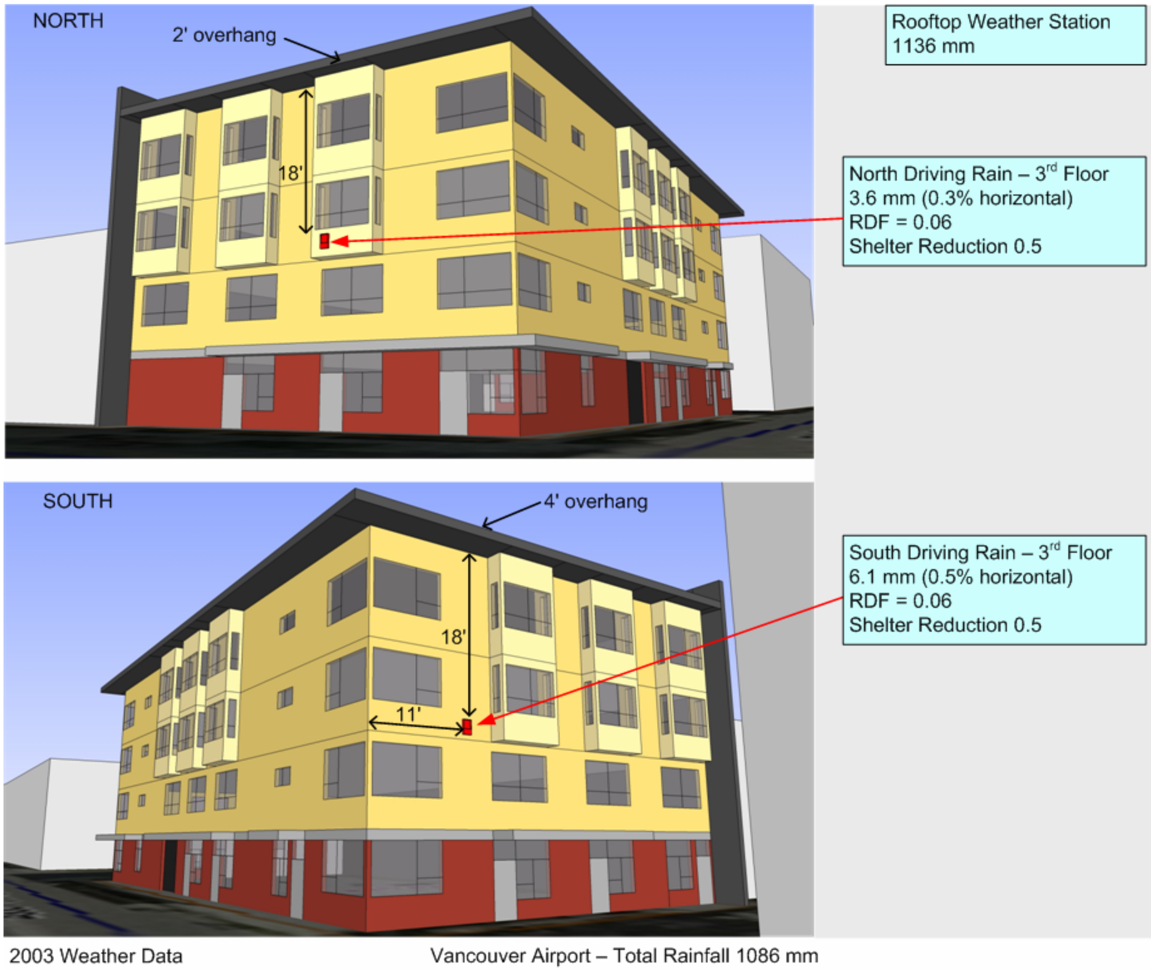


Figure 5-44: Building 4 – Driving Rain Gauge Location and Measurements

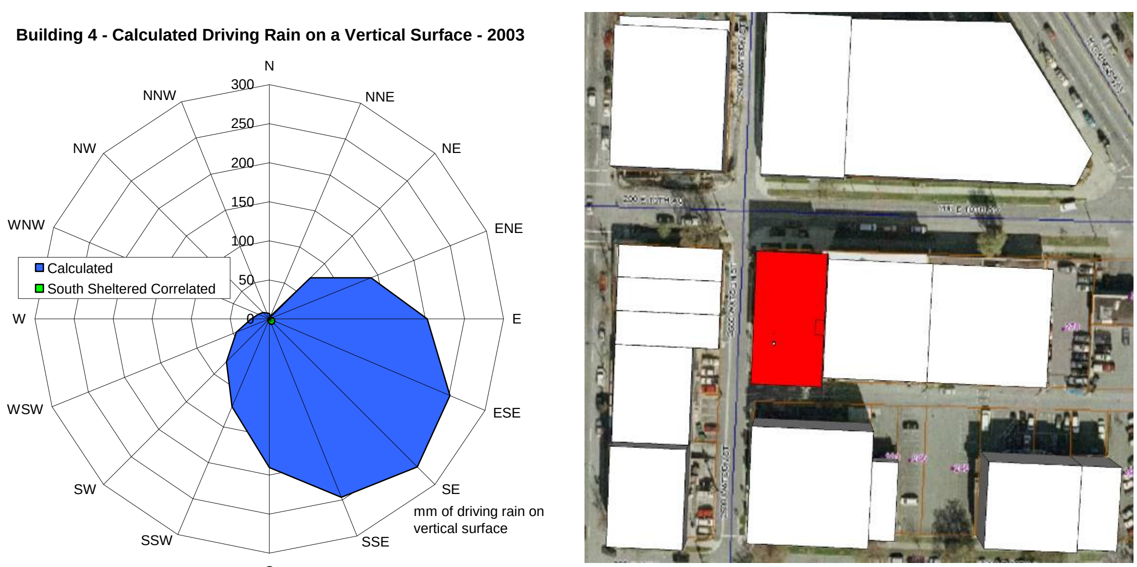


Figure 5-45: Building 4 - Calculated Driving Rain (Predicted Annual and Measured correlated with RDF/Shelter Factors) and Aerial Photo of Site.

Of the total predicted driving rain, approximately 0.5% was measured by the driving rain gauge on the south and 0.3% on the north. The very large building overhangs and sheltering from adjacent buildings reduced the total driving rain on these elevations significantly to almost negligible amounts.

The measured horizontal and driving rain is compared by month in Figure 5-46, noting the almost negligible driving rain deposition on the south and north elevations. Note the different scales between horizontal (left) and driving rain (right).

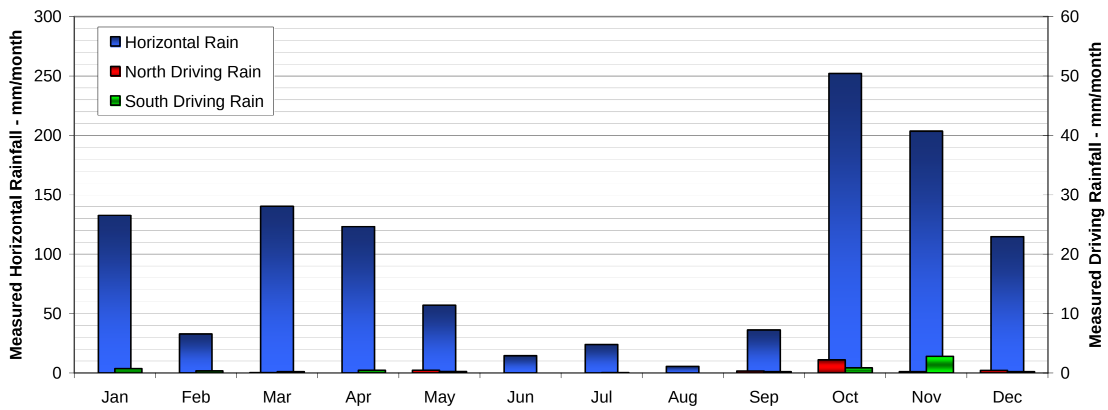


Figure 5-46: Building 4 – Measured Horizontal & Driving Rainfall 2003

5.5.3.5 Building 5

Data is presented for Building 5 from 2003 and 2004. Driving rain gauges are located on the southeast and southwest elevations located at the top 30th storey of the high-rise building. Driving rain gauges were also initially installed at the 6th floor but later painted by a contractor to match the wall color and became plugged and non-functional. The 30th floor gauges (unpainted) are well exposed to wind and rain, however were later realized to be situated on orientations away from the predominant wind-driven rain face for the north end of downtown Vancouver (unknown prior to this study). Therefore these gauges only saw a small percentage of the total building driving rain load calculated at the roof.

An overview of the building and surrounding downtown neighbourhood is shown in Figure 5-47, and a close-up of the gauges with driving rain data is shown in Figure 5-48 for 2003 and Figure 5-49 for 2004. A photograph showing the location of the driving rain gauges on the 30th floor is shown in Figure 5-50.

An annual calculated driving rain plot for 2004 and an aerial view of the building is shown in Figure 5-51.

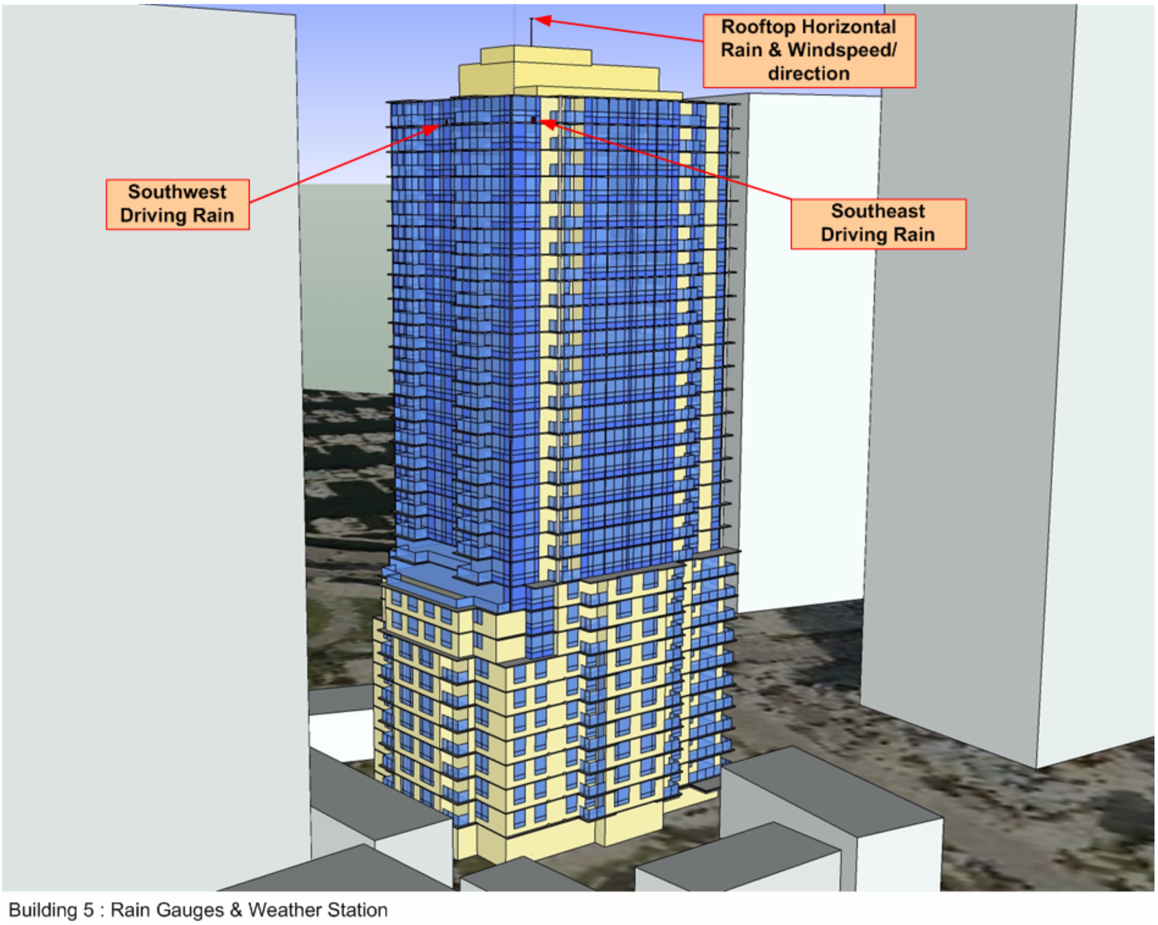


Figure 5-47: Building 5 – Overview and Location of Rain Gauges

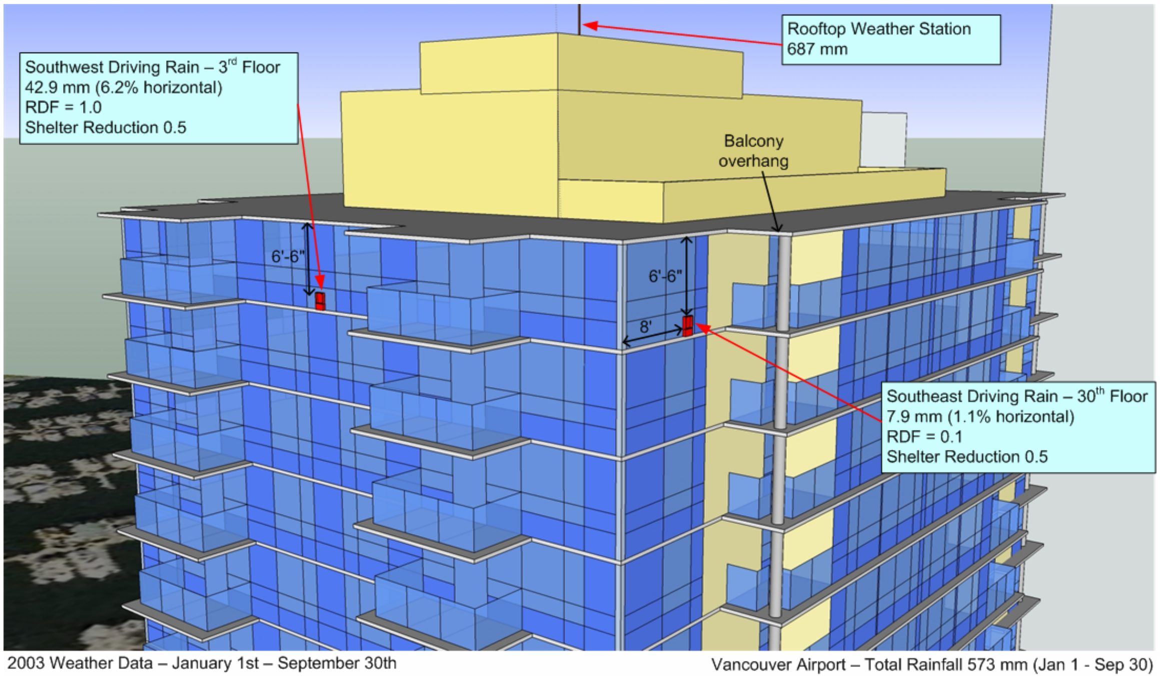


Figure 5-48: Building 5 – Driving Rain Gauge Location and Measurements (2003)

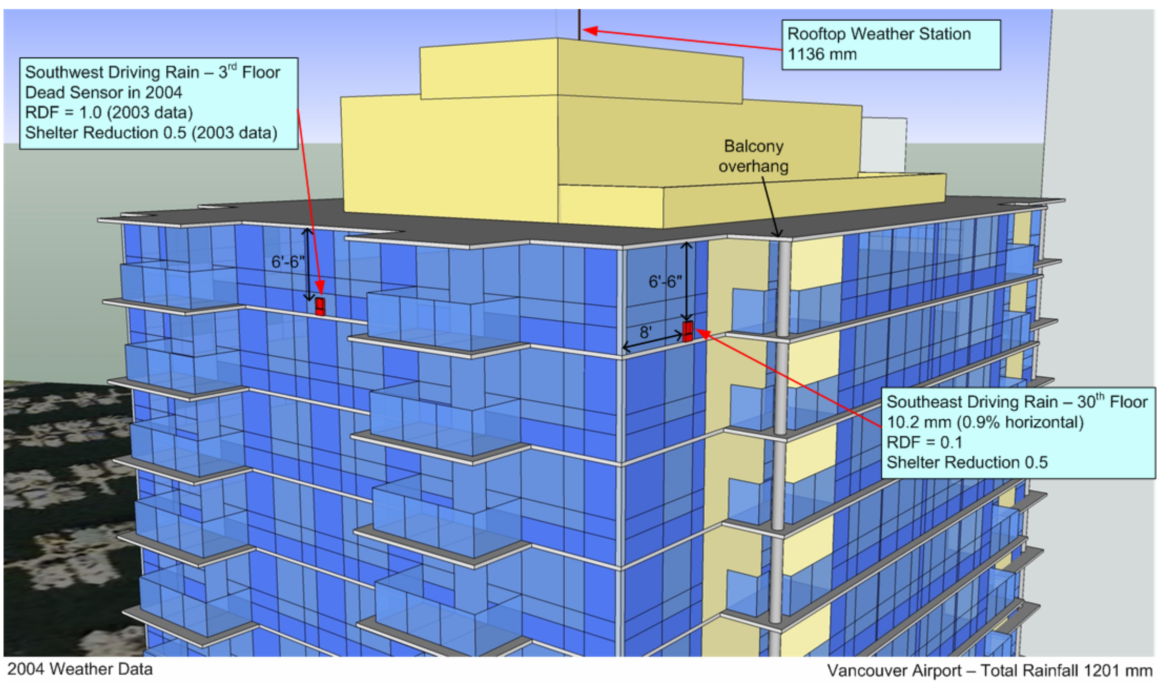


Figure 5-49: Building 4 – Driving Rain Gauge Location and Measurements (2004)

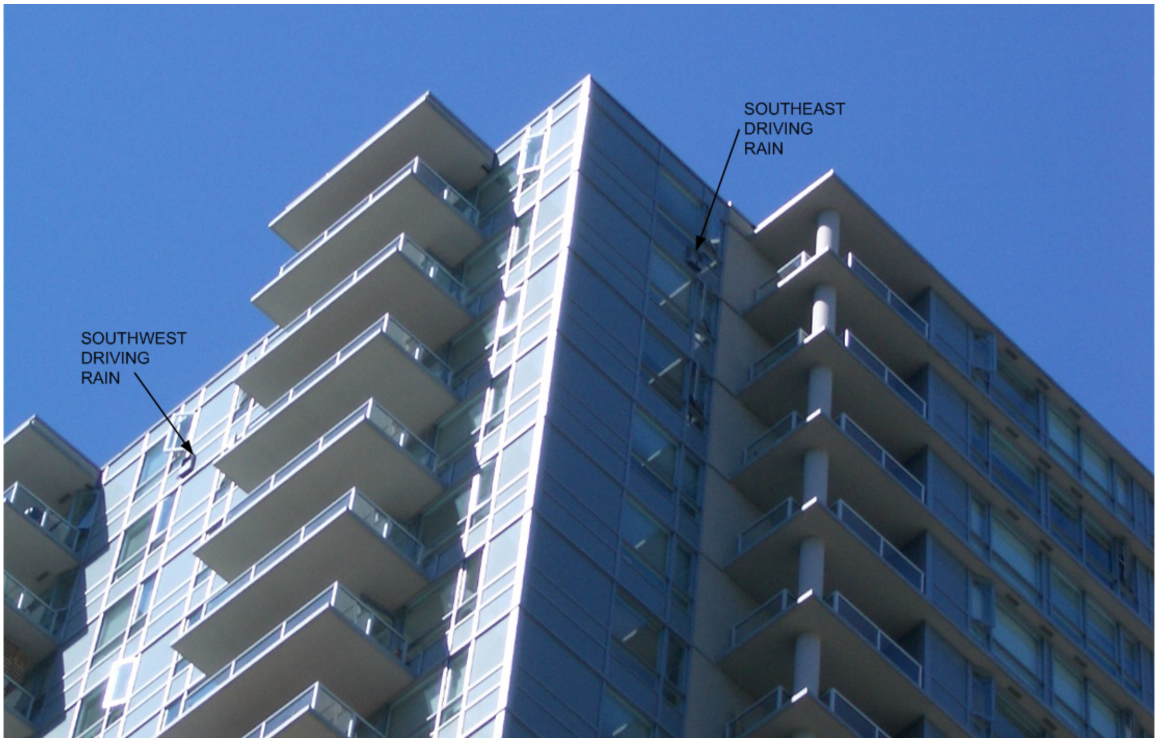


Figure 5-50: Photograph of 30th Floor Driving Rain Gauges

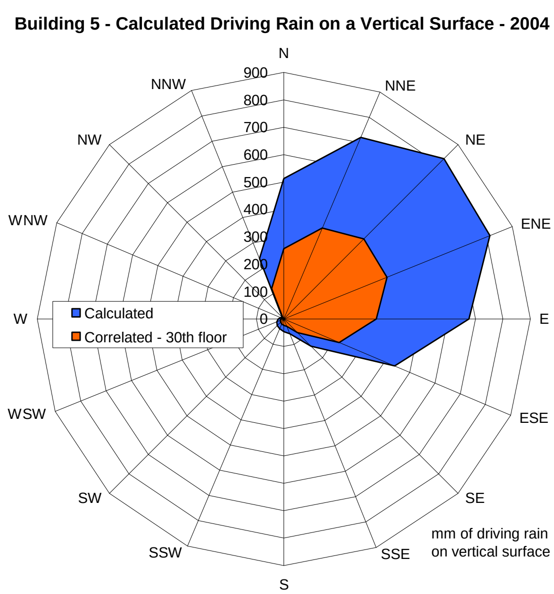


Figure 5-51: Building 5 - Calculated Driving Rain (Predicted Annual and Measured correlated with RDF/Shelter Factors) and Aerial Photo of Site.

Data from 2003 and 2004 is provided, as 2003 contained missing data from October through December, however driving rain measurements are provided from January through September. In 2004 the southwest driving rain gauge became plugged and/or malfunctioned for the entire year. The southeast gauge (which saw little rain both years) continued to function normally.

Of the total predicted driving rain, approximately 50% was measured by the driving rain gauge on the southwest and 5% on the southeast. The building geometry and sheltering from adjacent buildings reduced the total driving rain on both of these elevations. As shown the predominant wind direction for this location in downtown Vancouver is from the northeast, not east or southeast like other buildings in Vancouver.

The measured horizontal and driving rain is compared by month in Figure 5-42 from January – October 2003, showing the consistent difference in deposition between the southwest and southeast gauges. The southeast gauge is sheltered by a balcony when winds blow from the northeast (predominant direction), while the southwest gauge is located between two balconies. Note the different scales between horizontal (left) and driving rain (right).

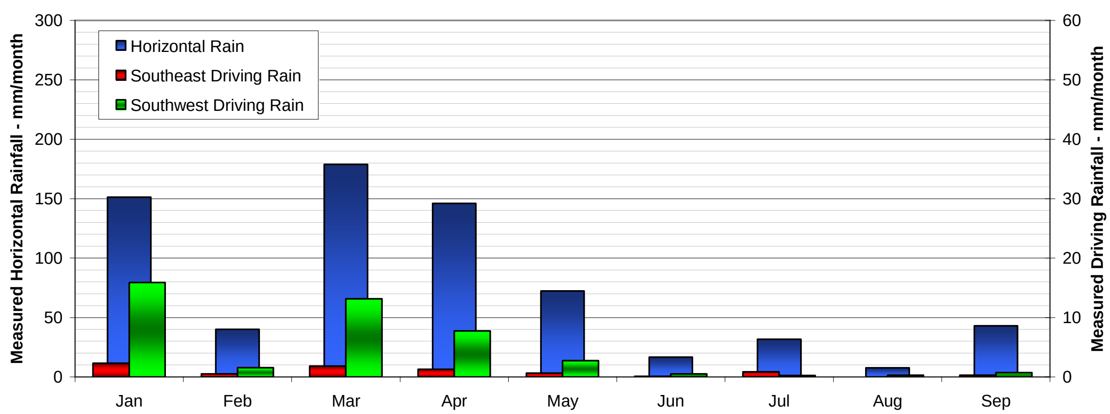


Figure 5-52: Building 5 – Measured Horizontal & Driving Rainfall Jan-Oct 2003

5.5.3.6 Summary of Driving Rain Loads in Vancouver

The total calculated driving rain for each of the buildings is presented in Figure 5-53 for all years with complete data (8760 hours) and in Figure 5-54 for the years presented above. The differences in driving rain between sites in Vancouver are apparent, and as would be predicted the high-rise and mid-rise had the highest calculated driving rain 2 to 3 times higher than the low-rises. For comparison an annual driving rain plot is shown for YVR which is calculated using 30 year average data (Straube and Schumacher 2006).

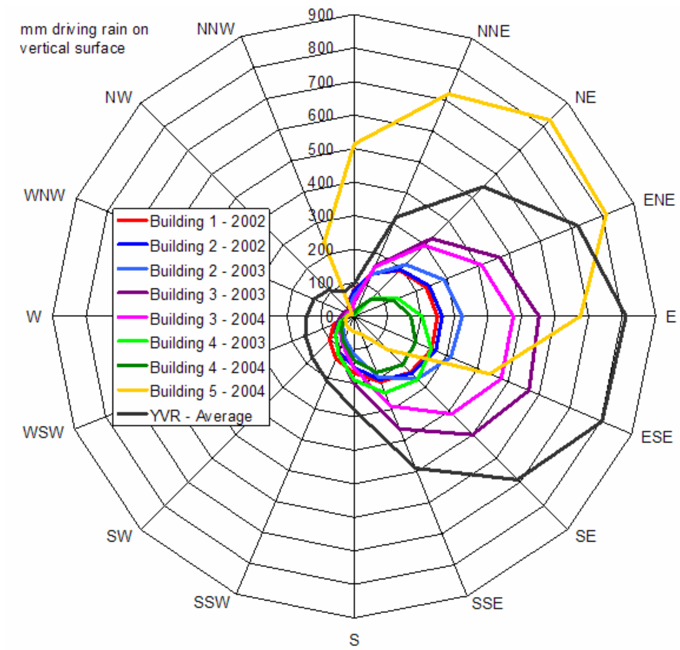


Figure 5-53: Summary of Calculated Maximum Driving Rain Potential – All Buildings/Years with Full Data Sets

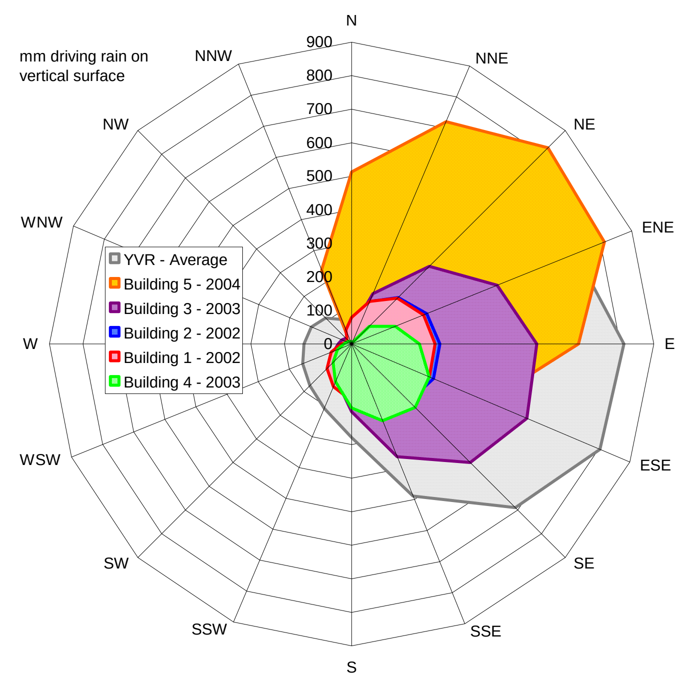


Figure 5-54: Summary of Calculated Maximum Driving Rain Potential

Building 5 (30 storey high-rise) had the highest annual driving rain potential with approximately 850 mm/yr), similar to the airport with 800 mm/yr. This was followed by Building 3 (6 storey mid-rise) with 550 mm/yr and Buildings 1, 2 and

4 (4 storey low-rises) with between 200-300 mm/yr. These are summarized on a map of Vancouver in Figure 5-55.

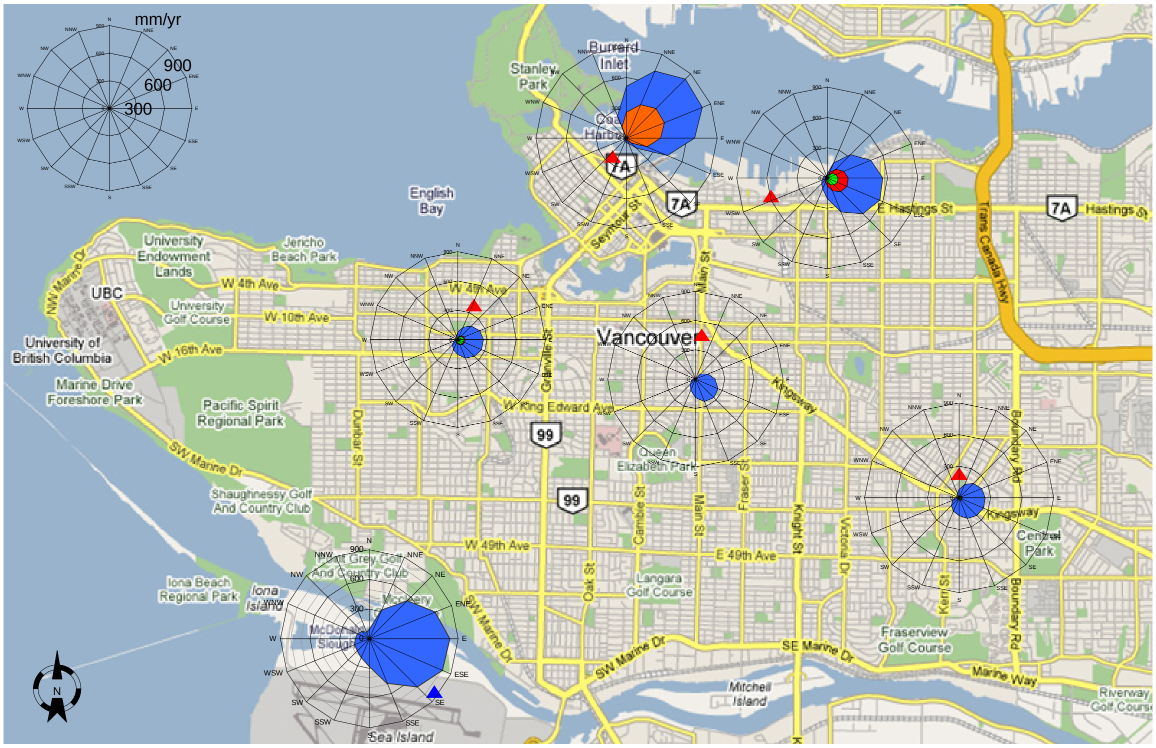


Figure 5-55: Summary of Driving Rain Loads across Vancouver (underlay map: Google Maps 2006)

While all buildings received similar rainfall amounts, Building 5 had the highest average windspeed (9.6 km/hr), followed by Building 3 (6.7 km/hr) and Buildings 1, 2 and 4 (5.4, 5.4, and 6.7 km/hr).

Field measurements were not taken on smaller less exposed buildings (ie one or two storey houses) as part of this study; however one could extrapolate and predict that the driving rain load on these less exposed buildings would be reduced. While horizontal rain loads may be similar across sites, wind speed has the most significant impact on the driving rain load, and as measured, exposed buildings receive considerably higher driving rain than sheltered buildings within the same city.

5.5.4 Correlation of Measurements with Prediction Models

The measured driving rain is compared to that predicted by the empirical model. The differences between the hourly calculated and measured values are shown and the accuracy of the empirical model is discussed.

Empirical methods are all based on similar assumptions; hence the results from one of the methods would produce similar hourly results to another method (ie. as in ASHRAE or some European Standards). A disagreement between the measured and predicted values would occur in all empirical methods (not just the one presented here). The discrepancies observed here can typically be explained by complex wind-rain flow patterns around buildings which cannot be captured by a simple empirical model. Several such examples are presented in this section.

The data from each of the five buildings was collected at 15 minute intervals and averaged hourly. For the rain measurements, the tipping bucket gauges count the number of tips per time interval; hence 15 minute data will be as accurate as hourly or even annual data. However for wind, windspeed and direction typically varies during storm events, therefore capturing an average every 15 minutes and especially every hour may not be accurate and lead to errors when using the empirical model. Peak windspeeds will not be captured, and it is during these events that peak levels of driving rain may be deposited.

While driving rain calculations were performed hourly, using average values, 15 minute calculations were performed to investigate the differences in results with using higher resolution. It was found that using 15 minute data did not significantly improve the correlation of the measured to calculated driving rain, and such the hourly results are presented here.

The errors observed in the following sections between the calculated and measured readings are likely as a result of one or more of the following factors:

- Average 15 minute or hourly wind speed/direction measurements do not capture peak or burst wind events which may deposit high levels of driving rain on the façade.
- The annual results assume that the gauges were fully functional over the entire year. Field reviews and data analysis suggests that this is a reasonable assumption for the data collected, except where noted for

Building 5. Potentially the sensors may have malfunctioned for some period resulting in errors.

- Averaging windspeed or direction would smooth out large peaks and may under predict the calculated driving rain load.
- The resolution of the tipping rain sensors is 0.05 mm, therefore differences will be seen when the calculated driving rain is less than 0.05 mm.
- Wind speed/direction measurements at the roof do not necessarily reflect that at the driving rain gauge as a result of local building geometry, or other factors. The empirical model may not be able to accurately capture driving rain phenomena for buildings where wind flow patterns around the building are significantly disrupted. Therefore CFD modeling would be required to determine sheltering and local wind speed/direction effects.
- During light rain events, water deposited on the driving rain gauge may evaporate before running down into the tipping bucket collector. This is potentially more of an issue during the summer, or under solar heating. The driving rain gauges were initially installed with a hydrophobic Teflon® coating on the catch basin surfaces, however after several years of weathering and UV damage would become more hydrophilic and prevent/slow run-down from occurring during light rain events. Recent research into this phenomenon by van Mook (2002) found significant evaporation from similar sized driving rain gauges during low intensity rain events which typically had insufficient accumulation to cause rundown. Van Mook suggested the use of wiper blades to ensure the total driving rain was measured.
- As suggested by Blocken and Carmeliet (2006a), the cosine method used in empirical models may be incorrect for wind angles not perpendicular to the gauge and result in significant errors in the calculated driving rain deposition.

Aside from the possible sources of error, this research is step forward in being able to predict driving rain loads on buildings. These five buildings provide some guidance to designers as to appropriate design loadings, and assistance to selecting appropriate RDF or sheltering factors. Calculations aside, the measured driving rain loads provide a real idea of appropriate loads for similar buildings under similar exposures.

The measurements and correlations for the five buildings are presented. It will be shown that the well exposed east elevation of building 3 showed best correlation to the empirical model, while correlation with the other four buildings had varying degrees of accuracy and the limitations of the empirical method are discussed.

5.5.4.1 Building 1

Measured driving rain from the southeast and southwest driving rain gauges on Building 1 is compared to the predicted deposition on an hourly basis. The cumulative driving rain is shown in Figure 5-56 for January 1st to December 31st, 2002 and in closer detail from January 1st to 15th (Figure 5-57).

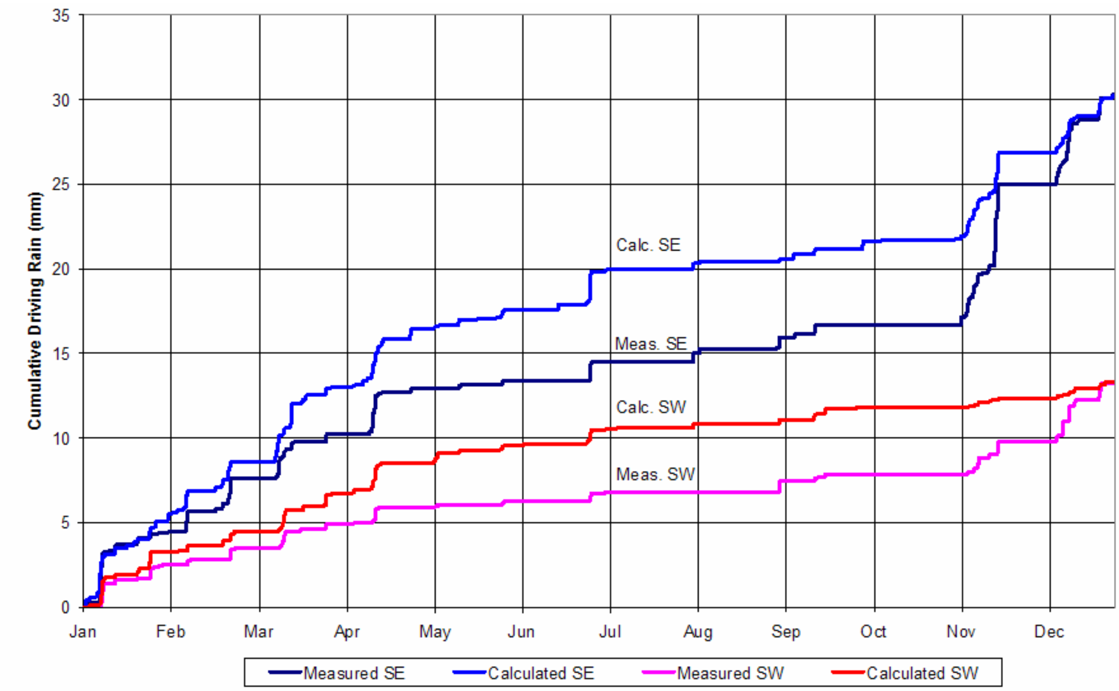


Figure 5-56: Building 1 – 2002: Calculated vs. Measured Driving Rain

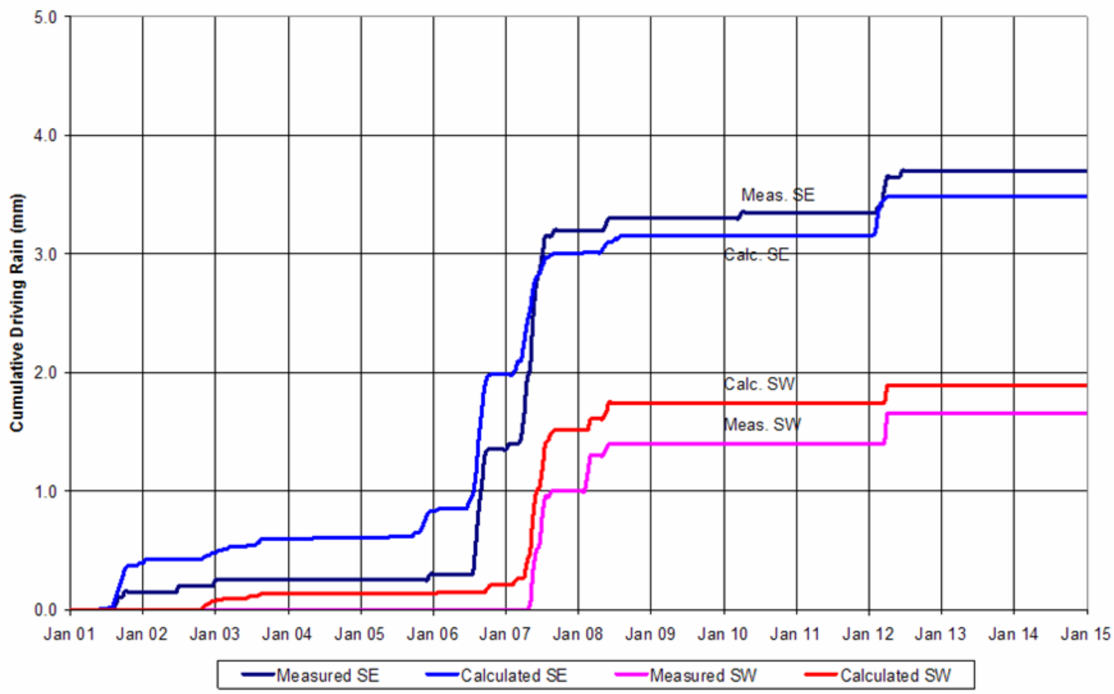


Figure 5-57: Building 1 – January 2002: Calculated vs. Measured Driving Rain

The measured versus calculated driving rain results deviate over the year, however return to the same total in December. During the first two weeks of the year, only a small deviation in the prediction occurs, however not all individual rain events are captured by the empirical method. In addition, several rain events were predicted but not measured. In general driving rain trends were captured by the method but errors resulted in a different magnitude of results.

These errors would suggest that the RDF or EHF factors vary with rain event; however the RDF and EHF factors are constant for a specific location. Therefore errors in prediction are associated with the fundamental limitations of the empirical method. As suggested by Blocken & Carmeliet (2006a) the use of numerical CFD models may be required to determine driving rain loads for more complex buildings, and in particular when the driving rain is at an angle not perpendicular to the wall.

A series of large driving rain event are compared on an hourly scale from November 8th to 11th in Figure 5-58. Differences between measured and calculated driving rain over a three day period are highlighted. Wind direction measurements are shown in Figure 5-59 for background.

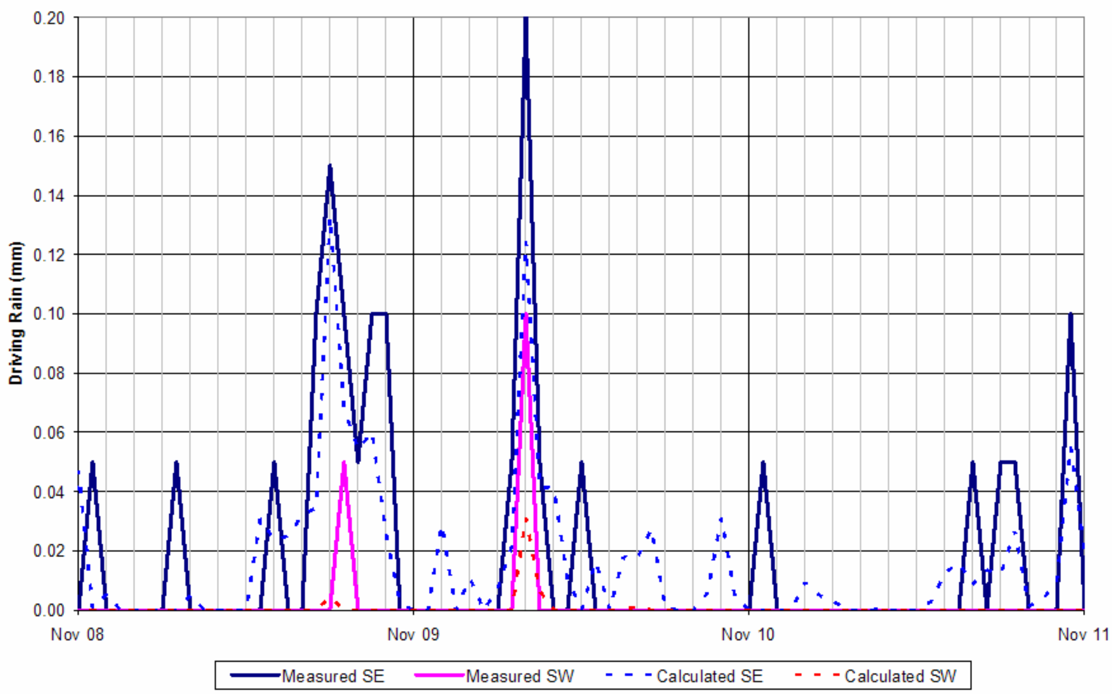


Figure 5-58: Building 1 – November 8-11 - Calculated vs. Measured Driving Rain

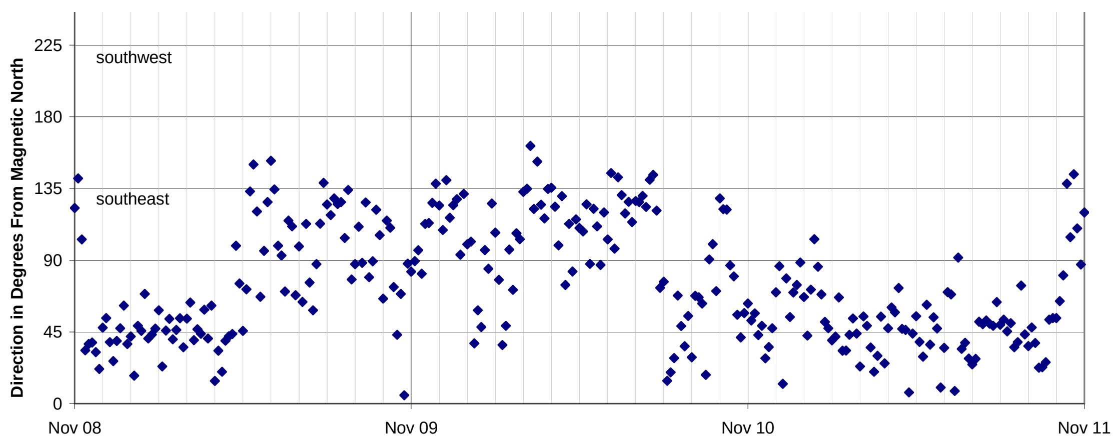


Figure 5-59: Building 1 - Wind direction

The differences in hourly measurements versus the empirical calculation are shown. During these three days, winds ranged from the south-east to north-east. While the trends were captured, absolute correlation between the measured and calculated amount was not attained. In this case, the total driving rain was under-predicted in this 3 day rain event on both the southeast and southwest by approximately 50%.

The role of wind direction with driving rain was further investigated for this building. Figure 5-60 plots the wind-direction with driving rain in each of the gauges, showing the differences observed between the southwest and southeast orientations. The majority of driving rain events did not occur at wind angles perpendicular to the wall, particularly on the southwest where the majority of the driving rain came from the south, at 45° to the wall.

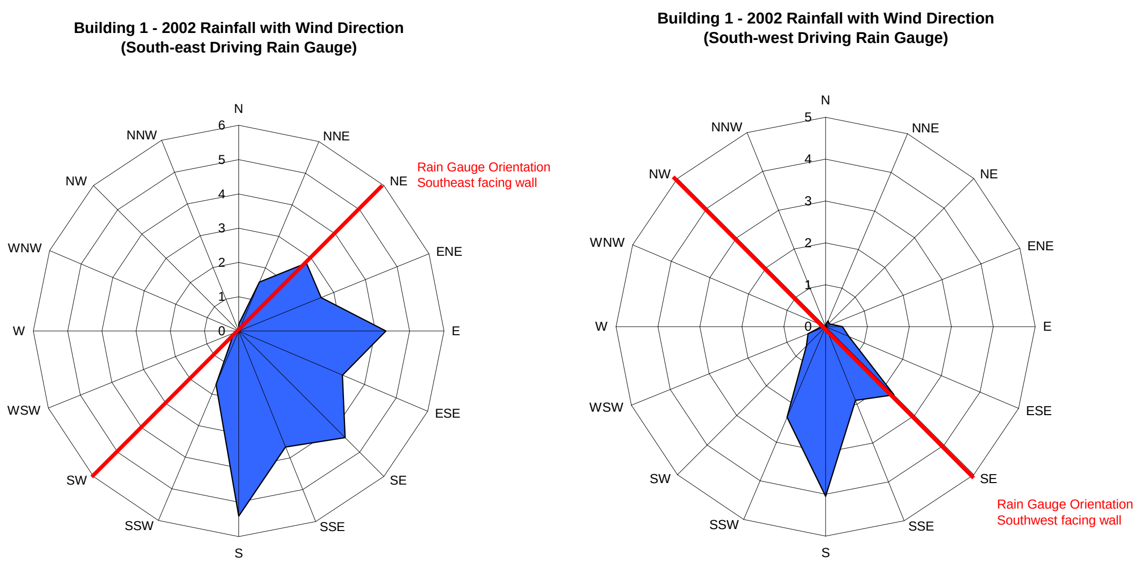
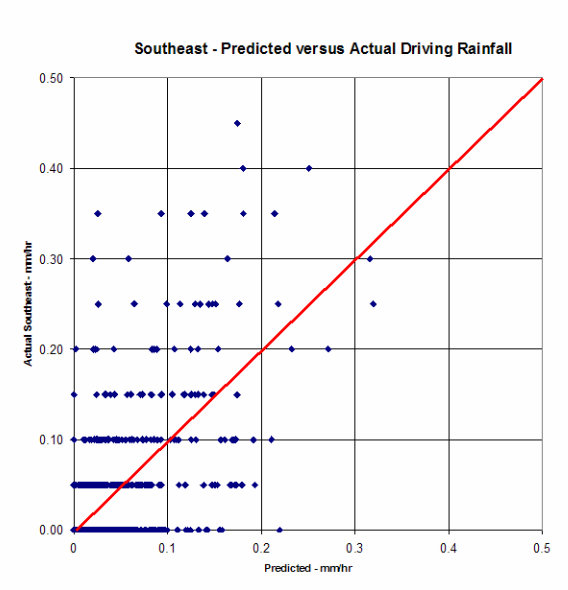
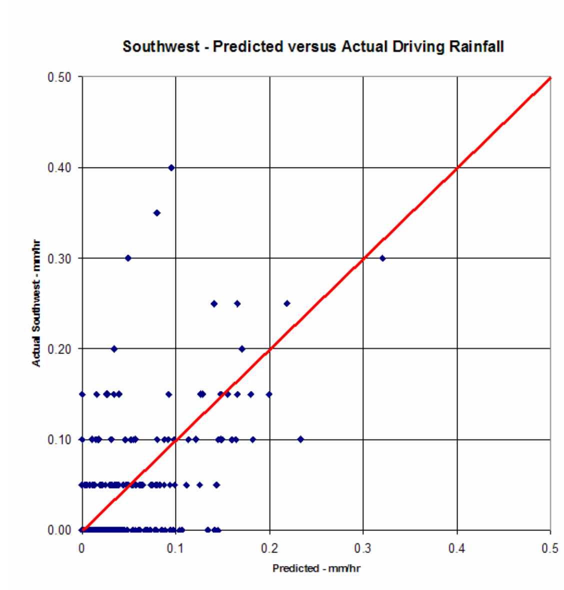


Figure 5-60: Building 1 – Southwest and Southeast: Measured Driving Rainfall Correlated with Wind Direction

Finally, the measured versus predicted hourly driving rain values are compared (Figure 5-61).





**points denote hourly measurements, red-line shows 100% correlation*

Figure 5-61: Building 1 – Southeast and Southwest Predicted versus Actual Driving Rain

The diagonal line represents a perfect correlation between the predicted and measured results. Considerable scatter was observed in the results showing that the accuracy of the hourly predictions was relatively poor for this building.

In conclusion, the empirical model was able to capture the driving rain trends for the two locations on this building, but could not capture the absolute measurements or hourly trends with great accuracy. Driving rain loads were relatively small for this building, the majority <0.10 mm/hr which may have an impact on the prediction model. The chosen RDF and EHF factors for this building are an indicator of annual performance on average.

5.5.4.2 Building 2

Measured driving rain from the south and east driving rain gauges on Building 2 is compared to the predicted deposition on an hourly basis. The cumulative driving rain is shown in Figure 5-62 for January 1st to December 31st, 2002 and in closer detail from January 1st to 15th in Figure 5-63. Wind direction from January 1st to 15th is shown in Figure 5-64.

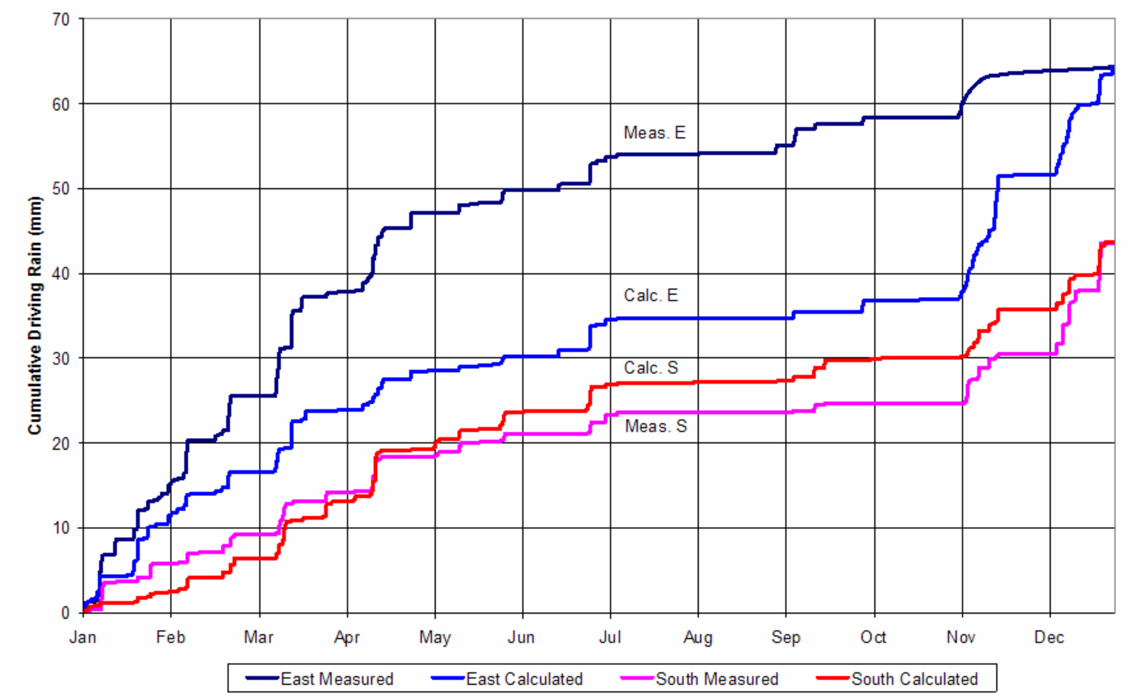


Figure 5-62: Building 2 – 2002: Calculated vs. Measured Driving Rain

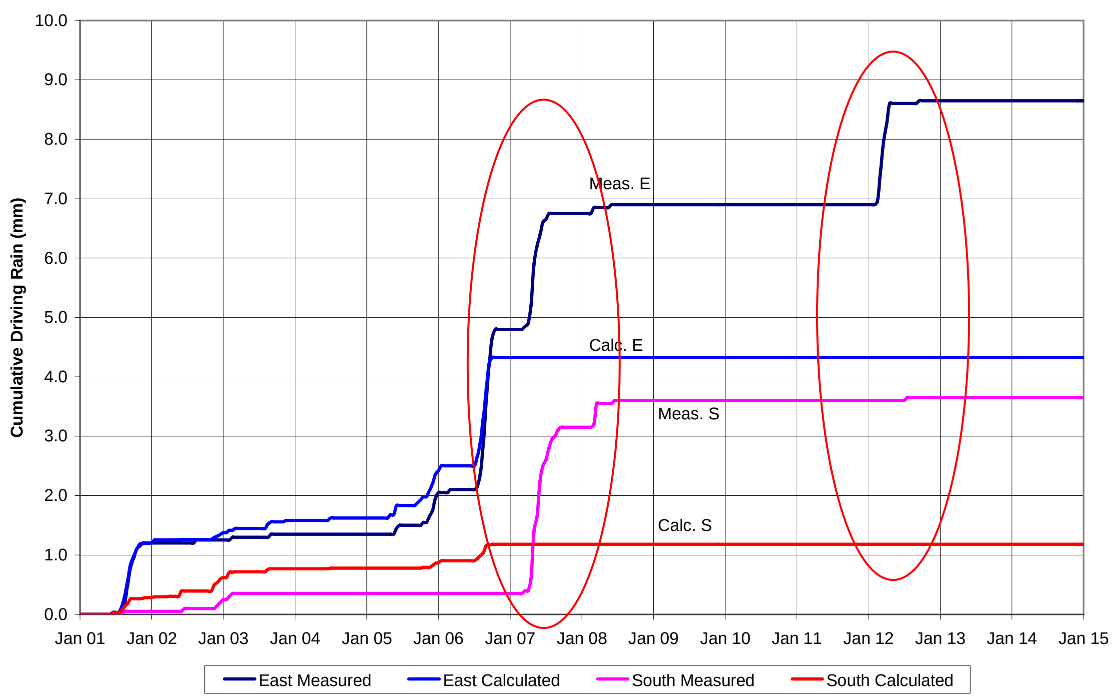


Figure 5-63: Building 2 – January 1-15: Calculated vs. Measured Driving Rain

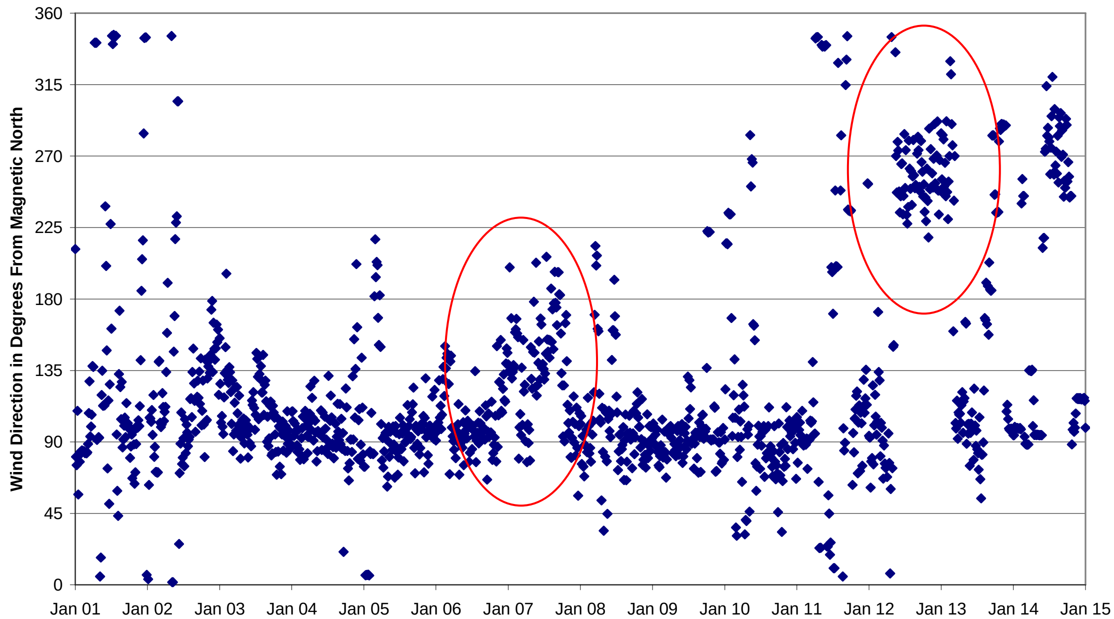
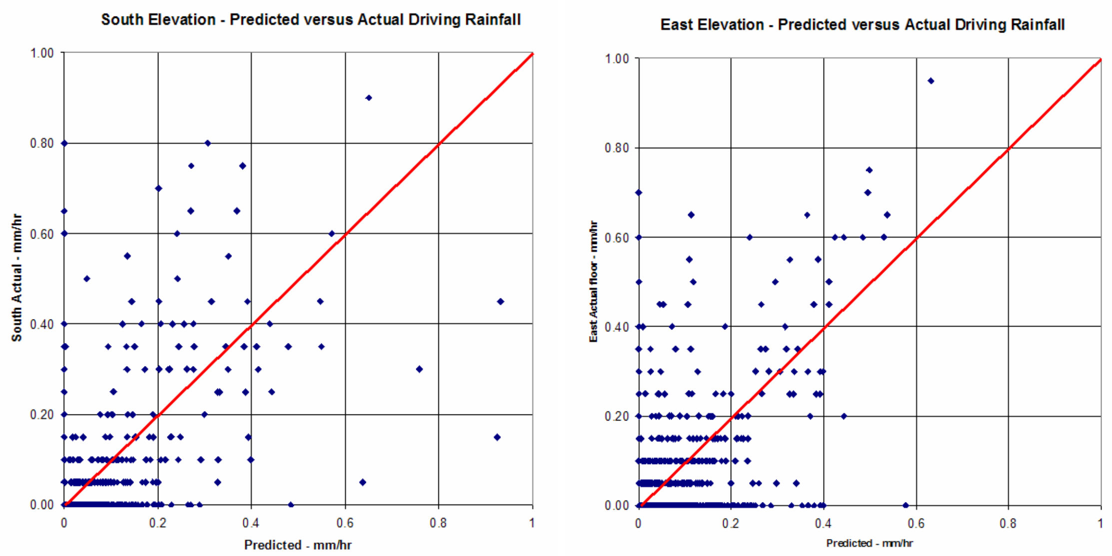


Figure 5-64: Building 2 – January 1-15: Wind Direction

To note some of the discrepancies between measured and predicted values, the driving rain gauge on the east elevation measured driving rain on January 12th, while winds were predominantly from the west and therefore driving rain would not be predicted by the model. Again on January 7th, winds shifted to the south but were measured at the east gauge, however not predicted by the model. This highlights some of the potential wind flow anomalies at this building that are causing rain deposition on this east face, but cannot be captured by the simple prediction model.

Similar to Building 1 the trends are captured, however the hourly prediction has varying accuracy. The hourly trends are captured relatively well on the south elevation, however not as well on the east (likely as a result of complex wind flow interactions described above). In addition, the east driving rain gauge appears to be partially sheltered by the adjacent building to the east and may be reflected here in the results (change in wind flow patterns at this location). The south driving rain gauge is well exposed just below the roof eave.



**points denote hourly measurements, red-line shows 100% correlation*

Figure 5-65: Building 2 – South and East Predicted versus Actual Driving Rain

The diagonal line represents a perfect correlation. Considerable scatter was observed in the results showing that the accuracy of the hourly predictions was relatively poor for this building.

In conclusion, the empirical model was able to capture the driving rain trends for the two locations on this building, but could not capture the absolute measurements or hourly trends with significant accuracy. The accuracy was however better for the locations on Building 2 than the locations on Building 1. The driving rain gauges were also more exposed and higher driving rain loads were also observed at Building 2. The chosen RDF and EHF factors for this building are an indicator of annual performance on average.

5.5.4.3 Building 3

Driving rain measurements from Building 3 provide the best correlation to the empirical model with good accuracy of the hourly and seasonal predictions. The monitored locations were well exposed and away from the influence of overhangs and adjacent buildings. In addition, the wall is facing due east; the primary direction of driving rain in Vancouver, therefore much of the wind-driven rain was perpendicular to the driving rain gauges. Building 3 also received the highest driving rain load of any of the buildings. Potential errors stemming from evaporation within the gauges or use of the cosine method are potentially minimized at this building.

Measured driving rain from the two east driving rain gauges is compared to the predicted deposition on an hourly basis. The cumulative driving rain is shown in Figure 5-66 for January 1st to December 31st, 2003 and in closer detail from January 1st to 7th in Figure 5-67. The wind direction from January 1st to 7th is also shown in Figure 5-70.

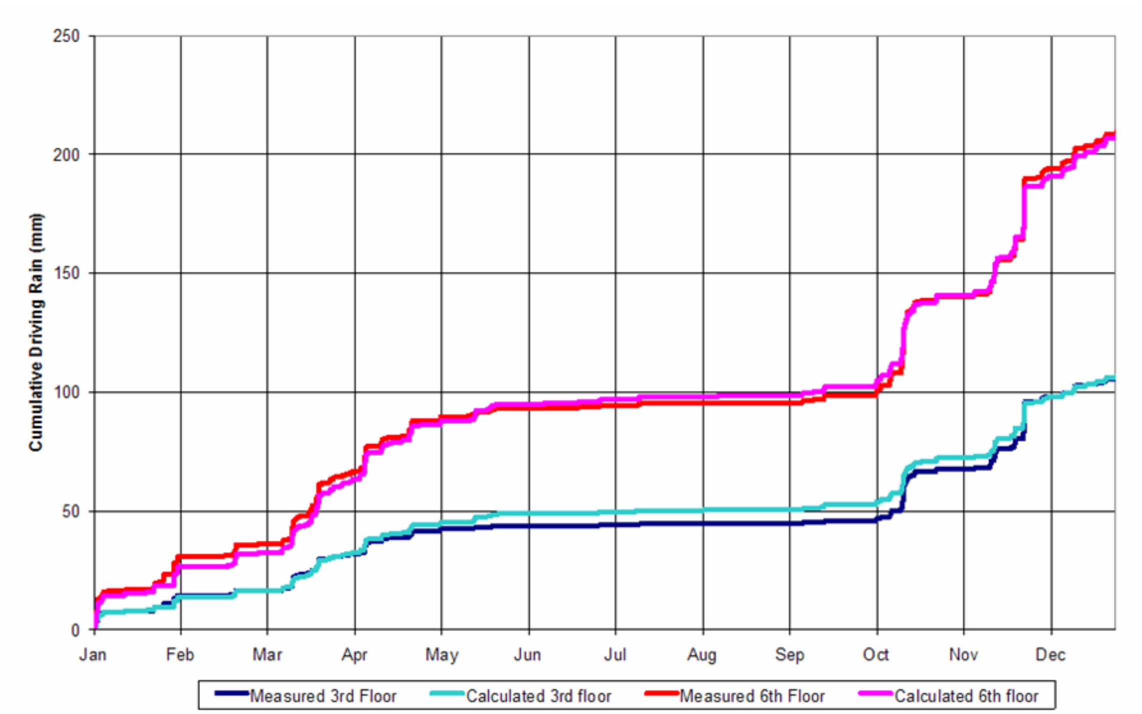


Figure 5-66: Building 3 – 2003: Calculated vs. Measured Driving Rain

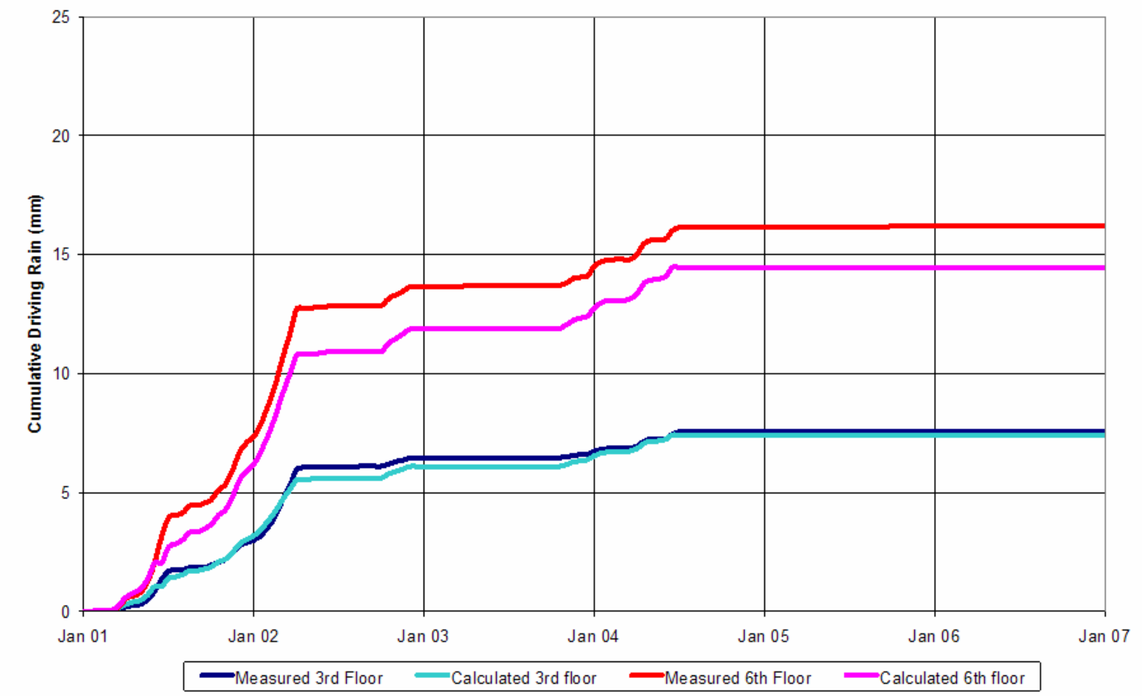


Figure 5-67: Building 3 – January 1-7: Calculated vs. Measured Driving Rain

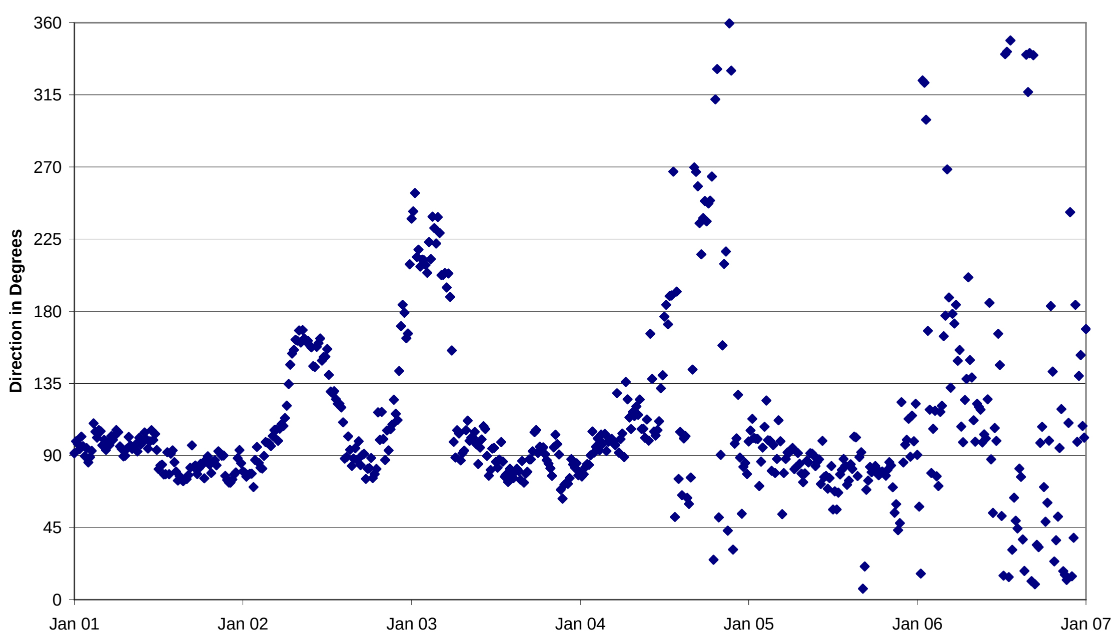


Figure 5-68: Building 3 – January 1-7: Wind Direction

The correlation between the measured and predicted values is good. Only slight variances between the measured and predicted values are observed. As shown wind direction during the driving rain events was to the east and perpendicular to the gauges. Considerably less scatter was also observed in the wind measurements compared to Building 1 and 2 previously.

A further comparison of the measured to the predicted results is compared for a large driving rain even from October 15th to 18th where hourly trends were well captured by the model (Figure 5-69). Wind direction during the driving rain event is shown in Figure 5-70.

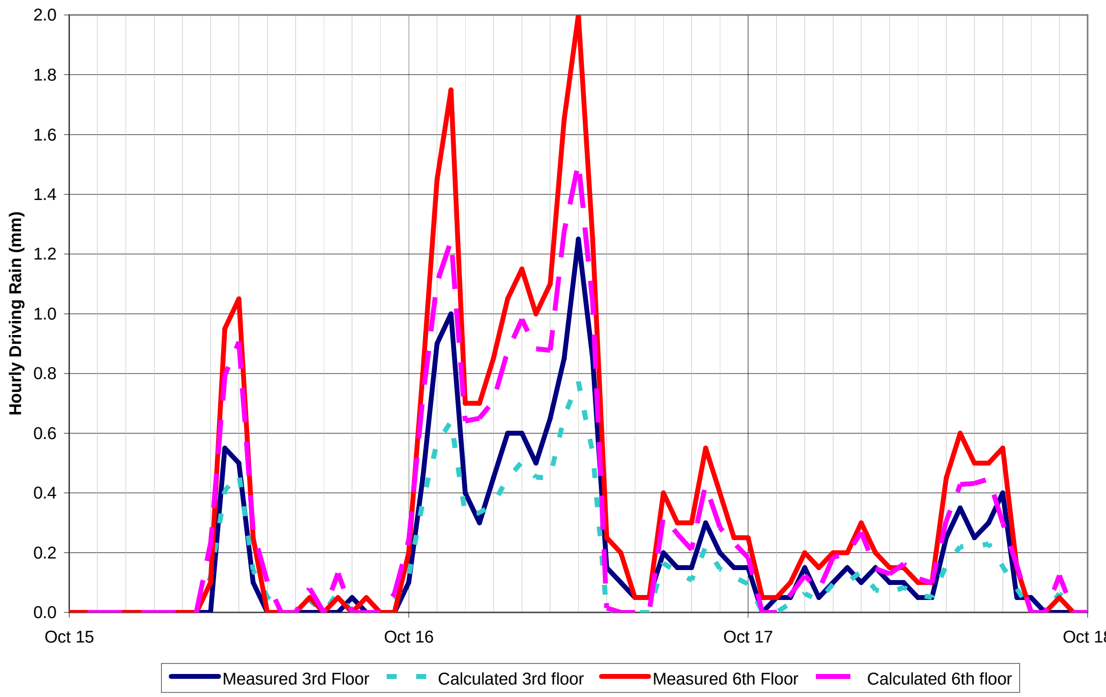


Figure 5-69: Building 3 – Hourly Predicted versus Measured Driving Rain, October 15-18

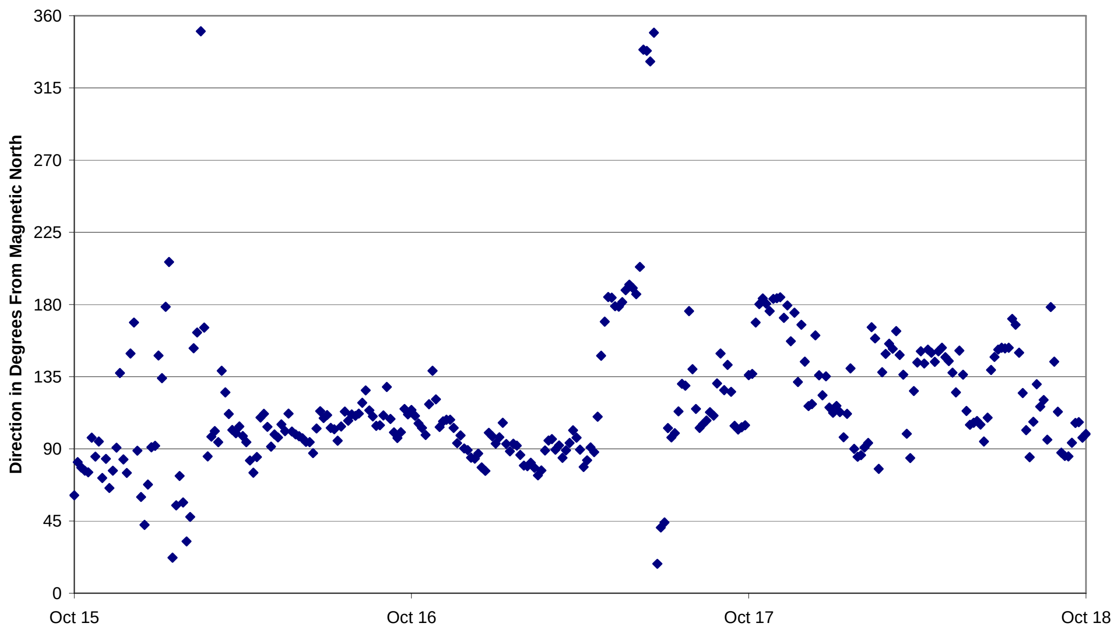


Figure 5-70: Building 3 – October 15-18: Wind Direction

Here the prediction was relatively close to the measured results on an hourly basis. The calculated driving rain was 0.2 mm less than the two large peaks measured at the 6th floor at 1.8 mm and 2.0 mm, however the hourly trend was well captured.

The model is able to predict the driving rain for this building relatively well and is a function of the predominant wind direction with rain events. As shown in Figure 5-71 the majority of the wind driven rain at the 6th floor occurs when the wind is from due east (~100 mm), or 12.5° south from the east-southeast (~60 mm). A similar relationship was also observed at the lower 3rd floor. Any potential error in the empirical model associated with the cosine method would therefore be minimized in the predictions at this building.

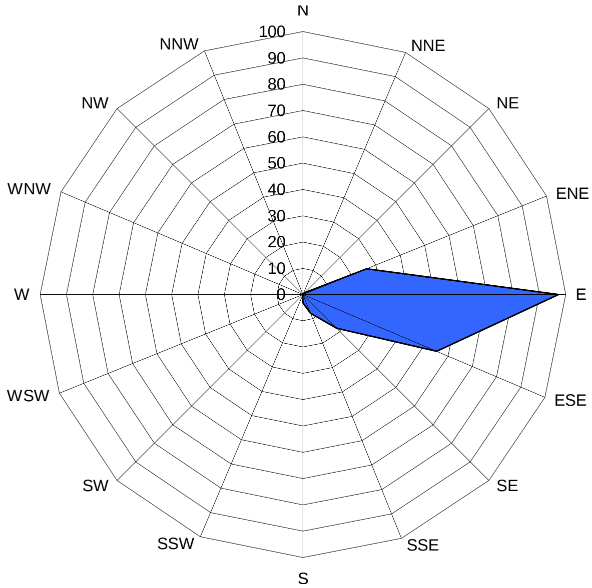


Figure 5-71: Building 3 – 2003: Driving Rain with Wind Direction, 6th floor

The predicted versus measured hourly driving rain correlation results are plotted in Figure 5-72 for the 6th and 3rd floor gauges showing the accuracy of the correlation

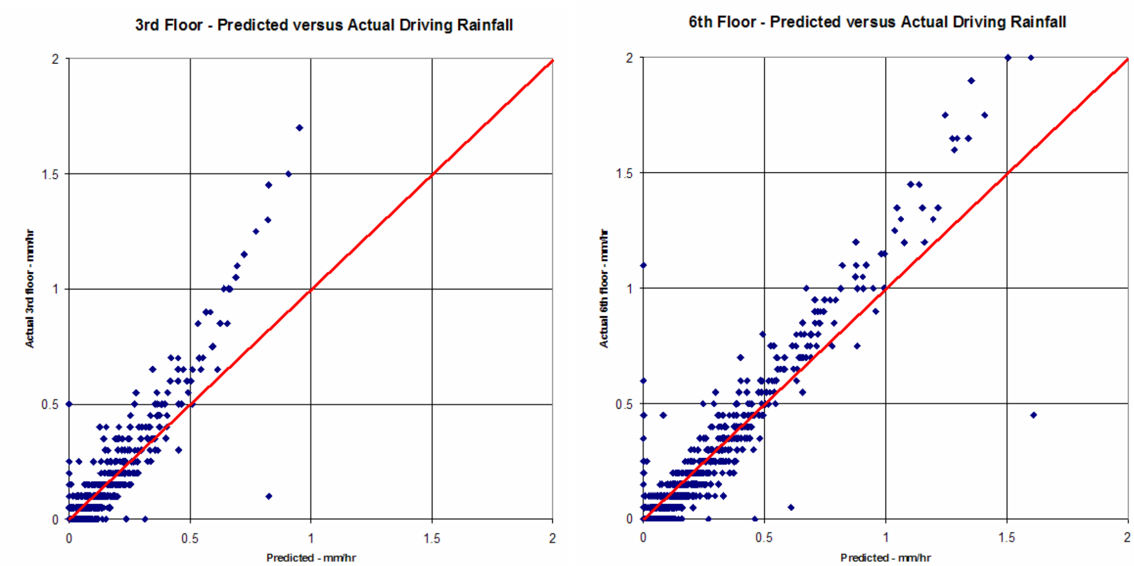


Figure 5-72: Building 3 - Comparison of Predicted versus Actual Driving Rain Measurements for 3rd and 6th Floors

The diagonal line represents a perfect correlation. As shown the correlation is relatively good, however at higher driving rain loads, the predicted is slightly less than the actual measured (similar to that discussed in Figure 5-69). Compared to the other four Buildings, the strongest trends were observed here.

At the two locations on this building the correlation of the measured to predicted driving rain load is excellent and shows the potential of empirical model to accurately predict driving rain loads on exposed and simple building shapes. The empirical model is able to predict the hourly trends with reasonable accuracy at both the 3rd and 6th floors on the east orientation. The RDF and EHF factors selected for this building are a good indicator of the hourly and seasonal driving rain deposition.

5.5.4.4 Building 4

Building 4 saw the lowest driving rain load of any of the buildings: 7 mm on the south, and 3 mm on the North. While this building provides little in terms of data to correlate driving rain measurements, it does provide important proof that a very large 1200 mm (4’) overhang can significantly reduce the amount of driving rain on the façade of a four-storey building to almost negligible levels.

While the empirical model was able to partially model the seasonal trends, the correlation is poor, particularly for the north elevation (Figure 5-73).

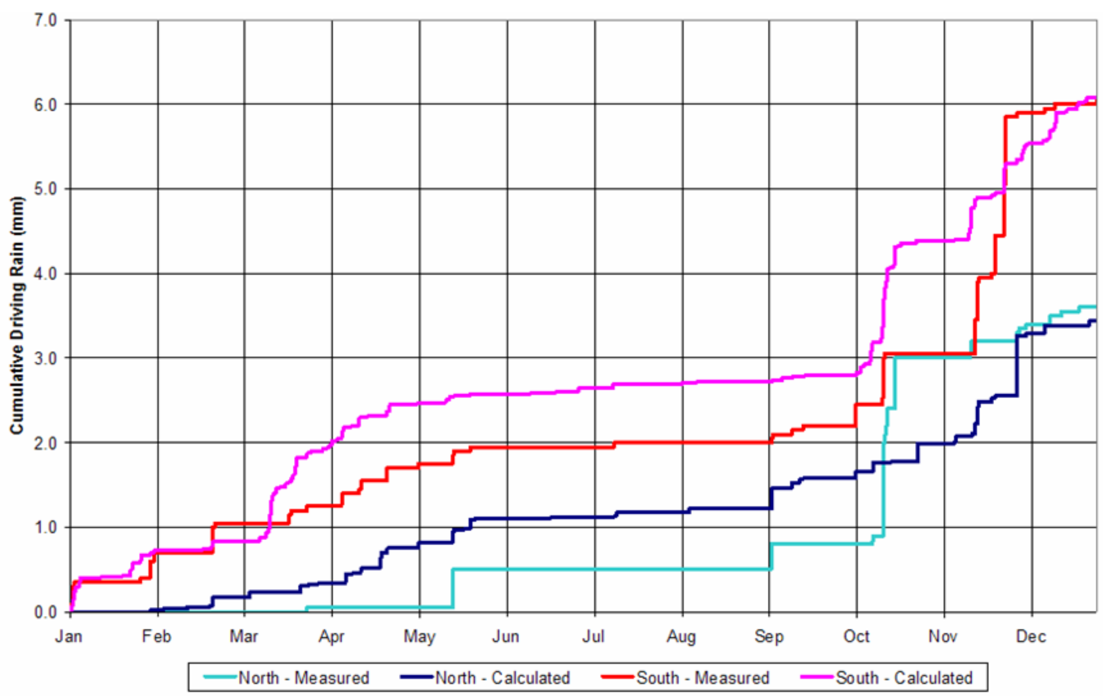


Figure 5-73: Building 4 – 2003: Calculated vs. Measured Driving Rain

For both orientations, the poor correlation can be explained by the wind direction during driving rain measurements. As shown in Figure 5-74, driving rain was measured at the north gauge while winds were 180° from the south (and potentially deposited rain as a result of wind vortices over the building). The driving rain measured at the south gauges was primarily measured during wind from the east-southeast (from the alley way), at a very low 12.5° to the wall.

The four-storey building directly to the south of Building 4 appears to have significantly sheltered this building from any driving rain from the south.

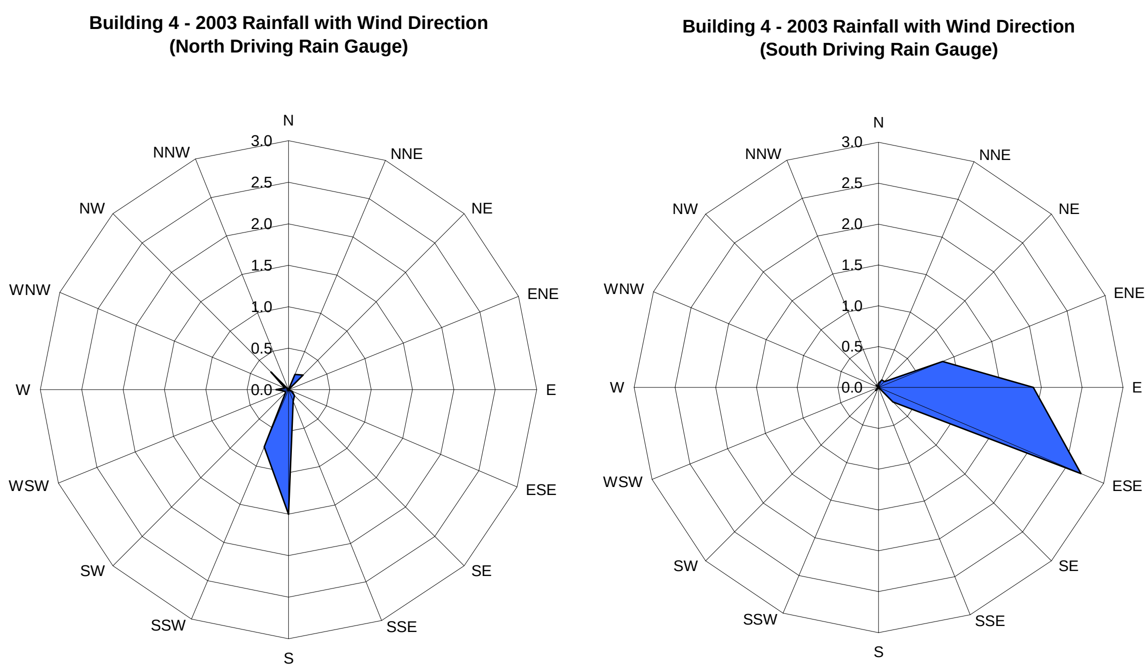


Figure 5-74: Building 4 – Direction of Wind with Rain showing anomalies with Driving Rain Predictions on North Elevation.

Very little driving rain was measured at this building as a result of large 1200 mm (4') overhangs and local sheltering. Almost negligible amounts of driving rain were deposited on the walls at the driving rain gauges. As a result, the empirical model was only able to partially capture the seasonal driving rain trends for the south gauge. The north driving rain gauge measured driving rain when winds were from the south, therefore the empirical model did not predict this deposition. This building received the least amount of driving rain and had the worst correlation with the empirical model. In addition, evaporation from the driving rain gauges was also potentially more of an issue at this building which received very light intensity driving rain (<1 mm per month).

The RDF and EHF factors selected for this building are very low (RDF of 0.06 and EHF of 0.5) and used to predict the annual driving rain load, however do not capture the trends well.

5.5.4.5 Building 5

The calculated driving rain at Building 5 was the highest of the five buildings, and was predominantly on the northeast orientation. As driving rain gauges were only installed on the southwest and southeast orientations, only a fraction of this driving rain was measured at these two gauges.

Measured driving rain from the southeast and southwest driving rain gauges is compared to the predicted deposition on an hourly basis. The cumulative driving rain is shown in Figure 5-75 for January 1st to September 30th, 2003 and in closer detail from January 1st to 7th in Figure 5-76. Wind direction from January 1st to 7th is shown in Figure 5-77.

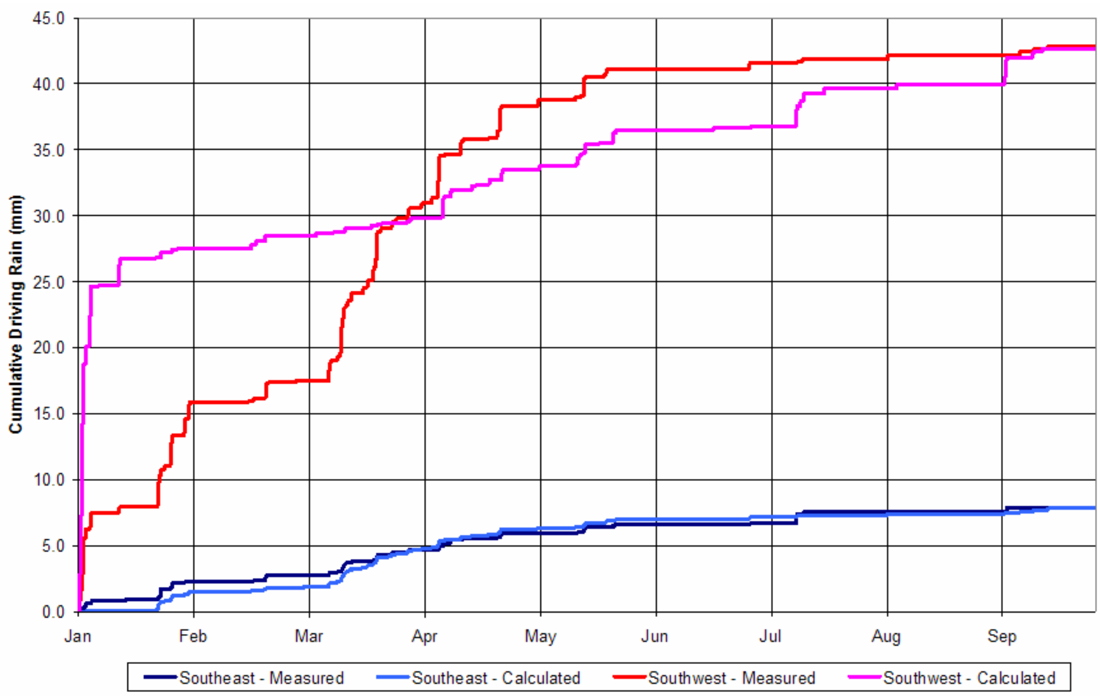


Figure 5-75: Building 5 – Jan-Oct, 2003: Calculated vs. Measured Driving Rain

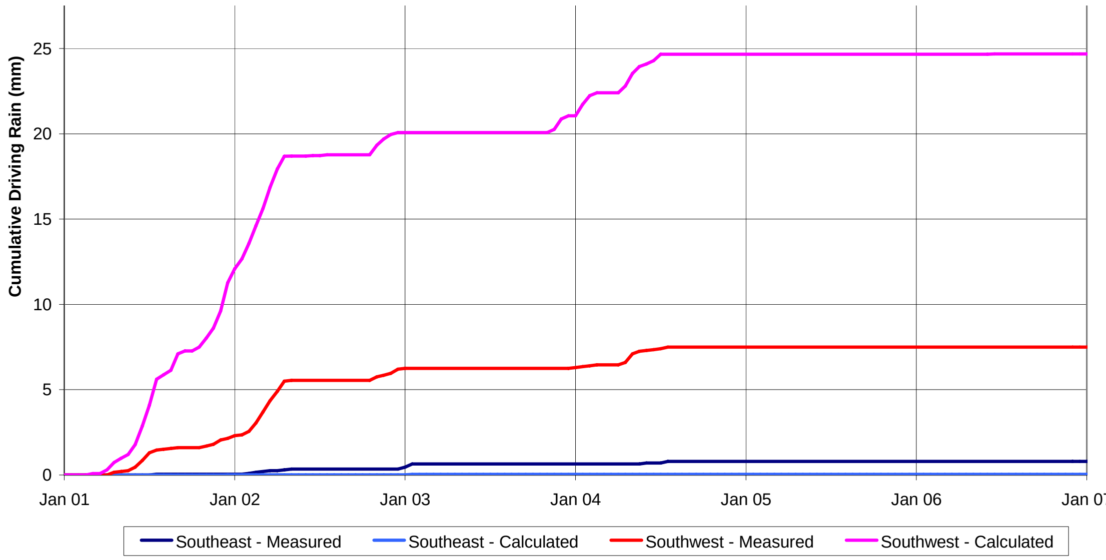


Figure 5-76: Building 5 – Jan 1-7: Calculated vs. Measured Driving Rain

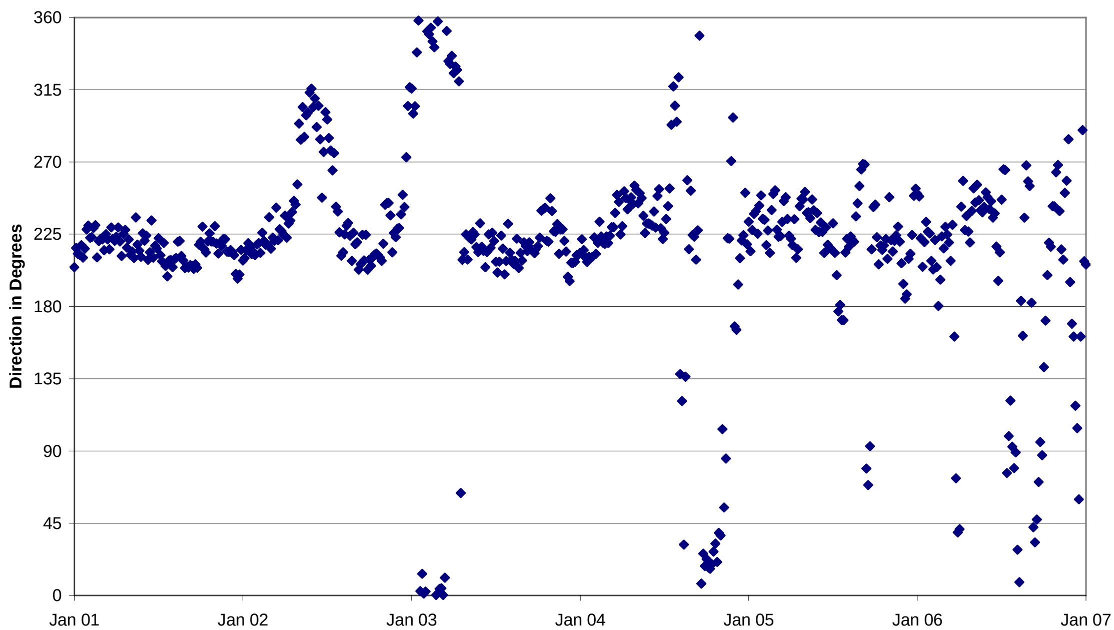
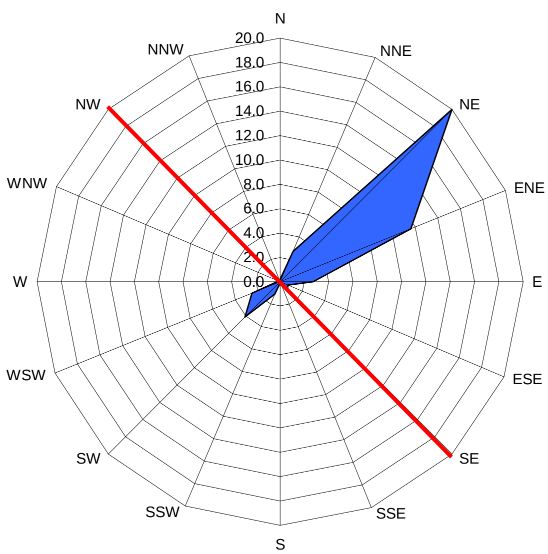


Figure 5-77: Building 5 – Jan 1-7: Wind Direction

On January 1st, the wind direction was predominantly from the southwest, and approximately 25 mm of driving rain was predicted at the southwest rain gauge during the event, but only 7 mm was measured. Other rain events at this southwest location were also only partially captured, indicating that the model was unable to predict the correct rain deposition for this location. In contrast, the driving rain predicted at the southeast gauge is much lower but shows reasonable accuracy compared to the measured results.

The role of wind direction with driving rain measurements was further investigated at the two driving rain gauge locations. Figure 5-78 shows the wind direction at the time of driving rain measurements for the southwest and southeast gauges. Interestingly a large percentage of the driving rain measured at the southwest gauge occurred when winds were from the northeast. Similar observations were made at the southeast gauge.

The empirical model would not predict driving rain deposition at the southwest gauge, when winds are from the northeast (180° away). At the southwest location, a complex interaction between the wind and driving rain is occurring which cannot be determined without the use of more advanced CFD modeling.



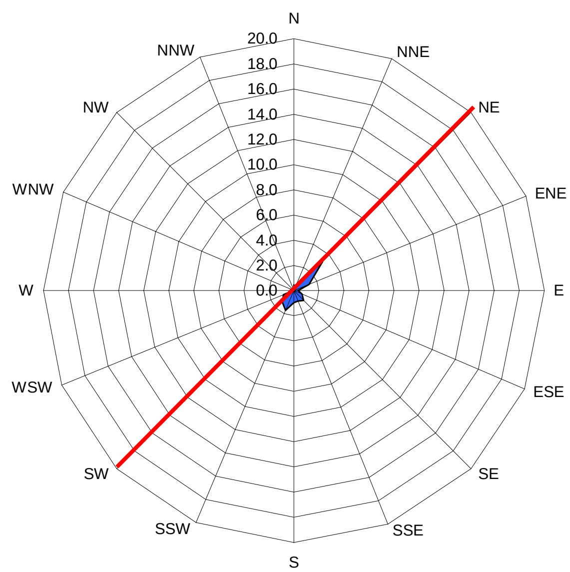


Figure 5-78: Building 5 – 2003: Wind Direction with Measured Driving Rain, 30th Floor Southwest (left) and Southeast (right)

In conclusion, the empirical model was only able to partially capture the driving rain trends for the two locations on this building, and could not capture the absolute measurements or hourly trends with great accuracy. The accuracy was greater at the southeast rather than the southwest gauge and complex wind driven rain phenomena was measured which could not be captured by the empirical model. The chosen RDF and EHF factors for this building are an indicator of annual performance on average, however due to complex wind phenomenon may not be representative for all high-rise buildings. The limitations of the empirical model are shown for predictions at this building.

5.6 WEATHER SOURCES AND DESIGN

Designers have a limited selection of climate files for design analysis, and understanding differences between data sources is important to in determining the most appropriate design load. Performing a simulation for a wall in the climate of Vancouver would yield obviously different results when simulated in Edmonton's. The same can hold true for two different Vancouver climate files, and depending on the sensitivity of the wall assembly may result in different performance.

Differences in monthly average measurements from six different climate sources are presented to assist designers in selecting appropriate climate files for analysis. Typically WUFI 4.1 "cold" and "hot" year data files or WUFI 3 standard data files are available to most designers. It is of interest to understand the monthly differences between those sources compared to CWEC and Environment Canada (EC) averages.

Monthly rainfall is compared in Figure 5-79, solar radiation in Figure 5-80, temperature in Figure 5-81, and relative humidity in Figure 5-82 for the six data sources.

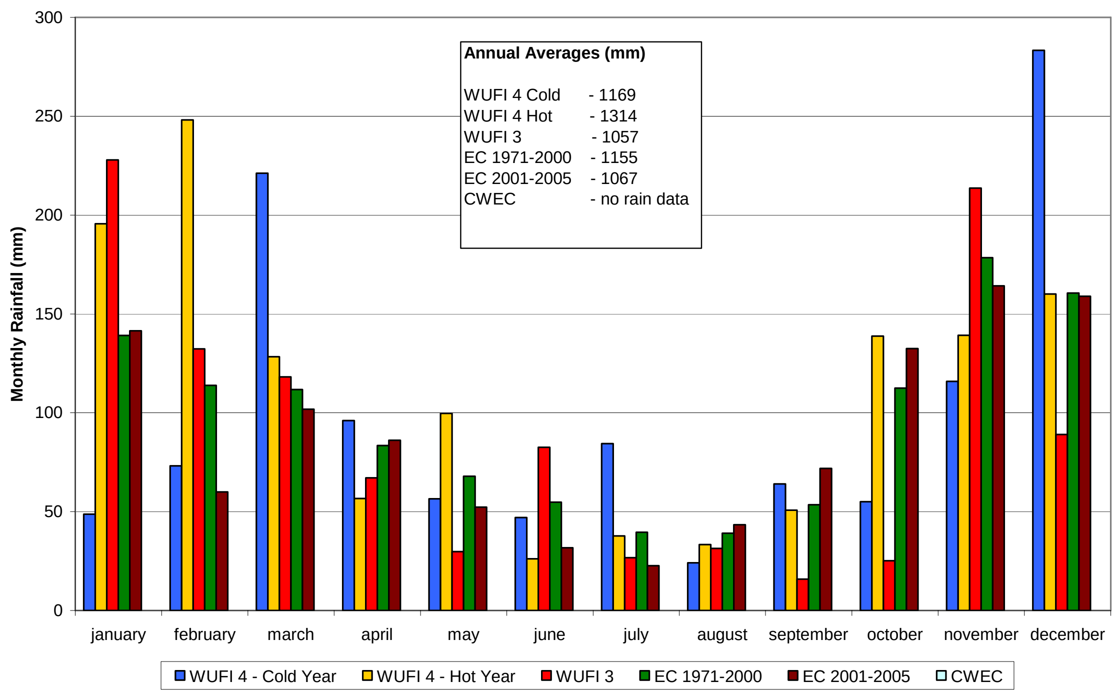


Figure 5-79: Comparison of Data Sources - Monthly Rainfall

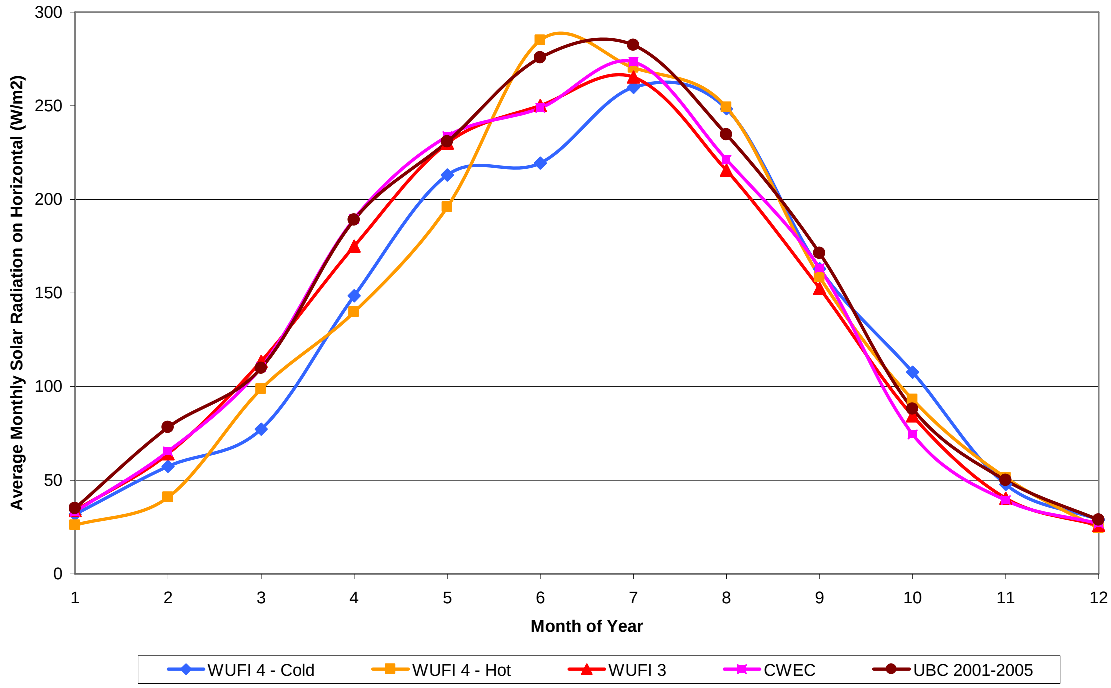


Figure 5-80: Comparison of Data Sources – Solar Radiation on Horizontal

Monthly air temperature data is presented bound by monthly minimum and maximum averages, showing where the climate files fit within the range.

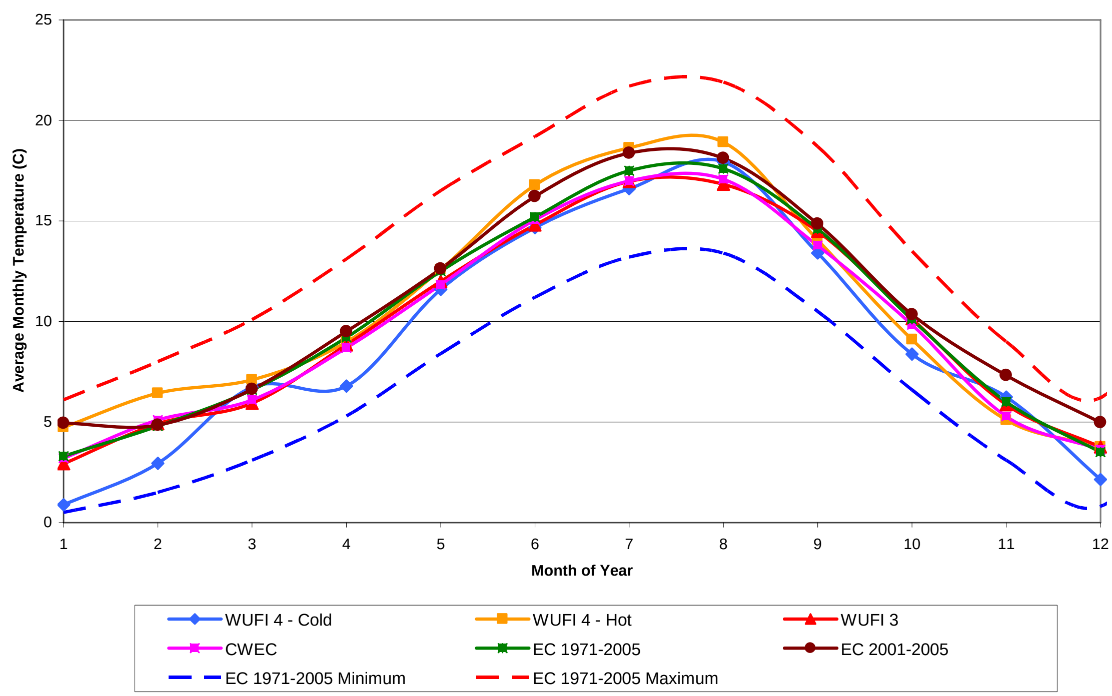


Figure 5-81: Comparison of Data Sources – Monthly Air Temperatures

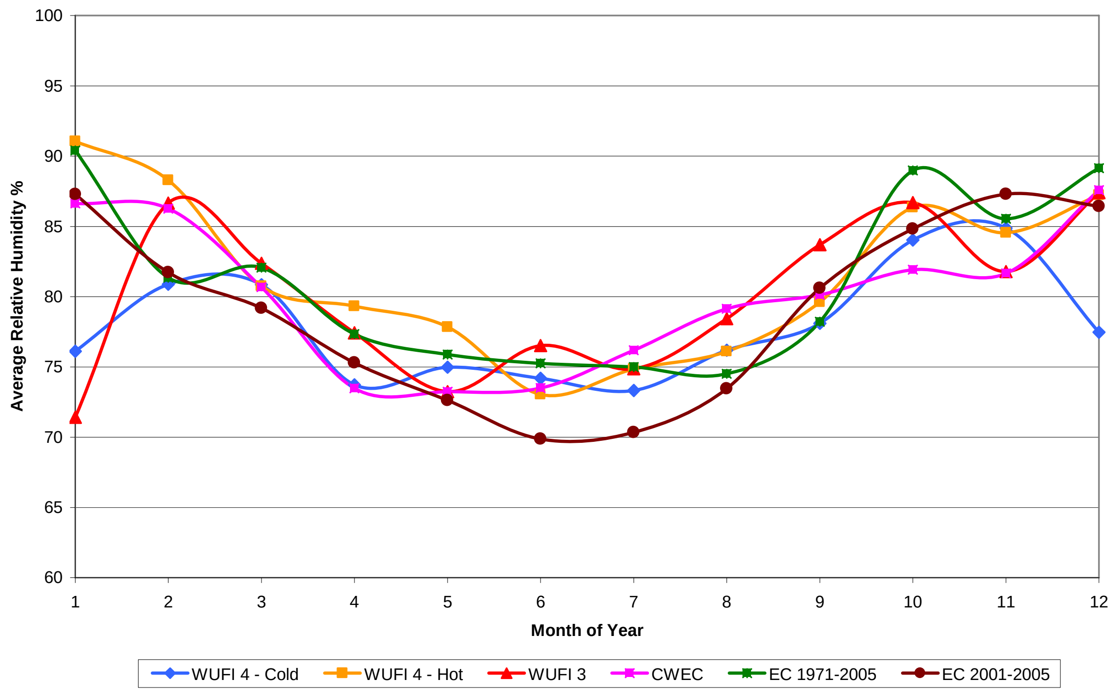


Figure 5-82: Comparison of Data Sources – Monthly Relative Humidity

The impact of climate file on Heating and Cooling Degree Day (HDD/CDD) calculations are highlighted in Figure 5-83.

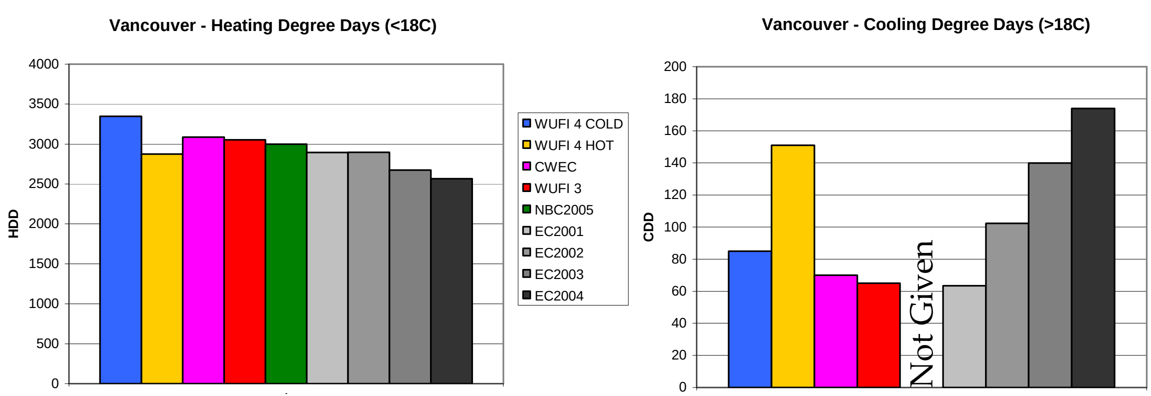


Figure 5-83: Comparison of Data Sources - Heating and Cooling Degree Days

Interestingly with the heating and cooling degree days, is the trend observed in he last four years of Environment Canada data showing the drop in HDD and almost double in CDD.

Driving rain loads for Vancouver from WUFI 4.1 are presented for comparison to the CWEC and five building data presented in previous sections. The hot and cold year climate files have different loads from 900-1100 mm/yr are shown in

Figure 5-84. The driving rain loads are calculated here using an empirical relationship, similar to that used here and shown in the text in Figure 5-85.

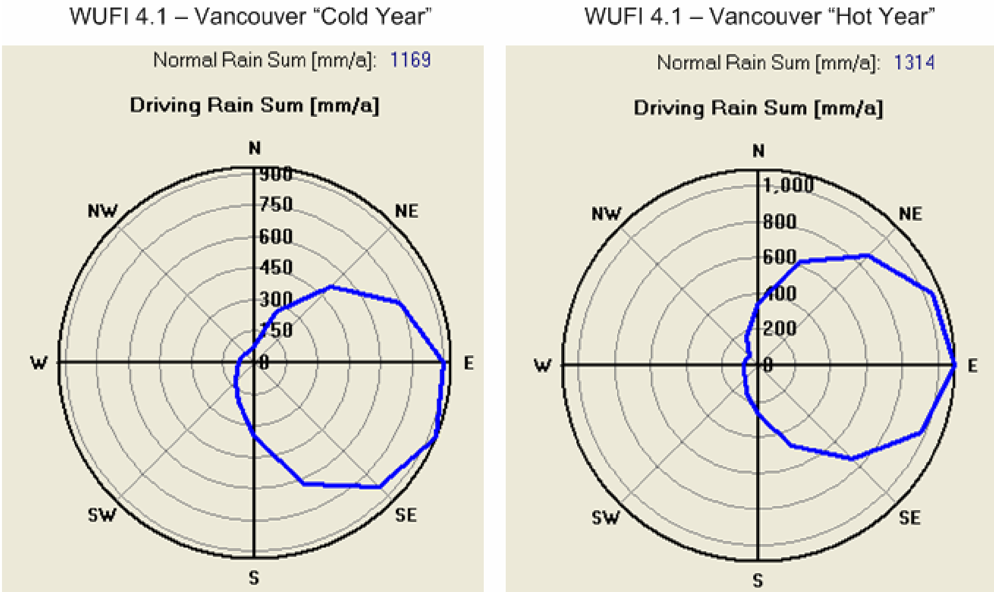


Figure 5-84: Calculated Driving Rain Loads for Vancouver

While these driving rain loads are higher than average conditions (800-900 mm/yr), they are representative of worst-case design loads. They are however too high to be representative for all building types and should be modified for exposure.

Referring to the calculated driving rain plots for Buildings 1 through 5 from the previous section: Building 5 (30 storey high-rise) had the highest annual driving rain potential with approximately 850 mm/yr, similar to the airport with 800 mm/yr, this was followed by Building 3 (6 storey mid-rise) with 550 mm/yr and Buildings 1, 2 and 4 (four-storey low-rises) with between 200-300 mm/yr.

The reduced driving rain load observed at the five buildings in the study can be accounted for by using exposure factors in WUFI. Figure 5-85 shows the driving rain coefficient selection boxes for WUFI 4.1 (using the ASHRAE Standard 160P formula), where modification factors for driving rain are input by the user. Other programs such as hygIRC and older versions of WUFI have similar interfaces.

Based on observations from this study, an exposure factor (EHF) of 0.5 and possibly as low as 0.25 could be used for sheltered four-storey buildings in Vancouver. For even less exposed buildings such as single family houses, a further reduction could be made based on professional judgement. As with all computer simulations, the impact of a higher driving rain load should be investigated on the assembly.

A rain deposition factor (RDF) is also input by the user depending on the location of the building which is to be simulated. For worst case scenarios a RDF of 1.0 or higher based on current literature is suggested.

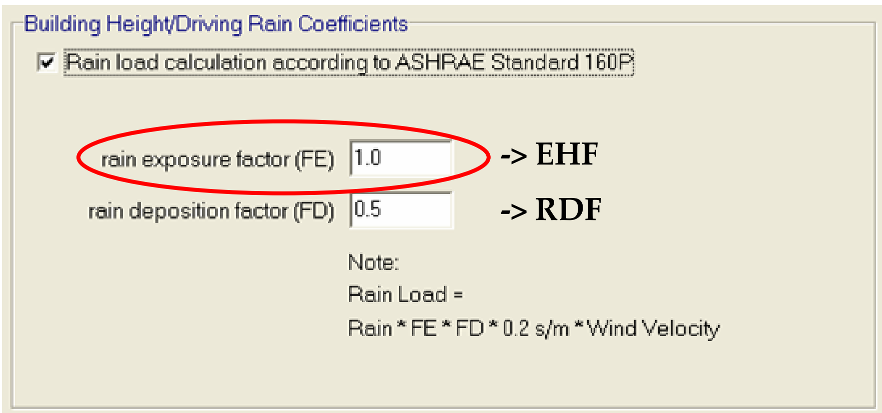


Figure 5-85: WUFI 4.1: Driving Rain Load Modifications

5.7 CONCLUSIONS

The local climate across the Greater Vancouver area varies. Differences in rain, wind speed, wind direction, temperature, and relative humidity were observed across the five buildings and the airport. Typically the airport receives less rain and records cooler temperatures than most areas of the city. The highest rainfall was observed at Building 5 in the downtown core. The predominant wind direction for most of Vancouver is from the east to south-east, however in the downtown area, particularly along the Burrard Inlet; northeast was found to be the predominant direction. The predominant wind direction was also found to be the predominant direction during driving rain events.

Driving rain was measured at two orientations on the five buildings in the study. Local sheltering from wind was found to reduce the amount of driving rain at the building significantly.

Driving rain was calculated using an empirical method to determine the total driving rain as a function of the climate (wind speed, direction and horizontal rainfall). Building 5 (30 storey high-rise) had the highest annual driving rain potential with approximately 850 mm/yr), similar to the airport with 800 mm/yr, this was followed by Building 3 (6 storey mid-rise) with 550 mm/yr and Buildings 1, 2 and 4 (four-storey low-rises) with between 200-300 mm/yr. The differences in calculated driving rain at each of the buildings and the airport are summarized in Figure 5-86 and shown across the city in Figure 5-87.

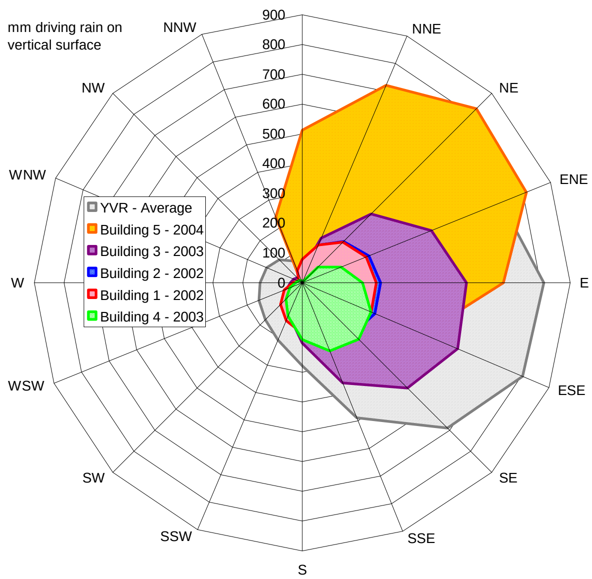


Figure 5-86: Summary of Driving Rain Loads at Buildings 1-5 & YVR

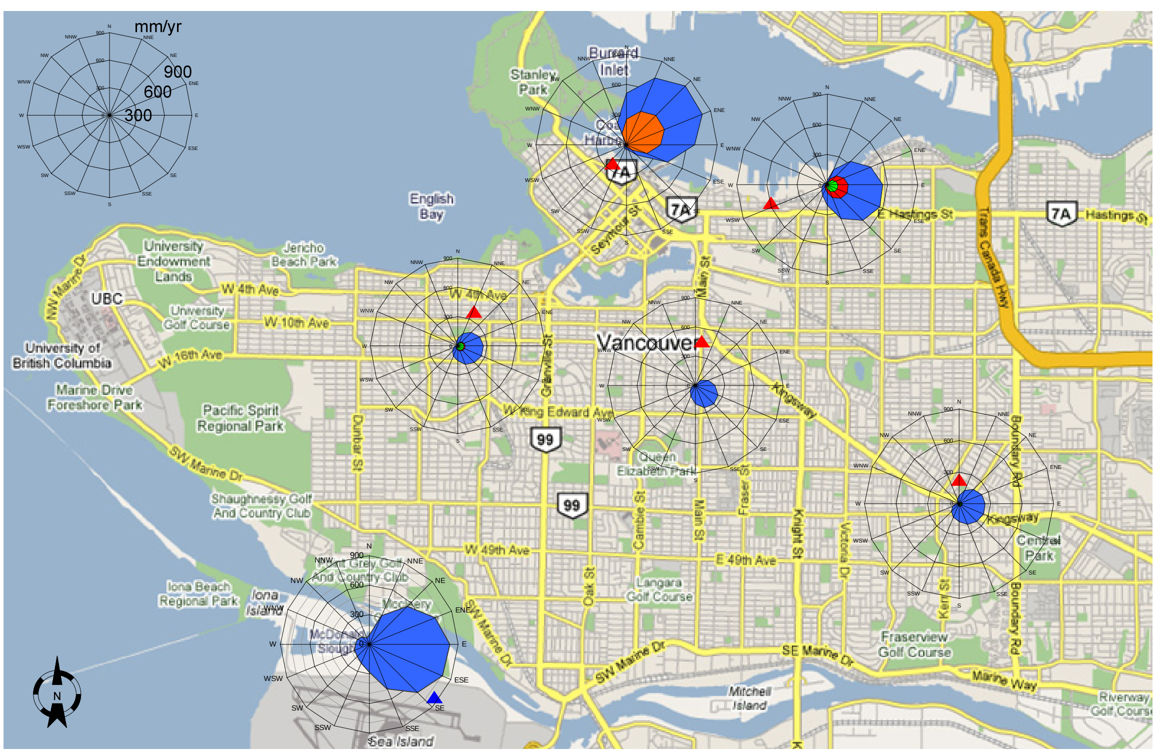


Figure 5-87: Summary of Driving Rain Loads Across Vancouver (underlay map: Google Maps 2006)

To determine the driving rain on the façade of a building, modification factors are applied to the calculated driving load. Reductions are made depending on the location on the building and are reflected in rain deposition (RDF) and exposure height (EHF) factors. RDF and EHF factors were determined for two locations on each of the five buildings by correlating the calculated driving rain with that measured by driving rain gauges.

An EHF factor of 0.5 was assumed and RDF factor determined to correlate the driving rain predictions to measurements. RDF factors generally agreed with previous literature and were found to range from 0.06 for Building 4 (well sheltered to 0.76 at the top corner of Building 3 and 1.0 at the top edge of Building 5.

Buildings 1 and 4 with moderate to large roof overhangs saw significantly reduced driving rain deposition compared to Buildings 2 and 3 without overhangs. Building 4 saw the lowest driving rain load: 7 mm/yr on the south, and 3 mm/yr on the North, significantly less than any of the other buildings. While providing little in terms of driving rain data, Building 4 does provide important proof that a very large 1200 mm (4') overhang can significantly reduce the amount of driving rain on the façade of a large four-storey building to almost negligible levels.

Empirical methods to calculate driving rain at a specific location on the building façade have varying accuracy, and are be influenced by a number of variables.

The accuracy of the empirical model was very good for the two exposed east facing locations on Building 3. The hourly and seasonal correlation of the measured to predicted driving rain load was excellent and showed the potential of empirical model to accurately predict driving rain loads on exposed and simple building shapes.

In contrast, at Buildings 1, 2, 4, and 5 the empirical model was able to capture the relative driving rain trends at the monitored locations on these buildings, but could not capture the absolute measurements or hourly trends with great accuracy. Errors were observed as a result of complex wind and rain interactions at these buildings which could not be predicted by the empirical model. The use of more sophisticated numerical CFD models may be required in these cases to accurately predict driving rain deposition for these more complicated buildings

Correlation with buildings that received driving rain predominantly perpendicular to the driving rain gauges was better than buildings where the driving rain came from a range of directions.

The limitations of the empirical method were shown, and further research should be performed into the validity of the cosine method assumption used by all empirical methods. The empirical model could possibly be improved with additional factors to correct for wind from angles not perpendicular to the wall.

Selecting an appropriate RDF and EHF factor is simple in hind-sight using measured data, and the RDF values generally agree with previously the published literature. However in foresight it may be difficult to predict RDF factors with confidence for design. Assumptions must be made based on experience of the designer, and it is always safer to choose a larger RDF factor resulting in a worst case loading.

Hygrothermal modeling software such as WUFI provide weather files for use with simulations. These weather files are typically derived from measurements at airports, and representative of worst case design loads. Exposure correction factors should be applied to reduce the driving rain loads from the airport to the building based on the designer's judgement and experience. RDF and EHF factors for the five buildings were provided to assist practitioners with selecting appropriate factors.

5.8 REFERENCES

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6 INTERIOR BOUNDARY CONDITIONS – THE INDOOR CLIMATE OF MULTI-UNIT RESIDENTIAL BUILDINGS

This chapter presents measured interior climate data from nine suites in the five monitored buildings in Vancouver. The measured conditions provide insight into the range of temperature and relative humidity to potentially expect in multi-unit residential buildings in Vancouver's climate and improve understanding into the performance of each monitored building. The influence of occupant behaviour and suite air tightness on interior temperature and humidity levels are shown.

6.1 INTRODUCTION

The interior environmental conditions within buildings are of interest to building designers and in particular mechanical engineers. Buildings can have a range of interior conditions, and predicting these conditions is required for design. Commercial or industrial process buildings are typically tightly controlled and as such designers can typically make assumptions based on controlled set points. In most residential buildings, occupants control their own environments within a usual range to what they find comfortable. In a multi-unit residential building, there can potentially be hundreds of different micro climates which impact the performance of the building and the occupant's health.

ASHRAE recommends that the interior temperatures during winter months be maintained between 20°C and 24°C and indoor temperatures during the summer months between 23°C and 26°C. ASHRAE also recommends that the interior relative humidity (RH) be maintained between 30% and 60%. An interior RH below 30% can cause occupant discomfort and the drying of mucous membranes and an RH above 60% for extended periods can promote microbial growth. Comfort is a personal choice, and in residential buildings, occupants are free to control the temperature and humidity to what suits them. Without proper knowledge, sometimes these preferred conditions can be damaging to buildings unbeknown to the occupant.

The interior temperature is influence by occupant control, exterior temperature, solar heat gain (windows), and the air exchange rate. Controlling the interior temperature in most residential buildings is performed using a simple wall mounted thermostat which controls the heating system whether it is electrical baseboard heaters, forced air furnace, or radiant heat flooring.

The interior humidity level is influenced by indoor moisture production, air exchange rate, outdoor air moisture content, and vapour stored and released from building materials. In residential buildings, the interior relative humidity is typically not controlled; however a humidistat is sometimes provided which turns on an exhaust fan when the relative humidity reaches a certain set point.

Building designers may assume that occupants will control the temperature to reasonable levels, and increase ventilation when the suite becomes too humid. Occupant behaviour cannot always be relied on, and some occupants may choose to have cooler or warmer than average temperatures or more humid living environments. This is an issue the designers of multi-unit residential buildings face, as it is not always possible to tightly control the conditions within every suite like other buildings. Therefore ensuring the HVAC system can cope with a range of reasonable environmental conditions, and maintain sufficient ventilation for occupant health and good building performance is required. In addition, the building enclosure should be able to withstand a range of reasonable conditions without causing failure.

In addition when interior conditions are not behaving as expected, it may not always be the fault of the occupants. The problems within Building 3 were initially thought to be as a result of occupant behaviour and excessive moisture generation, and while lifestyle may be a partial contributor, the widespread occurrence of the problem in the building lead to further monitoring and testing which discovered the problem to be a result of poor HVAC performance. So while you turning up the humidity in your suite one thing, your suite turning up the humidity as a result of insufficient ventilation is another, however both have the same effect.

The intent of this chapter is to present measured interior climate loads (temperature, relative humidity, dewpoint) to assist designers in selecting appropriate loads for use in design and in particular, hygrothermal models. In addition, air leakage testing results from Chapter 7 are discussed to further understand the interior climatic conditions and understand how suite ventilation rates can affect these conditions.

6.2 BACKGROUND & SUITE MECHANICAL SYSTEMS

The HVAC systems within all five of the buildings are similar. The suites in each building are heated using electrical baseboard heaters with the exception of suites in building 4 which are heated with hot-water radiant flooring. Cooling or air conditioning is not provided as is typical for most residential buildings in Vancouver's temperate climate.

The ventilation strategy for all buildings is also similar, and typical for the majority of multi-unit residential buildings in North America. Supply air is provided to pressurized hallways and is assumed to find its way to the suites, typically via intentional suite door undercuts. At the same time, stale air is exhausted through bathroom or kitchen fans, windows, or through small cracks and holes in the enclosure air barrier. Bathroom fans are typically the primary exhaust point, with kitchen fans providing additional flow while cooking. Humidistats are sometimes wired to control the bathroom exhaust fans to ensure the interior relative humidity remains below a certain set-point. A schematic of this ventilation system is shown in Figure 6-1.

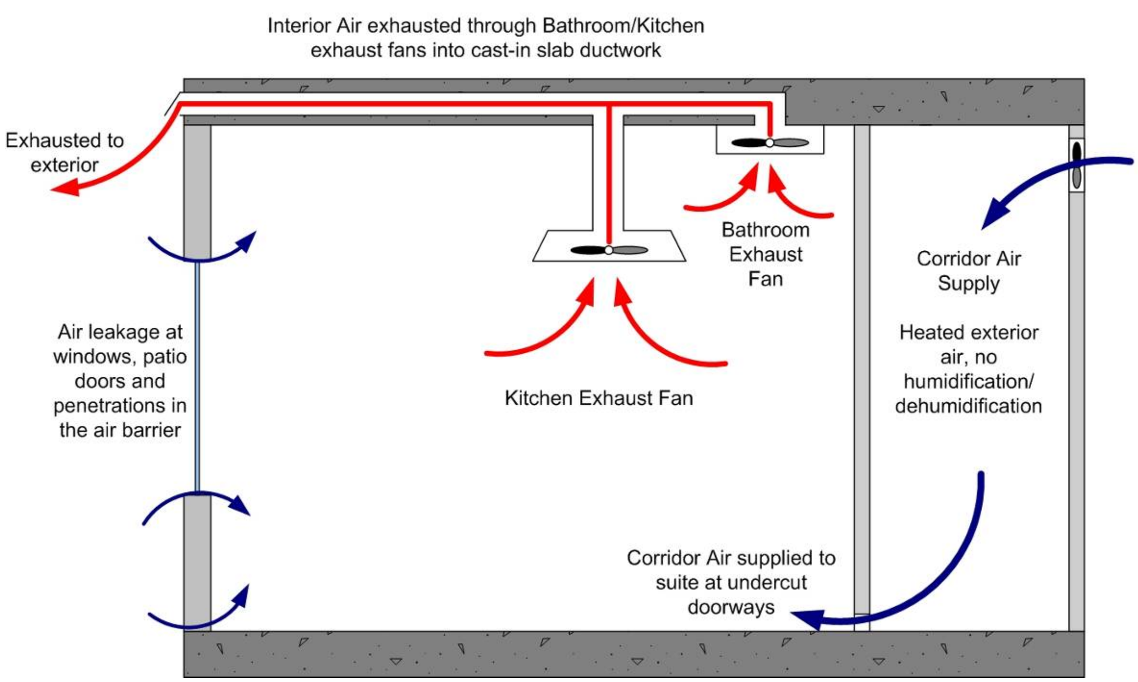


Figure 6-1: Suite Ventilation Schematic – Building 3 & 5

The two concrete frame buildings 3 and 5 have cast-in-slab ducts similar to that shown above. Wood frame buildings 1, 2, and 4 use mechanical ducts in drop ceiling plenums or between the floor joists.

Balancing pressurized corridor systems is difficult, and hallways should be pressurized at all times with respect to the suites. If pressurization does not occur as a result of: stack effect, wind, or where vertical chases such as elevators are not sealed from floor to floor, this system will perform poorly. Blocked door undercuts are a common issue and reduce the effectiveness of this system by preventing the flow of fresh air into suites.

An unbalanced system occurs when pressure differences between individual suites or common corridors are not maintained. In this case it can be common for one suite under pressure (either by running exhaust fan or due to wind or stack effect) to pull stale-air from adjacent suites thus diluting the make-up air. This is shown in Figure 6-2. A balanced system is shown in Figure 6-3 showing the intent of this system.

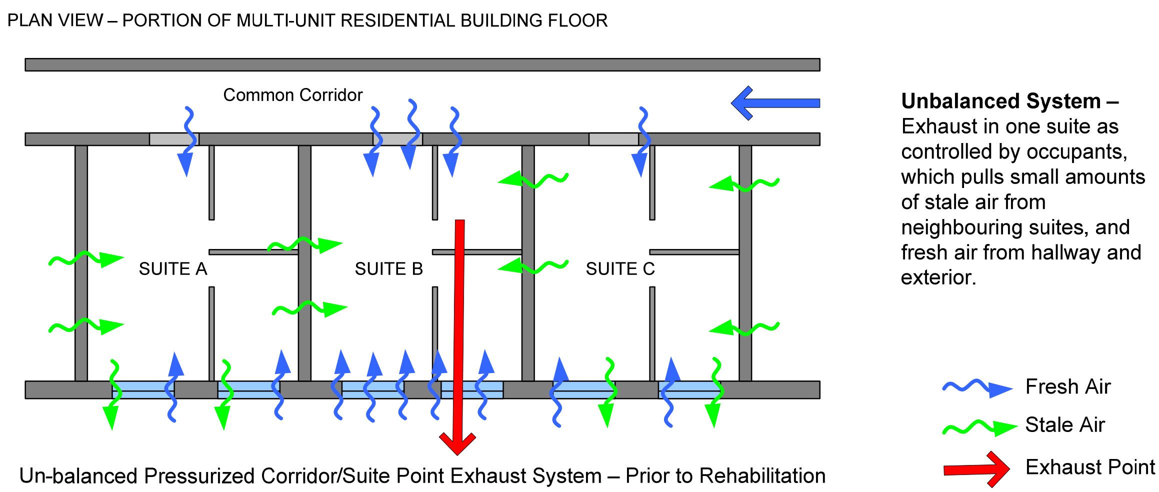


Figure 6-2: Schematic of an Un-balanced Ventilation System

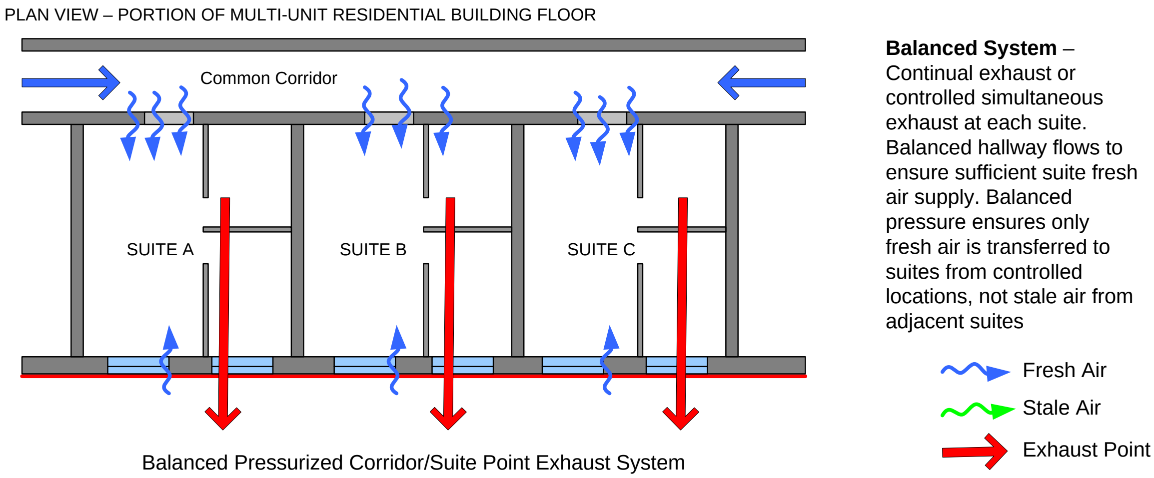


Figure 6-3: Schematic of a Balanced Ventilation System

In the past significant leakage may have occurred though unintentional openings in the air barrier. However in most modern buildings and retrofits, the air barrier systems are typically improved which significantly reduce or eliminate this leakage path. Unfortunately if the ventilation system had relied on this leakage path (as most do), interior moisture problems are likely to start. This is especially true, when the path for make-up air has already been blocked at the entrance door.

All of these issues reduce the efficiency and performance of pressurized corridor, passive exhaust systems, and why in some modern buildings, engineers have developed improved balanced systems provide supply air directly to suites, and sufficient and controlled exhaust. Several of these systems are outlined by Hubbs & Bombino (2005) as alternatives to the traditional pressurized corridor approach.

6.3 <u>MEASURED INTERIOR CONDITIONS</u>

Measured interior temperature, relative humidity, and dewpoint temperature data is presented for each of the monitored suites in the five buildings. Interior conditions were measured using HOBO Pro loggers mounted on the wall near the ceiling of a bedroom or the living area in each suite.

Table 6-1 provides a summary of the monitored suites, size, number of bedrooms, and number of occupants, whether it was air leakage tested and any additional information which may affect ventilation and or moisture generation within the suite.

Table 6-1: Summary of Monitored Interior Suites

Building/Suite (Room)	**No. Bed-rooms**	**Sq.ft (m^2)**	**No. Occu-pants**	**Air leakage tested (Ch.7)**	**Additional Information**
1 – Suite 206 (Master Bedroom)	2	859 ft^2 (80 m^2)	3	No	1 Bathroom
1 – Suite 206 (Bedroom 2)	"	"	"	No	"
2 – Suite 401 (Master Bedroom)	1	684 ft^2 (64 m^2)	1	Yes	1 Bathroom / large number of plants / humidifier in bedroom washer/dryer in suite
3 – Suite 311 (Bedroom 2)	2	682 ft^2 (63 m^2)	3	Yes	1 Bathroom
3 – Suite 611 (Office/Storage)	2	682 ft^2 (63 m^2)	2	Yes	1 Bathroom
4 – Suite 309 (Bachelor – Living)	Bachelor	378 ft^2 (35 m^2)	1	Yes	1 Bathroom
4 – Suite 303 (Bachelor – Living)	Bachelor	378 ft^2 (35 m^2)	1	No	1 Bathroom
5 – Suite 3005 (Living)	2	541 ft^2 (50 m^2)	2	No	1 Bathroom
5 – Suite 504 (Living)	2	541 ft^2 (50 m^2)	2	No	1 Bathroom

The interior data collected with HOBO Pro sensors is synchronized with that from the data logged wall sensors and used in together to analyze the wall performance. The measured interior conditions also provide some insight into the buildings HVAC system performance and occupant behaviour.

Data is presented here for an entire calendar year arranged from January to January for comparison between buildings. One year of continuous data is required to accurately generate seasonal averages and histograms. While other months of data was collected as part of the study, the data presented here is complete for an entire year and representative on average of conditions for that suite during the monitoring period (ie. same occupants, behaviour etc).

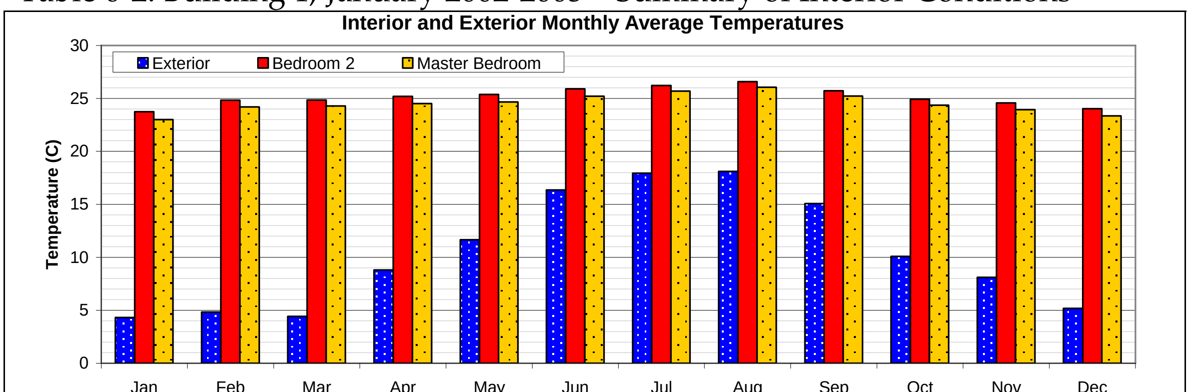
The seasonal and average results are discussed, and where possible, data from the air leakage testing (test setup and results presented in next chapter) is provided to supplement and further understand the monitored conditions.

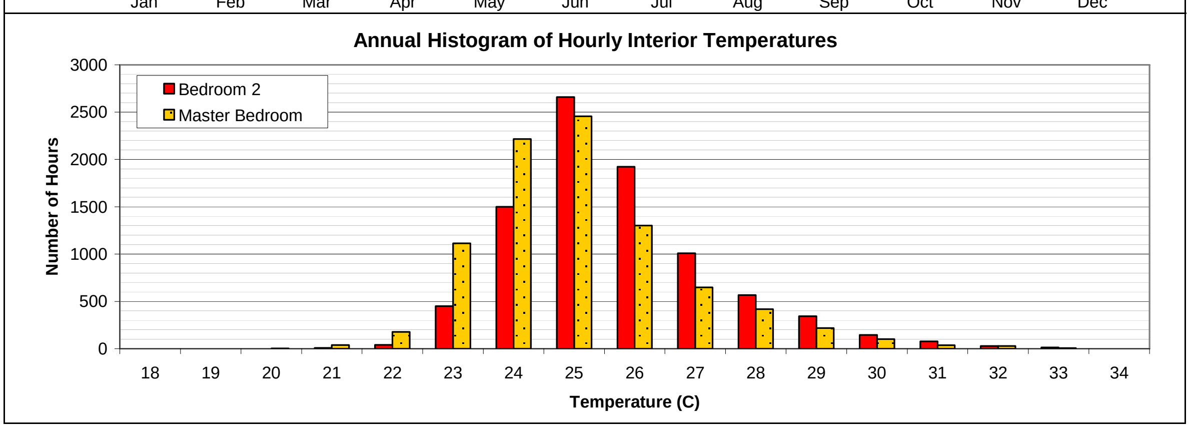
Further data can be found in *Appendix F: Supplemental Measured Data*.

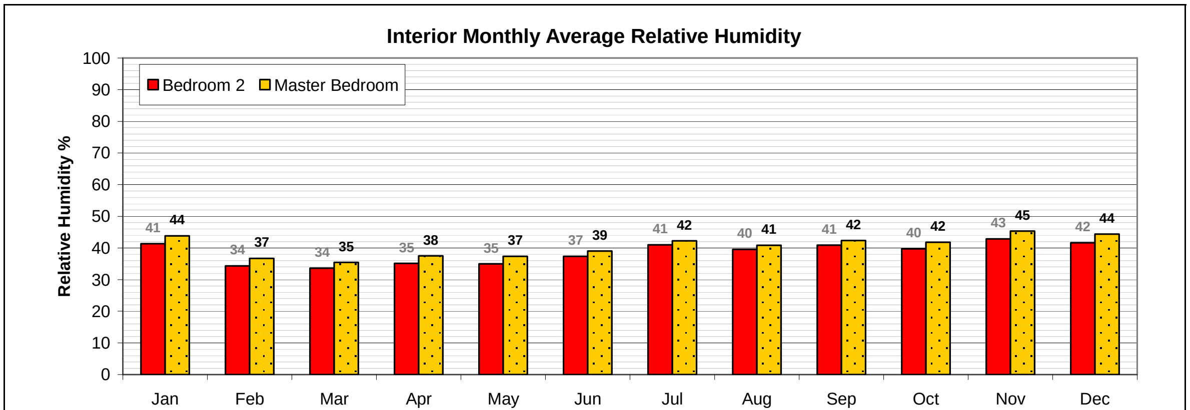
6.3.1 Building 1

Interior data from January 2002 to January 2003 is presented for Building 1. The two bedrooms of suite 206 were continuously monitored for the period. Table 6-2 summarizes the temperature, relative humidity, and dewpoint temperature using monthly averages and hourly histograms.

Table 6-2: Building 1, January 2002-2003 – Summary of Interior Conditions






Interior Monthly Average Relative Humidity
Bedroom 2
Master Bedroom
Relative Humidity %
100
90
80
70
60
50
40
30
20
10
0
41 44
34 37
34 35
35 38
35 37
37 39
41 42
40 41
41 42
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43 45
42 44
Jan
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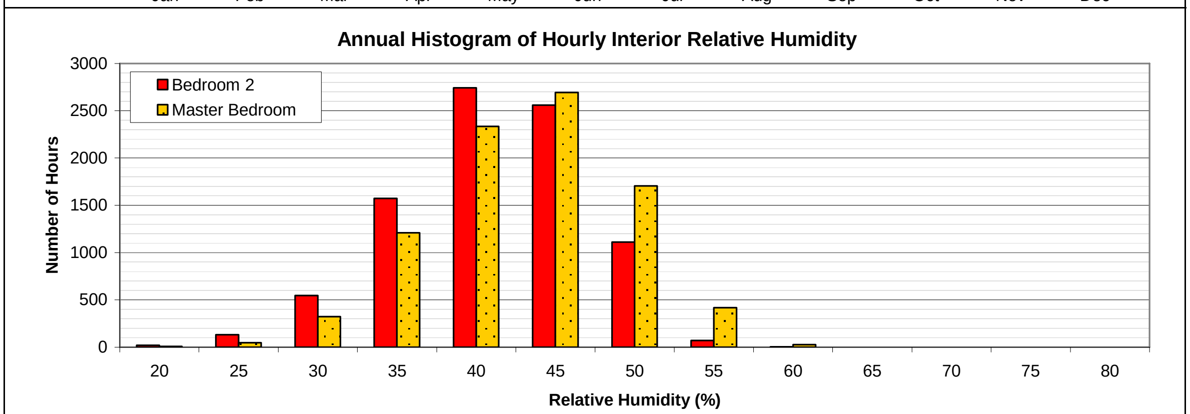
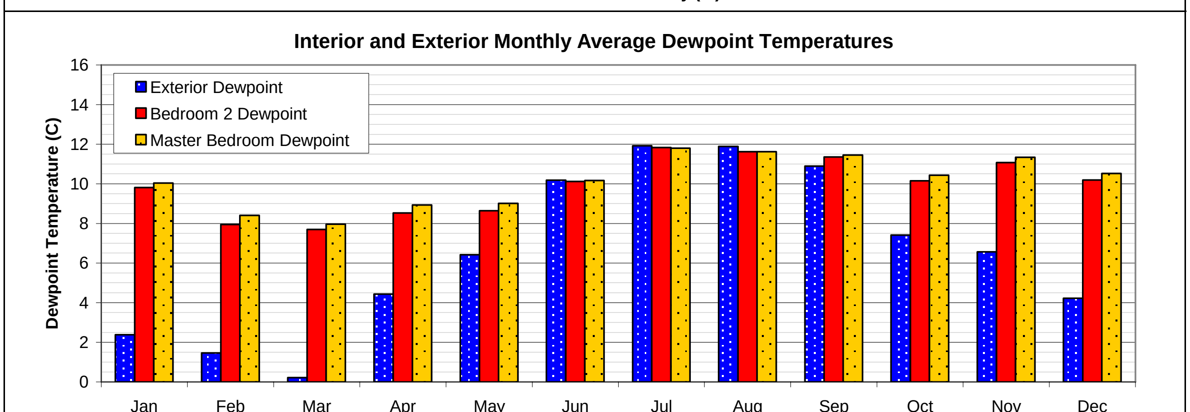
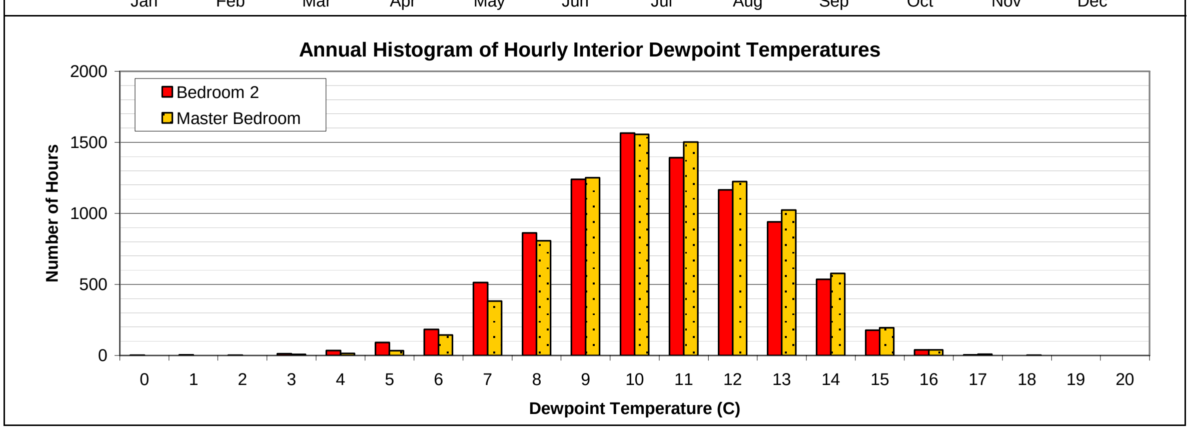

Annual Histogram of Hourly Interior Relative Humidity
Bedroom 2
Master Bedroom
Number of Hours
3000
2500
2000
1500
1000
500
0
20
25
30
35
40
45
50
55
60
65
70
75
80
Relative Humidity (%)


Interior and Exterior Monthly Average Dewpoint Temperatures
Exterior Dewpoint
Bedroom 2 Dewpoint
Master Bedroom Dewpoint
Dewpoint Temperature (C)
16
14
12
10
8
6
4
2
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


Annual Histogram of Hourly Interior Dewpoint Temperatures
Bedroom 2
Master Bedroom
Number of Hours
2000
1500
1000
500
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Dewpoint Temperature (C)

On an annual average, the exterior conditions measured were 10.4°C, 78% RH and 6.5°C dewpoint. The average interior conditions of both bedrooms were 25°C, 40% RH, and 10.0°C dewpoint. Looking at winter averages (December 1st to March 1st) the exterior conditions were 4.8°C, 87% RH, and 2.7°C dewpoint. The average interior conditions of both bedrooms were 24°C, 41% RH, and 9.5°C dewpoint. Temperatures during July and August were on average 25-27°C within suites, as air conditioning is not provided.

It was observed that the occupants of this suite set interior temperatures much higher than what is considered average for Canada. The average interior temperature was 23-25°C during the winter; and the relative humidity was between 35-45%. Had the temperatures been kept at normal 20-21°C levels, the relative humidity would have been higher, between 40-55% based on the observed dewpoint temperatures.

It was observed that the interior dewpoint during the winter months was much higher than the exterior (on average 6-8°C higher), while during the summer the interior and exterior dewpoints are similar, suggesting the tenants kept the windows open and had higher ventilation rates during these warmer months.

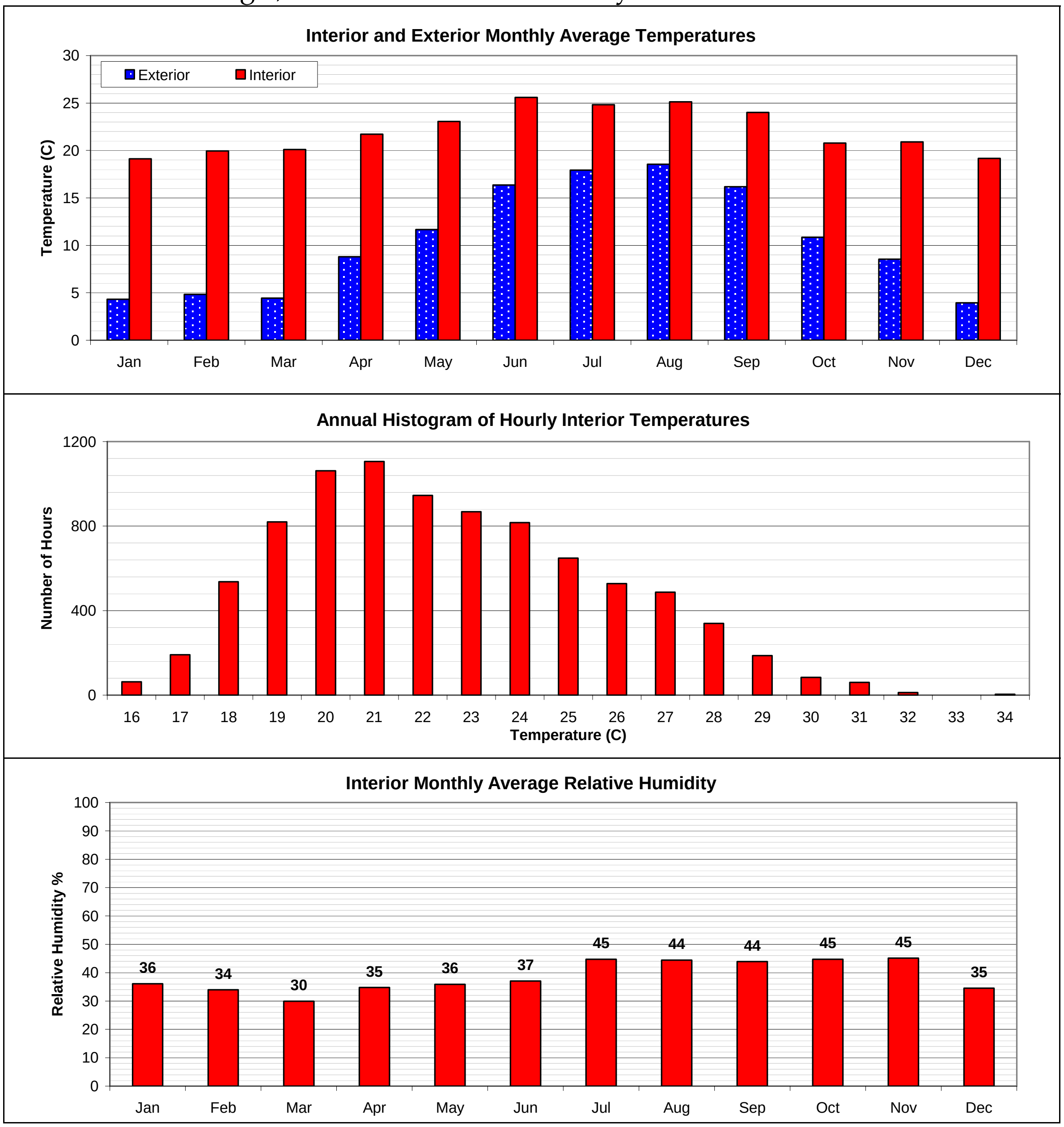
Air leakage testing of this suite was not performed to determine approximate ventilation rates. However, primary exhaust ventilation for this suite consists of a maximum 50 cfm bathroom fan which is occupant controlled (providing up to 0.44 ACH if running continuously).

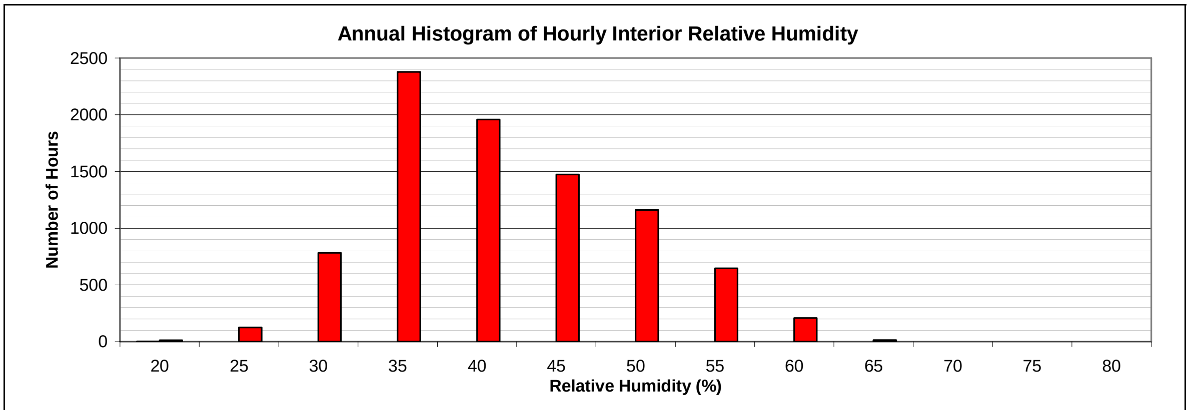
6.3.2 <u>Building 2</u>

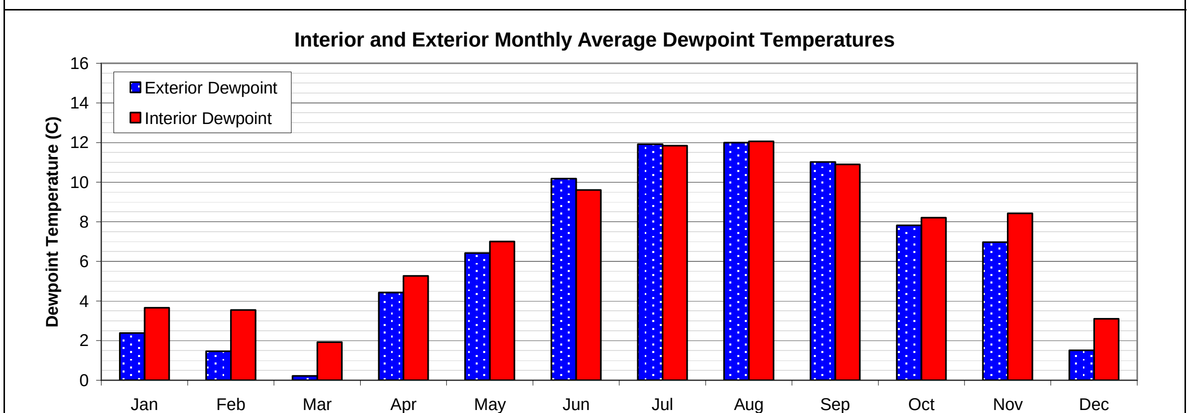
Interior data from December 2001 to December 2002 is presented for Building 2. Data is re-arranged from January to January for comparison between buildings. The bedroom in suite 401 was continuously monitored for the period.

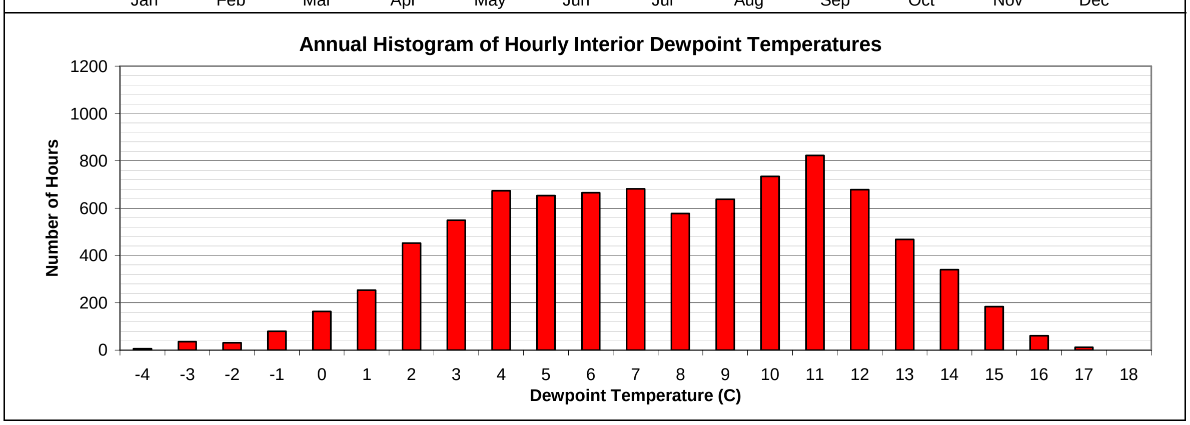
Table 6-3 summarizes the temperature, relative humidity, and dewpoint temperature using monthly averages and hourly histograms.

Table 6-3: Building 2, Dec. 2001-2002 – Summary of Interior Conditions









On an annual average, the exterior conditions were 10.6°C, 77% RH and 6.4°C dewpoint. The interior conditions were 22°C, 39% RH, and 7.1°C dewpoint. Looking at winter averages (December 1st to March 1st); the exterior conditions were 4.4°C, 84% RH and 1.8°C dewpoint. The interior conditions were 19.4°C, 35% RH, and 3.4°C dewpoint. Temperatures during July and August were on average 25-26°C within the suite, as air conditioning is not provided. This suite remained the coolest during the summer of all the building suites monitored during the study.

A wintertime relative humidity of 35% indoors is considered low in Vancouver's climate, however reviewing the average dewpoint temperatures, it is shown that this suite maintains conditions approximately equal to the exterior for almost all months of the year. Even during the winter months, the suite dewpoint temperatures are only slightly greater (<2°C) than the exterior. This observation indicates that this suite is well ventilated (either tenant keeps windows open year round), or that the suite is quite air-leaky and well ventilated to the exterior.

This suite is a top floor corner unit with plenty of windows, a balcony (with glass sliding door) and a skylight at a sloped cathedral ceiling. A washer and dryer (with exhaust vent to the exterior is also provided in this suite). Intentional exhaust for code ventilation requirements is provided by a maximum 50 cfm bathroom fan (providing up to 0.55 ACH when continually running). The apartment also has a natural-gas fireplace within the living room, which based on monitoring observations, the tenant frequently uses for space heating. The potential for air leakage and hence connection to exterior conditions is therefore quite high in this suite.

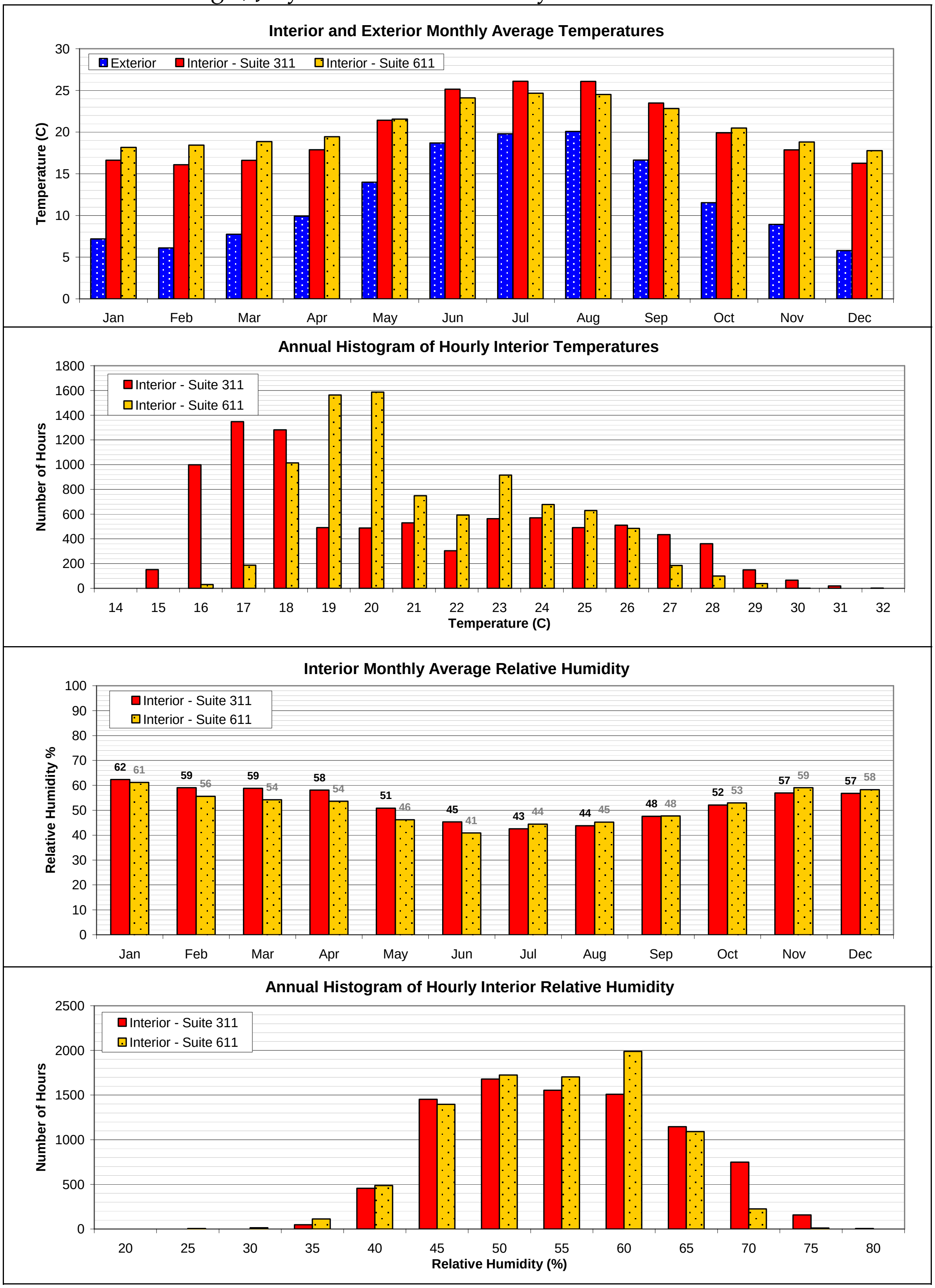
Air leakage testing, as discussed in the next chapter found this suite to be the leakiest of all the suites tested with an ACH 50 of 11.1 through the exterior enclosure (all interior surfaces neutralized) and more realistic ventilation rate of 2.5 to 3.9 ACH under 5 to 10 Pa of pressure. This is comparable to a hypothetical 225 to 350 cfm exhaust fan continually running in this suite 24 hrs/day; hence this one bedroom suite is very well ventilated.

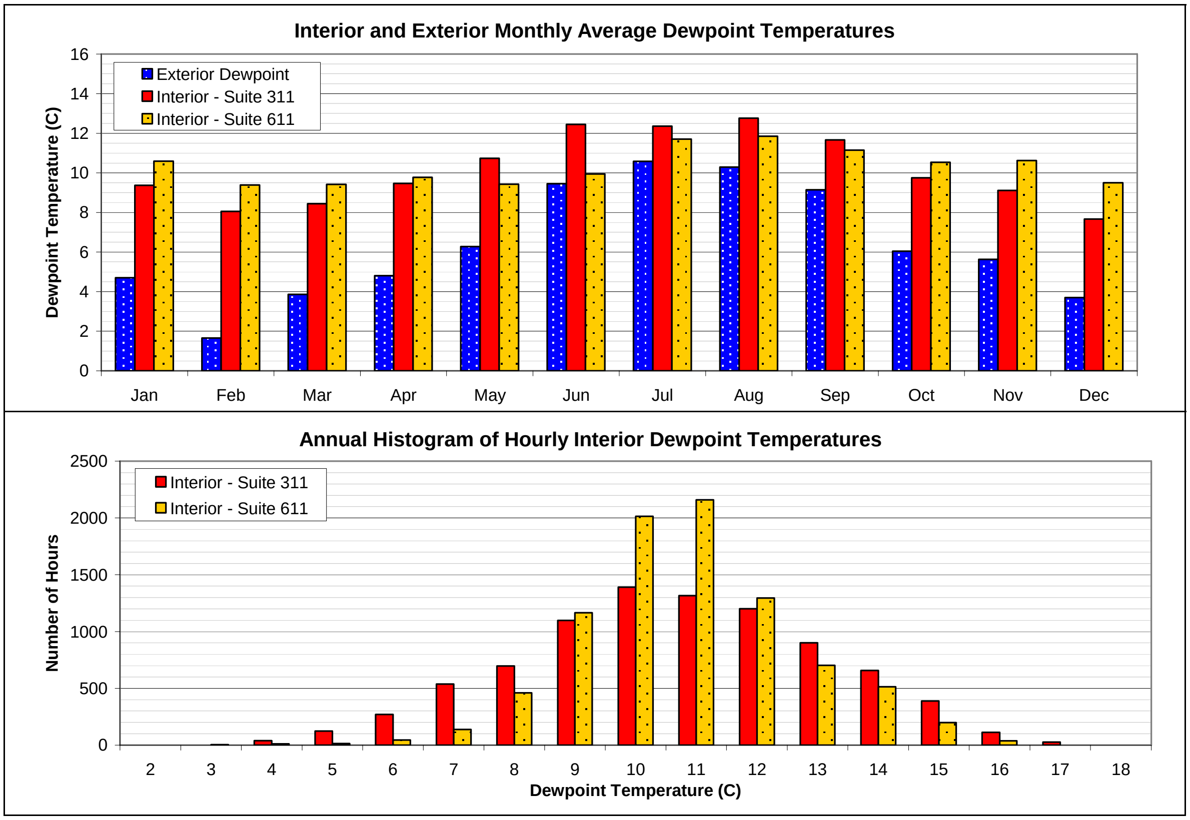
Utility bills were not reviewed for this suite or building but would likely be higher than the other buildings in this study. It would be of further research to investigate the energy impacts of such high ventilation rates on this building as they appear to be excessive.

6.3.3 <u>Building 3</u>

Interior data from July 2003 to July 2003 is presented for Building 3. Data is re-arranged from January to January for comparison between buildings. A bedroom in suite 311 and office area in suite 611 was continuously monitored for the period. Table 6-4 summarizes the temperature, relative humidity, and dewpoint temperature using monthly averages and hourly histograms.

Table 6-4: Building 3, July 2002-2003 – Summary of Interior Conditions





On an annual average, the exterior conditions were 12.2°C, 73% RH and 6.4°C dewpoint. The interior conditions of suite 311 were 20°C, 53% RH, and 10.2°C dewpoint and suite 611 were 21°C, 52% RH, and 10.3°C. Looking at winter averages (December 1st to March 1st); the exterior conditions were 6.4°C, 84% RH and 3.3°C dewpoint. The interior conditions of suite 311 were 16.3°C, 59% RH, and 8.4°C dewpoint and suite 611 were 18.1°C, 58% RH, and 9.8°C. Temperatures during July and August were on average 25-26°C within the suites, as air conditioning is not provided.

An average interior wintertime relative humidity of 50-65% with periods up to 70-75% is high in Vancouver's climate. It was also observed that the interior dewpoints during the winter months were much higher than the exterior (on average 6-8°C higher), while during the summer the interior and exterior dewpoints were closer, suggesting the tenants kept the windows open suites well ventilated to the exterior during these warmer months.

The high wintertime dewpoint temperatures resulted in moderate condensation and mould growth on cold interior surfaces (aluminium window and door frames and concrete slab thermal bridges) within several suites in this building.

Typical observations of condensation and mould growth on surfaces are shown in Table 6-5.

Table 6-5: Building 3 – Impacts of High Interior Dewpoint during Winter Months

 *Condensation on head of sliding door track*	 *Condensation and mildew on window frame*
 *Condensation and mildew on window glazing and frame*	 *Condensation resulting in mildew at cold thermal bridge (slab edge)*

The relatively low wintertime temperatures (16-20°C from November to May) are primarily a result of occupant behaviour. Heating is provided to each suite by baseboard electrical heaters, and each tenant is responsible for the utility cost associated with electrical heating. In addition, the building houses low-income families and in some cases, heating appears to be kept at a minimum or shut off to reduce electrical costs by some tenants. If temperatures were maintained at normal levels from 20-21°C during the winter, the relative humidity would be reduced to 50-60% based on the observed dewpoint temperatures.

The primary exhaust ventilation for each suite in this building consists of a maximum 50 cfm bathroom fan (providing up to 0.55 ACH if running continuously). Bathroom fans were found to be occupant controlled or on timers which were often over-ridden by occupants who complained of the fan noise. Testing of the actual fan flow in suites 311 and 611 was performed by Roppel et al. (2007) and found suite 311 to be running at 44 cfm for approximately 6 hours per day (on timer) and suite 611 to be at 50 cfm for less than 1 hour per day (non-functional timer).

Fresh makeup air is provided to suites via door-undercuts, and while suite 311 has a 13 mm undercut, suite 611 had weather-stripping sealing the opening. Ventilation issues are further exacerbated by inter-suite air leakage contributing stale make-up air and are further discussed in the next chapter.

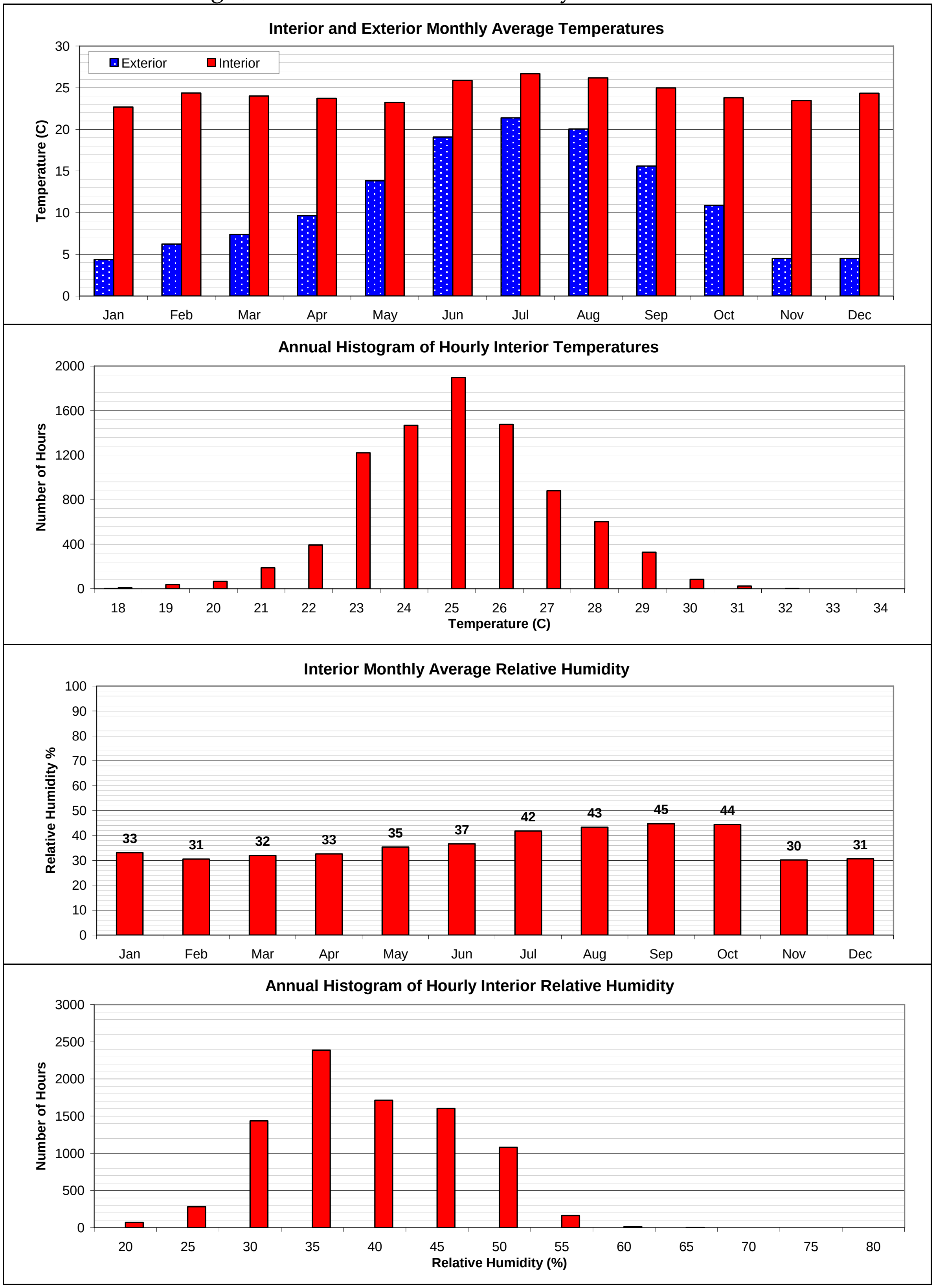
Air leakage testing, as discussed in the next chapter found these two suites to be the tightest of all the suites and buildings tested with an ACH 50 of 1.4 for suite 311 and 2.3 for suite 611 to the exterior (all interior surfaces neutralized) and a more realistic ventilation rate of 0.3 to 0.5 ACH for suite 311 and 0.5 to 0.8 ACH for suite 611 under 5 to 10 Pa of pressure.

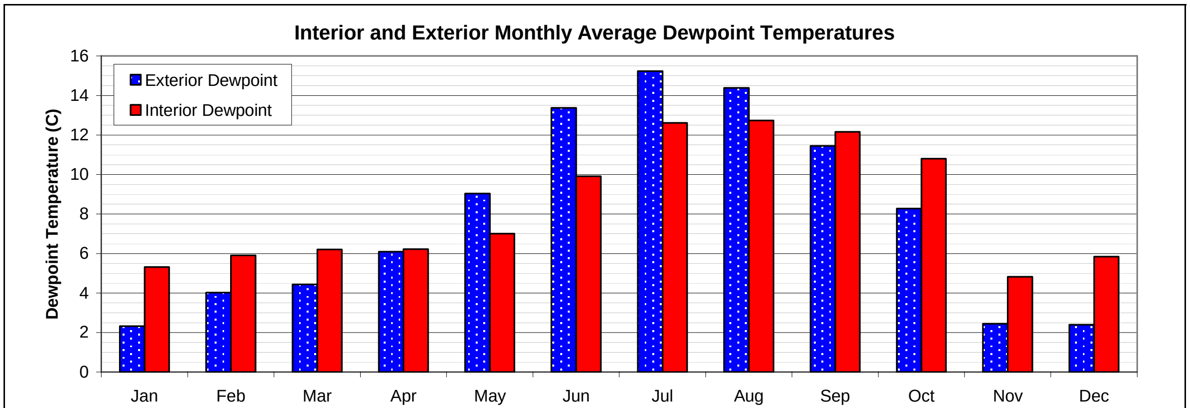
The potential causes of the high wintertime relative humidity and dewpoint are further discussed in Chapter 7, and the impact of the high interior moisture levels on the walls is discussed in Chapter 9.

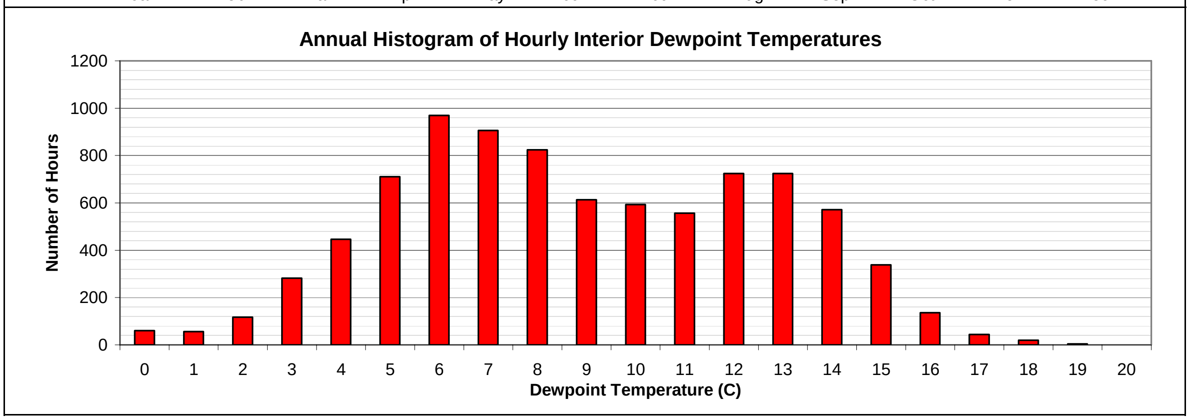
6.3.4 <u>Building 4</u>

Interior data from March 2003 to March 2004 is presented for Building 4. Data is re-arranged from January to January for comparison between buildings. The living areas of bachelor suites 303 and 309 were monitored for the project duration. Unfortunately a continuous 12 month period of data is only available for suite 309 and data from suite 303 is not shown here. Table 6-6 summarizes the temperature, relative humidity, and dewpoint temperature using monthly averages and hourly histograms.

Table 6-6: Building 4, March 2003-2004 - Summary of Interior Conditions







On an annual average, the exterior conditions were 11.5°C, 79% RH and 7.8°C dewpoint. The interior conditions were 24.4°C, 36% RH, and 8.3°C dewpoint. Looking at winter averages (December up to March); the exterior conditions were 5.0°C, 86% RH, and 2.9°C dewpoint. The interior conditions were 23.8°C, 31% RH, and 5.7°C dewpoint. Temperatures during July and August were on average 25-27°C within the suite, as air conditioning is not provided into the suites. Suite 303 not presented here, showed similar monthly trends to suite 309.

A wintertime relative humidity of 30% indoors is very low for wintertime in Vancouver's climate, however reviewing the average temperatures it can be explained. The single occupant of this suite kept interior temperatures higher than what is considered average. The average interior temperature was 23-25°C during the winter; as such the relative humidity was between 30-35%. Had the temperatures been kept at normal 20-21°C levels, the relative humidity would have been higher between 40-45% based on the observed dewpoint temperatures.

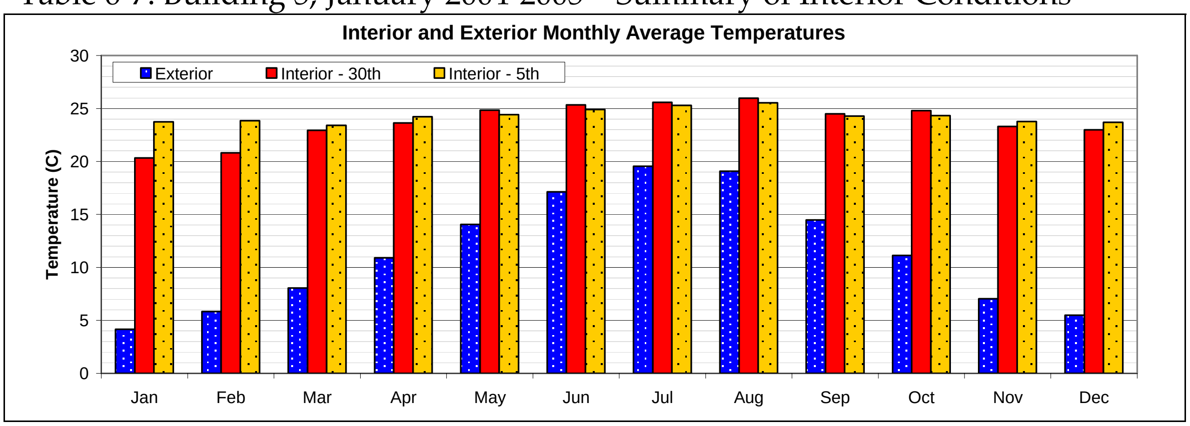
It is observed that the interior dewpoint during the winter months is slightly higher than the exterior (on average 2-4°C higher), while during the summer the exterior dewpoint is higher than the interior, suggesting that the hallway makeup air may be slightly air conditioned and/or dehumidified and thus less humid than the exterior air. In the spring and fall, the interior and exterior dewpoint temperatures were similar. These observations also indicate that this suite is well ventilated (either tenant keeps windows open year round), or that the suite is quite air-leaky and well ventilated to the exterior. The primary exhaust ventilation for each suite in this building consists of a maximum 90 cfm bathroom fan which is occupant controlled (providing up to 1.8 ACH if running continuously).

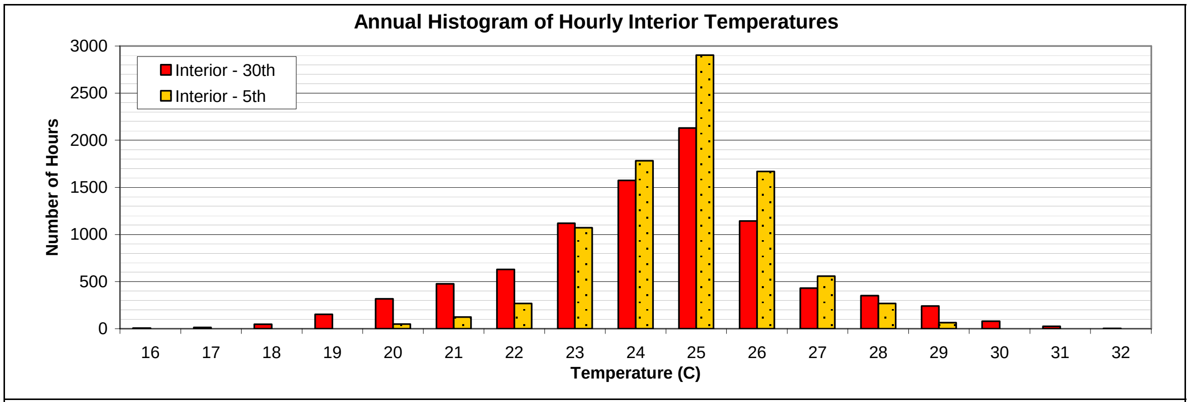
Air leakage testing, as discussed in the next chapter found this suite to be fairly leaky with an ACH 50 of 6.4 to the exterior (all interior surfaces neutralized) and more realistic ventilation rate of 1.4 to 2.3 ACH under 5 to 10 Pa of pressure. This is comparable to a 70-115 cfm exhaust fan continually running in this suite.

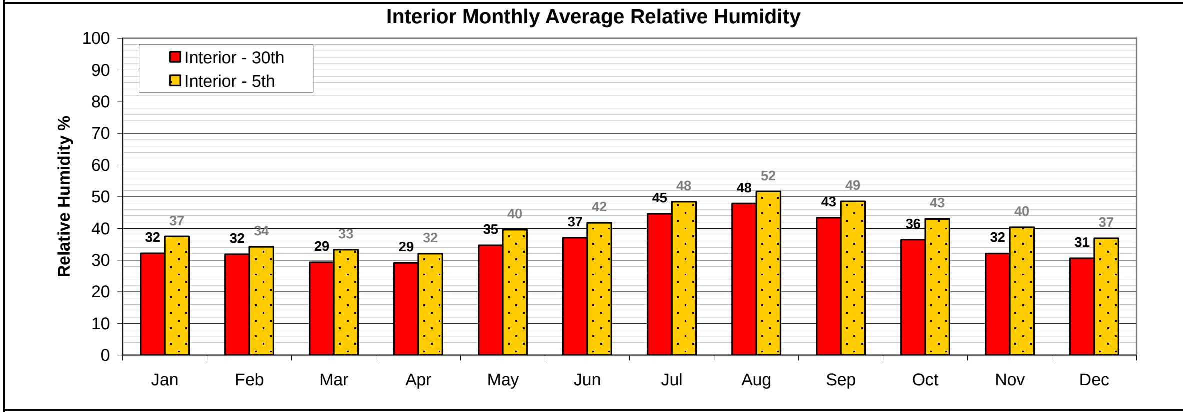
6.3.5 <u>Building 5</u>

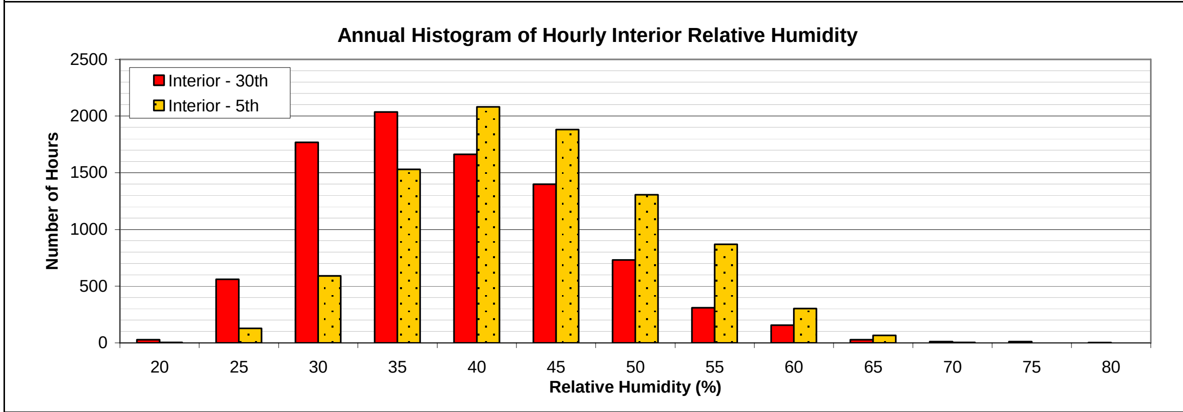
Interior data from January 2004 to January 2005 is presented for Building 5. The living areas in suite 3005 (30th floor) and suite 504 (5th floor) were continuously monitored for the period. The 30th floor suite is a condominium suite which the tenant owns, while the 5th floor suite is subsidized housing apartment rental. Table 6-7 summarizes the temperature, relative humidity, and dewpoint temperature using monthly averages and hourly histograms.

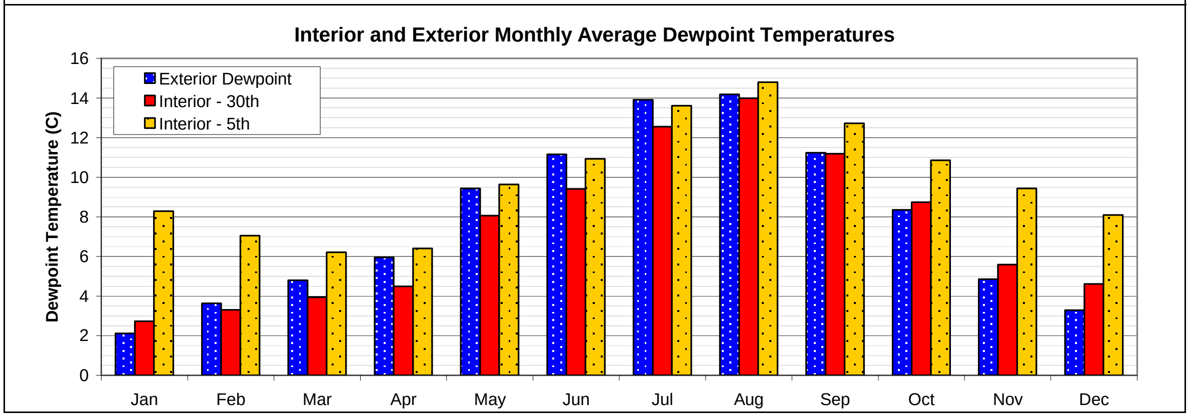
Table 6-7: Building 5, January 2004-2005 – Summary of Interior Conditions

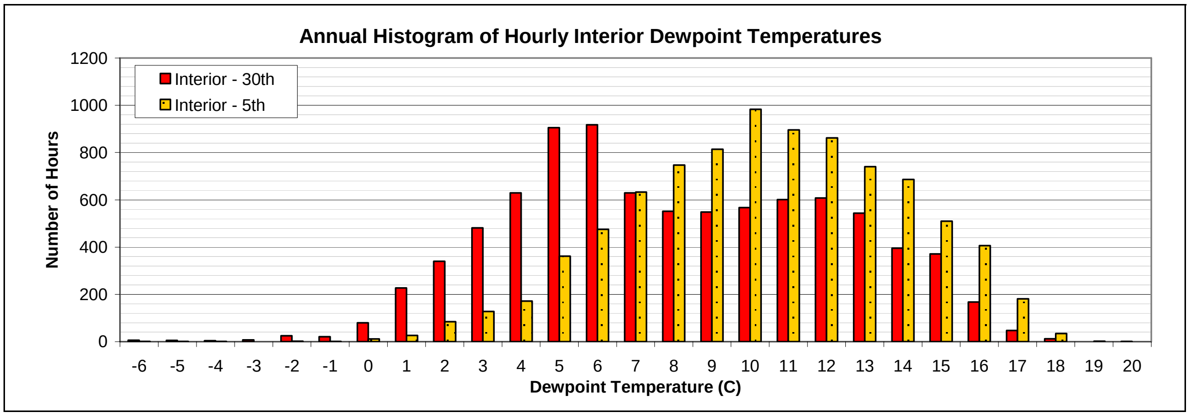



Annual Histogram of Hourly Interior Temperatures
Interior - 30th
Interior - 5th
Number of Hours
Temperature (C)


Interior Monthly Average Relative Humidity
Interior - 30th
Interior - 5th
Relative Humidity %
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Annual Histogram of Hourly Interior Relative Humidity
Interior - 30th
Interior - 5th
Number of Hours
Relative Humidity (%)


Interior and Exterior Monthly Average Dewpoint Temperatures
Exterior Dewpoint
Interior - 30th
Interior - 5th
Dewpoint Temperature (C)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec



On an annual average, the exterior conditions were 11.4°C, 79% RH and 7.8°C dewpoint. The interior conditions of suite 3005 were 23.8°C, 36% RH, and 7.4°C dewpoint and suite 504 were 24.3°C, 41% RH, and 9.9°C. Looking at winter averages (December 1st to March 1st); the exterior conditions were 5.2°C, 86% RH and 3.0°C dewpoint. The interior conditions of suite 3005 were 21.4°C, 32% RH, and 3.6°C dewpoint and suite 504 were 23.8°C, 36% RH, and 7.8°C. Temperatures during July and August were on average 25-26°C within the suite, as air conditioning is not provided in this building.

A significant difference in the average and hourly distribution of monitored interior conditions was observed between the two suites. Suite 3005 on the 30th floor was found to be on average cooler and less humid than suite 504. The dewpoint temperature of suite 3005 closely followed the exterior over the entire year while the dewpoint temperature of suite 504 was elevated during the winter months by 4-6°C. This suggests that the tenants in suite 3005 kept the windows open for much of the year or that air leakage and ventilation was higher in this suite. Construction differences between the 30th floor window-wall assembly (R-value of 2-3) and 5th floor stucco clad rainscreen wall assembly (R-value of 10) may also have an impact on the differences observed.

It was also observed that the occupants of suite 504 set interior temperatures much higher than what is considered average. The average interior temperature was 23-25°C during the winter and the relative humidity was 35-40%. Had the temperatures been kept at normal 20-21°C levels, the relative humidity in this suite would have been higher from 40 to 50% based on the observed dewpoint temperatures.

Air leakage testing of this suite was not performed to determine approximate ventilation rates. However, primary exhaust ventilation for these suites consists of a maximum 50 cfm bathroom fan which is occupant controlled (providing up to 0.70 ACH if running continuously).

6.4 CONCLUSIONS

Large differences in the interior environment were observed between nine suites in the five monitored buildings. Occupant behaviour and the building HVAC system influence the temperature, relative humidity, and dewpoint of the interior environment.

The measured interior conditions were different across all five buildings and none could be considered average (ie. 21°C). The temperatures varied as a result of occupant behaviour and in addition, the interior dewpoint and relative humidity varied considerably as a function of moisture generation and suite ventilation rates.

Within each of the suites the occupants had control over the temperature via a thermostat. In Building 3, the tenants kept their suites on average between 16-18°C during the winter months and found this to be acceptable. In Buildings 1, 4, and 5, the occupants kept their suites between 23-25°C on average during the winter months and found this to be comfortable, and presumably even affordable. In Building 2, the wintertime temperatures were kept near average at 19°C, however may have been warmer if ventilation rates weren't as high.

As none of the buildings have air conditioning systems, average interior suite temperatures of 25-27°C during July and August were normal. In addition, hourly peaks up to 34°C were recorded during the hottest summer days.

Relative humidity and temperature measurements from the five buildings from 2001 to 2005 are summarized in Figure 6-4. No provisions for control of relative humidity were made other than by opening a window or balcony door or turning on the bathroom/kitchen exhaust fan.

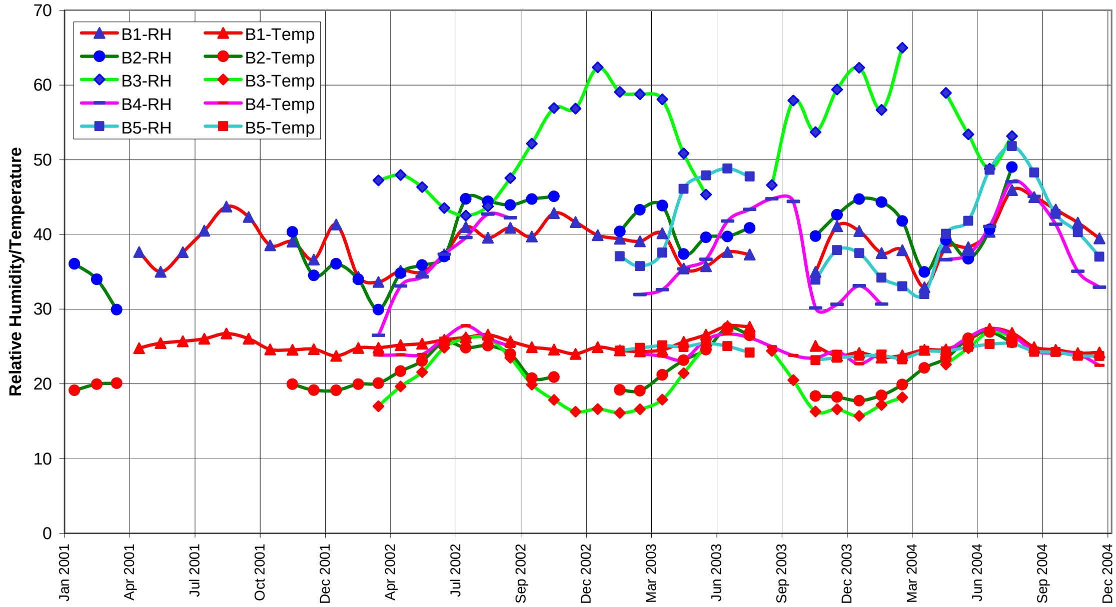


Figure 6-4: Summary of Monthly Temperature and RH – Buildings 1-5, 2001-2005

As shown, Buildings 1, 2, 4, and 5 showed similar seasonal trends, while Building 3 had elevated wintertime relative humidity levels in contrast to the other buildings. The average annual and wintertime conditions presented in the previous sections are summarized in Table 6-8.

Table 6-8: Summary of Temperature, Relative Humidity and Dewpoint for Buildings 1-5

Building	**Suite**	**Annual (Temp, RH, DP)**	**Winter (Temp, RH, DP)**	**Summer (Temp, RH)**
1	206	25°C, 40%, 10.0°C	24°C, 41%, 9.5°C	25-27°C, 40-45%
2	401	22°C, 39%, 7.1°C	19°C, 35%, 3.4°C	25-26°C, 40-45%
3	311	20°C, 53%, 10.2°C	16.3°C, 59%, 8.4°C	25-26°C, 40-50%
3	611	21°C, 52%, 10.3°C	18.1°C, 58%, 9.8°C	25-26°C, 40-50%
4	309	24.4°C, 36%, 8.3°C	23.8°C, 31%, 5.7°C	25-27°C, 35-45%
5	3005	23.8°C, 36%, 7.4°C	21.4°C, 32%, 3.6°C	25-26°C, 40-50%
5	504	24.3°C, 41% , 9.9°C	23.8°C, 36%, 7.8°C	25-26°C, 45-55%
Average ALL*		23.8°C, 38%, 8.5°C	22.4°C, 35%, 6°C	25-26°C, 40-50%
Range ALL		20-25°C, 36-53%, 7.1-10.3°C	16-24°C, 31-59%, 3.4-9.8°C	25-27°C, 35-55%

*except Building 3, which has abnormal conditions

Building 3 showed significantly different trends than the other four buildings. The issues with Building 3 are more complicated than a high wintertime relative humidity as a result of lower temperatures. The impacts of air tightness and ventilation system performance are discussed further for this building in the next chapter.

Residential building designers must be aware of the potential for the interior environment to deviate from the average 21°C standard assumption. Interior conditions will vary by season, and on average the annual temperature was measured between 20-25°C, the winter temperature deviated on average from 16-24°C.

The energy penalty with maintaining residential suites at high 23-25°C wintertime temperatures in temperate climates such as Vancouver is relatively low as compared to colder climates such as Edmonton. In colder climates such interior temperatures would cost significantly more to maintain discouraging tenants from wasting energy.

Contrary to the belief of some practitioners, it is also possible to achieve low (<35%) interior wintertime RH levels in Vancouver's temperate climate. Relative humidity is a function of interior moisture generation and building ventilation. Those suites that had low wintertime RH levels (30-40%) had sufficient - and in one case excessive - ventilation. High relative humidity levels (50-70%) were only observed in Building 3 as a result of insufficient suite ventilation. Moisture generation rates were not measured, but appeared to be normal based on occupancy.

While the five buildings are not statistically representative the entire population of buildings in Vancouver, they do provide insight into possible variances of interior environment for residential buildings. Allowing for the potential differences in temperature and relative humidity would be prudent in design of residential buildings, especially where easily performed using hygrothermal simulations.

6.5 REFERENCES

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7 AIR LEAKAGE TESTING OF INDIVIDUAL SUITES IN MULTI-UNIT RESIDENTIAL BUILDINGS

Air leakage testing of six suites in four multi-unit residential buildings in Vancouver, BC was performed to quantify air leakage between adjacent suites, floors, common spaces, and through the exterior building enclosure.

Testing was performed using up to four high power door-fans and an automated fan-control system that precisely controlled the test pressure across each wall sequentially in order to measure the leakage of the six sides of the suite separately.

Air leakage and flow path test results are expressed in terms of:

- Equivalent Leakage Area at 50 Pa (ELA_{50}): cm^2 @ 50 Pa & in^2 @ 50 Pa
- Air-Flow at 50 Pa(Q_{50}): l/s @ 50 Pa & ft^3/min @ 50 Pa (CFM_{50})
- Air-Changes per Hour at 50 Pa(ACH_{50}): $m^3/hr/m^3$ @ 50 Pa & $ft^3/hr/ft^3$ @ 50 Pa (CFM_{50})
- Normalized Leakage Area, over surface area of leakage path (NLA_{50}): cm^2/m^2 @ 50 Pa & $in^2/100\ ft^2$ @ 50 Pa.

This provides some baseline data for users performing similar type of testing in the future. Comparisons between different wall and floor assemblies are made using data from the six tested suites.

Three of the buildings tested were part of a larger study which monitored the hygrothermal performance of the exterior walls over the past five years. The fourth building was recently rehabilitated and was tested for this study as a result of complaints of high interior humidity during the wintertime. The air leakage testing results combined with the previous data and observations is used to better understand past performance and make conclusions regarding the interior air quality and ventilation rates within these buildings.

The impact of air-tightness on the existing mechanical systems and suite ventilation of the four buildings is shown. Recommendations to avoid ventilation and humidity problems within multiunit residential buildings, particularly with air-tight exterior enclosures are discussed.

7.1 INTRODUCTION

Control of air leakage in multi-unit residential buildings is important through the exterior enclosure but also through interior floors and walls between suites. Controlling the flow of air through the exterior building enclosure has been realized as critical for several decades to reduce heat loss/gain and minimize moisture related problems. Controlling the flow of air between suites and common spaces within the building is equally as important for fire, smoke, odour, contaminant, and sound control.

Individual suites in multiunit residential buildings are typically designed as separate compartments which are air-sealed from adjacent suites and to the exterior. Ventilation supply and exhaust air is controlled by mechanical means in most modern buildings. In multi-unit residential buildings it is common practice to supply fresh air to common corridors, allowing it to pass through door undercuts into the suites, and to exhaust stale air with fans in each suite.

By pressurizing the corridors, a constant flow of air exfiltrates into the suites provided there is a path to the suite. Depending on the size of the opening, and strength of the exhaust fan, makeup air for the suite may or may not be sufficient. A more suitable approach to duct fresh supply air into each individual suite may alternately be used and can overcome some of the issues with a pressurized corridor supply system.

Significant effort is also made to air-seal the exterior building enclosure and interior fire-separating walls; however small gaps, penetrations, or cracks may still exist in practice. Therefore understanding the source of the makeup air in these suites is critical to the understanding of problems in multi-unit buildings with insufficient ventilation, which can result in high interior humidity and air quality issues.

Quantifying air leakage in single-family dwellings or other whole buildings is commonly performed to determine the air-tightness. However quantifying air leakage within suites of a multi-unit building is difficult, as air leakage can occur through the adjacent interior walls, floors, and exterior building enclosure. Often it is of interest to isolate the air leakage of one suite to the outdoors only. This cannot be determined without pressure neutralizing all of the potential interior leakage paths while testing. This process is difficult and requires the use of several door-fans and man hours to complete the task.

Isolating a singular suite within a building and performing incremental air leakage testing to quantify the relative air leakage between adjacent suites, floors, common spaces and the exterior is not commonly performed due to the cost and effort required. The work presented here adapts testing methods developed for single buildings and uses some new techniques to achieve the desired results. There are no applicable standards or test procedures for this specific type of work.

Lessons learned and recommendations are made as to the testing procedure. Conclusions regarding inter-suite leakage and implications on performance of the building are also discussed. Concrete frame buildings are compared to wood-frame buildings and the differences in interior air leakage pathways between wall and floor assemblies. While the data collected here is statistically insignificant to the greater building population, it provides some baseline values and with further testing of this type, could be compiled to make recommendations as to normal/leaky/tight air-tightness guidelines for multi-unit residential buildings.

7.1.1 Scope

A field monitoring program was implemented in 2001 to measure the performance of rainscreen clad walls in the coastal climate of Vancouver, BC. As part of the program, the exterior walls of five buildings were instrumented and monitored for a period of up to five years. In each building the temperature and relative humidity of one or two suites were also monitored to determine the impact of the interior conditions on the exterior wall performance.

At the conclusion of the wall monitoring program in 2006, access was provided to three of the five buildings to perform the air leakage testing of the monitored suites. In addition, one high-rise building (not part of the previous mentioned monitoring program) was also tested as part of this air leakage study. Six suites in these four buildings were selected for individual air leakage testing.

The purpose of the air leakage testing was to quantify air leakage paths between adjacent suites, floors, common spaces, and ultimately determine leakage through the exterior building enclosure. Measured air leakage rates coupled with mechanical system data can be used to determine approximate ventilation rates in service. The air leakage testing results in combination with the data collected from the past five years is used to improve the understanding of the performance of these buildings.

Another goal of the field study was to determine the feasibility of such large scale testing on occupied buildings in service, and to develop a procedure and reference point for future air leakage testing of this type.

7.1.2 Background

Air leakage testing of buildings is commonly performed to measure air-tightness for energy performance quantification, building commissioning, to locate deficiencies in the air barrier system, or to ensure smoke and fire seals are properly installed. Buildings are often tested as whole units, and while individual suites within a larger building may be door-fan tested, the accuracy of such tests has been shown to be questionable due to multiple interior air leakage paths (ASHRAE 2005, Sherman & Chan 2004). To overcome these issues, the use of multiple door-fans are required to neutralize specific surfaces, or other test methods are employed using tracer gases (not discussed further here).

While the practice of neutralizing interior leakage paths to determine exterior leakage is recommended when testing individual units in multi-unit buildings it is not common practice due to the high cost of the required equipment and trained technicians. Testing of this type is also difficult because of the inherent nature of the test setup, requiring multiple operators to simultaneously control and balance pressures quickly.

Issues with testing of multi-unit buildings with multiple fans are discussed and techniques used to overcome them. Results from previous tests of multi-unit residential buildings are also presented.

7.1.2.1 Test Procedure and Issues

When testing multi-unit buildings it has been found to be difficult to balance and control multiple fans simultaneously to isolate interior surfaces. Tests of this type suffer from inaccuracies caused by the impractical nature of trying to control 2, 3 or 4 fans that are interacting with each other such that changing one fan speed causes pressures to change in several zones requiring simultaneous speed adjustments in each zone. Add to this the fact that the baseline pressure can be changing with wind speed and door openings and you have 4 fans chasing each other. It is not uncommon to take 20 minutes to balance the fans out using this method, provided the test is uninterrupted. Reducing interruptions in an occupied building during the tests requires the full cooperation of all residents, and can be an issue, particularly where plenums such as elevator cores or stairwells adjacent to the test area cannot be pressure isolated from the test area. A relatively common occurrence is for the elevator door to open at a pressurized hallway, requiring the fans to speed-up to compensate for the pressure drop, often requiring the restart of the test. Further the test results and repeatability are subjective and rely on several individual operators to accurately read and control fan speeds and pressures simultaneously.

To overcome some of these issues, the approach taken here was to let each fan be controlled by its own automatic fan control so that the system of compartments, leaks and pressure would come to equilibrium quickly. One operator will control and read pressures simultaneously from a central location and technicians will be on hand to setup and assist with potential issues that come up with access and residents. Central control was accomplished by running ethernet cable between each fan control and digital gauge so that the entire test could be performed without moving from the close proximity of the tested apartment.

Set-up time for panels has been an obstacle to this type of testing since many set ups are required to complete test on a single apartment. Rapid set up panels were used that allowed them to be set up in a few seconds and also allowed people to pass through them for access when required.

These same panels allowed for rapid testing in the depressurisation direction, since the fan merely had to be turned around. Being able to test in both directions allowed for more accurate readings since testing in both directions and averaging the results can be shown to be much more accurate than testing in one direction where offset pressures can throw result off a lot. The data shows results in both direction and it is apparent that neither pressurization nor depressurization alone was representative of the actual leakage.

7.1.2.2 Previous Testing of Multi-Unit Residential Buildings

Sherman & Chan (2004) performed a review of over 100 publications relating to air tightness research and practice across the world. They found that while thousands of single family dwellings have been tested since the 1970's when blower or fan door testing was introduced, few tests have been performed to measure individual suite air-tightness or leakage paths in multi-unit residential buildings. A few cases are presented which provide some insight into the range of potential results for this test.

Air tightness varies greatly among dwellings, across countries, and by construction type. Few correlations can be made from the large sample set, however typically newer more energy efficient homes where air-tightness was a consideration of the builder, are more air-tight than older homes. Typical values of air leakage can be found in the ASHRAE Handbook of Fundamentals (2005) referencing hundreds of previous studies for single-family dwellings. No such baseline values are provided for multi-unit buildings, particularly residential buildings which were tested here.

Few studies have been performed in the past on multi-unit residential buildings. Seven Canadian studies are referenced by Sherman & Chan (2004) which tested fewer than 100 units in approximately 40 buildings. Worldwide, less than 500 units have been tested. The sample set for multi-unit residential buildings is practically insignificant in comparison to the >100,000 single-family homes tested and documented. The largest database of single family dwellings is maintained by the Energy Performance of Buildings Group at LBNL which has over 73,000 from over the US. No such database exists for multi-unit residential buildings.

One study by Gulay et al. (1993) (of Wardrop Engineering in other literature) was performed for CMHC to determine air leakage rates through the building envelope, inter-floor, and inter-suite leakage rates in ten buildings investigated across Canada. The results indicated that leakage rates per unit of exterior wall area were found to be in the range of 2.10 to 3.15 L/s/m^2 at 50 Pa (3.8 to 5.7 cm^2/m^2 @50 Pa) during suite fan depressurization testing. When testing was conducted such that the corridor wall could not be isolated from leakage through the exterior wall, the range of air leakage rates increased to 4.56 to 8.33 L/s/m^2 at 50 Pa (8.2 to 15.0 cm^2/m^2 @50 Pa). Overall leakage rates per unit of exterior wall area found during full floor testing was 0.68 to 10.9 L/s/m^2 at 50 Pa (1.2 to 9.6 cm^2/m^2 @50 Pa) where interior surfaces were not isolated. It was also noted that these air leakage rates far exceeded the National Building Code of Canada guidelines of 0.05 to 0.15 L/s/m^2 at 75 Pa.

In a study from Sweden, Levin (1991) found internal leakage paths between apartment units in Stockholm to account for 12% to 33% of the total leakage at 50

Pa. Similar leakage values have been reported by others for other multi-unit residential buildings (Sherman & Chan 2004).

In another Canadian study, Shaw et al. (1991) found exterior wall air tightness values by be nine times greater that those of the floor/ceiling, and leakage to the left and right partitions (adjacent units) in between the two extremes. In the same study, they observed that the overall airtightness values of four buildings with different wall constructions were similar.

These previous tests provide some guidance as the range of air leakage values and flow paths that may be encountered during the testing. There is little consistency between the tests, and each building will likely be unique depending on construction practices, details and materials used.

7.2 TEST PROCEDURE AND MECHANICS

The test procedure and setup which was developed for the tests is discussed, as well as the flow mechanics and calculations performed to determine the flows, pressures and equivalent leakage areas.

7.2.1 Procedure and Setup

Testing was performed using up to four high-powered door-fans (Retrotec Model 3200 series, each providing up to 8500 cfm) which were automatically controlled from a central location using Retrotec DM-2A gauges. All fans were precisely controlled to maintain 50 Pa between the tested space and outdoors.

Neutralizing pressures were applied to incrementally isolate interior surfaces (adjacent walls, floors) of a test suite to determine the air leakage between specific surfaces. Suite air leakage testing and neutralization of adjacent surfaces was performed using 50 Pa of pressure with respect to the exterior. Lower pressures would be experienced under normal operating conditions; however it has been shown that tests performed at higher pressures such as 50 Pa are more accurate to remove environmental noise (effects of wind and thermal buoyancy (stack effect) pressures) (ASHRAE 2005).

The fans and digital pressure/control gauges were calibrated prior to testing to ensure accuracy of the readings. All pressures readings are referenced with respect to the exterior, common to all gauges, and as such the relative pressure differences between suites are only recorded.

Pressurization of the suite, followed by depressurization was performed for all suites tested. Depressurization in addition to pressurization was performed to offset stack, HVAC, and wind flows and determine average results. Test setup is described for a pressurization setup; depressurization is similar however the fans are reversed within the same door frame setup. The basic test setup used for each suite is as follows, and shown graphically in Figure 7-1:

1. Install door-fan in suite of interest as per manufacturer's installation guidelines. Reference pressure tubes located in suite and to exterior. Close all exterior windows and doors. Open interior room doors/closets to ensure equalized pressure throughout suite. Leave all intentional openings open (bathroom and kitchen exhaust fans). This fan will be taking all of the readings (equivalent leakage area and fan flow) therefore should be properly calibrated prior to use.
2. Install door-fan at the floor above such that the suite and common hallway space directly below the test suite can be pressurized. Often the door-fan can be installed in one of the stairwells instead of the actual suite door. The suite will be pressurized if the hallway door is opened at the time of hallway pressurization. This setup also eliminates any inter-hallway leakage between floors. The stairwell should be opened to the exterior to prevent the fan from depressurizing it. Reference pressure tubes to the suite/hallway and exterior. High powered fans or multiple fans may be required to pressurize entire floors of some larger or leaky buildings. In the buildings which were tested, one 8500 cfm fan was found to be sufficient in every case. This fan was only neutralizing the leakage across one of the 6 sides of the apartment.
3. Repeat Step 2 for floor below test suite.
4. Install door-fan in hallway on the same floor of the suite of interest. Often the door-fan can also be installed in one of the stairwell doors (open to the exterior). Reference pressure tubes to hallway and exterior. By installing the door-fan in the hallway, the two adjacent suites (left and right) can be pressurized by opening and closing suite hallway doors of those suites as needed. Opening the windows in those adjacent suites while the entrance door is closed will neutralize the suite to zero reference pressure. This fan will only be providing neutralizing pressures.

Reference pressure tubes and fan controls are run to a central location in hallway outside the test suite to allow the user to measure and control each unit simultaneously. The Retrotec DM-2A gauges allow the user to set the desired pressure drop across each fan to any desired pressure. In this case the fan speed was adjusted automatically by the DM-2A to maintain 50 Pa across the doorway ion which it was mounted. Automatic control speeds up and simplifies the testing procedure and as anyone who has tried this before knows, manually balancing four fans simultaneously can be quite difficult in the field.

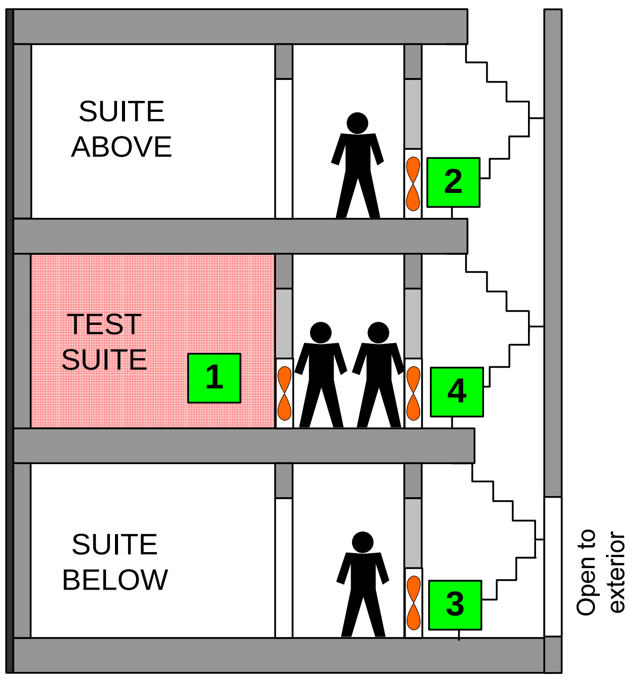


Figure 7-1: Door-fan test setup for isolation of individual test suite.

Computer software was used to continuously data-log the fan flow, test pressure and calculated equivalent leakage area measurements. Figure 7-2 shows the DM-2A speed controlling gauges interfaced with a laptop for data-logging and a door-fan installed in a hallway door. Test results can be displayed directly on the DM-2A in any units of equivalent leakage area, fan flow, flow per unit area, or air changes per hour.

Even though the data logged looked good on paper, it was shown to be unnecessary since the gauges read out directly in the results needed and appeared very stable. The added time to set up the laptop was found to be unnecessary although it did prove that the system balanced itself out quickly after 1 or 2 minutes and was stable enough that readings could be taken in confidence. One major contributor was the fact that the fans had regulated variable frequency speed controllers that enabled rapid acceleration to speed and ultra stable speed control that was unaffected by changes in pressure drop and voltage.


Figure 7-2: Control Equipment and Door-Fan Installed in Hallway Doorway.

The accuracy of the ELA/flow measurements is dependent on the operator taking the readings when neutralizing pressures are at equal to the test suite pressure (50 ±1 Pa). Accuracy is improved by using the @50 Pa function on the DM-2A gauge. In effect if the test pressure is say 50.5 Pa, the DM-2A extrapolates to exactly to 50 Pa mathematically and displays that result.

It was discovered that watching the leakage area across the suite settle down while monitoring the pressures across each surface worked well. After a short while the leakage area would stabilize as the controllers brought each fan up to the correct speed to maintain the 50 Pa test pressure.

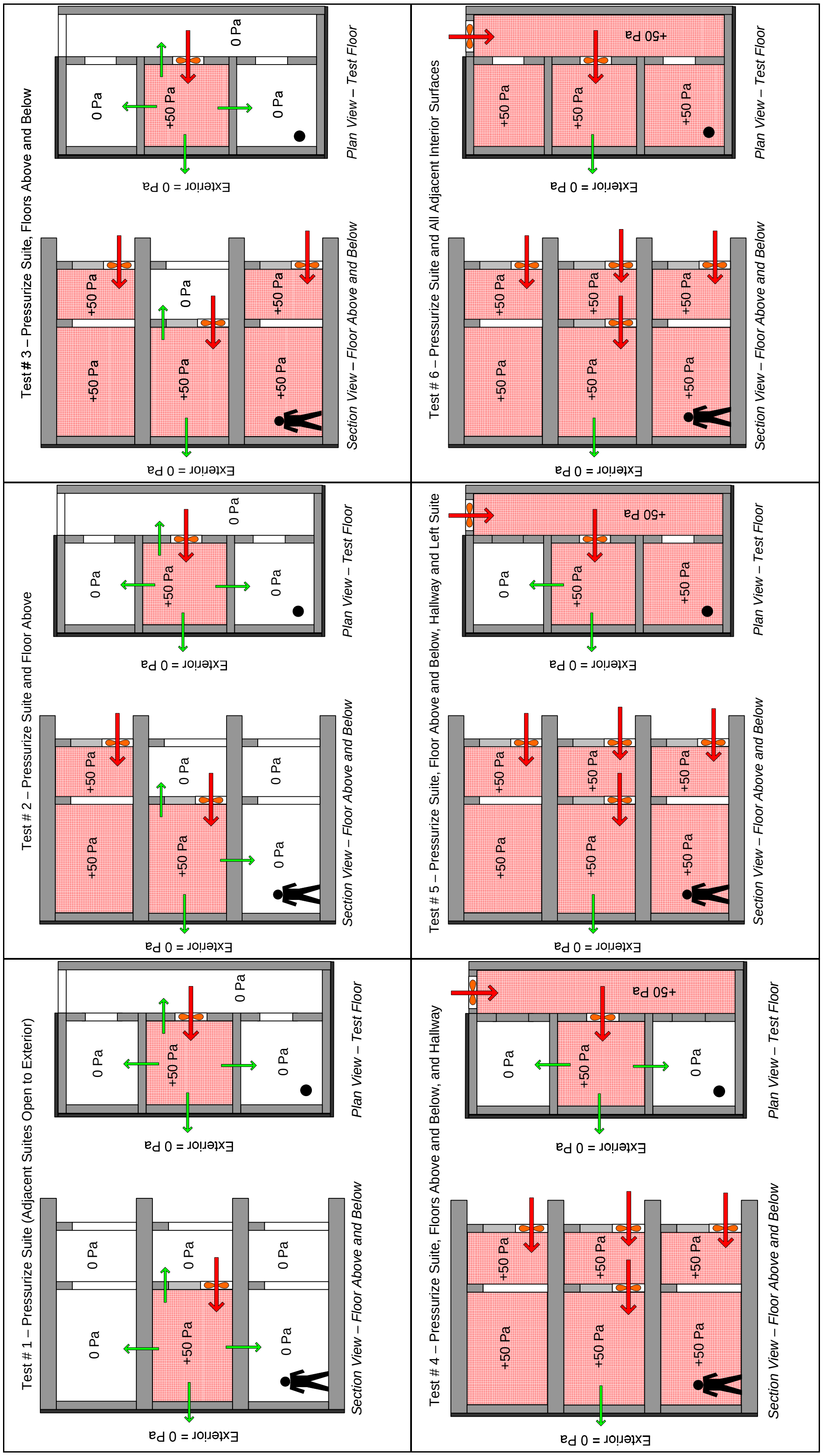
Winds were very calm during the day of the tests, and thus were not seen to have an effect on the readings (minimal pressure fluctuations). Had high winds been encountered, Retrotec has wind-dampening kits available that can dampen wind speeds up to 32 km/hr (20 mph) which could have been used had this been a problem.

After the door-fans are setup, they are controlled incrementally to pressurize surfaces adjacent to the test suite. For example if you wish to know the air leakage between the test suite and the one next door, you would pressurize the test suite, take a reading, then pressurize the one next door and take a second reading. The difference between the two readings is the air leakage between those suites.

This procedure is performed in steps to isolate and eliminate each surface until the leakage through the exterior enclosure can be isolated. The six step test procedure to incrementally determine air leakage between suites is illustrated on the following page. Large red arrows indicate fan flow direction and small green arrows indicate air leakage paths. The pressurized suites are highlighted in red, and when two pressurized suites are adjacent, the leakage is neutralized between those spaces. The de-pressurization tests are run with the fans turned around to face the opposite direction; however the door-fan setup remains the same.

There is the potential for leakage paths that bypass neutralized suites to exist in the field (ie. a duct or cavity that happens to only be open at the test suite which is not connected to the suite above and below (such as a duct or pipe chase from the first floor running up the entire building and open on the test floor). These leakage paths would show up as part of the exterior enclosure leakage area. In the four buildings tested, no evidence of such pipe chases or ducts were noted on the drawings or could be observed in the field; however it is something to be aware of when performing this type of testing.

Additional tests can alternately be performed to determine the impact of intentional exhaust vent openings within the test suite. A test can be performed with and without the exhaust ducts sealed (preferably from the exterior) to determine the portion of air leakage occurs through these openings.


Test # 1 – Pressurize Suite (Adjacent Suites Open to Exterior)
Section View – Floor Above and Below
Plan View – Test Floor
Exterior = 0 Pa
+50 Pa
0 Pa
Test # 2 – Pressurize Suite and Floor Above
Section View – Floor Above and Below
Plan View – Test Floor
Test # 3 – Pressurize Suite, Floors Above and Below
Section View – Floor Above and Below
Plan View – Test Floor
Test # 4 – Pressurize Suite, Floors Above and Below, and Hallway
Section View – Floor Above and Below
Plan View – Test Floor
Test # 5 – Pressurize Suite, Floor Above and Below, Hallway and Left Suite
Section View – Floor Above and Below
Plan View – Test Floor
Test # 6 – Pressurize Suite and All Adjacent Interior Surfaces
Section View – Floor Above and Below
Plan View – Test Floor

7.2.2 Flow Mechanics

Air leakage testing of buildings is based on the fundamental mechanics of air flow through openings. The amount of flow through an opening is determined by the geometry of the opening and pressure difference across it. Air flow, opening area and air pressure are related to each other using simple mathematical relationships.

Typically in air leakage testing the results can be described in one of three forms:

1. Fan flow required to create a specified pressure drop across the fan (ie. 500 cfm flow was required to pressurize the suite to 50 Pa).
2. Equivalent leakage area which is result of the applied flow and pressures. An "equivalent" leakage area is the size of fictitious rectangular opening. (ie. At 50 Pa, the suite had an equivalent leakage area of 400 cm^2).
3. Air exchange rate, often expressed in hourly air changes per hour, which is simply volume of the space being pressurized, divided by the fan flow. (ie. The air change rate of the suite to the exterior was 2.5 ACH at 50 Pa).

The relationship describing the airflow through an "equivalent" intentional opening is based on the Bernoulli equation. The general form of the equation is (ASHRAE 2005):

$$Q = C_D \cdot A \cdot \sqrt{\frac{2P}{\rho}} \qquad (1)$$

Where, Q = air flow (m^3/s),
A = area of opening (m^2)
P = pressure difference (Pa)
ρ = density of air (kg/m^3)

The discharge coefficient, C_D is a dimensionless number than depends on the geometry of the opening and the Reynolds number of the flow.

When calculating the equivalent leakage area, all of the openings through the walls/floor of the suite are combined into an overall opening area and discharge coefficient. Some guidance is provide in ASHRAE (2005) to select a discharge coefficient, C_D, however can be assumed to be 0.61 for a sharp edged orifice opening. The air leakage area of a building is, therefore, the area of an orifice (equivalent area) that would produce the same amount of leakage as the building enclosure at the tested pressure.

The relationship can be simplified to typical test units (imperial areas and metric pressures) as follows (Retrotec 2006).

$$Q = 1.0755 \cdot A \cdot \sqrt{P} \tag{2}$$

Where, *Q* = room supply flow (cfm),
A = equivalent leakage area, ELA (in^2)
P = pressure difference between room and exterior (Pa)
1.0755 = constant, including conversions for mix of metric/imperial units commonly used in practice

Unit or normalized leakage areas can be determined by dividing the equivalent leakage area over the surface area which the leakage occurs through (ie. exterior building enclosure area).

Air leakage measurements are commonly taken at a single test pressure, and for purposes of this test 50 Pa was used. However in practice typical pressures as a result of wind, stack effect, or mechanical systems will be much lower in the range of 1 to 10 Pa. Using the power law equation, the flow at any pressure can be calculated (ASHRAE 2005):

$$Q = C \cdot (\Delta P)^n \tag{3}$$

Where, *Q* = airflow through opening (m^3/s),
C = flow coefficient (m^3/s/Pa^n)
P = pressure difference between room and exterior (Pa)
n = pressure coefficient (dimensionless)

Values of *c* and *n* can be determined by testing the air leakage over a range of pressures (multipoint tests from 10 to 75 Pa). However if a multipoint test is not performed, a typical value of n is about 0.65 (ASHRAE 2005, Sherman 2004). If the value of *n* is assumed to be 0.65, the flow coefficient *C* can be calculated knowing the flow at the test pressure.

7.3 BUILDING AND TEST SUITE DESCRIPTION

Four buildings in Vancouver, BC were air leakage tested. A plan view of each building highlighting the tested suites is provided in *Appendix G: Air Leakage Testing* and should be referred in conjunction with the test procedure.

Building numbering is consistent with previous reports from the monitoring study (Buildings 2, 3 and 4), and the additional building is referred to as Building 'A' for purposes of this report.

Table 7-1 provides a summary the tested suite number in each building, and comments pertaining to adjacent suites which were pressurized and depressurized during testing to quantify the air leakage of individual surfaces.

Table 7-1: Building Number, Test Suite and Comments

Building	**Suite**	**Comments**
2	401	Top floor, corner, 3rd floor below, stairwell (left), suite 402 (right), hallway access
3	608	Top floor, 5th floor below, Lounge (Left), suite 609 (right), hallway access (open hallway to exterior)
3	611	Top floor, 5th floor below, suite 609 (left), stairwell (right), hallway access
3	311	Middle floor, 2nd floor below, 4th floor above, suite 309 (left), stairwell (right), hallway access
A	802	Middle floor, 7th floor below, 9th floor above, suite 801 (left), suite 803 (right), hallway access
4	309	Middle floor, 2nd floor below, 4th floor above, suite 308 (left), suite 310 (right), hallway access

The testing procedure was modified (ie. test steps were omitted) where the test suite was located in a corner of the building or had only one adjacent suite or at the top floor of the building. Each surface of the suite was isolated where at all possible and interior access was provided.

Each of the Buildings is described in more detail in the following sections and supplemental information is provided in *Appendix G: Air Leakage Testing*.

7.3.1 __Building 2__

Building 2 is a four-storey wood-frame condominium building which was constructed in the early 1990's. In 2001, the exterior walls and roof were rehabilitated as a result of widespread moisture related damage to the exterior walls. The exterior cladding and plywood sheathing was replaced with a stucco rainscreen clad system as shown in Figure 7-3. The SBPO house-wrap was taped and sealed during the rehabilitation and forms an integral portion of the exterior wall air barrier system. The polyethylene membrane was left intact from original construction and forms a portion of the air barrier system. Air sealing details between suites are unknown.

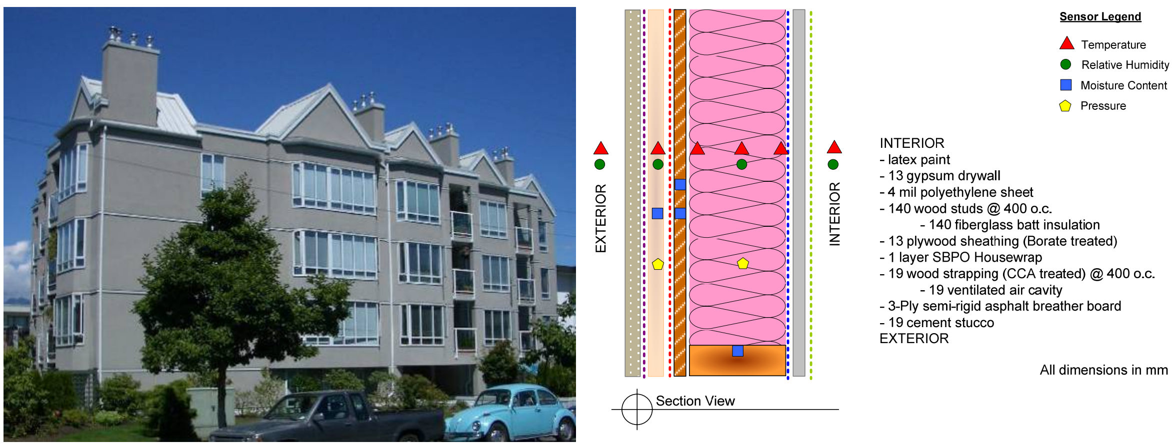


Figure 7-3: Building 2 – Overview and Wall Assembly Details.

Suite 401, highlighted in Figure 7-4 was tested as the interior conditions were monitored there for the past five years. A plan view of the 4th floor is shown in *Appendix G: Air Leakage Testing* showing the adjacent suites which were neutralized during the test.

Figure 7-4: Building 2 – Suite 401 Highlighted at Southeast Corner

The fourth floor suites have a vaulted cathedral ceiling and skylights over the living room as shown in the figure. Metal roof deck is used at these steep sloped sections and a two-ply modified bitumen roofing assembly is used at low-slope areas over the remainder of the suites.

Each suite has a gas fireplace with a 6″ diameter flue exhausting through common chimney build-outs at the roof (ie. 1st through 4th floor stacked suites use same chimney build-out). The fireplace dampers were closed during the testing of this suite, and the fireplace was off. A bathroom exhaust fan and kitchen range hood exhaust fan are located in this suite as the primary exhaust, however neither is continuously used. The occupant also has a portable humidifier and several large trees/plants. Two interior views of the suite are shown in Figure 7-5.

Figure 7-5: Building 2 – Suite 401 Interior at Living Room (left), Bedroom (right)

Suite 401 has a gross floor area of 684 ft^2, and a gross volume of 5472 ft^3. The exterior wall area is 720 ft^2 which includes four large windows and one sliding glass door.

7.3.2 <u>Building 3</u>

Building 3 is a six-storey concrete-frame residential building which was constructed in the early 1990's. In 2002, the exterior walls were rehabilitated and windows replaced as a result of widespread moisture related damage to the steel-stud and gypsum exterior walls. The exterior cladding was replaced with a stucco rainscreen clad system as shown in Figure 7-6. The exterior wall air barrier system consists of a self-adhered modified bitumen layer to the exterior of the gypsum sheathing (Figure 7-7). The roof consists of a two-ply modified bitumen roofing assembly. Air sealing details between suites are unknown.

Figure 7-6: Building 3 – Overview and Wall Assembly Details

Figure 7-7: Building 3 – Air Barrier Membrane over Gypsum Sheathing

Moisture problems within the rehabilitated exterior walls of Building 3 were noted by Finch et al. (2006) and found to be correlated with humid interior conditions and condensation at the gypsum sheathing during the winter.

Further monitoring and testing by Roppel et al. (2007) determined ventilation rates by measuring exhaust fan flow and CO_2 levels within several suites and found that the low ventilation levels were contributing to the high interior humidity levels.

The current VBBL and BCBC have similar minimum requirements as ASHRAE Standard 62 which recommends 15 cfm per person. Table 9.32.3.3.A requires a minimum ventilation rate for the principal exhaust, which may be the bathroom exhaust fan, based on the number of bedrooms.

The VBBL requires that the principal exhaust fan be controlled by an adjustable time control device to provide a minimum of two 4-hour operating periods per day, or be designed to run continuously. A separate requirement states that the bathroom fan should have a capacity of 50 CFM if run intermittently or 20 CFM if run continuously.

The primary exhaust fans (bathroom) were measured in fourteen of the suites by Roppel et al. (2007) and found a range of 20 to 61 cfm (average 43 cfm). While the fans were supposedly installed on timers, occupants reported that the fans were not all on the same time nor ran for the four hours twice per day as required by Vancouver Building Code.

The source of make-up supply air to the suites was also questioned as several door undercuts were missing or blocked with weather-stripping.

Suite 311, 611, and 608 highlighted in Figure 7-8 were tested. Interior conditions were monitored in suites 311 and 611 for the past five years and 608 for a period of 6 months during the past year. A plan view of the 3rd and 6th floors highlighting these suites is shown in *Appendix G: Air Leakage Testing*.

Figure 7-8: Building 3 – Suites 311, 611 and 608 Highlighted.

Suite 611 has a gross floor area of 742 ft^2, and a gross volume of 5936 ft^3. The exterior wall area is 488 ft^2 which includes three windows and one insulated metal panel glazed swing door.

Suite 611 is located off of conditioned hallway space. The entrance door is almost flush to the floor and weather-stripped therefore provisions for makeup air to this suite is unknown and likely through unintentional openings.

Suite 311 has a gross floor area of 742 ft^2, and a gross volume of 5936 ft^3. The exterior wall area is 488 ft^2 which includes three windows and one insulated metal panel glazed swing door.

Suite 311 is located off of conditioned hallway space. Supply or makeup air is partially provided to this suite via door undercut (13 mm).

Suite 608 has a gross floor area of 742 ft^2, and a gross volume of 5936 ft^3. The exterior wall area is 588 ft^2 which includes three windows, one insulated metal panel glazed swing door and one insulated metal swing door.

Suite 608 is located at the exterior exposed hallway, unlike the majority of the suites in the building which are located off of conditioned space. No provisions for supply or makeup air are provided to this suite. The doorway is fitted with weather stripping and makeup air is assumed to find its way through unintentional openings in the building enclosure. The exterior walls (except at the covered hallway) were retrofit in 2003 with a more airtight wall assembly than originally in was in place.

The interior conditions of suite 608 were monitored for a period of six months in 2005 and were found to be elevated to levels similar to suites 311 and 611 (monitored continuously from 2002 to 2006).

7.3.3 <u>Building 4</u>

Building 4 is a four-storey wood-frame residential building which was constructed in 2002. The exterior wall assembly is shown in Figure 7-9. The polyethylene is taped and sealed at penetrations and forms an integral part of the air barrier system.

The wood-frame floors are topped with a 2″ concrete topping which accommodates radiant heating pipes. As such the floor slab is expected to be relatively air-tight compared to a typical plywood floor. Air sealing details between suites are unknown.

Figure 7-9: Building 4– Overview and Wall Assembly Details

Suite 309, highlighted in Figure 7-4 was tested as the interior conditions were monitored there in this suite past five years. A plan view of the 4th floor is shown in *Appendix G: Air Leakage Testing*.

Figure 7-10: Building 4 – Suite 309, view of Northwest corner.

Suite 309 has a gross floor area of 378 ft², and a gross volume of 3024 ft³. The exterior wall area is 136 ft² which includes one large bay window.

7.3.4 Building A

Building 'A' is a 26 storey concrete-frame condominium building which was constructed in the 1987. In 2006-2007, the exterior walls were rehabilitated in as a result of widespread moisture related damage to the exterior steel stud and gypsum infill walls. The exterior cladding was replaced with a stucco rainscreen clad system and new windows. The exterior wall air barrier system consists of a self-adhered modified bitumen layer to the exterior of the gypsum sheathing, similar to Building 3. An exterior overview of the building is shown in Figure 7-11.

Figure 7-11: Building A – Overview of South Elevation

Suite 802 in the building was chosen for air leakage testing as the occupant had complained of high humidity and condensation on the windows during the winter months. It was suspected that insufficient ventilation was occurring in this suite (and others) in this recently rehabilitated building. The air leakage testing was performed to determine the source of the makeup air, and the air tightness of the exterior building enclosure which had recently been rehabilitated.

Suite 802 has a gross floor area of 1085 ft^2, and a gross volume of 8680 ft^3. The exterior wall area is 450 ft^2 which consists of approximately 53% glazing.

7.3.5 Test Dates

The air leakage testing of the four buildings was performed from December 5th through 8th. One building was tested per day, and one to three suites in each building was tested. The weather and exterior temperature during the tests are summarized in Table 7-2. Fortunately winds were calm and temperatures mild during the testing.

Table 7-2: Summary of Building Test Date and Weather/Temperature

Date	Building #	Floor #	Suite #	Weather
Dec. 5/06	2	4th	401	Cloudy, calm winds 5°C
Dec. 6/06	3	6th	608	Cloudy, calm winds, 6-8°C
Dec. 6/06	3	6th	611	Cloudy, calm winds, 6-8°C
Dec. 6/06	3	3rd	311	Cloudy, calm winds, 6-8°C
Dec. 7/06	A	8th	802	Overcast, calm winds, 8°C
Dec. 8/06	4	3rd	309	Overcast, calm winds, 8°C

7.4 TEST RESULTS

The test results are tabulated for each suite in the following sections. In addition, the results are compared by building type, wall/floor assembly to show the impact of construction on the relative air tightness. Raw data and supplemental building information is provided in *Appendix G: Air Leakage Testing*.

7.4.1 Building 2

Air leakage testing data for Suite #401 in Building 2 is presented in Table 7-3.

Table 7-3: Suite 401 – Building 2, Air Leakage Test Results

Surface	Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})			% of total	Flow @ 50 Pa	ACH @ 50 Pa	Normalized Leakage Area @ 50 Pa (NLA_{50})
	Pressurize	Depressurize	Average				
all 6 sides *165 m²* *(1778 ft²)*	1070 cm² (166 in²)	1060 cm² (164 in²)	1065 cm² (165 in²)	100%	1257 cfm (593 L/s)	13.8	6.5 cm²/m² (9.3 in²/100 sq.ft)
3rd floor + suite 301 *64 m²* *(684 ft²)*	64 cm² (10 in²)	84 cm² (13 in²)	74 cm² (11.5 in²)	7%	87 cfm (41 L/s)	1.0	1.2 cm²/m² (1.7 in²/100 sq.ft)
hallway 4th floor *8 m²* *(82 ft²)*	116 cm² (18 in²)	66 cm² (10 in²)	91 cm² (14 in²)	9%	107 cfm (51 L/s)	1.2	11.9 cm²/m² (23.8 in²/100 sq.ft)
left wall stairwell *6 m²* *(64 ft²)*	40 cm² (6 in²)	21 cm² (3 in²)	31 cm² (5 in²)	3%	36 cfm (17 L/s)	0.4	5.1 cm²/m² (7.4 in²/100 sq.ft)
right wall suite 402 *21 m²* *(227ft²)*	10 cm² (2 in²)	10 cm² (2 in²)	10 cm² (2 in²)	1%	12 cfm (6 L/s)	0.1	0.5 cm²/m² (0.7 in²/100 sq.ft)
exterior walls + roof *67 m²* *(720 ft²)*	840 cm² (130 in²)	879 cm² (136 in²)	860 cm² (133 in²)	81%	1014 cfm (479 L/s)	11.1	12.9 cm²/m² (18.5 in²/100 sq.ft)

The normalizing area for the exterior walls and roof above is taken at the exterior wall area only, excluding the roof area. Leakage through the roof could not be isolated from the exterior walls in this case however is assumed to be small. If the area of the roof was included the normalized equivalent leakage area would be 6.6 cm²/m² (9.9 in²/100 sq.ft) through the exterior building enclosure instead of 12.9 cm²/m² (18.5 in²/100 sq.ft).

It is shown that a relatively large percentage of the air leakage through this suite is through the exterior walls, roof, and exhaust ducts. The suite demising walls and floors are relatively well sealed. A high percentage of the interior air leakage is through the hallway through unintentional openings, potentially through the attic/cathedral ceiling space of this suite. Several penetrations through the gypsum drywall which are typically unsealed were observed in the hallway (sprinkler heads, lights, switches, receptacles etc.).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 7-12).

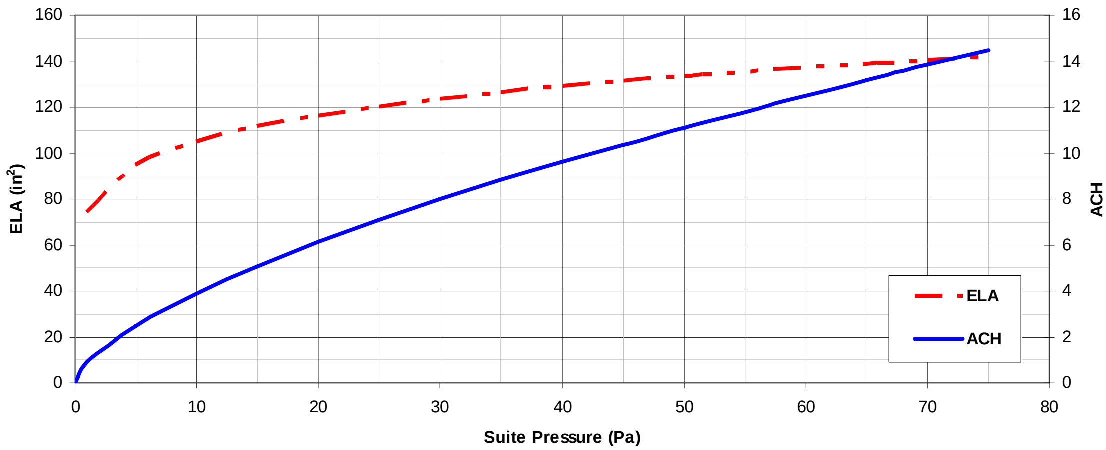


Figure 7-12: Exterior Wall ELA and ACH Relationships for Suite 401, Building 2

7.4.2 <u>Building 3</u>

Three suites in Building 3 were individually air leakage tested: 608, 611, and 311.

7.4.2.1 Suite 608

Air leakage testing data for Suite #608 in Building 3 is presented in Table 7-4. The floor below was not isolated from the testing due to access restrictions, however as shown by the tests of 611 and 311, inter-floor leakage between suites in this building was found to be insignificant.

Table 7-4: Suite 608 – Building 3, Air Leakage Test Results

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA_{50})**
	Pressurize	**Depressurize**	**Average**				
all 6 sides *235 m² (2532 ft²)*	341 cm² (53 in²)	330 cm² (51 in²)	336 cm² (52 in²)	100%	396 cfm (187 L/s)	4.0	1.4 cm²/m² (2.1 in²/100 sq.ft)
left wall lounge *10 m² (108 ft²)*	18 cm² (3 in²)	22 cm² (3 in²)	20 cm² (3 in²)	6%	24 cfm (11 L/s)	0.2	2.0 cm²/m² (2.9 in²/100 sq.ft)
right wall suite 609 *16 m² (176ft²)*	43 cm² (7 in²)	65 cm² (10 in²)	54 cm² (2 in²)	16%	64 cfm (30 L/s)	0.6	3.3 cm²/m² (4.8 in²/100 sq.ft)
exterior walls + roof *55 m² (588 ft²)*	280 cm² (43 in²)	243 cm² (38 in²)	262 cm² (41 in²)	78%	309 cfm (146 L/s)	3.1	4.8 cm²/m² (6.7 in²/100 sq.ft)

The normalizing area for the exterior walls and roof is taken at the exterior wall area only, not including the roof or floor below. As shown for suites 311 and 611, air leakage between floors in this building is negligible and is assumed to be so for this suite. Leakage through the roof could not be isolated from the exterior walls and is assumed to be negligible. If the area of the roof was included, the normalized equivalent leakage area would be 2.1 cm²/m² (3.1 in²/100 sq.ft) through the exterior building enclosure instead of 4.8 cm²/m² (6.7 in²/100 sq.ft).

While the majority of air leakage occurs through the exterior building enclosure (which is beneficial for this suite as no provisions were made for makeup air), some leakage occurs between adjacent suites (22%).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 7-13).

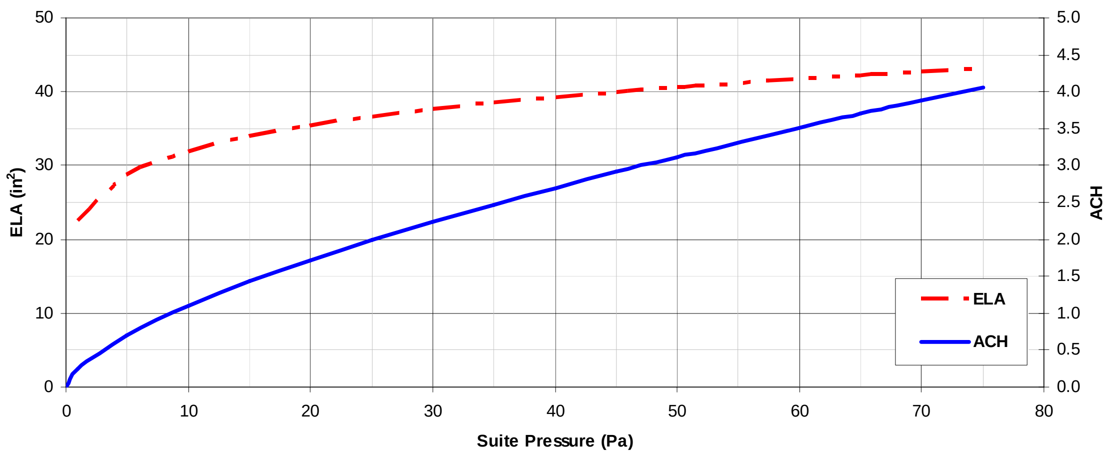


Figure 7-13: Exterior Wall ELA and ACH Relationships for Suite 608, Building 3

The impact of taping the bathroom and kitchen exhaust fan inlets was tested by performing a series of additional tests. At 50 Pa, when the bathroom duct inlet was sealed with plastic tape, the equivalent leakage area dropped by 26 cm^2, when both bathroom and kitchen ducts were sealed this dropped to 32 cm^2 from a total of 280 cm^2.

The exhaust ducts were cast into the concrete floor slab and have an unknown area, however typical 2.5 cm x 250 cm (1" x 10") ducts would have only an area of 63 cm^2 and something similar was likely used here. It is also possible that the ducts were damaged or partially constricted during installation reducing the area. Sealing the bathroom/kitchen fans may also only have a minimal impact, as air may be drawn from other openings (electrical outlets) which are attached to the pressurized plenum created by the fan. The remainder of the leakage to the exterior is assumed to occur around windows, and penetrations through the building enclosure.

7.4.2.2 Suite 611

Air leakage testing data for Suite #611 in Building 3 is presented in Table 7-5.

Table 7-5: Suite 611 – Building 3, Air Leakage Test Results

Surface	Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})			% of total	Flow @ 50 Pa	ACH @ 50 Pa	Normalized Leakage Area @ 50 Pa (NLA_{50})
	Pressurize	Depressurize	Average				
all 6 sides *225 m²* *(2423 ft²)*	540 cm² (84 in²)	492 cm² (77 in²)	516 cm² (80 in²)	100%	609 cfm (287 L/s)	6.2	2.3 cm²/m² 3.3 in²/100 sq.ft)
5th floor + suite 511 *69 m²* *(742 ft²)*	8 cm² (1in²)	5cm² (1 in²)	7cm² (1in²)	1%	8 cfm (4 L/s)	0.1	0.1 cm²/m² (0.1 in²/100 sq.ft)
hallway 6th floor *10 m²* *(107 ft²)*	204 cm² (32 in²)	270 cm² (42 in²)	237 cm² (37 in²)	46%	280 cfm (132 L/s)	2.8	23.9 cm²/m² 34.4 in²/100 sq.ft)
left wall suite 609 *20 m²* *(216ft²)*	88 cm² (14 in²)	82 cm² (12 in²)	85 cm² (13 in²)	16%	100 cfm (47 L/s)	1.0	4.2 cm²/m² (6.1 in²/100 sq.ft)
exterior walls + roof *45 m²* *(488 ft²)*	240 cm² (37 in²)	135 cm² (21 in²)	188 cm² (29 in²)	36%	221 cfm (104 L/s)	2.2	4.1 cm²/m² (6.0 in²/100 sq.ft)

The normalizing area for the exterior walls and roof is taken at the exterior wall area only, not including the roof or stairway wall. Leakage through the roof or stairwell could not be isolated from the exterior walls in this case however is assumed to be small (solid concrete with no penetrations). If the area of the roof and stairwell wall was included, the normalized equivalent leakage area would be 1.5 cm²/m² (2.1 in²/100 sq.ft) instead of 4.1 cm²/m² (6.0 in²/100 sq.ft).

The majority of air leakage into this suite occurs through unintentional openings in the hallway wall (46%) and adjacent suite (16%). A negligible amount of leakage is through the floor slab (<1%) and the remainder is through the exterior walls and roof (36%).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 7-14).

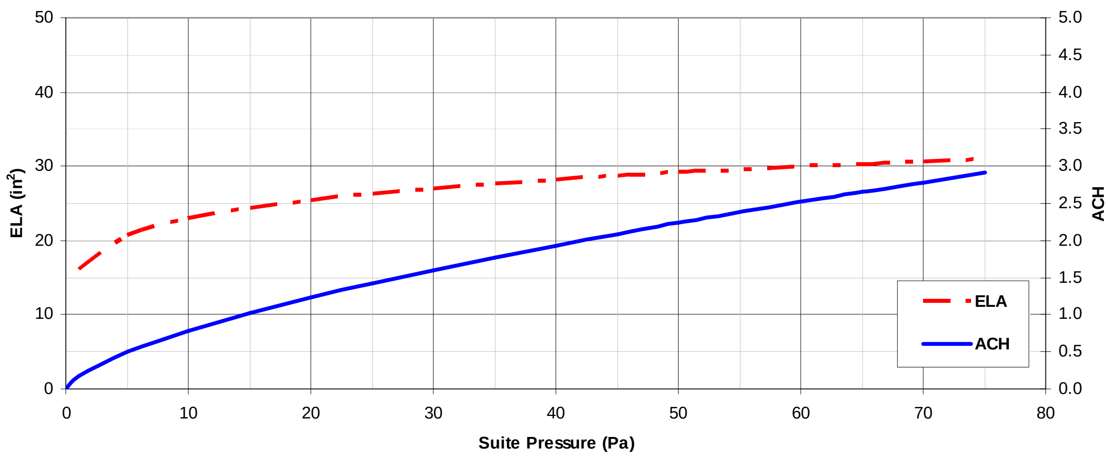


Figure 7-14: Exterior Wall ELA and ACH Relationships for Suite 611, Building 3

Like suite 608 the area of in-slab ducts make up approximately 50 cm^2 to 100 cm^2 of the exterior leakage area. The remainder of the leakage to the exterior is assumed to occur around windows, and penetrations through the building enclosure.

7.4.2.3 Suite 311

Air leakage testing data for Suite #311 in Building 3 is presented in Table 7-6.

Table 7-6: Suite 311 – Building 3, Air Leakage Test Results

Surface	Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})			% of total	Flow @ 50 Pa	ACH @ 50 Pa	Normalized Leakage Area @ 50 Pa (NLA_{50})
	Pressurize	Depressurize	Average				
all 6 sides *225 m²* *(2423 ft²)*	392 cm² (61 in²)	302 cm² (47 in²)	347 cm² (54 in²)	100%	409 cfm (193 L/s)	4.1	1.5 cm²/m² (3.1 in²/100 sq.ft)
4th floor + suite 411 *69 m²* *(742 ft²)*	3 cm² (1 in²)	6 cm² (1 in²)	5 cm² (1 in²)	1%	5 cfm (2 L/s)	0.1	0.1 cm²/m² (0.1 in²/100 sq.ft)
2nd floor + suite 211 *69 m²* *(742 ft²)*	9 cm² (1 in²)	8 cm² (1 in²)	9 cm² (1 in²)	2%	10 cfm (5 L/s)	0.1	0.1 cm²/m² (0.2 in²/100 sq.ft)
hallway 4th floor *10 m²* *(107 ft²)*	169 cm² (26 in²)	195 cm² (30 in²)	182 cm² (28 in²)	52%	215 cfm (101 L/s)	2.2	18.0 cm²/m² (26 in²/100 sq.ft)
left wall suite 309 *20 m²* *(216 ft²)*	46 cm² (7 in²)	30 cm² (5 in²)	38 cm² (6 in²)	11%	45 cfm (21 L/s)	0.5	1.9cm²/m² (2.7 in²/100 sq.ft)
exterior wall *45 m²* *(488 ft²)*	165 cm² (26 in²)	64 cm² (10 in²)	114 cm² (18 in²)	33%	135 cfm (64 L/s)	1.4	2.5 cm²/m² (3.6 in²/100 sq.ft)

The normalizing area for the exterior walls is taken as the exterior wall area only, not including stairway wall. Leakage through stairwell could not be isolated from the exterior walls in this case however is assumed to be small (solid concrete with no penetrations). If the area of the stairwell wall was included, the normalized equivalent leakage area would be 2.0 cm²/m² (2.9 in²/100 sq.ft).

The majority of air leakage into this suite occurs through unintentional openings in the hallway wall (52%) and adjacent suite (11%). A negligible amount of leakage is through the floor slabs (3%) and the remainder is through the exterior walls (33%).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 7-15).

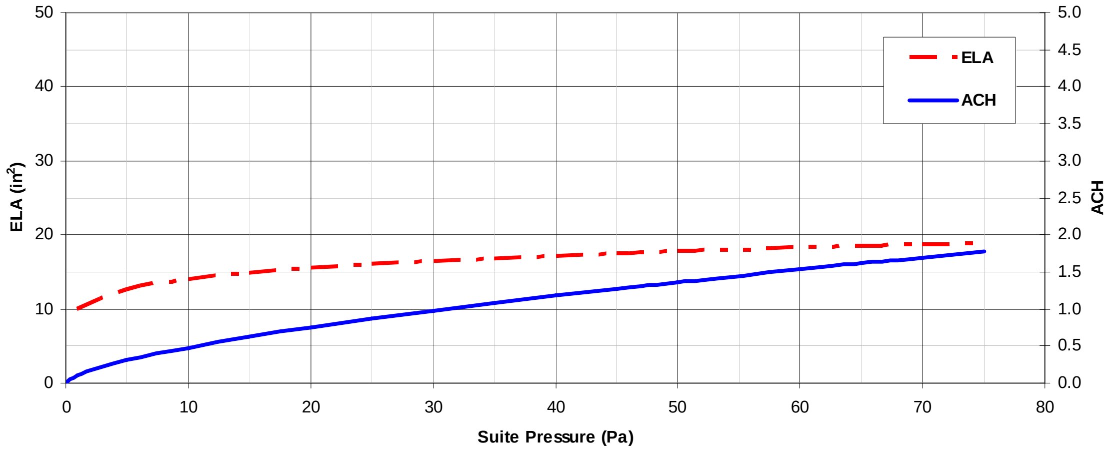


Figure 7-15: Exterior Wall ELA and ACH Relationships for Suite 311, Building 3

The impact of taping the bathroom and kitchen exhaust fan inlets were tested by performing a series of additional tests. At 50 Pa, when the bathroom duct inlet was sealed with plastic tape, the equivalent leakage area remained the same, indicating air was potentially bypassing the inlet grille, possibly at other penetrations in the wall or ceiling.

The three suites tested in Building 3 show similar air leakage results, particularly 311 and 611 which are of similar configuration. The building enclosures are relatively tight in all suites; however significant inter-suite and unintentional hallway to suite leakage is occurring.

7.4.3 <u>Building A</u>

Air leakage testing data for Suite #802 in Building 'A' is presented in Table 7-7.

Table 7-7: Suite 802 – Building A, Air Leakage Test Results

Surface	**Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})**			**% of total**	**Flow @ 50 Pa**	**ACH @ 50 Pa**	**Normalized Leakage Area @ 50 Pa (NLA_{50})**
	Pressurize	**Depressurize**	**Average**				
all 6 sides *314 m² (3381 ft²)*	347 cm² (54 in²)	290 cm² (45 in²)	319 cm² (49 in²)	100%	376 cfm (177 L/s)	2.6	1.0 cm²/m² (1.5 in²/100 sq.ft)
9th floor + suite 902 *101 m² (1085 ft²)*	61 cm² (9 in²)	54 cm² (8 in²)	58 cm² (9 in²)	18%	68 cfm (32 L/s)	0.5	0.6 cm²/m² (0.8 in²/100 sq.ft)
7th floor + suite 702 *101 m² (1085 ft²)*	16 cm² (3 in²)	16 cm² (3 in²)	16 cm² (3 in²)	5%	19 cfm (9 L/s)	0.1	0.2 cm²/m² (0.2 in²/100 sq.ft)
hallway 8th floor *11 m² (114 ft²)*	145 cm² (22 in²)	88cm² (14 in²)	117 cm² (18 in²)	37%	138 cfm (21 L/s)	1.0	11.0 cm²/m² (16.0 in²/100 sq.ft)
left wall suite 801 *33 m² (359 ft²)*	5 cm² (1 in²)	20 cm² (3 in²)	13 cm² (2 in²)	4%	15 cfm (7 L/s)	0.1	0.4 cm²/m² (0.5 in²/100 sq.ft)
right wall suite 803 *27 m² (288 ft²)*	5 cm² (1 in²)	4cm² (1 in²)	5 cm² (1 in²)	1%	5 cfm (2 L/s)	<0.1	0.2 cm²/m² (0.2 in²/100 sq.ft)
exterior walls *42 m² (450 ft²)*	115 cm² (18 in²)	108 cm² (17 in²)	112 cm² (17 in²)	35%	132 cfm (62 L/s)	0.9	2.7 cm²/m² (3.9 in²/100 sq.ft)

It was possible to neutralize all adjacent surfaces of the suite (unlike other Building 3, 2, or 4), therefore normalized values are accurate for the surfaces which were measured as no assumptions were made.

The majority of air leakage into this suite occurs through unintentional openings in the hallway wall (37%). Leakage between suites is small (solid concrete walls) at 5%, however significant leakage occurs between floors (23% total). The remainder (35%) is through the exterior walls.

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 7-16).

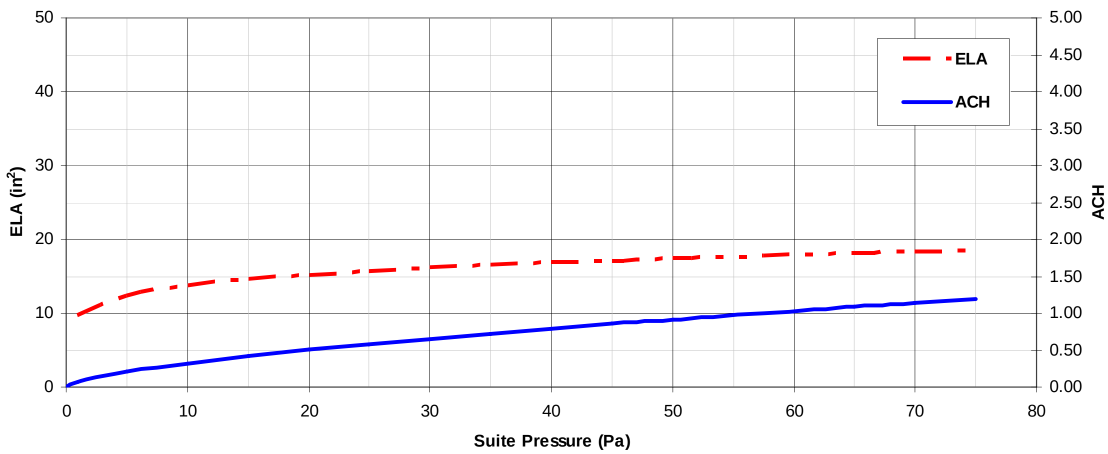


Figure 7-16: Exterior Wall ELA and ACH Relationships for Suite 802, Building A

The impact of taping the bathroom and kitchen exhaust fan inlets was tested by performing a series of additional tests. At 50 Pa, when the bathroom duct inlet was sealed with plastic tape, the equivalent leakage area dropped by 18 cm^2, when both bathroom and kitchen ducts were sealed this total dropped to 29 cm^2 from a total exterior enclosure leakage of 115 cm^2.

The exhaust ducts were cast into the concrete floor slab and have an unknown area, however typical 2.5 cm x 250 cm (1" x 10") ducts would have only an area of 63 cm^2 each (126 cm^2 total) and something similar was likely used here. It is also possible that the ducts were damaged or partially constricted during installation reducing the area. Sealing the bathroom/kitchen fans may also only have a minimal impact, as air may be drawn from other openings (electrical outlets) which are attached to the pressurized plenum created by the fan. The remainder of the leakage to the exterior is assumed to occur around windows, and penetrations through the building enclosure, which was the tightest of the six tests performed.

Air leakage values through the exterior walls measured for this suite are similar in range to those from Building 3 (which has similar construction). Plotted to the same scale, both buildings have approximately the same exterior wall leakage characteristics (Figure 7-16 versus Figure 7-14 and Figure 7-15).

7.4.4 <u>Building 4</u>

Air leakage testing data for Suite #309 in Building 4 is presented in Table 7-8.

Table 7-8: Suite 309 – Building 4, Air Leakage Test Results

Surface	Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})			% of total	Flow @ 50 Pa	ACH @ 50 Pa	Normalized Leakage Area @ 50 Pa (NLA_{50})
	Pressurize	Depressurize	Average				
all 6 sides *133 m²* *(1428 ft²)*	470 cm² (73 in²)	360 cm² (56 in²)	415 cm² (64 in²)	100%	490 cfm (231 L/s)	9.7	3.1 cm²/m² (4.5 in²/100 sq.ft)
4th floor + suite 902 *35 m²* *(378 ft²)*	0 cm² (0 in²)	0 cm² (0 in²)	0cm² (0 in²)	0%	0 cfm (0 L/s)	0	0 cm²/m² (0 in²/100 sq.ft)
2nd floor + suite 702 *35 m²* *(378 ft²)*	0 cm² (0 in²)	0 cm² (0 in²)	0 cm² (0 in²)	0%	0 cfm (0 L/s)	0	0 cm²/m² (0 in²/100 sq.ft)
hallway 3rd floor *6 m²* *(68 ft²)*	120 cm² (19 in²)	140cm² (22 in²)	130 cm² (20 in²)	31%	153 cfm (72 L/s)	3.0	20.6 cm²/m² (30.0 in²/100 sq.ft)
left wall suite 308 *24 m²* *(256 ft²)*	15 cm² (2 in²)	5 cm² (1 in²)	10 cm² (2 in²)	2%	12 cfm (6 L/s)	0.2	0.4 cm²/m² (0.6 in²/100 sq.ft)
exterior walls *13 m²* *(136 ft²)*	335 cm² (52 in²)	215 cm² (33 in²)	275 cm² (43 in²)	67%	325 cfm (50 L/s)	6.5	21.8 cm²/m² (31.3 in²/100 sq.ft)

Access was not provided to the adjacent suite 310; therefore the right wall could not be isolated from the total air leakage to the exterior. However as shown the leakage between adjacent suites (308 on left side) was found to be minimal (2%). Therefore it is assumed that the leakage between suites 309 and 310 would also be small. As a check during testing, the pressure difference across the door of suite 310 when the hallway was pressurized was approximately 50 Pa, therefore the door undercut and any incidental leakage was balancing this suite.

It is shown that a relatively large percentage of the air leakage through this suite is through the exterior walls and exhaust ducts. The suite demising walls and floors are relatively well sealed. A high percentage of the interior air leakage is from the hallway through unintentional openings. Several penetrations through the gypsum drywall which are typically unsealed were observed in the hallway (sprinkler heads, lights, switches, receptacles etc.).

A consistent air leakage difference was observed between pressurizing and depressurizing this suite. Unlike the other buildings, this difference was consistent and can likely be attributed to use of polyethylene as the air barrier. While pressurizing the suite, the polyethylene is pushed out into insulation of the stud bays, increasing the size of any openings. When depressurizing the suite the polyethylene would be pulled against the solid gypsum drywall and thus any openings would be partially restricted and smaller. The average difference is consistently 110 to 130 cm^2 through the tests and an average of 116 cm^2 (18 in^2).

If a pressure coefficient of 0.65 is assumed, the 50 Pa measurements can be converted to a range of pressures more commonly seen in service (Figure 7-17).

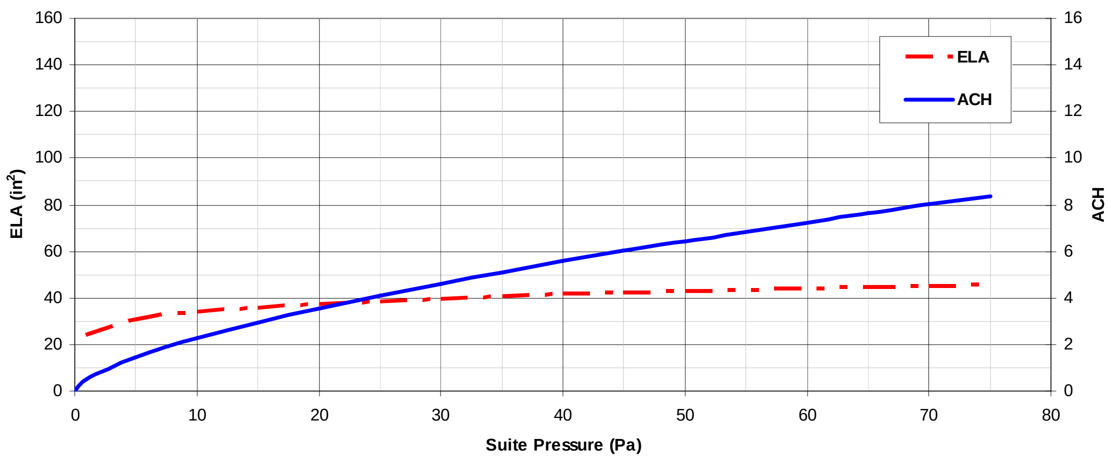


Figure 7-17: Exterior Wall ELA and ACH Relationships for Suite 309, Building 4

The impact of taping the bathroom and kitchen exhaust fan inlets was tested by performing a series of additional tests. At 50 Pa, when the bathroom duct inlet was sealed with plastic tape, the equivalent leakage remained the same. Sealing the bathroom/kitchen fans may also only have a minimal impact, as air may be drawn from other openings (electrical outlets) which are attached to the pressurized plenum created by the fan.

Air leakage values measured for this suite are similar in range to those from Building 2 (similar wood-frame construction). Figure 7-17 is plotted to the same scale as Figure 7-12 for comparison of the two buildings.

7.4.5 Summary

The air leakage through the exterior building enclosure from the six tests is summarized in Table 7-9.

Table 7-9: Summary of Air Leakage to Exterior for all Tested Buildings

Surface	Equivalent Leakage Area, ELA @ 50 Pa (ELA_{50})			% of total	Flow @ 50 Pa	ACH @ 50 Pa	Normalized Leakage Area @ 50 Pa (NLA_{50})
	Pressurize	Depressurize	Average				
BLDG 2 - 401 exterior walls *67 m^2 (720 ft^2)*	840 cm^2 (130 in^2)	879 cm^2 (136 in^2)	860 cm^2 (133 in^2)	81%	1014 cfm (479 L/s)	11.1	12.9 cm^2/m^2 (18.5 in^2/100 sq.ft)
BLDG 3 - 608 exterior walls *55 m^2 (588 ft^2)*	280 cm^2 (43 in^2)	243 cm^2 (38 in^2)	262 cm^2 (41 in^2)	78%	309 cfm (146 L/s)	3.1	4.8 cm^2/m^2 (6.7 in^2/100 sq.ft)
BLDG 3 - 611 exterior walls *45 m^2 (488 ft^2)*	240 cm^2 (37 in^2)	135 cm^2 (21 in^2)	188 cm^2 (29 in^2)	36%	221 cfm (104 L/s)	2.2	4.1 cm^2/m^2 (6.0 in^2/100 sq.ft)
BLDG 3 - 311 exterior wall *45 m^2 (488 ft^2)*	165 cm^2 (26 in^2)	64 cm^2 (10 in^2)	114 cm^2 (18 in^2)	33%	135 cfm (64 L/s)	1.4	2.5 cm^2/m^2 (3.6 in^2/100 sq.ft)
BLDG A - 802 exterior walls *42 m^2 (450 ft^2)*	115 cm^2 (18 in^2)	108 cm^2 (17 in^2)	112 cm^2 (17 in^2)	35%	132 cfm (62 L/s)	0.9	2.7 cm^2/m^2 (3.9 in^2/100 sq.ft)
BLDG 4 – 309 exterior walls *13 m^2 (136 ft^2)*	335 cm^2 (52 in^2)	215 cm^2 (33 in^2)	275 cm^2 (43 in^2)	35%	325 cfm (50 L/s)	6.5	21.8 cm^2/m^2 (31.3 in^2/100 sq.ft)

Comparison to Previous Published Values

The air leakage results for the six tested suites in Vancouver are compared to the previous results from five other Canadian buildings (Gulay et al. 1993), in normalized units of L/s/m^2 at 50 Pa. These are further compared to the NBCC 2005 requirements for building enclosure air tightness.

Table 7-10: Summary of Individual Suite Air Leakage – L/s/m^2 @ 50 Pa

Test Suite/Building	**Entire Suite Leakage, normalized to total surface area (L/s/m^2 @ 50 Pa)**	**Exterior Wall Leakage normalized to wall surface area (L/s/m^2 @ 50 Pa)**
Gulay et al (1993) – Range of 10 buildings	4.56 to 8.33 (normalizing area unknown)	2.10 to 3.15
NBCC 2005 Requirements	No Standard	0.05 to 0.15 (@ 75 Pa)
401/Building 2	3.59	7.16
608/Building 3	0.56	1.49
611/Building 3	0.79	2.67
311/Building 3	0.86	1.40
802/Building A	1.28	2.30
309/Building 4	1.74	12.12

The previous test results are similar in range to those measured in the four Vancouver buildings, with the two wood-frame buildings having higher leakage rates than the concrete frame buildings. However, both tests show results that are significantly higher than the NBCC 2005 requirements for building enclosure air tightness. The NBCC values however exclude the impact of intentional openings such as exhaust ducts which were not isolated in the Vancouver or other previous tests.

Impact of Construction on Air Tightness

The data from the six suites is summarized and compared to determine if any consistencies between wall or floor assemblies can be determined from the limited data set. While statistically insignificant, the results confirm predicted differences between assembly types.

Figure 7-18 compares the air leakage between wall exterior building enclosure assemblies.

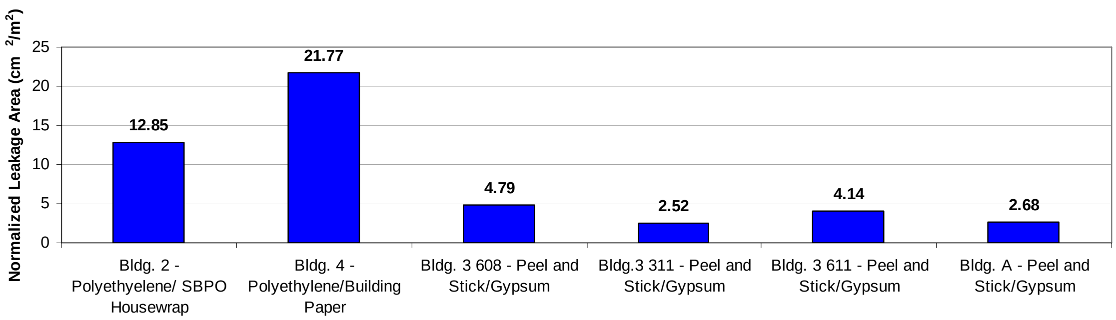


Figure 7-18: Comparison of Normalized Air Leakage through Exterior Walls

Here the two wood-frame exterior walls had the highest normalized leakage area, consistently higher than the steel stud and gypsum walls with the peel and stick air barrier. Suites 608 and 611 at the top floor of Building 3 had higher leakage areas than the other two of this set as likely some air leakage through the roof was measured but could not be isolated from the results.

The differences in air leakage through the floor assembly by type are compared in Figure 7-19.

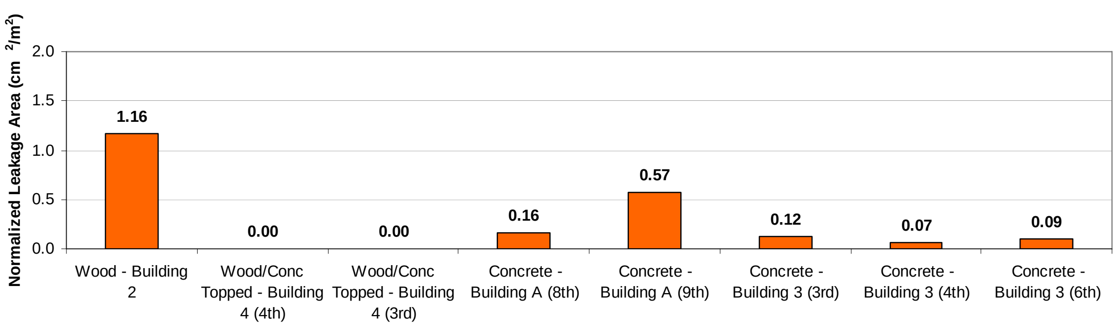


Figure 7-19: Comparison of Normalized Air Leakage through Floors by Type

The tightest system was the concrete topped wood frame wall followed by the concrete slab floor. The wood frame floor had the highest air leakage. The air leakage through a floor slab depends largely on how well the penetrations were fire/smoke sealed. It appears in Building A, one or several of the penetrations were poorly sealed, contributing to the higher than average leakage through this solid concrete slab. The wood frame floor as could be expected had a higher leakage area, due to penetrations, gaps, or shrinkage of the plywood and wood joist floor.

The differences in air leakage through suite demising walls by type are compared in Figure 7-20.

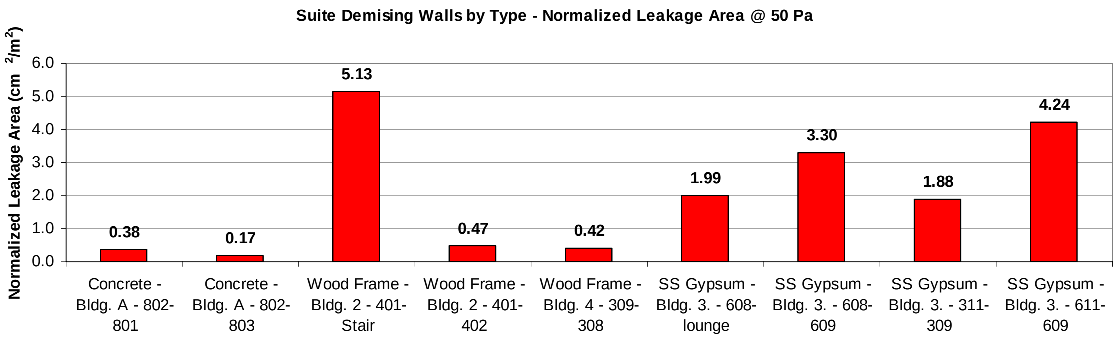


Figure 7-20: Comparison of Normalized Air Leakage through Demising Walls

The solid concrete walls were the tightest, followed by the wood frame walls (with exception of one location), and finally the steel-stud and gypsum demising walls. The differences between solid concrete and the framed walls are obvious, however it appears that wood-framed walls were constructed tighter than steel-stud and gypsum framed walls.

The differences in air leakage through the walls between the common hallway and suite are compared in Figure 7-21.

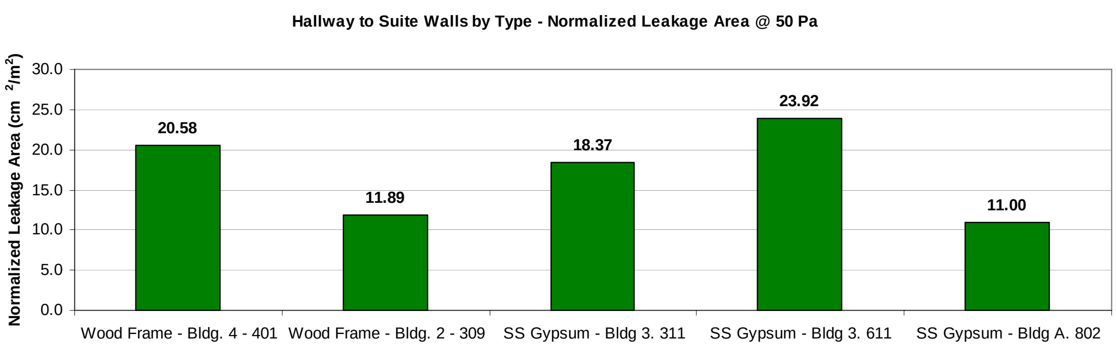


Figure 7-21: Comparison of Normalized Air Leakage through Hallway Walls

Air leakage through the hallway door is excluded from these tests, which has a leakage area is in the order of 50 cm^2/m^2 for a standard entrance door with a 1 cm door undercut normalized over the total area of the door frame. Therefore the measured leakage here is potentially through unintentional openings such as plumbing penetrations, cracks, gaps, or electrical boxes/switches.

The hallway demising walls were significantly leakier than the suite demising walls, possibly as openings were more frequent or poorly sealed. While the leakage area is unintentional (not through passive vents or door undercuts) it may be beneficial for suite supply air in cases where suite owners intentionally block the door undercut.

The following conclusions can be drawn from the results, which also reflect field experience with these types of assemblies. Solid concrete assemblies are less leaky than wood, however wood assemblies are less leaky than steel stud/gypsum. Suite demising walls and floors are more air tight than hallway walls. Exterior walls with peel-and-stick as an air barrier are more air tight than those with polyethylene or sealed taped house-wrap.

Leakage through interior walls and floors becomes increasingly significant as the exterior building enclosure becomes increasingly more air-tight. As shown in the next section, this has implications on building performance if not addressed, particularly during rehabilitations where the exterior walls are replaced and constructed more air-tight than the original walls and existing mechanical systems remain in place.

7.4.6 Lessons Learned With Multi-Unit Residential Building Testing

The minimum test setup to test and neutralize one individual suite within a larger building requires 4 fans, more if the building is very leaky or one fan cannot pressurize an entire floor (for neutralizing pressures). A total of four technicians are also required, one for each fan as a safety precaution and remain with each fan during testing should a problem occur.

When the elevator core is also located off of the tested hallway, the elevator doors opening and closing will affect pressurization. Curious tenants opening suite doors or going about their daily activities will also impact the pressurization. Performing the testing when the building is unoccupied would be ideal, however is not typically possible unless a new construction job.

The testing is by all means obtrusive and requires full cooperation of building manager and occupants to run smoothly. The testing requires the temporary blockage of an emergency fire exit. Modern and most older buildings have a minimum of two stairwells, and by no means can both be blocked. The door-fan operator must remain at the door-fan on each floor and be able to quickly take down and remove door-fan in an emergency or if a tenant wishes to use the stairwell.

Access can also be an issue, several suites to be simultaneously open, but also require access to open or close windows and doors within suites. Depressurization times should be minimized in winter. Ensuring the tenants are aware of the purpose generally helps to smooth the process out. Plan to test 1 or 2 suites per 8 hour day allowing for setup, adjustment, and cleanup.

The procedure showed that air leakage testing of individual suites in multi-unit residential buildings is possible, and that consistent results can be achieved using the methods provided.

7.5 DISCUSSION OF BUILDING PERFORMANCE

A discussion of the interior performance of the tested suites is discussed followed by a review of the mechanical systems and ventilation strategies for the four buildings.

7.5.1 Past Performance

Temperature and relative humidity (RH) data has been collected for the past five years from the interior of the tested suites in Buildings 2, 3 and 4, and spot measured during the past year in Building A. The impact of air-tightness can be shown, as all suites had similar occupancy loads, and similar mechanical ventilation systems (exhaust by bathroom fan occupant controlled or on timers with makeup air provided by door undercuts from pressurized hallways).

Monthly average suite dewpoint temperatures are plotted in Figure 7-22 for five suites in Buildings 2, 3, and 4 from January 2002 to January 2005. Figure 7-23 plots the corresponding relative humidity within the suites over the same time period.

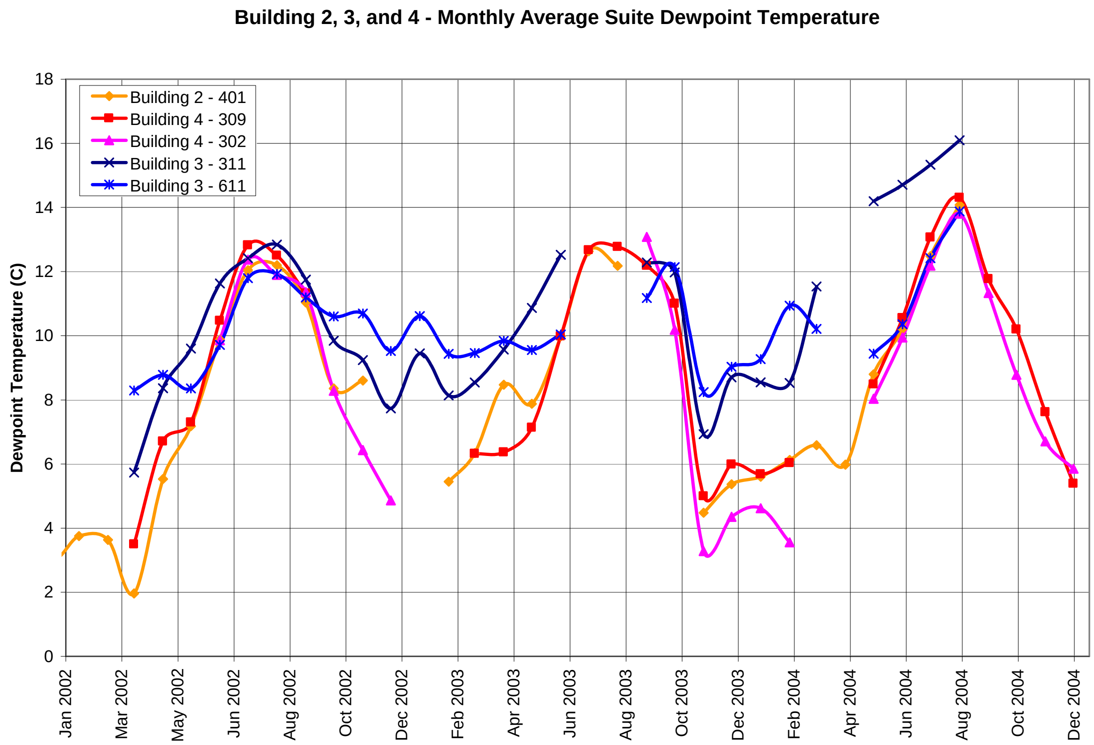


Figure 7-22: Building 2, 3 and 4 – Monthly Average Suite Dewpoint Temperature

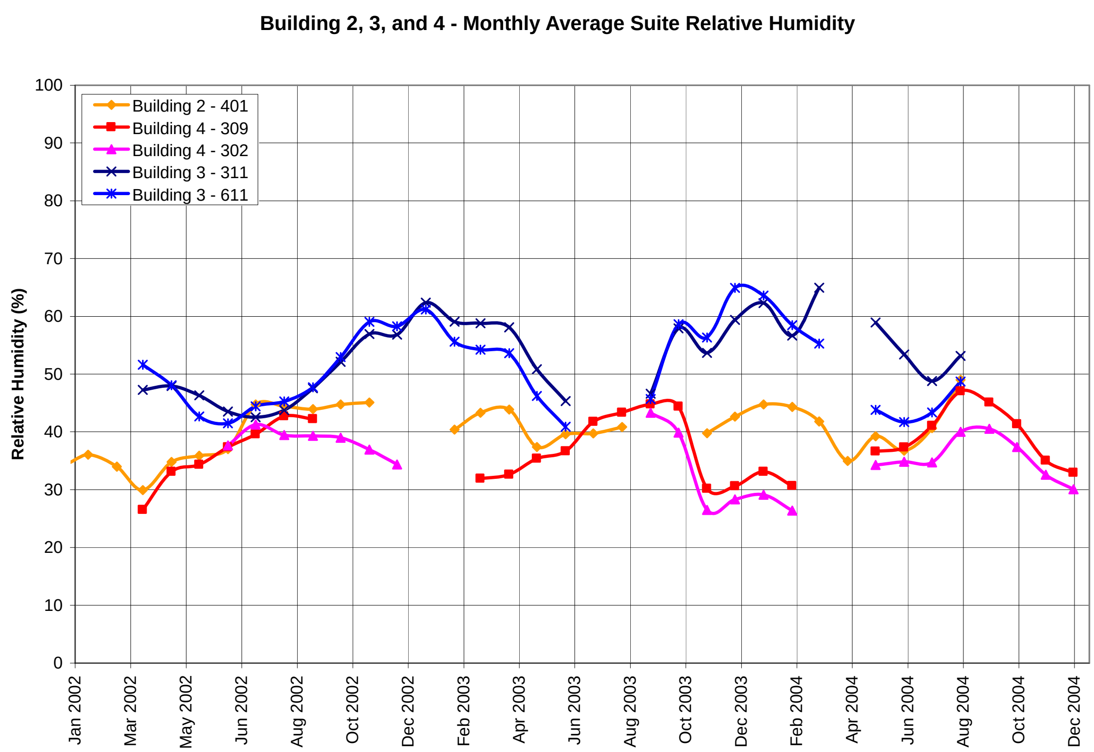


Figure 7-23: Building 2, 3 and 4 – Monthly Average Suite Relative Humidity

The interior dewpoint and relative humidity within suites of Buildings 2 and 4 remain relatively close over the three years, showing similar seasonal trends which are average for Vancouver. Building 2 is slightly more humid than Building 4, however the occupant in Building 2 uses a humidifier during the winter and has a number of large plants which would increase wintertime humidity.

During the same period the two monitored suites in Building 3 show a significantly different trend. Average wintertime dewpoint temperatures are elevated (8-10°C) as are the relative humidities which approach unsafe levels (average of 60-70% for several months). As previously discussed, Building 3 has moisture problems within the exterior walls, and condensation and mildew on interior surfaces during the winter months which correlate with the elevated interior dewpoint/humidity levels in this building.

Building A was not monitored during this period; however the interior temperature and relative humidity in several suites in Building ‘A’ were measured in November and December 2006. A summary of average readings taken during field reviews are as follows:

- Suite 802 was measured at 24°C and 65% RH when exterior conditions were 5°C and >80% RH.
- Suite 902 was measured at 17°C and 61% RH while hallway conditions were 21°C and 25% RH during an exceptional cold period in Vancouver when the exterior temperature was -8°C and 50% RH.
- Suite 1107 was measured at 19°C and 63% RH while hallway conditions were 22°C and 30%, exterior conditions were 3°C and >80% RH.

Complaints of condensation on window sills and glazing were also reported in Building A, which has occurred post-rehabilitation.

7.5.2 <u>Impact of Air-Tightness on Mechanical Systems</u>

The mechanical systems within the four tested buildings are similar. A pressurized corridor supplies make-up air into the suites (typically through 13 mm (½”) door undercuts). Air is exhausted through bathroom fans (50 to 90 cfm rated) on timers and/or humidistat/occupant controlled. Additional exhaust fans are provided in the kitchen however used only when cooking and are occupant controlled. Therefore the ventilation rate of the suite is dependent on the supply of makeup air, exhaust fan flow, windows if used, and potentially additional air leakage through a leaky exterior enclosure. Ventilation efficiency is reduced when stale makeup air is drawn in from adjacent suites, which can be significant depending on the distribution and percentage of the total suite leakage area. Heating in all of the buildings investigated consists of electrical base-board heaters at the perimeter walls below windows which is set by an occupant controlled thermostat.

The four tested suites in Buildings 3 and 'A' were found to be relatively air-tight compared to the other Buildings 2 and 4. Wintertime elevated humidity and moisture problems are evident and have lead to damage in Building 3 and condensation and humidity problems have been reported in Building A. In contrast, the two tested suites in Buildings 2 and 4 were found to be relatively air-leaky. Elevated humidity or moisture problems have not been reported within Building 2 and 4 over the past four years.

Buildings 3 and 'A' were rehabilitated in 2002 and 2006 with similar air-tight exterior wall assemblies with an air-tight peel and stick membrane over a gypsum sheathed steel stud wall and new air-tight windows. Testing has confirmed the relative air-tightness of these assemblies as constructed. Subsequently a large percentage of the air leakage into these suites is through adjacent suites and common areas and one-third of the total suite air leakage is through the exterior building enclosure. In both of these buildings the existing mechanical systems remained in place after the exterior wall rehabilitation. In both buildings, the height of the door-undercut varies from tightly sealed up to a 13 mm (1/2") open gap.

With the existing mechanical system, there is no provision to deliver fresh make-up air directly to the suites in any of these buildings. Therefore, make-up air will be drawn from a combination of the corridors, adjacent suites, and the exterior walls/roof. The path of air exchange is dependent on leakage area and pressure differentials between the suite and adjacent zones (corridor, adjacent suites, and exterior environment). If a suite is tight to the exterior, but relatively leaky to the adjacent suite or common spaces, the majority of makeup air will come from these leakier locations. Drawing stale, moisture laden air from adjacent suites will increase the relative humidity within the suites as the effective ventilation rate is significantly reduced.

Air-tightness combined with the existing mechanical system is a contributing factor in the interior performance of Buildings 3 and 'A'. Additional mechanical ventilation is required for these tighter buildings as opposed to the leakier wood-frame enclosures (Buildings 2 and 4) which were tested. This by no means implies that airtight buildings or buildings with peel and stick will have interior moisture problems, or that wood-frame buildings will not have problems. A number of factors contribute to interior moisture problems, and air tightness coupled with deficient mechanical ventilation is the most significant issue.

Mechanical systems must be designed for each individual building and assumptions as to base air leakage rates through the building enclosure are no longer valid with modern wall assemblies.

Figure 7-24 graphically shows the impact of air tightening the exterior wall of a building (such as during a rehabilitation) on suite ventilation and how problems could be avoided by using a balanced system, with continual or controlled exhaust in each suite, while ensuring sufficient makeup air reaches each suite.

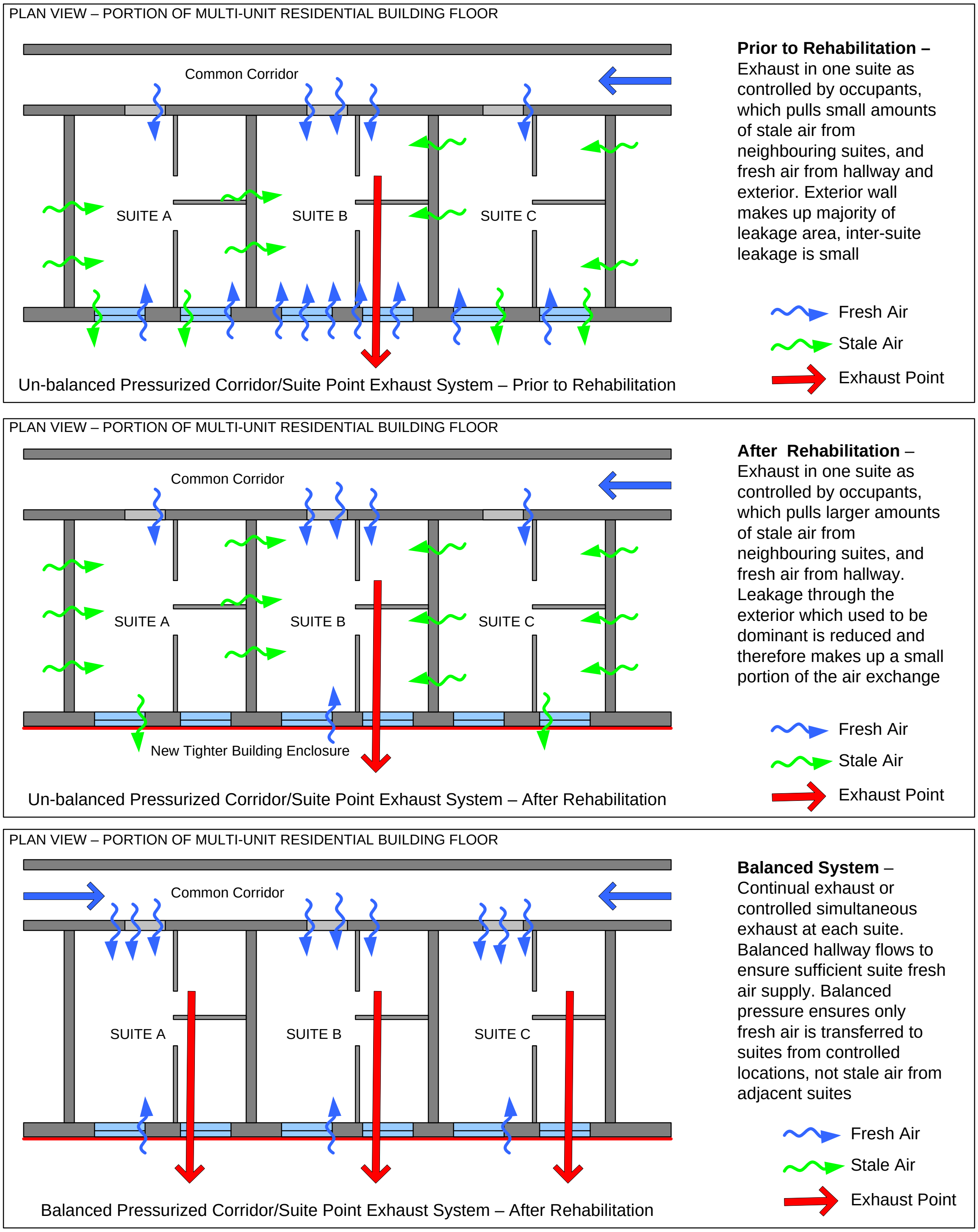


Figure 7-24: Impact of Air Tightness of Walls on Mechanical Systems

7.6 CONCLUSIONS

Air leakage testing of six suites in four multi-unit residential buildings was performed to quantify air leakage between adjacent suites, floors, common spaces and through the exterior walls.

The following conclusions can be made from the results, which also reflect field experience with these types of assemblies. Solid concrete assemblies were constructed more airtight than wood assemblies and wood assemblies were more airtight than steel stud/gypsum. Suite demising walls and floors were typically constructed more air tight than hallway walls. Exterior walls with peel-and-stick as an air barrier were more air tight than those with polyethylene (at the interior) or taped polyolefin house wrap (to the exterior of the sheathing).

The test method allowed the air leakage through the exterior building enclosure to be isolated. The concrete frame buildings with exterior walls constructed with a peel and stick air/vapour/water barrier membrane over gypsum and steel stud wall were the tightest and had a range of leakage from 2.5 to 4.8 cm^2/m^2 @50 Pa. The wood-frame walls with polyethylene and/or taped and sealed polyolefin house wrap were considerably leakier at 12.9 to 21.8 cm^2/m^2 @50 Pa. All measurements were taken with intentional exhaust ducts left as they would be in practice and would be common to all measurements. The leakiest building at 21.8 cm^2/m^2 @50 Pa of exterior enclosure leakage included a fireplace and was a corner unit on the top floor, which had the highest enclosure surface area which may explain its difference from the other buildings.

The leakage rates for the six Vancouver buildings ranged from 1.40 to 12.1 $L/s/m^2$ at 50 Pa (2.5 to 21.8 cm^2/m^2 @50 Pa) whereas previous testing from Gulay et al. (1993) measured values from 2.10 to 3.15 $L/s/m^2$ (3.8 to 5.7 cm^2/m^2 @50 Pa) for ten buildings across Canada.

ASHRAE Standard 160P suggests typical air-tightness guidelines for use with hygrothermal models. For standard construction 0.29 cm^2/m^2 is suggested and for air-tight construction 0.055 cm^2/m^2 is suggested at 5 Pa. The values measured in the testing here are an order of magnitude or two higher (10 to 100 times).

Leakage through interior walls and floors becomes more significant and cannot be ignored, especially as the exterior building enclosure is increasingly constructed more air-tight. The need for balanced mechanical systems is more important with these new tighter building enclosures, otherwise moisture problems may develop as a result of insufficient ventilation (natural or mechanical).

Corridor supply and suite exhaust mechanical systems may have worked in the past in multi-unit residential buildings when the building enclosures were leakier, however may not work with today's modern air-tight buildings. In addition, air leakage between suites and common spaces will increasingly become more important as the exterior enclosure increasingly becomes tighter. While the air-tightness of these interior partition walls/floors should be improved, it will not make up for insufficient mechanical ventilation. Preferably, fresh make-up air would be ducted and supplied to each suite and pressures balanced to eliminate inter suite leakage (as is done in many new buildings). For rehabilitation projects, the cost of such an option may be prohibitive and the existing mechanical systems may have to be upgraded to accommodate higher mechanical ventilation rates. This can include the use of continuous in-line fans with low noise (sone) level and possibly the use of heat recovery ventilators (HRVs) within each suite or floor to reduce energy costs.

While air-tight buildings are desirable for energy efficiency and thermal and occupant comfort, a higher level of performance is required from the mechanical and ventilation systems. Air-tight buildings put a higher demand on the mechanical ventilation systems to actually perform in service and deficient systems can have serious ramifications on building performance and occupant comfort. While holistic consideration in design for the integration of all building components (structural, mechanical, building enclosure, etc) has been called upon by practitioners for years, and as we strive to achieve higher performance buildings it becomes an absolute necessity.

7.7 ACKNOWLEDGEMENTS

Performing such large scale testing requires the assistance of several people in the field and the use of specialized test equipment. I would like to thank first of all Colin Genge at Retrotec for his guidance and assistance with the testing and to Retrotec for providing all of the required test equipment for the week. Also to Hua Ge and Wendy Ye at BCIT, Matthew Mulleray, Shen Huang, and Chris Black at RDH Building Engineering, Mark Lawton and Anik Teasdale St-Hilaire at Morrison Hershfield for their assistance in the field with the setup, testing, and cleanup on site. In addition Brian Simpson at BC Housing (Building 3), Jim

McKenzie at Building 2, Ed Starkins, Patrick Snowolf, and Don Driedger at Building 4 for providing access to the suites, and to all of the building tenants for their understanding during the testing.

7.8 REFERENCES

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8 MEASURED WOOD-FRAME RAINSCREEN WALL PERFORMANCE

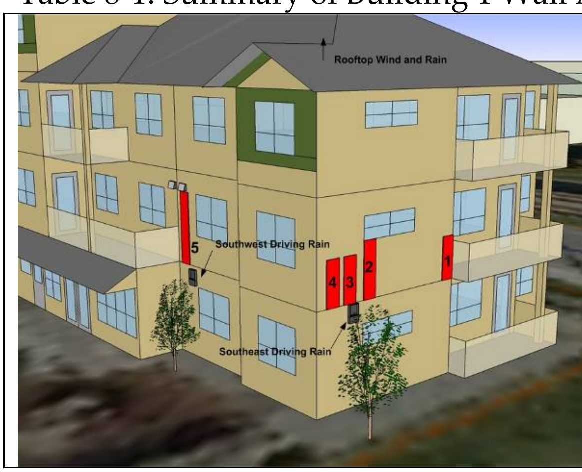
Field data from 2001 to 2006 indicates that the wood-frame rainscreen walls generally appear to be limiting the seasonal accumulation of moisture to safe levels, bordering 20% at the plywood with seasonal drying observed. The moisture content of the plywood sheathing within the walls of the three buildings follows similar trends, with little difference between cladding type used (stucco, cement board, or vinyl siding), indicating that ventilation within the strapped cavities is effectively decoupling the cladding from the sheathing for these three buildings. The one brick veneer wall at Building 4 had slightly higher moisture levels as a result of reduced ventilation and an absorptive brick cladding.

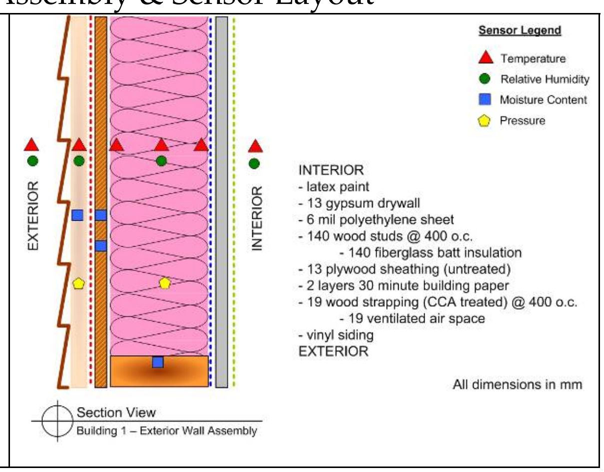
Measured data is presented from each of the three buildings and the performance is discussed.

8.1 BUILDING 1

The measured performance of the vinyl clad rainscreen walls of Building 1 is presented. For reference the sensor layout and wall assembly is shown in Table 8-1.

Table 8-1: Summary of Building 1 Wall Assembly & Sensor Layout





8.1.1 Moisture Content

Moisture content data is presented for Building 1 from January 2002 to 2003 for the ten monitored locations in Figure 8-1. The eight southeast sensors (walls 1-4) are compared to the two southwest sensors (wall 5 below vent) in Figure 8-2. Seasonal moisture contents of 15 to 20% were typically observed during the winter months with peaks up to 25% at one location.

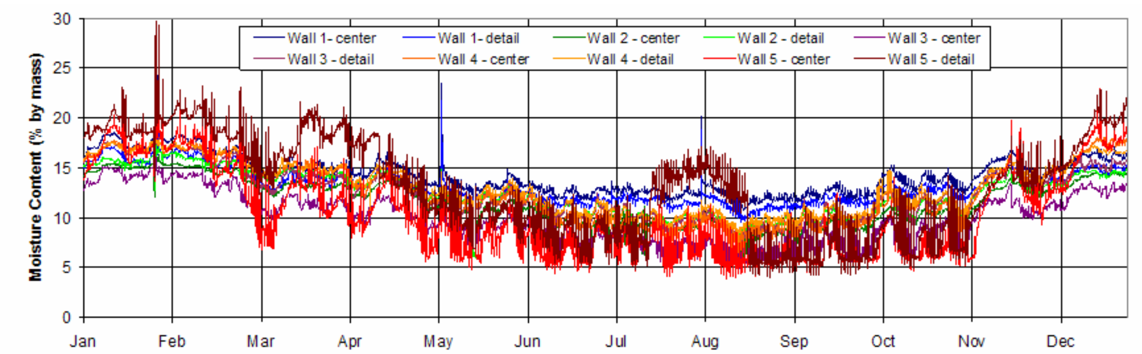


Figure 8-1: Building 1 – Sheathing Moisture Content 2002 Data – Walls 1-5

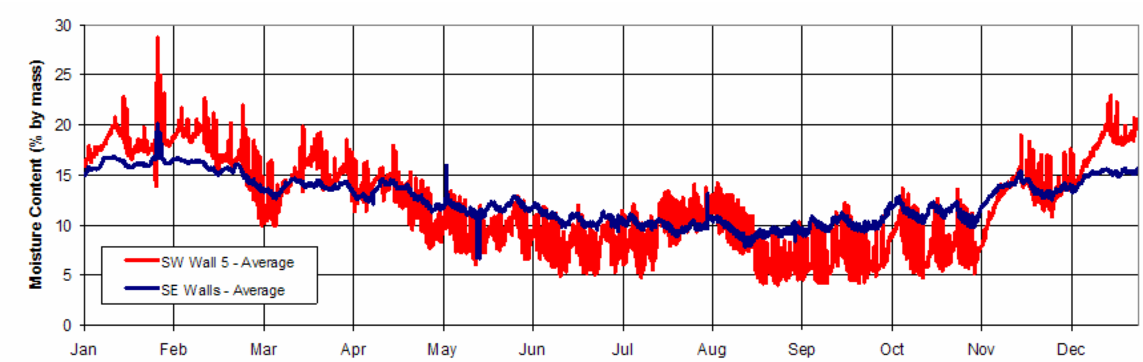


Figure 8-2: Building 1 - Sheathing Moisture Content 2002 Data – Southeast compared to Southwest Average Values

In the plots "detail" refers to moisture pins placed in the sheathing below details (window edge, balconies, vents) which could potentially introduce a leak and "center" refers to moisture pins placed well away from details between the strapping. Typically the readings are similar, which indicates that the as-built details are managing and shedding rainwater effectively in these buildings.

The ten wall locations follow similar trends (wetting and drying events) however a range in the moisture content is observed. Wall location 5 on the southwest shown higher variability and increased wintertime moisture levels than the four locations on the southeast. Variations accounted for location within the wall include, non homogenous plywood properties, varying cavity ventilation rates, and variance in the temperature of sheathing as a result of thermal bridging or solar radiation.

Moisture content of the wood strapping (19 mm x 38 mm borate treated lumber) follows similar trends of the sheathing however had lower observed moisture contents (Figure 8-3). The differences are possibly as a result of the borate treatment causing the moisture content to be calculated incorrectly or because of the reduce size and exposure to ventilation.

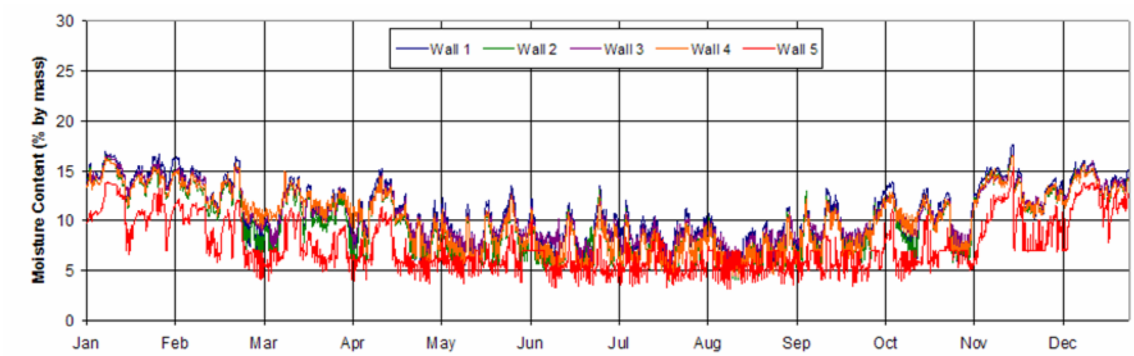


Figure 8-3: Building 1 – Wood Strapping Moisture Content, 2002 Data.

Moisture contents at the center of the sill plates was also monitored and observed to be much lower than the sheathing, rarely exceeding 10% during the winter months (Figure 8-4). This indicates that conditions within the center of the stud cavity are dry, and that wetting source is from the exterior.

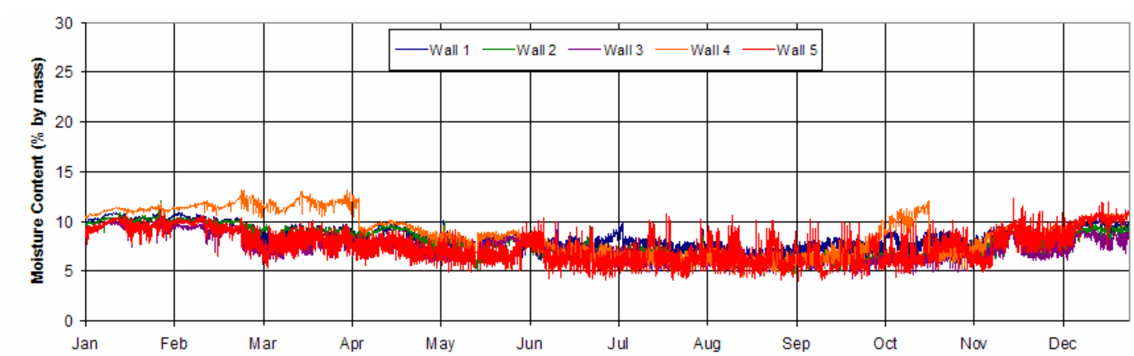


Figure 8-4: Building 1 – Stud Sill-plate Moisture Content, 2002 Data.

8.1.2 <u>Relative Humidity Levels</u>

While the moisture content of the wood sheathing generally remains below 20%, the relative humidity at the interior sheathing surface ranges from approximately 50% during the summer, and between 70-95% during the winter with events up to 100% indicating a potential for condensation on the exterior sheathing. Seasonal relative humidity trends at the backside of the sheathing are shown in Figure 8-5 with wintertime conditions from January 2002 in Figure 8-6.

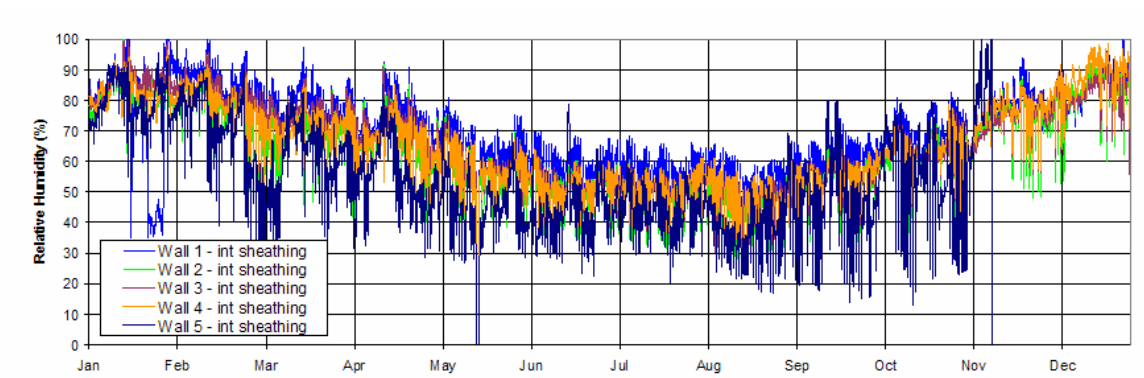


Figure 8-5: Building 1 – RH at Interior Surface of Sheathing, 2002 Data.

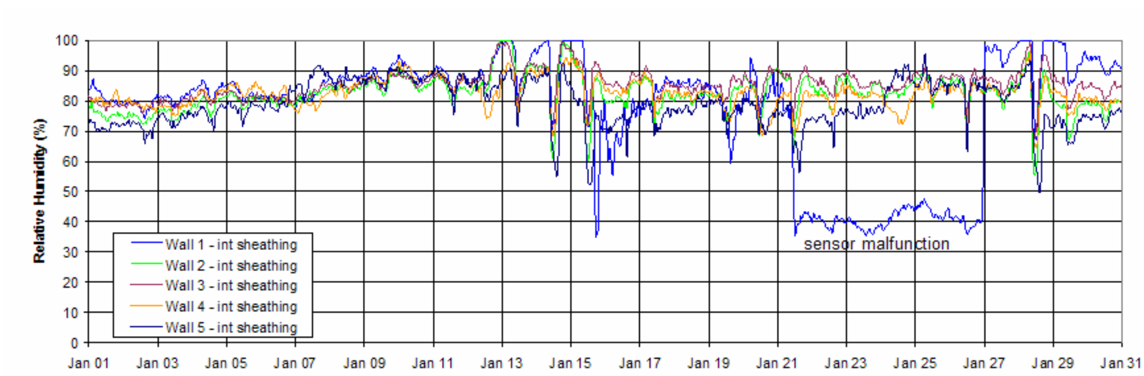


Figure 8-6: Building 1 – RH at Interior Surface of Sheathing, January 2002 Data

Relative humidity levels above 80% at the plywood sheathing and within the stud cavity are of potential concern for microbial growth, especially as it has been shown that the presence of liquid water from condensation rapidly increases the potential for mould growth (Black 2006).

8.1.3 <u>Impacts of Rainwater Leaks</u>

The wood sheathing moisture content during the winter is generally in the 15-20% range under the monitored conditions for Building 1 and the other two wood-frame buildings (discussed in the following sections). This provides very little safety factor in case of a rainwater leak or wintertime air-leakage condensation in these walls. During the winter, the drying potential is low and a rainwater leak or air leakage condensation event could further increase the moisture content of the sheathing to unsafe levels.

At only one wall location in the monitoring study was an observable leak detected by the sensors. The leak was noted in Building 1 below a bathroom exhaust vent (Figure 8-7) in January 2001 during the first winter after the sensors were installed. The moisture content of the sheathing was appreciably higher than other wall locations of the same building and ranged between 20-30% during January and February (Figure 8-8).

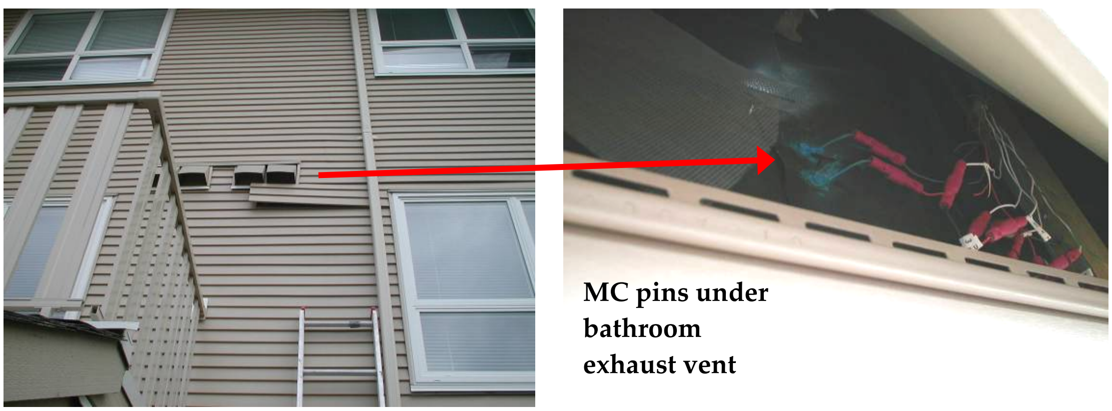


Figure 8-7: Location of Monitored Wall #5, Below Exhaust Vent

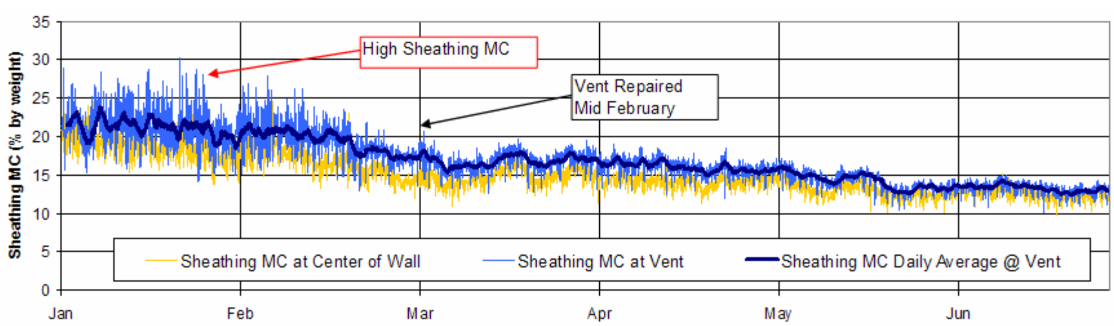


Figure 8-8: Building 1 – High Moisture Content at Bathroom Exhaust Vent (January to July 2001)

It appears that rain water leakage into the cavity at the corner of the vinyl J-trim combined with a reverse lapped building paper detail, contributed to the abnormally high moisture levels at this location. As a result of this monitoring project, repairs were made quickly in mid February to correct the detail before moisture damage could occur. In March, the moisture content dropped down to normal seasonal levels, similar to seasonal trends observed at the sensor in the center of the wall. No damage was observed at time of repair (however only a few months of wetting had occurred). Based on observations for this location as presented in Figure 8-1 and Figure 8-2 it appears that some moisture may still getting into the cavity at this location in 2002.

While only one leak was observed in the study, it provides information into the potential risks of leaks within the rainscreen cavity. Further testing where water is injected into the walls to simulate a leak should be performed and studied as part of this study and others in Vancouver to better understand the impact of rainwater leaks on rainscreen walls in this climate.

8.1.4 Sources of Moisture

Within the rainscreen clad walls, seasonal moisture fluctuations do not generally appear to correlate with rainwater leakage into the cavity (except where discussed), but rather from the relatively humid conditions within the ventilated cladding cavity. The cavity conditions typically follow exterior temperature and relative humidity levels, but are also influenced by solar radiation, cladding type and orientation. Typical ventilated cavity conditions are compared to the exterior (temperature and relative humidity) in Figure 8-9.

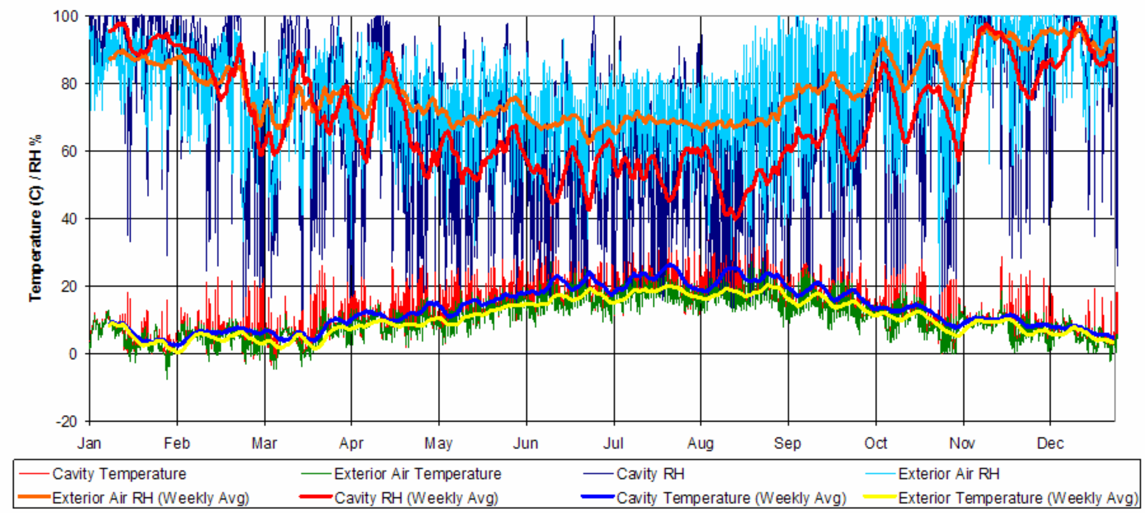


Figure 8-9: Building 1 – Exterior and Strapped Cavity Temperature and Relative Humidity – 2002 Data

Average RH and temperature within the strapped cavity during the wet winter months from October to March was 82% and 7.8°C (837 Pa) while the exterior was 85% and 6.2°C (810 Pa). On an annual average the vapour pressures of the exterior and strapped cavity was equal at 1015 Pa, however not on a monthly basis. Vapour pressures within the ventilated cavity were higher during the winter but lower in the summer months than the exterior.

The relative humidity within the ventilated cavities for walls 1 through 4 (Wall 5 sensor malfunctioned) is shown in Figure 8-10 for the entire year and in Figure 8-11 during January. Spikes in cavity temperature cause the RH to drop below 50% during the day when solar radiation heats the cavity space.

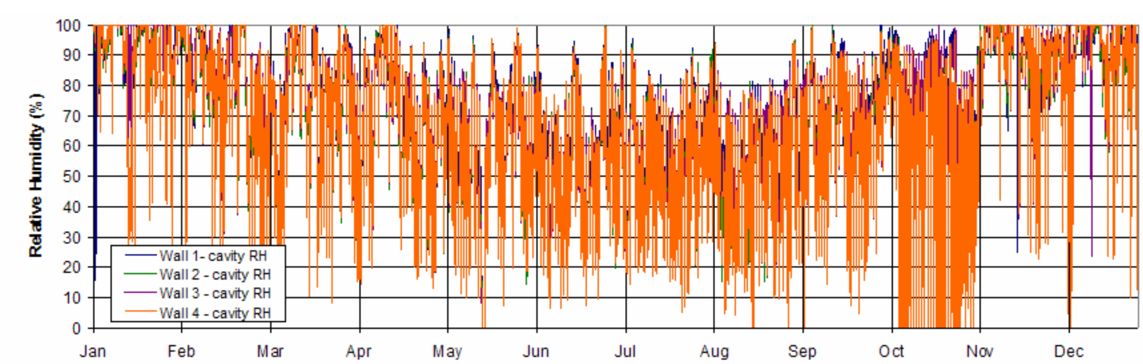


Figure 8-10: Building 1 - Relative Humidity within Ventilated Cavity – 2002 Data

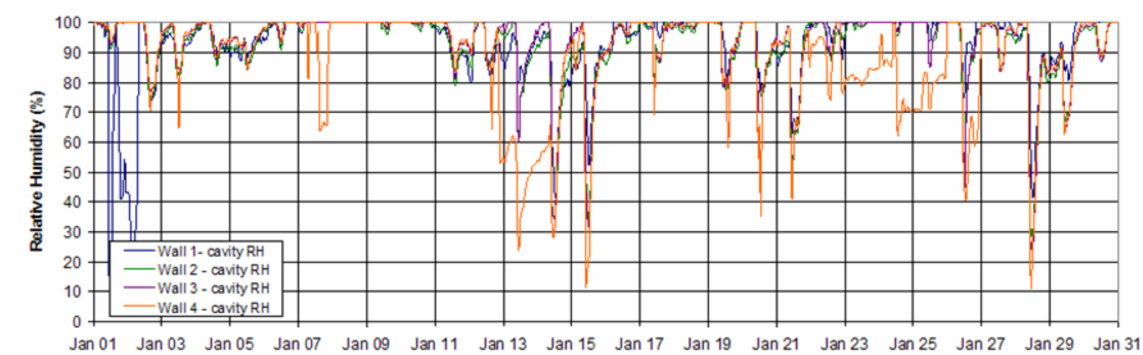


Figure 8-11: Building 1 - Relative Humidity within Ventilated Cavity – January 2002

Ventilation drying of the sheathing occurs as a result of the airflow within the airspace behind the cladding. Openings at the top and bottom of the wall, at floor height provide adequate volume of air flow to keep the cavity conditions close to the exterior. While ventilation is beneficial to remove excess moisture from the wall and cladding, the plywood is in equilibrium with 80-95% RH ventilation air, resulting in moisture contents of 15% to 25% during the winter. During the summer the RH is lower in the cavity and the plywood dries to moisture content levels corresponding to equilibrium with the lower RH.

To further highlight the impact of cavity relative humidity on the sheathing moisture content; rainfall, solar radiation, and cavity dewpoint/temperature are plotted against moisture content for January 2002 (Figure 8-12).

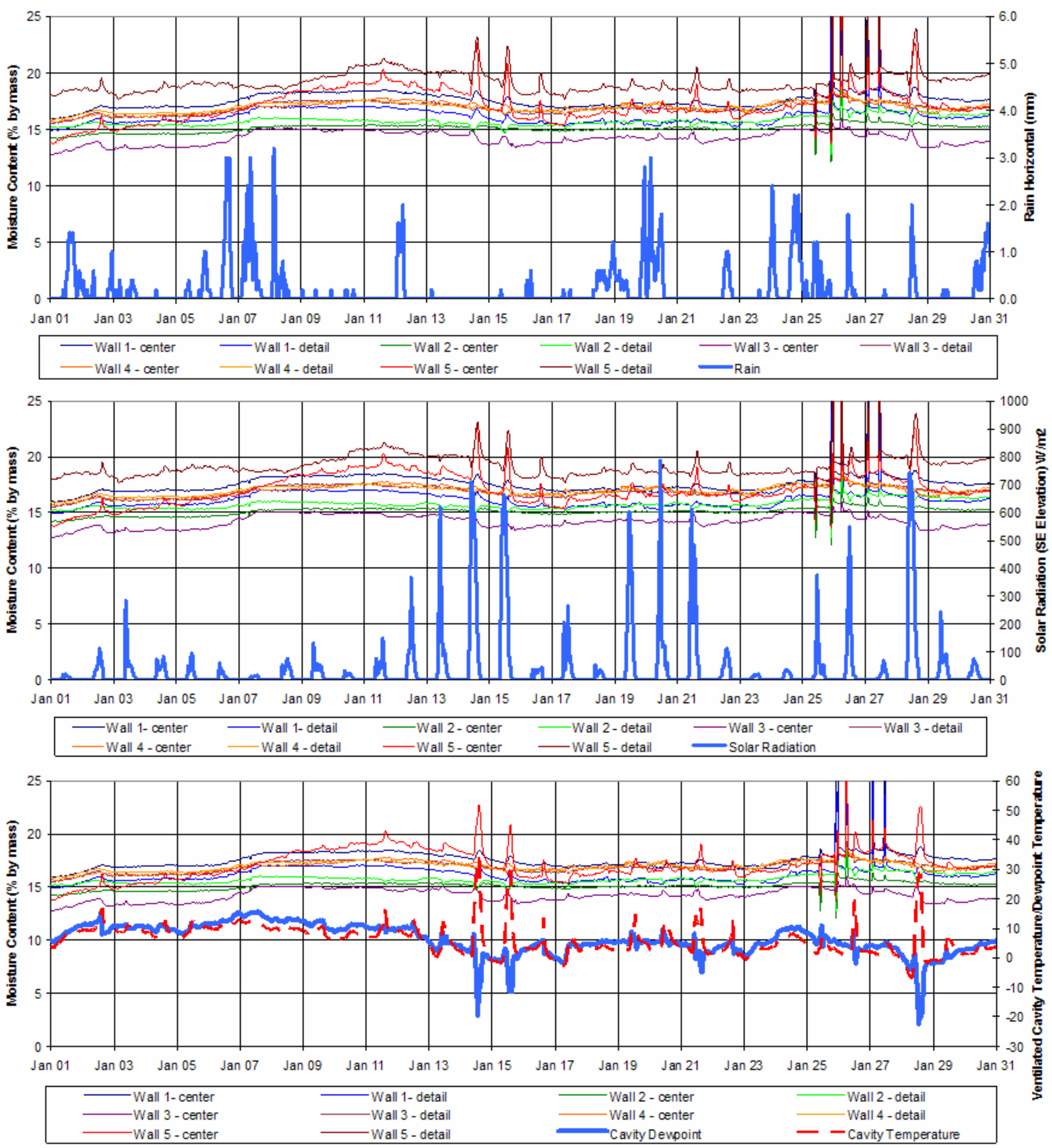


Figure 8-12: Building 1 - Impact of Rainfall, Solar Radiation, & Cavity Dewpoint on Sheathing Moisture Content

As shown, sheathing moisture increases do not correlate with rainfall events. Solar radiation heats the cladding and cavity space, which results in drying (result of increased ventilation and evaporation). The most significant influence however is the cavity relative humidity which is shown by the dewpoint and cavity temperature. When the relative humidity is near 100% (cavity temp = dewpoint) the moisture content increases. When the relative humidity drops (cavity temp > dewpoint) drying is observed. Large spikes in cavity temperature as a result of solar radiation results in immediate drying.

8.1.5 Vapour Pressure Analysis

Drying and wetting potentials are analyzed using vapour pressure gradients from Wall 1 of Building 1 for 2002. During the winter (Figure 8-13) interior vapour pressures are higher indoors, resulting in a vapour drive to the exterior. The vapour pressure in the ventilated cavity is also higher than the sheathing, resulting in a drive to the sheathing from the exterior. During the summer (Figure 8-14), vapour pressures at the sheathing are higher than the interior and cavity space, resulting in a vapour gradient both inwards and outwards. Drying to and wetting from the interior is however retarded by the polyethylene vapour barrier. Average interior suite conditions were 40% and 23°C for the winter and 40% and 25°C during the summer as discussed in Chapter 6.

Relatively small vapour pressure differences exist during the winter, compared to summer, when solar radiation heats up the wall assembly, resulting in a high sheathing temperature and subsequent large vapour pressures. These large vapour pressure gradients result in fast drying during the summer months.

Monthly average vapour pressure differences between the sheathing and the interior (diffusion to interior) and between the sheathing and cavity air space (diffusion to exterior) are plotted in Figure 8-15 for Wall 1 in Building 1 from 2002. Positive values indicate that the sheathing has a higher net vapour pressure than the interior suite and ventilated cavity space, and will result in drying, negative indicates the opposite and a net wetting will occur.

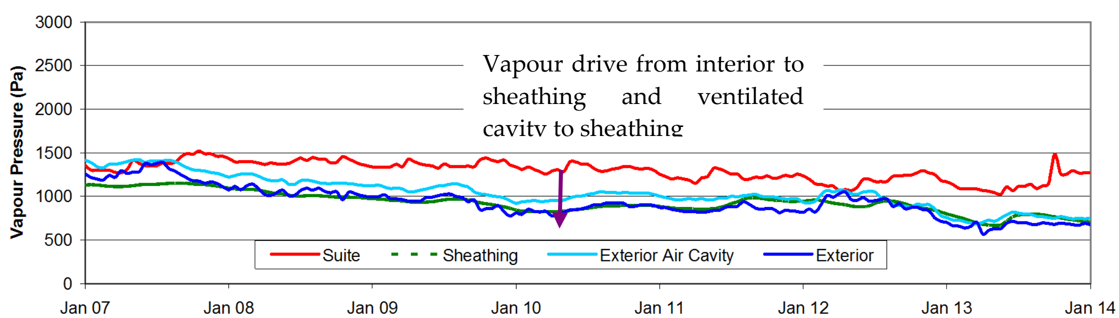


Figure 8-13: Building 1 – Vapour Pressure Gradient – January 7-14, 2002 (Typical Winter Conditions)

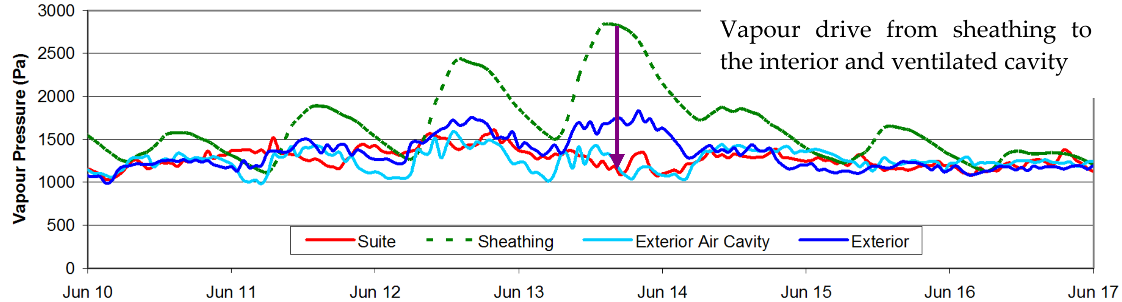


Figure 8-14: Building 1 – Vapour Pressure Gradient – June 10-17, 2002 (Typical Summer Conditions)

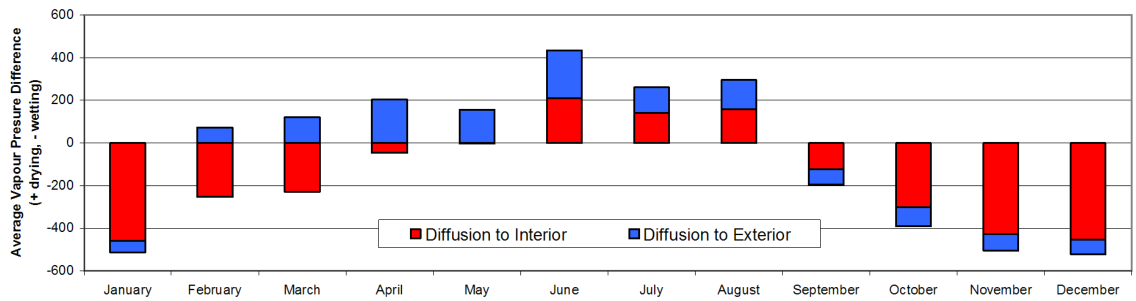


Figure 8-15: Building 1 – Monthly Vapour Pressure Differences from Sheathing to Interior and Exterior

The importance of interior vapour control from September to March is shown, when vapour diffusion drives would result in wetting. On the contrast, from April to August when vapour pressure differences are positive, the sheathing is able to dry by diffusion to both exterior and interior. However the ventilation provided by the rainscreen cladding overwhelms the diffusion drying to the exterior and the interior polyethylene prevents drying through to the interior.

Taking into account the vapour permeance of the wall assembly materials, the net vapour diffusion balance is calculated on a monthly basis (Figure 8-16). The net monthly diffusion balance is plotted against the monthly average moisture content of the sheathing to show that when vapour balance is negative the sheathing is accumulating moisture and when positive the sheathing is drying.

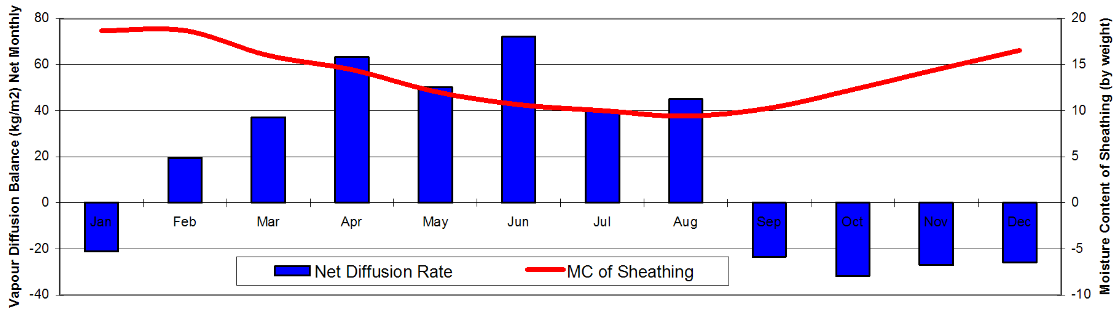


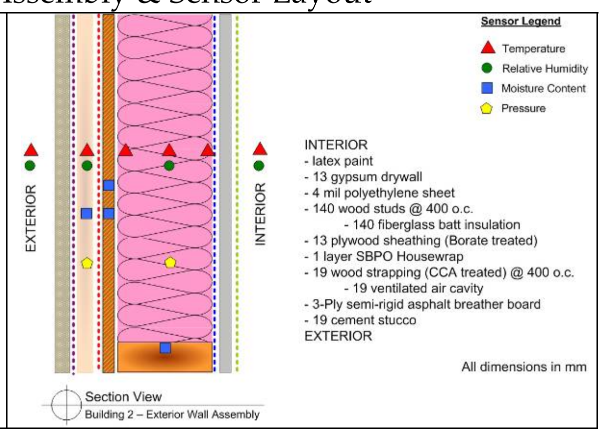
Figure 8-16: Building 1 – Monthly Vapour Flow Compared to Sheathing Moisture Content

An analysis of net vapour pressure gradients indicates diffusion flow wetted the sheathing from September to March and dried the sheathing from April to August. The monthly average vapour pressure gradients as shown are higher on average during the winter, indicating that interior vapour control is required for this wall assembly in this climate to prevent additional wetting from the interior.

8.2 BUILDING 2

The measured performance of the stucco clad rainscreen walls of Building 2 is presented. For reference the sensor layout and wall assembly is shown in Table 8-2.

Table 8-2: Summary of Building 2 Wall Assembly & Sensor Layout



8.2.1 <u>Moisture Content</u>

Moisture content data is presented for Building 2 from January 2002 to 2003 for the ten monitored locations in Figure 8-17. The eight east sensors (walls 1-4) are compared to the two south sensors (wall 5 balcony interface at fireplace) in Figure 8-18. Seasonal moisture contents of 15 to 20% were typically observed during the winter months with significantly lower levels at Wall 5 (discussed later).

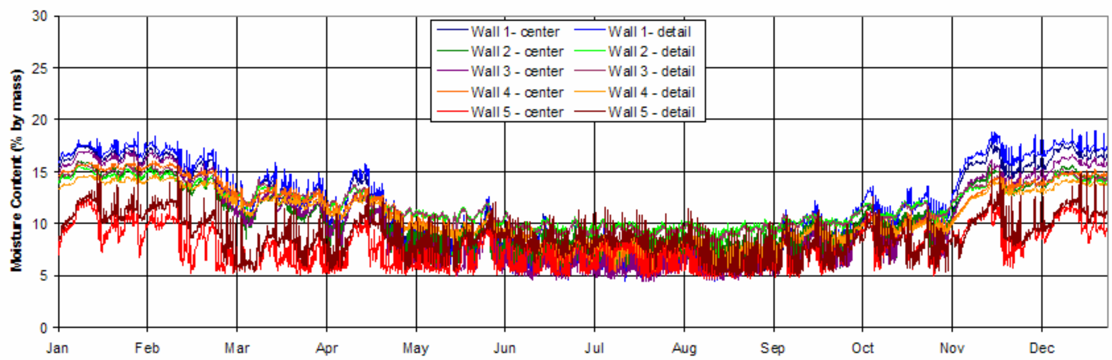


Figure 8-17: Building 2 – Sheathing Moisture Content 2002 Data – Walls 1-5

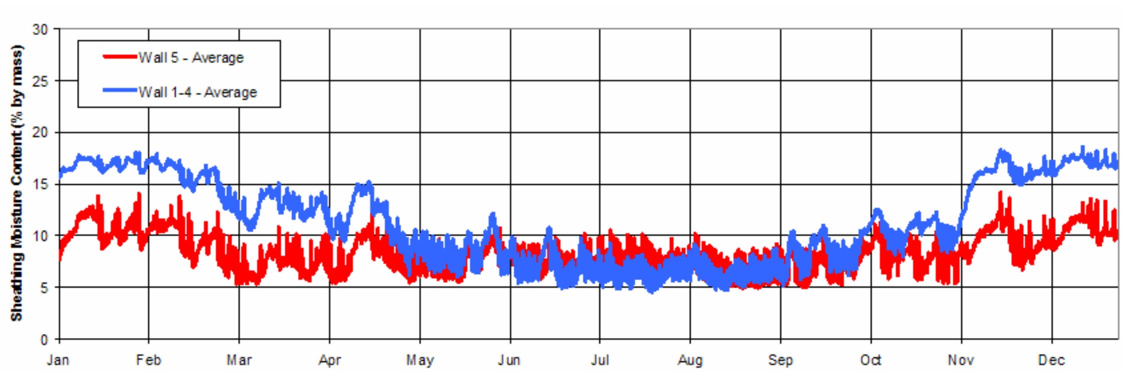


Figure 8-18: Building 1 – Sheathing Moisture Content 2002 Data – Walls 1-4 compared to Wall 5

The moisture content anomaly at Wall 5 is further discussed in Section 8.2.3.

Similar to Building 1, the seasonal wetting trend observed during the late-fall was as a result of high relative humidity within the ventilated cavity. The cavity temperature and dewpoint temperature are compared to the moisture content and shown in Figure 8-19.

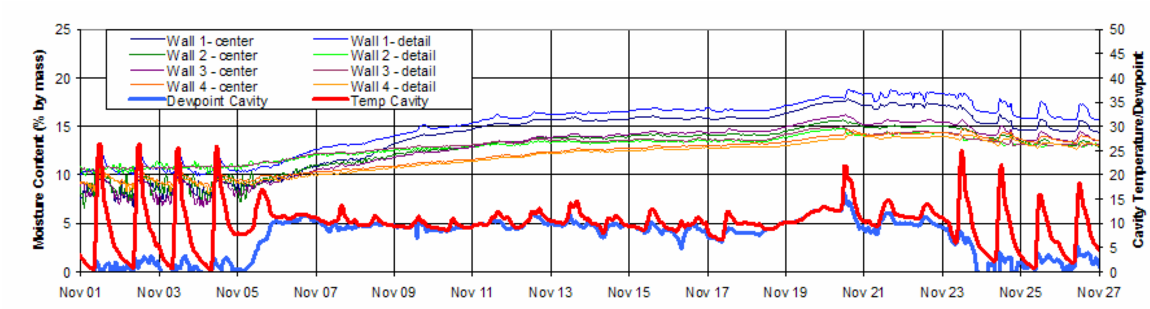


Figure 8-19: Building 2 – Impact of Cavity Relative Humidity on Moisture Content

Buildings 1 and 2 had very similar performance throughout the monitoring project and are compared in Figure 8-20 from 2002.

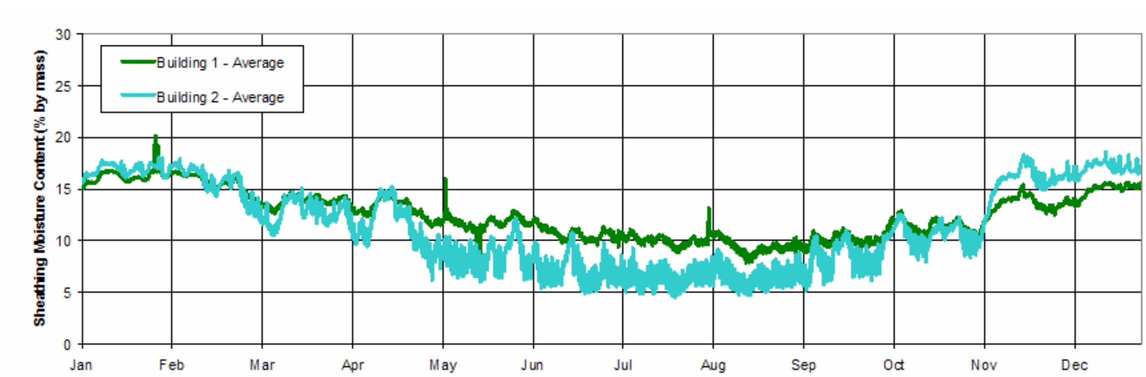


Figure 8-20: Comparison of Average Sheathing Moisture Contents for Buildings 1 & 2, 2002 Data

8.2.2 Relative Humidity Levels

The relative humidity within the ventilated cavities for walls 1 through 4 (wall 5 is discussed later) is shown in Figure 8-21 from January 2002-2003 and in Figure 8-22 for January 2002.

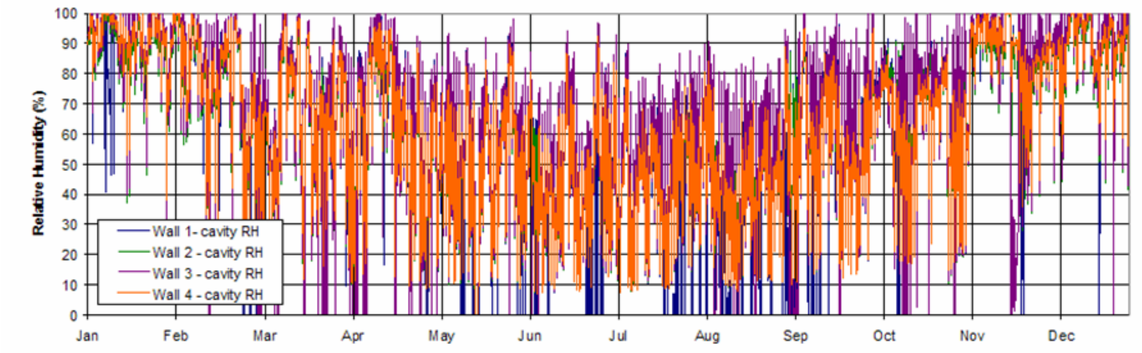


Figure 8-21: Building 2 – RH in Ventilated Cavity, 2002 Trends

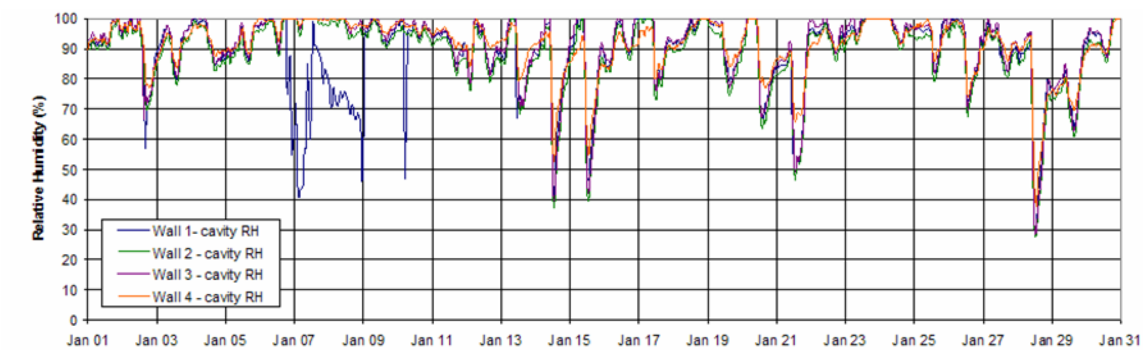


Figure 8-22: Building 2 – RH in Ventilated Cavity, January 2002

While the moisture content of the wood sheathing generally remains below 20%, the relative humidity at the interior sheathing surface ranges from approximately 50% during the summer, and between 70-90% during the winter. Seasonal relative humidity trends at the backside of the sheathing are shown in Figure 8-23 and it should be noted that that conditions were drier than at Building 1.

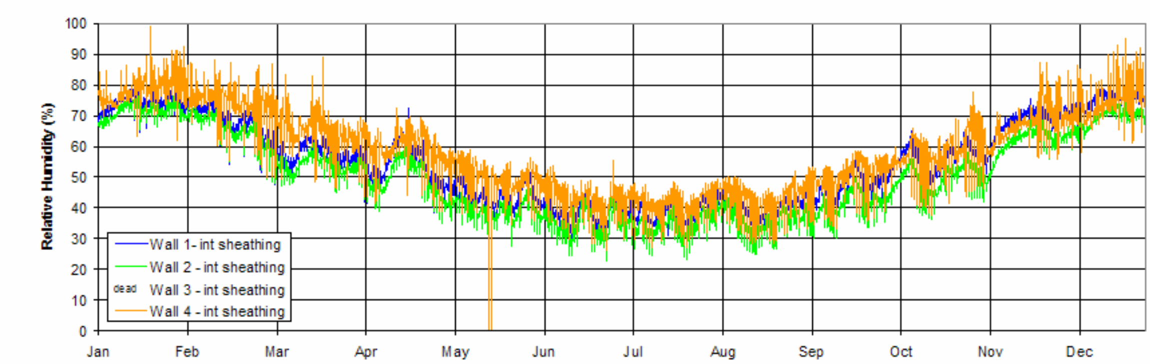


Figure 8-23: Building 2 – Relative at Interior Side of Sheathing, 2002 data

8.2.3 Wall Location 5 - Thermal Anomaly

At monitored wall location 5 on the south elevation, consistently drier moisture contents were observed at the two sheathing sensors over the four years of monitoring (Figure 8-24).

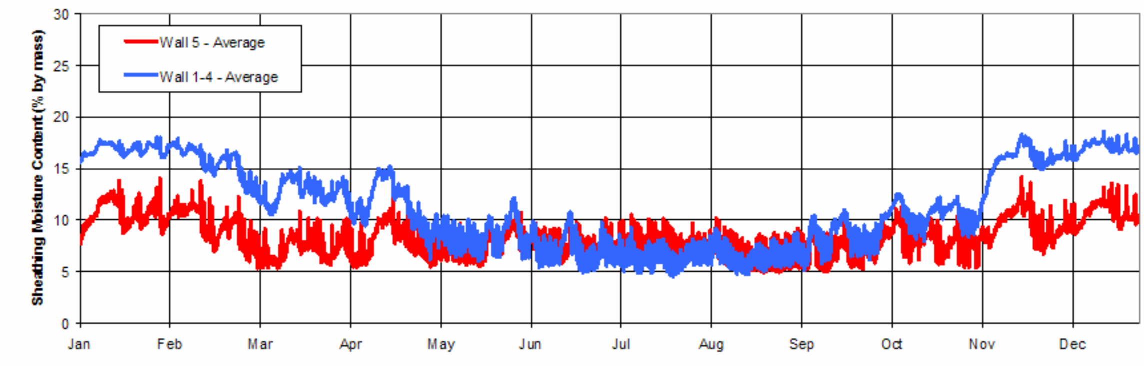


Figure 8-24: Building 2 – 2002, Difference between Sheathing MC at Walls 1-4 and Wall 5

Initially it was thought that the sensor was returning bad data, however upon a closer analysis of the data it was found that very high temperatures (40-50°C) were consistently observed throughout the wall assembly. Reviewing the monitored wall location during a field visit found the sensors to be located directly in-line with the gas fireplace and four-storey chimney which runs up the edge of the suite (Figure 8-25).

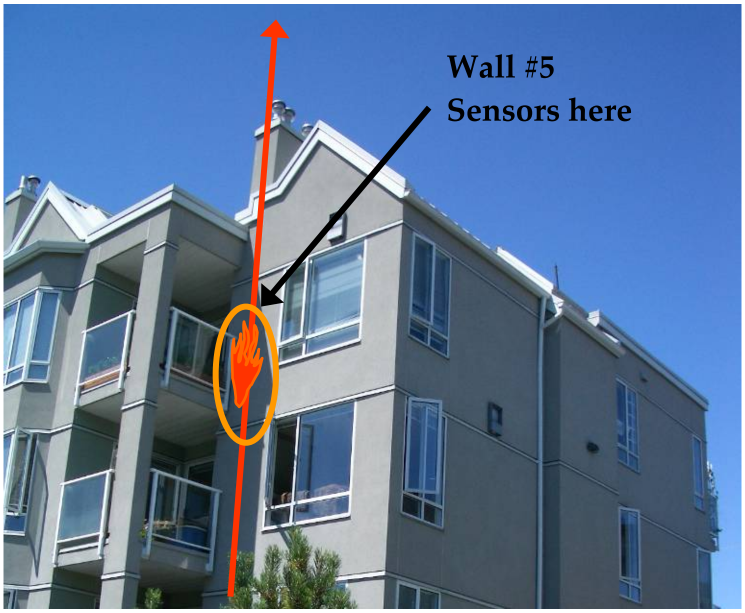


Figure 8-25: Location of Wall Assembly #5 on South at Fireplace Chimney.

While it appears that the sensor placement was accidental as performed from the exterior and attempting to capture the influence of the balcony interface, it does provide some interesting data for analysis.

The suites within the building are heated using electrical baseboard heaters and a gas-fireplace. Both can be controlled using a thermostat. While the suite temperature set-point may be 20-25°C, the fireplace obviously gets much hotter. Refer to Chapters 6 & 7 for a discussion of the interior conditions of suite 401. As the wall sensors were located in the wall to the outside of the insulated fireplace, heat from the fireplace heated the wall assembly daily. The daily trends are shown in Figure 8-26 for January 2002 when the fireplace was used every day and in Figure 8-27 during late May when the fireplace was used less frequently as exterior temperatures were high enough to not require indoor heating.

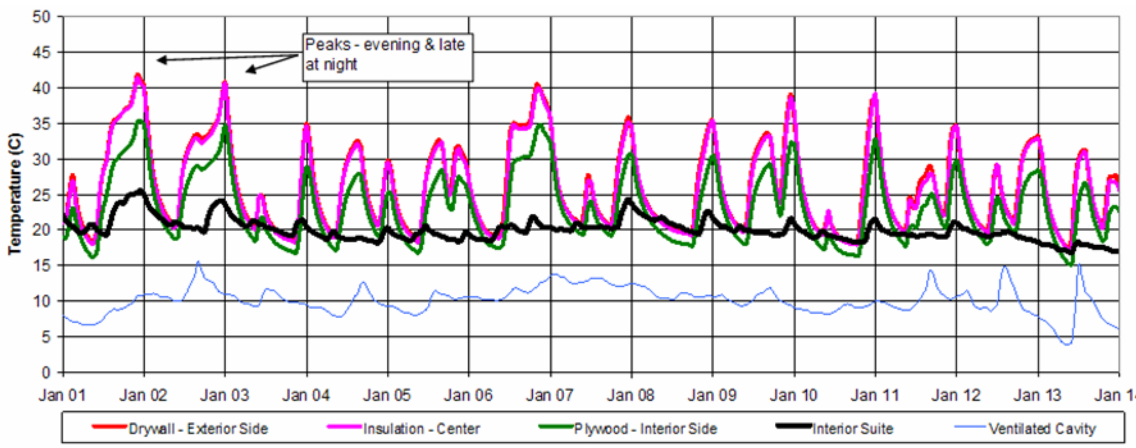


Figure 8-26: Building 2 – Wall 5 – Temperatures through Wall – Winter

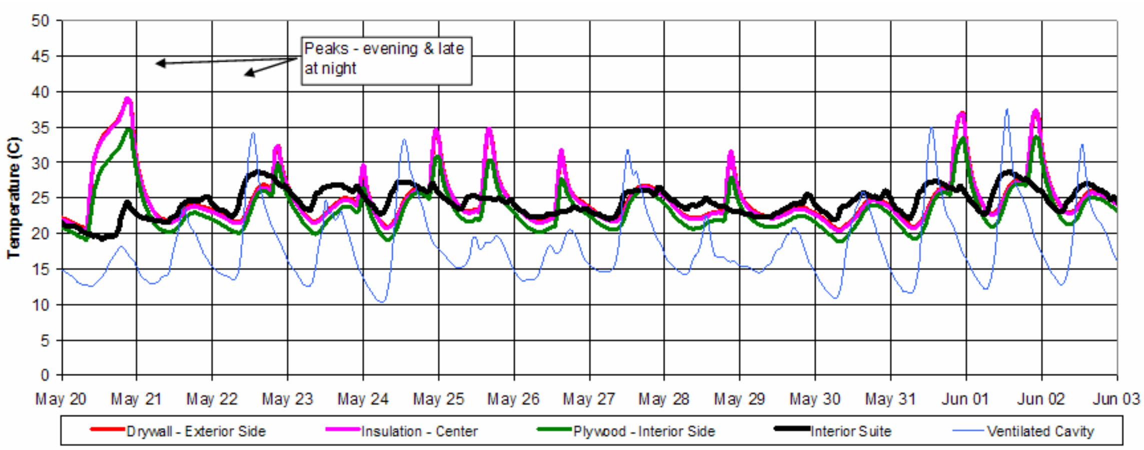


Figure 8-27: Building 2 – Wall 5 – Temperatures through Wall – Late Spring

The data indicates that it may be possible to dry exterior walls should a accidental rainwater or pipe leak occur by heating the interior of the suite between 30-40°C. While not recommended for extended periods of time or normal application, in post-disaster repair situations could prove to be useful. Potentially even during construction, after closing in the wall assembly, the interior could be heated for several days to drive off excess stud and sheathing moisture.

8.2.4 Wall Location 4 – Effect of Rainwater Leaks on Strapping

The moisture content of the wood strapping (19 mm x 38 mm borate treated lumber) follows similar trends of the sheathing with moisture contents between 10-15% during the winter months (Figure 8-28). Wall 5 moisture levels were lower during the winter months for reasons discussed in the previous section. While wall locations 1-3 had similar performance, an anomaly in the data was observed at wall location 4 in November 2002 following two weeks of rain.

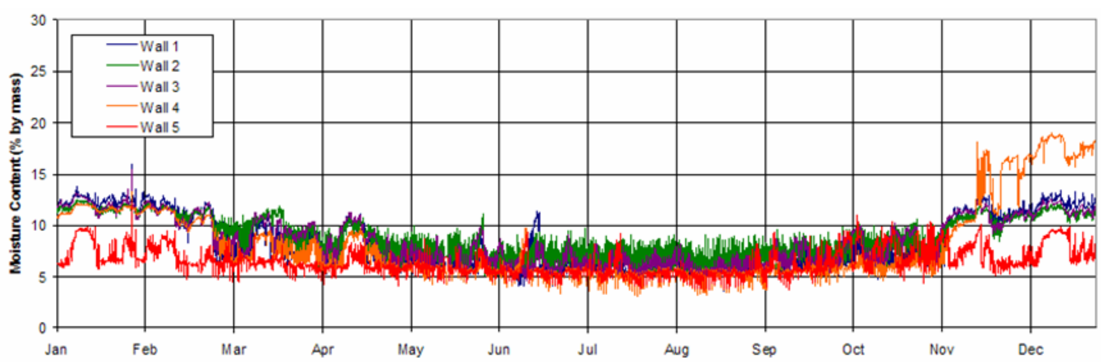


Figure 8-28: Building 2 – Strapping Moisture Content - 2002

As shown in Figure 8-29, the sheathing and strapping followed consistent seasonal trends until November 19th during a particularly large rain event when the strapping moisture content increased suddenly. The jump in moisture content occurs during a very large rain storm (90 mm of rain measured at the roof in 48 hours). It appears that some rainwater was able to penetrate the cladding below the corner of the window. The water then appears to have contacted the strapping and pushed the moisture content above seasonal normals (while still remaining below 20%). The sheathing was unaffected by the rainwater leak into the cavity, presumably protected by the water resistive barrier.

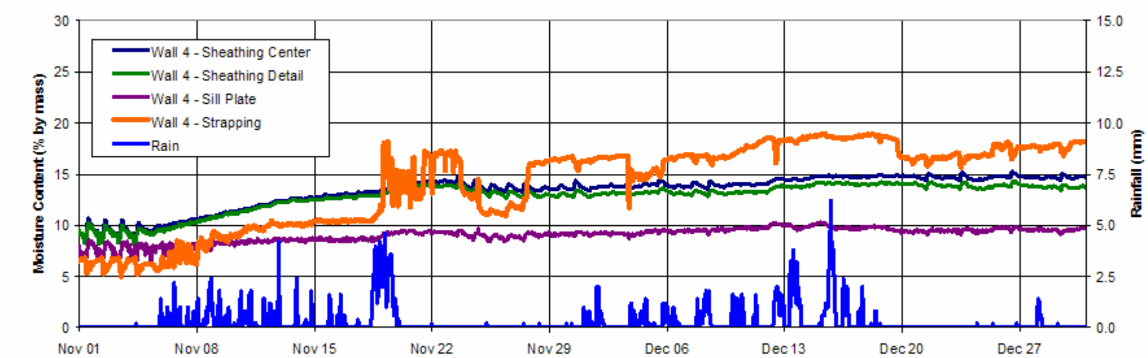


Figure 8-29: Building 2, Wall 4 – Moisture Content of Components Compared to Rainfall

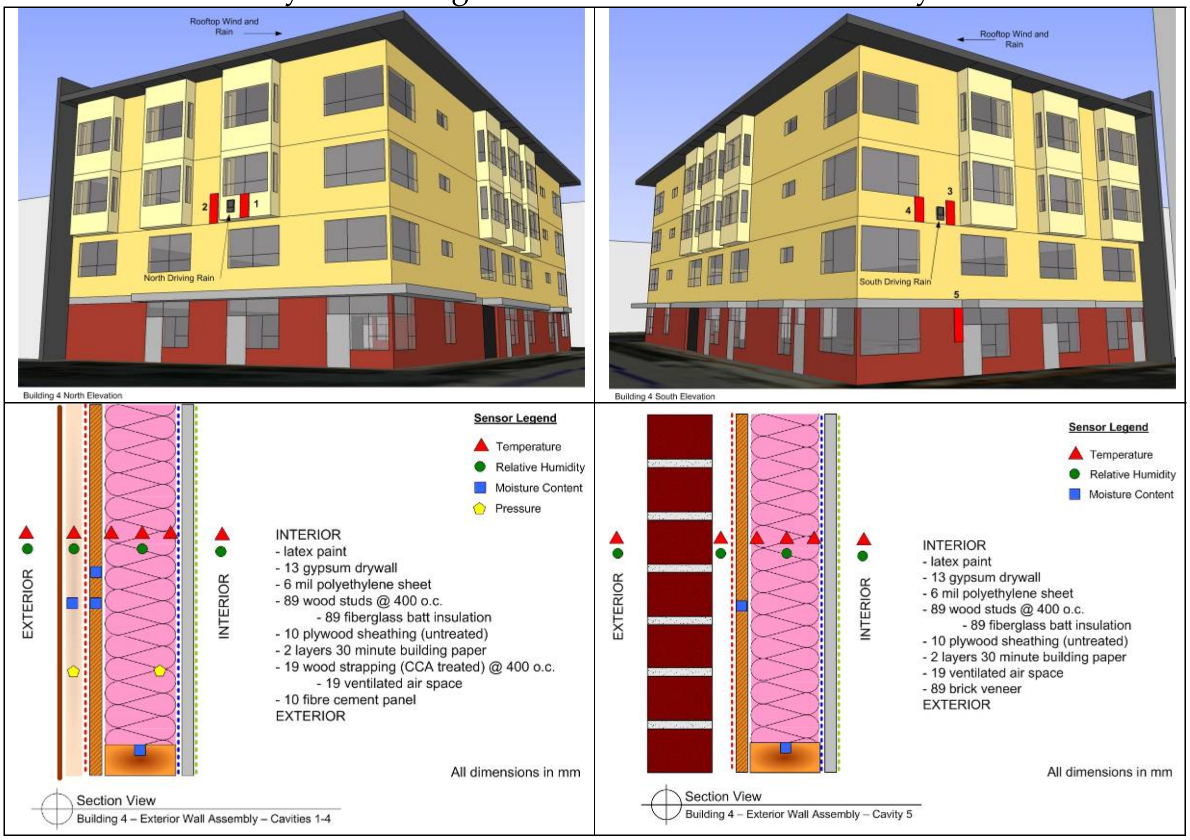
The moisture content of the strapping remained elevated beyond normal between 15-20% for the remainder of the winter and finally dried to normal levels in spring of 2003.

This data indicates that rain-water penetration into rainscreen cavities does happen in the field, and in this event occurred during a very large rain event (90 mm) below the corner of window. The leak came into contact with the vertical wood strapping, was absorbed, and increased the moisture content from 10% to 18% within one-day. The strapping remained at this elevated level throughout the winter (above normal levels for strapping) and eventually dried to seasonal normal levels during the spring.

8.3 <u>BUILDING 4</u>

The measured performance of the cement board rainscreen and brick veneer walls of Building 4 is presented. For reference the sensor layout and wall assembly is shown in Table 8-3.

Table 8-3: Summary of Building 4 Wall Assemblies & Sensor Layout



8.3.1 Moisture Content

Moisture content data is presented for Building 4 from January 2003 to 2004 in Figure 8-30 presenting averages from: all walls (1-5), north walls (1&2), south walls (3&4), and the south brick wall (wall 5). The south wall sensors are compared to the north wall sensors in Figure 8-31. Seasonal moisture contents of 15 to 20% were typically observed during the winter months, similar to Buildings 1 and 2.

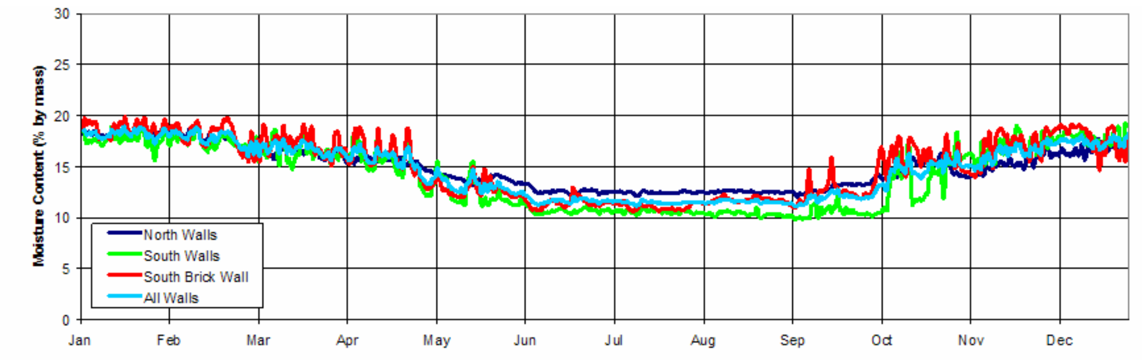


Figure 8-30: Building 4 – Sheathing Moisture Content 2003 Data – Average for All Walls

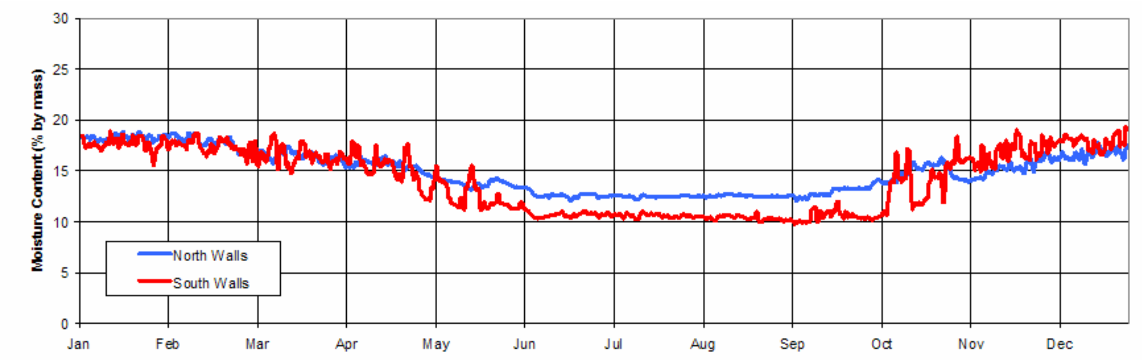


Figure 8-31: Building 4 – Sheathing Moisture Content 2003 Data – North versus South Walls

At the brick veneer at the ground level of Building 4, slightly higher sheathing moisture contents were observed than at the walls, potentially as a result of reduced cavity ventilation behind the absorptive brick veneer. As the brick veneer say very little driving rain, moisture contents were relatively low, but could potentially have been higher with more rain exposure.

The south walls also remained drier than the north walls during the summer months, likely as a result of solar heating drying the sheathing.

The strapping also followed similar trends as the sheathing as shown in Figure 8-32.

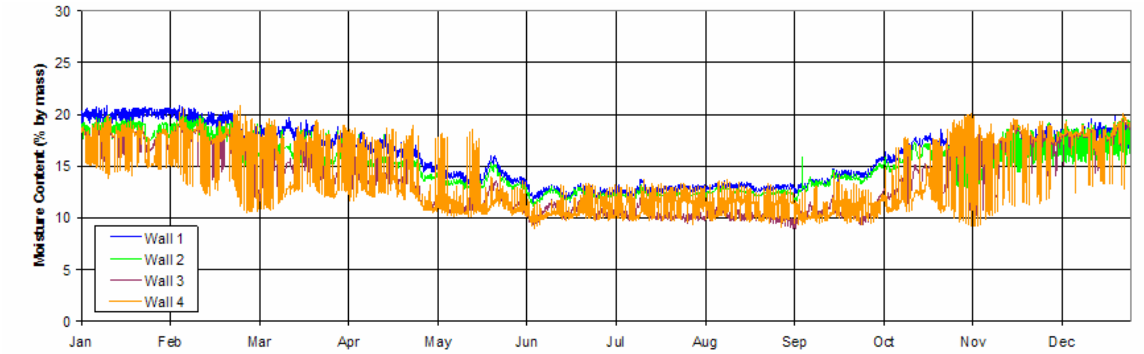


Figure 8-32: Building 4 – Wood Strapping Moisture Content, 2003 Data.

8.3.2 Relative Humidity

The relative humidity within the ventilated cavities for walls 1 through 5 is shown in Figure 8-33 from January 2003-2004.

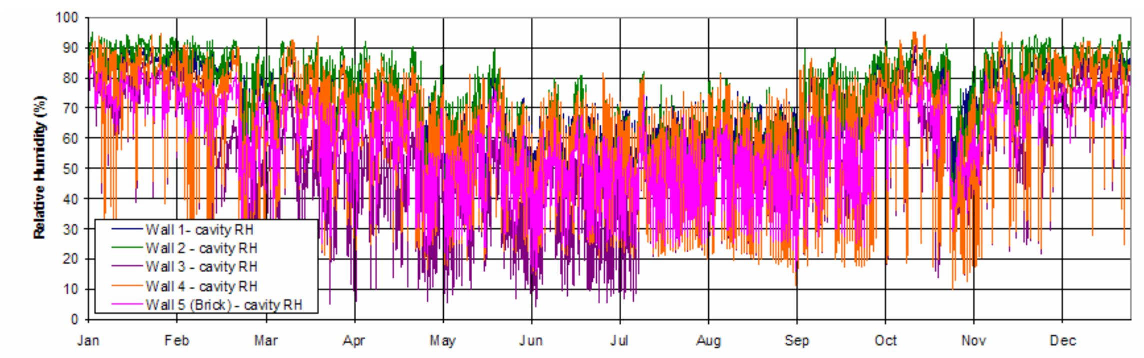


Figure 8-33: Building 4 – Relative Humidity within Ventilated Cavity

No appreciable difference was noticed between the cement board and brick veneer, again likely as a result of the very low driving rain observed on either of the claddings.

The relative humidity at the interior sheathing surface of the sheathing ranges from approximately 40-50% during the summer, and between 60-80% during the winter (Figure 8-34). It should be noted that that conditions were drier than at Buildings 1 or 2.

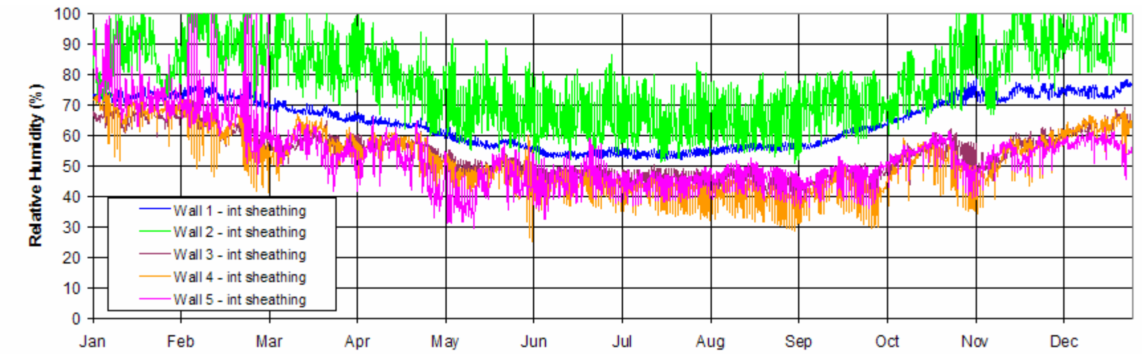


Figure 8-34: Building 4 – Relative Humidity at Interior of Sheathing

8.4 CONCLUSIONS & DISCUSSION OF PERFORMANCE

Similar seasonal moisture trends were observed across the three rainscreen building during the five years of monitoring. A typical year is shown in Figure 8-35 highlighting the wetting and drying events further discussed in Figure 8-36 and Figure 8-37.

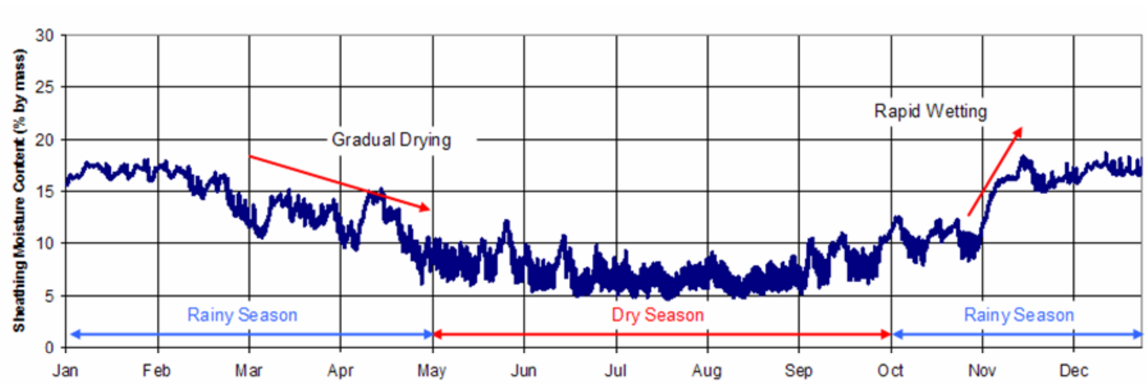


Figure 8-35: Sheathing Wetting & Drying Trends for the 3 Wood-frame Buildings

During the summer months the sheathing moisture content ranged between 5-10% depending on the relative humidity within the ventilated cavity. In late fall at the start of Vancouver's rainy season the sheathing moisture content increased up to 15-20% within a few weeks as the cavity RH increases up to 80-100%. The sheathing moisture content fluctuates during the winter months however remains at levels below 20% on average. Peaks up to 25% MC were observed at a few wetter locations. In the spring when the rainfall largely stops and sun comes out for extended periods, the walls dry back down to 5-10% MC.

The seasonal wetting trend is highlighted in Figure 8-36, showing the influence of rainfall, solar radiation, and cavity dewpoint/relative humidity.

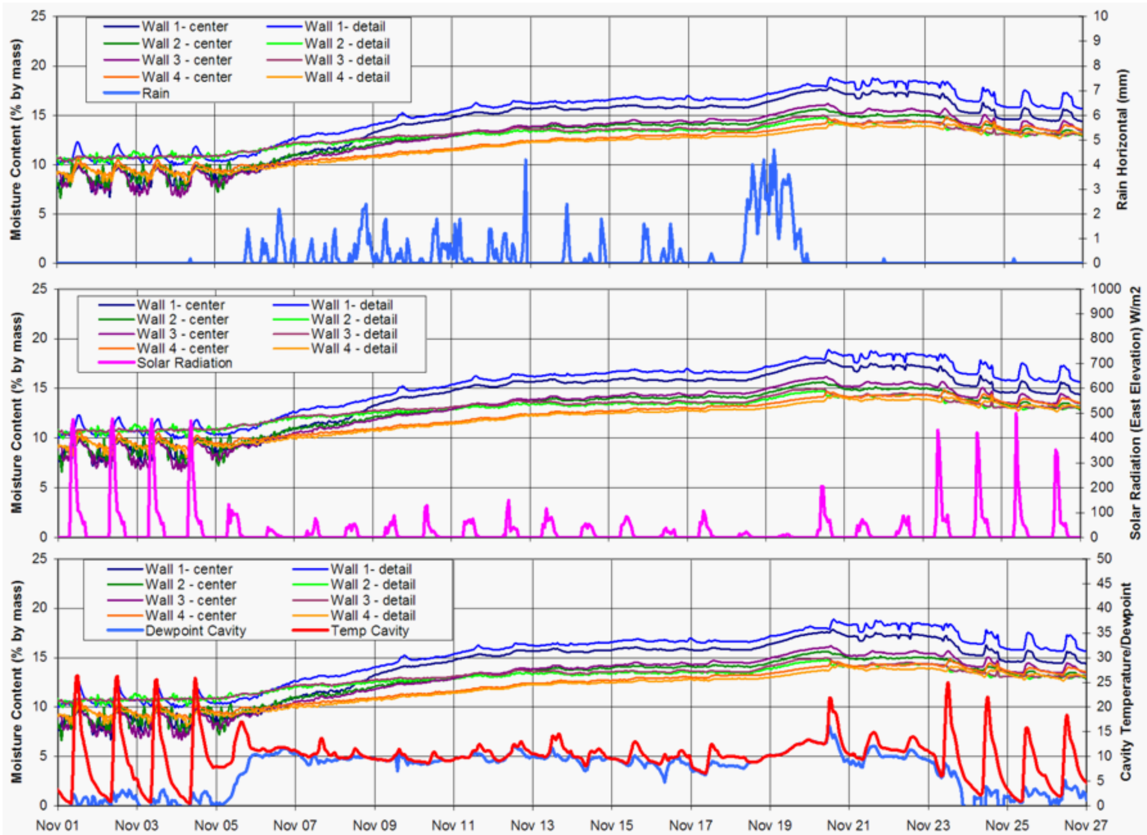


Figure 8-36: Seasonal Sheathing Wetting Trend for Buildings 1, 2, & 4

While raining during the moisture increase, the rain does not directly impact the sheathing moisture content. However during rainy weather the relative humidity outdoors is at 100%. The reduced cavity temperature and solar heating results in the relative humidity within the cavity space to be near outdoor conditions. As a result, the sheathing moisture content increases to reach equilibrium with the relative humidity within the cavity (between 80-90% on average). If the relative humidity drops (over a daily average), the sheathing moisture content also drops.

The spring drying trend is highlighted in Figure 8-37, showing the strong influence of solar radiation on the cavity temperatures which reduces the relative humidity within the space and dries the sheathing. Cavity temperatures of up to 40-50°C result in evaporation of moisture from the sheathing which is subsequently carried away by ventilation flow.

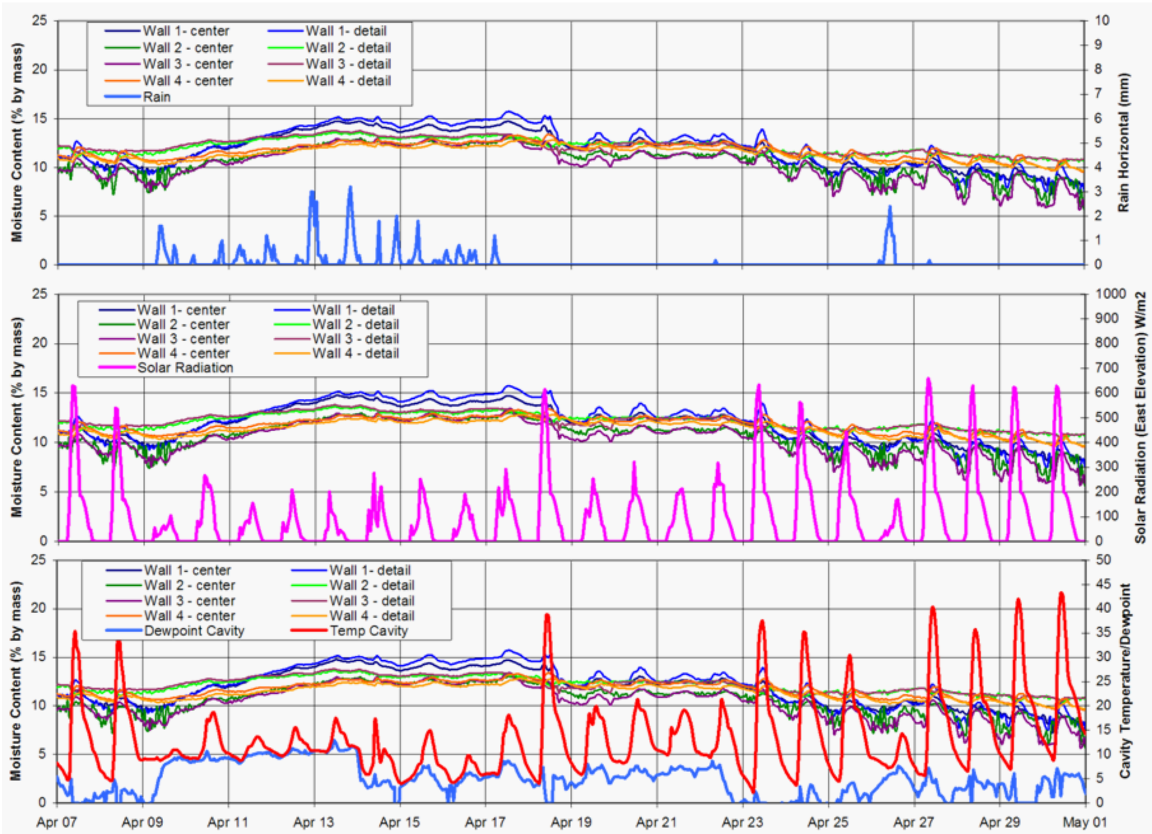


Figure 8-37: Seasonal Sheathing Drying Trend for Buildings 1, 2, & 4

All three buildings, regardless of cladding type and driving rain exposure had similar seasonal performance. The brick veneer at Building 4 had a slightly higher average moisture content, potentially as a result of the absorptive cladding and reduced ventilation drying. In no cases were moisture contents elevated for periods long enough to sustain damage (i.e. above fiber saturation). However, the relative humidity within the ventilated cavity and at the inside face of the sheathing was at levels between 80-100% RH for several months during the winter at all monitored locations. The implication of the high relative humidity levels observed on microbial growth is uncertain.

Two separate rainwater leaks were observed in the measured data and further analyzed. The first leak occurred at Building 1 and impacted the moisture content of the plywood sheathing. The leak occurred at a reverse lapped building paper detail at a vent penetration in 2001, during the first winter of monitoring. As a result of the monitoring project observations, the leak was investigated and repaired to address the water penetration issue. The observations showed that while the leak was likely small, it was able to raise the sheathing moisture content up to 30% during the winter months. It also showed that rainscreen walls are not immune to leaks, and that ventilation alone during the winter months could not reduce the moisture content down to safe levels (<20% MC).

The second leak occurred at Building 2, into the rainscreen cavity below a window corner. The leak occurred during a very large rain event (90 mm measured at the roof in 48 hours) where liquid water came into contact with the vertical wood strapping, was absorbed, and increased the moisture content from 10% to 18% within a few days. The strapping remained at this elevated level throughout the winter (above normal levels for strapping) and eventually dried to normal seasonal levels during the spring. This observation showed that leaks into the strapped cavity can happen; however the water resistive barrier prevented the sheathing from being wetted. After the moisture content was increased, the strapping remained at levels above normal (for strapping) for the remainder of the winter months.

When performing condition assessments of wood-frame buildings in Vancouver, the investigator should be aware of the normal seasonal sheathing moisture contents. Moisture contents between 15 to 20% during the wet and rainy months from October to May are observed to be normal. Moisture contents of up to 25% may also be observed, however if moisture levels above 25-30% are observed, additional investigation should be performed as an additional moisture source is likely present (rainwater leaks, air leakage condensation etc).

While the performance of wood-frame rainscreen walls appears to be better than the face-sealed or concealed-barrier approaches used in the past, sheathing moisture levels are bordering safe limits. The sheathing moisture content was observed up to 20-25% for up to 6 months during the winter, and the relative humidity levels at the ventilated cavity and interior of the sheathing may be of concern between 80-90% for several months.

Evidence also suggests that rainwater leaks may still be able to cause damage to the sheathing and therefore further improvements to the wall assembly should be investigated to reduce wetting events and improve the drying performance of interior insulated rainscreen wall assemblies.

9 MEASURED STEEL-STUD/GYPSUM RAINSCREEN WALL PERFORMANCE

This chapter presents the measured wall performance of Buildings 3 and 5. The walls constructed at Buildings 3 and 5 consist of a partially or fully exterior-insulated assembly with an impermeable air/vapour/moisture barrier applied over the gypsum sheathing. As the moisture sensitive components are protected from the exterior environment (both thermally and from moisture), these loads have less an impact on the wall performance. Instead, the interior conditions play a significant role on wall performance.

As presented in Chapter 6, the interior boundary conditions vary widely across the five buildings, and in Building 3 were shown to be exceptionally humid during the winter months. The influence air-tightness on interior humidity and moisture damage at Building 3 was further discussed in Chapter 7. The impact of those parameters on the performance of the exterior walls is discussed here.

The performance of a steel-stud and gypsum sheathed wall assembly can be analyzed using the temperature, relative humidity, gypsum sheathing moisture content, and relative wetness measurements. The performance of the wall can be judged on the basis of its balance of wetting, drying, and safe storage. Extended periods of time with elevated moisture levels or high relative humidity at moisture sensitive materials can cause deterioration and possibly long-term failure of the wall assembly.

As discussed in *Appendix A: Exterior Gypsum Sheathing*, a significant reduction in the strength of gypsum sheathing is observed with as little as 1% moisture content. Published sorption isotherms for gypsum sheathing indicate that when exposed to relative humidity levels between 85% and 90% an equilibrium moisture content of 1% is attained. Prolonged exposure to 95%-100% RH can lead to much higher moisture contents (>2%) and at a rapid rate. Refer to the Appendix for a further discussion of the humidified properties of gypsum sheathing and the moisture content-electrical resistance correlation developed for use with the collected data from Buildings 3 and 5.

9.1 BUILDING 3

A background of the construction of Building 3 is presented, followed by a discussion of the monitored wall performance and results of the exploratory field openings.

9.1.1 Background

Observations from Building 3 indicate high moisture levels within the stud cavities at all eight monitored wall locations. As will be shown the systemic moisture issue is not as a result of exterior rainwater leaks, but as a result of a sensitive wall assembly exposed to a high humidity interior environment. The wall assembly is sensitive as it is a split-insulated system with an impermeable layer between the two insulation layers (Figure 9-1), which depresses the sheathing temperature and exposes it to condensation from interior air leakage or vapour diffusion.

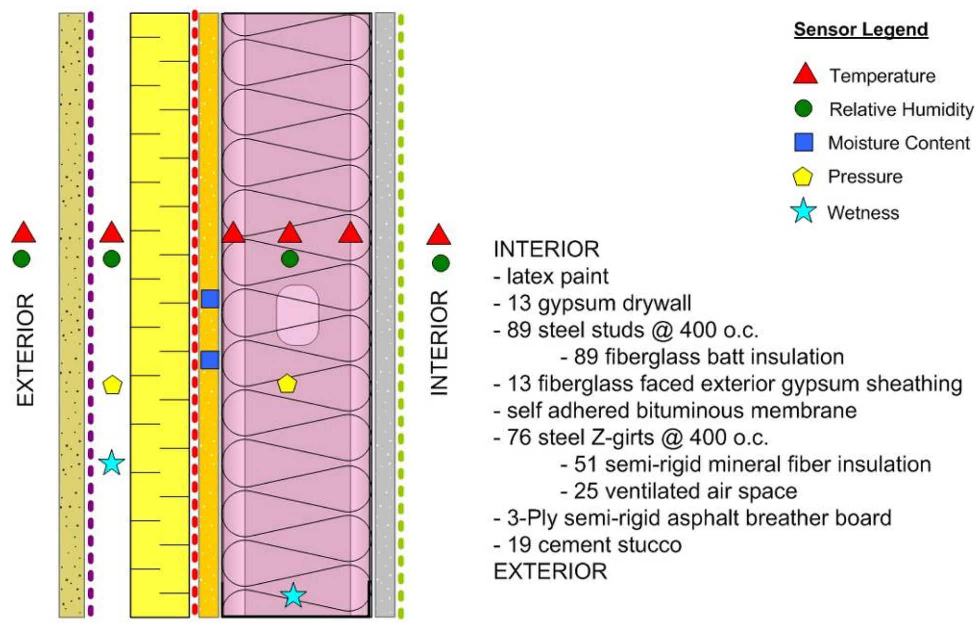


Figure 9-1: Building 3 – Typical Exterior Wall Assembly (Section View)

The exterior walls of Building 3 prior to the 2001 restoration consisted of (from the exterior): cement stucco (face-sealed), building paper, exterior gypsum sheathing (paper-faced), R-8 fiberglass batt insulation within 89 mm light gauge steel studs, polyethylene vapour barrier, and latex painted gypsum drywall.

When the building was restored, the exterior walls were re-built primarily from the exterior side to allow tenants to remain in the suites. During this procedure, the original interior polyethylene vapour barrier was completely removed and in some places the original R-8 fiberglass batt insulation was replaced with R-12 fiberglass batt. In addition, badly corroded steel studs were replaced with heavier gauge studs where deemed necessary. New fiberglass faced gypsum sheathing was installed followed by a bituminous peel-and-stick membrane, steel z-girts, R-8 mineral wool insulation, and finally a stucco cladding over a semi-rigid asphalt breather board.

As the impermeable air/vapour layer is placed between the two layers insulation, moisture has the potential to be trapped on the interior side within the stud cavity. While the placement of insulation on the exterior of the sheathing keeps it warmer during the winter, the interior insulation has the effect of keeping the sheathing below the interior temperature. While in this climate this is a better situation than the insulation entirely to the inside of the sheathing and impermeable membrane, the potential for vapour diffusion or air leakage condensation still exists. The interior vapour control layer consists of painted gypsum drywall (approximately 250-500 ng/Pa m^2 s), and the control of air leakage is poor with un-sealed electrical penetrations and other small openings. Thus the potential for vapour diffusion or air leakage into the stud cavity from the interior is high.

Section 9.25.1.2 of the National Building Code of Canada outlines requirements for the ratio of insulation outboard to inboard of an impermeable <60 ng/Pa m^2 s layer (in this case 2 ng/Pa m^2 s peel-and-stick) and is reproduced in Table 9-1.

Table 9-1: NBCC 2005 - Table 9.25.1.2

Table 9.25.1.2.
Ratio of Outboard to Inboard Thermal Resistance
Forming Part of Sentence 9.25.1.2.(2)

Heating Degree-days of Building Location, Celsius degree-days	Minimum Ratio, Total Thermal Resistance Outboard of Material's Inner Surface to Total Thermal Resistance Inboard of Material's Inner Surface
Up to 4 999	0.20
5 000 to 5 999	0.30
6 000 to 6 999	0.35
7 000 to 7 999	0.40
8 000 to 8 999	0.50
9 000 to 9 999	0.55
10 000 to 10 999	0.60
11 000 to 11 999	0.65
12 000 or higher	0.75

Vancouver has a <3500 Heating Degree Day climate, and thus the minimum insulation ratio is 0.2 for exterior insulated assemblies.

At Building 3, the thermal insulation consists of R-8 mineral wool on the exterior, and either R-8 or R-12 batt plus two layers of ½" gypsum (R-1) on the interior. This results in an insulation ratio of approximately 0.9 or 0.62 correspondingly which well exceeds the minimum code requirements in either case.

The above table is only recommended when interior relative humidity levels are kept below 60% during winter months. The relative humidity within Building 3 exceeded 60% for several months with daily peaks up to 70%. In addition, this table does not account for the potential effects of air leakage at these high humidity levels.

While the wall assembly technically meets code by a fairly large margin, interior relative humidity during the winter months is higher than 60% and air leakage may play a role. In addition, just because a wall meets the guidelines of Table 9.25.1.2, doesn't mean it will be immune to moisture problems.

The monitored performance of the exterior walls and a discussion of the field openings are presented for Building 3.

9.1.2 Monitored Performance

To assess the performance of the walls at Building 3, moisture sensitive materials within the stud space including the exterior gypsum sheathing, interior gypsum drywall, and steel studs were analyzed. Relative humidity within the stud cavity, moisture content of the gypsum sheathing and relative wetness readings are presented. Results are presented here from July 2002 to July 2003 which provides a continuous uninterrupted year of data at all sensor locations. Other years from 2002 to 2007 with partial data, show similar trends to those presented here and are not shown. The eight monitored wall locations are shown again here for quick reference and for analysis of the data (Figure 9-2).

Figure 9-2: Building 3 – Monitored Wall Locations

As addressed in Chapter 6, the interior dewpoint, and subsequent relative humidity levels within the monitored suites at Building 3 were high during the year, and in particular during the winter. Normal seasonal trends as observed at the other four buildings in the study were not observed at Building 3. A plot of the hourly temperature, dewpoint, and relative humidity is shown in Figure 9-3. Note first that higher relative humidity levels were observed indoors during the winter than in the summer, opposite to usual seasonal indoor trends.

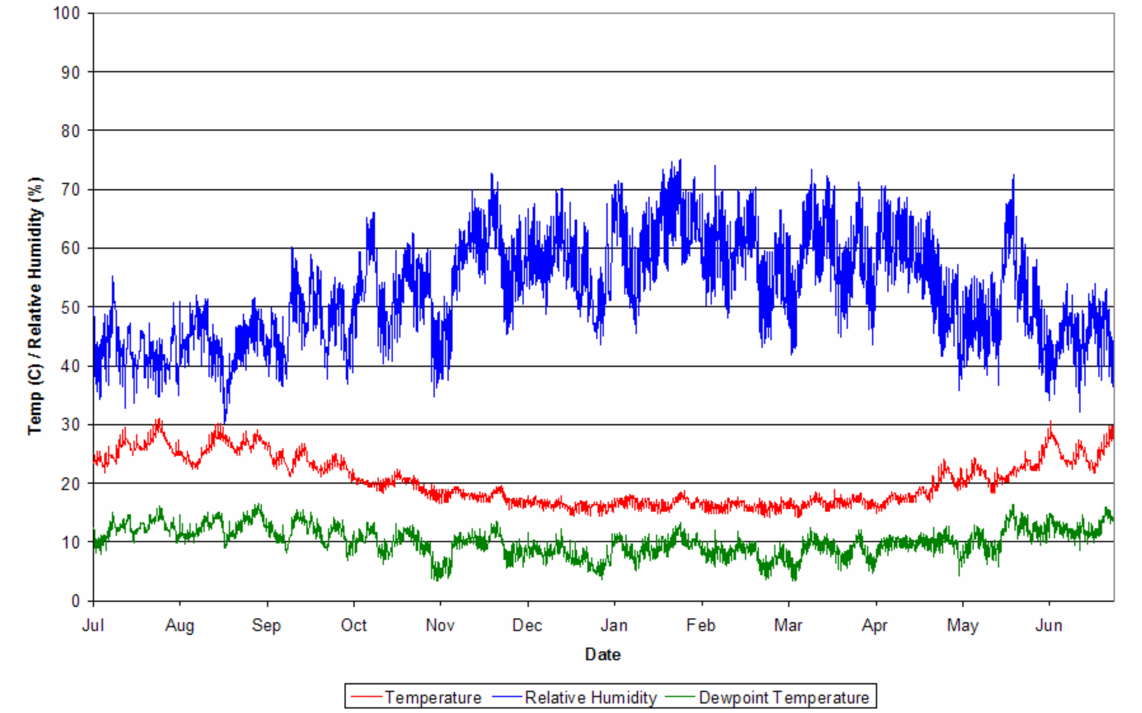


Figure 9-3: Building 3, Suite 311 – Interior Conditions July 2002 to July 2003.

Without interior vapour control, the relative humidity within the insulated stud cavity is also elevated, from 80% to 90% (measured at the center of batt insulation) for six months of the year (Figure 9-4).

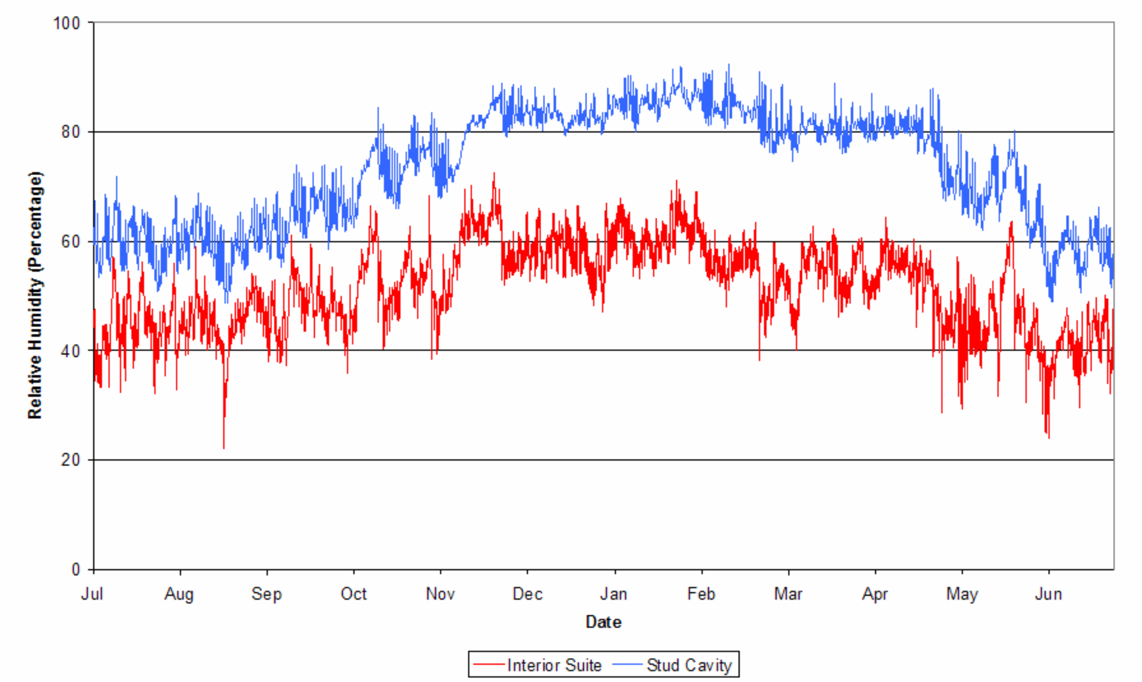


Figure 9-4: Building 3, Suite 611 Interior RH and RH in Stud Cavity, Wall #7

The elevated RH within the stud cavity is of concern for corrosion of the steel studs and possibly microbial growth on the gypsum sheathing or interior drywall.

The RH at the surface of the sheathing can then be calculated from the stud cavity RH at sheathing temperature assuming a constant vapour pressure within the stud space.

The relative humidity at the inside surface of the exterior sheathing is shown in Figure 9-5 for all eight locations, the subsequent gypsum moisture contents in Figure 9-6, and relative wetness within the stud cavity sill track in Figure 9-7 for wall location #8 (others similar). Monitored locations 1-4 are at the 2nd and 3rd floor, while locations 5-8 are at the 5th and 6th floors. In general, the exterior gypsum sheathing within all eight wall cavities is experiencing the same general wetting and drying trends.

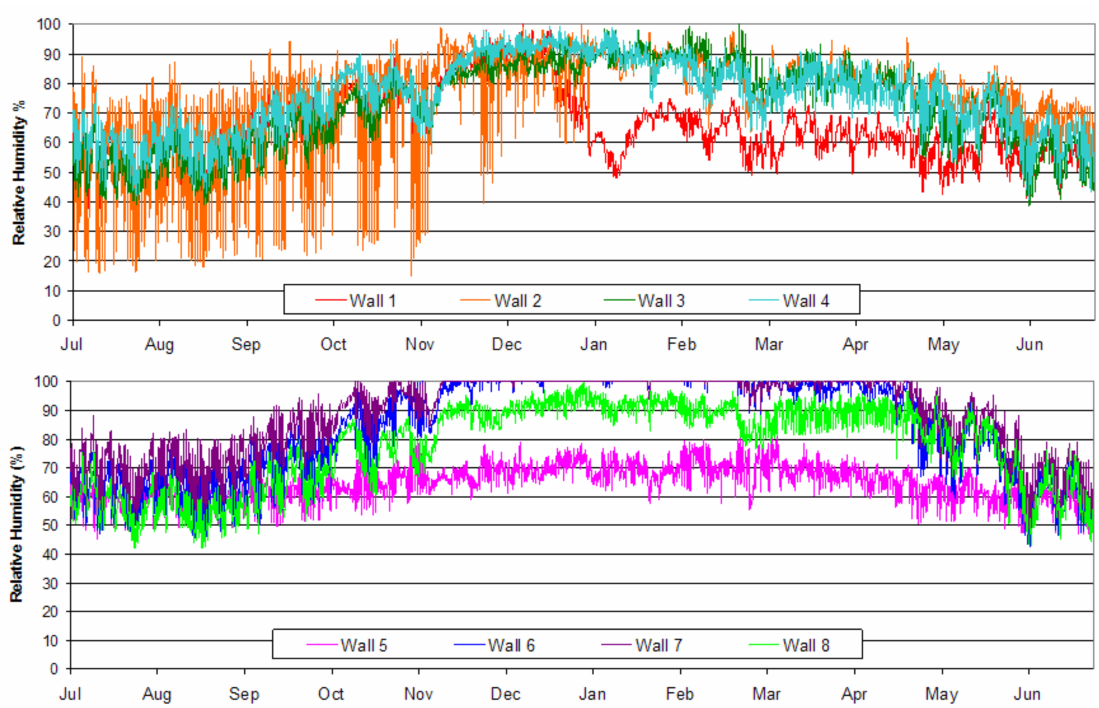


Figure 9-5: Building 3, Wall Locations 1-8 – RH at exterior sheathing

The RH at the interior surface of the exterior sheathing tracks around 50-80% during the summer months (May through August). In September the RH rises to up to 90-100% and remains at these higher levels until May when it decreases to 50-80% again. Analysis of data from 2002 to 2007 indicates that this same wetting and drying trend repeats annually. A year over year trend of increasing moisture content was not observed as the moisture within the stud cavity largely dries out during the summer months.

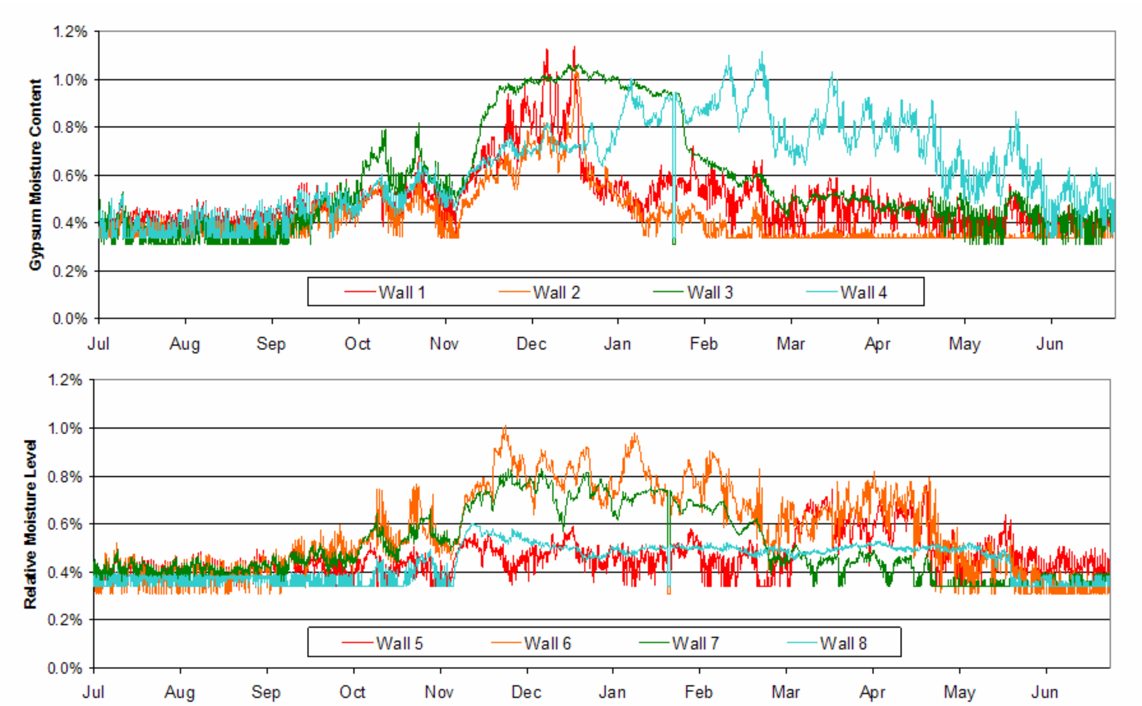


Figure 9-6: Building 3, Wall Locations 1-8 – Gypsum Sheathing Moisture Content

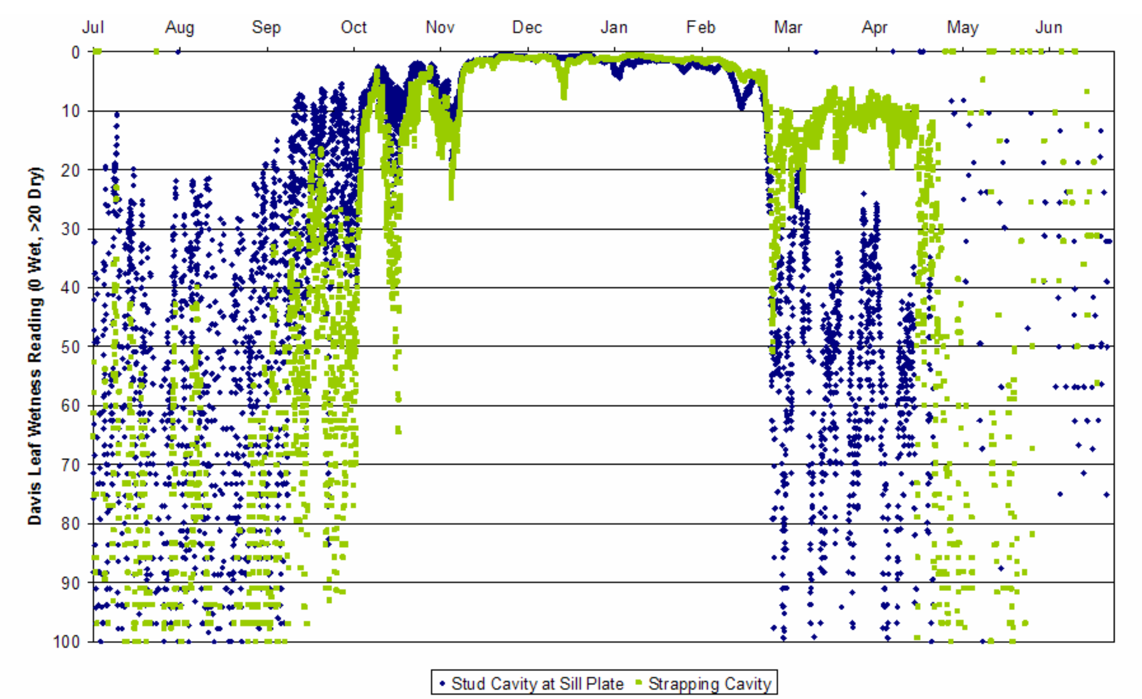


Figure 9-7: Building 3, Wall Location 7, 6th Floor – Relative Wetness in Stud Track

The gypsum moisture content and relative wetness readings correlate directly with the high stud cavity relative humidity levels. Gypsum moisture contents (up to 1%) are expected to be higher based on the sorption isotherm, however it is possible that moisture distribution and drying of the gypsum is occurring preventing very high levels from being attained. The developed moisture content correlation may also be different for the gypsum sheathing at this location (however a similar sample was correlated in the lab testing), as it appears to be under-predicting the sheathing moisture content.

Two wetness sensors are placed within each cavity, one in the strapping cavity behind the stucco and one in the sill plate of the stud cavity. Low values (0-10) indicate the sensor is wet, either because of very high RH or liquid water on the sensor. Scattered readings above about 20 indicate the sensor is dry and hence returning high resistance readings. Wet readings correspond well with high (90-100%) relative humidity levels.

In order to quantitatively compare the different wall cavities, a measure of the performance is required. The number of hours the interior surface of the exterior sheathing is above 80% RH is used for comparison and summarized in Table 9-2.

Table 9-2: Summary of Relative Humidity at Exterior Sheathing

Wall Location	Average RH %	Standard Deviation	Hours when RH>80%	% of Time
1	64.9	12.3	1125	13%
2	74.1	16.7	3892	44%
3	72.3	14.6	3490	40%
4	75.0	12.7	3429	39%
5	64.4	6.3	13	0%
6	83.7	16.9	5286	60%
7	88.0	14.0	6142	70%
8	77.2	14.9	4810	55%

The results indicate that all of the wall locations with the exception of 1 and 5 are experiencing RH levels greater than 80% for more than 40% of the year. Wall locations 1 and 5 appear to behave differently because they are at exhaust vent locations. At both of these locations the sheathing temperature is on average 1-4°C warmer than the other wall cavity locations during the winter months. While leakage of warm moist exhaust air into the wall could potentially increase the

RH and moisture level, no increase in moisture was observed. On the contrary it appears that the conductive heat transfer from the ductwork increases the temperature of the exterior sheathing and studs which lowers the observed moisture levels. This had the result of reducing the potential for condensation in the stud cavity, reduced the average sheathing RH, and allowed the wall to dry out at a faster rate than the other unheated locations.

The vapour pressures within the stud cavity, interior suite, and exterior ventilated cavity are compared in an attempt to understand the high interior humidity levels observed within the walls. Hourly vapour pressures for an entire year are shown in Figure 9-8 indicating that the vapour pressure within the enclosed stud cavity are elevated above the exterior and interior for the entire year, possibly suggesting entrapped moisture within the stud space.

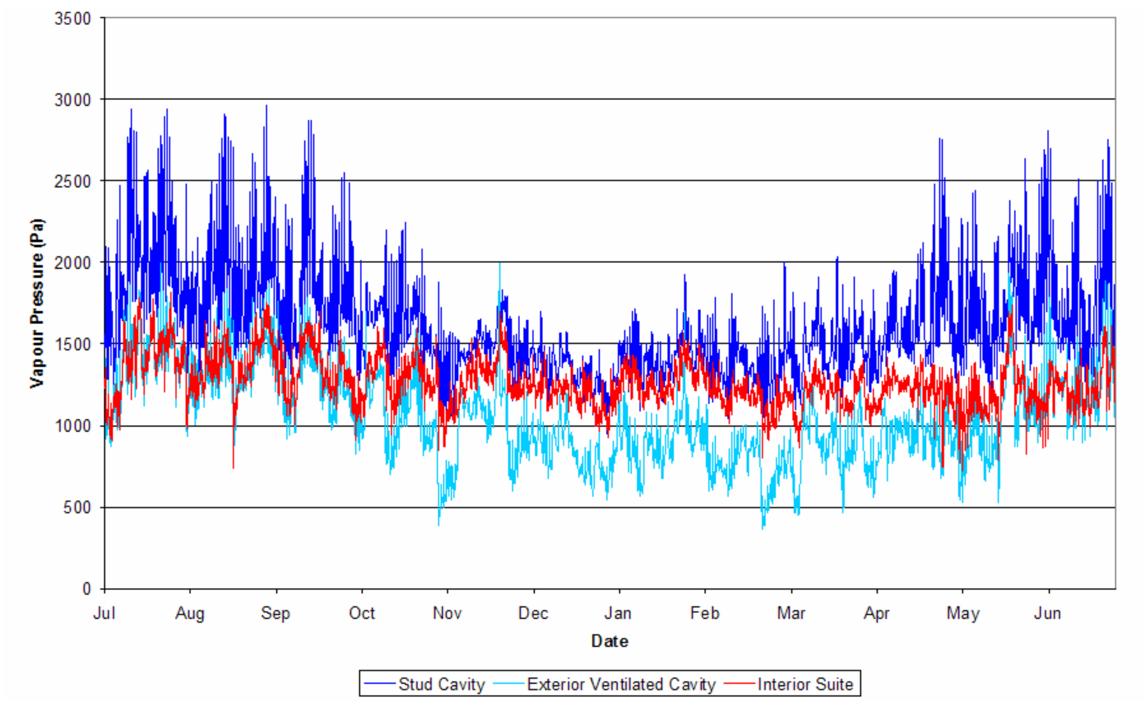


Figure 9-8: Building 3 – Wall Location 7, Vapour Pressures Across Wall

A typical two-week period during the winter is shown in Figure 9-9 and a two-week period during the summer in Figure 9-10.

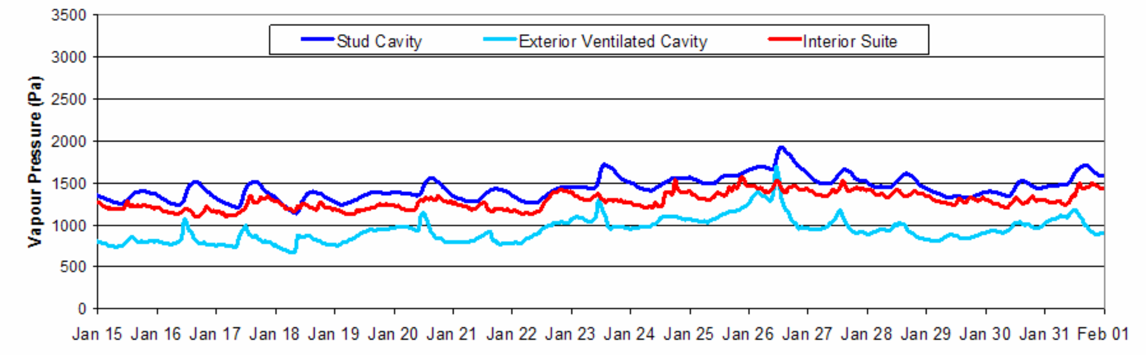


Figure 9-9: Building 3 – Wall Location 7, Vapour Pressures – Winter Typical

During the winter months, the vapour pressure in the stud cavity is actually higher than the interior suite, which would indicate a steady vapour flow drying to the interior. However as shown the stud cavity remains humid over the entire winter, this indicates that potentially air leakage from the interior into the stud cavity is overpowering the reverse diffusion drying to the interior. Potentially moisture as a result of a rainwater leak could also be trapped within the stud cavity and unable to dry out, however as observed in the field openings in the next section, appears unlikely.

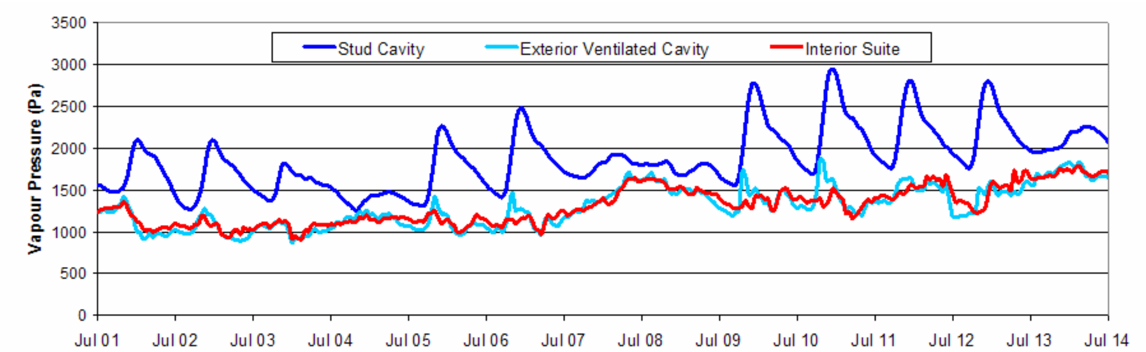


Figure 9-10: Building 3 – Wall Location 7, Vapour Pressures – Summer Typical

In the summer the vapour pressure within the stud cavity remains above the interior or exterior, indicating entrapped moisture within the stud space or an inability to completely dry out. During the summer the cavity relative humidity drops to between 50-80% and the air still contains more water vapour than the interior or exterior.

The vapour pressure analysis suggests that moisture potentially as a result of vapour diffusion and exacerbated by air leakage is wetting the exterior sheathing.

Aside from the moisture performance, also of interest are peak temperatures through the wall assembly. As shown in Figure 9-11, peak temperatures of up to 45°C were observed within the ventilated strapped cavity as a result of solar radiation. A week long period during 35°C exterior temperatures are shown in further detail in Figure 9-12.

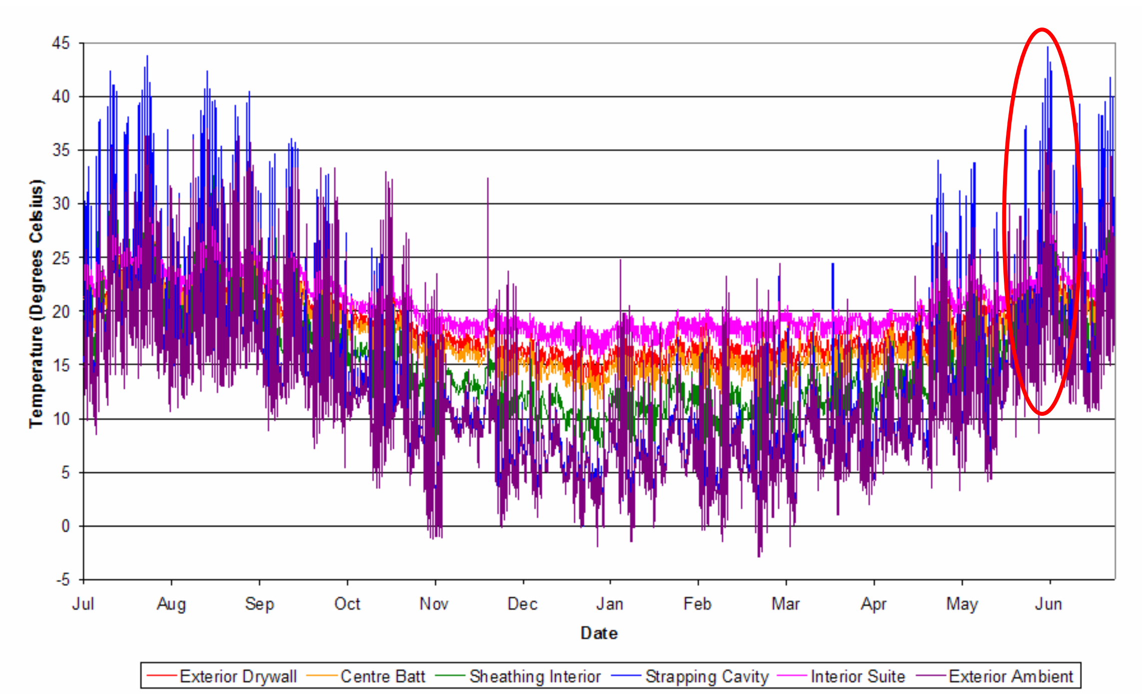


Figure 9-11: Building 3, Wall Location 7, 6th Floor – Temperatures July-July

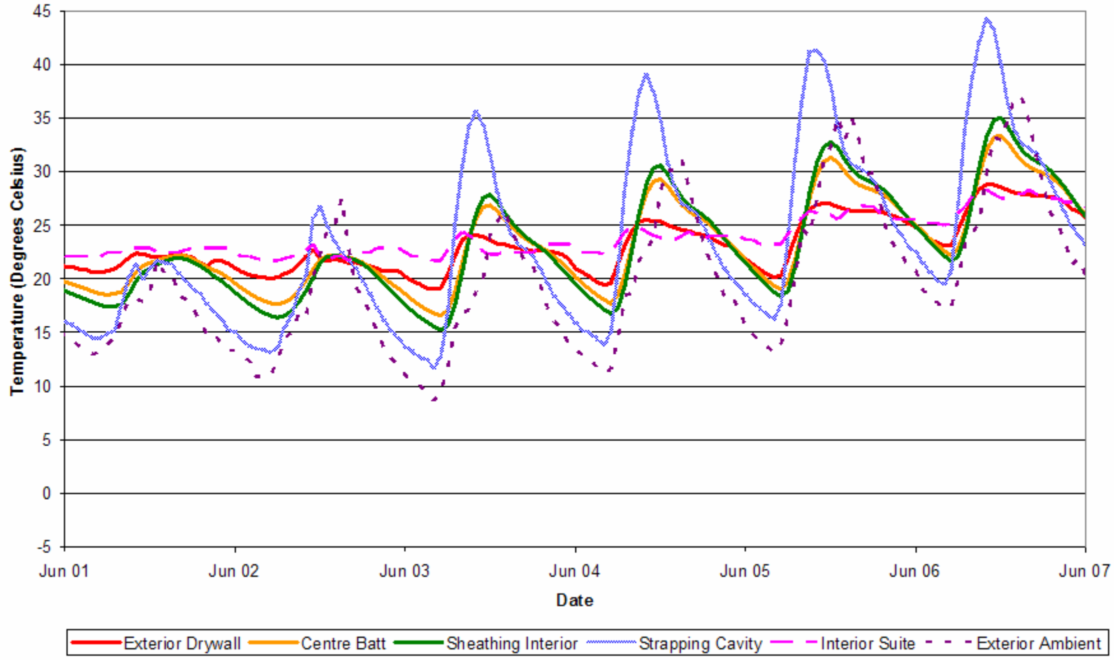


Figure 9-12: Building 3, Wall Location 7, 6th Floor – Temperatures June 1-7

The influence of solar radiation on this exposed east elevation is shown to cause cavity temperatures up to 10°C higher than the exterior air.

9.1.3 Summary of Monitored Results

During the winter the RH within the stud cavity increases to high levels from 80-100% at the sheathing. At or below the dewpoint temperature, water will condense on the surface of the exterior sheathing and will be stored by the material. As gypsum has a very low safe storage capacity, critical moisture levels are attained rapidly.

Moisture may also condense on the steel studs, but these are likely to be warmer than the sheathing on account of thermal bridging through the studs. However, if condensation did occur on the studs, water would drain into the sill track as steel has no storage capacity. Liquid water and high humidity at the steel studs is of concern for corrosion.

The gypsum moisture content and relative wetness sensor readings both correlate well with high relative humidity readings within the stud cavity and at the sheathing.

Since the membrane on the exterior of the sheathing is impervious to water vapour, drying can only occur inwards; either by vapour diffusion or air convection. As the interior batt insulation is lowering the temperature of the exterior sheathing and maintaining a high humidity during the winter months, drying will not occur until heat flow through the walls is reversed during warmer months. Drying was observed to occur in summer, however vapour pressures within the stud cavity were still elevated in comparison to exterior or interior conditions indicating that the cavity space could still be drier.

9.1.4 <u>Exploratory Field Openings</u>

A total of five exploratory openings were made into the exterior walls from the interior of the building. The openings were made to confirm the installed sensor readings and observed the impact of high moisture levels for the past four years.

The five test openings confirm that the sensors are working properly and that moisture sensitive materials are experiencing wetting to varying degrees. At an exterior corner of the building it was observed interstitial condensation is providing a significant moisture source within the insulated stud walls.

In an attempt to fully understand the conditions observed during the test openings, the monitored conditions are first reviewed.

9.1.4.1 Interior Environmental Conditions Prior to Openings

As part of the original monitoring study, the environmental conditions within two suites (311 and 611) were monitored using wall mounted HOBO Pros. In July 2005, two additional suites (308 and 602) were monitored after observing evidence of mould growth on the interior surfaces in those suites.

Figure 9-13, Figure 9-14, and Figure 9-15 plot the interior temperature, dewpoint and relative humidity for the 6 months prior to wall openings from July 2005 to January 2006.

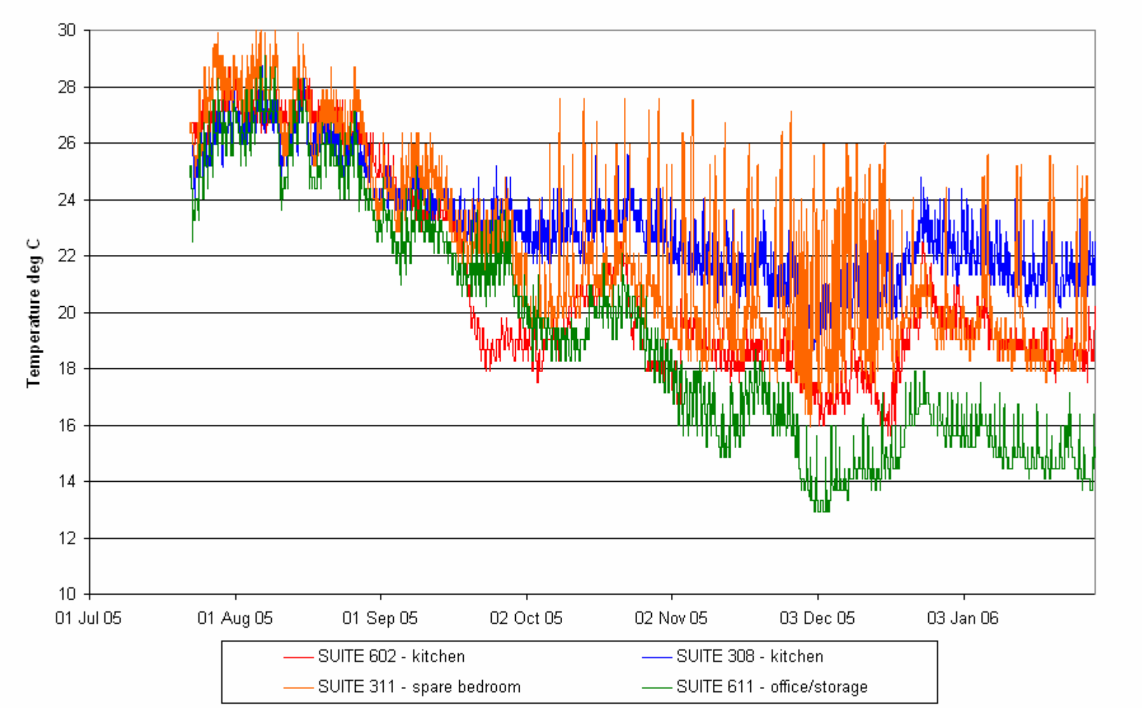


Figure 9-13: Interior Suite Temperatures July 2005 to January 2006

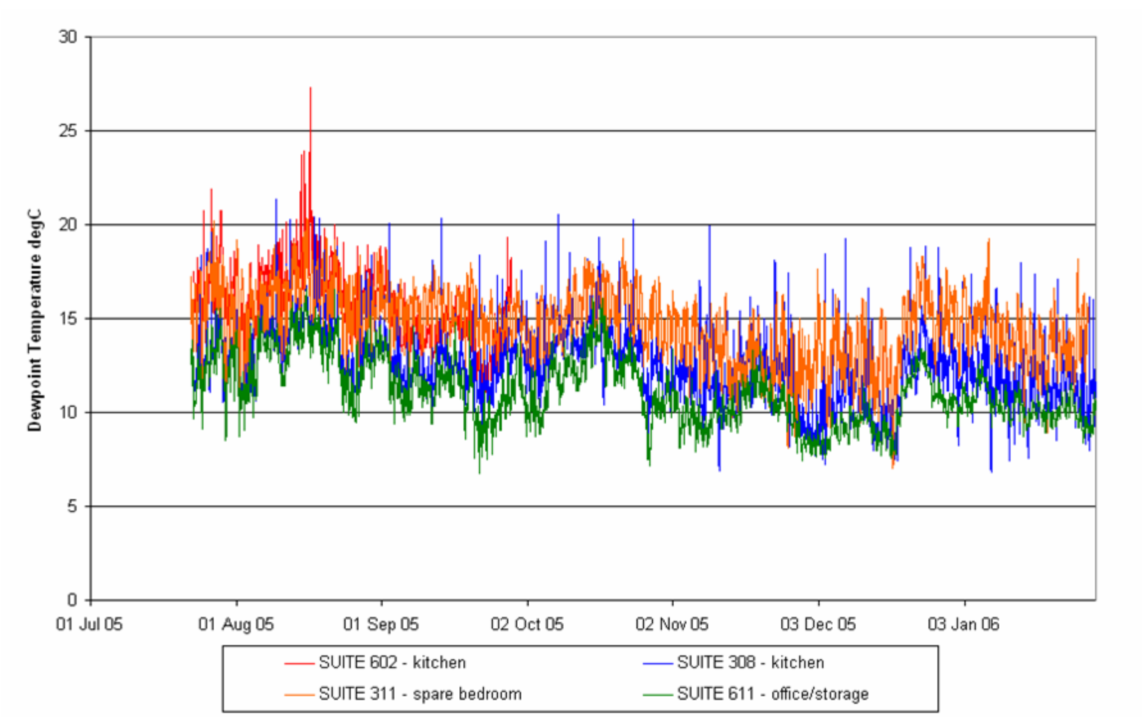


Figure 9-14: Suite Dew-point Temperatures July 2005 to January 2006

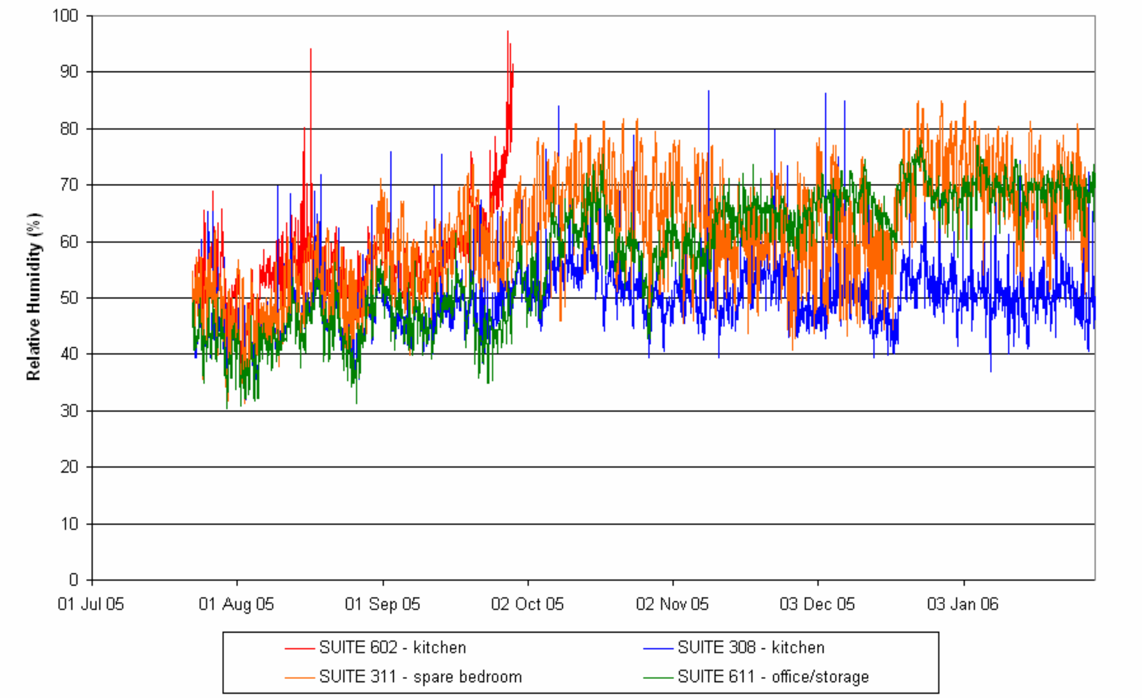


Figure 9-15: Suite Relative Humidity July 2005 to January 2006

The high relative humidity levels during January are further shown in Figure 9-16.

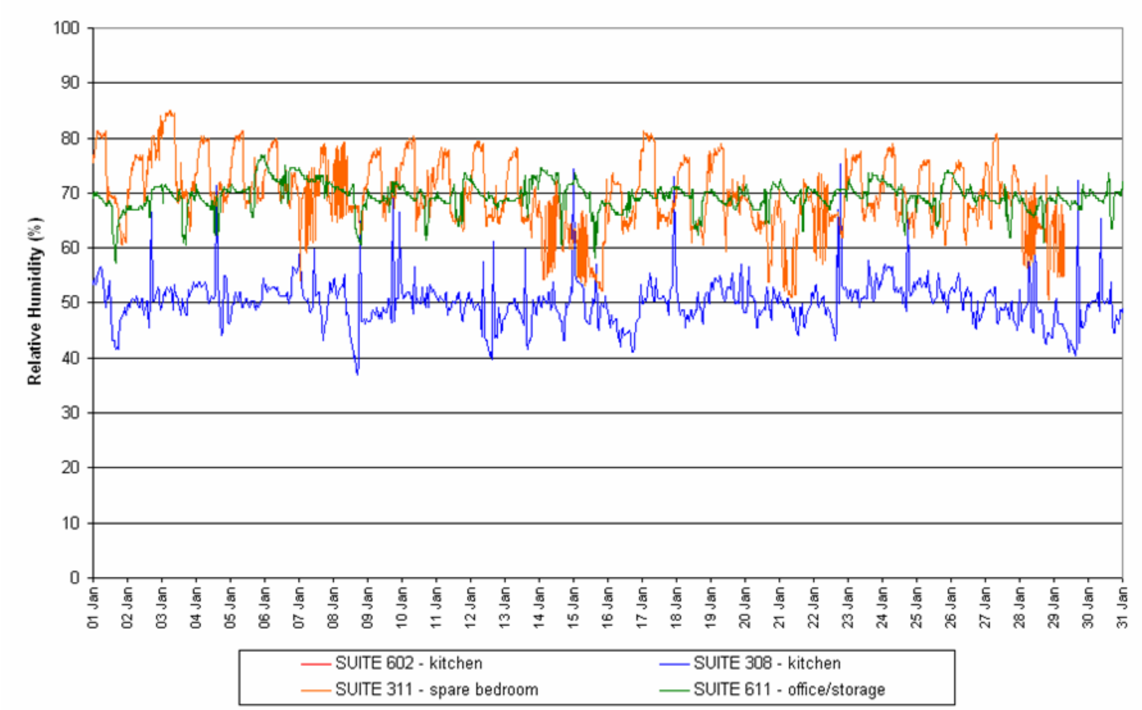


Figure 9-16: Suite Relative Humidity January 2006

Note the similar temperatures observed in all suites during the summer months when the interior suites are fairly warm (26-30°C). At this time, the windows were likely open to increase ventilation and reduce the temperature within the suites. During the fall and winter months, the suite temperatures diverge as occupants close up the windows, reducing ventilation rates and control the temperature by thermostat to their own preference.

The temperature in suite 611 is lower than the rest of the suites as the sensor is located in the office/storage room which the two occupants infrequently use. Field observations indicate warmer temperatures within the bedroom and living areas of that suite however were not monitored for extended periods.

Note that the RH sensor in suite 602 peaked and went offline in October when interior relative humidity levels approached 100%. The sensor continued to malfunction until physically removed from the suite in January, and when it was, began to work again. When the sensor was removed from the suite, mould growth was observed on the ceiling at a slab edge thermal bridge, and the aluminium framed sliding glass door frame was dripping with condensation moisture (Figure 9-17).


Figure 9-17: Interior Mould Growth and Condensation Observed in Suite 602

9.1.4.2 Wall Conditions Prior to Openings

The relative humidity within the eight monitored wall locations are shown for the 6 months leading up to the field openings.

The relative humidity at the center of the insulated stud space from July 2005 to February 2006 is shown in Figure 9-18 and in detail for January 2006 in Figure 9-19.

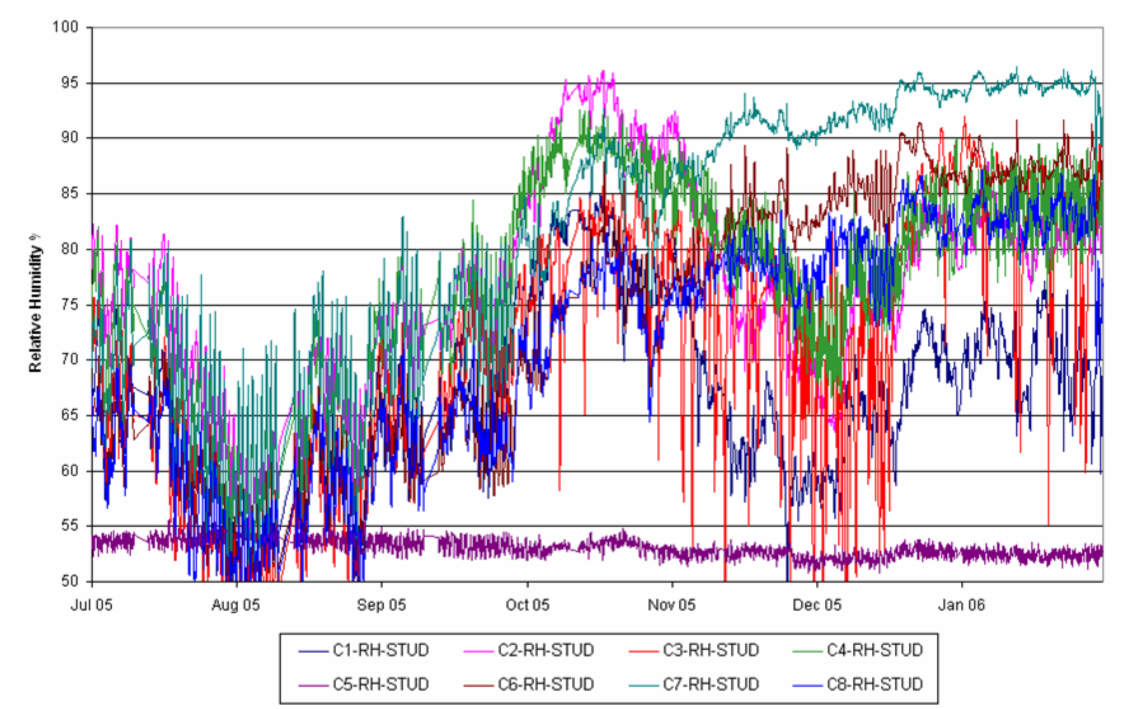


Figure 9-18: Relative Humidity within Stud Space for Cavities 1 through 8

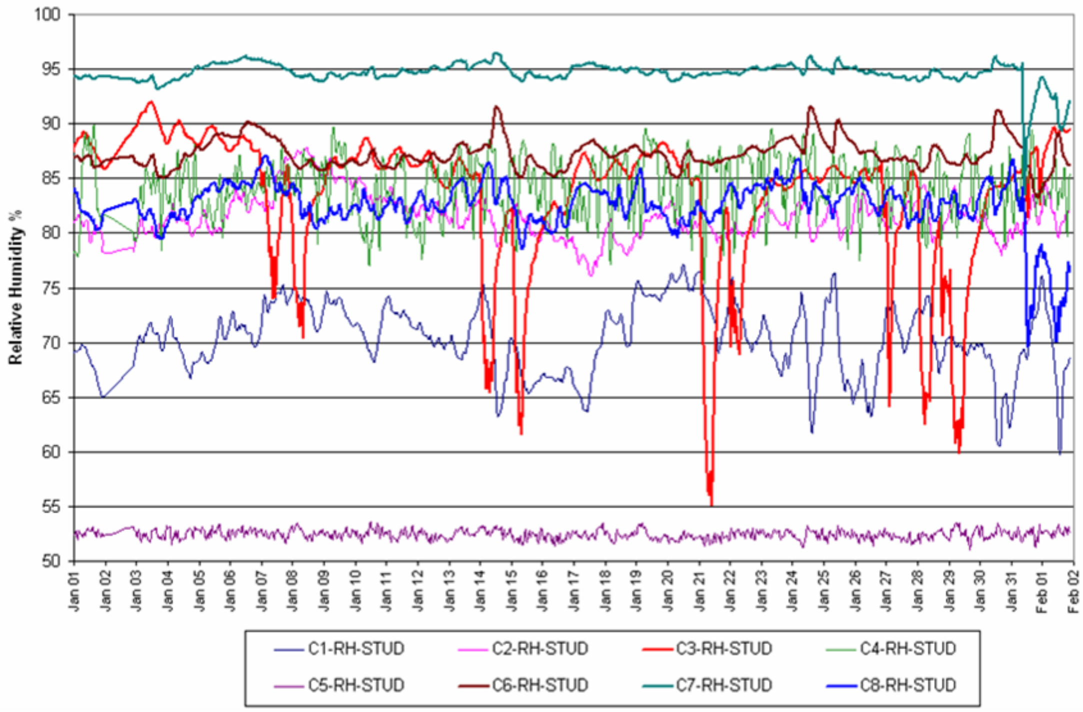


Figure 9-19: Relative Humidity within Stud Space for January 2006

The intermittent use of the second bedroom in suite 311 has a direct impact on the relative humidity within the stud space of monitored wall location #3 (below window in bedroom). When the temperature in the bedroom increases the relative humidity within the stud cavity decreases.

Note the sudden drop in relative humidity on January 31 as the wall openings were made and exposed to interior conditions.

9.1.4.3 Exploratory Openings

Five test openings were made into the exterior walls of Building 3 on January 31, 2006 between 9:00 am and 2:00 pm. Two openings were made in suite 611, one opening was made in suite 608 and two openings were made in suite 311.

The purpose of the test openings was to confirm conditions reported by the sensors and to observe and document the environmental conditions within the stud space and interior suites.

Figure 15 shows the locations of the five exploratory openings over the monitored wall locations.

Figure 9-20: Location of Five Exploratory Openings Made on January 31, 2006.

Exterior conditions during the review were 6-8°C and 70-90% RH and cloudy with light rain showers, the interior temperature and humidity varied as discussed.

A discussion of the observations is provided for each test opening below. Additional photographs are provided in *Appendix E: Supplemental Building Information and Photographs*.

Opening #1 – Suite 611

Opening 1 consists of two openings, 1L and 1H, representing an opening a lower and higher portion of the wall. The following observations were made during the review:

- The monitored room consists of a storage area/office space, boxes and piled halfway up and in contact with the exterior walls. Temperature within suite is 18°C and 62% RH. Electrical baseboard heater set-point is at

15°C and the heater is located below the window behind a number of boxes

- Condensation is observed at corners of double-glazed units. Black mould growth is also present.
- Thermal dusting/darkening of the interior paint finish is observed at locations of steel studs on the exterior walls. The dusting is more pronounced behind the storage boxes.
- Opening made below window and is 36″x18″ and exposes monitored location #8 below window, and #6 at corner of wall.
- Fiberglass insulation is poorly installed and ill-fitting around electrical conduit.
- Sensors all appear to be in good working order with signs of minor corrosion on exposed wires. Mould growth is observed on the PVC pressure sensor tubes.
- Moderate mould growth is observed on the backside of the gypsum sheathing. The cavity smells musty and organic
- Gypsum sheathing is soft to probe and liquid condensation droplets are observed on the backside of the sheathing at the corner (see photos).
- 2-3 mm of liquid water is observed in the sill track, and the bottom 1″ of the insulation is completely saturated and dripped when pulled out of the stud cavity.
- Liquid water was visually observed covering 50% of the Leaf Wetness sensor area which was returning 0 or wet readings at the time.
- The gypsum relative moisture level is greater than 100, or 40% wood MC using Delmhorst BD-10
- Light corrosion is observed on the surface of the steel stud flanges. Mild to surface corrosion is observed on the exposed fastener threads.

Thermal Dusting at interior steel studs

Mould and Condensation droplets on sheathing

Condensation and corrosion on steel stud

Mould growth on backside of gypsum sheathing

Figure 9-21: Photographs from Opening #1

A drawing showing the location of the two monitored wall locations and the corner detail is presented in Figure 9-22.

The conditions within the stud cavity were significantly worse at the corner (also away from sensors). To determine the potential cause for this, a two-dimensional thermal model was made using THERM 5.2, which highlighted the lower corner temperatures and increased condensation potential (Figure 9-23).

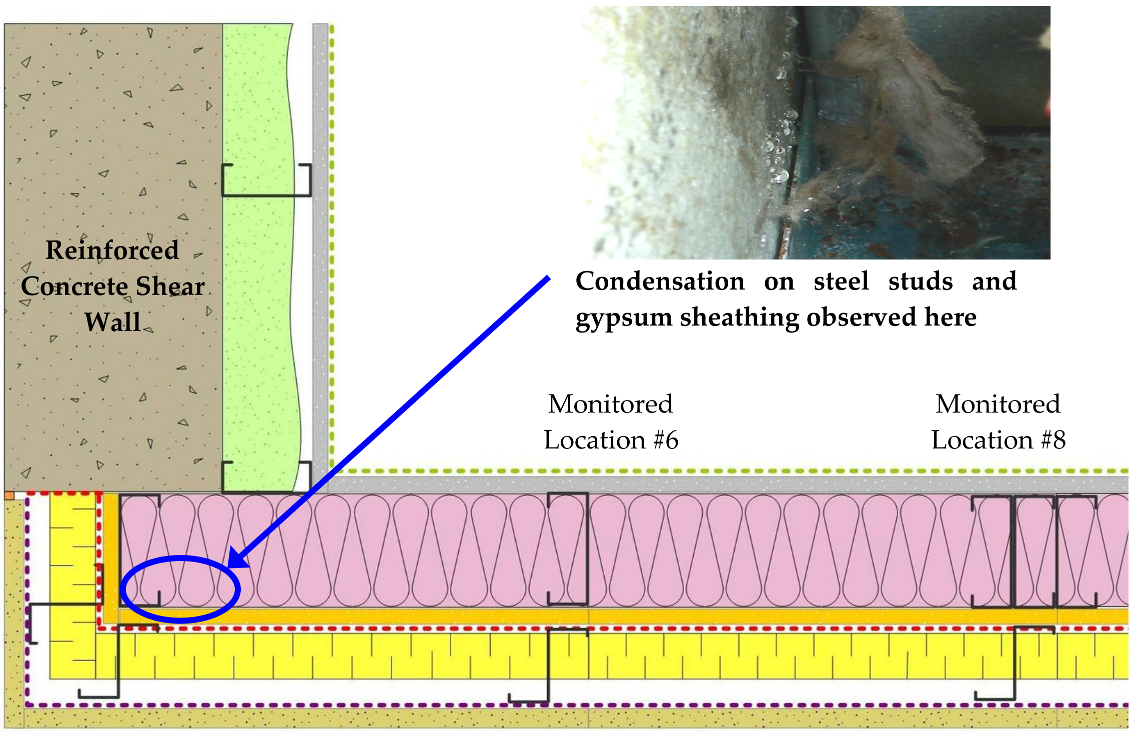


Figure 9-22: Plan View of Wall at Corner

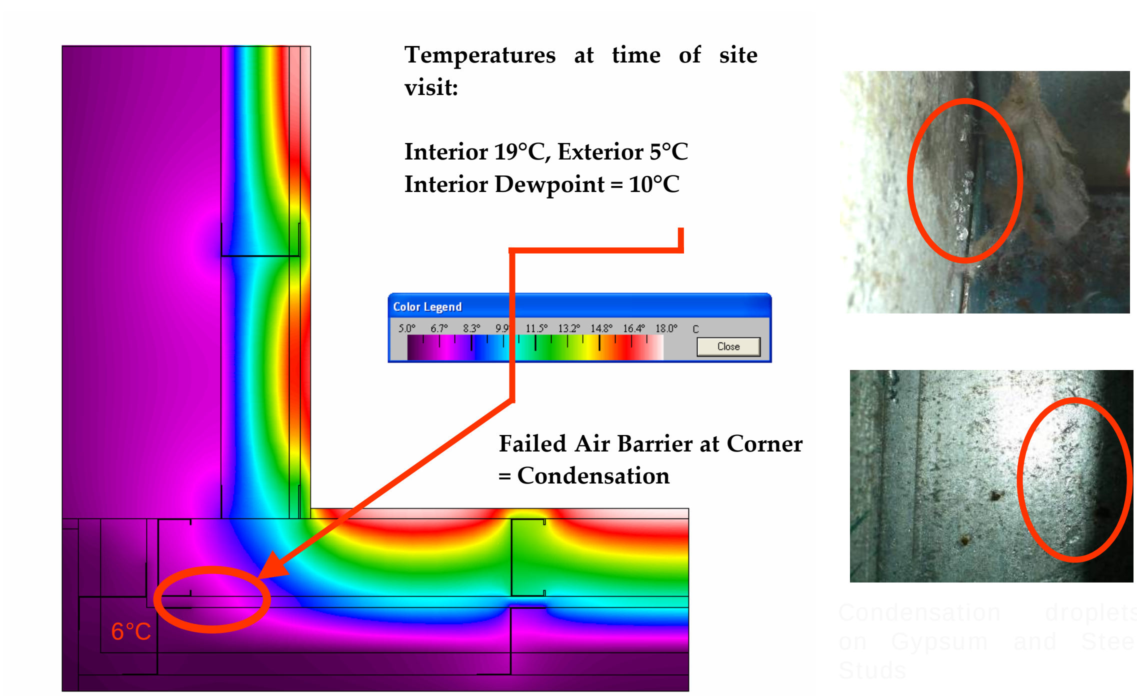


Figure 9-23: Thermal Model Showing Condensation Potential and Observed Condensation at Corner Detail.

The thermal impacts of the corner detail are shown by the model and were visually confirmed on site. In the colder regions, below the interior dewpoint temperature, condensation was observed. Mould growth and gypsum "softness" was also greater at the corner location.

The thermal analysis also indicated a total wall R-value of 10.3, as opposed to R-16 or R-20 designed as a result of the thermal bridging around the steel studs and z-girts. This is consistent with results for other steel-stud walls.

Opening #2 – Suite 611

Opening 2 is located at monitored wall location 7, adjacent Opening #1. The following observations were made during the review:

- Same interior observations as Opening #1 apply here.
- Opening is made in corner below north side of window and exposed monitored location #7 (at balcony-wall interface).
- Cavity was clear of mould or liquid water and the sheathing had a relative moisture level of 80. Conditions within the wall were not as wet or deteriorated as opening #1.

Opening #3 – Suite 608

Opening 3 is located within suite 608 and was made to determine the construction at the concrete spandrel panel area and determine the conditions within this wall assembly. The wall assembly is shown in Figure 9-24.

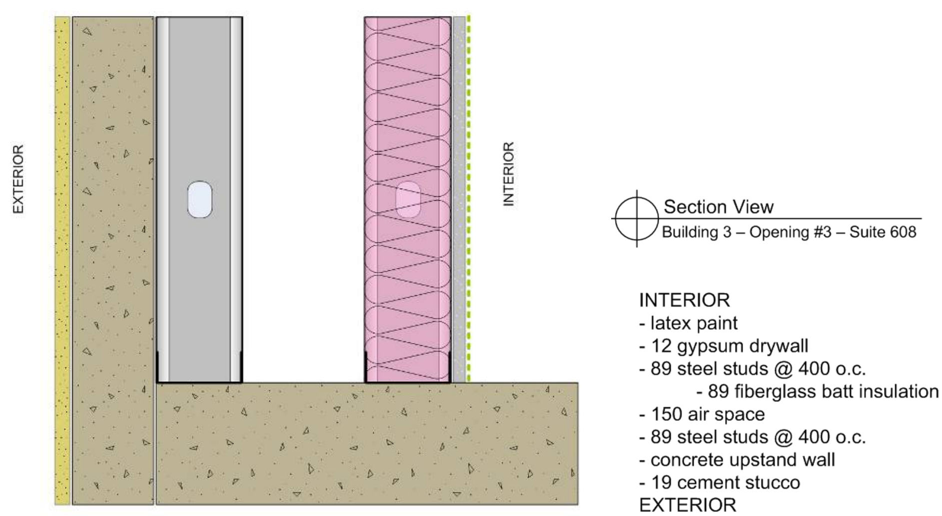


Figure 9-24: Wall Assembly Details at Opening #3

Evidence of moisture penetration was observed on the exposed concrete slab emanating from the exterior edge (see photo). No damage to the exposed gypsum drywall or corrosion of steel studs was observed. No interior vapour retarder was located at this location, even though the assembly here differed from the typical wall assembly for this building.

Figure 9-25: Photographs from Opening #3

Opening #4 – Suite 311

Opening 4 is located in suite 311 at monitored wall location #3. The suite here has elevated interior relative humidity levels (up to 80-85%) prior to the test openings. The following observations were made during the review:

- The monitored room consists of a secondary bedroom with the furniture away from the exterior walls. Temperature within suite is 18°C and 75% RH.
- Severe condensation is observed the bottom half of the window glazing and frame (see photo). The tenant reports wiping down the windows every morning to remove condensation moisture. Black mould growth is observed on the frame and glazing corners and the wood trim is discoloured and damaged from the moisture.
- The opening is made below the window and exposes monitored location #3 sensors.
- Sensors all appear to be in good working order with signs of minor corrosion on exposed wires.
- Light mould growth is observed on the backside of the gypsum sheathing in some isolated locations (see photo). Liquid condensation is observed at a few locations on the backside of the sheathing near the window frame. The cavity smells slightly musty.

- Liquid water droplets are also observed on the exterior face of the interior gypsum drywall.
- Gypsum sheathing is very soft to probe and a relative moisture reading of 100 is recorded (see photo). A small sample is taken from the back half of the gypsum sheathing including half of the core and the interior fiberglass facer. The sample is weighed then dried (back at laboratory) and weighed again to determine an approximate moisture content of 6%.
- Light corrosion is observed on the surface of the steel stud flanges. Mild to surface corrosion is observed on the exposed fastener threads.

Figure 9-26: Photographs from Opening #4

Opening #5 – Suite 311

Opening 4 is located in suite 311 below the living room window. The following observations were made during the review:

- The opening is made below the living room window; no sensors are located at this location.
- The gypsum sheathing is slightly soft and a relative moisture reading of 80 is recorded.
- Light corrosion is observed on the surface of the steel stud flanges. Mild to corrosion is observed on the exposed fastener threads.
- Stud cavity is drier than the other locations observed.

Summary of Field Openings

In summary, the monitored conditions within the eight wall locations indicated humid and wet sheathing prior to the field openings. Five openings were made into the exterior walls which confirmed that the sensors were returning valid data and the presence of moisture within the stud cavities. While condensation, corrosion, and small areas of mould growth were observed the damage was minimal in comparison to other failed buildings and indicates that a repair is possible for this building.

A thermal bridge at the building corner detail is further worsening the moisture problems at the wall corners, as in Opening #1. Moisture levels were higher at this location, and liquid water was observed within the stud sill track.

9.1.5 <u>Impact of Interior Conditions</u>

Hygrothermal modeling was used to determine the impact of the interior relative humidity on the performance of the wall assembly. The wall assembly was modeled using WUFI 4.1. The average interior conditions were modeled where a case of the current ventilation rate was halved and then doubled to show the impact of the suite relative humidity on the wall performance. This was done by correlating the measured interior conditions with a moisture generation and ventilation rate using methods outlined in ASHRAE 160P, then halving and doubling the ventilation rate.

The interior relative humidity for the three modeled cases is presented in Figure 9-27 and the relative humidity at the sheathing surface is shown in Figure 9-28.

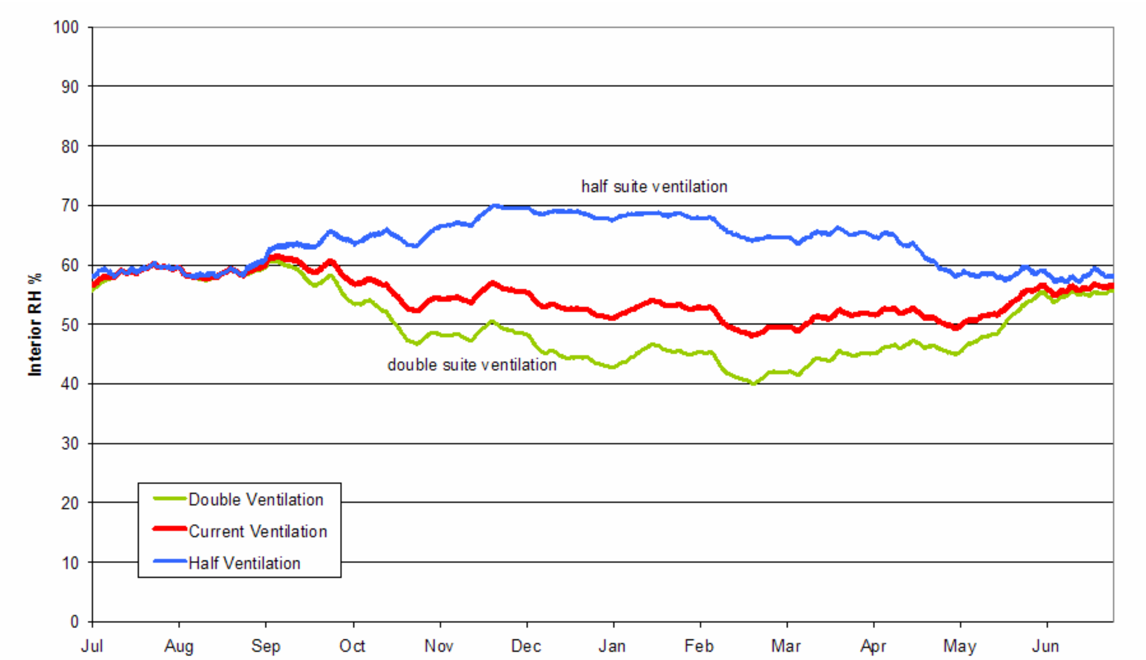


Figure 9-27: Impact of suite Ventilation Rate on Interior RH

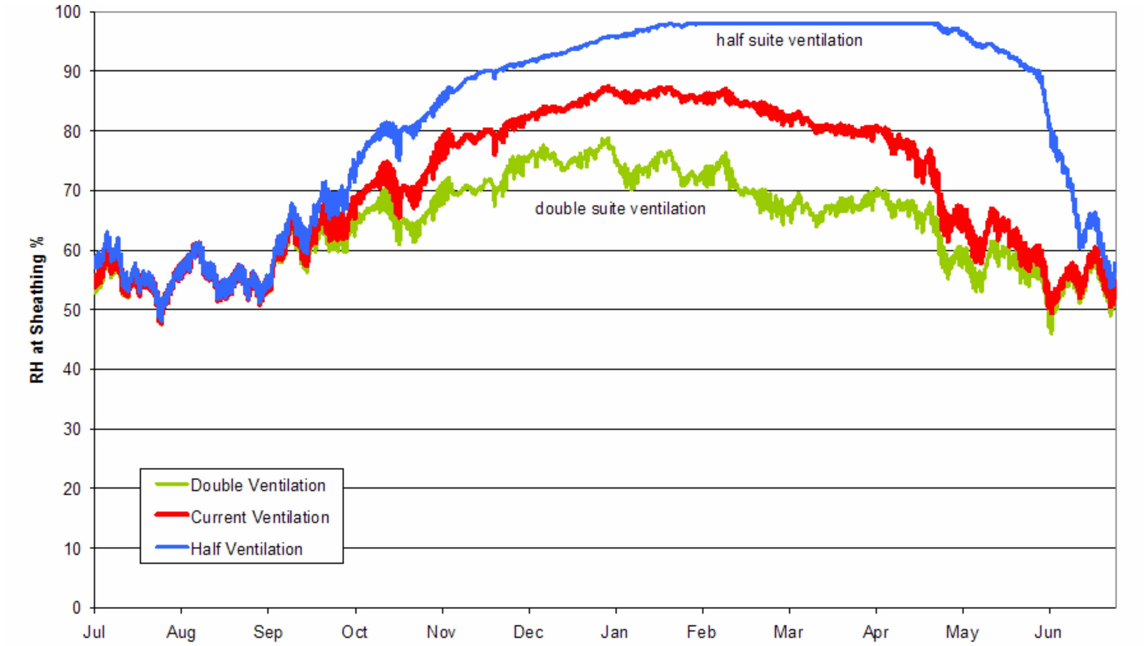


Figure 9-28: Impact of suite Ventilation Rate on Interior RH

As shown, a wintertime average RH above 50% results in very high (80-100%) RH levels at the sheathing, whereas the double ventilation case (where interior RH is between 40-50% during the winter) results in safer sheathing RH levels, and subsequently gypsum moisture content. Further hygrothermal modeling scenarios are compared in Chapter 10.

9.1.6 <u>Conclusions – Building 3</u>

The split-insulated stucco rainscreen wall assembly performed poorly at Building 3 as a result of humid interior conditions. The results show that vapour diffusion and/or air leakage is wetting the stud cavity and exterior sheathing during winter months. High relative humidity within the stud cavity and elevated moisture contents of the gypsum sheathing were observed in all eight wall locations.

Field openings confirmed the sensor readings and also the presence of moisture within the wall cavities. The impacts of the high moisture levels included: minor surface corrosion on the screw fasteners and steel stud flanges, liquid water on backside of sheathing and pooled within sill track, and localized mould growth on the exterior sheathing. As a result, the future durability of the steel studs, fasteners and fiberglass faced exterior gypsum sheathing is in question.

The elevated interior relative humidity levels correlate with the wetting and drying events. The lack of a controlled ventilation system combined with an air-tight wall assembly, occupant loading, and lifestyle contributes to the high overall relative humidity observed in the building.

The high interior humidity was shown to have a direct impact on the wall performance, and that doubling the current ventilation levels would reduce the relative humidity within the stud cavity to safe levels. Further improvements could still be made to improve the performance and are discussed in Chapter 10. Exterior conditions such as driving rain and orientation had little effect on the performance of this wall assembly

Currently a mechanical system upgrade is being designed to improve ventilation rates and reduce the interior dewpoint within the suites. A unique opportunity exists to monitor the impact of the mechanical system improvements on the condition of the exterior walls and to determine if further remediation is required.

While many of the problems in Vancouver in recent years have been a result of rain from the exterior, this case study reinforces that vapour diffusion and interior relative humidity must not be overlooked. Measures such as upgrading mechanical systems should be considered when rehabilitating the exterior building enclosure.

9.2 BUILDING 5

The monitored performance of the wall assemblies at Building 5 is presented. Data from 2004 is presented here, data from 2003 and 2005 is incomplete due to missing data points; however show similar trends to that presented here.

The measured temperature, relative humidity, and sheathing moisture content readings are presented and discussed for all eight monitored wall locations on the southeast and southwest elevations.

9.2.1 Background

Building 5 had the best (driest) performance of all the buildings, which can be attributed to the wall assembly details. Monitored wall locations 1 through 5 consist of an exterior insulated stucco rainscreen assembly while wall locations 6 through 8 consist of exterior insulated window-wall glazed spandrel panels.

The stucco rainscreen wall assembly (Figure 9-29) is constructed with gypsum sheathing over light gauge steel studs. The moisture sensitive gypsum sheathing is protected by an impermeable peel-and-stick air/vapour/moisture barrier and insulated with 51 mm (2") of rigid XPS insulation. The only way the gypsum sheathing could be wetted or damaged would be as a result of a rain-water leak, or high interior humidity levels resulting in air leakage or vapour diffusion condensation at the sheathing. Lacking the interior insulation as in Building 3, the exterior sheathing temperature is very close to the interior.

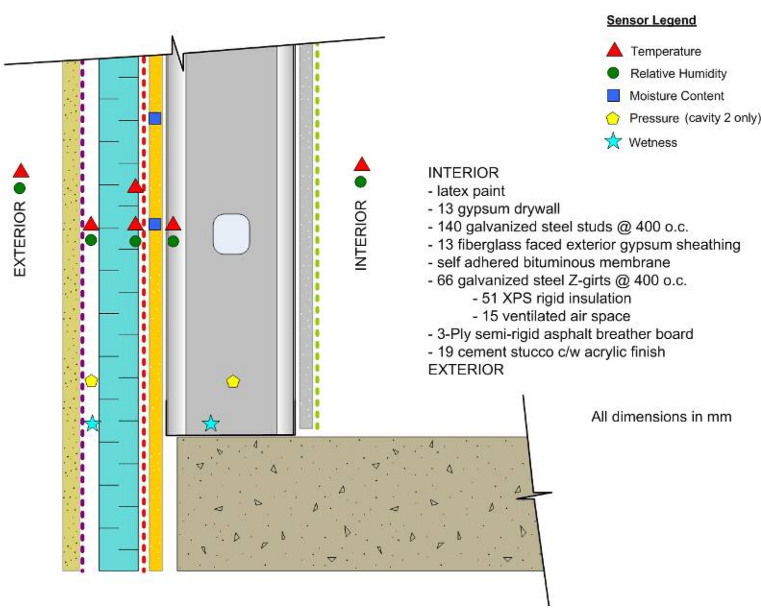


Figure 9-29: Building 5 – Exterior Wall Assembly at Monitored Locations 1 -5

The window-wall spandrel panel assembly (Figure 9-30) is constructed of largely non-moisture sensitive materials and unlikely to be damaged by moisture, however non-corrosion protected elements may be affected by high relative humidity levels. The interior of the wall is finished with light-gauge steel-studs and finished with painted gypsum drywall which could be damaged by water leaks which penetrate past the spandrel panels, or by high interior humidity.

Steel fasteners may also be damaged by liquid moisture or high relative humidity levels within the cavity spaces.

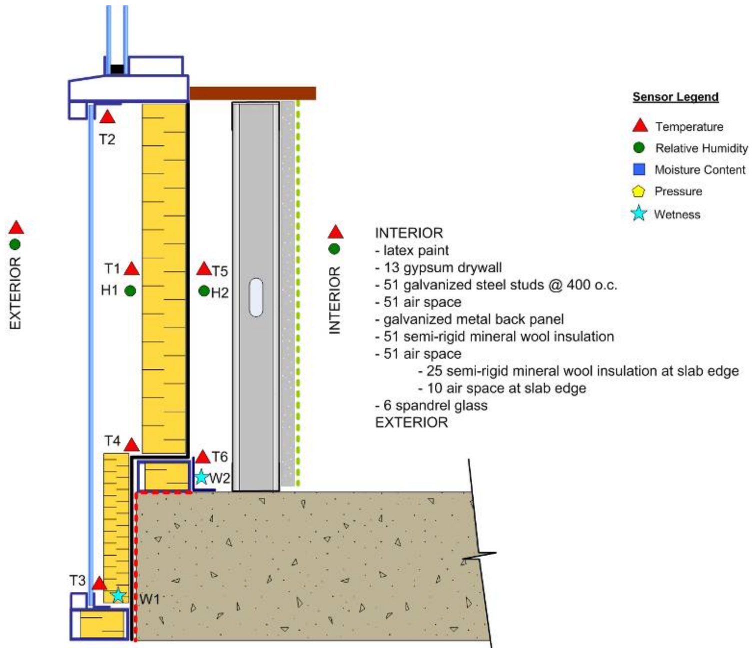


Figure 9-30: Building 5 – Exterior Wall Assembly at Monitored Locations 6-8

Data is presented from the stucco rainscreen and the spandrel panel assemblies separately in the following sections.

9.2.1.1 Uninsulated Stud Cavity Conditions

The relative humidity trends within the uninsulated stud cavities for the eight monitored walls are presented. Figure 9-31 shows data from the five stucco rainscreen wall assemblies and Figure 9-32 shows data from the three spandrel panel assemblies. Data from January 1st 2004 to December 31st 2004 is presented in all cases.

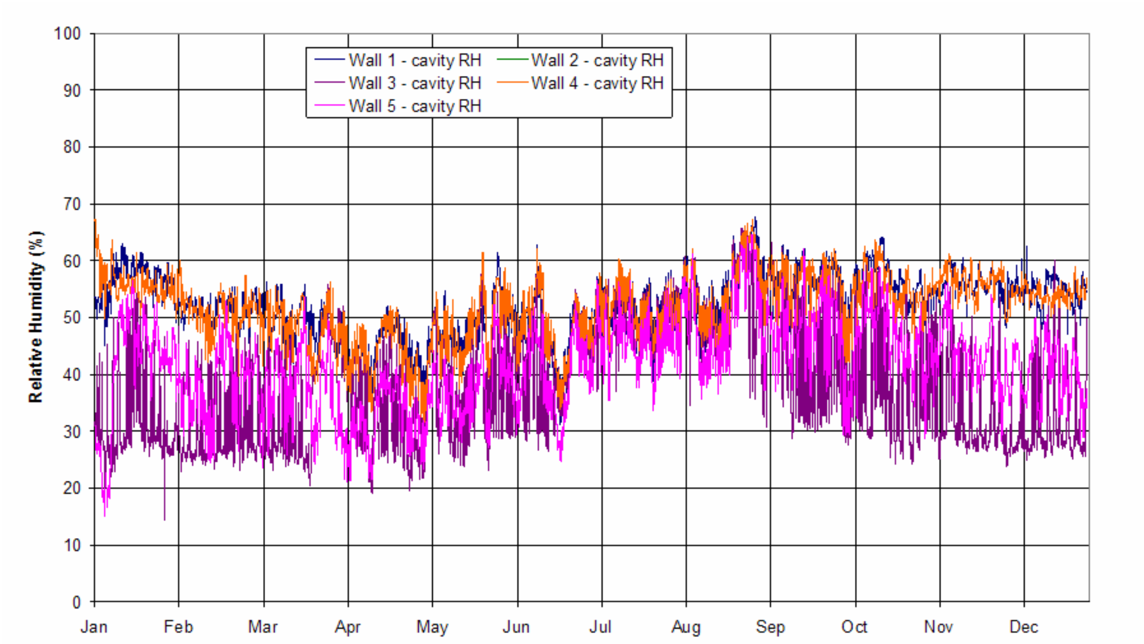


Figure 9-31: Relative Humidity within Uninsulated Stud Cavities (Wall 1-5)

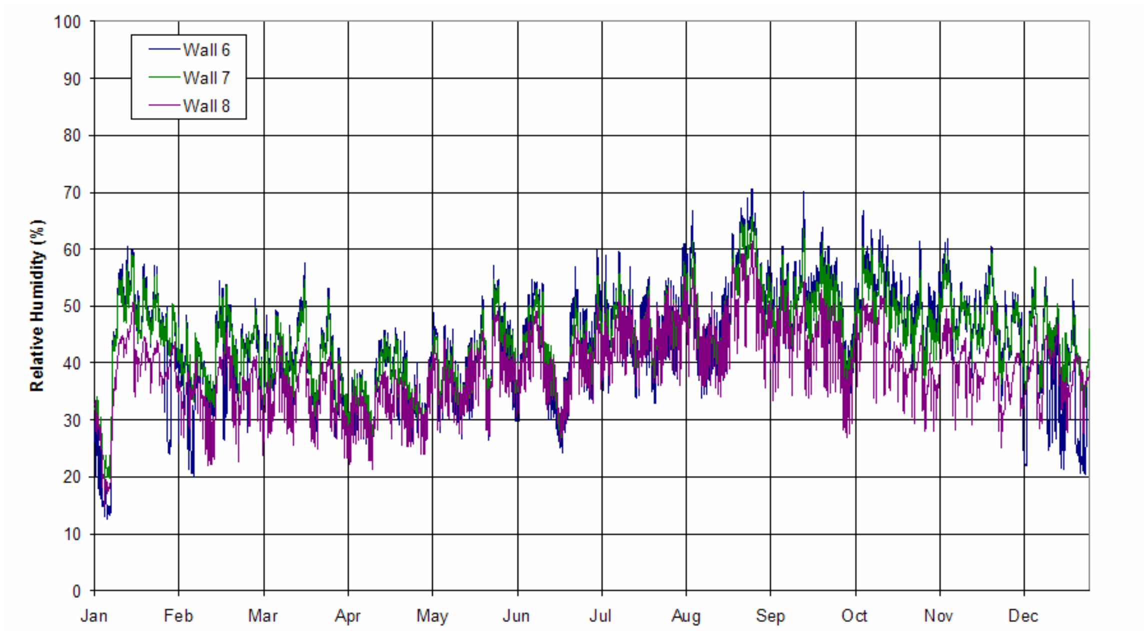


Figure 9-32: Relative Humidity within Uninsulated Stud Cavities (Wall 6-8)

The relative humidity levels within this stud space remain well within safe limits, below 50% on average, with peaks up to 70% for a few days during the summer. The relative humidity within the stud cavity is a function of the interior relative humidity, separated only by painted gypsum drywall and not well air sealed. The interior relative humidity is shown in Figure 9-33 for suite 3005 and 504.

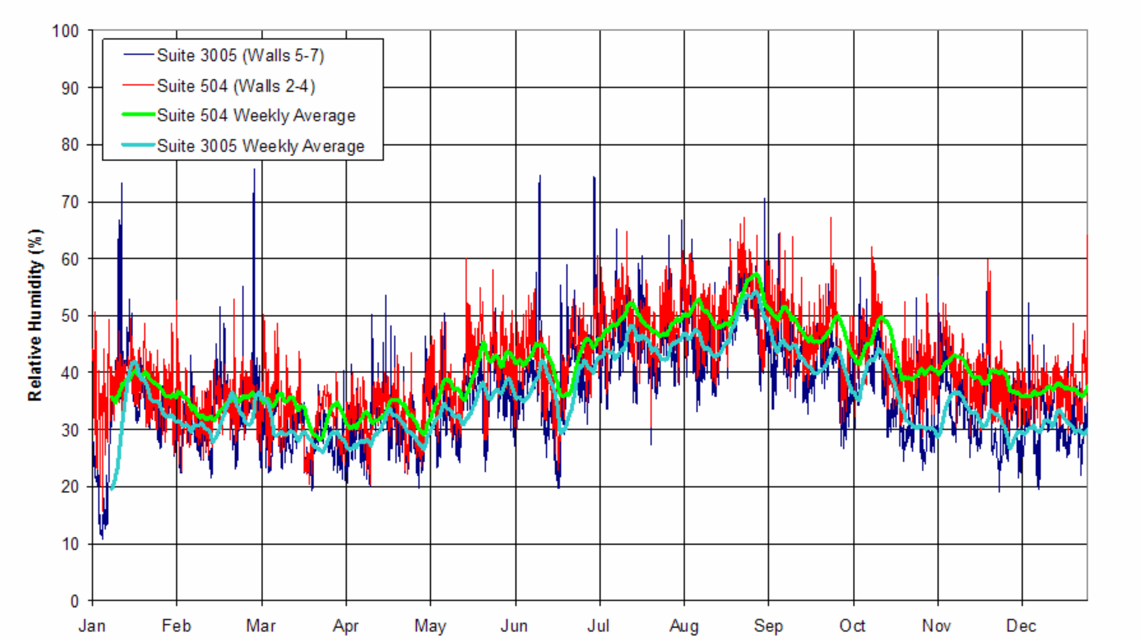


Figure 9-33: Relative Humidity within Interior of Monitored Suites

As the relative humidity levels within the stud space in contact with the gypsum sheathing remained below 50% on average, the moisture content of the gypsum sheathing remained very low (Figure 9-34). The conditions were dry enough that for much of the year a reading was not recorded (ie. electrical resistance is too high, >1000 MΩ) and defaulted to the lowest calculated value of 0.32% MC.

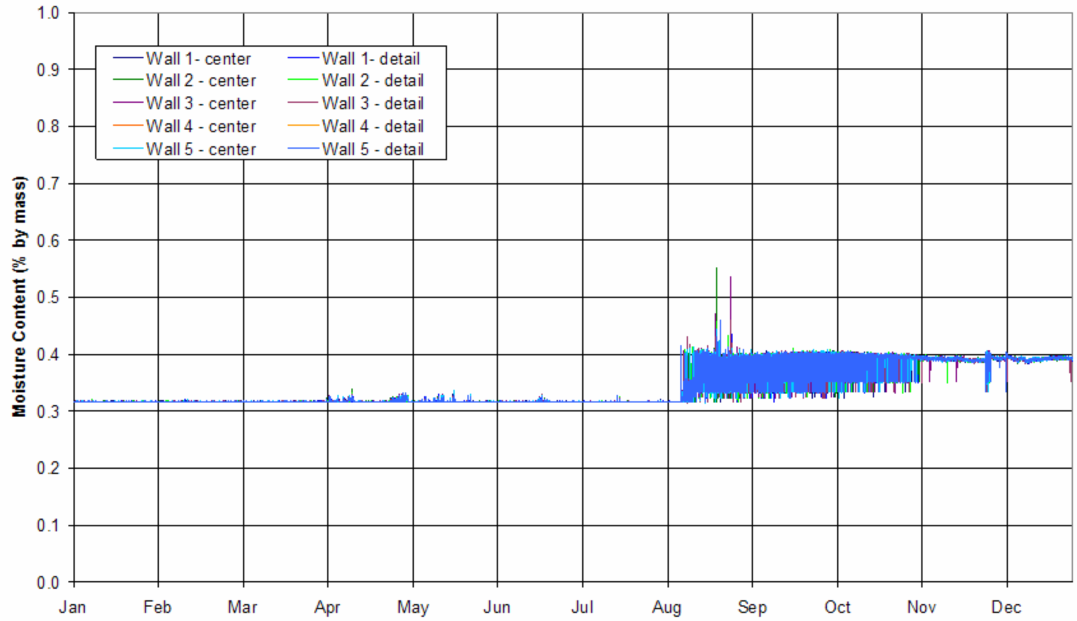


Figure 9-34: Gypsum Sheathing Moisture Content

A jump in moisture content readings occurs in August corresponding to when relative humidity levels rose slightly from 50% to 60% RH, however remained at dry and safe levels.

9.2.1.2 Ventilated Rainscreen Cavity

The relative humidity and temperature trends within the ventilated spandrel cavity are presented for monitored wall locations 1 through 5. The hourly cavity temperatures are shown in Figure 9-35 and a one week peak period August is further examined in Figure 9-36. Relative humidity levels within the ventilated cavity are also shown in Figure 9-37.

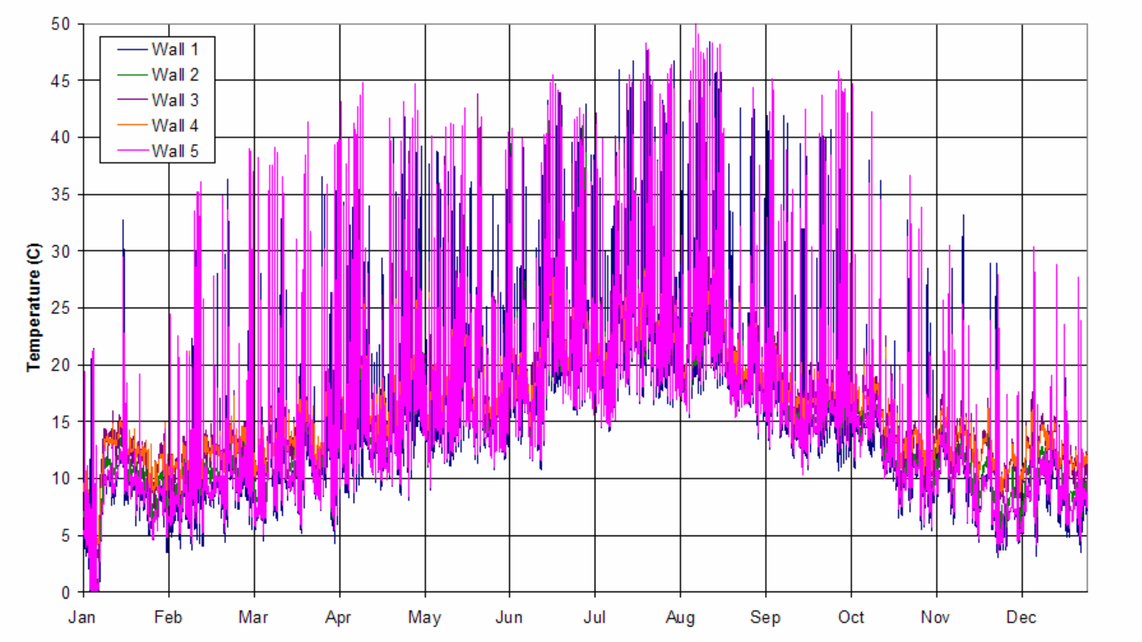


Figure 9-35: Temperature within Ventilated Rainscreen Cavity – Wall 1-5

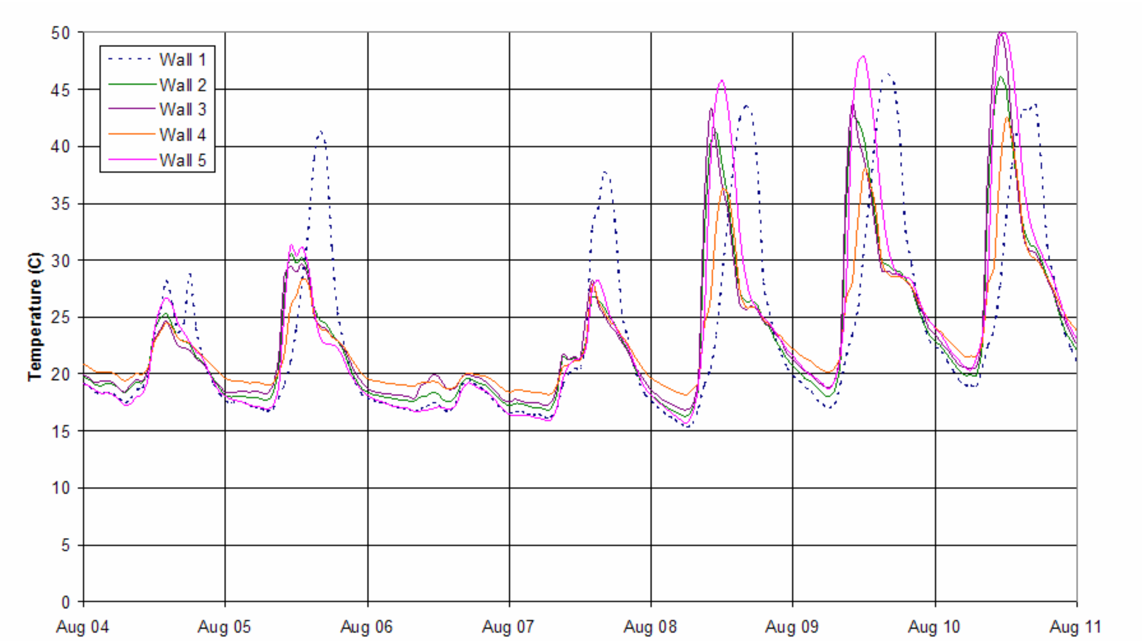


Figure 9-36: Temperature within Ventilated Rainscreen Cavity – Wall 1-5, August 4th to 11th, 2004.

Temperatures within the cavity during the summer months are consistently up to 50°C within the ventilated cavity. Note that walls 2 through 5 are on the southeast and wall 1 is on southwest, hence the delayed peak temperature on the southwest. High cavity temperatures were also observed in the winter months when cavity temperatures regularly rise to 10-30°C above ambient conditions.

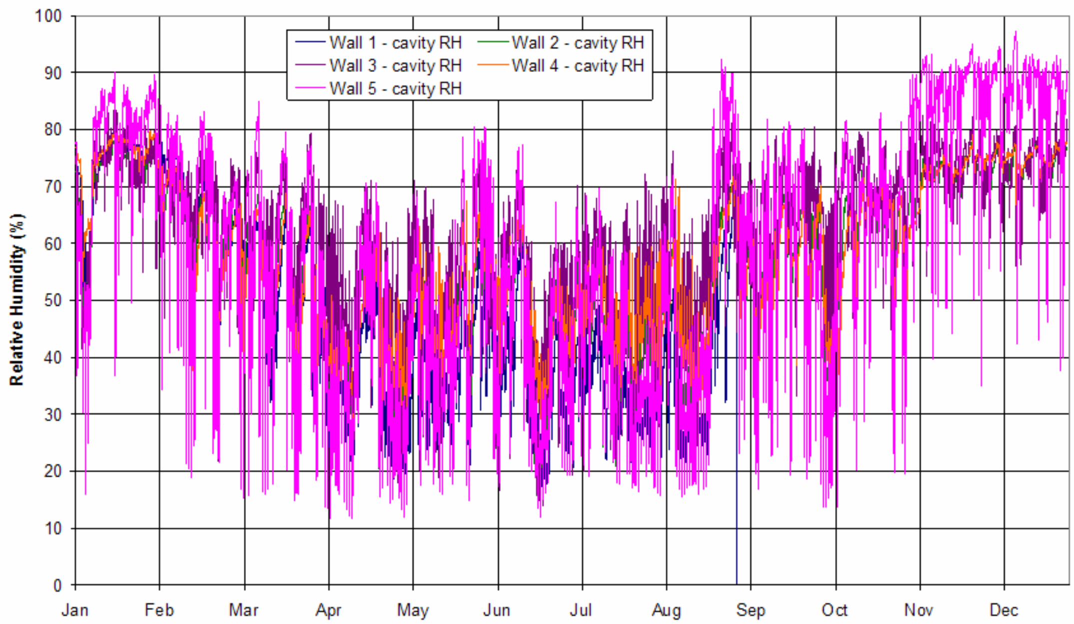


Figure 9-37: Relative Humidity within Ventilated Rainscreen Cavity – Wall 1-5

On average the ventilated cavity remained drier and warmer than the exterior measured at the roof-top. On average the exterior conditions were annually 11.4°C, 79% RH and 7.8°C dewpoint at the roof, while in the ventilated cavities were 16.1°C, 58% RH and 6.5°C dewpoint.

Lower cavity relative humidity and dewpoint levels were observed at this building compared to the wood frame rainscreen walls. The benefits of cladding ventilation are also not realized with this type of exterior insulated and air/vapour/moisture sealed assembly, where there the non-moisture sensitive components do not benefit from the drying effects of ventilation. Ventilation does however allow inward driven moisture from absorptive claddings (ie. stucco) to escape and keep the cavity relative humidity levels drier than the exterior.

9.2.1.3 Spandrel Panel Cavity

The relative humidity and temperature loads within the spandrel cavities are also of interest to window-wall manufacturers to understand field exposure conditions, and with selecting appropriate materials to withstand these potentially challenging conditions. The temperatures observed within the spandrel cavity reach up to 70°C for several hours on numerous occasions and are shown in Figure 9-38 for the entire year and in Figure 9-39 during a peak event in August. Solar radiation on a horizontal surface is also plotted to show the impact it has on the spandrel cavity temperatures.

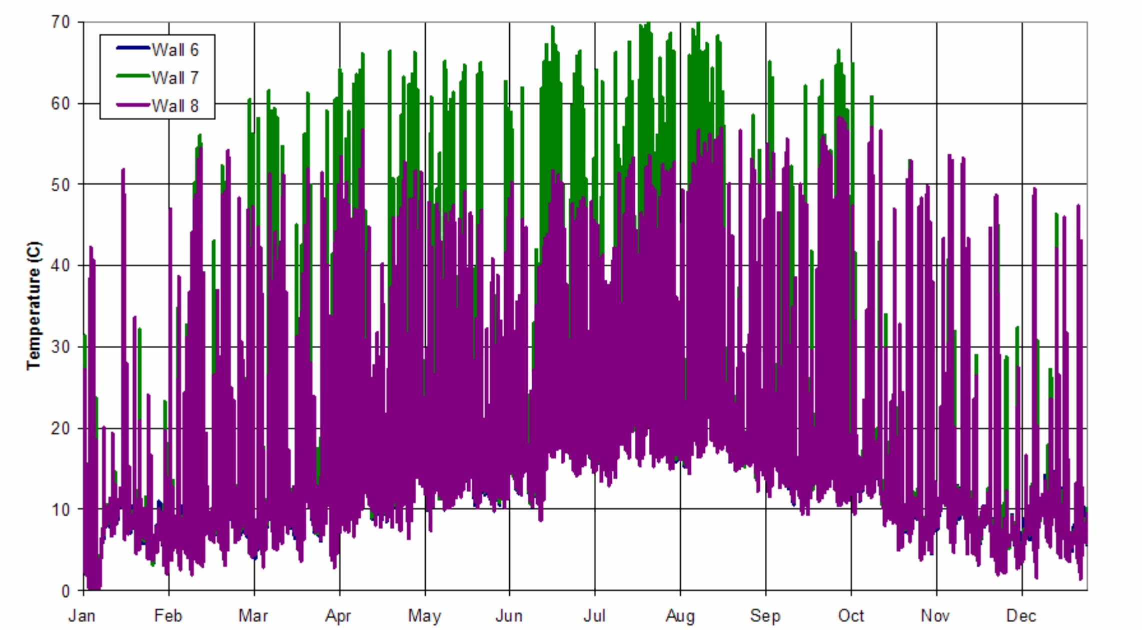


Figure 9-38: Building 5 – Spandrel Panel Temperatures, Jan-Dec 2004

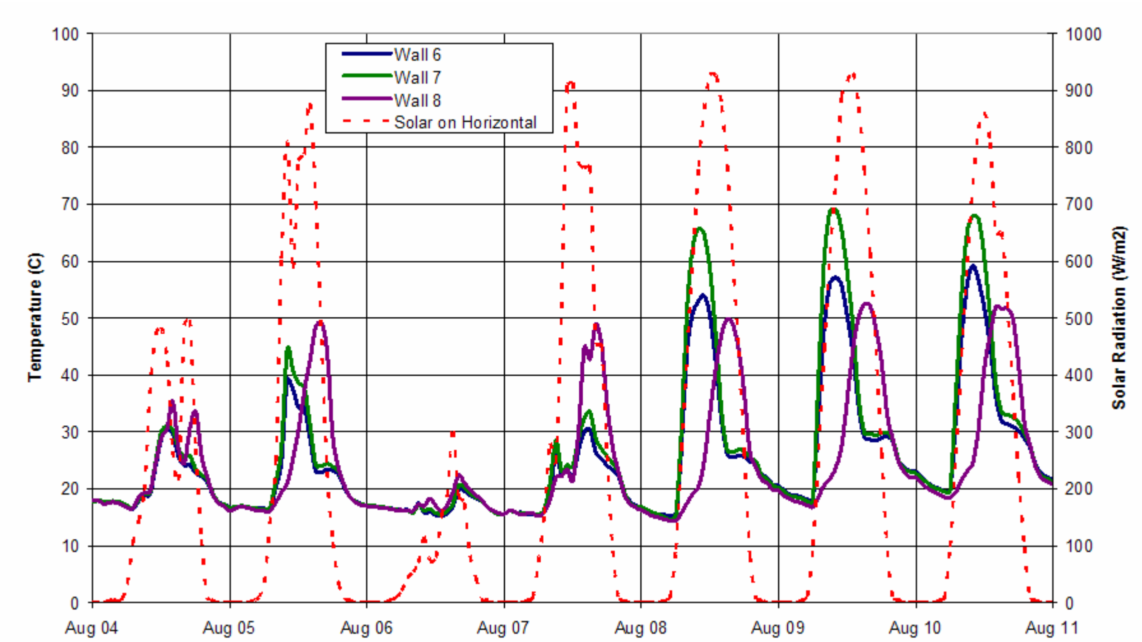


Figure 9-39: Building 5 – Spandrel Panel Temperatures, Aug 4-11, 2004.

As shown, temperatures within the spandrel cavities are up to 50°C higher than ambient air temperatures. Note that walls 6 and 7 are on the southeast, while wall 8 is at the southwest, again with a later peak temperature.

The significant impact of solar radiation is shown on August 6th, which was a cloudy day where the walls were only exposed to diffuse radiation. On this day the spandrel cavity temperatures remained close to the ambient air temperature. In contrast the days following with full direct solar radiation saw the highest temperatures, immediately up to 30-50°C higher.

The hourly temperature difference between the spandrel space and exterior ambient conditions is shown in Figure 9-40, showing regular peaks between 40-50°C above ambient conditions.

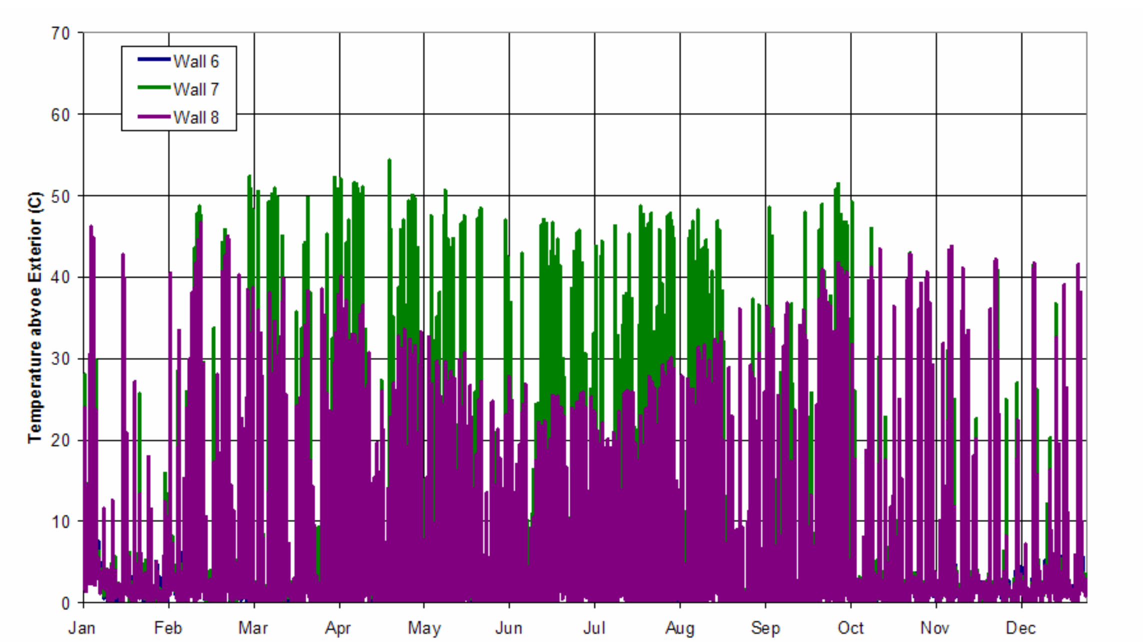


Figure 9-40: Temperature Difference between Spandrel Panel and Exterior

The peak temperature differences between the spandrel cavity and exterior air occur in spring and fall as a result of high solar radiation combined with lower exterior temperatures.

The relative humidity levels within the two spandrel cavities is also shown in Figure 9-41, and observed to be between 90-100% for most of the year. The spandrel panels are not ventilated; however some small drainage holes were provided which may have provided some venting of the air space. The source of moisture is potentially entrapped moisture or as a result of small water leaks into the assembly. The concrete slab edge may also be partially exposed allowing the evaporation of construction moisture into the cavity.

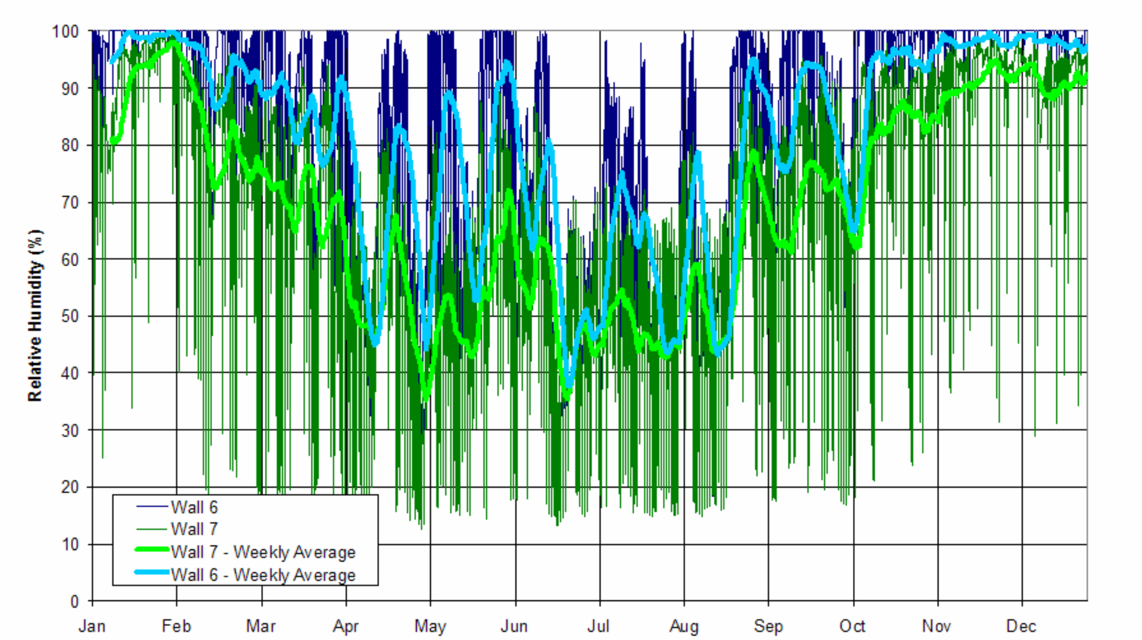


Figure 9-41: Relative Humidity within Spandrel Cavity

The high relative humidity within the spandrel cavities are potentially of concern for corrosion of some elements. The insulation when damp will also have reduced performance, however could not be measured here. Potentially allowing ventilation within this space would reduce the relative humidity levels however may have implications for design.

9.2.2 <u>Conclusions – Building 5</u>

The exterior insulated stucco rainscreen wall assembly performed very well at Building 5. Moisture sensitive materials were kept dry and the relative humidity within the interior stud space remained at levels only slightly above interior conditions. No evidence of moisture penetration was observed at any of the wall locations.

The window-wall spandrel panel assemblies also appeared to perform well, however the impacts of the high temperatures and relative humidity levels within the spandrel cavity space could not be ascertained. It is likely that the conditions observed are normal; however other field data and measurements for this type of wall assembly is generally lacking. The impact of such high temperatures on the long-term adhesion of the exposed peel-and-stick air/vapour barrier at transitions within the spandrel panel is questionable. Mineral wool insulation as used here is typically used in spandrel cavities not only for its ease of fitting, but also resistance to high temperatures. Materials such as XPS or EPS or even polyurethane sprayfoam may not perform as well and can be degraded or even melt at high temperatures.

It is important to realize that the high temperatures and subsequent vapour pressures observed within the ventilated rainscreen cavity or spandrel cavity spaces are loads on the rest of the wall assembly. Temperature gradients are significantly higher than predicted by ambient exterior conditions and for simple calculations or modeling applications (energy or hygrothermal) these temperatures need to be considered. These high solar induced temperatures impact building mechanical systems, and as observed in this building, interior temperatures during the summer were frequently in the 25-30°C range as air-conditioning was not provided.

10 WALLS FOR THE FUTURE: LEASONS LEARNED AND MOVING FORWARD

In summarizing the performance of the different monitored rainscreen wall assemblies (interior insulated wood-frame and exterior/split insulated steel-stud/gypsum frame), hygrothermal modeling is used to further understand the hygrothermal performance and to recognize the susceptibility of the chosen assemblies to different boundary conditions and assembly details. With knowledge of the observed measured performance and predicted performance using a validated hygrothermal model, recommendations for improvements can be made with greater confidence.

The hygrothermal model used to perform the analysis is presented and discussed in *Appendix B: Hygrothermal Modeling*. In summary, the model was found to be accurate in predicting the observed measured performance of the rainscreen wall assemblies as discussed in Chapters 8 & 9.

10.1 WOOD-FRAME WALL ASSEMBLIES

Hygrothermal modeling was used to investigate the impact of boundary conditions and assembly details on the performance of interior insulated wood-frame rainscreen walls. Using the validated hygrothermal model, the impact of cladding ventilation, rainwater leaks, exterior insulation, interior vapour control strategy, and interior relative humidity is shown on the wall assemblies for Buildings 1, 2, & 4.

10.1.1 Predicted versus Measured Conditions

The accuracy of the hygrothermal model is shown in Figure 10-1, comparing the measured to the predicted sheathing moisture content at Building 1 (ventilated vinyl siding clad rainscreen). Data is presented for one year from January 1st to December 31st 2002 and in detail for two months from October 1st to November 30th.

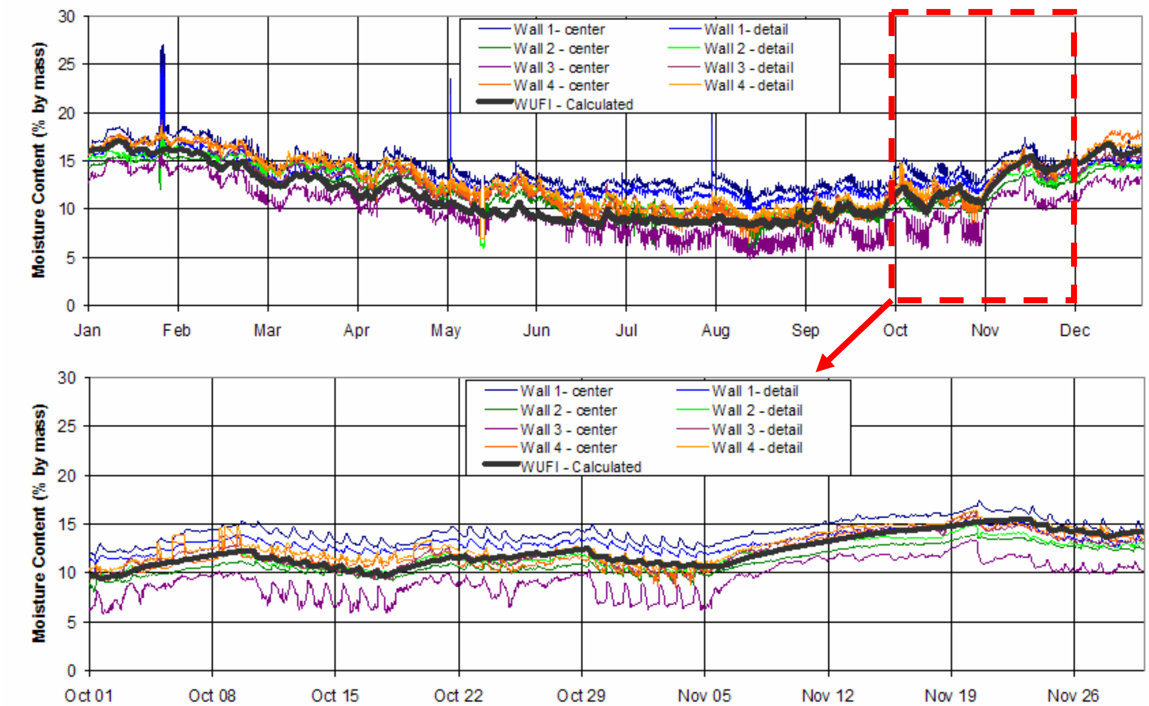


Figure 10-1: Building 1 – Comparison of Sheathing

The accuracy of the hygrothermal model to predict the performance of Buildings 2 and 4 (stucco and cement board clad ventilated rainscreen) was also good and is further discussed in the Appendix.

Using the validated base model for each building and wall assembly, individual parameters (materials or boundary conditions) were modified and modeled separately to determine the relative impact on wall performance. This process provides confidence in the accuracy of the model when extrapolating to further cases.

10.1.2 Modeling Past Failures

After validating the WUFI hygrothermal model the same boundary conditions are applied to a few historical wall designs, in an attempt to help explain some of the previous wall failures seen in Vancouver. The ventilated rainscreen wall is compared to two direct applied face-seal stucco walls (a cement and lime-stucco case), a rainscreen wall without cladding ventilation, and a case where the rain load is doubled for a face-seal cement stucco wall. Two-year simulations were run to determine if a net annual moisture accumulation occurs and the results are presented in Figure 10-2.

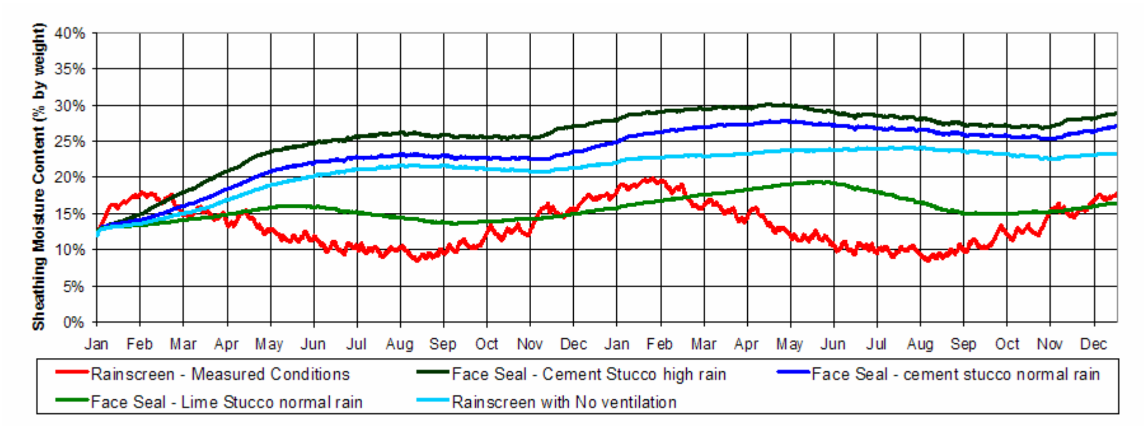


Figure 10-2: Comparison of Rainscreen to Historical Face-Sealed Assemblies

The results show that the cement stucco assemblies accumulate moisture over each year, gradually leading to dangerous moisture contents (>30% within 3 years). The lime-stucco face-seal wall performed better than the cement-stucco as it is approximately two-times as vapour permeable as the cement-stucco. While this is not the reason for the failure of all face-sealed stucco assemblies, it does show the importance of the vapour permeability (and drying potential) of an absorptive cladding in a non-ventilated wall case. Also of note is the onset of the peak moisture loading of the sheathing in the simulated cases, occurring later in the spring-summer, where as with the measured ventilated rainscreen case, the peak moisture content is from January to February.

10.1.3 <u>Impact of Cladding Ventilation</u>

As discussed in Chapter 2, the ventilation rate behind the cladding has an impact on the performance of the wall assembly. The impact of ventilation was investigated with the model for the stucco rainscreen clad walls at Building 2. Fixed ventilation rates of 1, 10, 50, 100, 140, and 200 ACH were considered as well as an hourly varying ventilation rate calculated from the measured buoyancy pressures (refer to Chapter 2 - average 140 ACH) in Figure 10-3.

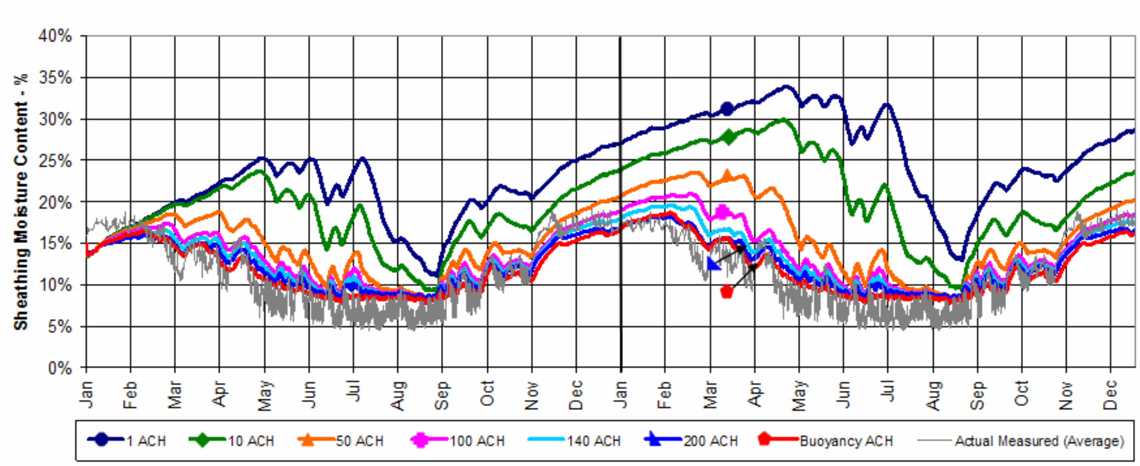


Figure 10-3: Effect of Cladding Ventilation on Moisture Content of Sheathing.

From the results, it is clear that the cladding ventilation rate can have an significant effect on the modeled performance of rainscreen walls in Vancouver's climate. Lower ventilation rates will result in higher sheathing moisture contents for prolonged periods of time during the warm spring-summer months, which could allow mould growth and decay. Similar observations were made by Karagiozis (2002) using the Moisture-Expert computer model for ventilated stucco walls in Seattle (Figure 10-4).

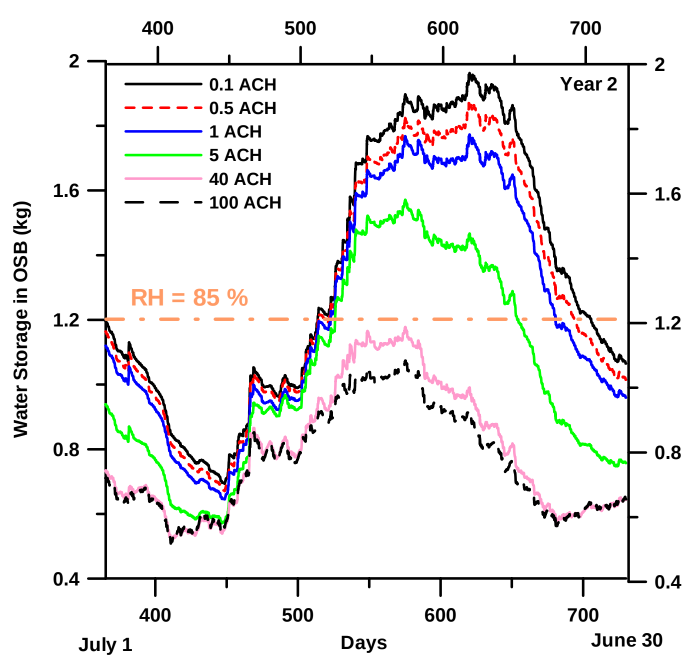


Figure 10-4: Effect of Cladding Ventilation on Water Storage in OSB Sheathing – 2nd year of modeling (Karagiozis 2002).

The results highlight the importance of cladding ventilation for interior insulated wood-frame rainscreen wall assemblies. Modeling shows that higher ventilation rates could improve the performance of wall assemblies, but there appears to be a limit in this case around 200 ACH. For example providing 1000 ACH does not significantly improve the drying under normal conditions. The modeling also shows that if the cavity ventilation rates were lower (more restrictive vent openings); high sheathing moisture contents would likely be observed. Preventing ventilation completely (i.e. blocking vent openings) has a potentially catastrophic effect, and measures should be taken in the field to ensure vent openings at the top and bottom of the wall cavities.

As discussed in Chapter 2, the larger the cavity, the greater the ventilation flow for similar driving pressures. The vent details are an important consideration in rainscreen wall design, and should be made as large and unobstructed as possible without allowing rain penetration or bird/animal/insect ingress.

10.1.4 Impact of Rainwater Leaks

As suggested by the monitoring observations, rainwater leaks have the potential to raise sheathing moisture contents to unsafe levels. Therefore the impact of controlled rainwater leaks into the wall assembly was modeled. The stucco-clad rainscreen model (Building 2) was used in the modeling scenario with a leak depositing moisture at one of three locations within the wall assembly. The leak was inserted as a percentage of the driving rain, and representative of a detail which leaked during every rain event. The total driving rain for the simulation was 373 kg/m^2 and the three modeled cases consisted of: 0.1% (0.37 kg/m^2), 0.5% (1.87 kg/m^2) and 1.0% (3.73 kg/m^2). The moisture source was placed into the model at either the exterior or interior surface of the plywood sheathing or at the exterior of the sheathing membrane.

It was found that adding the leak to the exterior surface of the sheathing membrane had a negligible impact on the sheathing moisture content, as the additional moisture was easily removed by ventilation flow for this particular wall assembly. However when the leak occurred at either plywood surface, past the sheathing membrane, the moisture was absorbed and increased the sheathing moisture content. The results for six cases are presented in Figure 10-5. The leak at the exterior side of the sheathing shown in the left plot, and the leak at the interior insulation/sheathing interface is shown in the right plot. Vapour diffusion drying was prevented to the interior by the use of an interior polyethylene vapour barrier, and as no annual storage was observed, all added moisture from the leak was removed from the wall assembly by ventilation to the exterior.

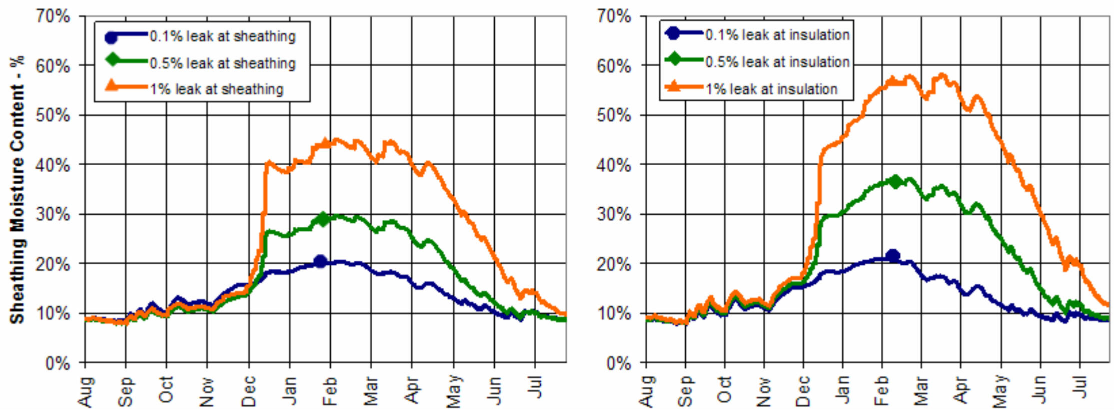


Figure 10-5: Effect of Rainwater Leaks within Stucco Clad Rainscreen Walls in Vancouver, BC

All cases dry-out by the summer in this climate but reach dangerous levels for several months if greater than 0.1% (> 0.4 kg/m^2) leakage occurs. The location of the leak is shown to have an impact on the results, where higher sheathing moisture contents were attained when the leak occurred at the interior face of the sheathing. As suggested the vapour permeance and moisture transport properties of the sheathing can limit or reduce the drying potential.

In reality, most leaks tend to be localized not uniformly distributed as assumed by the model and hence some redistribution of moisture will occur within the wall assembly (i.e. from wet to dry areas). To model the effect of a small leak and the impact it has on the surrounding materials, two-dimensional or three dimensional models are required to account for moisture redistribution to un-wetted materials. The one-dimensional model can show the effect of large widespread leaks, but may not be able to accurately model small isolated leaks. Further research is required in this field before guidelines can be developed to accurately model most leaks.

The modeling confirms the field observations that rainwater leaks have the potential to raise sheathing moisture contents to unsafe levels during the winter months. Small leaks may be safely stored by the sheathing; however larger leaks can elevate the sheathing moisture content to unsafe levels for several months of the year. Leaks that penetrated the strapped cavity but not the sheathing membrane were removed by ventilation.

10.1.5 Impact of Driving Rain

The impact of the driving rain load on the performance of rainscreen walls was investigated (without leaks). Stucco clad Building 2 was used for the analysis and the base-case consisted of a rain deposition factor (RDF) of 0.5 and shelter factor of 0.5. Higher and lower driving rain deposition was modeled by adjusting the RDF and sheltering factors. In addition, the driving rain load was tripled from approximately 300 mm/yr to 900 mm/yr as measured at YVR (see Chapter 5) and modeled. A two year simulation is presented starting on January 1st in Figure 10-6.

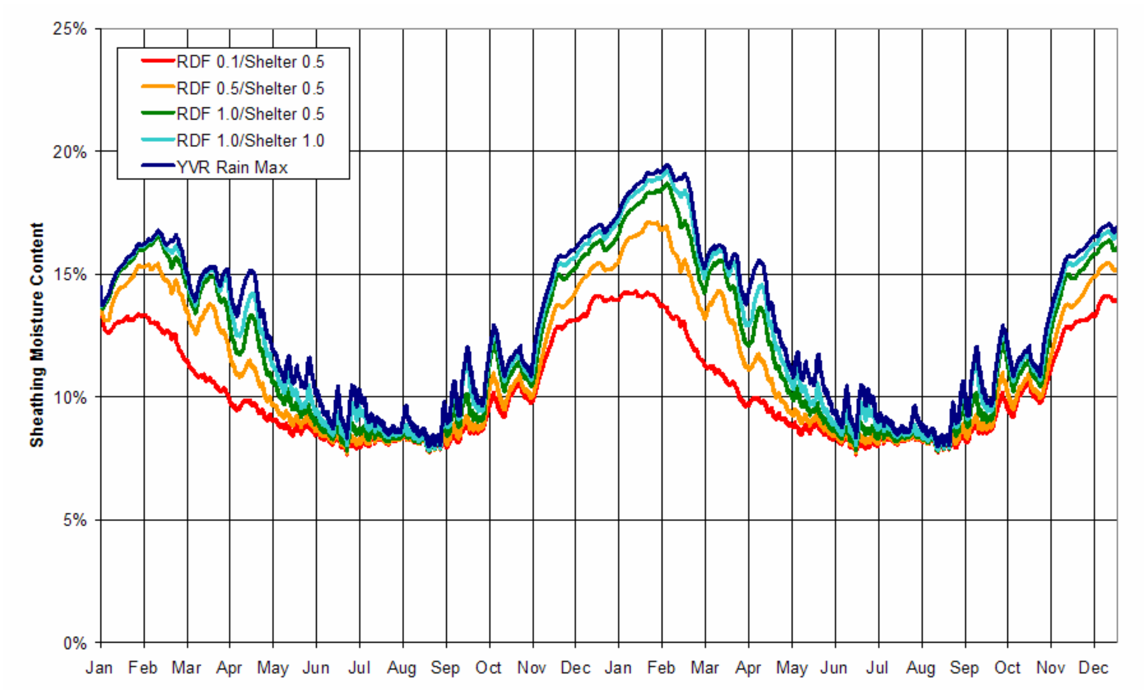


Figure 10-6: Impact of Driving Rain Load on Ventilated Stucco Cladding

The modeling shows that while the cladding is decoupled from the wall by a ventilated cavity, absorptive claddings act as a small moisture source to increase the relative humidity within the ventilated cavity and subsequently the sheathing moisture content of the sheathing. However, the increase in moisture content is small and not significant enough to raise the sheathing moisture content above 20% for this particular ventilated wall assembly. It also shows that modeling the precise driving rain load on a building may not necessarily be critical to the analysis of a well ventilated rainscreen wall assembly (provided leaks are not modeled). Again if the cladding ventilation was reduced, the moisture content of the sheathing would be affected as shown in Figure 10-7 for the 900 mm/yr case and similar to results presented in Figure 10-3 showing the relative importance of ventilation.

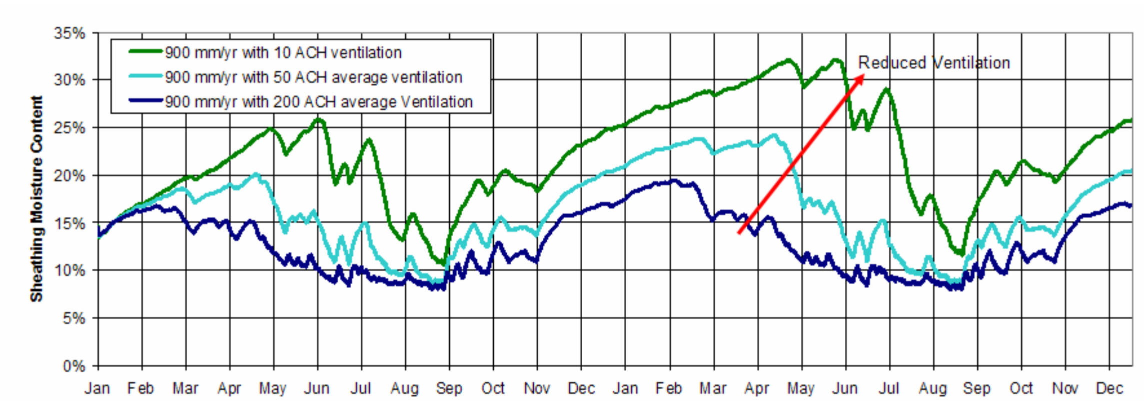


Figure 10-7: Impact of Cladding Ventilation on High Driving Rain Load

10.1.6 <u>Impact of Vapour Control</u>

It has been suggested by some that the interior vapour control layer may be too tight and restrict drying in case of a leak into the stud cavity. Therefore the impact of the permeance of the vapour control layer was modeled on the performance of the wall. Four cases are compared to the measured conditions comparing: vapour retarding paint (35 ng/Pa m^2 s), latex paint (250-500 ng/Pa m^2 s) and a smart vapour retarder (Künzel 1998) in Figure 10-8.

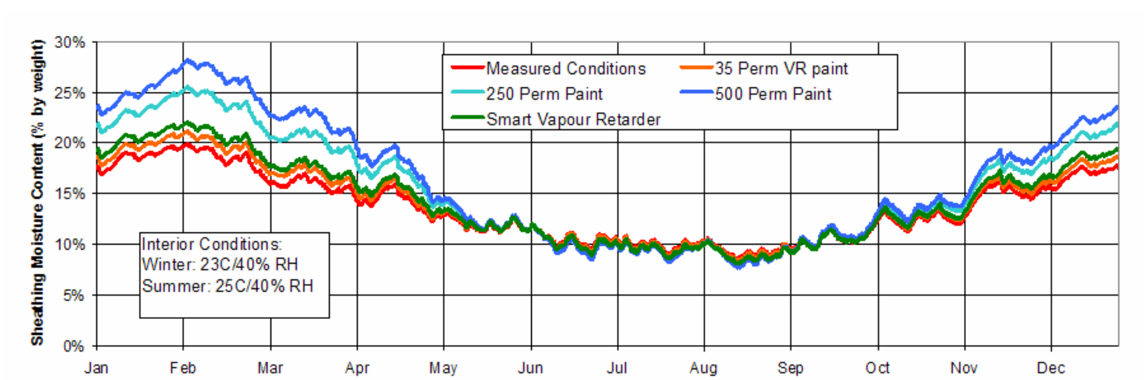


Figure 10-8: Impact of Interior Vapour Control Permeance

The results show the importance of vapour control under design conditions (no air leakage or rain leaks). Replacing the polyethylene vapour barrier with paint will result in higher wintertime moisture levels in the exterior sheathing as a result of vapour diffusion from the interior. This results as paint allows more moisture to flow into the wall from the interior during the winter, even in Vancouver's temperate climate. In more severe climates such as Edmonton or Ottawa the impact of interior vapour control is more severe than shown here.

If the polyethylene vapour barrier is removed, the interior conditions become much more important to the performance of this wall assembly and are analyzed. Air leakage must also be controlled using other means, such as interior drywall and sealed penetrations. Air leakage would exacerbate the results in Figure 10-8, potentially increasing moisture contents to unsafe levels during the winter.

Four different interior boundary condition cases were modeled varying the average wintertime RH from 40% to 55% (a probable range for Vancouver based on the interior RH from the five buildings of this study) to show the impact of RH on sheathing moisture content (Figure 10-9). The interior vapour permeance was set at 250 ng/Pa·m²·s (latex paint) and interior temperature at 21°C for simplicity of the analysis.

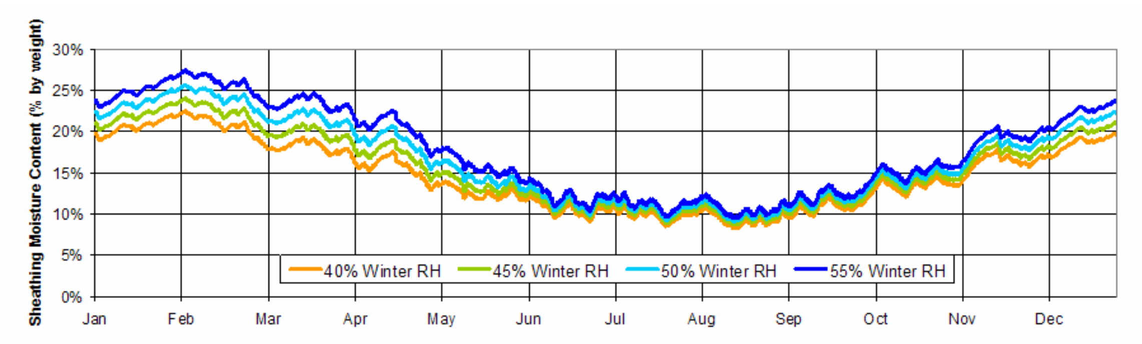


Figure 10-9: Impact of Interior RH on Sheathing Moisture Content

The simulations show that under the modeled conditions of an average 40% wintertime RH, the 250 ng/Pa·m²·s paint will perform marginally, as the moisture level of the sheathing will remain above 20% from mid January to mid February. At higher interior RH levels, a 5% increase during the winter will result in an approximately 2% increase in the peak sheathing moisture content for this particular wall and exterior conditions.

The seasonal vapour pressure differences are compared in Figure 10-10. Vapour pressure differences are measured between the sheathing and the interior, and between the sheathing and the ventilated cavity. A positive value indicates a drying potential and a negative indicates wetting. The plot shows the importance of interior humidity control, particularly during the fall and winter months, when a difference between 55% and 40% RH can more than triple the vapour pressure differential resulting in wetting of the sheathing.

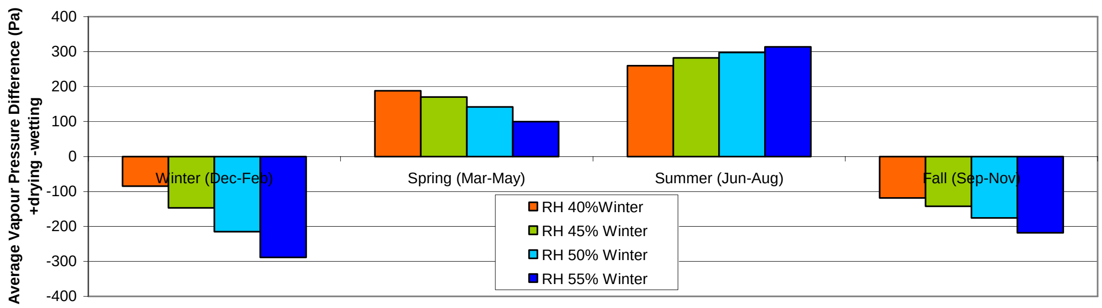


Figure 10-10: Seasonal Vapour Pressure Differences – Impact of Interior Relative Humidity

For an interior-insulated rainscreen wall assembly, it was shown that removing the interior polyethylene vapour control layer will increase wintertime wetting in Vancouver's climate at a rate depending on the permeance of the interior vapour control layer. As the vapour permeance of the interior surface is increased, the interior relative humidity becomes more critical to the performance of this wall assembly.

10.1.7 <u>Improving Rainscreen Wall Performance</u>

For a typical interior-insulated rainscreen wall in Vancouver, the relative humidity within the ventilated cavity has a significant impact on the moisture content of the sheathing. The sheathing will come into equilibrium with the ventilated cavity conditions which can be elevated between 80-100% RH during the wet humid-winter months. To protect the sheathing from the humid ventilated cavity, a layer of exterior insulation is suggested. This has the result of increasing the sheathing temperature and lowering the RH at the sheathing surface. It also increases the drying potential of the sheathing in event of a leak (warmer drier surface) as discussed in *Appendix C: Maximum Drying Potential Model*.

The more insulation placed on the exterior of the sheathing the better the energy and moisture performance. While a wall system with the insulation placed entirely on the exterior of the exterior sheathing may perform the best, this approach may not always provide sufficient overall thermal resistance for all building types/locations. Therefore, insulation should be placed on both the exterior of the sheathing and within the stud space to achieve high thermal values (split-insulation). For stud cavity insulation, fiberglass batt, or other vapour-open insulation materials such as open-cell sprayfoam or cellulose, should be placed within the stud space to allow drying to the interior.

Stud cavity insulation is particularly beneficial in wood frame buildings, where thermal bridging effects of the wood studs past the insulation is minor compared to walls with steel studs. For steel stud framed walls, the benefit of using stud cavity insulation is reduced to the extent where R-20 fiberglass batt installed properly results in an overall thermal resistance of less than R-10.

A base rainscreen wall case is modeled for comparison with the potential upgrades. In addition, the impacts of leaks (1% of 222 kg/m^2) or 2.2 kg/m^2 and ventilation (or lack thereof) is modeled for each upgrade. The base wall assembly modeled consists of stucco cladding, a 19 mm ventilated airspace (calculated based on buoyancy pressures, average 150 ACH), building paper, plywood sheathing, 140 mm R-19 batt insulation, polyethylene vapour barrier, and latex painted gypsum drywall (250 ng/Pa m^2 s).

The effects of ventilation, leaks, and interior vapour control layer are shown in Figure 10-11. Four cases are compared to the measured conditions: ventilated without a leak, ventilated with a leak, no ventilation and no leak, and a leak in a wall without polyethylene.

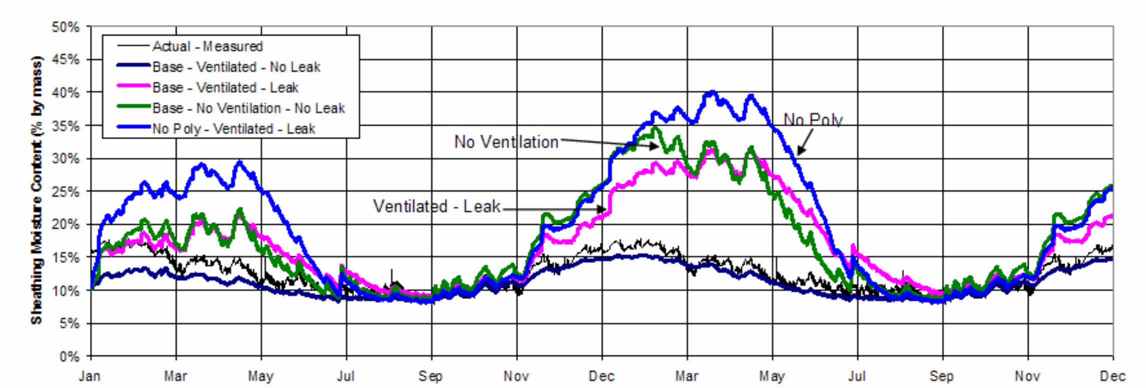


Figure 10-11: Base Rainscreen Wall Model – Effect of Ventilation, Leaks, & Interior Vapour Control on Plywood Sheathing MC

As shown, removing the polyethylene from a wall assembly that is insulated on the interior of the sheathing does not improve the drying potential in the case of a leak. In this case, outward vapour diffusion during the winter further wets the sheathing, above the driving rain moisture level and does not appear to benefit from drying to the interior. The impacts of ventilation and leaks are shown, and similar to that discussed in the past sections.

To improve the performance of the wood-frame rainscreen walls, exterior insulation is applied. Aside from the obvious thermal and energy benefits, it sufficiently warms the sheathing which reduces the wetting potential and improves the drying potential. A rigid vapour impermeable XPS insulation (25 ng/Pa·m²·s) is compared to a semi-rigid vapour permeable mineral wool insulation (~2000 ng/Pa·m²·s) in Figure 10-12. In each case shown, 50 mm of insulation was modeled; however 25 mm also had similar performance.

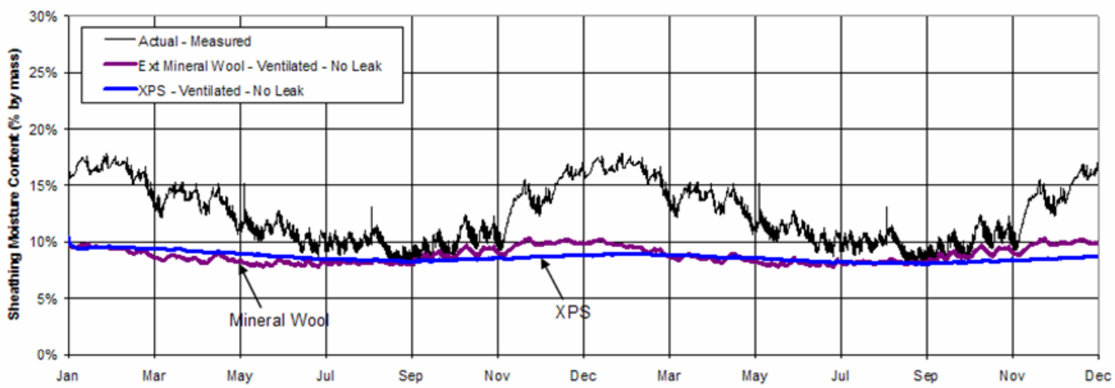


Figure 10-12: Impact of Exterior Insulation on Plywood Sheathing Moisture Content

The performance of both the impermeable and impermeable insulations is shown to be the same, with the XPS resulting in slightly drier conditions and few fluctuations. The impact of rainwater leaks are further modeled for the exterior insulation cases to ensure that in the event of an accidental leak, moisture does not remain trapped at the sheathing.

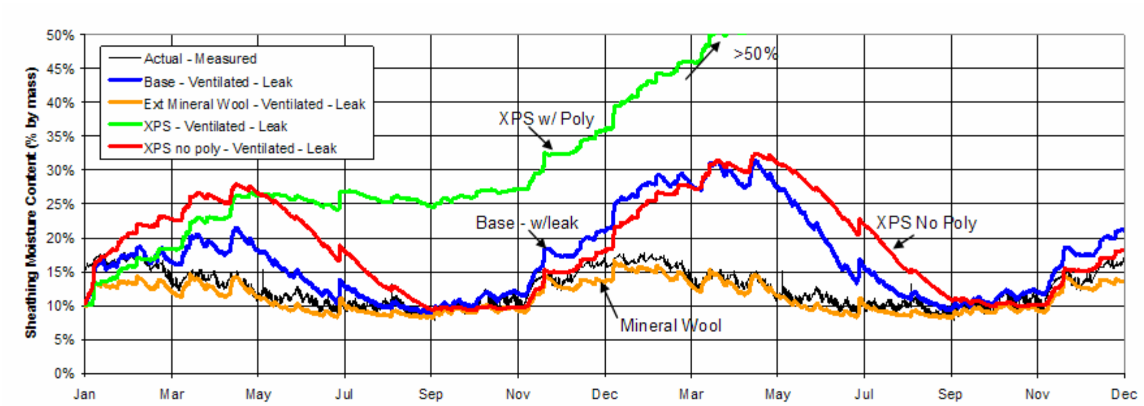


Figure 10-13: Impact of Exterior Insulation type with Rainwater Leaks on Plywood Sheathing MC.

The difference between the vapour open and impermeable insulation is clearly shown, and the vapour open mineral wool outperforms the XPS by a large margin. With the XPS, drying is prohibited to the interior and exterior when the poly is left in the wall, and prevented to the exterior when the poly is removed. By removing the polyethylene from the interior, the performance is similar to that of the base case with leaks. EPS insulation while having a higher vapour permeance than XPS (100-150 compared to 25 ng/Pa·m^2·s for XPS) has similar poor drying performance in the event of a leak and these boundary conditions.

With an exterior insulated assembly, ventilation becomes less important to the wall performance as moisture evaporating at the surface of the sheathing is no longer removed by the stream of ventilation air. Instead the moisture must diffuse through the insulation and be evaporated into the cavity. Ventilation still remains helpful in reducing inward driven vapour as a result of solar loading. The difference between a ventilated and unventilated wall is shown in Figure 10-14 for the mineral wall case.

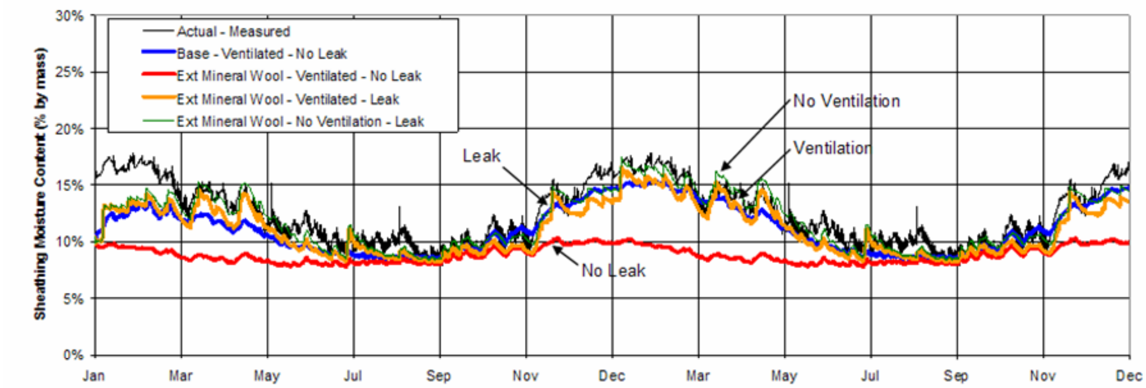


Figure 10-14: Mineral Wool Exterior Insulation – Impact of Leaks & Ventilation on Plywood Sheathing MC

The modeling shows that once the exterior of the sheathing is insulated, cladding ventilation has a reduced role on performance. As a result a vented or drained only cladding will have similar performance as a ventilated one. Therefore for walls that are inherently less ventilated such as brick veneer or pre-cast concrete with small discrete vents, exterior insulation can greatly improve performance.

One of the potential issues with adding exterior insulation is the increased thickness of the wall. Typically 2x6 studs are used in construction; however 2x6 studs are often not structurally required but used to meet thermal requirements (i.e. use of 140 mm of R-20 fiberglass batt insulation). Alternatively 2x4 studs can often be used with 2" of exterior insulation. The wall would have the same overall thickness but improved energy and moisture performance. Where 2x6 studs are structurally required (for very tall walls) and space is tight, as little as 25 mm (1") of exterior applied insulation can improve performance of the wall.

It can be seen that adding 25 to 50 mm (1-2") of insulation to the exterior of the sheathing in ventilated rainscreen walls improves the performance significantly. The use of vapour open insulation materials such as semi-rigid fiberglass or mineral-wool is more desirable from a drying standpoint, particularly in the event of a rainwater leak which penetrates to the sheathing. Less permeable insulations such as EPS or XPS may trap moisture at the sheathing in the event of a leak.

Providing additional insulation on the exterior of the sheathing will continue to improve the performance of the wall and has the added energy savings benefit. When sufficient insulation is applied to the exterior of the sheathing, a more permeable vapour control layer such as latex paint could be used instead.

Hygrothermal modeling should be used when designing wall systems to determine what level of vapour control is required for a specific climate and exposure.

Construction details may need to be modified to accommodate the additional insulation recommended, but could employ use of deeper strapping or other cladding attachment methods.

10.1.8 Conclusions

Results from this study indicate that rainwater leaks have the potential to raise sheathing moisture contents to unsafe levels during the winter. However, further testing should be performed to study the drying response of ventilated rainscreen walls wet by accidental moisture entry under controlled circumstances so more useful guidelines can be developed.

In this climate, the use of polyethylene is being reconsidered by some practitioners and builders. Common latex paint could be used as an interior vapour control layer, but it is not recommended in a traditionally constructed frame wall assembly (insulated stud space without insulation to the exterior of the sheathing) with high interior relative humidity. Vapour retarding paint (<60 ng/Pa·s·m^2) could be used as a replacement for the polyethylene; however an air barrier (typically in the form of the Airtight Drywall Approach) is still required.

Interior relative humidity control becomes more important as the interior vapour control layer becomes more permeable (i.e. if using standard paint). Hence, providing sufficient indoor ventilation is required to keep relative humidity levels indoors low.

In the coastal climate of Vancouver, one of the best ways to improve the performance of ventilated or drained rainscreen walls is to protect the sheathing from the ventilation airspace by use of thermal insulation, and the more the better. Providing as little as 25 mm of exterior insulation can greatly improve the performance by reducing the sheathing moisture content. This provides an improved factor of safety against accidental wetting from rain or interior air leakage. Ideally the insulation should be vapour permeable to allow for drying of potential rainwater leaks and removal of interior moisture. Less vapour permeable insulations such as XPS, closed cell polyurethane, sprayfoam, foil-faced polyisocyanurate, or EPS may trap moisture at the sheathing and result in damage.

In addition, as insulation is added to the exterior of the sheathing, cladding ventilation becomes less important to the performance of the wall. Therefore the performance of walls which are inherently less ventilated (such as brick veneers) could easily be improved with exterior insulation instead of trying to increase ventilation flow by larger vents etc.

With increasing energy prices and a growing interest in achieving more energy-efficient buildings, the thermal resistance of walls is likely to increase in the future. Using standard frame wall designs and increasing stud cavity insulation levels results in a reduction of the drying potential of the sheathing. Additional insulation should therefore be placed on the exterior of moisture sensitive sheathings to increase the temperature of the moisture sensitive components, and increase drying potentials. As sufficient insulation is placed on the exterior, vapour impermeable layers such as polyethylene can be removed from the interior of wall assemblies to improve drying to the interior. Hygrothermal models can be used to make informed design decisions for required vapour control.

10.2 STEEL-STUD/GYPSUM WALL ASSEMBLIES

Hygrothermal modeling was used to investigate the impact of boundary conditions and assembly details on the performance of the rainscreen walls at Buildings 3 and 5.

10.2.1 Building 3

As moisture problems were observed in the walls of Building 3, it is of interest to determine if these problems could have been predicted prior to construction. In addition the impacts of the interior boundary conditions and assembly details were investigated to develop potential repair strategies for this wall.

10.2.1.1 Predicted versus Measured Conditions

To model the performance of the wall assembly at Building 3, WUFI version 3.3, 4.0, and 4.1 were used since the inception of this thesis. As previous discussed, version 4.1 incorporates ventilation behind the cladding space; however for this wall assembly, cladding ventilation is shown to have negligible impact on the performance on the materials inboard of the exterior insulation and impermeable air/vapour/moisture membrane outside of the gypsum sheathing. Therefore WUFI 3.3 and 4.0 were able to accurately predict the performance for this assembly as well as the more advanced version 4.1.

The output from WUFI 4.1 is compared to the measured field results. Figure 10-15 plots the RH at the interior face of the exterior sheathing and Figure 10-16 plots the gypsum moisture content for the eight field wall cavities for the one year period from July 1st 2002 to 2003.

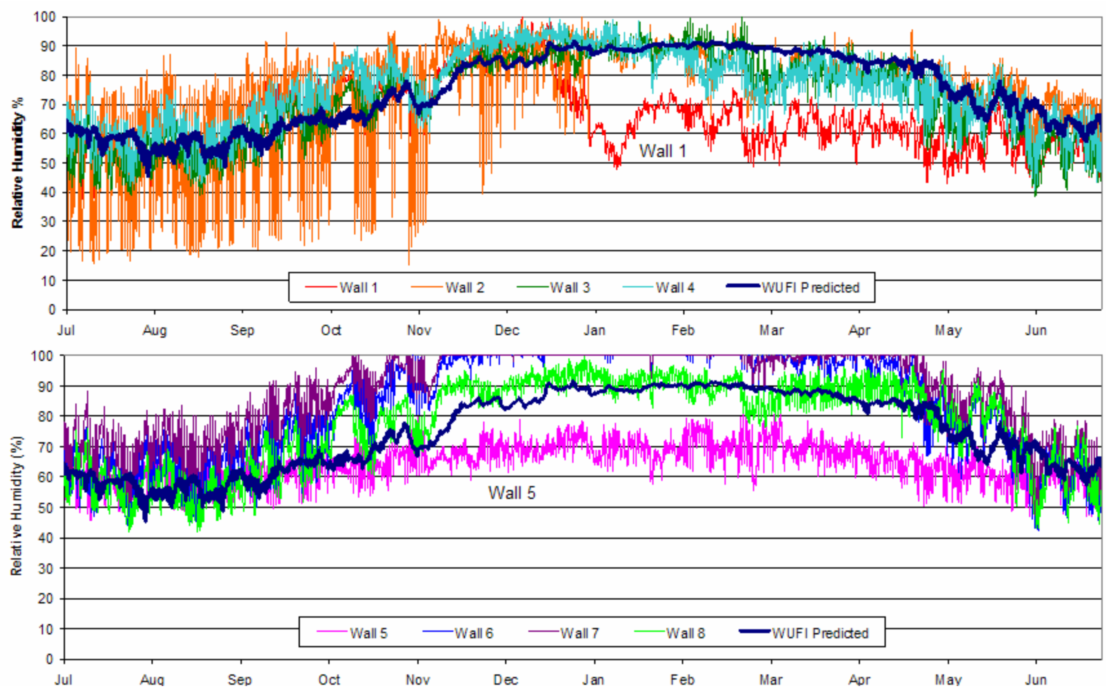


Figure 10-15: Comparison of RH at interior face of sheathing – Walls 1-8 compared to WUFI.

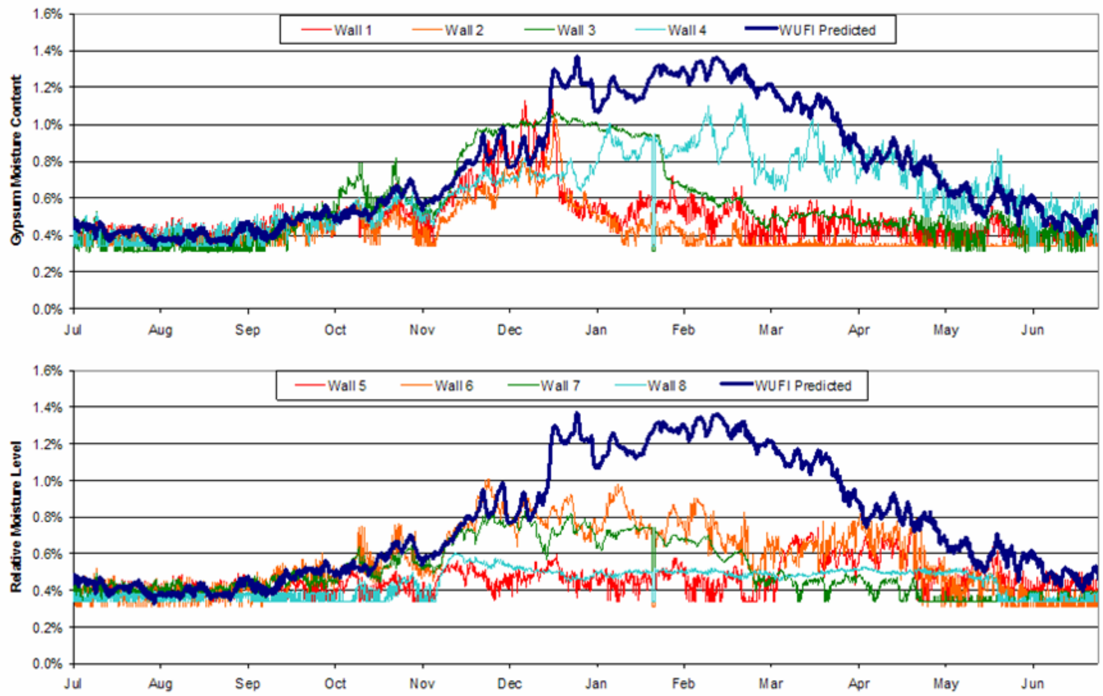


Figure 10-16: Comparison of Gypsum Moisture Content – Walls 1-8 compared to WUFI.

From the results, it is shown that WUFI is able to model the observed field results for all eight walls with varying accuracy at predicting the absolute wetness. Walls 1 and 5, at the dryer vents showed lower than expected readings than WUFI; this is expected as these vents modified the thermal conditions. It should be noted that walls 3 and 8, located below windows compare closest to the WUFI model. The 3rd floor walls also compare closer to the WUFI results than the 6th floor, which were much wetter.

Similar trends were observed across the eight walls; however the absolute values were different. The sensors were located at different details (below window, near base of wall, or below vent at top of wall), and thus subject to interior temperature conditions. As shown in Chapter 9, the interior conditions had the greatest impact on the results; therefore if the interior temperature profile were modified (say at a colder corner compared to the center of the wall) the conditions within the wall assembly would also be different. As furniture or other interior items were sometimes placed at the monitored wall locations, differences in the measured results are expected.

The exterior sheathing relative moisture level and RH readings are generally higher on the 5th and 6th floors than the 2nd and 3rd floor walls. The neutral pressure plane for the building is near the 4th floor slab. Theoretically stack effect pressures during cold weather should be drawing outdoor air inward on the 2nd and 3rd floors and pushing indoor air outward at the 5th and 6th floor levels. If air leakage occurs through the monitored cavities, one would expect slightly higher RH in the upper floors, and slight lower RH in the lower floors.

The remaining differences between the field and simulated data could be from any number of potential sources, including:

- Air leakage is not accounted for in the WUFI model. Air leakage through electrical outlets, penetrations, and the base of wall will also increase the volume of air flow in the wall cavity and thus a higher risk of condensation.
- Outward air leakage could be occurring and causing the higher relative humidities observed in the 5th and 6th floor wall cavities.
- Thermal bridging is not modeled in WUFI 1D. The steel studs in the stud cavity and Z-girts in the strapping cavity are bridging the insulation and resulting in different temperatures at the sheathing. Warmer temperatures resulting in drier conditions and cooler temperatures resulting in wetter conditions.

10.2.1.2 Impact of Interior Relative Humidity

Hygrothermal modeling was used to determine the impact of the interior relative humidity on the performance of the wall assembly. The wall assembly was modeled using WUFI 4.1. The average interior conditions were modeled where a case of the current ventilation rate was halved and then doubled to show the impact of the suite relative humidity on the wall performance. This was done by correlating the measured interior conditions with a moisture generation and ventilation rate using methods outlined in ASHRAE 160P, then halving and doubling the ventilation rate.

The interior relative humidity for the three modeled cases is presented in Figure 9-27 and the relative humidity at the sheathing surface is shown in Figure 9-28.

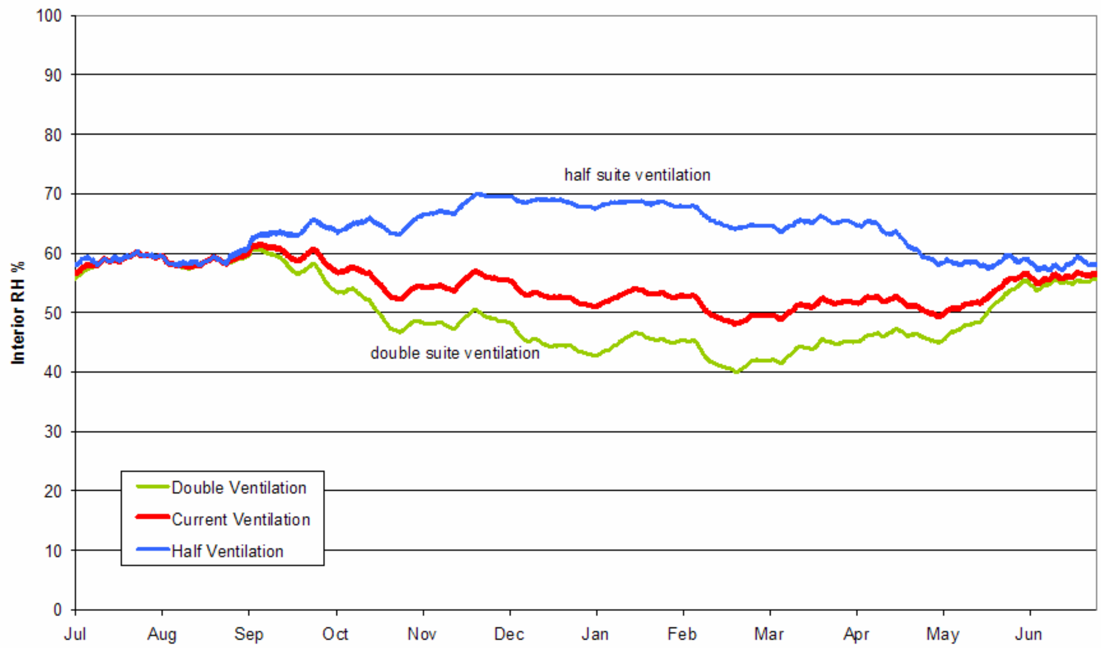


Figure 10-17: Impact of suite Ventilation Rate on Interior RH

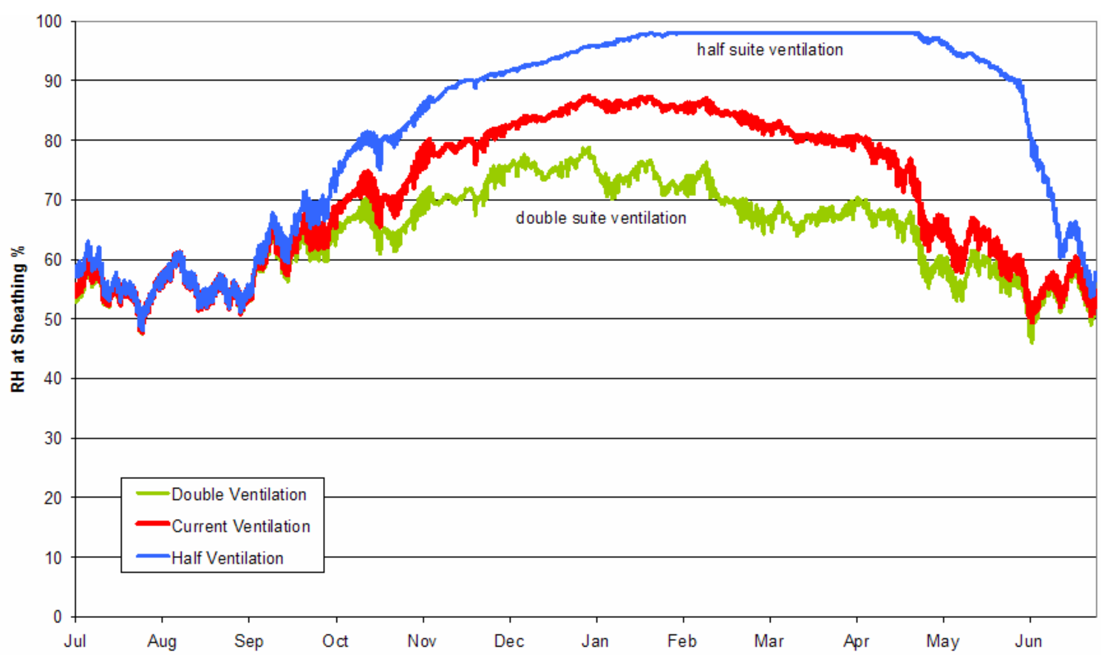


Figure 10-18: Impact of suite Ventilation Rate on Interior RH

As shown, a wintertime average RH above 50% results in very high (80-100%) RH levels at the sheathing, whereas the double ventilation case (where interior RH is between 40-50% during the winter) results in safer sheathing RH levels, and subsequently gypsum moisture content.

10.2.1.3 Impact of Wall Construction

The impact of the location of the thermal insulation and vapour control layer within the wall assembly was modeled.

Three cases are compared to the as-built wall assembly in Figure 10-19 (RH at interior of sheathing) and in Figure 10-20 (gypsum sheathing moisture content):

1. 100 mm (4") of mineral wool insulation on the exterior, no insulation within stud space, peel-and-stick air/vapour control layer on exterior of sheathing.
2. 50 mm (4") of mineral wool insulation on the exterior, no insulation within stud space, peel-and-stick air/vapour control layer on exterior of sheathing.
3. As-built insulation (50 mm mineral wool on exterior, 89 mm fiberglass on interior) but with a vapour-permeable air barrier (400 ng/Pa m² s) on the sheathing instead of the impermeable (<2 ng/Pa m² s) peel-and-stick layer.

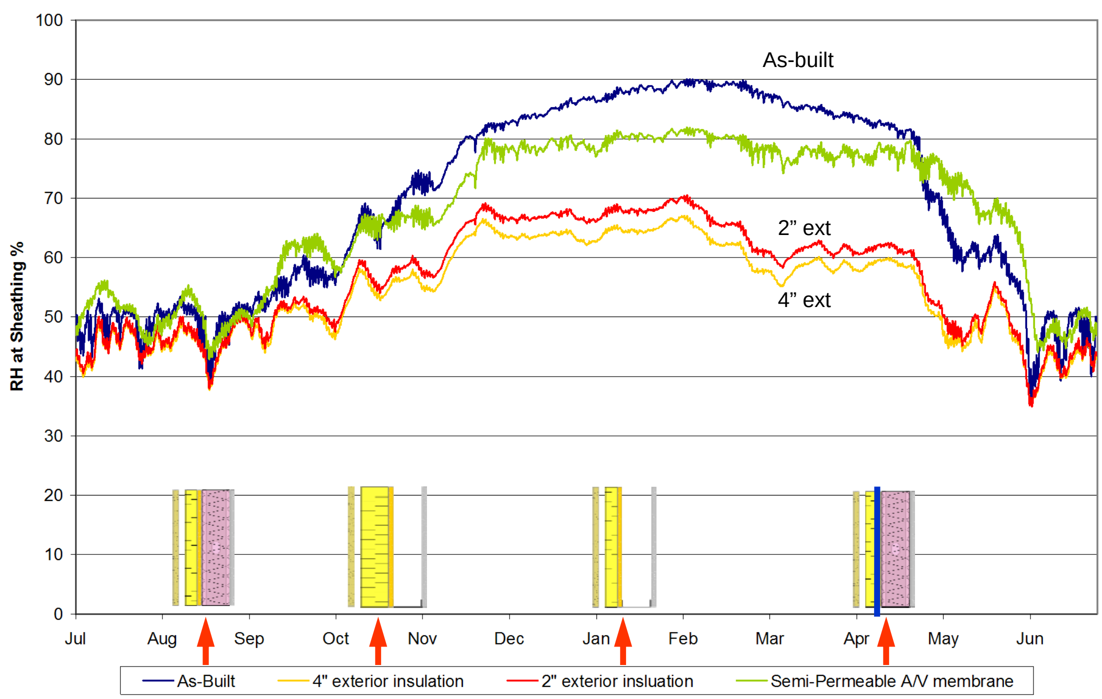


Figure 10-19: Impact of Insulation Distribution on RH at interior of sheathing

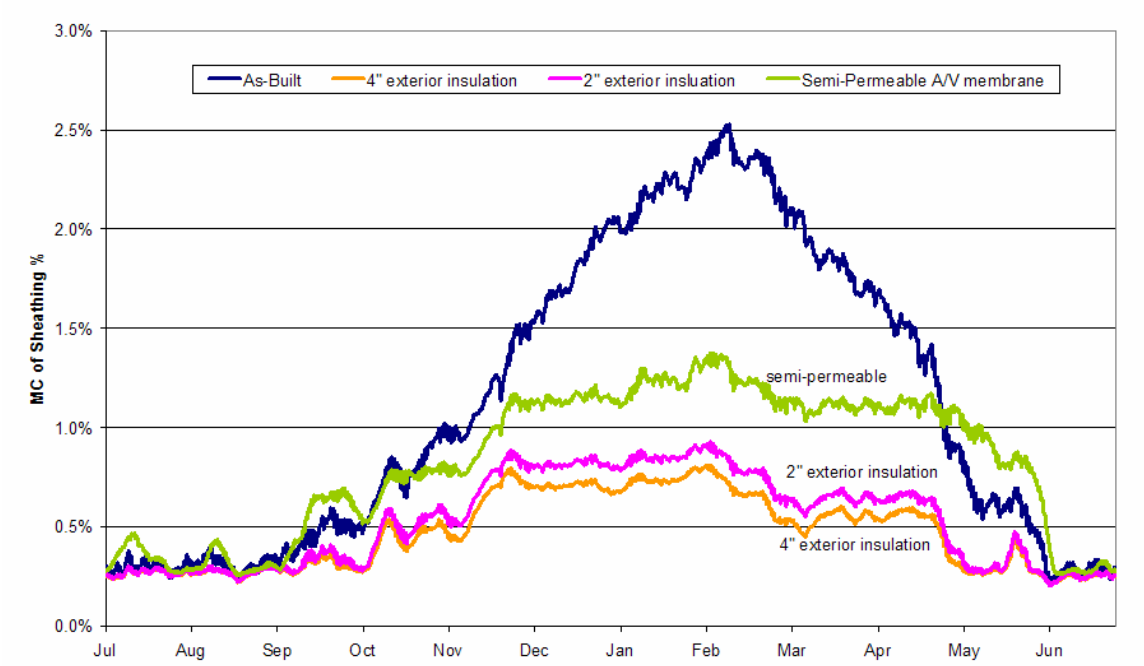


Figure 10-20: Impact of Insulation Distribution on Gypsum Moisture Content

Moving the insulation balance to the exterior obviously reduces the relative humidity at the sheathing as it is now warmer and less prone to air-leakage or diffusion condensation. 100 mm (4”) of insulation provides slightly better performance than 50 mm (2”) as expected. Installing a semi-permeable air/vapour membrane, such as a trowel applied air barrier (400 ng/Pa m^2 s) provides slightly better performance than the impermeable peel-and-stick membrane as drying is allowed to the exterior.

The impact of the vapour permeance to the interior of the wall assembly was also modeled on the as-built assembly. Four cases were modeled comparing: 6 mil polyethylene (2 ng/Pa·m^2·s), 35 ng/Pa·m^2·s vapour retarding paint, 150 and 300 ng/Pa·m^2·s latex paint.

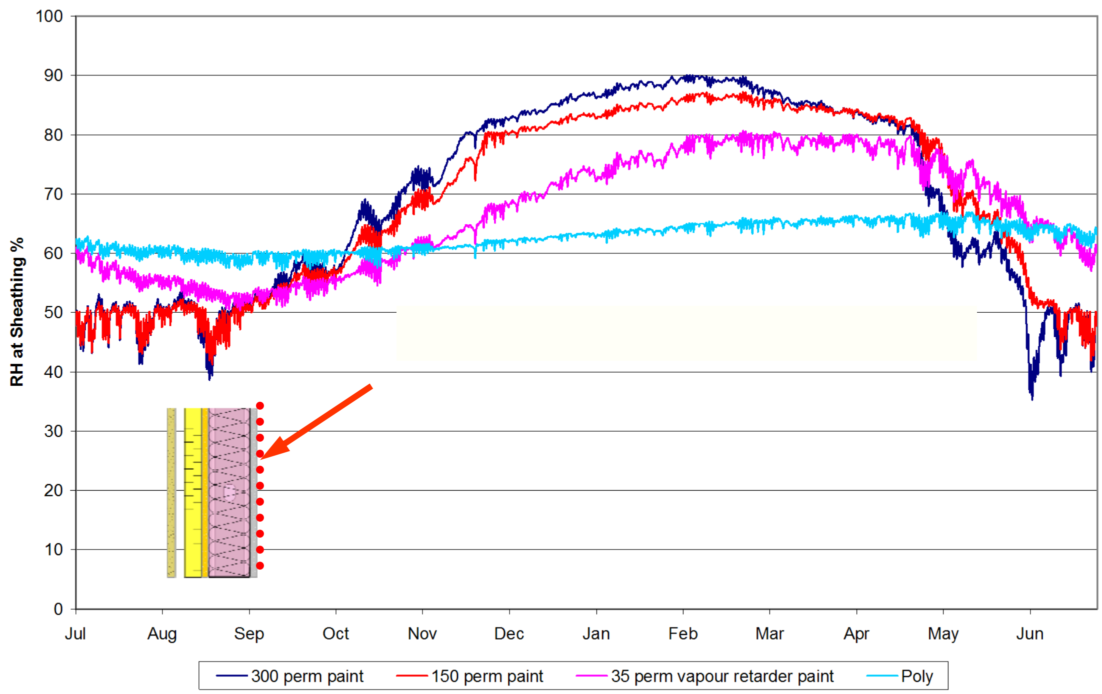


Figure 10-21: Impact of Interior Layer Vapour Permeance

Low permeability paint (35 ng/Pa·m²·s) improves performance of the wall, by providing moderate vapour control from humid interior air, while more permeable latex paint (as installed) allow sufficient vapour to pass during the winter to cause wetting and damage to the sheathing.

The effect of the poly left in-place is shown for comparison only. In theory could work (perfect system), however in practice perfect barriers are impossible to construct in the field and small air/water leaks into the assembly would become trapped and result in damage.

Air leakage was not modeled, however would have the effect of exacerbating the effects of vapour diffusion as shown in the previous plots. Therefore it is critical that unintentional air-leakage into the wall be controlled.

10.2.1.4 Building 3 Repair Strategy

To prevent moisture problems from reoccurring at Building 3, the high interior moisture levels and path into the exterior walls need to be addressed. As the problem is widespread and not isolated to a single suite or elevation, the whole building will require a similar repair strategy. The most economical solution is preferred and the exterior walls and cladding in the current state do not need to be replaced. Therefore it would be preferable if the moisture problems could be addressed by using mechanical or interior retrofits instead of an entire exterior re-clad as was performed recently in 2001.

First, the interior humidity should be controlled to reasonably dry levels (40-50% RH during winter). To do this, the suite ventilation needs to be increased during the winter, and can easily be retrofit installing more powerful (50-100 cfm actual flow) primary suite exhaust fans (bathroom). The fans should be continually running or be hooked up to a humidistat, but hard-wired to remain on when the RH in the suite is above 50%. To address noise issues, several quiet (low sone) level fans are available. If sufficient fan-flow cannot be attained using existing cast-in-place slab ducts, additional ducts within a drop ceiling/plenum should be installed. Measures should also be taken as discussed in Chapter 7 to balance the suite ventilation systems to prevent inter-suite leakage, and ensure sufficient fresh air is reaching the suites from the pressurized corridor.

Controlling the interior relative humidity and moisture levels will also reduce the instance of condensation and mould growth on cold surfaces such as window/door frames and cold corners.

Improving the suite ventilation reduces the RH at the sheathing from 90-100% to 80% during the wintertime; however this can be further reduced providing interior vapour and air flow control. Therefore as a second measure, low vapour-permeance vapour retarder paint (approximately 35-50 $ng/Pa{\cdot}m^2{\cdot}s$) should be applied to the exterior walls. In addition all wall penetrations (electrical outlets, baseboard heater wiring, window/door frames etc.) should be well air-sealed. It is suggested that the vapour retarding paint & air tightening repair strategy be trialed in the monitored suites and monitored after the interior humidity issue is already addressed. As all air leakage pathways may not be accessible or sealed during an interior retrofit, the vapour retarder paint may have a negligible impact due to continued air leakage overwhelming the moisture flow into the assembly. Monitoring of the retrofit assembly also provides confidence that the repair will work in the rest of the building.

The impact of the proposed repairs on the relative humidity and moisture content of the sheathing are shown in Figure 10-22.

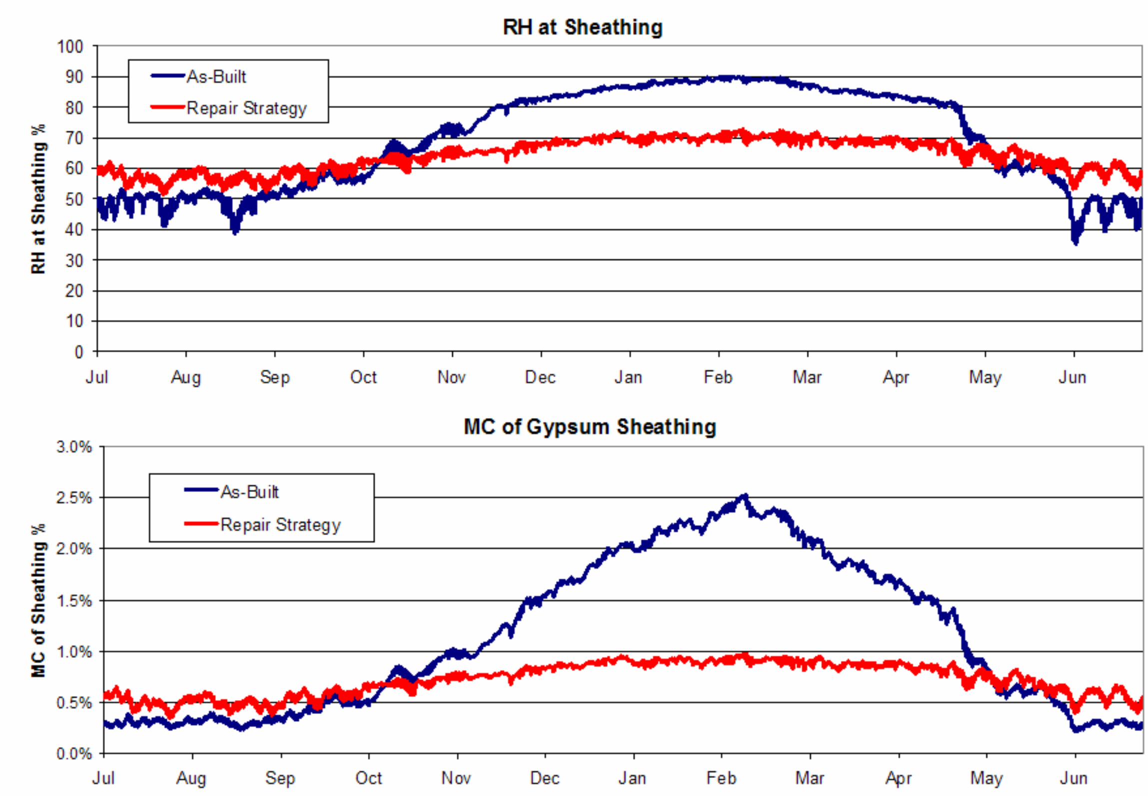


Figure 10-22: Impact of Repair Strategy (Reduced RH and Vapour Retarding Paint) on the performance of Building 3 Walls.

10.2.2 <u>Building 5</u>

As the exterior walls of Building 5 performed well, it is of interest to understand how this wall assembly (exterior insulated, exterior air/vapour/moisture membrane) would perform under different boundary conditions, exposed to high interior humidity or rainwater leaks, or how it would perform with alternate materials.

10.2.2.1 Predicted versus Measured Conditions

The accuracy of the hygrothermal model is shown in Figure 10-23, comparing the measured to predicted relative humidity at the sheathing of monitored wall 5 (suite 3005) from January 1st to December 31st 2004.

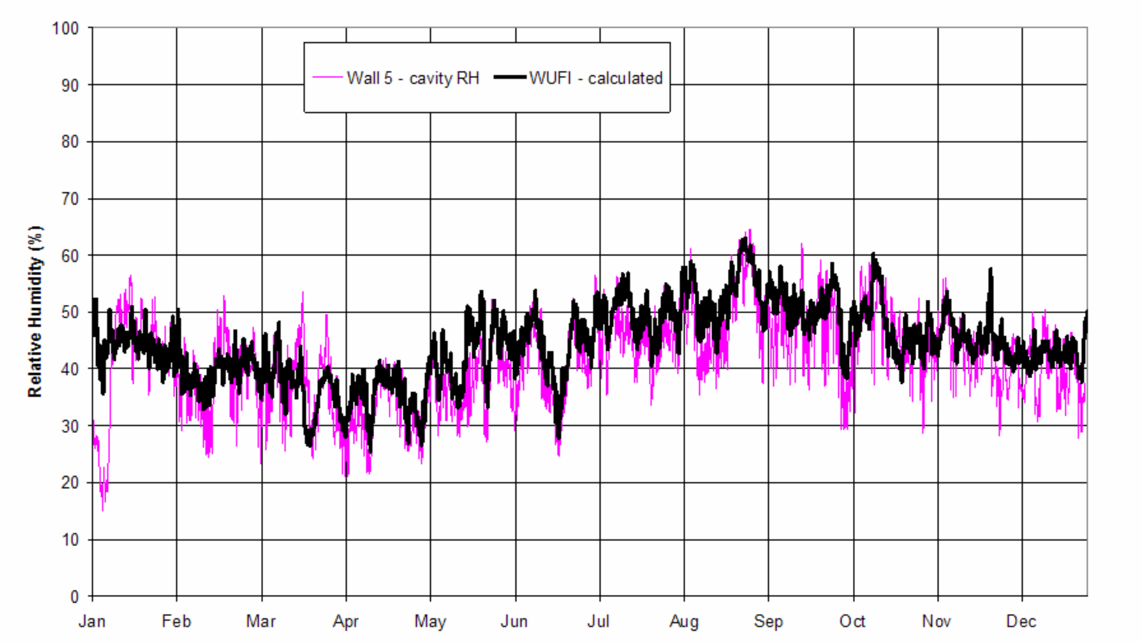


Figure 10-23: Measured RH within Stud Cavity compared to WUFI

As shown, the hygrothermal model is able to model the trends captured at wall 5, and also walls 1-4 (suite 506) as discussed in *Appendix B: Hygrothermal Modeling*. Walls 6-8 are insulated metal spandrel panel assemblies, and were not modeled. As discussed in Chapter 9, the relative humidity at the sheathing closely follows the interior relative humidity, separated only by painted gypsum drywall.

Cladding ventilation plays little role in the performance of the exterior insulated and exterior air/vapour/water sealed assemblies. The benefits of cladding ventilation are not realized when non-moisture sensitive materials line the cavity, as compared to the three wood-frame buildings. Cladding ventilation does not improve drying in case of a leak, nor does it reduce wetting from inward driven moisture. Ventilation can only lower the cavity relative humidity levels and reduce inward driven moisture (but in this assembly is prevented by the impermeable sheathing layer.

10.2.2.2 Impact of Interior Conditions

In Chapter 9, the interior RH was shown to have a direct impact on the RH at the backside of the gypsum sheathing; therefore it is of interest to determine at what interior RH levels damage to the sheathing would result.

The impact of a very high interior humidity (i.e. poorly ventilated swimming pool enclosure) is shown in Figure 10-24 compared to the measured conditions. In this case, the hourly relative humidity was simulated using the measured interior temperatures with a high moisture generation rate to simulate the relative humidity in WUFI 4.1.

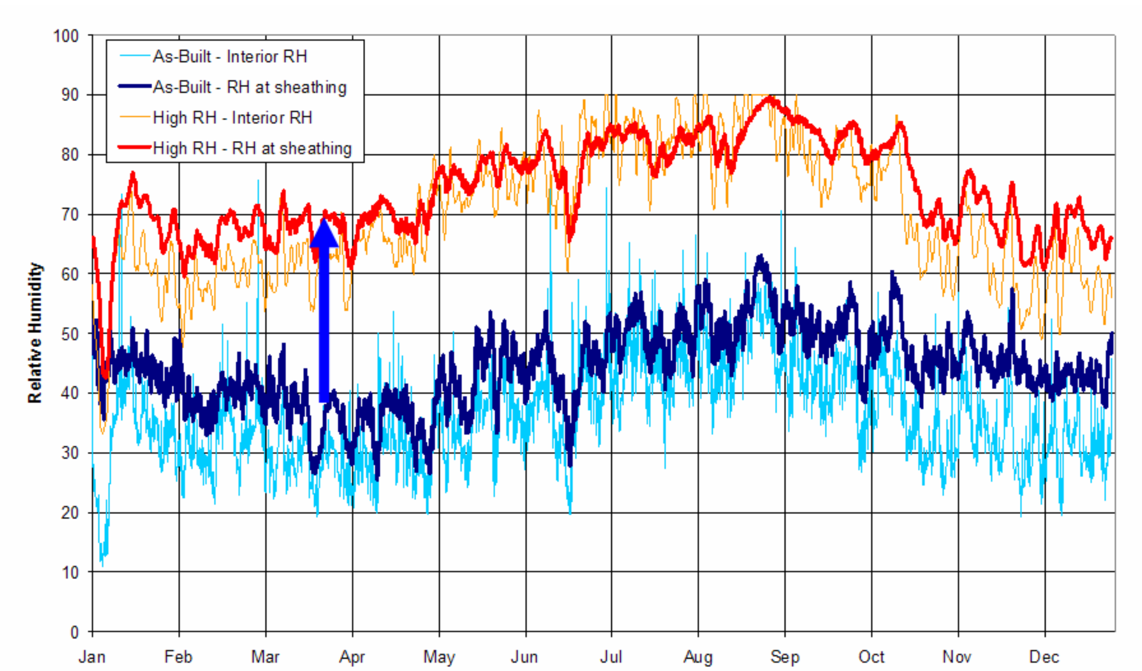


Figure 10-24: Impact of High Interior RH on RH at gypsum sheathing.

As the thermal insulation is placed to the exterior of the sheathing, the sheathing remains at temperatures close to the interior. Therefore the relative humidity within the stud cavity and at the sheathing is on average is equal to the interior conditions. As a result, the interior relative humidity would have to be high enough to cause damage to the interior finishes before it would damage the sheathing or cause corrosion in the stud cavity.

10.2.2.3 Impact of Rainwater Leaks

The impacts of rainwater leaks as a fraction of the driving rain load were simulated using WUFI to determine the drying capacity of this wall assembly. A leak as a percentage of the driving rain on this building was simulated for the exposed northeast corner (790 mm of driving rain per year). A 1% (7.9 $kg/m^2/yr$) and 2% (16 $kg/m^2/yr$) sized leak were simulated to represent a case where water penetrates through the wall and is absorbed by the gypsum sheathing. The impact on the gypsum moisture content and relative humidity within the stud space are shown in Figure 10-25 and Figure 10-26 comparing the two leak scenarios to the as-built conditions over a 2 year period.

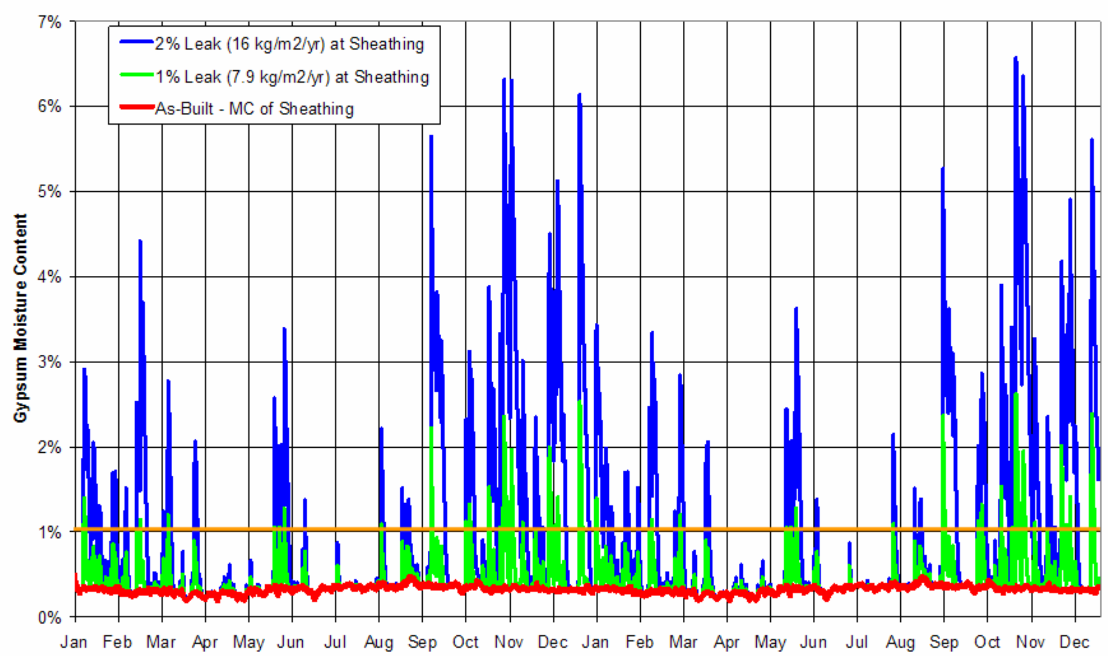


Figure 10-25: Impact of 1% & 2% Rainwater leaks on Gypsum Sheathing MC

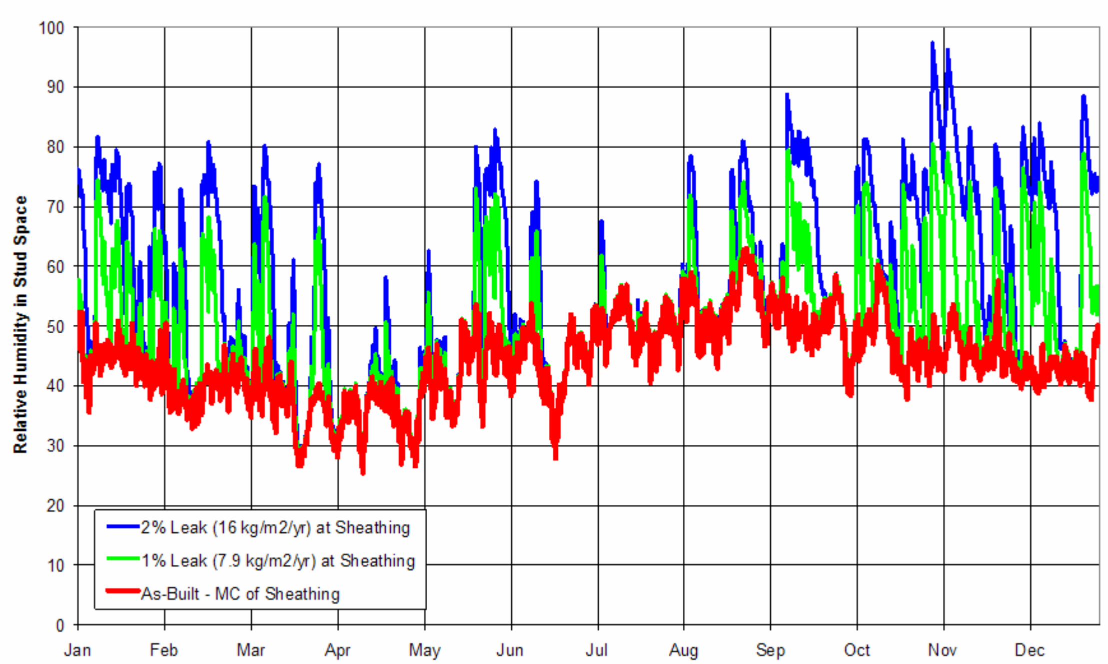


Figure 10-26: Impact of 1% & 2% Rainwater leaks on Stud Cavity RH

As shown, the exterior insulated wall assembly is relatively tolerant to rainwater leaks. A 1% (7.9 kg/m^2/yr) leak can be tolerated by the gypsum sheathing without prolonged dangerous moisture levels (>2%). After each rain event the gypsum peaks at a maximum moisture content but dries down to safe levels within a week. Exposed to a 2% leak, the moisture peaks were higher, and drying took slightly longer (1-2 days). The impact of the higher moisture levels (2-6%) within the gypsum sheathing for several weeks is unknown, but should be avoided.

As the gypsum sheathing is kept warm near and near interior temperatures, the gypsum sheathing is able to dry out through the interior preventing sustained high moisture levels. To ensure inward drying in event of a leak the interior finishes should be selected to allow vapour diffusion drying, i.e. avoid use of impermeable vinyl wallpaper or polyethylene which would inhibit drying.

Impact of Sheathing Material

An alternate simulation was performed where the gypsum sheathing was replaced with plywood (all other materials the same), to represent a low-rise residential application where gypsum sheathing is not required for fire-code requirements. Plywood or OSB has the capacity to safely store more moisture than gypsum sheathing, but dries slower; therefore it is of interest to determine how much moisture could be safely stored when exposed to rainwater leaks.

As shown in Section 10.1.4, the interior insulated ventilated rainscreen wall assembly could only store a 0.4 kg/m$^{2/}$yr leak safely in the plywood and at 2.0 kg/m^2/yr, elevated moisture contents up to 30% were observed for several months during the winter.

Again a 1% (7.9 kg/m^2/yr) and 2% (16 kg/m^2/yr) rain water leaks were simulated within the wall assembly and results are plotted in Figure 10-27 over a 2 year period showing the relative differences in performance between gypsum and plywood sheathings.

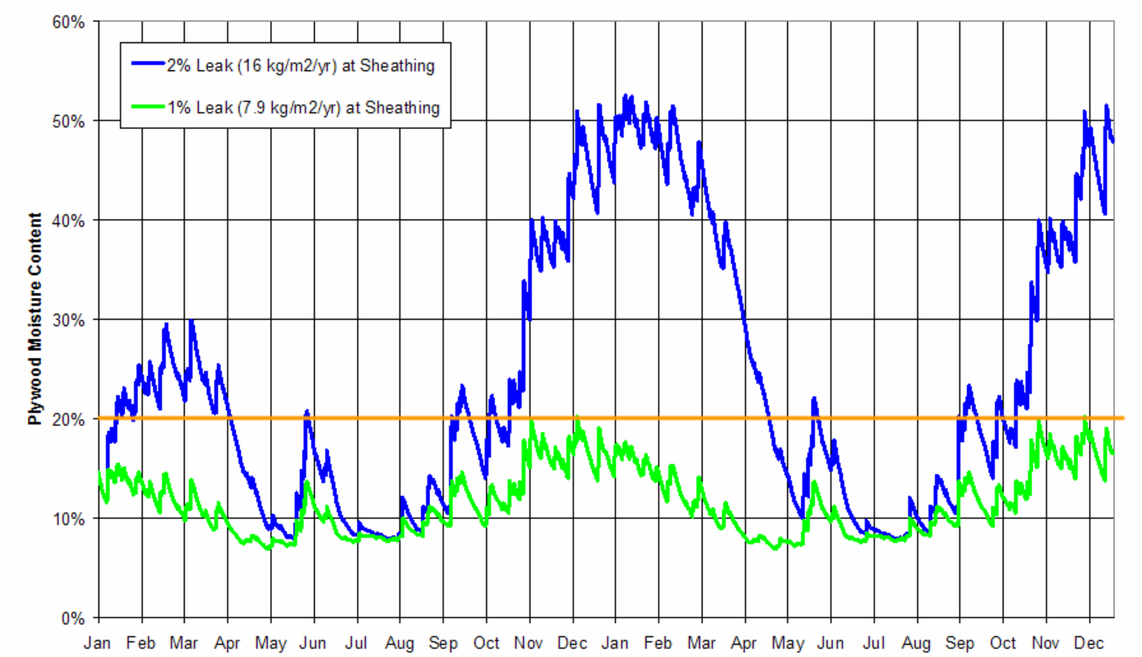


Figure 10-27: Impact of 1% & 2% Rainwater leaks on Plywood Sheathing MC

When a 1% (7.9 kg/m²/yr) driving rain leak was introduced, the plywood performed reasonably well, similar to the gypsum, dampening the high moisture fluxes observed with gypsum, as wood has a greater storage capacity. At a 2% (16 kg/m²/yr) leak, the plywood reached fiber saturation for greater than 6 months per year, and would be considered to have failed. The results indicate a maximum leak size for this wall assembly between 1-2% (8-16 kg/m²/yr).

The differences between the exterior insulated assembly (here) and interior insulated assembly in Section 10.1.4 are shown. From the hygrothermal analysis it was demonstrated that the exterior insulated assembly (with plywood sheathing) can tolerate a leak up to 20 times larger than the interior insulated assembly, and hence a more durable assembly.

If wall performance is to be judged based on the size of leak it can handle, i.e. the 1% driving rain load as suggested by ASHRAE Standard 160P, then as shown correctly determining the driving rain load is critical to the analysis. A leak of 1% of 300 mm/yr (1% = 3 kg/m²/yr) versus 900 mm/yr (1% = 9 kg/m²/yr) has a significant impact on a the sheathing material that ranges from 4.5 kg/m² to 10 kg/m².

Impact of Alternate Interior Finish Materials

The role of diffusion drying to the interior is shown by modeling a case with gypsum sheathing and vinyl wallpaper at the interior surface. This case may not be all that uncommon as in most hotels and many other buildings owners may prefer to use vinyl wallpaper or other vapour impermeable materials as the interior finish.

A 1% (7.9 kg/m²/yr) and 2% (16 kg/m²/yr) driving rain leak were first modeled, and it was found that both resulted in almost immediate failure. Therefore an additional case of 0.1% (0.8 kg/m²/yr) was simulated. The moisture content of the gypsum sheathing and relative humidity within the uninsulated interior stud cavity are shown in Figure 10-28 and Figure 10-29 for a 0.1% and 1.0% leak over 2 years to highlight the annual accumulation observed.

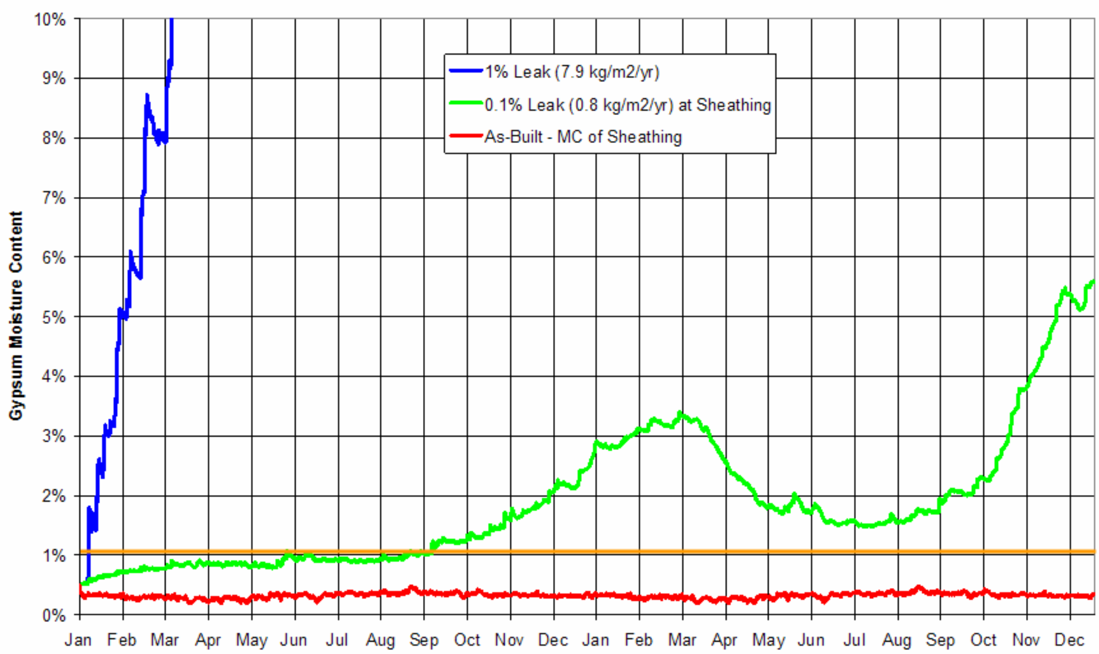


Figure 10-28: Impact of small rainwater leaks with vinyl wallpaper – Gypsum MC

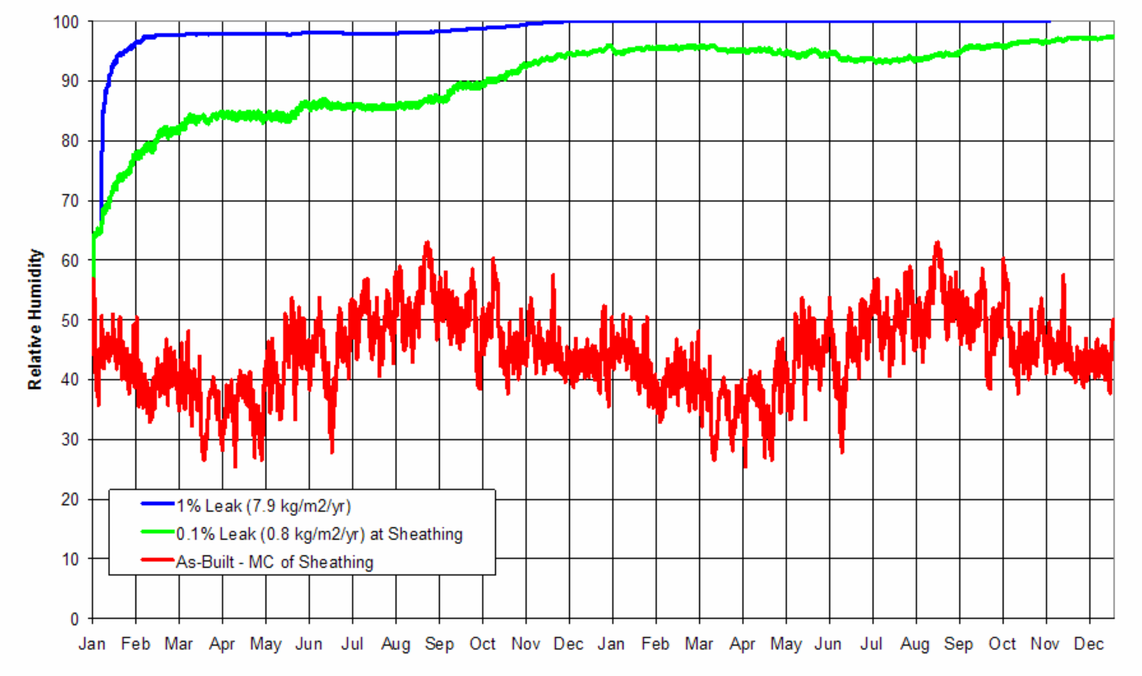


Figure 10-29: Impact of small rainwater leaks with vinyl wallpaper – Cavity RH

As shown even a small rainwater leak would be catastrophic to this wall assembly. The 1% leak scenario failed within one-month and the 0.1% scenario failed in less than 1 year. The importance of avoiding interior vapour barriers or double vapour barriers is clearly shown.

10.2.2.4 Potential Improvements

While the exterior insulated wall assembly performed very well under normal and even extreme conditions, it is of interest to modify the wall assembly to allow for impermeable interior finishes such as vinyl wallpaper, tile, and many other modern finishes to be used.

To allow these assemblies to work, the impermeable air/vapour/moisture membrane over the gypsum sheathing must be replaced with a more vapour permeable layer and the rigid XPS insulation with a more vapour permeable insulation.

Two scenarios were simulated and compared to the as-built conditions using the existing boundary conditions (Figure 10-30):

1. As-built assembly but with an air-tight, semi-permeable vapour control layer over the gypsum sheathing (400 ng/Pa·m²·s) instead of peel-and-stick.
2. Semi-permeable vapour control layer plus mineral wool insulation (~2000 ng/Pa·m²·s) instead of XPS.

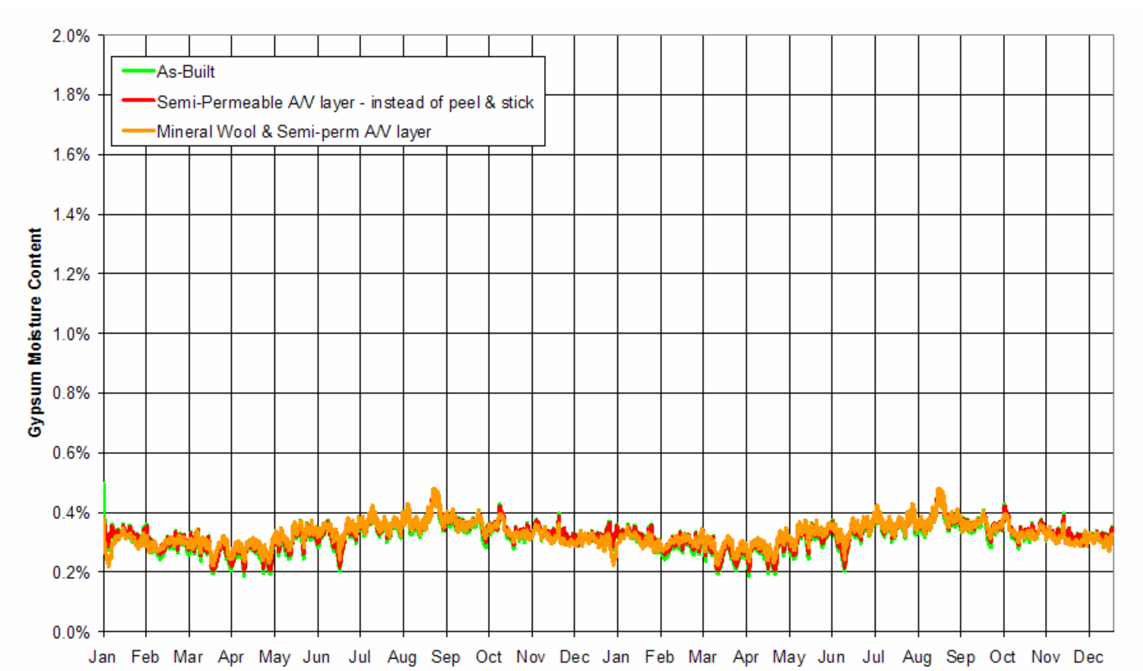


Figure 10-30: Building 5 - Impact of Wall Modifications

As shown both modifications have a negligible impact on the performance of the wall assembly under normal conditions and would perform as-well as the as-built case.

The impact a 1% rainwater leak is modeled for the wall assembly with mineral wool insulation and the semi-permeable sheathing membrane and with and without an impermeable vinyl wallpaper interior finish (Figure 10-31).

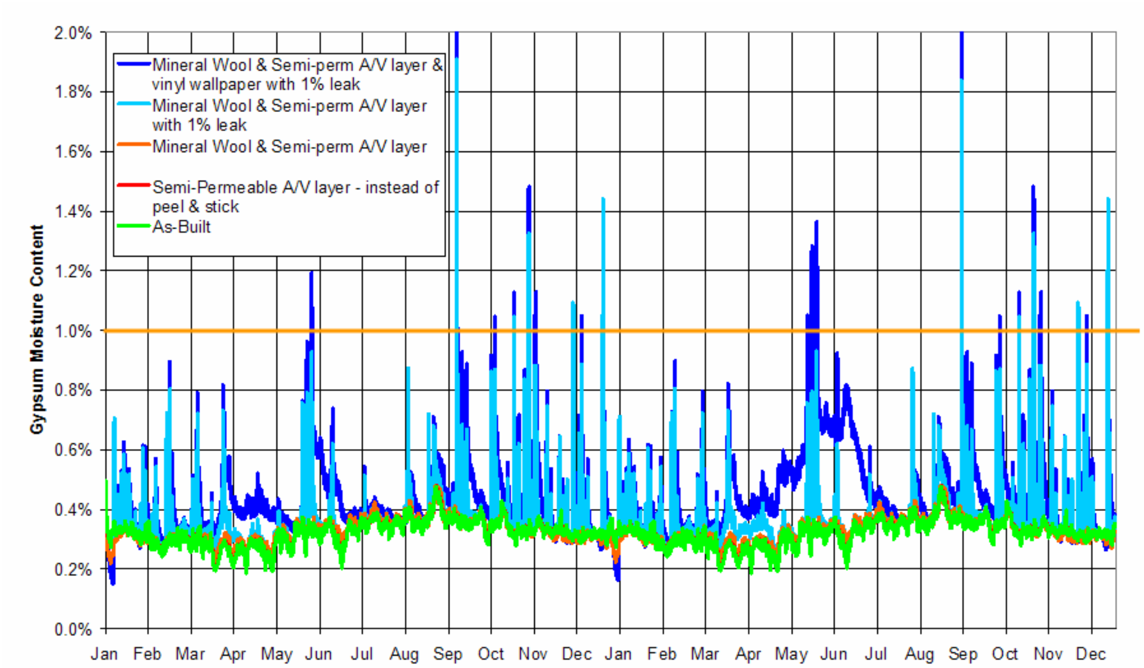


Figure 10-31: Building 5 - Impact of Wall Modifications with Leaks

As shown when the vapour permeance of the materials to the exterior of the sheathing is increased, the wall assembly is able to handle a substantially rainwater leak when vinyl wall-paper is used.

10.2.3 Building 5 - Conclusions

The exterior insulated wall assembly as used at Building 5 performs very well as expected. The moisture sensitive wall components are kept dry, and in case of a leak have a high drying potential. Hygrothermal model shows that an exterior insulated assembly can safely manage a 20x larger leak than an interior insulated assembly with similar materials.

In summary, the exterior insulated wall assembly as-built performs very well under normal conditions and when exposed to small rainwater leaks. Problems can be encountered with this assembly if an impermeable interior finish such as vinyl wallpaper is used. Therefore if an impermeable interior finish is required, the vapour permeance of the insulation and sheathing membrane must be increased to allow drying to the exterior. As shown using a vapour permeable sheathing membrane and mineral wool insulation allows for impermeable interior finishes such as vinyl wall-paper to be used and tolerant of small rainwater leaks.

10.3 REFERENCES

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Künzel, H.M. 1998. "More Moisture Load Tolerance of Construction Assemblies Through the Application of a Smart Vapour Retarder", *Performance of Exterior Envelopes of Whole Buildings VIII*, Clearwater Beach, Florida, December 1998, pp. 1129-132.

11 SYNTHESIS

The major conclusions from the previous chapters are reiterated and synthesized to fully understand the impact of all the researched variables on the performance of rainscreen wall assemblies in coastal British Columbia.

The primary objective of this thesis was to understand and report on the performance of buildings in Vancouver's coastal climate, in particular those constructed with rainscreen wall assemblies.

First, an understanding of building physics was developed, specifically how heat, air, and moisture can impact the performance of building enclosures. This was followed by a literature review of the history of wood frame walls which lead up to and including the failures of thousands of buildings in the Pacific Northwest, presented to understand fully how we built in the past, and why we build the way we do now.

Next, the field monitoring program was introduced and a the interior and exterior boundary conditions were presented to develop an understanding of the actual climate loads the monitored buildings were subjected to, and how well these loads reflect our current design assumptions for Vancouver.

Driving rain was discussed in further detail as it is a significant load on the exterior building enclosure. Understanding and predicting the stochastic relationship of wind and rain deposition on building façades has improved in past decades but field measurements are still limited. Measured driving rain data for the five buildings was presented and compared to prediction models, in an attempt to improve our understanding of wind-rain relationships on buildings.

Interior boundary conditions are another significant load on the building enclosure and were presented to understand the variability of environments within residential buildings. To understand the monitored interior conditions, air leakage testing was performed to quantitatively determine air tightness of the monitored suites and approximate ventilation rates. Another objective of the testing was to determine how airtightness of the building enclosure and between suites/common areas may affect ventilation and make-up air. A case study of Building 3 was presented highlighting the importance of sufficient interior ventilation, and the impact of air leakage pathways on overall building performance.

With an understanding of the building physics, historical background, and interior and exterior boundary conditions, the performance of the exterior walls was presented. The objective was to present the monitored performance but also to explain the trends and anomalies observed in the five years of data. The performance of the three wood-frame rainscreen clad buildings (1, 2 & 4) was presented separately from the two steel-stud/gypsum rainscreen clad buildings (3&5) as they had different performance characteristics. The wood frame walls were insulated within the stud cavity, while the gypsum & steel-stud frame walls were insulated to the exterior (and interior of Building 3) of the sheathing and such behaved differently.

To further understand the performance of the gypsum sheathing, material testing of fiberglass faced gypsum sheathing was performed to determine the relationship between moisture content and electrical resistance. The correlation was used to convert raw resistance readings into moisture content results for the two gypsum sheathed buildings (3 & 5).

The final objective was to compare predictions from an advanced hygrothermal model with the measured data from the five buildings. The validated model was then used to investigate the impacts of additional climatic or construction variables, determining possible methods to improve the performance of rainscreen walls.

In conclusion the analysis of all components is synthesized to report on the performance of rainscreen walls in Vancouver’s climate. Looking ahead, potential improvements are discussed to improve rainscreen wall assemblies to make buildings more durable, sustainable, and healthy for occupants.

11.1 BUILDING ENCLOSURE BACKGROUND

The fundamental function of the building enclosure is to separate the exterior and interior environments while maintaining healthy and safe indoor conditions for the occupants. The building enclosure will weather and gradually deteriorate over time and require ongoing work to maintain the appearance, performance, and efficiency.

Moisture in all its physical forms is regarded as the single greatest threat to the durability and long-term performance of a building and will accelerate the deterioration process. Excessive moisture cannot only cause significant damage to many building materials and components, but can lead to unhealthy indoor environments.

The balance between wetting, drying, and safe storage is critical to the long term performance of building enclosures. Where wetting cannot be controlled to acceptable levels, safe storage within materials and drying become critical. Many common building materials have little safe storage capacity, that is, they cannot be exposed to high levels of moisture for long periods of time, particularly when at above-freezing temperatures. Wall "performance" is hinged upon this balance. A wall is said to have good performance when it is typically dry (safe storage and drying exceed wetting) and poor performance when wetting exceeds the drying rate and safe storage of the material. A failed wall is one where damage mechanisms become present; including mould growth, metal corrosion, or loss of structural integrity.

Recent building enclosure failures have shown that the drying potential of some wall assemblies in certain climates may be insufficient when exposed to accidental wetting or leaks. As a response to these failures, drained and screened walls have been widely recommended to deal with rainwater penetration. However, cladding ventilation may be needed or useful to increase drying for some wall assemblies in some climates. Ventilated claddings can also control wetting due to inward driven vapour from rain wetted absorbent claddings. The use of large ventilated and drained cavity has already been mandated by some building codes.

While some previous research of ventilation drying shows conflicting results, the consensus in recent years is that cladding ventilation has the potential to increase the drying potential of a wall and reduce wetting from absorptive claddings and sun-driven moisture. Higher ventilation rates are shown to result in faster drying rates of wood sheathings. Measured ventilation rates in the field and laboratory show good agreement with the predicted rates calculated from fluid flow mechanics theory. The probable range of ventilation rates depend on the cladding type, cavity dimensions, and venting arrangement, and are driven by thermal and moisture buoyancy and wind pressures.

Cladding ventilation rates were calculated for the buildings in the monitoring study to further understand the impact of cladding ventilation on wall performance and are later used in the hygrothermal modeling programs. The average hourly ventilation rate was 40 ACH for the brick veneer and 220 ACH at the cement board on the south elevation of Building 4, 140 ACH for the east on stucco clad Building 2, and 170 ACH for the southeast vinyl clad Building 1. Ventilation rates were calculated based on thermal and moisture buoyancy pressures.

Building enclosure failures can be prevented. Failures can occur from accidents or acts-of-god, but all too often are as a result of improper design, poor construction, and insufficient maintenance. By understanding and applying the principles of building science in design, and a performing ongoing maintenance, most building enclosure problems can be avoided. The design requires knowledge of the exterior and interior environmental loads; heat, air, and moisture transport mechanisms; and the properties and limitations of the materials and assemblies used.

11.2 HISTORICAL BACKGROUND OF THE WOOD FRAME WALL

One of the basic needs of humans is shelter, and soon after we came out of our caves and natural shelters we had found, we started building our own. The built shelters were crude and simple at first, however over thousands of years developed into the simple structural technique known as post and beam construction. We built with the materials we had available to us at the time. In the Middle East where the first civilizations grew, wood was initially used, however when it quickly ran out, stone and eventually brick construction methods were developed. During the Middle-Ages, post and beam half-timbered construction evolved suiting the climate of much of northern Europe.

Post and beam timber framing was brought to North America by European settlers over 400 years ago, however changes were made to designs to accommodate the new harsher climate. Walls previously filled-in with clay or rubble stone no longer provided sufficient protection from the elements, so the builders added wood siding as a screen from the wind and rain. Other details and building techniques were modified to accommodate the new climatic conditions. Eventually the clay and rubble stone infill was removed, and the frame filled in with lighter timbers to support the cladding.

Technological advances which mechanized nail and timber cutting lead to the development of an entirely new more efficient wood frame, known as balloon framing. The advent of balloon framing meant that more people could build their own houses using readily available materials, and quickly. Gold rushes and immigration throughout the 1800's both lead to the widespread use of balloon framing in North America. To deal with wind and rain in these new light-framed buildings sheathing paper was added to the walls for protection. But since we had reduced the wall thickness and thermal mass of our older designs, we began to get cold in this harsh climate again, and found it difficult to heat our homes and maintain wintertime comfort.

Initially more efficient stoves and heating methods were developed to address the effect; however we then approached the cause of heat-loss. We began experimenting with low density materials, filling the open stud spaces with a new invention called insulation. At first we experimented with scrap and waste materials such as wood shavings, rubble stone, or seaweed and in the late 1800's invented mineral wool insulation. As soon as the benefits of insulation were realized, manufacturers developed dozens of new products, all hoping to capitalize on this new market. By the 1930's insulation was commonly used in homes to reduce heating and increase thermal comfort.

We then began to see moisture problems in the walls, and the cladding started to deteriorate from moisture. In the 1940's we introduced vapour barriers, based on research largely in the colder areas of Canada and the United States as a solution to all of the countries moisture problems. Unfortunately these regulations were applied even in the warmer or more temperate areas that weren't experiencing problems. After the Second World War we built a lot of homes for a new wave of immigrants fleeing from war and economically depressed Europe. Manufacturers that developed materials for the war-effort modified the materials to the new building market. Of these, several new insulation products were introduced to the market, advertising significant improvements over the old and dependable ones. Many of these new insulation products were doomed to fail without proper testing and consideration of health the compatibility effects, and did so at some time later.

With all of these seemingly small improvements we were still seeing moisture problems in homes, somewhat worse than before. In the 1960's it was realized that air leakage condensation was causing the majority of our moisture problems, eclipsing that could be caused by vapour diffusion. By the 1970's we had tried to seal up the vapour barrier in hopes that it would resolve the issue. The energy crises of 1973 and 1979 made us realize our dependence on the supply and price of oil. So we developed electrical heat and increased insulation amounts to reduce our oil dependence and to conserve energy.

Still we continued to see more wall failures, this time with health side-effects blamed on damp and mouldy interior environments, particularly in the temperate coastal climate of Atlantic Canada. This time we blamed the problems on the reduced ventilation and air exchange when switching from combustion furnaces with flue to electrical heat. These overcrowded and humid houses exacerbated air leakage and diffusion problems causing deterioration of moisture sensitive materials in the exterior walls. As a result we added minimum mechanical ventilation requirements and continued to further tighten up the air-barrier. In the rest of the country we watched and postulated on whether problems could occur in our homes, so we too applied recommendations to improve air-tightness and mechanically ventilate.

In the 1980's and early 1990's we saw a decade of boom building conditions in Canada and the United States fuelled by immigration from Europe and Asia. We built as fast as we could with the technology we had been fine-tuning for years, however found it difficult to keep up with the demand. Single family dwellings were displaced in our cities by multi-unit residences, and the condominium building became the norm.

But in the mid-1990's thousands buildings began to experience severe and wide-spread moisture issues in coastal BC and other parts of the North America including Minnesota and North Carolina. In Vancouver this became known as the leaky condo crisis, a term coined by the media for the extensive moisture problems experienced primarily in 3-4 storey wood-frame condos. At first we first blamed the new materials, or the rapid construction practices, and then slowly realized some of the impacts of changes we had been making for several decades. While designing to absolutely negate wetting from interior moisture sources, rain turned out to be our worst enemy. Health and safety issues were prevalent, mould became a litigious problem. More than just condos were affected by the issues; the whole building industry was on its heels.

If anything good came out of these failures, some significant changes to construction practice were made across the country. Improved water shedding details and rainscreen wall designs with ventilated cavities were instituted in coastal BC, addressing the largest potential moisture source of all, Rain. But hadn't we figured out rain hundreds of years ago? We had, but the details and materials had evolved, with moisture tolerant materials gradually replaced by cheaper and more moisture sensitive and less forgiving ones. Finally a threshold was reached, and the balance of wetting, drying, and safe storage was tipped towards failure.

Today there is recognition that we need to build with more durable materials, however when we can't, we must protect the moisture sensitive ones from water. The consensus is leaning towards vapour open yet air tight construction, which prevent the trapping of moisture and allow accidental or seasonal moisture to dry-through the walls. Energy efficiency is also as important; if not more than it was in the 1970's. Use of increased insulation levels for energy efficiency but also correctly placed or distributed to protect moisture sensitive materials appears to be the answer. Indoor air quality and humidity should controlled by mechanical or well designed and tested passive means to prevent problems with air-tight building enclosures.

Air-tight building enclosures are not the problem; we however must approach the design of buildings holistically. Consideration for integration of all building components including the mechanical, electrical, structural, and enclosure systems must be made while conserving energy and maintaining safe and comfortable environments for the occupants. The approach is scientific; we now widely use laboratory and field testing and computer modeling to test new materials and walls in specific climates. Tailored wall design to climate and exposure is the future, and as long as designers build-in safety factors to designs we will reduce the instance of failures.

We have realized through our successes and failures through history that no singular design is appropriate for all climates. Buildings should be built to their local environment; national building codes that spread requirements over all climates are being phased out, replaced with guidelines and objective requirements based on local climate. Vitruvius knew this over 2000 years ago, yet for a while our society blindly forgot:

> "Firmness Commodity Delight" "These are properly designed, when due regard is had to the country and climate in which they are erected. For the method of building which is suited to Egypt would be very improper in Spain, and that in use in Pontus would be absurd at Rome: so in other parts of the world a style suitable to one climate, would be very unsuitable to another: for one part of the world is distant from it, and another, between the two is temperate" – Marcus Vitruvius Pollio

The wisdom of Vitruvius is still very applicable today in North America, and why shouldn't it be. Today we now realize that a wall designed in Ottawa cannot expect the same performance in Miami, Vancouver, or Las Vegas, four very different climatic zones. In one of these climates it may even fail. Through our history of success and failure we have eventually come to realize this. In Vancouver and other parts of coastal British Columbia, this realization came abruptly in the mid-1990's as discussed in the next section.

11.3 COASTAL BRITISH COLUMBIA PROBLEMS

Moisture related building enclosure failures during the 1990's in Vancouver and other parts of coastal British Columbia brought about new research and understanding of building science issues. Catastrophic failures of wood and steel stud/gypsum frame buildings brought the issue of rain control back into focus. As a result of small incremental changes made to construction practice during the 1970's and 1980's in details and new materials, wall systems in wet climates became prone to failure.

The relatively air-tight, highly insulated homes of the 1990's were unforgiving. The interior was typically finished with drywall over 6 mil polyethylene taped and sealed at the joints, resulting in a near perfect barrier to vapour. High levels of insulation in the stud space meant the sheathing was close to the exterior temperature and vapour pressures. New materials including OSB sheathing was less moisture tolerant and less vapour permeable than the plywood or board sheathing it replaced. Paper faced gypsum and steel stud framing, a low-cost alternative to concrete masonry block were inherently less moisture tolerant, and more prone to deterioration under wet conditions.

Window technology largely carried over the 1970's and 1980's in terms of interface details and often found to leak, particularly at frame corners. Waterproofing and flashing details were often left up to the tradesmen on site, with little or no guidance from the architect or engineer, and possibly little experience. As a result water shedding details around windows and penetrations were generally poorly constructed and allowed the intrusion of large amounts of water into the wall cavities.

With a vapour and air tight interior the only way for moisture that got into the wall to dry was outwards, which for times of the year was difficult. The stucco or other claddings were applied directly to the building paper, and were constantly wetted by rain during the winter months, thus the moisture couldn't very well dry out through the cladding either. Acrylic or pure cement stucco (no lime) and EIFS, relatively new cladding products were also less vapour permeable, and when used, significantly reduced drying. The lack of a drying potential combined with high instance of wetting resulted in moisture accumulation over time leading to the extensive and catastrophic deterioration of many wood frame and steel stud and gypsum buildings.

Drainage was found to be critical at removing bulk water, i.e. due to a rainwater leak and studies found that drying was important to remove any additional moisture that wasn't drained. It was found that the drying rate could be increased by use of ventilated or vented air spaces behind claddings (rainscreen walls). However it was also found that there is a maximum amount of moisture that can be dried out of walls to avoid damage. In most cases in British Columbia, North Carolina, and Minnesota that the amount of water that penetrated the walls could not be removed by vapour diffusion drying or even air convection alone. It therefore cannot be stressed enough, that wetting must be controlled by use of good detailing at penetrations, cladding drainage, and in some cases venting or ventilation (rainscreen claddings).

The failures in coastal British Columbia lead to the mandated use of rainscreen walls constructed of light claddings over wood strapping and improved rainwater shedding details and flashings. Thus the widespread execution of recommendations which had been suggested by numerous researchers and practitioners over the past 50 years including Johansson (1946), Hutcheon (1953), Ritchie (1960), Garden (1963), Marshall (1983), Morrison Hershfield (1992) and several others.

At the time of their introduction in the late 1990's, rainscreen walls were largely untested in Vancouver's climate. However several earlier CMHC studies – in the early 1980's in Atlantic and Eastern Canada, and later laboratory studies in the late 1990's – showed promise for the performance of rainscreen walls. This leads into the rainscreen field monitoring program, which provided the data for the analysis in this thesis.

11.4 RAINSCREEN MONITORING PROGRAM

Continuing Canada's leadership in building construction and research, a very large field monitoring program was implemented in 2000 to study the performance of rainscreen walls in Vancouver's coastal climate. The monitoring program was undertaken by RDH Building Engineering Ltd. (RDH), the Canadian Mortgage and Housing Corporation (CMHC), the Homeowner Protection Office (HPO), and the British Columbia Housing Management Commission (BCHMC). The primary purpose of this study was to understand the performance of rainscreen walls under local field conditions and to provide feedback to building industry about whether these walls and details were effective at preventing moisture problems.

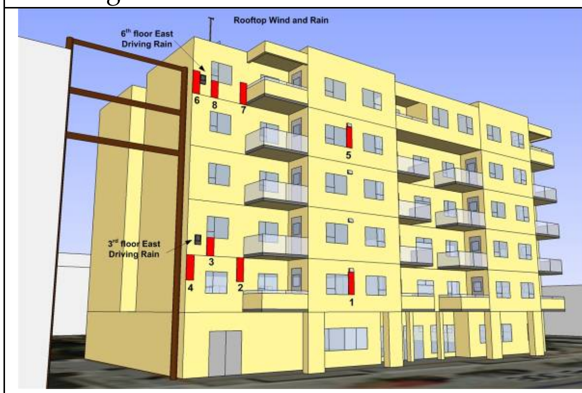
To perform the study, five new or rehabilitated buildings (former leaky condos) constructed with rainscreen walls were selected for monitoring from the local housing stock. Within the five buildings, at least five different wall locations were instrumented with sensors to measure temperature, relative humidity, moisture content, relative wetness, and pressure differential across the wall assemblies. Temperature and relative humidity levels of interior suites were also monitored and weather stations were installed on each rooftop to measure wind, rain, temperature and relative humidity. Driving rain gauges were installed on two orientations of each building to further understand the exterior loads.

The majority of the monitored locations were chosen to be representative of areas most likely to be wetted during severe weather, while a single location was located in the center of the wall, away from details, to act as a control. The monitored locations were generally chosen on the east and south elevations at key details such as vents, windows, balcony transitions, and saddle flashings where historically, high moisture levels have been observed. The monitored wall locations are shown for each building in Table 11-1.

Table 11-1: Summary of Monitored Wall Locations

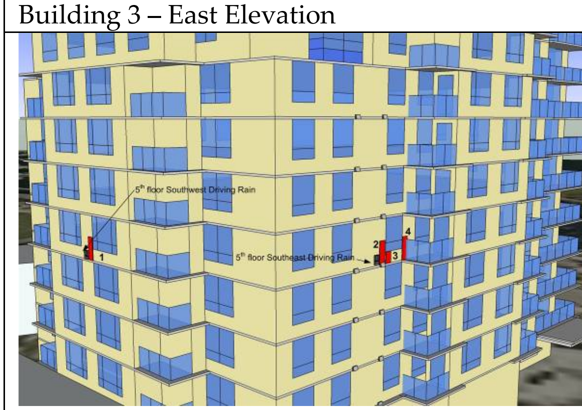
Building 1 – Southeast & Southwest Elevations

Building 2 – South & East Elevations

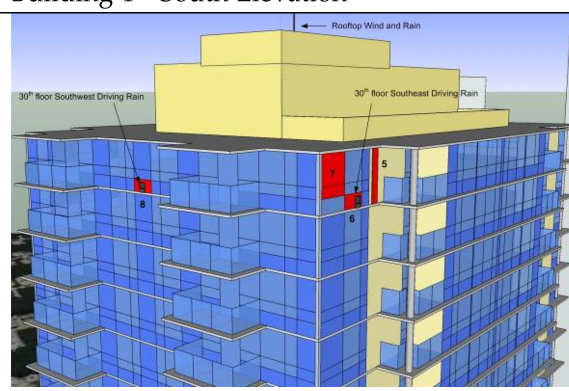


Building 3 – East Elevation

Building 4 – South Elevation



Building 5 – 5th Floor Southeast & Southwest



Building 5 – 30th Floor Southeast & Southwest

11.5 GYPSUM SHEATHING LABORATORY TESTING

It is important to be able to determine the moisture content of gypsum sheathing in such applications in field investigations, monitoring projects and for forensic use. For purposes of this thesis, it was also of interest to determine the moisture content of the gypsum sheathing in Buildings 3 & 5 where electrical resistance readings of the gypsum were recorded for the past five years.

As gypsum sheathing is very moisture sensitive, having a general understanding of whether the product is wet, dry, or somewhere in-between is necessary. Little research has been published in the past on the correlation of electrical resistance with moisture content for gypsum products; particularly commonly used fiberglass faced exterior gypsum sheathing. A series of laboratory experiments were therefore performed at the University of Waterloo to correlate the electrical resistance of fiberglass faced gypsum sheathing with gravimetric moisture content.

A review of the previous literature indicated a significant reduction in strength of all gypsum sheathing products with as little as 1% moisture content. Strength loss and integrity continues to degrade with higher moisture content. Published sorption isotherms for gypsum sheathing indicate that when exposed to relative humidity levels between 85% and 90% an equilibrium moisture content of 1% is attained. Prolonged exposure to 95-100% RH can lead to much higher moisture contents and at a fast rate. Water-vapour was shown to damage gypsum sheathing in the laboratory and in the field in Building 3.

It was also shown that gypsum products marketed as "water-resistant" while resistant to liquid-water to some extent will readily absorb water-vapour in the air from humid (i.e. exterior) environments. It was also shown that while gypsum sheathing will rapidly absorb moisture from humid air; it can even more rapidly lose that moisture when exposed to dry conditions. Therefore in most field conditions, very high moisture levels will likely only be attained under severe wetting conditions, or where moisture is trapped within an assembly.

Walls constructed with gypsum sheathing and steel studs do not have the same safe storage capacity of comparable wood framed systems. An 1% moisture content over 1 m^2 of 13 mm gypsum (density 850 kg/m^3 – 11.1 kg/m^2) means that approximately 111 g/m^2 of water can be safely stored in gypsum sheathing, where as 1% MC in 13 mm plywood sheathing (density 500 kg/m^3 – 6.5 kg/m^2) means that 65 g of water can be stored per 1%. As wood can safely store up to 20% moisture content, 1300 g/m^2 of water may be safely stored. In addition the wood studs also store some moisture, in the same order of magnitude as the wood sheathing. Steel studs do not have the capacity to store moisture, and exposure to humid environments will lead to corrosion. The difference to seasonally store 111 g/m^2 in gypsum compared to 1300 g/m^2 in wood highlights the sensitivity of gypsum sheathing products to humid environments and the importance to keep walls constructed with gypsum sheathing dry or able to dry quickly if they get wet.

While many fiberglass faced gypsum products are marketed as “mould-resistant” after meeting ASTM test standards, mould was shown to grown on surface contaminants, accelerated by liquid water from condensation in the laboratory and the field. When condensation occurs on gypsum sheathing - as the surface is hydrophobic - the moisture will bead up (unlike on wood where it will be absorbed and redistributed). It appears that these condensation droplets can capture dirt and mold spores which become sites for mould growth. While the mould-growth observed in the field and laboratory was not extensive or anywhere as severe as what would occur on paper-faced gypsum products, it may be a concern in some cases.

There is some debate as to safe relative humidity levels which gypsum can be exposed to for extended periods. Many sources have recommended a maximum exposure of 80% RH. This will result in a gypsum moisture content of less than 1% and is a conservative threshold. Potentially this threshold could be increased to 90% RH for fiberglass faced gypsum, as long as condensation is avoided. 90% RH is the tipping point on the sorption isotherm where for small changes in RH the moisture content rapidly increases. It is however important to avoid extended periods of exposure at 90% RH or higher for structural, corrosion (of fasteners & studs), and also mould/microbial concerns.

The laboratory work demonstrated that the moisture content of gypsum sheathing can be measured using electrical resistance, similar in relationship to that is well developed for wood. The fiberglass faced gypsum sheathing correlation was compared to previous work which tested different gypsum products with good agreement.

An equation was developed to correlate gravimetric moisture content with measured electrical resistance for gypsum sheathing (Figure 11-1 and Equation 1). The correlation while developed specifically using a commonly used fiberglass faced gypsum sheathing product can potentially be applied to other gypsum sheathing products with a small test calibration. Importantly, the laboratory testing shows that such work can be performed for gypsum and yield useful results.

$$GypsumMC(\%) = \frac{1}{((62.0693 * (\log(\Omega))) - 243.0790)} \qquad \text{(Eqn. 1)}$$

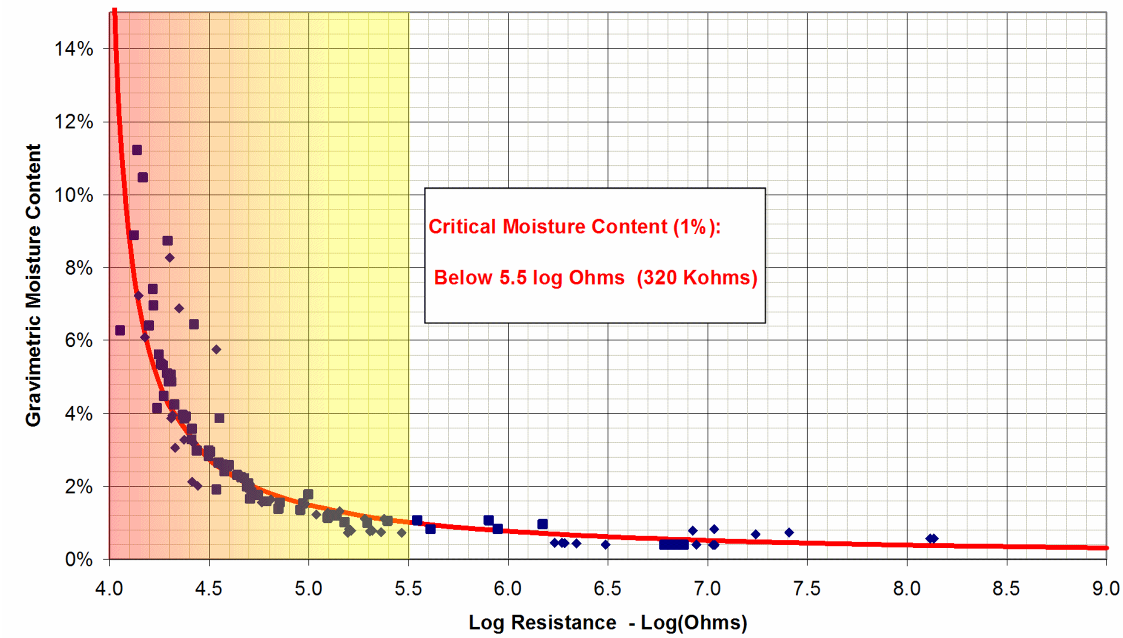


Figure 11-1: Measured Electrical Resistance versus Gravimetric Gypsum Moisture Content.

The gypsum moisture content relationship was further correlated to an equivalent wood moisture content which can be measured using standard handheld meters calibrated specifically for wood. A relationship was presented so that existing wood moisture meters can be used to read approximate gypsum moisture contents in the field (Figure 11-2).

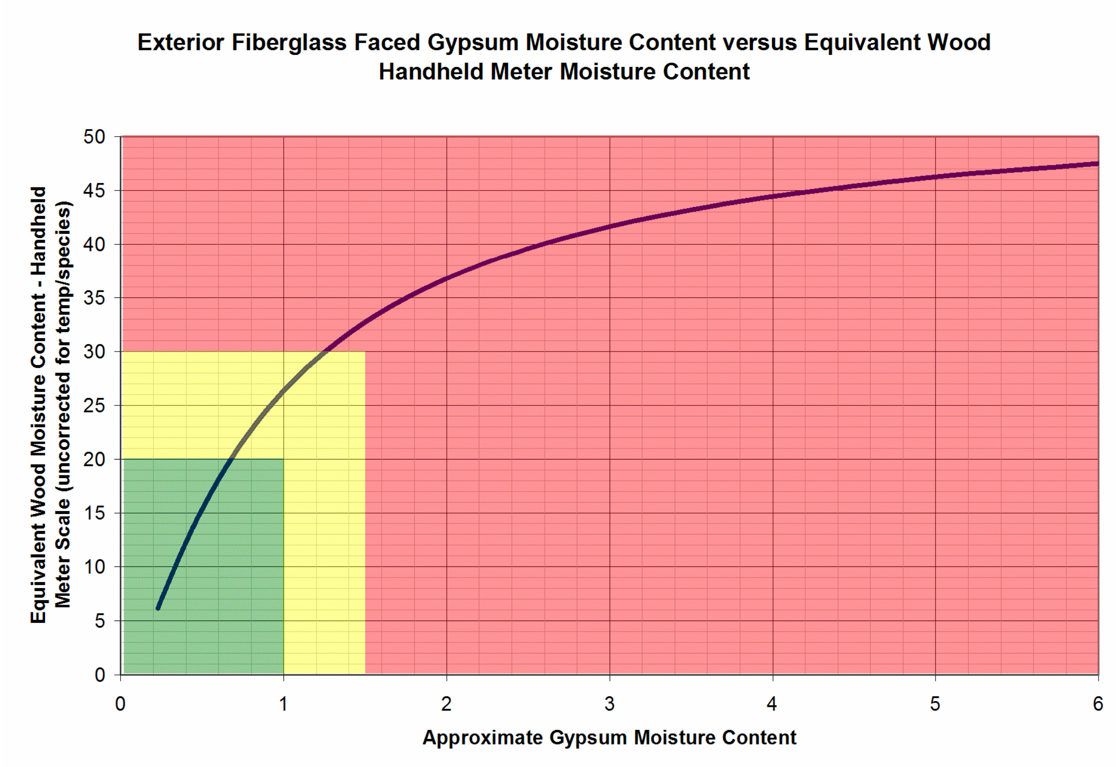


Figure 11-2: Moisture Content – Wood Scale Reading Relationship

11.6 EXTERIOR BOUNDARY CONDITIONS

The local climate across the Greater Vancouver area varies. Differences in rain, wind speed, wind direction, temperature, and relative humidity were observed across the five buildings and the airport. Typically the airport receives less rain and records cooler temperatures than most areas of the city. Across the five monitoring buildings, the highest rainfall was observed at Building 5 in the downtown core. The predominant wind direction for most of Vancouver is from the east to south-east, however in the downtown area, particularly along the Burrard Inlet; northeast was found to be the predominant direction as at Building 5. The predominant wind direction was also found to be the principal direction during driving rain events (Figure 11-3).

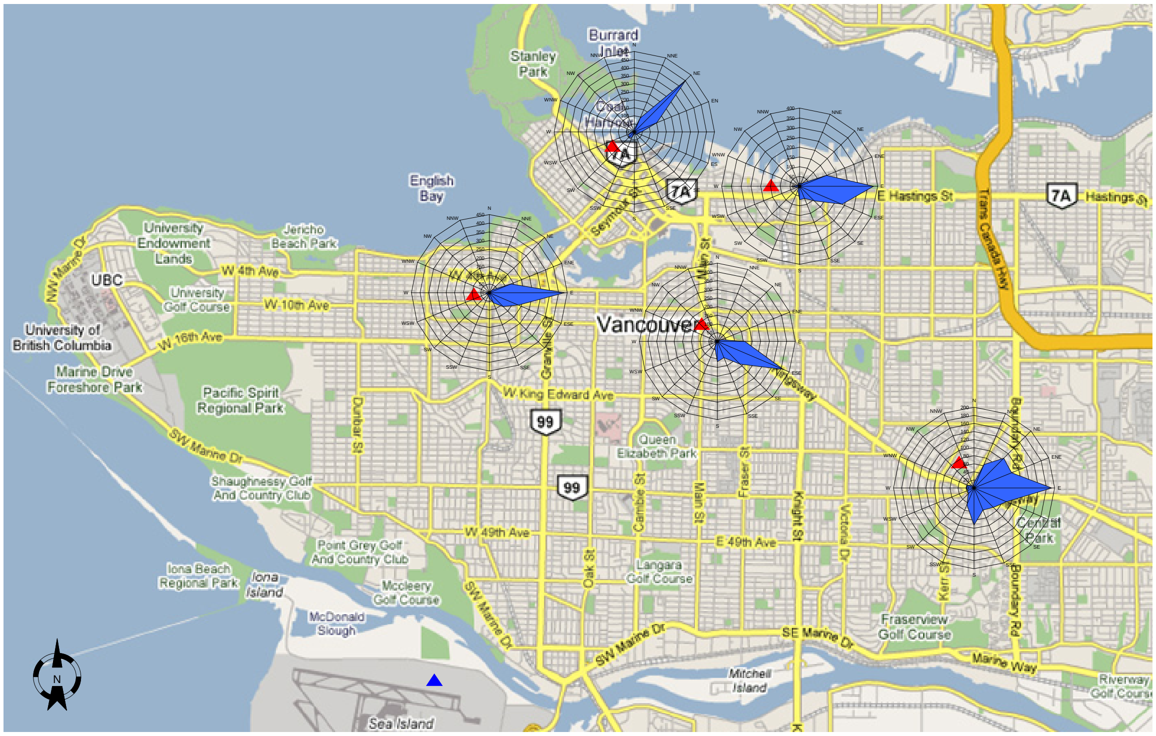


Figure 11-3: Measured Wind Direction during Rain Events across the 5 Monitored Buildings (underlay map: Google Maps 2006)

Driving rain was measured at two orientations on the five buildings in the study. Local wind sheltering was found to reduce the amount of driving rain at the building significantly in comparison to the airport.

Driving rain was calculated using an empirical method to determine the total driving rain as a function of the climate (wind speed, direction and horizontal rainfall). Building 5 (30 storey high-rise) had the highest annual driving rain potential with approximately 850 mm/yr), similar to the airport with 800 mm/yr, this was followed by Building 3 (6 storey mid-rise) with 550 mm/yr and Buildings 1, 2 and 4 (four-storey low-rises) with between 200-300 mm/yr. The differences in calculated driving rain at each of the buildings and the airport are summarized in Figure 11-4 and shown across the city in Figure 11-5.

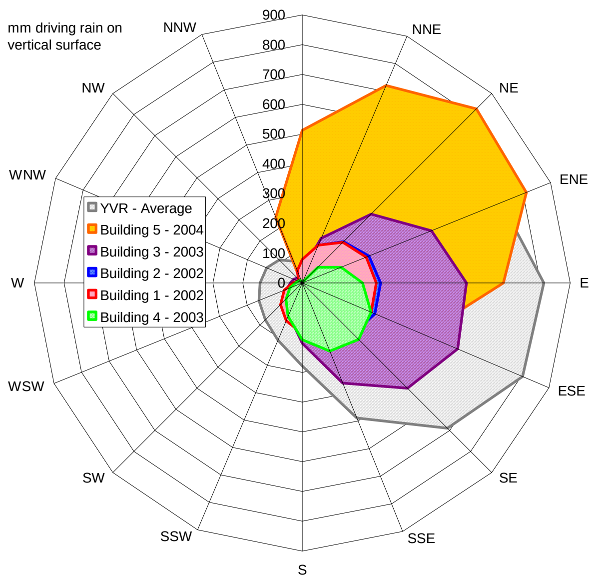


Figure 11-4: Calculated Driving Rain for the 5 Buildings and Airport

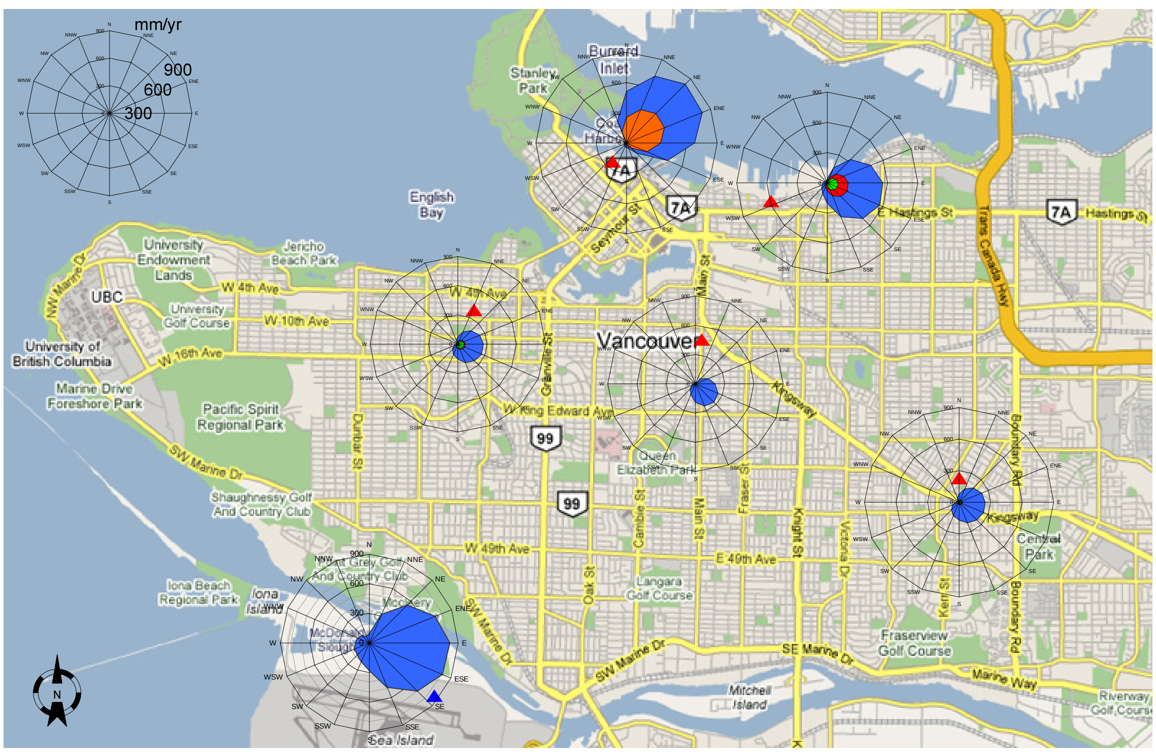


Figure 11-5: Calculated Driving Rain across the 5 Monitored Buildings and Airport (underlay map: Google Maps 2006).

To determine the driving rain on the façade of a building, modification factors are applied to the calculated driving load. Reductions are made depending on the location on the building and are reflected in rain deposition (RDF) and exposure height (EHF) factors. RDF and EHF factors were determined for two locations on each of the five buildings by correlating the calculated driving rain with that measured by driving rain gauges.

An EHF factor of 0.5 was assumed and RDF factor determined to correlate the driving rain predictions to measurements. RDF factors generally agreed with previous literature and were found to range from 0.06 for Building 4 (well sheltered to 0.76 at the top corner of Building 3 and 1.0 at the top edge of Building 5.

Buildings 1 and 4 with moderate to large roof overhangs saw significantly reduced driving rain deposition compared to Buildings 2 and 3 without overhangs. Building 4 saw the lowest driving rain load: 7 mm/yr on the south, and 3 mm/yr on the North, significantly less than any of the other buildings. While providing little in terms of driving rain data, Building 4 does provide important proof that a very large 1200 mm (4′) overhang can significantly reduce the amount of driving rain on the façade of a large four-storey building to almost negligible levels.

Empirical methods to calculate driving rain at a specific location on the building façade have varying accuracy, and are be influenced by a number of variables.

The accuracy of the empirical model was very good for the two exposed east facing locations on Building 3. The hourly and seasonal correlation of the measured to predicted driving rain load was excellent and showed the potential of empirical model to accurately predict driving rain loads on exposed and simple building shapes.

In contrast, at Buildings 1, 2, 4, and 5 the empirical model was able to capture the relative driving rain trends at the monitored locations on these buildings, but could not capture the absolute measurements or hourly trends with great accuracy. Errors were observed as a result of complex wind and rain interactions at these buildings which could not be predicted by the empirical model. The use of more sophisticated numerical CFD models may be required in these cases to accurately predict driving rain deposition for these more complicated buildings

Correlation with buildings that received driving rain predominantly perpendicular to the driving rain gauges was better than buildings where the driving rain came from a range of directions.

The limitations of the empirical method were shown, and further research should be performed into the validity of the cosine method assumption used by all empirical methods. The empirical model could possibly be improved with additional factors to correct for wind from angles not perpendicular to the wall.

Selecting an appropriate RDF and EHF factor is simple in hind-sight using measured data, and the RDF values generally agree with previously the published literature. However in foresight it may be difficult to predict RDF factors with confidence for design. Assumptions must be made based on experience of the designer, and it is always safer to choose a larger RDF factor resulting in a worst case loading.

Hygrothermal modeling software such as WUFI provide weather files for use with simulations. These weather files are typically derived from measurements at airports. In Vancouver, exposure correction factors should be applied to reduce the driving rain loads from the airport to the building site based on the designer's judgement and experience. RDF and EHF factors for the five buildings were provided to assist practitioners with selecting appropriate factors.

11.7 INTERIOR BOUNDARY CONDITIONS

Large differences in the interior environment were observed between nine suites in the five monitored buildings. Occupant behaviour and the building HVAC system influence the temperature, relative humidity, and dewpoint of the interior environment.

The measured interior conditions were different across all five buildings and none could be considered average (i.e. controlled to 21°C). The temperatures varied as a result of occupant behaviour and in addition, the interior dewpoint and relative humidity varied considerably as a function of moisture generation and suite ventilation rates.

Within each of the suites the occupants had control over the temperature via a thermostat. In Building 3, the tenants kept their suites on average between 16-18°C during the winter months and found this to be acceptable. In Buildings 1, 4, and 5, the occupants kept their suites between 23-25°C on average during the winter months and found this to be comfortable, and presumably even affordable. In Building 2, the wintertime temperatures were kept the closest average at 19°C, however may have been warmer if ventilation rates weren't as high.

As none of the buildings have air conditioning systems, average interior suite temperatures of 25-27°C during July and August were normal. In addition, hourly peaks up to 34°C were recorded during the hottest summer days.

Relative humidity and temperature measurements from the five buildings from 2001 to 2005 are summarized in Figure 6-4. No provisions for control of relative humidity were made other than by the tenants opening a window or turning on the bathroom/kitchen exhaust fan.

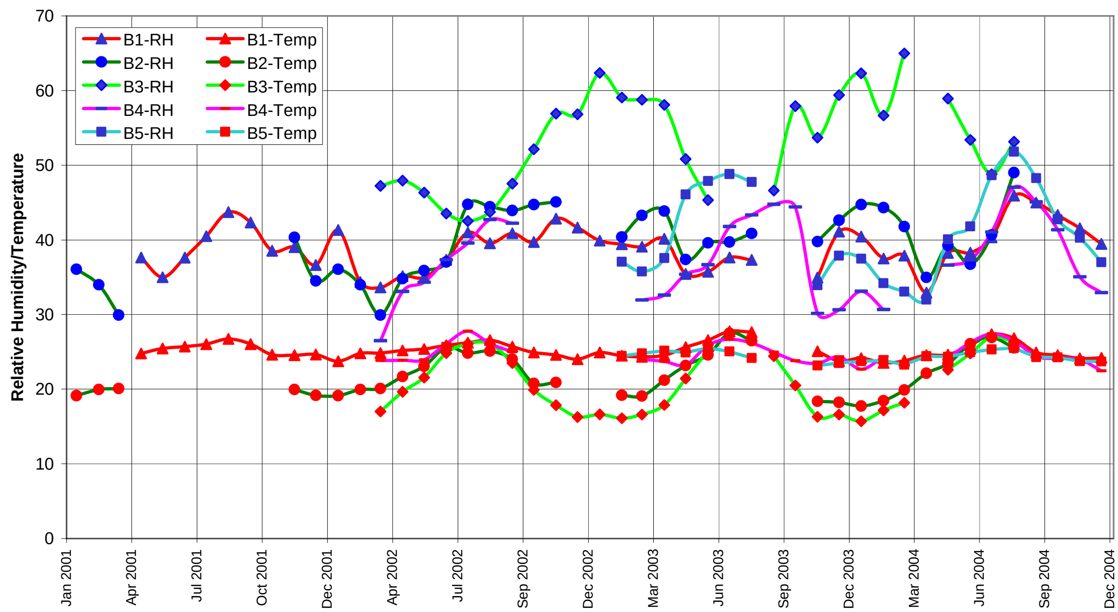


Figure 11-6: Summary of Monthly Temperature and RH – Buildings 1-5, 2001-2005

As shown, Buildings 1, 2, 4, and 5 showed similar seasonal trends, while Building 3 had elevated wintertime relative humidity levels in contrast to the other buildings. The average annual and wintertime conditions presented in the previous sections are summarized in Table 6-8.

Table 11-2: Summary of Temperature, Relative Humidity and Dewpoint for Buildings 1-5

Building	**Suite**	**Annual (Temp, RH, DP)**	**Winter (Temp, RH, DP)**	**Summer (Temp, RH)**
1	206	25°C, 40%, 10.0°C	24°C, 41%, 9.5°C	25-27°C, 40-45%
2	401	22°C, 39%, 7.1°C	19°C, 35%, 3.4°C	25-26°C, 40-45%
3	311	20°C, 53%, 10.2°C	16.3°C, 59%, 8.4°C	25-26°C, 40-50%
3	611	21°C, 52%, 10.3°C	18.1°C, 58%, 9.8°C	25-26°C, 40-50%
4	309	24.4°C, 36%, 8.3°C	23.8°C, 31%, 5.7°C	25-27°C, 35-45%
5	3005	23.8°C, 36%, 7.4°C	21.4°C, 32%, 3.6°C	25-26°C, 40-50%
5	504	24.3°C, 41% , 9.9°C	23.8°C, 36%, 7.8°C	25-26°C, 45-55%
Average ALL*		23.8°C, 38%, 8.5°C	22.4°C, 35%, 6°C	25-26°C, 40-50%
Range ALL		20-25°C, 36-53%, 7.1-10.3°C	16-24°C, 31-59%, 3.4-9.8°C	25-27°C, 35-55%

**except Building 3, which has abnormal conditions*

Building 3 showed significantly different trends than the other four buildings. The issues with Building 3 are more complicated than a high wintertime relative humidity as a result of lower temperatures. The impacts of air tightness and ventilation system performance are discussed further for this building in the discussion on air leakage testing in the following section.

Residential building designers must be aware of the potential for the interior environment to deviate from the average 21°C standard assumption. Interior conditions will vary by season, and on average the annual temperature was measured between 20-25°C, the winter temperature deviated on average from 16-24°C.

The energy penalty with maintaining residential suites at high 23-25°C wintertime temperatures in temperate climates such as Vancouver is relatively low as compared to colder climates such as Edmonton. In colder climates such interior temperatures would cost significantly more to maintain discouraging tenants from wasting energy.

Contrary to the belief of some practitioners, it is also possible to achieve low (<35%) interior wintertime RH levels in Vancouver's temperate climate. Relative humidity is a function of interior moisture generation and building ventilation. Those suites that had low wintertime RH levels (30-40%) had sufficient - and in one case excessive - ventilation. High relative humidity levels (50-70%) were only observed in Building 3 as a result of insufficient suite ventilation. Moisture generation rates were not measured, but appeared to be normal based on occupancy.

While the five buildings are not statistically representative the entire population of buildings in Vancouver, they do provide insight into possible variances of interior environment for residential buildings. Allowing for the potential differences in temperature and relative humidity would be prudent in design of residential buildings, especially where easily performed using hygrothermal simulations.

11.8 AIR LEAKAGE TESTING

Air leakage testing of six suites in four multi-unit residential buildings was performed to quantify air leakage between adjacent suites, floors, common spaces and through the exterior walls. Three buildings from the monitoring study (Buildings 2, 3, & 4) and one additional building with similar moisture problems to Building 3 were air-leakage tested.

The following airtightness conclusions can be made from the results, which also reflect field experience with these types of assemblies. Solid concrete assemblies were constructed more airtight than wood assemblies and wood assemblies were more airtight than steel stud/gypsum. Suite demising walls and floors were typically constructed more air tight than hallway walls. Exterior walls with peel-and-stick as an air barrier were more air tight than those with polyethylene (at the interior) or taped polyolefin house wrap (to the exterior of the sheathing).

The test method allowed the air leakage through the exterior building enclosure to be isolated. The concrete frame buildings with exterior walls constructed with a peel and stick air/vapour/water barrier membrane over gypsum and steel stud wall were the tightest and had a range of leakage from 2.5 to 4.8 cm^2/m^2 @50 Pa. The wood-frame walls with polyethylene and/or taped and sealed polyolefin house wrap and gypsum drywall as the air barrier system were considerably leakier at 12.9 to 21.8 cm^2/m^2 @50 Pa. All measurements were taken with intentional exhaust ducts left as they would be in practice and would be common to all measurements. The leakiest building at 21.8 cm^2/m^2 @50 Pa of exterior enclosure leakage included a fireplace and was a corner unit on the top floor, which had the highest enclosure surface area which may explain its difference from the other buildings. The air leakage testing results are summarized in Table 11-3 for the four buildings.

Table 11-3: Summary of Air Leakage Test Results

Building - Suite	**Total Air Leakage through all 6 surfaces (ACH_{50} - NLA_{50})**	**Leakage through interior surfaces (% - NLA_{50})**	**Leakage though exterior enclosure (% - ACH_{50} - NLA_{50})**
Building 2 - 401	13.8 ACH_{50} – 6.5 cm²/m²	19% - 2.1 cm²/m²	81% - 11.1 ACH_{50} - 12.9 cm²/m²
Building 3 – 608	4.0 ACH_{50} – 1.4 cm²/m²	22% - 2.8 cm²/m²	78% - 3.1 ACH_{50} - 4.8 cm²/m²
Building 3 – 611	6.2 ACH_{50} – 2.3 cm²/m²	64% - 3.3 cm²/m²	36% - 2.2 ACH_{50} - 4.1 cm²/m²
Building 3 – 311	4.1 ACH_{50} – 1.5 cm²/m²	67% - 1.4 cm²/m²	33% - 1.4 ACH_{50} – 2.5 cm²/m²
Building A - 802	2.6 ACH_{50} – 1.0 cm²/m²	65% - 0.8 cm²/m²	35% - 0.9 ACH_{50} – 2.7 cm²/m²
Building 4 - 309	9.7 ACH_{50} – 3.1 cm²/m²	33% - 1.4 cm²/m²	67% - 6.5 ACH_{50} – 21.8 cm²/m²

The leakage rates for the six Vancouver buildings ranged from 2.5 to 21.8 cm^2/m^2 @50 Pa whereas previous testing from Gulay et al. (1993) measured values from 3.8 to 5.7 cm^2/m^2 @50 Pa for ten buildings across Canada.

ASHRAE Standard 160P suggests typical air-tightness guidelines for use with hygrothermal models. For standard construction 0.29 cm^2/m^2 is suggested and for air-tight construction 0.055 cm^2/m^2 is suggested at 5 Pa. The values measured in the testing here are an order of magnitude or two higher (10 to 100 times).

Leakage through interior walls and floors is significant and cannot be ignored, and becomes more critical as the exterior building enclosure is increasingly constructed more air-tight. The need for balanced mechanical systems is more important with these new tighter building enclosures, otherwise moisture problems may develop as a result of insufficient ventilation (either natural or mechanical) and drawing stale-air from adjacent suites. The inherent faults of the mechanical systems in Buildings 3 & A became aware after the rehabilitations, and had Buildings 2 & 4 been constructed more air-tight, problems may likely have been noticed there as well. Instead "passive" or accidental air leakage through the exterior building enclosure is assisting with ventilation and preventing interior problems from occurring at the leakier buildings.

Corridor supply and suite exhaust mechanical systems may have worked in the past in multi-unit residential buildings when the building enclosures were leakier, however may not work well with today's modern air-tight buildings. In addition, air leakage between suites and common spaces will increasingly become more important as the exterior enclosure increasingly becomes tighter. While the air-tightness of these interior partition walls/floors should be improved, it will not make up for insufficient mechanical ventilation. Preferably, fresh make-up air would be ducted and supplied to each suite and pressures balanced to eliminate inter-suite air leakage (as is done in a few new buildings). For rehabilitation projects, the cost of such an option may be prohibitive and the existing mechanical systems may have to be upgraded to accommodate higher ventilation rates. This can include the use of continuous in-line fans with low noise (sone) level and possibly the use of heat recovery ventilators (HRVs) within each suite or floor to reduce energy costs.

While an air-tight building enclosure is desirable for energy efficiency and thermal comfort, a higher level of performance is required from the mechanical and ventilation systems. Air-tight buildings put a higher demand on the mechanical ventilation systems to actually perform in service and deficient systems can have serious ramifications on building performance and occupant comfort. While holistic consideration in design for the integration of all building components (structural, mechanical, building enclosure, etc) has been called upon by practitioners for years, and as we strive to achieve higher performance buildings it becomes an absolute necessity.

11.9 WOOD-FRAME WALL PERFORMANCE

Similar seasonal moisture trends were observed across the three rainscreen building during the five years of monitoring. A typical year is shown in Figure 8-35 highlighting the wetting and drying events further discussed in Figure 8-36 and Figure 8-37.

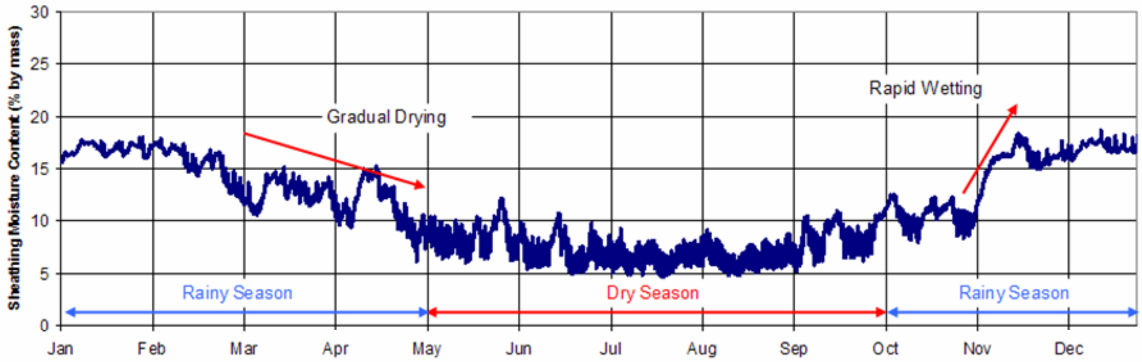


Figure 11-7: Sheathing Wetting & Drying Trends for the 3 Wood-frame Buildings

During the summer months the sheathing moisture content ranged between 5-10% depending on the relative humidity within the ventilated cavity. In late fall at the start of Vancouver's rainy season the sheathing moisture content increased up to 15-20% within a few weeks as the cavity RH increases up to 80-100%. The sheathing moisture content fluctuates during the winter months however remains at levels below 20% on average. Peaks up to 25% MC were observed at a few wetter locations. In the spring when the rainfall largely stops and sun comes out for extended periods, the walls dry back down to 5-10% MC.

The seasonal wetting trend is highlighted in Figure 8-36, showing the influence of rainfall, solar radiation, and cavity dewpoint/relative humidity.

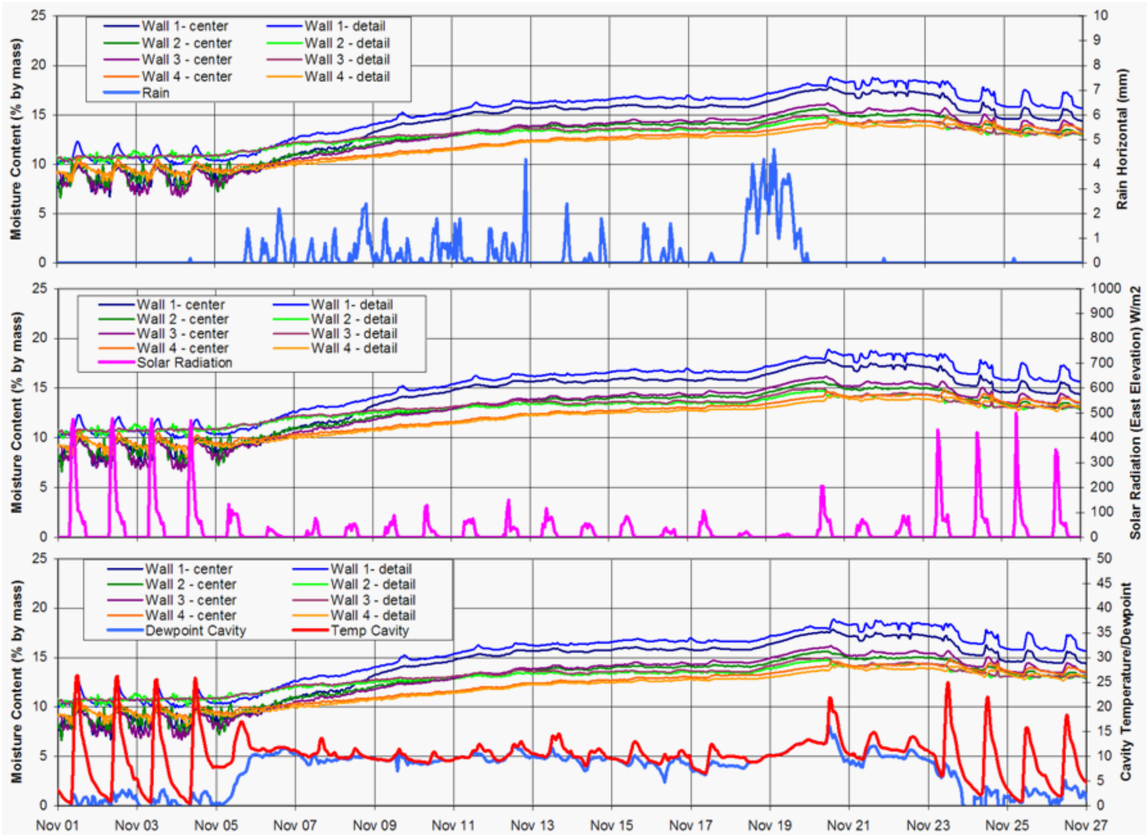


Figure 11-8: Seasonal Sheathing Wetting Trend for Buildings 1, 2, & 4

While raining during the moisture increase, the rain does not directly impact the sheathing moisture content. However during rainy weather the relative humidity outdoors is at 100%. The reduced cavity temperature and solar heating results in the relative humidity within the cavity space to be near outdoor conditions. As a result, the sheathing moisture content increases to reach equilibrium with the relative humidity within the cavity (between 80-90% on average). If the relative humidity drops (over a daily average), the sheathing moisture content also drops.

The spring drying trend is highlighted in Figure 8-37, showing the strong influence of solar radiation on the cavity temperatures which reduces the relative humidity within the space and dries the sheathing. Cavity temperatures of up to 40-50°C result in evaporation of moisture from the sheathing which is subsequently carried away by ventilation flow.

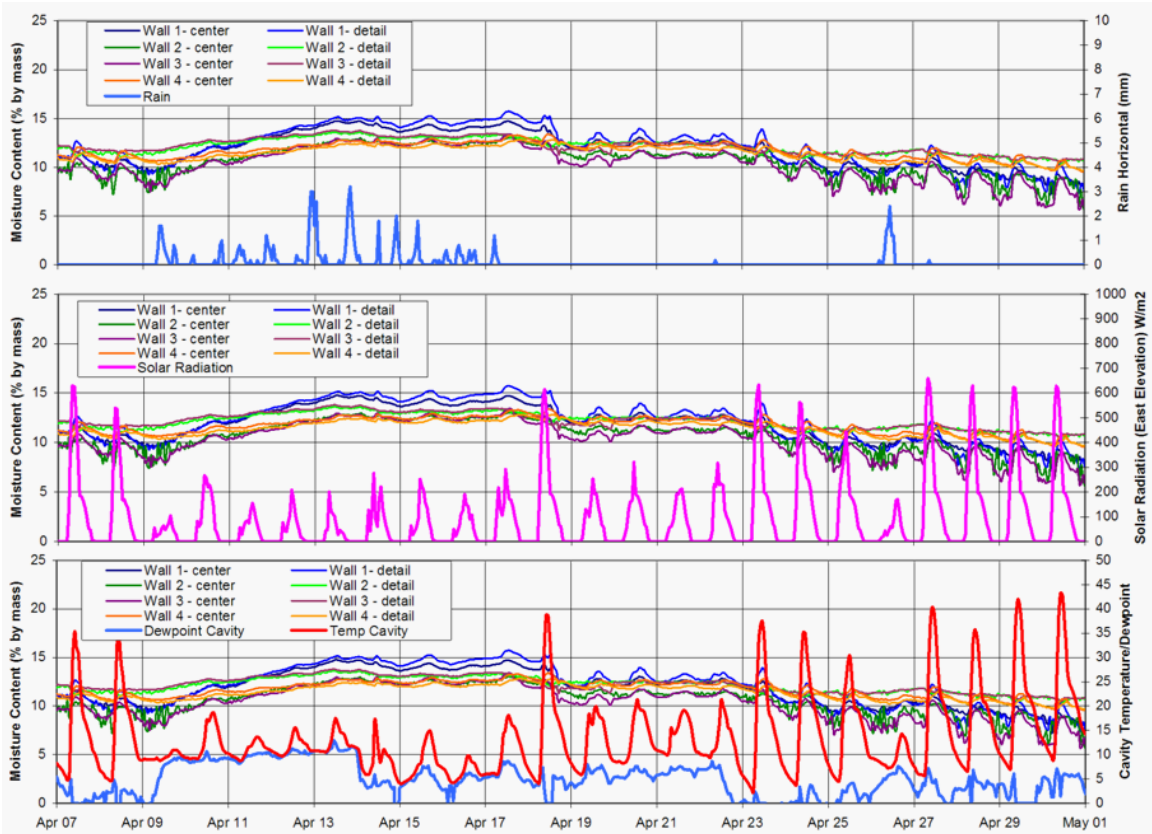


Figure 11-9: Seasonal Sheathing Drying Trend for Buildings 1, 2, & 4

All three buildings, regardless of cladding type and driving rain exposure had similar seasonal performance. The brick veneer at Building 4 had slightly higher average moisture contents, potentially as a result of the absorptive cladding and reduced ventilation drying. In no cases were moisture contents elevated for periods long enough to sustain damage (i.e. above fiber saturation). However, the relative humidity within the ventilated cavity and at the inside face of the sheathing was at levels between 80-100% RH for several months during the winter at all monitored locations. The implication of the high relative humidity levels observed on microbial growth is uncertain.

Two separate rainwater leaks were observed in the measured data and further analyzed. The first leak occurred at Building 1 and impacted the moisture content of the plywood sheathing. The leak occurred at a reverse lapped building paper detail at a vent penetration in 2001, during the first winter of monitoring. As a result of the monitoring project observations, the leak was investigated and repaired to address the water penetration issue. The observations showed that while the leak was likely small, it was able to raise the sheathing moisture content up to 30% during the winter months. It also showed that rainscreen walls are not immune to leaks, and that ventilation alone during the winter months could not reduce the moisture content down to safe levels (<20% MC).

The second leak occurred at Building 2, into the rainscreen cavity below a window corner. The leak occurred during a very large rain event (90 mm measured at the roof in 48 hours) where liquid water came into contact with the vertical wood strapping, was absorbed, and increased the moisture content from 10% to 18% within a few days. The strapping remained at this elevated level throughout the winter (above normal levels for strapping) and eventually dried to normal seasonal levels during the spring. This observation showed that leaks into the strapped cavity can happen; however the water resistive barrier prevented the sheathing from being wetted. After the moisture content was increased, the strapping remained at levels above normal (for strapping) for the remainder of the winter months.

When performing condition assessments of wood-frame buildings in Vancouver, the investigator should be aware of the normal seasonal sheathing moisture contents. Moisture contents between 15 to 20% during the wet and rainy months from October to May are observed to be normal. Moisture contents of up to 25% may also be observed, however if moisture levels above 25-30% are observed, additional investigation should be performed as an additional moisture source is likely present (rainwater leaks, air leakage condensation etc).

While the performance of wood-frame rainscreen walls appears to be better than the face-sealed or concealed-barrier approaches used in the past, sheathing moisture levels are bordering safe limits. The sheathing moisture content was observed up to 20-25% for up to 6 months during the winter, and the relative humidity levels at the ventilated cavity and interior of the sheathing may be of concern between 80-90% for several months.

Evidence also suggests that rainwater leaks may still be able to cause damage to the sheathing and therefore further improvements to the wall assembly should be investigated to reduce wetting events and improve the drying performance of interior insulated rainscreen wall assemblies.

11.10 STEEL STUD & GYPSUM WALL PERFORMANCE

11.10.1 Building 3

The split-insulated stucco rainscreen wall assembly performed poorly at Building 3 as a result of humid interior conditions. The monitored data indicates that water vapour flow by diffusion and/or air convection is wetting the stud cavity and exterior gypsum sheathing during winter months. High relative humidity within the stud cavity and elevated moisture contents of the gypsum sheathing were observed in all eight wall locations and followed consistent seasonal trends.

Field openings confirmed the sensor readings and also the presence of moisture within the wall cavities. The impacts of the high moisture levels included: minor surface corrosion on the screw fasteners and steel stud flanges, liquid water on backside of sheathing and pooled within sill track, structural softening and localized mould growth on the surface of the fiberglass faced gypsum sheathing. As a result, the future durability of the steel studs, fasteners, and gypsum sheathing is in question.

The elevated interior relative humidity levels correlate with the wetting and drying events. The lack of a controlled ventilation system combined with an air-tight wall assembly, occupant loading, and lifestyle contributes to the high overall relative humidity observed in the building.

Currently a mechanical system upgrade is being designed to improve ventilation rates and reduce the interior dewpoint within the suites. A unique opportunity exists to monitor the impact of the mechanical system improvements on the condition of the exterior walls and to determine if further remediation is required.

While many of the problems in Vancouver in recent years have been a result of rain from the exterior, this case study reinforces that vapour diffusion and interior relative humidity must not be overlooked. Measures such as upgrading mechanical systems should be considered when rehabilitating the exterior building enclosure.

11.10.2 Building 5

The exterior-insulated stucco rainscreen wall assembly at Building 5 performed very well. Moisture sensitive materials were kept dry and the relative humidity within the interior stud space at moisture sensitive materials remained at levels only slightly above interior conditions. No evidence of exterior moisture penetration or condensation was observed at any of the wall locations.

The window-wall spandrel panel assemblies also appeared to perform well, however the impacts of the high temperatures and relative humidity levels within the spandrel cavity space could not be ascertained. It is likely that the conditions observed are normal; however other field data and measurements for this type of wall assembly is generally lacking. The impact of such high temperatures on the long-term adhesion of the exposed peel-and-stick air/vapour barrier at transitions within the spandrel panel is questionable. Mineral wool insulation as used here is typical for glazed spandrel cavities not only for its ease of fitting, but also resistance to high temperatures. Materials such as XPS or EPS or even polyurethane sprayfoam may not perform as well and can be degraded or even melt at the high temperatures observed.

It is important to realize that the high temperatures and subsequent vapour pressures observed within the ventilated rainscreen cavity or spandrel cavity spaces are loads on the rest of the wall assembly. Temperature gradients are significantly higher than predicted by ambient exterior conditions and for simple calculations or modeling applications (energy or hygrothermal) these temperatures need to be considered. These high solar induced temperatures impact building mechanical systems, and as observed in this building, interior temperatures during the summer were frequently in the 25-30°C range as air-conditioning was not provided.

11.11 HYGROTHERMAL MODELING

It was shown that current one-dimensional hygrothermal software has a limited ability to model the wetting and drying of walls with ventilated claddings. Modeling “tweaks” were found to be limited in their accuracy for some ventilated cladding scenarios. The new version of one-dimensional WUFI 4.1 which can model heat and moisture “sources and sinks” within wall assemblies can overcome many of the limitations of using 1-D models. This hygrothermal model was validated with measured field data from the three wood-frame buildings (1, 2, & 4).

11.11.1 Interior Insulated Wood-Frame Rainscreen Assemblies

Results from this study indicate that rainwater leaks have the potential to raise sheathing moisture contents to unsafe levels during the winter. However, further testing should be performed to study the drying response of ventilated rainscreen walls wet by accidental moisture entry under controlled circumstances so more useful guidelines can be developed.

Results from the hygrothermal model highlight the importance of cladding ventilation for rainscreen wall assemblies where the sheathing is exposed to the ventilated cavity. When hourly or annual average cladding ventilation rates are calculated using the theory outlined and ventilation modeled as a source/sink, the correlation between the field measured and modeled results is excellent.

The larger the cavity, the greater the ventilation flow for similar driving pressures. The vent openings are an important design detail, and should be made as large and unobstructed as possible without allowing rain penetration or bird/animal/insect ingress. Brick vent bug-screen inserts are especially problematic for brick veneer walls, and by removing the inserts the ventilation rate can be increased by a factor of 10 for similar driving pressures. Alternately, larger or additional vent openings (between every brick) may be an option to improve ventilation rates and thus drying potential.

In this climate, the use of polyethylene is being reconsidered by some practitioners and builders. Common latex paint could be used as an interior vapour control layer, but it is not recommended in a traditionally constructed frame wall assembly (insulated stud space without insulation to the exterior of the sheathing) with high interior relative humidity. Vapour retarding paint (<60 ng/Pa·s·m^2) could be used as a replacement for the polyethylene; however an air barrier (typically in the form of the Airtight Drywall Approach) is still required.

Interior relative humidity control becomes more important as the interior vapour control layer becomes more permeable (i.e. if using standard paint). Hence, providing sufficient indoor ventilation is required to keep relative humidity levels indoors low.

In the coastal climate of Vancouver, one of the best ways to improve the performance of ventilated or drained rainscreen walls is to protect the sheathing from the ventilation airspace by use of thermal insulation, and the more the better. Providing as little as 25 mm of exterior insulation can greatly improve the performance by reducing the sheathing moisture content. This provides an improved factor of safety against accidental wetting from rain or interior air leakage. Ideally the insulation should be vapour permeable to allow for drying of potential rainwater leaks and removal of interior moisture. Less vapour permeable insulations such as XPS, closed cell polyurethane, sprayfoam, foil-faced polyisocyanurate, or EPS may trap moisture at the sheathing in leak events and result in damage.

In addition, as insulation is added to the exterior of the sheathing, cladding ventilation becomes less important to the performance of the wall. Therefore the performance of walls which are inherently less ventilated (such as brick veneers) could easily be improved with exterior insulation instead of trying to increase ventilation flow by larger vents etc.

With increasing energy prices and a growing interest in achieving more energy-efficient buildings, the thermal resistance of walls is likely to increase in the future. Using standard frame wall designs and increasing stud cavity insulation levels results in a reduction of the drying potential of the sheathing. Additional insulation should therefore be placed on the exterior of moisture sensitive sheathings to increase the temperature of the moisture sensitive components, and increase drying potentials. As sufficient insulation is placed on the exterior, vapour impermeable layers such as polyethylene can be removed from the interior of wall assemblies to improve drying to the interior. Hygrothermal models can be used to make informed design decisions for required vapour control.

11.11.2 <u>Building 3</u>

The high interior humidity was shown to have a direct impact on the wall performance, and that doubling the current ventilation levels would reduce the relative humidity within the stud cavity to safe levels. Further improvements could still be made to improve the performance and are discussed in the following section. Exterior boundary conditions such as driving rain and orientation had little effect on the performance of this wall assembly.

To prevent moisture problems from reoccurring at Building 3, the high interior moisture levels and path into the exterior walls need to be addressed. As the problem is widespread and not isolated to a single suite or elevation, the whole building will require a similar repair strategy. The most economical solution is preferred and the exterior walls and cladding in the current state do not need to be replaced. Therefore it would be preferable if the moisture problems could be addressed by using mechanical or interior retrofits instead of an entire exterior re-clad as was performed recently in 2001.

First, the interior humidity should be controlled to reasonably dry levels (40-50% RH during winter). To do this, the suite ventilation needs to be increased during the winter, and can easily be retrofit installing more powerful (50-100 cfm actual flow) primary suite exhaust fans (bathroom). The fans should be continually running or be hooked up to a humidistat, but hard-wired to remain on when the RH in the suite is above 50%. To address noise issues, several quiet (low sone) level fans are available. If sufficient fan-flow cannot be attained using existing cast-in-place slab ducts, additional ducts within a drop ceiling/plenum should be installed. Measures should also be taken as discussed in Chapter 7 to balance the suite ventilation systems to prevent inter-suite leakage, and ensure sufficient fresh air is reaching the suites from the pressurized corridor.

Controlling the interior relative humidity and moisture levels will also reduce the instance of condensation and mould growth on cold surfaces such as window/door frames and cold corners.

Improving the suite ventilation reduces the RH at the sheathing from 90-100% to 80% during the wintertime; however this can be further reduced providing interior vapour and air flow control. Therefore as a second measure, low vapour-permeance vapour retarder paint (approximately 35-50 $ng/Pa \cdot m^2 \cdot s$) should be applied to the exterior walls. In addition all wall penetrations (electrical outlets, baseboard heater wiring, window/door frames etc.) should be well air-sealed. It is suggested that the vapour retarding paint & air tightening repair strategy be trialed in the monitored suites and monitored after the interior humidity issue is already addressed. As all air leakage pathways may not be accessible or sealed during an interior retrofit, the vapour retarder paint may have a negligible impact due to continued air leakage overwhelming the moisture flow into the assembly. Monitoring of the retrofit assembly also provides confidence that the repair will work in the rest of the building.

11.11.3 Building 5

The exterior insulated wall assembly as used at Building 5 performs very well as expected. The moisture sensitive wall components are kept dry, and in case of a leak have a high drying potential. Hygrothermal model shows that an exterior insulated assembly can safely manage a 20x larger leak than an interior insulated assembly with similar materials.

In summary, the exterior insulated wall assembly as-built performs very well under normal conditions and when exposed to small rainwater leaks. Problems can be encountered with this assembly if an impermeable interior finish such as vinyl wallpaper is used. Therefore if an impermeable interior finish is required, the vapour permeance of the insulation and sheathing membrane must be increased to allow drying to the exterior. As shown using a vapour permeable sheathing membrane and mineral wool insulation allows for impermeable interior finishes such as vinyl wall-paper to be used.

11.12 RAINSCREEN WALL DESIGN: FINAL SYNTHESIS

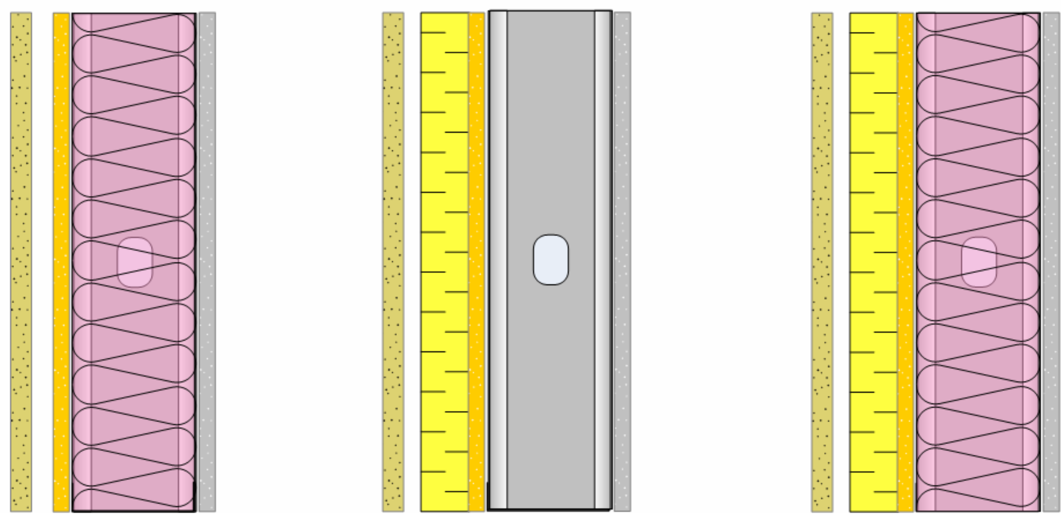
Rainscreen wall performance is a function of the exterior and interior boundary conditions and the materials employed in construction. Of these materials the placement of the thermal insulation and vapour control layer can have the largest impact on performance. Performance is measured by the ability of the wall assembly to balance wetting, drying and safe storage while maintaining safe and healthy conditions for the occupants. Most problems can be minimized or eliminated by good design.

Three different rainscreen wall types were monitored, and can be characterized by the placement of the insulation and vapour control layers.

1. ***Interior Insulated***, traditional construction approach with thermal insulation within the structure of the framed wall assembly. The moisture and air control layers are located at the interior of the insulation layer in cold climates and to the exterior in hot climates. It is a well established residential wall assembly with mixed success. The use of a drained a ventilated cavity behind the cladding is a recent improvement, not typically installed in the past.

2. ***Exterior Insulated***, modern construction approach with the thermal, moisture and air control layers to the exterior of the moisture sensitive components. It is an excellent performing commercial or residential wall assembly that will work in any climate.

3. ***Split-Insulated***, dual approach with thermal insulation within the framed wall assembly and to the exterior of the sheathing. Vapour and air control layers are placed either between the insulation layers or at the interior surface depending on exterior and interior climates and materials used. It is a good performing wall when properly designed and very high thermal insulation values can be attained.



Interior Insulated *Exterior Insulated* *Split Insulated*

Figure 11-10: Insulated Rainscreen Wall Types

A balance between the architectural constraints (wall thickness and possibly aesthetics), thermal performance, cost, and constructability must be made when choosing what type of assembly to use. In a well designed assembly the air and vapour control layers are placed appropriately depending on the interior and exterior climates to which it will be exposed.

The three rainscreen wall assemblies are ranked in risk from low to high risk of potential problems when accidents such as air leakage or rainwater leaks occur.

1. Exterior Insulated – lowest risk, can manage air leakage, rainwater leaks and has minimal thermal bridging. Cladding ventilation has minimal impact on the performance of the assembly where impermeable air/vapour/moisture barriers are used. Wall assembly is recommended for

all applications, however due to thermal insulation constraints, wall thickness may be restricted, requiring the use of a split-insulated assembly.

2. Split Insulated – lower risk the higher the ratio of insulation on the exterior to the interior is. Can manage air leakage and rainwater leaks however not as well as an entirely insulated assembly. Thermal bridging is also reduced as compared to an interior insulated system. Cladding ventilation has an impact on the performance of the assembly depending on the materials used within the cavity space. Improved performance over an interior insulated assembly and recommended for most wood-frame wall applications.

3. Interior Insulated – highest risk, susceptible to rainwater leaks and air leakage condensation. Numerous field cases have shown failure as a result of air leakage in cold climates or rainwater penetration in wet temperature climates. Rainscreen approach improves performance over perfect-barrier, however still susceptible to moisture damage. Cladding ventilation has as significant impact on the performance of this wall assembly, and should be maximized when possible.

While the much of the commercial and parts of the residential construction sectors have readily accepted the concept of exterior applied insulation, much of the residential sector and primarily those building single and even multi-family dwellings have not. It is time for industry to embrace the fact that insulation is required on the exterior of modern structures with several purposes. Additional insulation not only reduces heat loss and energy costs but also keeps critical components warm so they remain dry, or are able to dry out when accidentally wetted.

Building a rainscreen wall is not a panacea for wall moisture problems. The drained and ventilated cavity does reduce the likeliness of moisture coming into contact with sensitive materials within a wall assembly, however does not guarantee problem-free performance. In addition, air leakage and vapour diffusion from the interior are ever present moisture sources and cannot be neglected in design.

Risk can be reduced by using an exterior insulated assembly as opposed to an interior-insulated assembly. However, in any case the end performance relies on a properly designed, detailed, and constructed wall assembly which prevents rain penetration or air leakage from occurring.

While an air-tight building enclosure is desirable for energy efficiency and thermal comfort, a higher level of performance is required from the mechanical and ventilation systems. Air-tight buildings put a higher demand on the mechanical ventilation systems to actually perform in service and deficient systems can have serious ramifications on building performance and occupant comfort.

While holistic consideration in design for the integration of all building components (structural, mechanical, building enclosure, etc) has been called upon by practitioners for years, and as we strive to achieve higher performance buildings it becomes an absolute necessity.

12 CONCLUSIONS

Using a combination of detailed long-term field measurements from the five buildings, hygrothermal modeling and supporting laboratory testing, the following conclusions were made.

Ventilated and drained claddings (i.e. rainscreen) reduce the sensitivity of wood frame buildings to moisture damage. Ventilation of the cladding was shown to be particularly important. Natural buoyancy forces (from temperature and humidity differences between cavity and exterior) are usually sufficient to provide good ventilation drying. Solar radiation has a significant impact on these ventilation rates.

Both modeling and field measurements showed that exterior insulation can significantly improve wall performance, reducing wetting from both exterior and interior and increasing drying to the interior. More vapour-permeable insulation also increases outward drying in exterior insulated systems. When additional insulation is placed outside the sheathing, the vapour resistance of the interior layers should be reduced to improve overall drying.

Interior boundary conditions are almost as significant as exterior boundary conditions. Elevated interior humidity, resulting from inadequate ventilation, can be exacerbated by inter-zonal airflow within multi-unit residential buildings. The airflow measured between adjacent suites was unexpectedly high in several cases. The volume of inter-zonal air leakage recorded brings the suitability of corridor supply ventilation systems into question. It is recommended to provide fresh air to each suite directly, to ensure adequate ventilation in suites with modern air-tight exterior wall construction.

While an air-tight building enclosure is desirable for energy efficiency and thermal comfort, a high level of performance is required from the mechanical and ventilation systems. Air-tight buildings put a higher demand on the mechanical ventilation systems to actually perform in service and deficient systems can have serious ramifications on building performance and occupant comfort.

Micro-climate and site factors in urban Vancouver were shown to have a tremendous impact on driving rain load, wind speed and direction. Driving rain loads across the city can vary by an order of magnitude from predictions based on Vancouver airport data. In addition, temperatures were shown to deviate from airport data by as much as 3 to 4°C in the summer.

For some simple configurations and exposure, driving rain loads on the building façade can be calculated with reasonable accuracy via empirical models. However building shape and architectural details, such as overhangs or balconies, which affect wind-flow patterns greatly reduce the precision of empirical prediction models.

Hygrothermal computer modeling was proven capable of predicting the performance of ventilation claddings, with sufficient accuracy to be very useful for the building industry. Experience and knowledge of how systems function, boundary conditions, and material properties are all necessary for successful modeling.

The moisture content of fiberglass faced gypsum sheathing was measured using electrical resistance. An equation was developed from laboratory testing and applied to the field measurements with good accuracy.

In the Pacific Northwest climate, rainy winter conditions are such that wetting of exterior wall components (sheathing, strapping, cladding and in contact ventilated cavity space) can be expected from fall until spring, even when direct rain contact is avoided. Drying can occur quickly in the spring, especially under the influence of solar radiation exposure, because of the heating and buoyancy-driven ventilation that occurs.

Field measurements and modeling suggests that rainwater leaks may still be able to cause damage within rainscreen wall assemblies. Water shedding details (i.e. around penetrations) still remain important, and a poorly constructed detail can result in moisture problems. The drained and ventilated cavity of the rainscreen wall assembly does reduce the likeliness of moisture coming into contact with sensitive materials within a wall assembly, however does not guarantee problem-free performance. In addition, air leakage and vapour diffusion from the interior, even in Vancouver's temperate climate, are ever-present moisture sources and cannot be neglected in design.

13 RECOMMENDATIONS

Recommendations are made to the building industry for best practice, to research institutions for further research and field monitoring studies.

13.1 FOR THE BUILDING INDUSTRY

From the conclusions of the thesis, recommendations are made to the building industry on selecting appropriate exterior and interior climate loads, calculating driving rain on buildings, ensuring sufficient ventilation within multi-unit residential buildings, designing rainscreen walls assemblies, and performing hygrothermal modeling simulations.

Exterior & Interior Climate Loads

Climate loads provided for the Vancouver Airport (such as those in WUFI, HygIRC etc), may not always be representative for a building situated within the city. Exposure correction factors are required for wind and driving rain, and temperatures are generally warmer within the urban areas. The selection of appropriate and realistic climate loads for a building is critical for some modeling scenarios. While differences may not always impact the results, an understanding of which loads could is necessary.

Knowledge of local climate differences is beneficial to those who design buildings in Vancouver and several references are available. It is also expected that similar climatic differences occur between airport data and other large cities and is not just a function of Vancouver's topography or climate.

As for the interior climate, assuming average temperature and relative humidity levels for multi-unit residential buildings may be a poor assumption. Designers should be aware of a possible range in temperature and relative humidity. When designing wall assemblies which are sensitive to indoor conditions, worst case scenarios beyond ASHRAE recommendations should be modeled and potentially designed for. An unforeseen humid interior climate, while a result of insufficient ventilation resulted in the wetting and moisture damage to the wall assembly at Building 3.

For building owners of multi-unit residential buildings, it is recommended that the interior temperature and relative humidity be monitored in a few suites to determine how well the suite HVAC system is performing and if sufficient ventilation is being provided to prevent high interior moisture levels. Catching moisture problems early can save potentially millions of dollars later should the exterior walls be damaged as a result. Occupants should also be educated on what interior conditions may result in problems within buildings and instructed not to turn off the heat or shut off rooms during the winter-time.

Driving Rain Calculation

Using empirical calculation methods, the driving rain load can be determined for a site using measured hourly wind and rain data, and applied to any location on the building façade using a rain deposition factor (RDF). The accuracy of empirical model in correctly predicting driving rain was found to be good when the building façade was well exposed and when the predominant wind direction during driving rain was perpendicular to the wall. The empirical models however had mixed accuracy capturing the driving rain load on facades which were sheltered, or at the very exposed locations as a result of wind flow anomalies. The annual trends were good and correlated RDF factors were reasonable, however hourly prediction was poor in some cases.

Large overhangs were shown to reduce driving rain deposition on buildings significantly. While excessively large, a 1200 mm (4') overhang on a relatively sheltered 4-storey building reduced driving rain loads to almost negligible levels. More typical 400-600 mm (18-24") overhangs also significantly reduced the driving rain load on two four-storey buildings.

Air tightness & Ventilation of Multi-unit Residential Buildings

A procedure was developed to air-leakage test an individual suite within a multi-unit residential building. The test method allowed the air leakage through the wall & floor assemblies and finally the exterior building enclosure to be individually determined. The measurements provided insight into the relative airtightness but also further understanding of the makeup air for suite ventilation system. The procedure may be used for several applications; including the commissioning of new buildings and for the investigation of indoor air quality or moisture problems.

As the exterior building enclosure is increasingly constructed more air-tight for new buildings, leakage through interior walls and floors becomes more significant and cannot be ignored. The need for balanced mechanical systems is more important with these new tighter building enclosures, otherwise moisture problems may develop as a result of insufficient ventilation and stale air being drawn from adjacent suites. Consideration of mechanical systems during building enclosure retrofits is essential and cannot be ignored. Two case studies were shown where the mechanical systems were not upgraded during enclosure retrofits and interior moisture problems immediately became apparent after construction.

Corridor supply and suite exhaust mechanical systems may have worked in the past in multi-unit residential buildings when the building enclosures were leakier, however may not work with today's modern air-tight buildings. One of the biggest issues is ensuring fresh air is provided directly to each suite. Inter-suite leakage was shown to be an issue in the four buildings tested and under normal conditions, results in stale-air being recycled between suites reducing the air quality and increasing the moisture load.

Preferably, fresh make-up air should be ducted and supplied to each suite directly and pressures balanced to eliminate inter-suite leakage (as is done in some new buildings). For rehabilitation projects, the cost of such an option may be prohibitive and the existing mechanical systems may have to be upgraded to accommodate higher mechanical ventilation rates. This can include the use of continuous in-line fans with low noise (sone) level and possibly the use of heat recovery ventilators within each suite or floor to reduce energy costs.

Rainscreen Walls

A rainscreen wall design is not necessarily the panacea for wall moisture problems. Because a rainscreen wall has been specified, it does not mean that the wall assembly is completely water resistant or will be immune to all moisture problems. Problems were shown to occur still as a result of rainwater leaks, or from humid interiors. In addition, the location of the thermal insulation and vapour control layers affect the performance and durability of different rainscreen walls. Interface and air-sealing details still remain important, and a poorly constructed detail can result in moisture problems within the rainscreen wall assembly.

Cladding ventilation has a considerable impact on the performance of rainscreen walls where the sheathing is located behind the cladding (i.e. not exterior insulated). Preventing ventilation from occurring or only allowing venting (bottom vents only) may result in moisture problems behind some absorptive claddings. Where at all possible, vent openings should be made as large as possible while preventing water ingress.

While drained and ventilated rainscreen wall assemblies are a great improvement over the perfect-barrier assemblies they replaced, moisture problems can still occur. The risk between assemblies is obviously reduced, however further improvements could be made. The performance of traditionally constructed walls can be greatly improved by adding 25 to 50 mm of exterior insulation. Insulation on the exterior of the sheathing reduces the relative humidity in contact with the sheathing can protect from rainwater leaks or air leakage condensation, and increases the drying potential of the assembly. Vapour open insulation such as mineral wool or fiberglass has the best drying performance compared to rigid XPS or EPS insulation which both have the potential to trap moisture from leaks.

For a ventilated rainscreen wall the driving rain load has only a minor impact on the performance, as the cladding is effectively de-coupled from the wall assembly. The risk of leaks however increases with high driving-rain loads and wind-pressures. Only in cases with absorptive cladding (i.e. brick, concrete, or stone etc.) and low ventilation rates (i.e. brick veneer) did the amount of driving rain have an impact on wall performance. Reducing driving rain load however, improves the performance of all wall types.

Exterior insulated rainscreen walls have excellent performance, and can typically tolerate small rain-water leaks or high interior humidity levels. The safest and most durable wall is an entirely exterior insulated assembly. However, in cases where higher thermal resistance is required that an exterior insulated system can provide, insulation can be placed within the stud cavity. In this case, the need for vapour control depends on the climate and ratio of thermal insulation to the outside of the moisture sensitive components.

Hygrothermal Modeling

The one-dimensional WUFI 4.1 model was found to be able accurately predict the performance and conditions within the walls of the five different buildings monitored. Measured boundary conditions were input into the model, and the very similar results as measured were produced. The model showed good agreement with temperature, relative humidity, and moisture content of the interfaces and elements throughout the wall.

To correctly model the ventilation flow behind rainscreen claddings WUFI 4.1 incorporates “source” and “sink” heat and moisture terms into the model. This allows the one-dimensional model to model such effects as ventilation, air leakage or rainwater leaks. Materials provided in the database for the types of walls monitored, generally provided reasonable results.

Hygrothermal modeling highlighted the importance of the interior boundary conditions for Building 3, and rainwater leaks and ventilation for Buildings 1, 2, & 4. Care should be taken when modeling leaks as it is a one-dimensional model and assumes a leak will be evenly distributed over the entire wall assembly. While possibly representative of a large and well distributed leak, for isolated cases it may over predict the moisture content. Further field research and development of improved three-dimensional models are obviously required before further recommendations as to acceptable leak size is determined.

The new WUFI 4.1 hygrothermal model could also be updated to calculate flow versus pressure relationships for user defined wall assemblies and vent configurations. The hourly ventilation flow rates could then be determined by the software based on thermal and moisture buoyancy and wind pressures.

13.2 FURTHER RESEARCH

Based on observations from this thesis, further research should be performed to investigate the following topics. Recommendations are for further monitoring, laboratory work, and potentially material development.

1. **Building 3** - Continue to monitor Building 3 after mechanical/enclosure repairs are made to ensure the wall performance is improved and if necessary make further improvements. The existing monitoring system provides a unique opportunity to ensure retrofit is successful.
    a. The repair will likely require new bathroom and/or kitchen exhaust fans installed to run continuously, or controlled by an automated system. Suite door undercuts should be sufficiently sized to allow supply air into the suites and if required through-wall vents may

be installed from the hallways. Ideally fresh air would be ducted from the hallway supply to each suite if the budget allows.

b. The building tenants should be educated in the use of the new ventilation systems, and safeguards should be put in place so tenants cannot tamper with or turn off the fans or block supply air from entering suite (i.e. install weather-stripping etc).
c. Monitoring of the temperature and relative humidity within the suites should continue until the wintertime dewpoint and relative humidity return to safe levels.
d. Further modifications can be made to the wall assembly if the initial repairs do not sufficiently lower moisture levels within the walls. As suggested by the hygrothermal modeling, vapour retarding paint over the gypsum drywall may be required. If pursued, the strategy should first be tested in suites 311 and 611 so that the effect of the repair can be monitored before applying to the whole building.

2. **Air Leakage of Suites within Multi-unit Residential Buildings** - Air leakage testing should be performed on more suites within multi-unit residential buildings to develop useful guidelines and realistic air leakage values for multi-unit residential buildings. Based on current measurements, current air-tightness ratings appear to be too-low and potentially unattainable.
    a. Eventually guidelines should be put into place regarding the air-tightness of adjacent occupied suites. For noise, odour, smoke, and fire control, these walls are supposed to be air-tight, however ranges in the relative air-tightness were observed.
    b. As the exterior enclosure increasingly becomes air-tight because of new materials and code requirements, the effect of inter-suite leakage will become more predominant. A well controlled and balanced mechanical system can overcome some of these issues.

3. **Rainscreen Wall Assemblies** - As suggested by the performance of the interior insulated wood-frame rainscreen walls, rainwater leaks still have the potential to cause moisture problems in the walls. Further testing should be performed to better understand the size and frequency of leaks which can result in problems.
    a. Wood-frame rainscreen wall assemblies with exterior insulation as recommended from the hygrothermal modeling should be tested in

the field exposure and subjected to rainwater leaks or condensation events.

b. Ventilation effectiveness is reduced when the sheathing is protected by thermal insulation. Selecting appropriate insulation materials (whether impermeable XPS or very permeable mineral wool) for exterior insulation in rainscreen walls is of interest. Balancing the need for some vapour control to prevent inward driven moisture, but also allow rainwater leaks to dry out is of interest. If ventilation rates are sufficient it is likely that mineral wool would be the most appropriate choice to improve the drying potential.
c. While rigid XPS or EPS insulation board products such as are preferred as exterior insulation for constructability purposes (wood strapping nailed to outside through insulation without deformation), the vapour permeability is relatively low, and may trap moisture in some wall designs. Semi-rigid products such as mineral wool or fiberglass while having low vapour permeance, to allow outward drying, can be difficult to construct with in rainscreen wall assemblies requiring additional details to support the cladding. For further material development, possibly a rigid board insulation that was vapour-open, and moisture tolerant could be developed to suit this purpose.

4. **Gypsum Sheathing Electrical Resistance** - Further laboratory testing of gypsum sheathing should be performed to fine tune the moisture content and electrical resistance correlation, specifically at low moisture contents (below 1% MC). Additional products should also be tested to expand and confirm the correlation for more uses.

5. **Gypsum Sheathing R&D** - Further research and development of gypsum sheathing is also recommended. Gypsum sheathing is a durable, fire resistant, recyclable and green building product, however has some inherent drawbacks when exposed to humid environments. It often replaces wood sheathing but does not have the same moisture tolerances. Improvements could be made to the product, or develop a new product which could capture the benefits of both gypsum and wood sheathing products.
   a. It may be of interest to develop an understanding of the gypsum properties chemically at different moisture contents to possibly

develop a more water resistant gypsum core material that does not structurally degrade with moisture content.

b. While some gypsum sheathing products are marketed as "water-resistant", they are often just as easily affected by moisture from humid environments as non water-resistant counterparts. It may be desirable to develop a gypsum sheathing board in the future which will safely store moisture at an order of magnitude similar to the safe storage capacity of wood.

6. **Driving Rain Calculations** - Further research is required to determine if the empirical calculation method can be improved to more accurately calculate driving rain on building facades. The data from the five buildings should also be revisited to determine if available CFD models are able to predict driving rain more accurately before assuming that CFD models are the solution.

13.3 FUTURE MONITORING STUDIES

From the analysis of the data collected from the monitoring program a number of suggestions can be made for future field monitoring studies. These suggested improvements were not foreseen at the onset of the project and therefore not criticism of those who set up the monitoring project, but may improve future projects of this type.

Data Collection Methods

- Collecting more data than can be reasonably managed in unnecessary and wastes time during data compilation and analysis. Data was collected at 15 minute intervals for this project, which is 35,040 data points per year. For one, the limitations of Microsoft Excel and other spreadsheet programs limit the number of consecutive data points which can be plotted to 32,000 on one graph. Therefore a continuous year of data cannot be fully plotted for comparison. The precision of 15 minute data is also not warranted for the analysis of 5 years of data. 15 minute data may more appropriate for short-term (ie 1-2 month projects), but not when dealing with longer time periods. The accuracy of 15 minute versus 1 hour data did not yield any further understanding of the results and was detrimental to the analysis requiring additional time to collect, convert, and manipulate for analysis and presentation.

- Interior and Exterior Temperature and RH was collected using stand-alone HOBO Pro dataloggers not connected to the wall sensor datalogger. Therefore the buildings had to be physically visited every few months to download the interior data. In addition, the interior data had to be synced to the other datalogger data. If the clocks or time stamps were off, errors were introduced into the data. Several months of data were also lost during this project as a result of a dead battery, missing an interior download, or HOBO sensor malfunction. Collecting data at a 15 minute data also fills up the HOBO Pro sensor relatively quickly. In future all sensors should be connected to the same datalogger and collected at the same time period.

- The dataloggers at Buildings 3, 4 & 5 were connected to a modem and phone line and could be downloaded remotely. Buildings 1 & 2 had to be physically visited to download the data, which required coordination with a site contact and fair weather to perform the download from the roof. The ability to download the data remotely saved dozens of hours on this project and allowed frequent downloads and data-checks to ensure the sensors were functioning properly.

- Powering the dataloggers using a 12 V car battery, charged using a solar panel worked very well. While several power-outages occurred at the buildings, the dataloggers continued to collect data for several years without any problems.

- Wind speed and direction measurements were measured every 5 seconds and averaged and recorded every 15 minutes, therefore peaks were averaged out and not fully captured. As the intent of the project was not to measure weather, providing average readings was sufficient to understanding wall performance. However for more accurate driving rain studies, it is recommended that a frequency of 1 minute may be required, and similar for rain deposition.

Selection of Monitored Locations

- One of the original intents of the monitoring project was to determine if the improved interface details were effective at managing rainwater. While being able to potentially determine if a leak occurred at that specific location, the data is potentially thermally affected by the detail, and may not be representative of the performance at the rest of the wall assembly. Fortunately in addition to the "detail" sensor, "control" sensors were also placed away from the details to capture performance through a typical assembly.

- Some of the sensors were also installed in close proximity to thermal bridges which would affect the temperature profile monitored location. In addition, at a few buildings the monitored wall was located at an electrical baseboard heater, and in one case at the fire-place resulting in thermal data that did not accurately reflect the rest of the building. While the sensors showed that heating the wall to 40°C every day during the winter results in drying, it was not the intent of the study.

Sensor Selection

- The pressure sensors were installed to measure the differential pressure across the wall assembly from the ventilated cavity space to the interior or within the stud cavity. Unfortunately several pressure tubes were misplaced in the assembly or blocked (drywall or painted over) at the interior. The pressure sensors used also did not have sufficient resolution (15 minute collection frequency) to capture peak pressures occurring to peak wind events.

- Exterior relative humidity and temperature measurements were initially collected with the same sensors as used within the walls, however failed within a few months when exposed to high exterior relative humidity and potentially rainwater. Exterior grade sensors are available and could have been used initially. Instead exterior grade HOBO Pros were used, which were able withstand up to 4 years of humid exterior conditions protected from the rain. Interestingly the relative humidity and temperature sensors within the ventilated cavities typically performed well under the humid conditions, however were not exposed to liquid water.

- Surface temperature measurements were not collected at the claddings however would have been useful to the analysis.

- Rooftop rain gauges should be sheltered to prevent wind from affecting the results.

- Driving rain gauges can be fitted with a wiper blade to reduce evaporation losses from the exposed gauge surface as shown by van Mook (2002).

- Solar radiation data was not collected at the any of the buildings however could easily be added to the existing weather station. Pyranometers are relatively cheap and provide useful data for understanding wall performance. Fortunately data was collected at a nearby university for the years required and donated to the project.

Appendix A: Exterior Gypsum Sheathing – Electrical Resistance and Humidified Properties

SUMMARY

It is important to be able to determine the moisture content of gypsum sheathing in such applications in field investigations, monitoring projects and for forensic use. As gypsum sheathing is extremely moisture sensitive, having a general understanding of whether the product is wet, dry, or somewhere in between is necessary. Little research has been published in the past on the correlation of electrical resistance with moisture content for gypsum, particularly commonly used DensGlass Gold exterior gypsum sheathing. A series of laboratory experiments were therefore performed at the University of Waterloo to correlate the electrical resistance of DensGlass Gold gypsum sheathing with gravimetric moisture content.

A review of previous literature indicated a significant reduction in strength of all gypsum sheathing products with as little as 1% moisture content. Published sorption isotherms for gypsum sheathing indicate that when exposed to relative humidity levels between 85% and 90% an equilibrium moisture content of 1% is attained. Prolonged exposure to 100% RH can lead to much higher moisture contents and at a fast rate.

The material properties of gypsum are discussed and it is shown that gypsum products marketed as “water-resistant” while resistant to liquid water to some extent will readily absorb moisture from humid environments. It is also shown that while gypsum sheathing will rapidly absorb moisture from humid air; it will even more rapidly lose that moisture when exposed to dry conditions.

The laboratory work demonstrates that the moisture content of gypsum sheathing can be measured using electrical resistance, similar in relationship to that is well developed for wood. DensGlass Gold results were compared to previous work which tested different gypsum products with good agreement.

An equation was developed to correlate gravimetric moisture content with measured electrical resistance for gypsum sheathing. The correlation while developed specifically for common ½” DensGlass Gold can be applied to other gypsum sheathing products as well. The gypsum moisture content correlation was compared to an equivalent wood moisture content which could be measured using standard handheld meters calibrated specifically for wood. A relationship is presented so that existing wood moisture meters can be used to read approximate gypsum moisture contents in the field.

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1 INTRODUCTION

Exterior grade gypsum sheathing is used extensively in the construction of non-combustible steel-stud frame walls common to high-rise residential, commercial and institutional building applications. The sheathing is typically placed outside of the steel-stud frame and provides structural strength, fire resistance, support for cladding materials, and can form part of the air and or water resistant barriers in some cases if properly detailed.

Gypsum sheathing boards are constructed of a gypsum core sandwiched together between two thin facer materials of either paper or fiberglass for strength. Gypsum sheathing boards are commonly available in 4′ x 8′ (1219 mm x 2438 mm) sheets in thicknesses of 1/2″ (13 mm) or 5/8″ (16 mm).

Fiberglass faced gypsum sheathing boards such as DensGlass Gold manufactured by Georgia Pacific Gypsum (G-P Gypsum) have almost completely replaced moisture sensitive paper-faced gypsum boards in exterior sheathing applications in the last decade due to mould and moisture degradation issues with paper faced gypsum and non-water resistant gypsum cores.

DensGlass Gold has a significant share of the exterior gypsum sheathing market, proof of which is the number of buildings visible during construction in North America with the very obvious yellow fiberglass exterior sheathing. Georgia Pacific was the first company to manufacturer paperless, fiberglass matt gypsum in 1986. They also produce a number of other similar fiberglass faced products for different applications including roofing, bathrooms and interior finishing. For typical use of the product, Figure 1 shows two buildings being constructed with DensGlass Gold exterior sheathing prior to installation of the remainder of the wall assembly including the cladding.

Figure 1: Two Buildings with DensGlass Gold Exterior Sheathing (G-P Gypsum)

Other comparable "water-resistant" exterior sheathing products without paper based facers are now produced in North America, such as US Gypsum's Fiberock "Aqua-Tough" however is not specifically discussed in this report.

Two buildings as part of the monitoring study (Building 3 and 5) were constructed with ½" DensGlass Gold exterior sheathing over insulated steel stud framed walls. Electrical resistance readings were taken in the sheathing to measure an approximate relative moisture level to determine the hygrothermal performance of the walls. The observation of elevated moisture readings (low electrical resistance) within the exterior sheathing at all eight observed locations in Building 3 prompted the need for correlation of gravimetric moisture content with electrical resistance, similar to that commonly performed for wood products.

While the experimental testing was performed only on ½" DensGlass gold exterior sheathing, it will be shown that the properties for this product, as compared to other gypsum board products from prior testing yield similar results, and therefore could be applied to other products with some caution.

A series of laboratory tests were performed to measure the electrical resistance of gypsum sheathing at different relative humidity levels and moisture contents. A series of tests were also performed to compare the relative wetting and drying rates for gypsum sheathing.

Gypsum properties, the laboratory test procedure and results are discussed. Correlation of gypsum board electrical resistance with gravimetric moisture content was performed and results are presented. Comparison of gypsum moisture content with wood moisture content (commonly read on handheld meters) is presented. Structural testing was not performed however reference is made to other current industry research.

Field data from current projects employing DensGlass Gold Sheathing at the University of Waterloo and from the Vancouver, BC monitoring project are presented using the correlated results.

2 BACKGROUND

Previous research into the properties of gypsum boards was investigated and significant results related to the laboratory work of this report are presented.

2.1 Previous Work

Little work has been done in the past on correlating gypsum board moisture content with electrical resistance, similar to that performed on wood products by Forintek, US Forest Products and others in the 1970s and 1980s. It is known qualitatively that moisture negatively affects the structural performance of gypsum sheathing, however only recently were quantitative results published for a number of gypsum products at a range of moisture levels.

Recent work in 2005 by Levelton Engineering Ltd. with CMHC compared the structural strength of gypsum at elevated moisture contents and is discussed in detail below. A NORDTEST (Finland) publication from 1997 used moisture meters calibrated for wood to measure the equivalent wood moisture content of gypsum and silicate wall boards exposed to a range relative humidity levels and is further discussed. CMHC work in the 1990's looked at the performance of gypsum sheathed walls and measured gypsum moisture contents gravimetrically. In-house work by RDH Building Engineering Ltd. in 2000 correlated the reference scale of the Delmhorst BD-10 Moisture meter with approximate gypsum moisture levels which is further developed and discussed.

2.1.1 Levelton 2005

Recent work by Levelton Engineering Ltd., sponsored by CMHC tested the structural strength of a number of gypsum board products at varying moisture contents, and showed a significant strength loss (flexural strength, pullout resistance and adhesion with elevated moisture contents, as low as 1% MC (Levelton 2005).

Levelton conditioned samples of gypsum to moisture contents of 0, 1, 2, 4, 6, and 8% moisture contents by adding a measured amount of liquid water to the samples, and storing for 2 weeks to reach equilibrium. Fiberglass faced gypsum (DensGlass Gold), exterior grade paper faced gypsum sheathing, and interior paper faced gypsum wallboard were tested in 1/2" and 5/8" thicknesses.

The following results are presented here from the Levelton report, which show the physical strength characteristics when exposed to high humidity conditions. Figure 2 shows the results of fastener pull-through resistance for ½" gypsum samples.

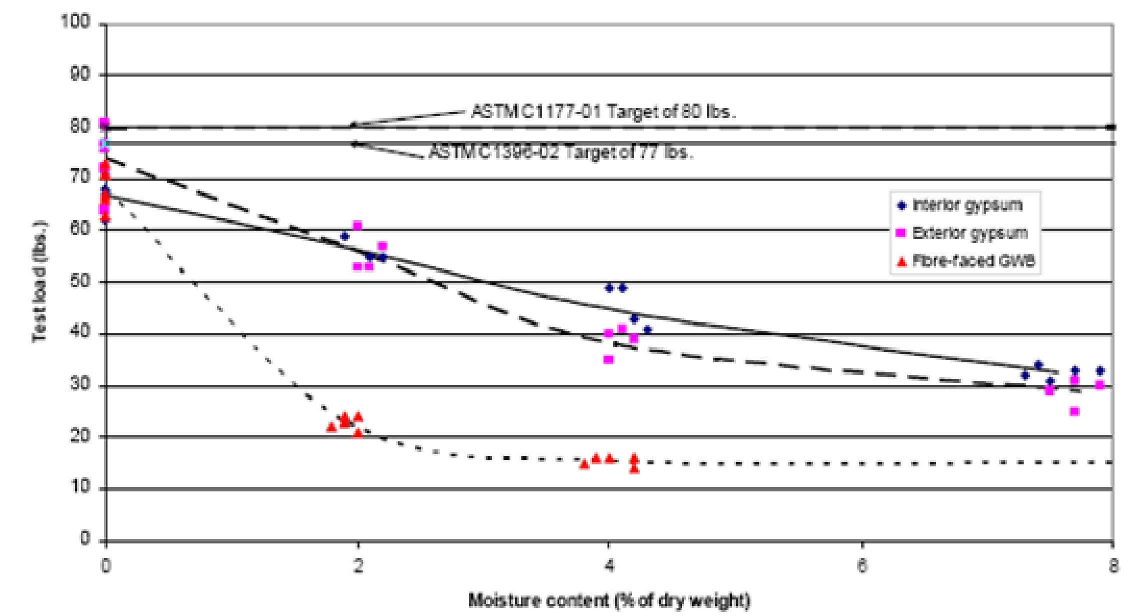


Figure 2: Fastener Pull-Through Resistance for ½" Gypsum (Levelton 2005)

Interestingly, the fiberglass faced gypsum (red triangles) showed the worst performance when compared to exterior and interior grade paper faced gypsum.

From the same tests, the failure mechanisms of the pull-through test are shown graphically in Figure 3.

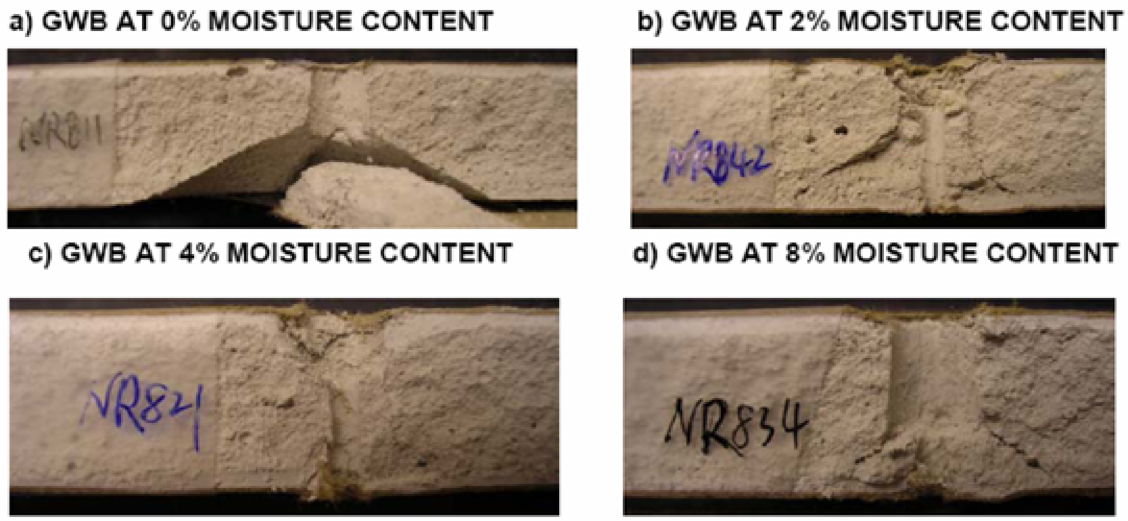


Figure 3: Failure Mechanisms for Pull-through Resistance Test with Elevated Moisture Content (Levelton 2005)

It is shown that at elevated moisture contents, the gypsum is soft, and the fastener pulls right through the gypsum board in a ductile crushing failure, where as at 0% MC, the mechanism is a brittle shear failure, as a conical section of the gypsum has failed around the fastener.

Flexural strength, perpendicular and parallel to the grain was also tested. Figure 4 presents the results from testing of the three gypsum types, perpendicular to the grain.

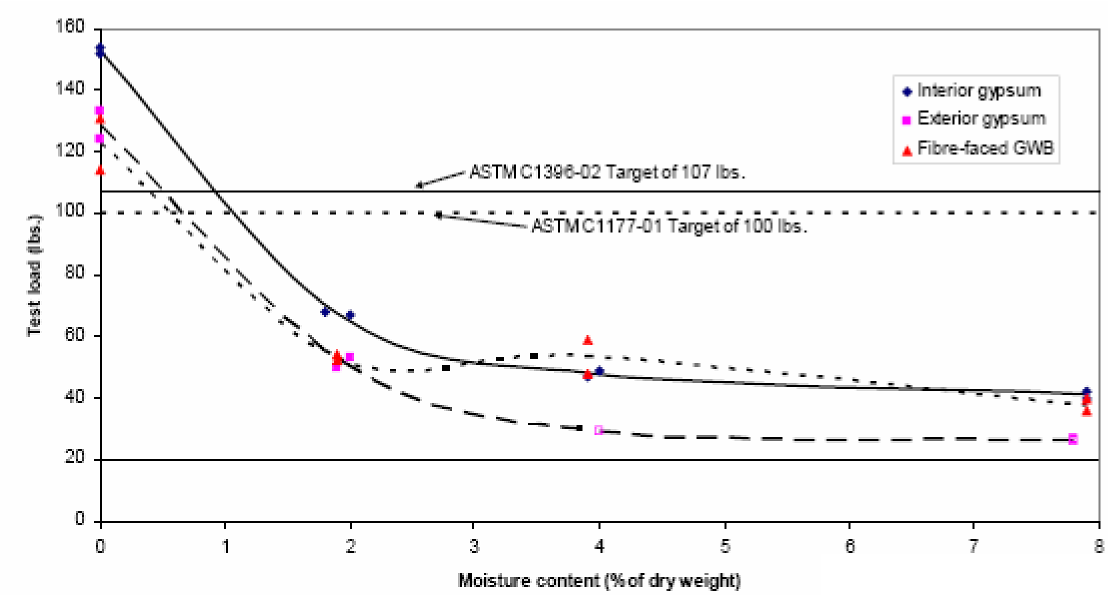


Figure 4: Flexural Strength Tests (Perpendicular) for ½″ Gypsum (Levelton 2005)

As in the pullout testing, there is a rapid decrease in the strength below 1% MC, bottoming out at approximately 2% MC. Results for parallel to the grain are similar for fiber-glass faced gypsum board.

Finally, facer adhesion testing was performed; again the results again show reduced strength with elevated moisture levels above 1% MC. Figure 5 presents the results for ½″ gypsum boards.

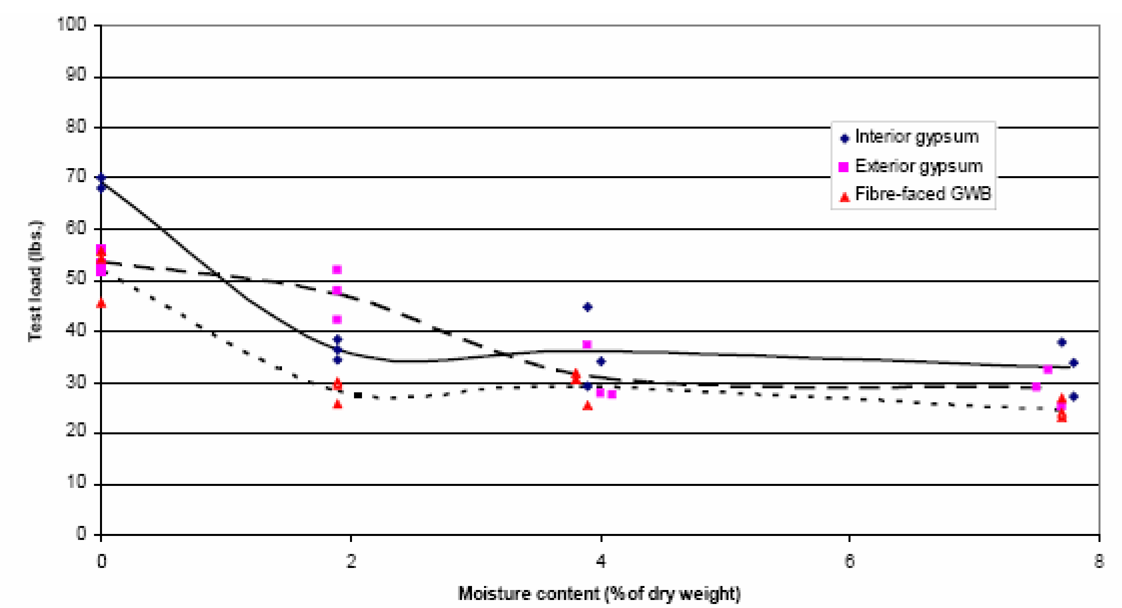


Figure 5: Facer Adhesion Tests for ½″ Gypsum (Levelton 2005)

Again the fiberglass faced gypsum had the worst performance, possibly as indicated the paper facers had stronger adhesion to the gypsum core than the fiberglass facer.

Levelton stated the following conclusion in the report: “The overall conclusion is that gypsum sheathing exposed to exterior relative humidity levels of 60 – 75% can attain moisture contents of 8 – 10% (as a percentage of dry weight). This does not even consider the moisture-content levels that one might expect in the presence of liquid water (due to wind-driven rain, plumbing leak, or accumulation of condensation in the wall assembly). “

The author of this paper does not agree with this conclusion, and believes that moisture contents of 8-10% are only achieved under severe conditions, and for prolonged periods of time. As reported by others, and validated during the laboratory experiment, levels of 60-75% RH result in relatively dry and safe gypsum moisture levels below 1% moisture content. Only above 95% RH do moisture levels approach 8-10%, even then under extended periods of time.

It is believed, from discussions with the authors of this paper that the sorption isotherm Levelton used to develop this conclusion (From WUFI 3.1 and NRC HygIRC database) was incorrect and data was possibly taken from an old sample. Newer versions of WUFI 3.3 and 4.0 provide more recent data for gypsum board products which in the author’s opinion (from field experience and lab testing) are more representative of commonly available gypsum board products.

2.1.2 NORDTEST 1997

A NORDTEST (Finland) publication from 1997 used wood moisture meters to measure the equivalent wood moisture content of gypsum and silicate wall boards exposed to a range relative humidity levels (NORDTEST 1997).

Using electrical resistance meters with pin electrodes they measured the wood moisture content reading and also the electrical resistance in log Mega-ohms at the surface and in the middle of six different gypsum board types at varying relative humidity levels. The samples include both paper and fiberglass faced gypsum boards. Figure 6 and Figure 7 present the results from the publication.

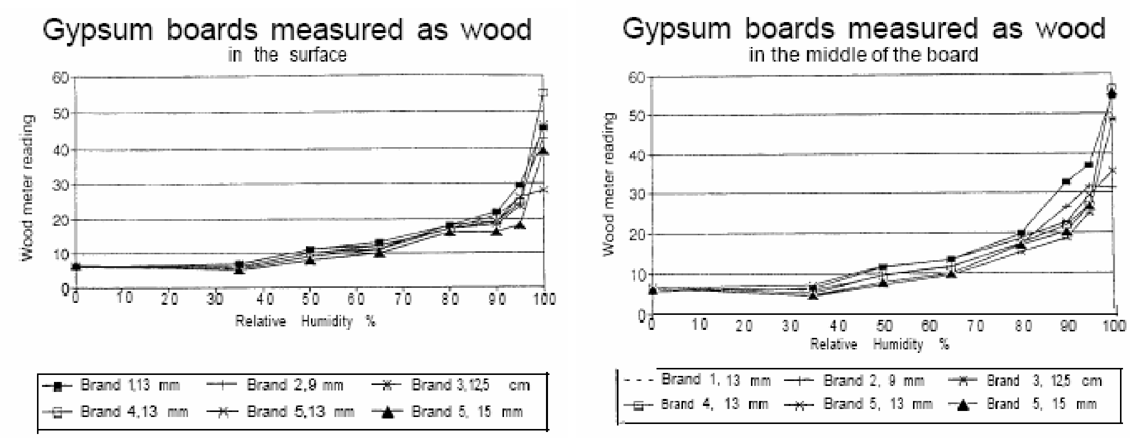


Figure 6: Gypsum boards measured as wood (NORDTEST 1997)

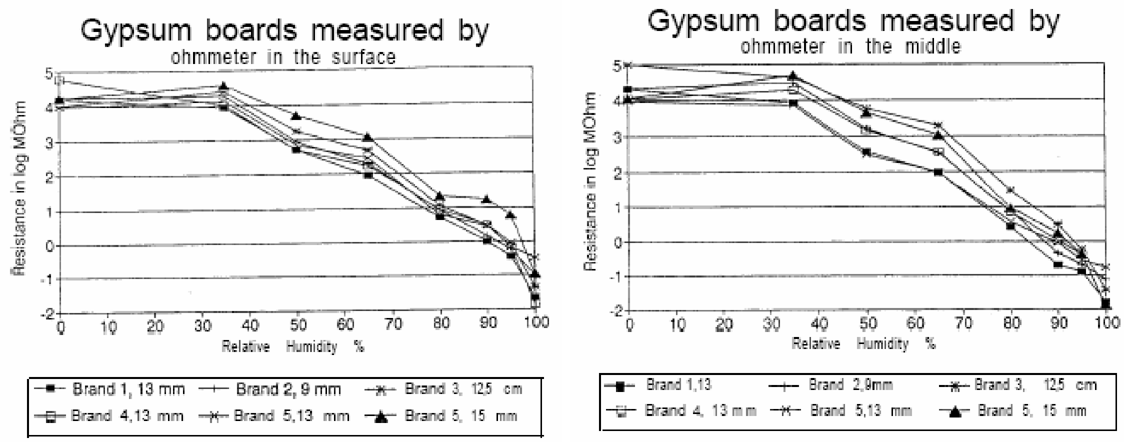


Figure 7: Gypsum boards measured using electrical resistance (NORDTEST 1997)

While there is some scatter between the materials, all show a definite correlation of moisture content and electrical resistance with equilibrium relative humidity.

The results from the DensGlass testing are further compared and overlaid on these NORDTEST results later in this report.

2.1.3 CMHC Funded Testing 1990's

Work funded by the Canadian Mortgage and Housing Corporation (CHMC) in 1993 and 1997 (Handegord 1993, Pressnail et al., 1997) looked at the performance of gypsum sheathing as used in typical insulated steel stud walls. Of concern, the moisture source of focus being wintertime vapour diffusion condensation, and how to reduce condensation using exterior insulation and interior air/vapour control.

Laboratory testing, field testing and computer modeling using EMPTIED and MOIST were used. Threshold moisture contents for condensation and mould growth are discussed. Field measurements of gypsum moisture content in field panels exposed to vapour diffusion condensation were also made.

The literature referenced at the time stated that: "gypsum sheathing moisture contents in excess of 1.4% are high enough to support mould and mildew growth" (Burch and TenWolde, 1993), referring to paper faced gypsum commonly used. Further work referenced also stated that the equilibrium moisture content of gypsum sheathing at 100% RH is from 2.5% to 3.0% moisture content by weight (Richards et al., 1992).

It was known that high moisture contents in gypsum sheathing reduce its rigidity, requiring other wall components to provide lateral resistance. This can also result in corrosion of the steel studs, and mould or mildew (Pressnail et al., 1997).

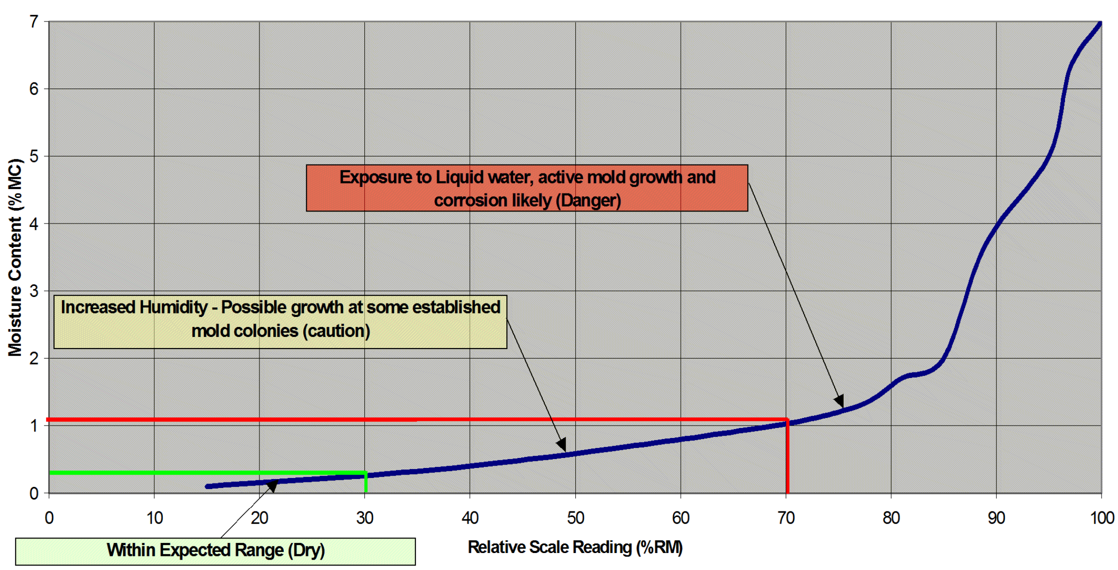
Pressnail et al. showed that winter season vapour diffusion and air convection condensing at the gypsum sheathing were sufficient to cause unsafe gypsum moisture contents in conventional fiberglass batt insulated/steel stud walls without and without interior air or vapour control. Vapour diffusion and air convection for 15 days of the test resulted in moisture accumulation at the gypsum sheathing resulting in 4 to 14% moisture content in the walls without interior air or vapour control (vapour pressure differences across the wall of 1250 to 1550 Pa). Gypsum sheathing in walls with interior vapour barrier (poly) or interior air barrier (SBPO) had much lower and reasonably safe moisture contents of between 0.4 and 1.4% MC. Moisture contents were measured using gravimetric samples.

They found under winter conditions that high permeance fiberglass insulation applied to the exterior (cold side) of the gypsum sheathing significantly improved the performance of the walls as it reduced condensation and subsequently reduced gypsum moisture contents. Gypsum sheathing installed behind low permeance XPS and EPS insulation had poorer performance than fiberglass, however had improved performance than walls without insulation.

Field testing was performed on full-scale walls in Calgary, Alberta during the winter of 1994-1995 using conventional insulated steel stud wall, similar to the laboratory testing. At the end of the 68 days of testing they found very high moisture contents within the gypsum sheathing as a result of vapour diffusion condensation. Most notable was the distribution of moisture within the 2130 mm high wall panels. They found a very large moisture gradient from bottom to top of the panels, with moisture contents of between 35-37% at the base of the wall to 1-2% in the middle of the wall and <1% at the top. This potential shows the effect of convective air loops, resulting in stratification with cold air at the bottom of walls and increased condensation. On the other hand gravity (potentially from condensation or within the material) on increased moisture levels within the gypsum walls is also suggested.

2.1.4 RDH In-House Gypsum Testing 2000.

RDH Building Engineering Ltd. performed some basic calibration testing of the handheld Delmhorst BD-10 moisture meter with saturated salt solutions to correlate the reference moisture scale on the BD-10 with gypsum samples exposed to equilibrium relative humidity levels of 33, 75 and 100%. (Hubbs & Hircock, 2000). The correlation is reproduced in Figure 8 which was subsequently used by RDH to correlate resistance readings from DensGlass sheathed Buildings 3 & 5 from the monitoring project.



		Exterior Grade Gypsum	Interior Grade Gypsum	Dens-Glass Gold
	Normal Range (RH<75%)	%RM < 39	%RM < 39	%RM < 59
	Caution (75-100% RH, possible growth of mould at some established colonies)	40 < %RM > 69	40 < %RM > 69	60 < %RM > 79
	Danger (Exposure to liquid water, mould growth likely)	70 < %RM	70 < %RM	80< %RM

Figure 8: RDH correlation for Delmhorst BD-10 (Hubbs and Hircock, 2000)

Samples that were left in the humidified chambers for approximately 3 years were reviewed in 2004. The samples which were exposed to 75 and 100% RH were found to be saturated and deteriorated to a point where they were soft and malleable enough to be easily damaged by finger pressure. It appears that the 75% RH samples came into contact with liquid water at some time during the test which may have resulted in the degradation observed. However it could be expected that the 100% RH samples would be deteriorated after this length of time. The samples were weighed and dried in 2006 and it was determined that the samples had moisture contents greater than approximately 20% by weight.

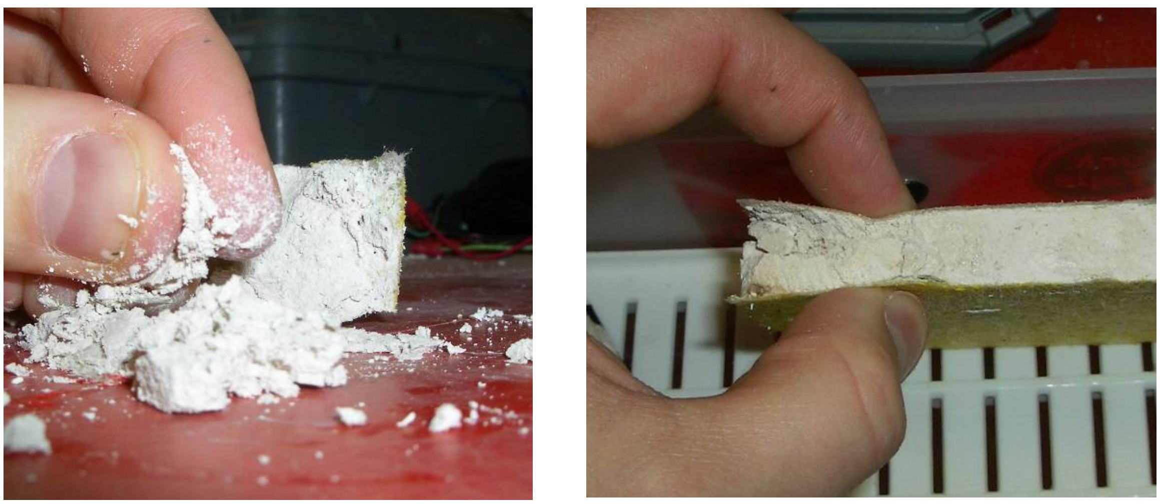


Figure 9: Gypsum exposed to a 100% RH environment for several years

The RDH testing presented a correlation of electrical resistance of gypsum to moisture content using commonly available handheld Delmhorst pin type moisture meters. The impact of long term exposure to high humidity environments on the DensGlass Gold was also demonstrated.

2.2 Testing Procedure

The moisture content (or relative moisture level) of gypsum sheathing is often used in the assessment of the condition of walls in-situ using handheld moisture meters. The electrical resistance and moisture content is also often recorded in monitoring projects or test huts where full-scale walls with gypsum sheathing are used.

Moisture content is actual measure of water within a material determined by gravimetric analysis. Numerically, it is the mass of water in the sample divided by the oven dry sample mass. The mass of water is the difference between the wet sample and a desiccated dry sample (0% RH). Moisture content can also be determined volumetrically; however this procedure is not commonly used and thus not discussed in this report.

To date, a standardized approach to the measurement of moisture contents using electrical resistance of gypsum based sheathings does not exist. Currently most consultants use handheld moisture meters which are calibrated for wood, some of which have scales which can be used to approximate the relative moisture level of gypsum products, insulation, concrete and other non-wood building materials. Some handheld meters have a gypsum scale, and Levelton made an attempt to correlate the measured moisture content with gravimetric moisture content as shown in Figure 10 (Levelton 2005).

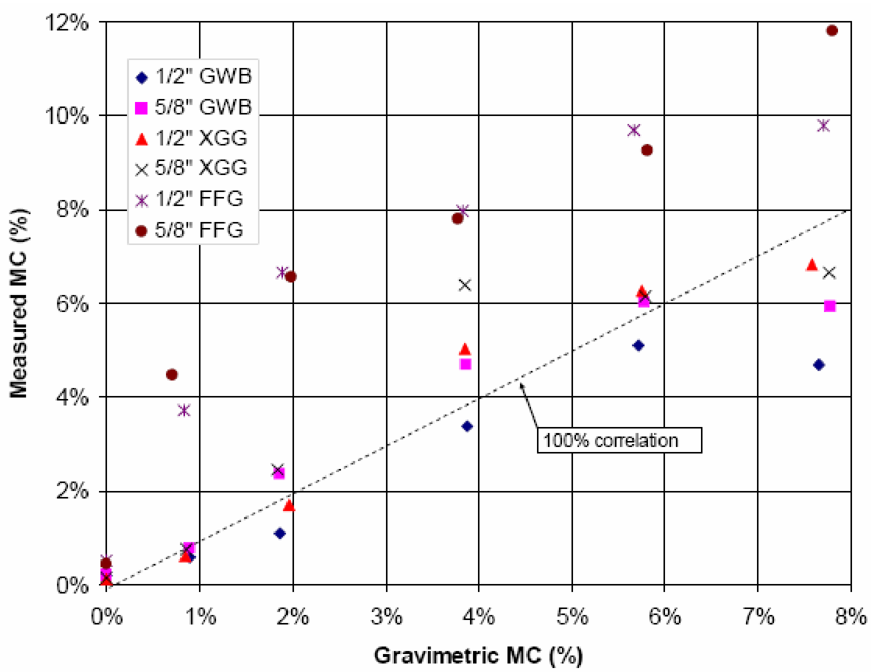


Figure 10: Correlation of Measured and Gravimetric Moisture Content for Handheld Moisture Meter (Levelton 2005)

It is shown that there is considerable spread between sample types (particularly between 1/2" and 5/8" samples). It is unknown what model of handheld meter was used for this test, and how it was calibrated for gypsum. A much simpler approach using existing handheld meters (which most consultants already have) which are calibrated for standard wood species (Douglas Fir) and developing a correlation with gypsum moisture contents is proposed later in this report.

Both conductance (resistance) and impedance (capacitance) (surface) meters are available. Resistive type moisture meters utilize insulated pins which penetrate the sample to measure the resistance at depth. Electrical resistance was measured using both insulated and uninsulated pins connected in a circuit similar to that commonly used to measure the electrical resistance of wood samples in field experiments (Straube et al. 2002).

Temperature correction for the gypsum sheathing was beyond the scope of this report, and testing was performed at controlled laboratory conditions of 20°C. Further testing could be performed to develop temperature correction factors. However under the normal range of exposure conditions, particularly Vancouver, the range of temperatures the exterior sheathing in Building 3 experienced was between 10 and 25°C.

3 GYPSUM BOARD PROPERTIES

The chemical composition of gypsum boards is discussed with a brief overview of paper faced gypsum boards and into the unique properties which DensGlass Gold advertises.

3.1 Chemical Composition

Gypsum sheathing board is made from gypsum plaster, the semi-hydrous form of calcium sulfate ($CaSO_4.½ H_2O$), also know as calcined gypsum. The gypsum plaster is mixed with water, fiber reinforcing (paper or fiberglass) a foaming agent, and additives to increase the fire and mould/mildew resistance. Georgia Pacific adds either silicone or paraffin (wax) to the core of DensGlass Gold for water resistance. The gypsum is sandwiched and pressed between two sheets of paper or fiberglass mats, and when dry the board becomes rigid and suitable for a building material.

Gypsum is a soft mineral composed of calcium sulfate di-hydrate ($CaSO_4 \cdot 2H_2O$). Heating the gypsum between 100C and 150°C partially dehydrates the mineral by driving off exactly 75% of the water contained in its chemical structure. This reaction takes on the form:

$CaSO_4 \cdot 2H_2O$ + heat → $CaSO_4 \cdot \frac{1}{2}H_2O$ + $1\frac{1}{2}H_2O$ (water vapour)

If the gypsum is heated above approximately 180°C, the water can be completely driven off, and anhydrous calcium sulfate (anhydrite) is formed, $CaSO_4$, which is commercially used as a desiccant.

The dehydration, known as calcination begins at approximately 80°C, although in dry air, some dehydration will take place at 50°C. The initial heat energy delivered to the gypsum drives off the water vapour rather than increase the temperature of the material. The endothermic nature of this reaction gives gypsum drywall its fire resistance, as it is typically used for.

When the gypsum is re-formed into boards it rehydrates into its original di-hydrate form and physically sets into its solid state.

It is therefore important to avoid high temperatures during the testing, and avoid oven-drying the samples to attain a dry material weight. Therefore anhydrous calcium sulfate was used as a desiccant to dry the samples down to 0% RH.

3.2 Paper Faced Gypsum

There two categories of paper faced gypsum, gypsum wallboards suited for interior use and paper faced gypsum sheathings suited for exterior sheathing applications.

Gypsum sheathings have facers and a core which are sometimes treated for water resistance, and hence more durable in exposed applications. Fiberglass faced gypsum sheathings have almost completely replaced paper faced gypsum sheathing boards in the past 5-10 years.

Gypsum wallboard is commonly used as an interior finish, however has a moisture sensitive gypsum core and paper facers, which are sensitive to mould growth and structural deterioration under high humidity or liquid water exposure. Often the damage is to the extent where replacement is required after it gets wet. Figure 11 shows the severity of mould growth as seen on painted paper faced gypsum board one month after a flood event. Figure 12 shows the mould growth and water staining on the exterior paper faced sheathing of Building 3 (of the monitoring project) in 1999 prior to rehabilitation.

Figure 11: Mould Growth on Interior Gypsum Wallboard exposed to a water leak

Figure 12: Mould growth on exterior paper faced gypsum sheathing of Building 3 prior to remediation (Morrison Hershfield, 1999)

Thousands of buildings are affected by mould growth and water damage to paper faced gypsum products every year. Damage to multi-storey residential buildings in Vancouver, BC with paper faced exterior gypsum sheathing (RDH 2001) and recent publicity from the severe moisture and mould damage to the interior gypsum wallboard of homes in the southern United States caused by hurricanes in the 2004 and 2005 season has further raised awareness of the consequences of using paper faced gypsum boards. Fiberglass faced gypsum products typically reduce the severity of the mould problems, and are now recently becoming more popular as interior finishes in addition to a sheathing product. Some gypsum manufacturers no longer produce paper faced gypsum boards.

3.3 DensGlass Gold

The following statement is from the product literature supplied by G-P Gypsum for DensGlass Gold:

"DensGlass Gold® exterior sheathing is a totally unique sheathing. It's paperless, glass mat facers and treated, water-resistant core make it exceptionally resistant to wicking, moisture penetration and delamination caused by surface water exposure. In fact, DensGlass Gold exterior sheathing is so weather-resistant that six months of exposure to the elements won't affect its performance. We warrant it."

However, G-P further notes that "…is exceptionally resistant to weather, but it is not intended for immersion in water or sustained exposure to water and moisture".

The core of DensGlass Gold is treated with hydrophobic materials such as paraffin (wax) or silicone to make it water-resistant. As this protection is proprietary, information regarding the composition and quantities of paraffin or silicone is unknown. What is known is that one or a combination of the materials is used for water resistance, and it is likely that this composition has changed in the past. Samples taken from Vancouver, BC in 2001 and Waterloo, ON in 2005 were tested to determine the differences (if any) this has on the electrical resistance and humidified properties.

Figure 13 shows the liquid "water-resistance" of the DensGlass Gold sheathing, and how liquid water beads up on the on the hydrophobic fiberglass facer surface.

Figure 13: Water Beading on Surface of DensGlass Gold Sheathing

While the manufacturer claims the sheathing to be "water-resistant" to rain and liquid water sources, it will be shown that the properties of the gypsum core are impacted significantly by high exterior relative humidity: levels (90-100% RH) which are not uncommon during wet or humid periods of construction prior to protecting the sheathing. It will be shown that high humidity levels alone are sufficient enough to lead to strength degradation of the material, and should be properly protected. "Water resistant" does not mean water-vapour resistant, which would imply a vapour impermeable material, which gypsum sheathing, certainly is not. DensGlass gold has a vapour permeance of 1320 ng/Pa·m^2·s, where as normal interior gypsum has a vapour permeance of approximately 2000 to 4500 ng/Pa·m^2·s (ASHRAE 2005).

G-P Gypsum further states the following information in regards to mould resistance:

"Independent tests confirm that DensGlass Gold, with its patented, inorganic glass mat design, resists the growth of mold when tested, as manufactured, per ASTM D 3273."

ASTM Standard D 3273 is a mould resistance test where samples are subjected to a relative humidity of 95% to 98% and 32.2°C in a chamber for 4 weeks to determine if mould/mildew growth will occur on the surface. If mould growth occurs then the material is considered to have failed the test.

Inorganic materials resist the growth of mould as they do not provide food (organic material) to sustain mould growth. However organic airborne contaminants that land on the surface can result in surface mould growth when the conditions are conducive to mould growth. The laboratory testing and field observations from Building 3 will show that mould growth can occur on the surface of DensGlass Gold sheathing which is exposed to humid conditions and naturally occurring contaminants.

The testing was performed by no means to discredit the test methods in place by ASTM, but to show under humid conditions in normally exposed environments mould growth may be of concern on fiberglass faced gypsum board, and other inorganic materials which provide a base for contaminants to spur mould growth.

3.4 <u>Sorption Isotherm</u>

The sorption isotherm for gypsum is presented graphically in Figure 14. Data was taken from the WUFI 4.0 database which provides a full sorption isotherm from 0 to 100% RH.

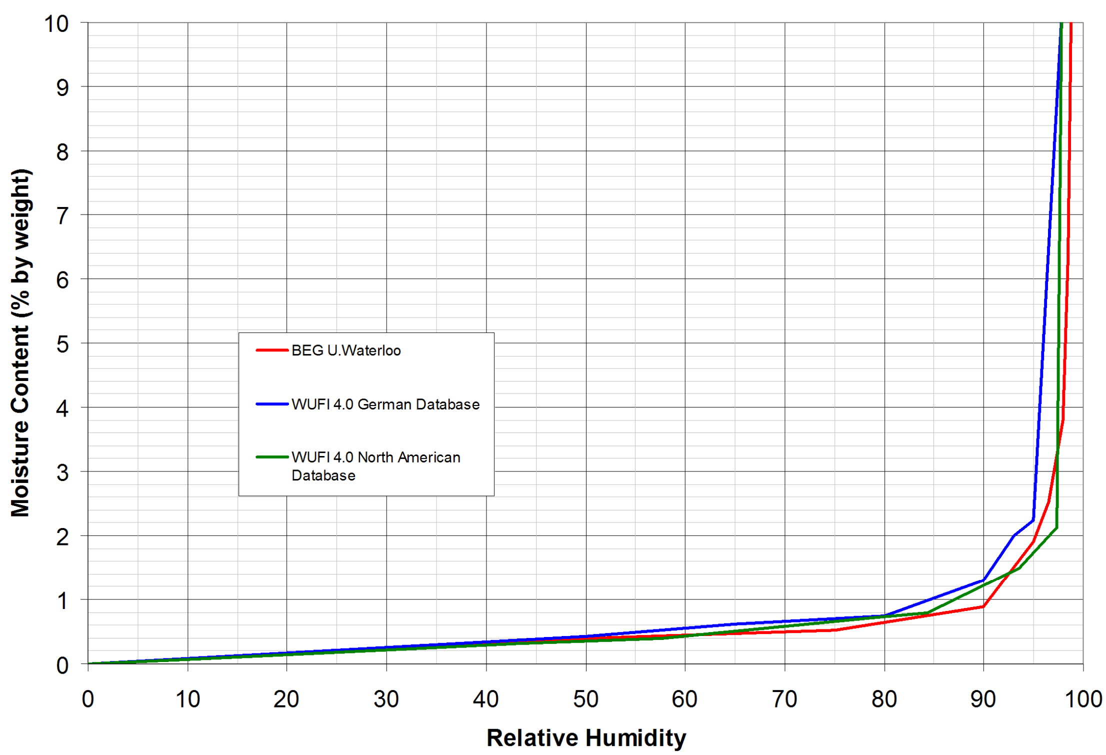


Figure 14: Sorption Isotherms for Three Different Gypsum Board Products

The data used is from the following sources.

- WUFI 4.0 German Database - Is from Institut for Building Physics Holzkirchen, Germany for "Gypsum Board"

- WUFI 4.0 North American database - Is from either: NIST publications, ORNL publications and ASHRAE TRP 1018 for "Gypsum Board (USA)".

- BEG U. Waterloo data - Is from previous laboratory testing of Gypsum Sheathing from the Building Engineering Group (BEG) at the University of Waterloo.

The three independent sources provide a generally consistent sorption isotherm for gypsum sheathing. These sorption isotherms are confirmed later in this report, with points from the DensGlass Gold testing. The purpose of the lab testing was not to develop a sorption isotherm for DensGlass Gold but to determine if an existing gypsum sheathing product could be used.

4 LABORATORY SETUP AND PROCEDURE

Two laboratory tests were performed to measure the electrical resistance versus gravimetric moisture content of DensGlass Gold exterior gypsum sheathing. Additional performance measures into the structural properties, relative wetting and drying rates, as well as visible mould resistance are discussed.

Test 1 consisted of three different sample sets (A, B and C) exposed to different conditions, and manually monitoring the electrical resistance and gravimetric moisture content.

Test 2 consisted of samples from three different batches of DensGlass Gold exposed to different relative humidity levels, continuously monitored using an automated datalogger system. This allowed for precise measurements of the electrical resistance, and to be able to observe subtle changes in the electrical resistance with time, and to determine relative wetting and drying rates.

4.1 Test 1 (Manual Tests)

The purpose, experimental setup, and procedure are discussed for Test 1.

4.1.1 Purpose

The purpose of the first series of tests was to:

1. Correlate electrical resistance with gravimetric moisture content,
2. Monitor the effect of prolonged exposure in high humidity (100%) environment on the material properties and mould resistance,
3. Determine the maximum moisture content,
4. Compare the effect of liquid versus vapour water contact,
5. Compare the relative effect of edge sealing, one side sealed, and/or a combination of the both on the moisture uptake of the samples.

4.1.2 Experimental Set-up

Three sample sets (A, B and C), each set containing seven to nine samples were placed in sealed containers exposed to 100% relative humidity to simulate wetting conditions, and electrical resistance and gravimetric moisture content was measured at periodic intervals.

Figure 15 shows the typical container setup on the sample tray. Water is placed beneath the sample tray and the lid sealed, resulting in a near 100% relative humidity environment for the samples. The samples are protected from splashing by the sample tray.

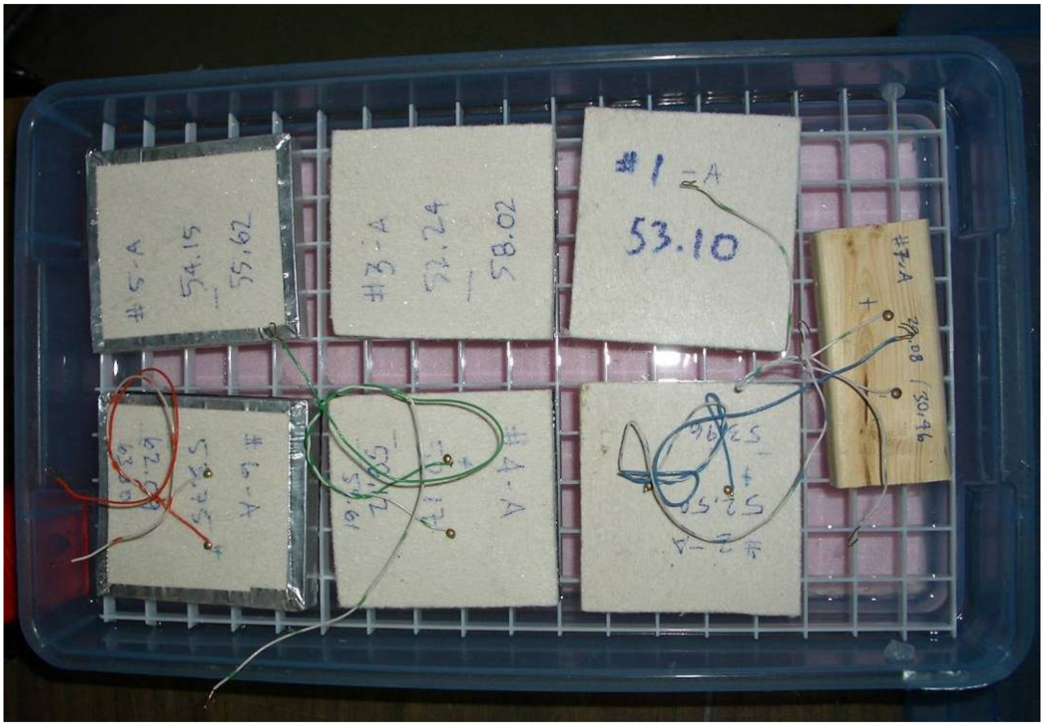


Figure 15: Typical Material Layout in Container

Set 'A' samples were put in the container at 100% RH and left in the controlled lab space with a temperature of 20°C.

Set 'B' samples were put in the container at 100% RH and in contact (one surface) with liquid water. The purpose was to determine the impact of liquid water on the results. Two additional samples were placed beneath the sample tray, to determine the impact of fully submerging gypsum board.

Set 'C' samples were put in the container at 100% RH and left in an environmental chamber (where another experiment was running) which had cyclical temperatures between 20°C to 35°C. The purpose was to promote condensation on the samples and within the sample container for an increased moisture load.

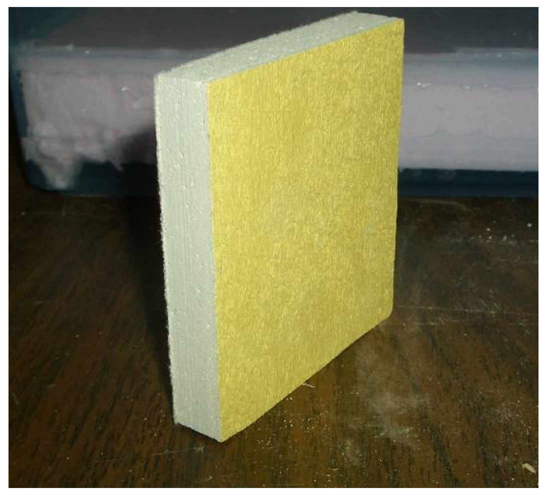
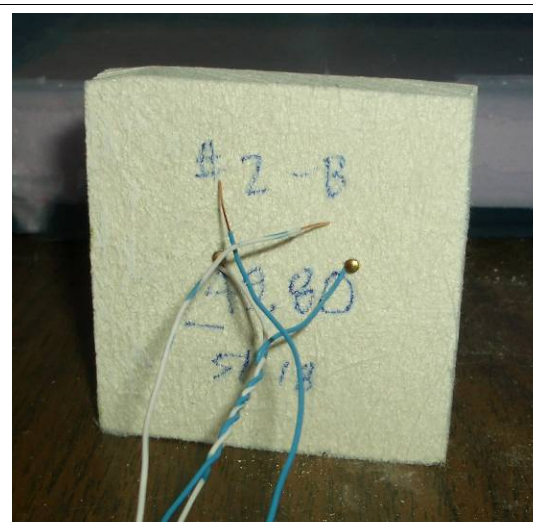
Within each set a total of seven samples were placed in the container (nine samples in set B). Six of the samples are DensGlass Gold and one sample of pine was placed into each container to compare the relative wetting rate to wood to gypsum.

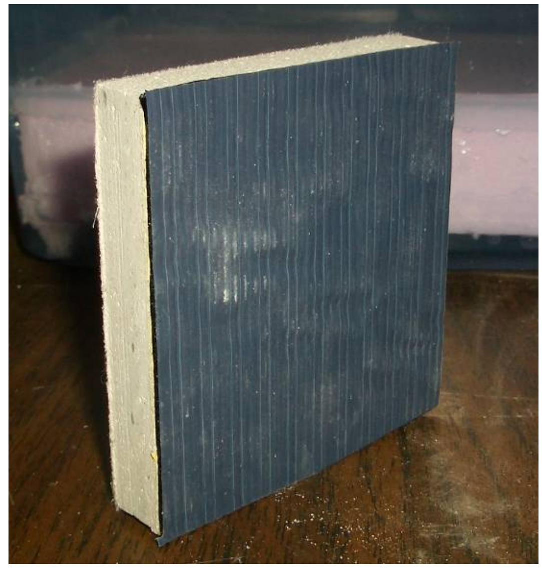
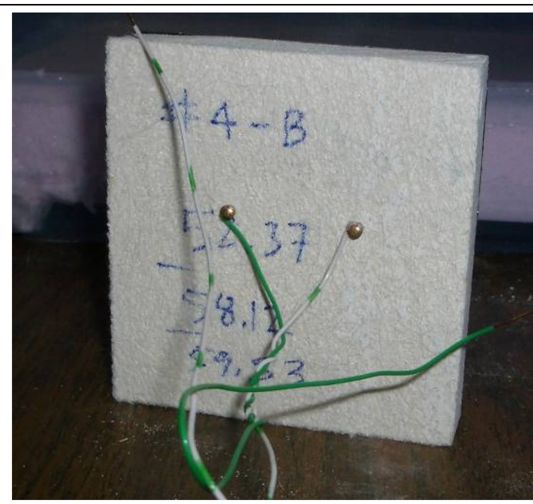
Table 1 describes the treatment to each of the samples for sets A, B, and C.

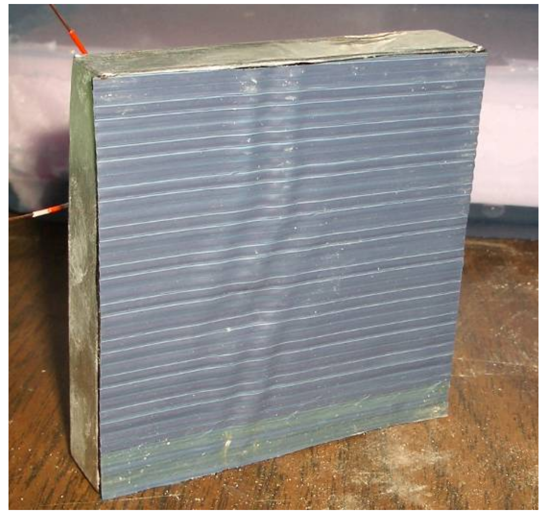
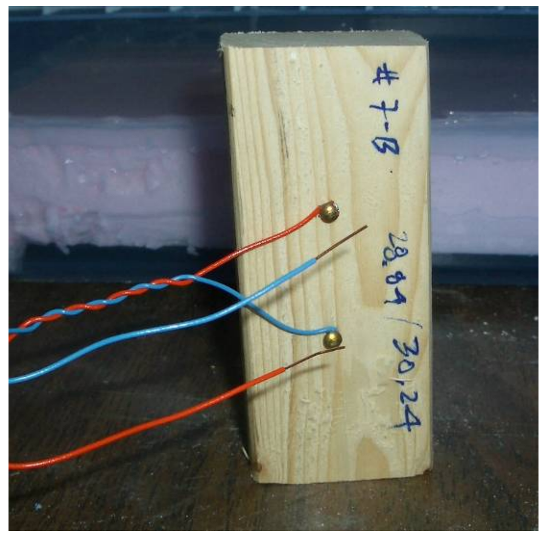
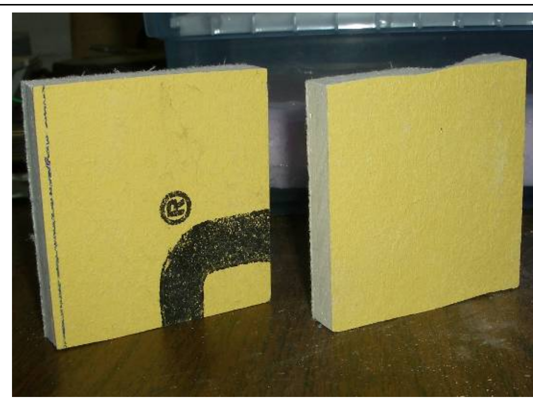
Brass nails were placed in the noted samples to measure the worst case electrical resistance using a simple 9V circuit at periodic intervals, the method described by Straube et al. (2002). Insulated pins were not used as it was found that measuring the resistance at the surface versus the middle of the sample had negligible impact on the results. Either the sample quickly comes into equilibrium right through the sample, or the insulated pins are shorted by the path of least resistance in the gypsum core. Regardless it was found to be unnecessary for gypsum samples to insulated pins.

The samples are approximately 75 mm x 75 mm x 13 mm and were cut from the same sample of ½" DensGlass Gold sheathing, received from a contractor at a local jobsite in Waterloo, Ontario in September 2005.

Table 1: Test#1 – Gypsum Sample Descriptions

Sample #	Treatment	Photograph
1	Control Sample	
2	Control Sample (w/ MC pins)	

3	Self-Adhered water-proof and vapour impermeable membrane applied to exterior face. Sample placed exposed side up	
4	Self-Adhered water-proof and vapour impermeable membrane applied to exterior face (w/ MC pins). Sample placed exposed side up	
5	Edges sealed with aluminum foil impermeable tape	

6	Self-Adhered water-tight and impermeable membrane applied to exterior face and edges sealed with aluminum foil impermeable tape (w/ MC pins). Sample placed exposed face up.	
7	Pine Sample – 19 mm x 38 mm x 75 mm. (w/ MC pins)	
8 (B only)	Control Sample – completely submerged	
9 (B only)	Control Sample – completely submerged	

4.1.3 Procedure

The experiment was started on October 11, 2005 and ran for 94 days until January 13, 2006. The samples were initially weighed to determine the starting moisture content. At the end of the experiment, the samples were placed in a desiccated chamber (0% RH) to determine the dry mass of each sample, which was used to calculate the measured moisture contents of each the samples recorded throughout the test.

The mass of each of the samples and electrical resistance of samples measured across the embedded moisture pins was recorded at intervals at the Time and Dates shown in Table 2.

Table 2: Time and Date of Measurements for Test# 1

Date: Time	**Days past start of Experiment (Test 1)**
11 Oct/05 – 15:00	-
12 Oct/05 – 15:00	1
14 Oct/05 – 17:00	3
21 Oct/05 – 11:00	10
31 Oct/05 – 11:00	20
08 Nov/05 – 11:00	28
17 Nov/05 – 12:00	37
28 Nov/05 – 16:00	48
13 Dec/05 – 15:00	63
13 Jan/06 – 15:00	94

Observations were made at the time of measurements as to the condition of the samples and mould growth if any.

4.2 <u>Test 2 (Datalogger Tests)</u>

The purpose, experimental setup, and procedure are discussed for Test 2.

4.2.1 Purpose

The purpose of the second series of tests was to:

1. Correlate electrical resistance with gravimetric moisture content,
2. Correlate moisture content with different relative humidity levels (50, 75, 85% RH) and the impact of 100% RH on the rate of wetting.
3. Observe relative wetting and drying rates for samples wetted using 100% RH, and dried in 50% RH conditions,

4. Compare three different gypsum samples from 2001 and 2005 to determine the impact on the electrical resistance – moisture content correlation.

4.2.2 Experimental Set-up

A series of tests was performed using the Campbell Scientific CR-1000 data-loggers, which measured the electrical resistance across the moisture pins every 5 minutes and averaged hourly. For each test performed, six gypsum samples were measured. Moisture pins were installed on three of the samples, and three of the samples were used as surrogate samples for gravimetric moisture content measurements, to be representative on average to the samples of which the electrical resistance was measured continuously. Surrogate samples were used as the moisture pins and datalogger was connected to the samples, and it was felt that removing and replacing the pins at every measurement period would negatively impact the results. At the end of each test, all samples were weighed and it was found that on average the surrogate samples had the same moisture content as the samples with the moisture pins.

In the first set of tests, samples were cut from the same gypsum board as Test 1, referred to as “Waterloo 1”. All of the samples were intitially acclimatized to 50% RH and 20°C in the laboratory for several weeks.

Second the samples were placed in 75% RH and 85% RH chambers of saturated salt solutions at 20°C. 75% RH was achieved using NaCl (Common table salt) and 85% RH was achieved using $MgSO4$ (Epsom salts), both were checked periodically with a humidity sensor to ensure the RH was consistent.

Third the samples were placed in 100% RH chambers and monitored for a length of time, cycling from 100% RH (in chamber) to 50% RH (in lab) allowing the samples to wet and dry, and attaining several measurements to correlate the moisture content with electrical resistance.

Fourth, two new DensGlass Gold samples were placed in 100% RH chambers to determine if there was a difference in the electrical resistance-moisture content relationship between DensGlass Gold produced and supplied to Vancouver, BC in 2001 and Waterloo, Ontario in 2005, referred to as “Vancouver” and “Waterloo 2”. It is unknown where the DensGlass sheathing originated for either location, but it is known that Georgia Pacific has gypsum plants on both the west and east coasts of North America, and it is unlikely that both samples came from the same plant.

Figure 16 shows the typical sample and container setup for the datalogger tests. Water or saturated salts are placed beneath the sample tray and the lid sealed, resulting in the desired relative humidity environment for the samples. The humidity was periodically checked, however the accuracy of the 100% RH chambers could not be accurately determined using conventional sensors, and was assumed to be near 100% RH. The samples are protected from splashing by the sample tray. The sample edges were left uncovered.

Figure 16: Datalogger Test Sample Setup.

All samples in each test were cut form the same sheathing board, and measure approximately 75 mm x 75 mm x 13 mm thick.

4.2.3 Procedure

The datalogger tests were started on November 11, 2005 and continued until May 4, 2006. All samples were initially weighed to determine the starting moisture content. The samples were then subjected to varying conditions, and monitored, periodically measuring the gravimetric moisture content. Observations were made at the time of measurements as to the condition of the samples and mould growth if any.

At the end of the experiment, the samples were placed in a desiccated chamber (0% RH) to determine the dry mass of each sample, which was used to calculate the measured moisture contents of each of the samples recorded throughout the tests.

5 <u>RESULTS AND DISCUSSION</u>

The results from the test #1 and #2 are compiled and presented in the following sections. The results of the testing are then compared to the previous literature and the predicted response from the WUFI hygrothermal model. A correlation between gypsum moisture content and electrical resistance is developed and further applied to an equivalent wood-scale so that the moisture content of gypsum could be measured using existing wood moisture meters. Finally the correlation is applied to two field studies to measure the gypsum moisture contents observed.

5.1 <u>Test 1 (Manual Tests)</u>

The results comparing moisture content and electrical resistance is presented as well as plots showing the wetting response for samples exposed to a 100% RH environment including the samples in contact with water. The observed physical properties and mould resistance of the DensGlass Gold sheathing throughout the test are also discussed.

5.1.1 Moisture Content – Electrical Resistance Correlation

All of the measurements taken from the A & C samples (exposed to 100% RH) are compiled and gravimetric moisture content versus electrical resistance (log scale) is plotted in Figure 17.

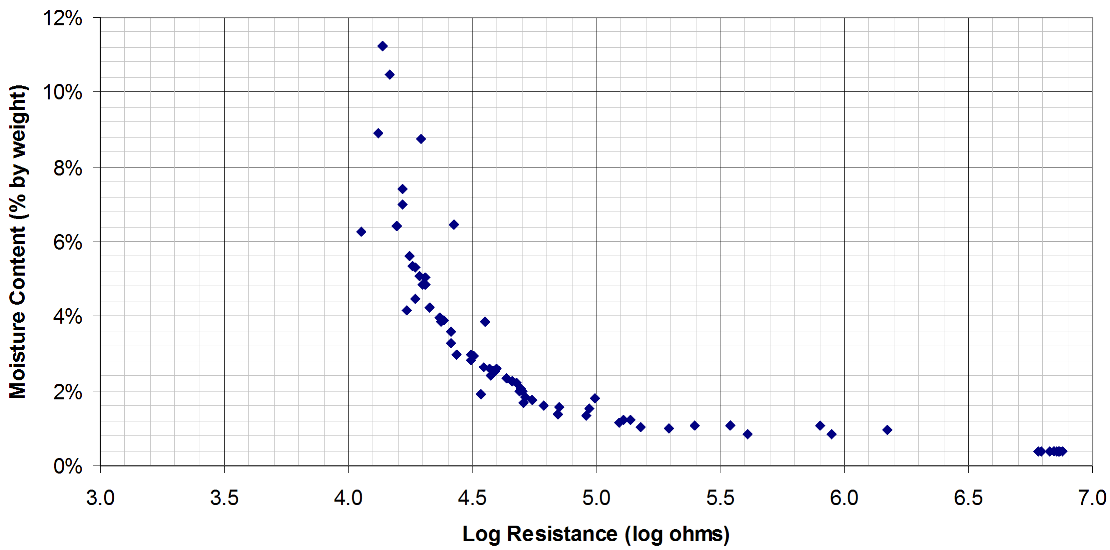


Figure 17: Moisture Content versus Electrical Resistance (100% RH samples)

As shown there is a strong non-linear correlation observed between 1 and 6% moisture content for the gypsum samples tested. Some data scatter exists above 6% MC, and Figure 18 plots the results above 5% MC for the "C" samples which were in contact with liquid water, and subsequently had much higher moisture contents, and possibly scattered due to shorting of the readings.

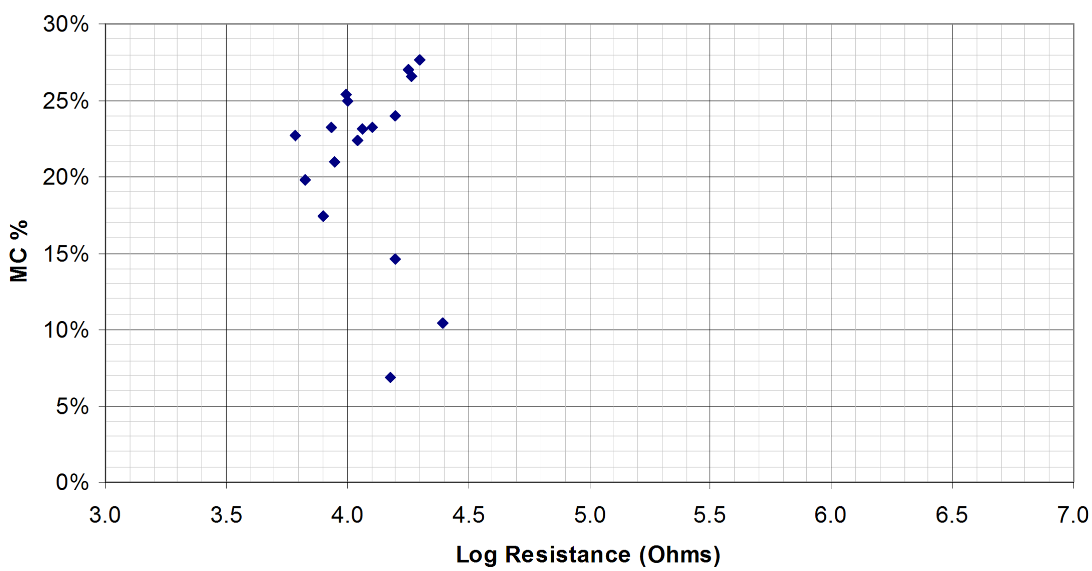


Figure 18: Moisture Content versus Electrical Resistance (samples in water contact)

It appears that the moisture content electrical resistance relationship is weaker at high moisture levels as the physical and chemical properties of the gypsum were adversely affected (saturated, very soft, and dissolved edges observed).

For reference the results for the pine samples are presented in Figure 19, showing the known correlation of wood moisture content and electrical resistance. Note the very high saturated moisture contents the wood samples up to 110% by weight at the end of the test.

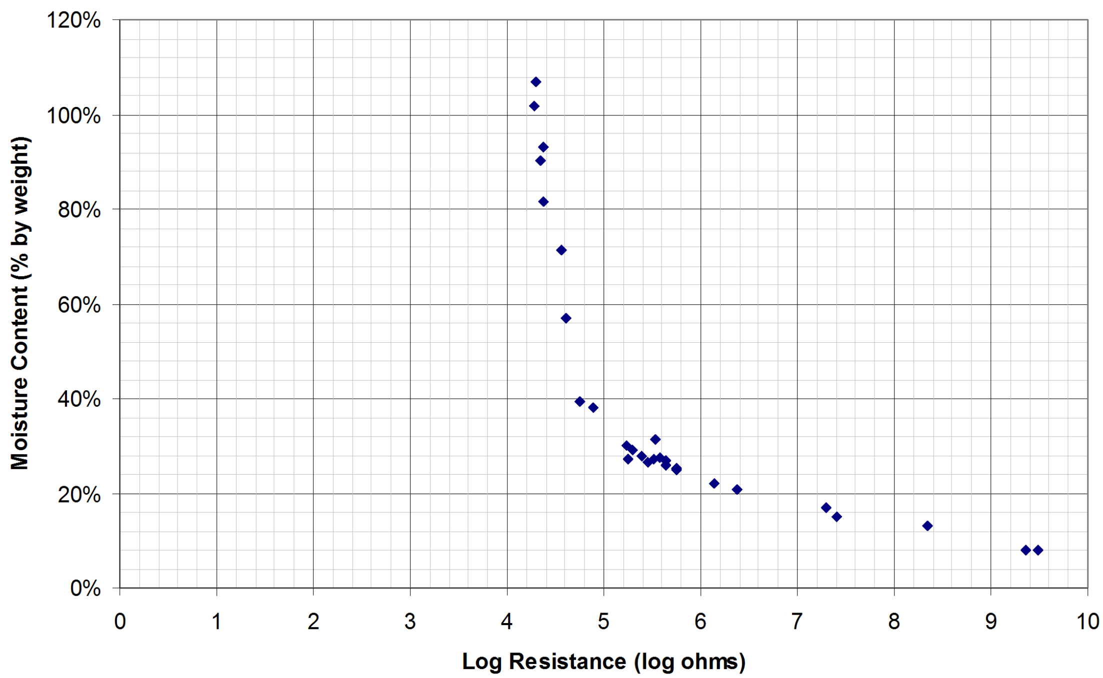


Figure 19: Moisture Content versus Electrical Resistance (pine samples)

5.1.2 Wetting Response

For each of the samples, the gravimetric gypsum moisture content is presented versus time to show the relative uptake of moisture for each the different samples and to compare edge and one-side covered effects.

Figure 20 presents the results for the 'A' samples for the 94 day test duration, and Figure 21 presents the results for the initial 5 days of the test when the rate of moisture uptake was the quickest.

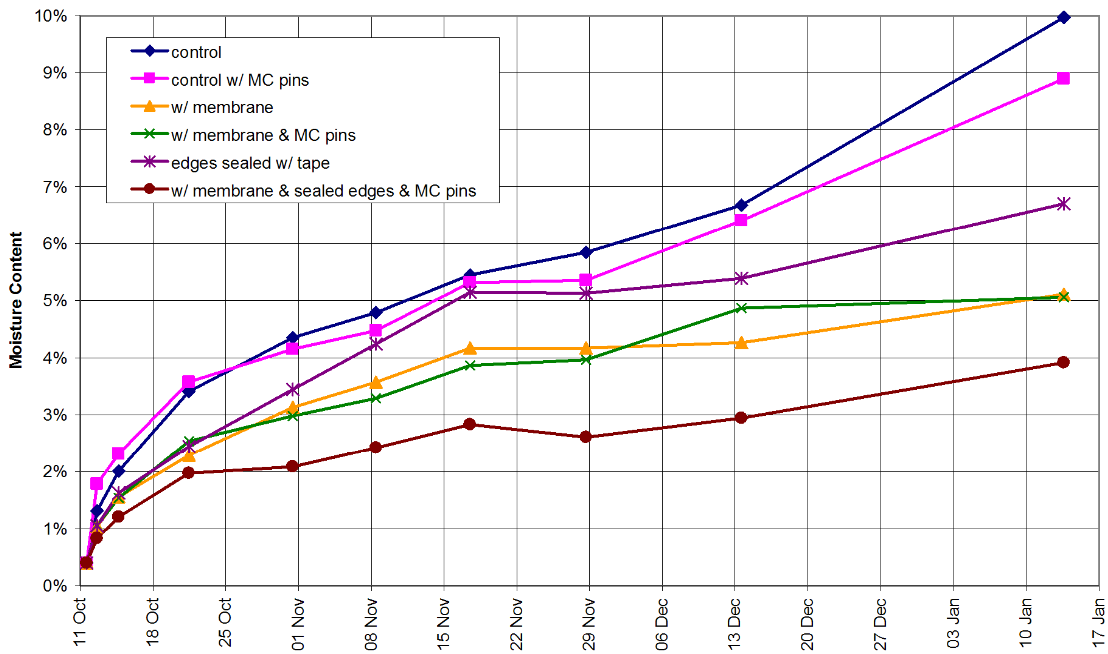


Figure 20: Moisture Content versus Time – “A” Samples (94 days)

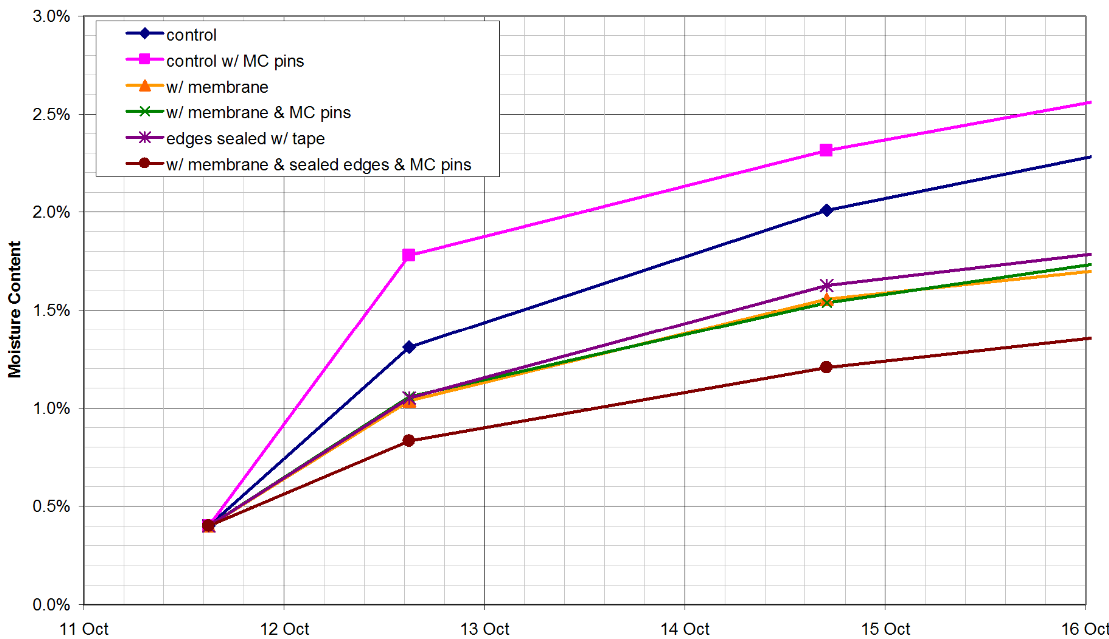


Figure 21: Moisture Content versus Time – “A” Samples (Initial 5 days)

As shown the initial moisture uptake is very rapid when exposed to 100% RH. Samples with less surface area took up moisture at a reduced rate, however as shown, the exposed edges of the small samples have only a minor impact on the results compared to those with sealed edges. For comparison, the ‘C’ samples are shown in Figure 22 which were exposed to the same temperature conditions as the 'A' samples for the initial 5 days.

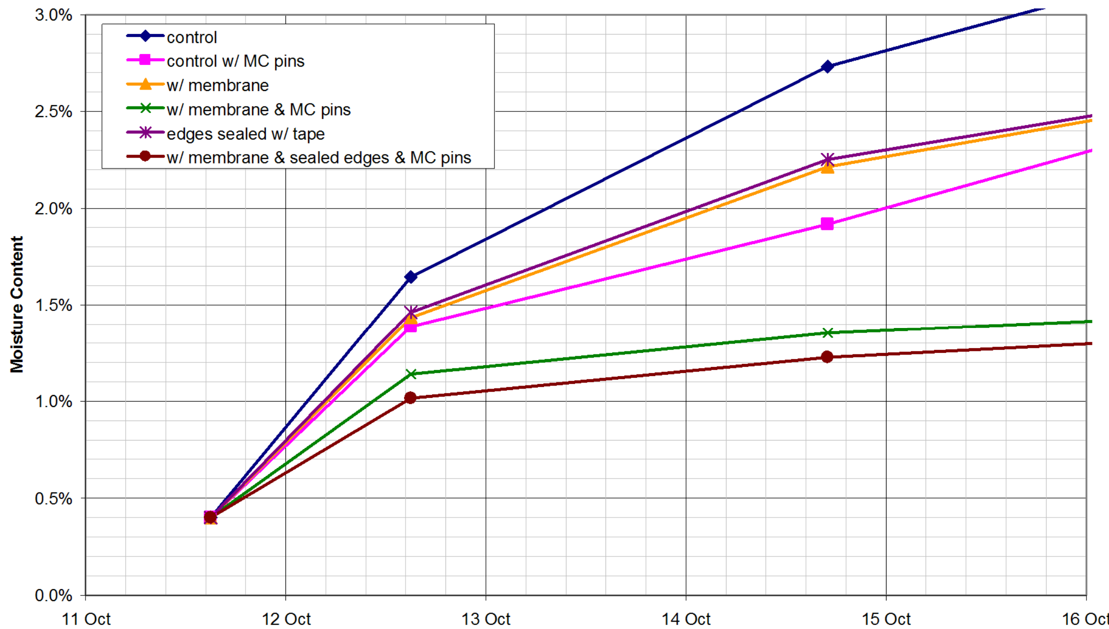


Figure 22: Moisture Content versus Time – "C" Samples (Initial 5 days)

The 'C' samples had similar moisture uptake rates as the 'A' samples, however differences between samples of the same type were observed (ie. the four control samples had different moisture uptake rates).

The 'B' samples, in contact with liquid water had a significantly faster moisture uptake than the 'A' and 'C' samples as shown in Figure 23 for the 94 day test duration and Figure 24 for the initial 5 days of the test.

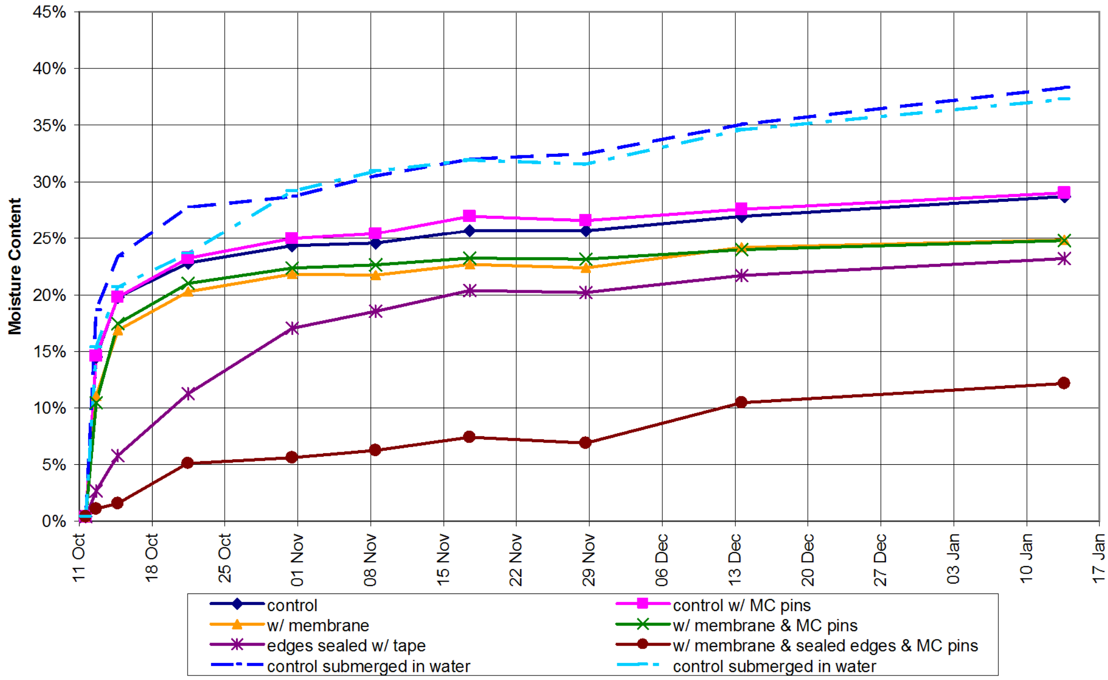


Figure 23: Moisture Content versus Time – "B" Samples in water (94 days)

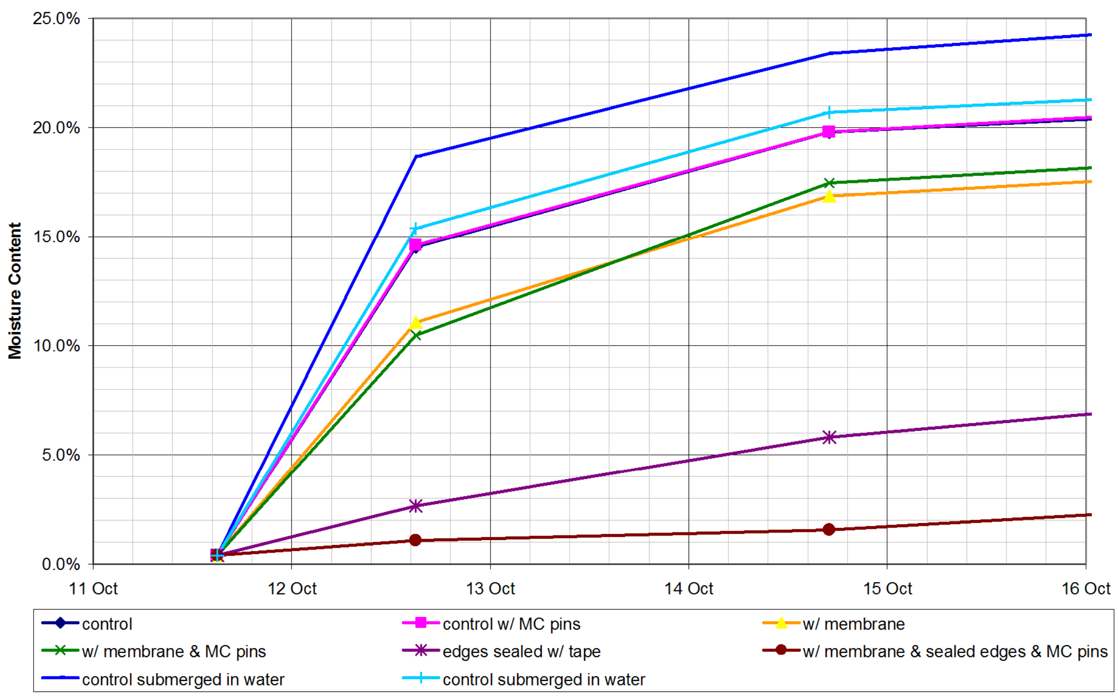


Figure 24: Moisture Content versus Time – "B" Samples in water (Initial 5 days)

The effect of the exposed edges on liquid water uptake is shown; the two samples with sealed edges had reduced moisture uptake rates; however a large quantity of moisture was still absorbed into the samples through the "water-resistant" fiberglass facers. The moisture content increase in the first 24 hours is the most rapid with increases between 10 and 15% MC observed, showing the potential for liquid water from a rain or flood event to rapidly wet the gypsum.

The sample with the membrane and edges sealed was placed with the exposed face up, sealed where in contact with liquid water. Moisture was thus absorbed through the top facer exposed to 100% RH similar to 'A' and 'C' samples and hence the lowest rate of water uptake.

The two submerged samples are shown as the maximum moisture uptake rate which could potentially be achieved under normal conditions. At the end of the test at 94 days, the moisture content of all the samples was still increasing slightly, noting that the maximum saturation had not yet been achieved.

The moisture content of the pine samples is shown for reference in Figure 25.

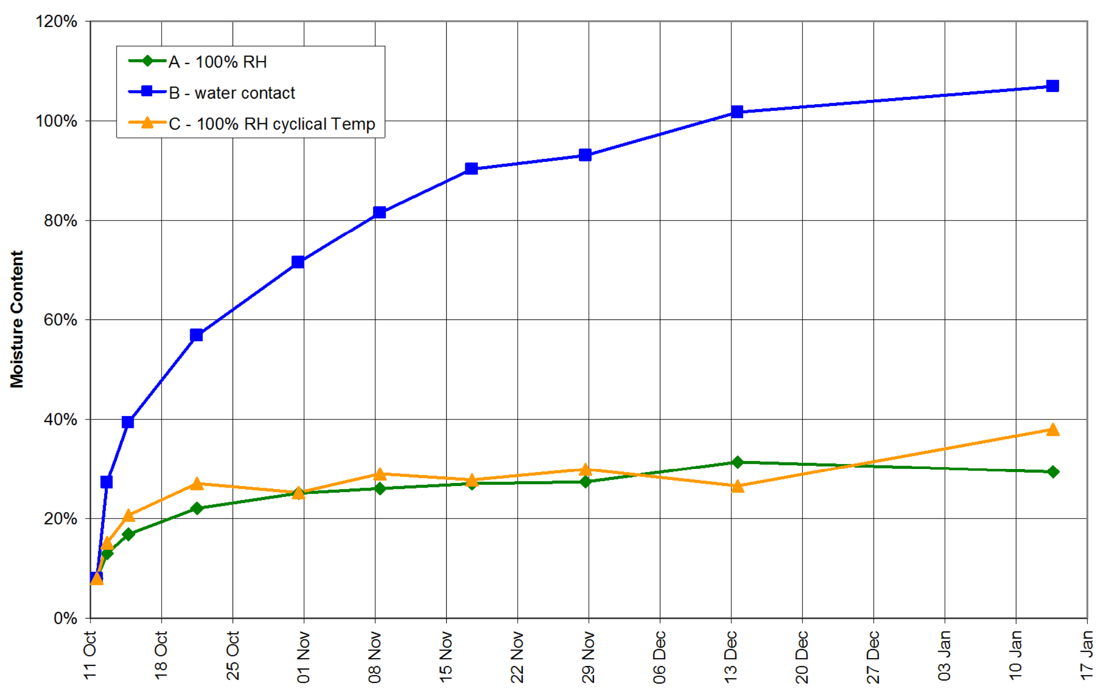


Figure 25: Moisture uptake of Pine Samples A, B and C

5.1.3 Physical Properties and Mould Resistance

The physical properties and mould/mildew resistance of the DensGlass gold gypsum samples are discussed.

Mould was observed on the wood samples within the first week, and subsequently increased to what appeared to be wood decay fungi within the first month. The moisture contents of the pine were well above saturation (30%) in those samples so it should not be a surprise that decay fungi were noted on this organic material. However it was surprising to see mould growth (small black colonies on the surface of all the gypsum samples. It is possible that mould growth on the wood samples lead to the contamination of the gypsum samples; however it will be shown in Test #2 that mould was observed on those samples (not exposed to mould contaminated wood) as well.

The fungi growth on the pine sample in contact with water is shown in Figure 26.

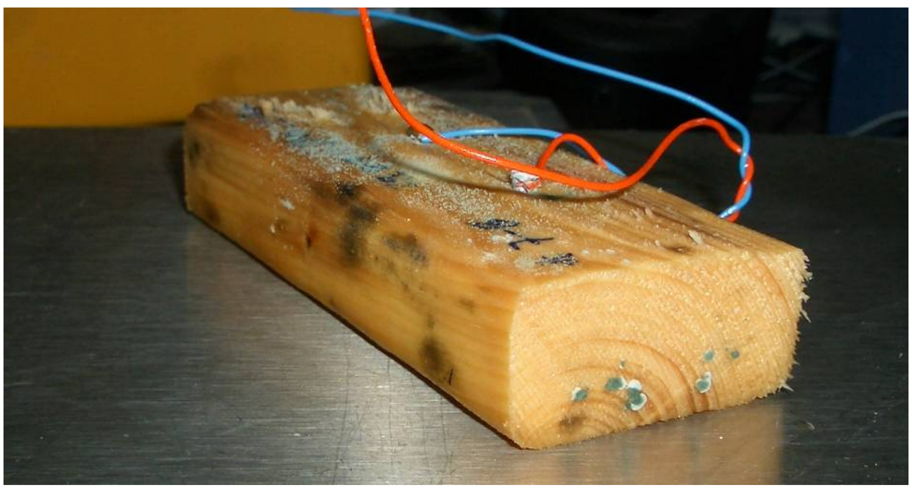


Figure 26: Pine Sample 'B' after 1 month of testing (approximately 80% MC)

Mould was observed on the top surfaces of the 'B' gypsum samples (in contact with water) at 10 days. These samples had very high moisture contents (>15%), and also were observed to have droplets of condensation liquid on the top sample surfaces. Mould was later observed on the wettest of the 'A' and 'C' samples exposed to 100% RH after 30 days when the moisture contents were above 5% by weight.

The mould growth observed on the 'B' samples is shown in Figure 27 and Figure 28.

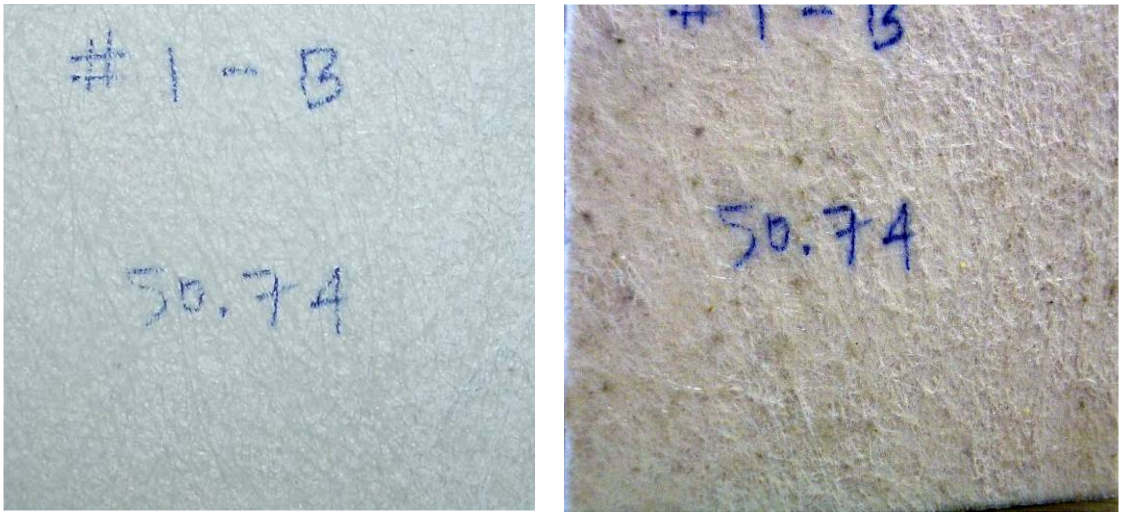


Figure 27: Mould growth on surface (Day 1, left to Day 20, right)

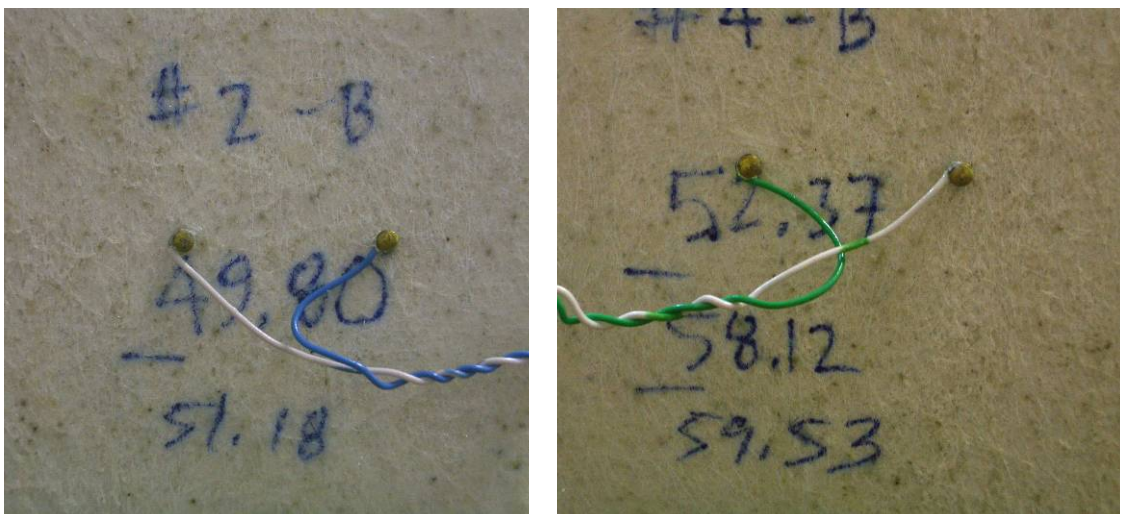


Figure 28: Mould growth on surface of samples 2-B (left) and 4-B (right) after 94 days

Another observation made was that the aluminum edge sealing tape was observed to be visibly corroded at day 10 for samples in contact with water ('B' samples), and by the end of the 94 day test, large sections of the tape were missing around the edges where in contact with the fiberglass. This is shown for two samples in Figure 29.

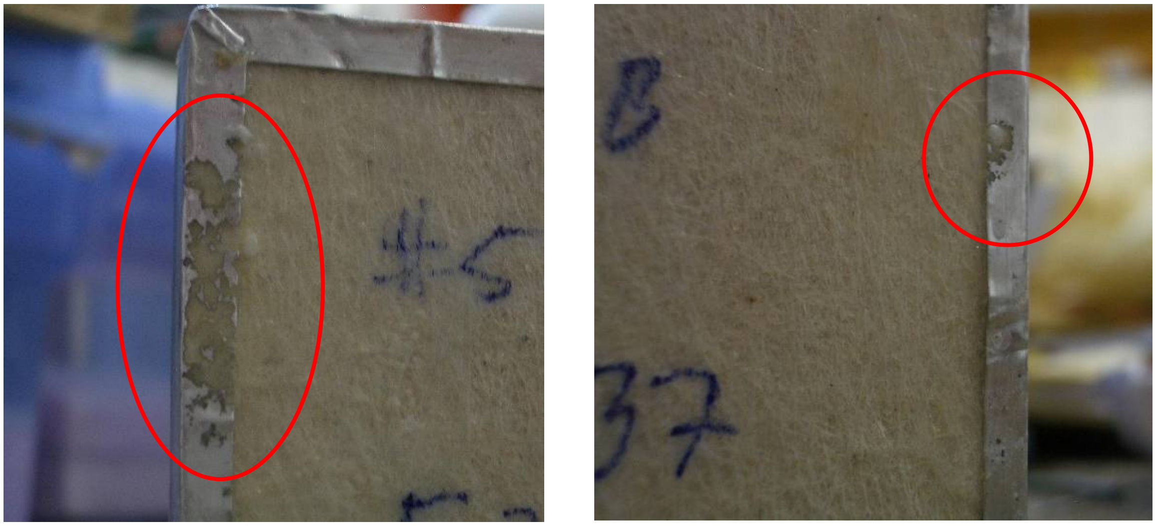


Figure 29: Corroded Aluminium tape on "B" samples after 94 days

The reactivity of metal in contact with wet gypsum sheathing is known, and can be observed in practice by the accelerated corrosion of steel stud flanges in contact with wet gypsum, where the chemical composition of wet gypsum accelerates the corrosion process of the steel.

The two submerged samples were observed to be floating and dissolving around the edges during the first week. However, both samples sank (when their density became greater than that of water) between day 10 and 20, and continued to dissolve for the duration of the test. Figure 30 shows the dissolved gypsum at the edges of the samples at the end of the 94 days.

Figure 30: Dissolved edges of two submerged samples after 94 days

The humidified 'A' and 'C' gypsum samples were noticeably soft to the touch by the second day (MC 1-2%), and were subsequently softer at the one week (MC 3-4%) and at the end of the test (MC 5-10%). The 'B' samples in contact with water were much softer than humidified samples 'A' and 'C' however was expected as the 'B' samples had much higher moisture contents.

The wet gypsum samples were easily deformed to the touch, and could be easily damaged. Structural testing was not performed on the samples, but reference to the Levelton report regarding the structural properties is made.

While all of the wet samples were soft to the touch and could easily be deformed with finger pressure, a few of the humidified wet samples (>10% MC) were compared to dry samples by cutting with a knife blade and observing the ease of cut made from edge to edge (as shown in Figure 31) .

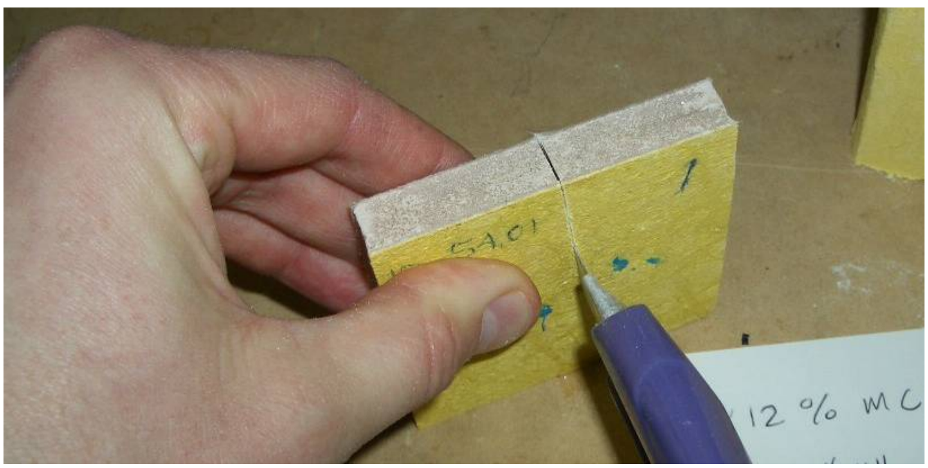


Figure 31: Cut test of saturated DensGlass Sample

The wet samples cut easily and cleanly, in one cut with the consistency of hard butter, while the dry samples were too hard to cut across the edges as shown, and had to be cut by scoring in two cuts across the facer and breaking the samples in half.

5.2 <u>Test 2 (Datalogger Tests)</u>

The results of the datalogger tests are presented which compare the moisture content and electrical resistance for exposure to 50, 75, 85 and 100% RH environments. Using the results of tests #1 and #2, a correlation is developed and presented between the gravimetric moisture content of DensGlass Gold with measured electrical resistance.

The sorption isotherm for gypsum sheathing (previously discussed) is compared to measured results of DensGlass Gold samples from the 50, 75 and 85% RH chambers.

The wetting and drying response for gypsum samples cycled between 100% and 50% RH is discussed.

Finally the physical properties and mould resistance of the DensGlass Gold sheathing observed throughout the tests is discussed.

5.2.1 Moisture Content – Electrical Resistance Correlation

<u>50% Relative Humidity (Tempered Laboratory Environment)</u>

Using the data-logger, continuous measurements were taken of the electrical resistance of the samples. This allowed a real time measurement of the gypsum response to relative humidity fluctuations within the laboratory. Figure 32 shows that gypsum responds very quickly to the slightest changes in relative humidity, which on average were controlled to 50% and 20°C.

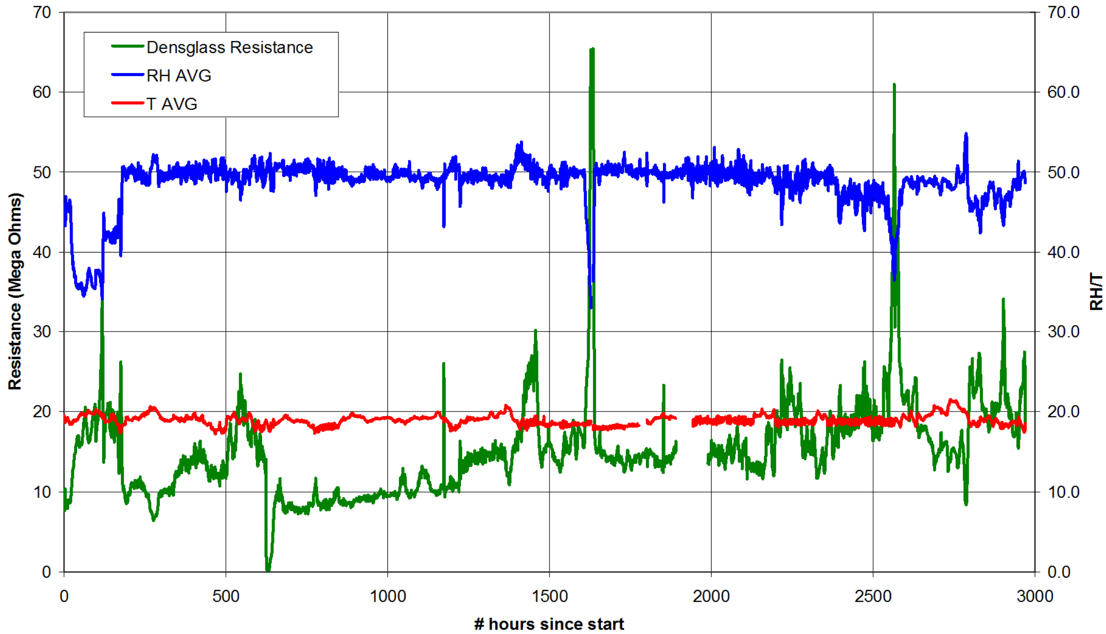


Figure 32: Response of Gypsum Electrical Resistance to Fluctuations of RH in Laboratory

Large spikes in the laboratory relative humidity around hour 1600 and 2600 from 50% RH to approximately 35% RH and the large electrical resistance change from 10-20 MΩ to 60-70 MΩ as the samples dried out at the lower RH.

<u>75% Relative Humidity</u>

Samples in the 75% RH chamber (NaCl salt solution) quickly came to equilibrium in approximately 1 day, with a minimal increase in moisture content for a relatively large change in the electrical resistance.

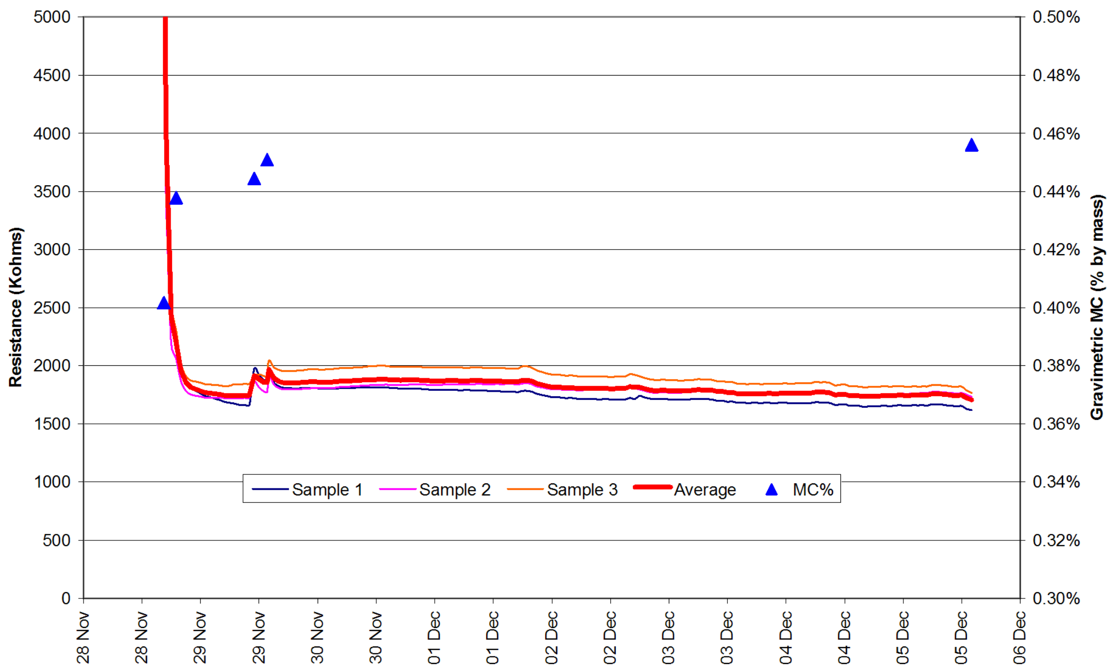


Figure 33: Moisture Content and Electrical Resistance of Samples exposed to 75% RH

It is shown that at 75% RH, the electrical resistance will be approximately 1700 kΩ and a moisture content of approximately 0.45%.

<u>85% Relative Humidity</u>

Samples in the 85% RH chamber ($MgSO_4$ salt solution) quickly came to equilibrium in approximately 3 days, with a moderate increase in moisture content.

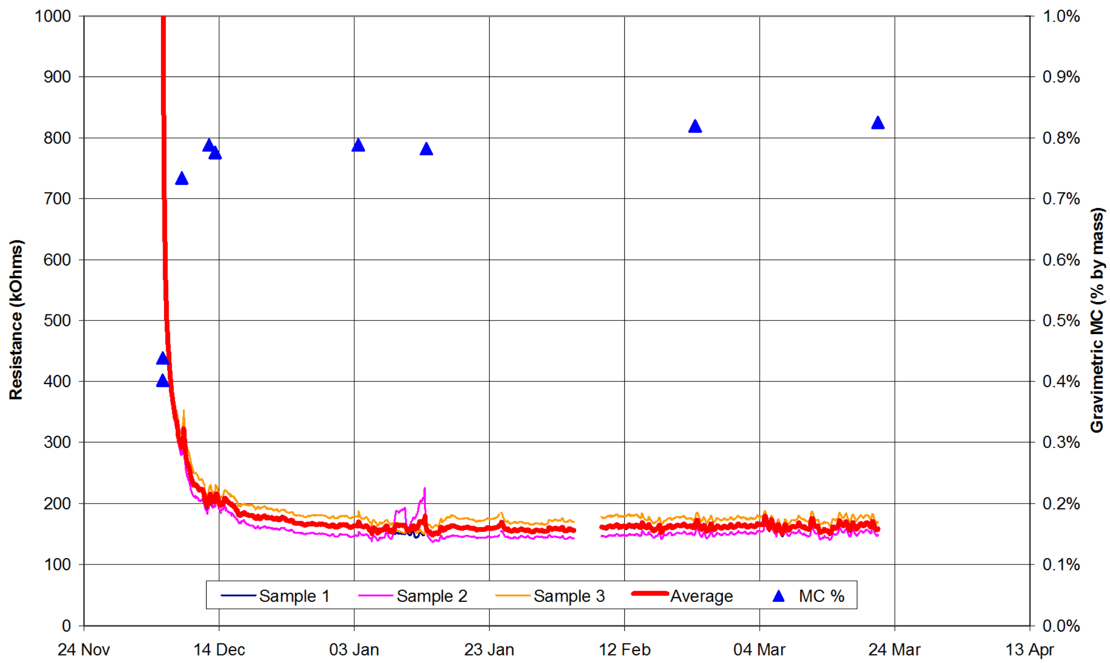


Figure 34: Moisture Content and Electrical Resistance of Samples exposed to 85% RH

It is shown that at 85% RH, the electrical resistance will be approximately 170 kΩ and a moisture content of approximately 0.82%.

<u>100% Relative Humidity</u>

Samples in the 100% RH chamber (over water) did not reach equilibrium at any point during the tests; however several intermediate moisture content measurements were correlated with electrical resistance. To attain additional points, the samples were exposed to 100% RH and then dried to 50% and cycled several times. One wetting and drying cycle is shown for "Waterloo 1" DensGlass samples, comparing the electrical resistance to moisture content in Figure 35.

Three different sources of DensGlass Gold sheathing were used, and are plotted together in Figure 36 and include "Waterloo 1 & 2", and "Vancouver". "Waterloo 1" is the same DensGlass used in Test#1. "Waterloo 2" and "Vancouver" samples are further compared in Section 5.2.3.

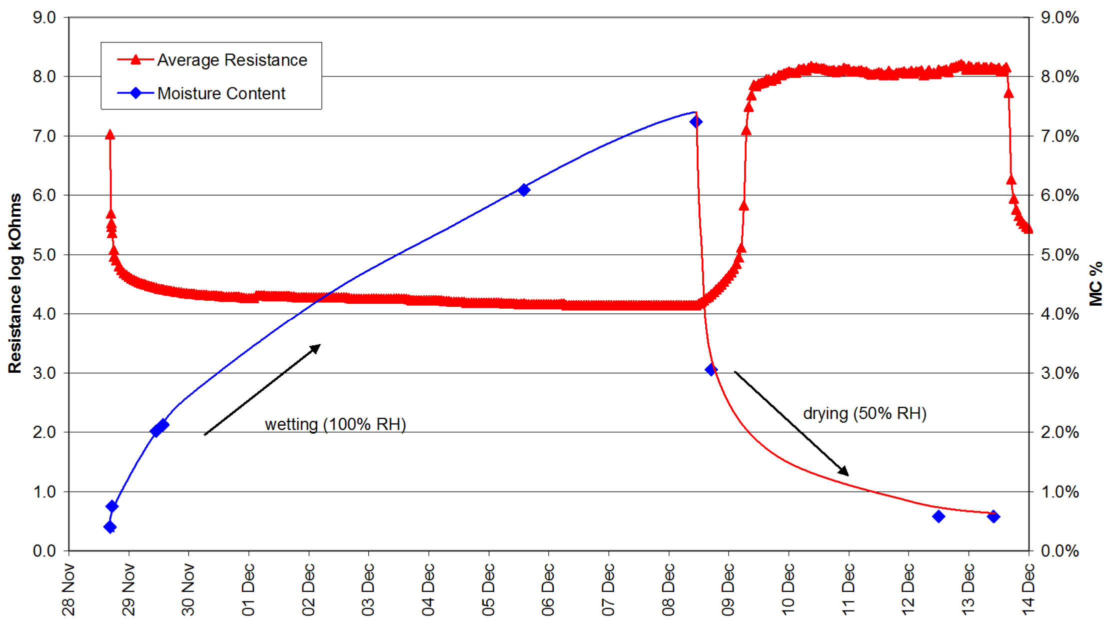


Figure 35: Moisture Content and Electrical Resistance of Samples exposed to 100% RH

Summary of Results

The results comparing moisture content and electrical resistance (average points) are shown in Figure 36.

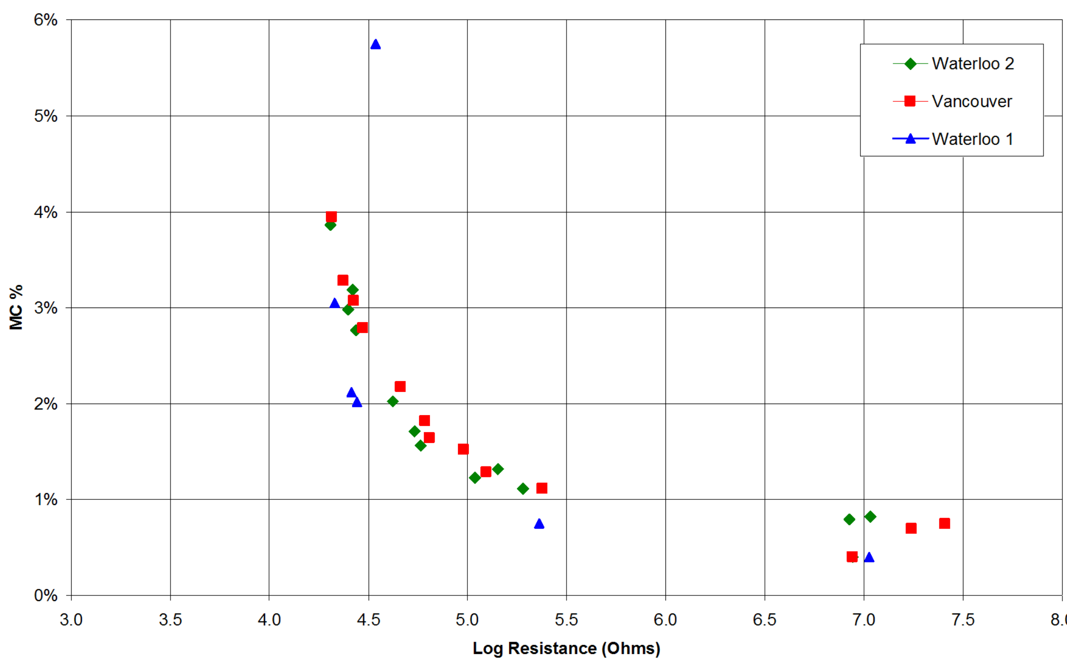


Figure 36: Log Resistance versus Moisture Content for Test#2 Samples

The relationship between electrical resistance and moisture content observed in Test #2 is very similar to that produced from Test#1.

A mathematical equation was correlated to the measured data from tests #1 and #2 using Curve Expert 1.3, a mathematical curve-fit program. A simple equation was produced which is used to calculate the moisture content based on electrical resistance which has potential uses for field experiments and investigations. Figure 37 plots this relationship against the measured results from tests #1 and #2.

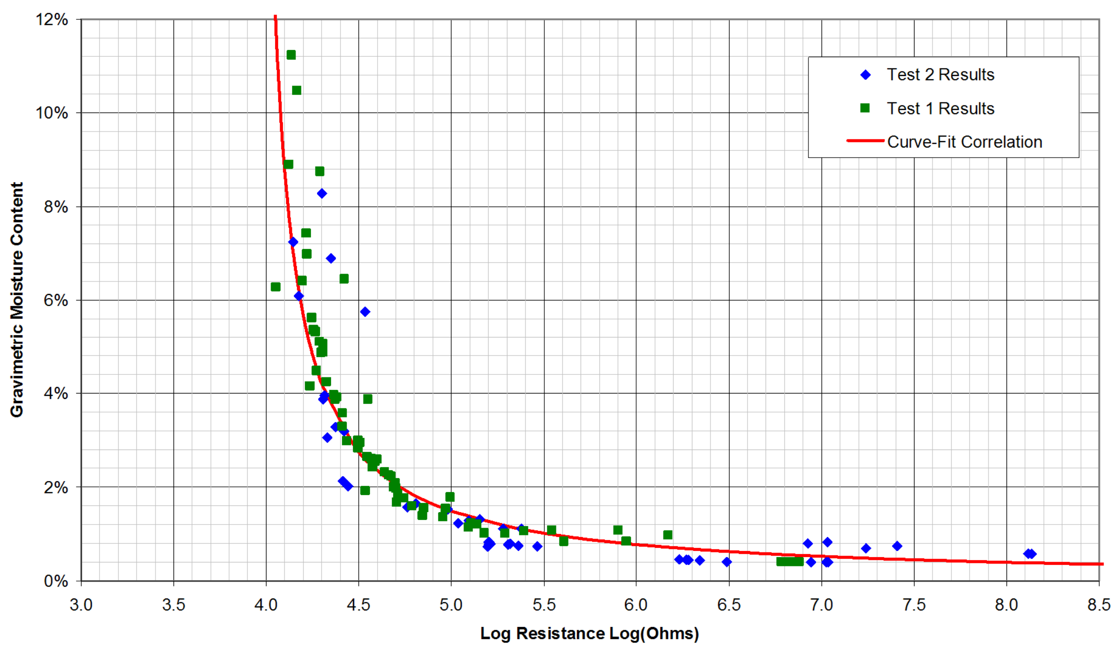


Figure 37: Correlation of Log Resistance and Moisture Content for Test#1 and #2 Samples

The equation for the curve-fit was found to be an inverse reciprocal function, taking the form of (1/(A*X+B) presented in Equation 1:

$$GypsumMC(\%) = 1/((62.0693 * (\log(\text{resistance}))) - 243.0790) \qquad \text{Equation 1}$$

Where electrical resistance is measured in Ohms (Ω), and a log scale (base 10) is used. The coefficients A and B of the equation form Y=A*X+B were determined using the curve-fit program, where A is 62.0693 and B is -243.0790. The standard error using all measured data from 0 to 10% MC was 0.01, and the correlation coefficient was 0.93. Eliminating obvious erroneous data, scattered above 6%

MC can further increase the accuracy of the curve-fit to the data. The correlation between measured and predicted moisture content is shown in Figure 38.

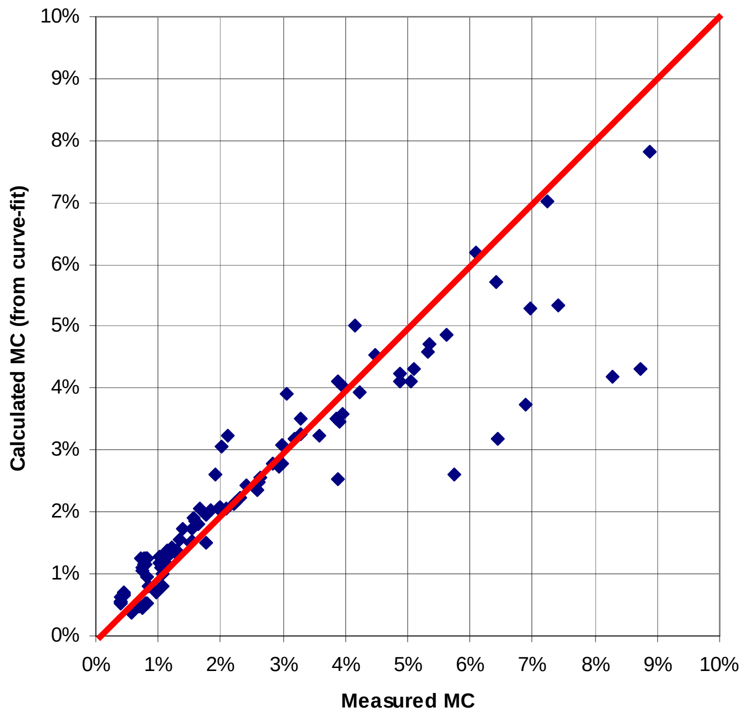


Figure 38: Comparison of Calculated versus Measured MC

5.2.2 Effect of Relative Humidity – Sorption Isotherm

The sorption isotherm for gypsum sheathing is compared to measured moisture content of DensGlass Gold samples in the 50, 75 and 85% RH chambers in Figure 39. Points for 100% are not shown as the tests never achieved equilibrium with a known RH, however all observations would fall near the line above 95% RH.

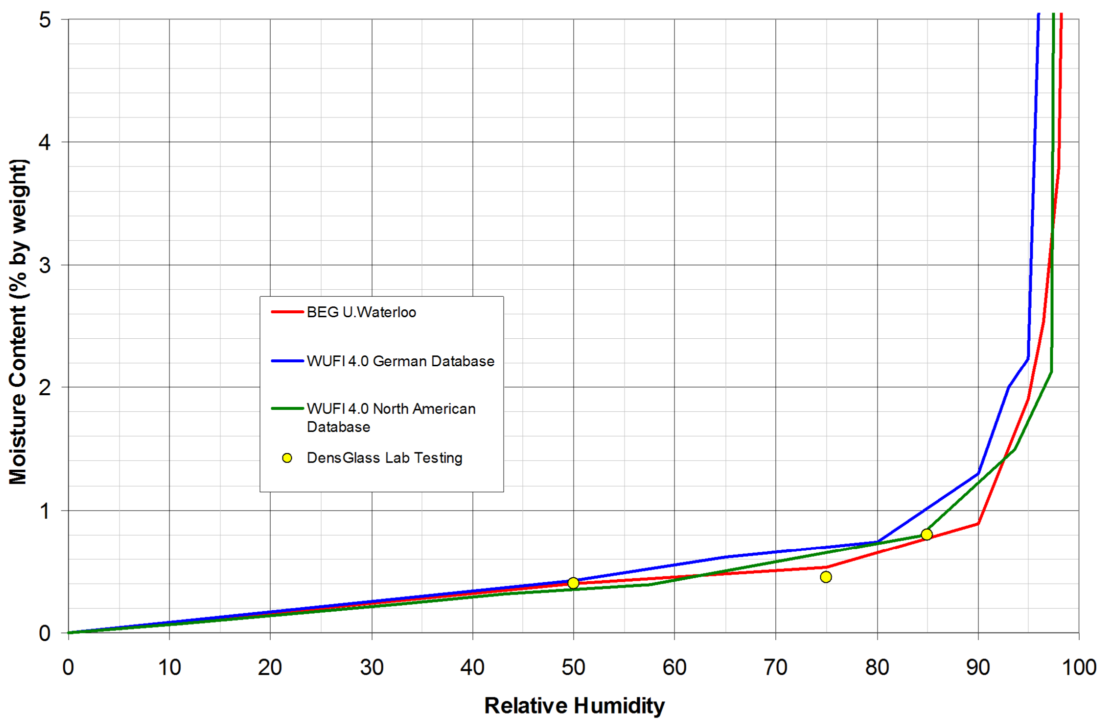


Figure 39: Sorption Isotherm for Gypsum Sheathing – with DensGlass results

The DensGlass samples generally agree with the existing published sorption isotherms for gypsum sheathing in WUFI 4.1. Points above 90% were not measured, however as confirmed by the testing, a rapid increase in moisture when exposed to 100% occurs, as suggested by the sorption isotherm.

5.2.3 Wetting and Drying Response

To attain additional points over a range of moisture contents, the samples were cycled between 100% RH and 50% RH and monitored. This cycling produced some interesting observations into the wetting and drying responses of gypsum sheathing. Measured and calculated moisture as well as the electrical resistance are shown for three cycles of "Waterloo 2" and "Vancouver" DensGlass Gold in Figure 40.

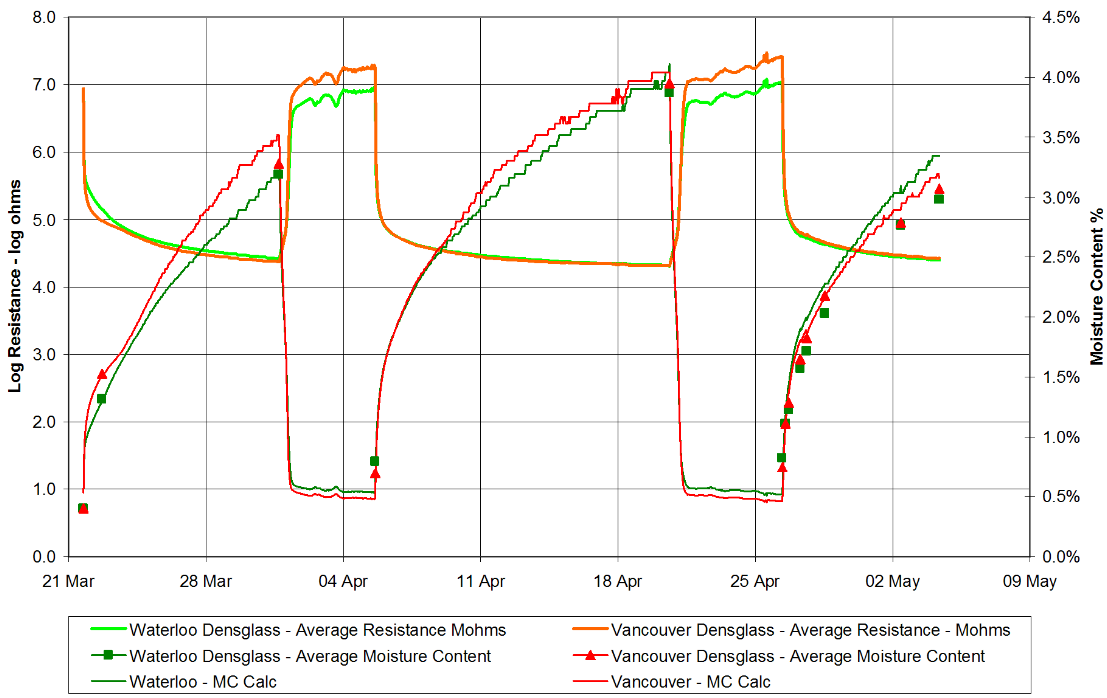


Figure 40: Wetting and Drying Response of DensGlass Gold Samples (100% RH wetting, 50% RH drying)

The three cycles show similar wetting and drying rates. Wetting occurs rapidly in the first few days and slows as the gypsum pores become full of water. However when comparing to the drying rate, the wetting process is relatively slow in comparison, as it takes much less time (hours) to dry as it does to wet (days).

The final wetting cycle from Figure 40 is shown in more detail on an hourly scale in Figure 41, which is representative of the wetting rate for the samples from tests #1 and #2.

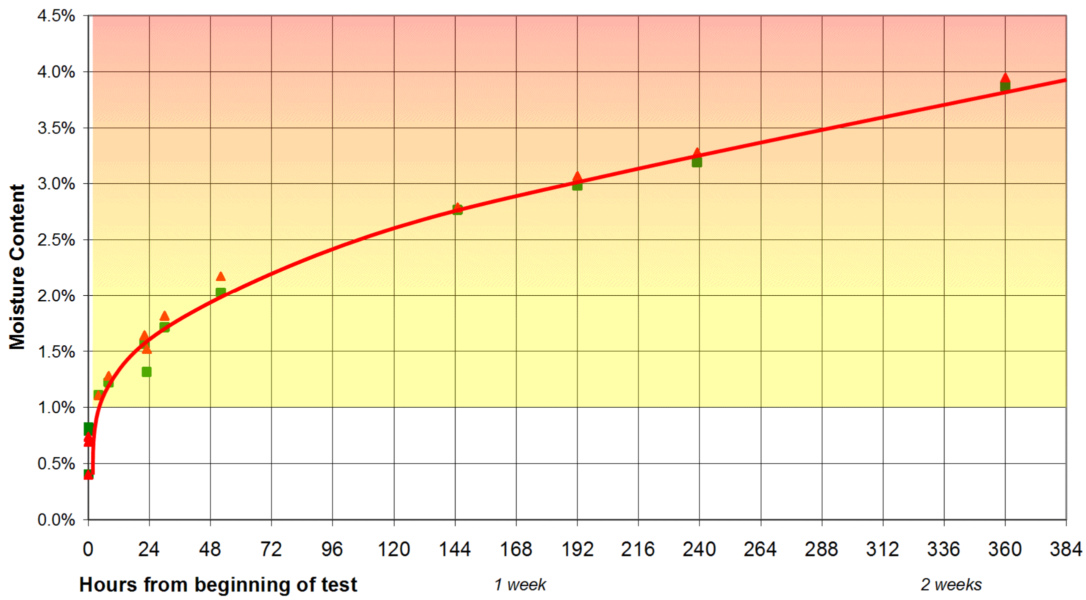


Figure 41: Wetting Response (24hour) of DensGlass Gold Samples exposed to 100% RH

In 14 days, the moisture content was approximately 4% for these particular samples of DensGlass Gold. Approximately the same rate was observed in the Test # 1 'A' samples exposed to the same conditions.

5.2.4 Physical Properties and Mould Resistance

As observed in Test#1, the samples were very soft to the touch above approximately 1% moisture content.

Mould growth was observed on the surface samples exposed to 100% RH conditions, but only after 1 month of exposure with moisture contents in excess of 5% were small black colonies observed presumably where condensation droplets had formed on the sample surfaces.

5.3 Comparison to WUFI Modeling

Gypsum sheathing was modeled in WUFI 4.1, the boundary conditions were set at 100% RH, and test ran until saturation. The vapour permeance of DensGlass Gold was used from published literature instead of the provided values for paper-faced gypsum. It took approximately 180 days to reach total saturation

(47% MC). From complete saturation, it took less than 4 days to dry to equilibrium with 50% RH. This same relatively slow wetting, extremely fast drying phenomenon was also shown during testing the laboratory cyclical testing. It should be noted when compared to other materials such as wood, the wetting time is much faster for gypsum.

Figure 42 plots moisture uptake and drying for a 15 day period modeled in WUFI. The sample is exposed to 100% RH (both sides) for the first 13 days, and subsequently dried to 50% RH at the end of the 13th day.

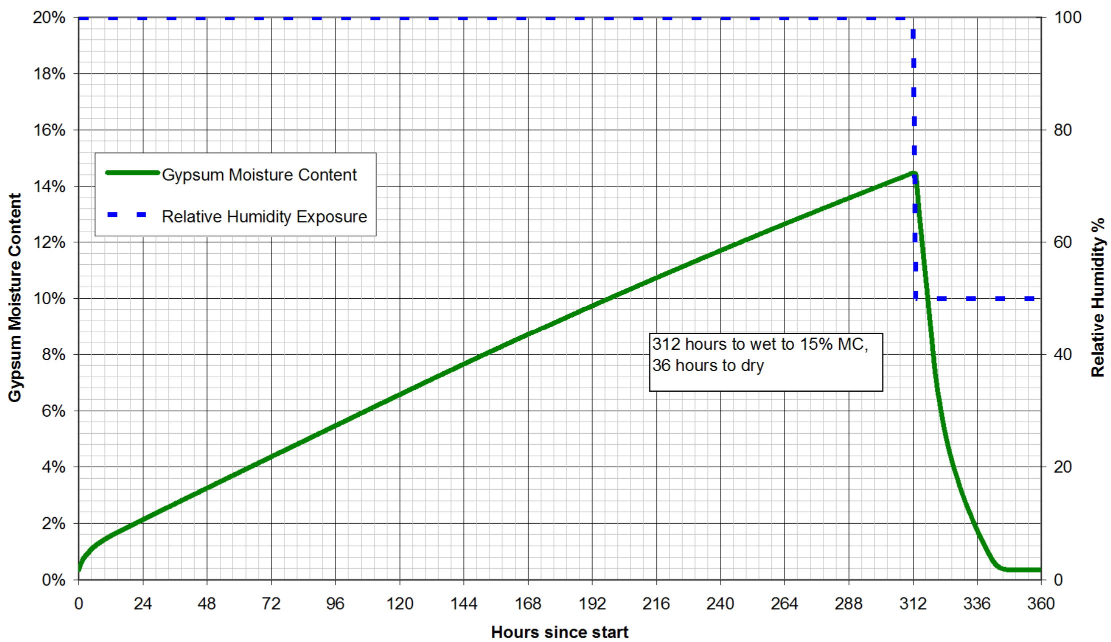


Figure 42: WUFI Predicted Wetting Rate for 100% RH exposure

Here is it shown that in 13 days (312) hours the moisture content of gypsum sheathing would reach approximately 15%. When exposed to 50% RH, it took 36 hours for the gypsum to dry back to original levels in equilibrium with 50% RH .

The moisture uptake rate modeled in WUFI was much faster and higher than that observed in the series of laboratory experiments. This is either a function of the material properties in the WUFI database, or the conditions which the laboratory samples were exposed to.

It can be shown by hygrothermal modeling that the relative humidity of the boundary layer has the most significant impact to the rate of moisture uptake, because of the steep slope of the sorption isotherm above 95% RH.

A sensitivity analysis was performed and significant impact was observed by changing the surface boundary layer in WUFI from 100% to 97.9% RH. The results are shown in Figure 43 compared to the laboratory measurements.

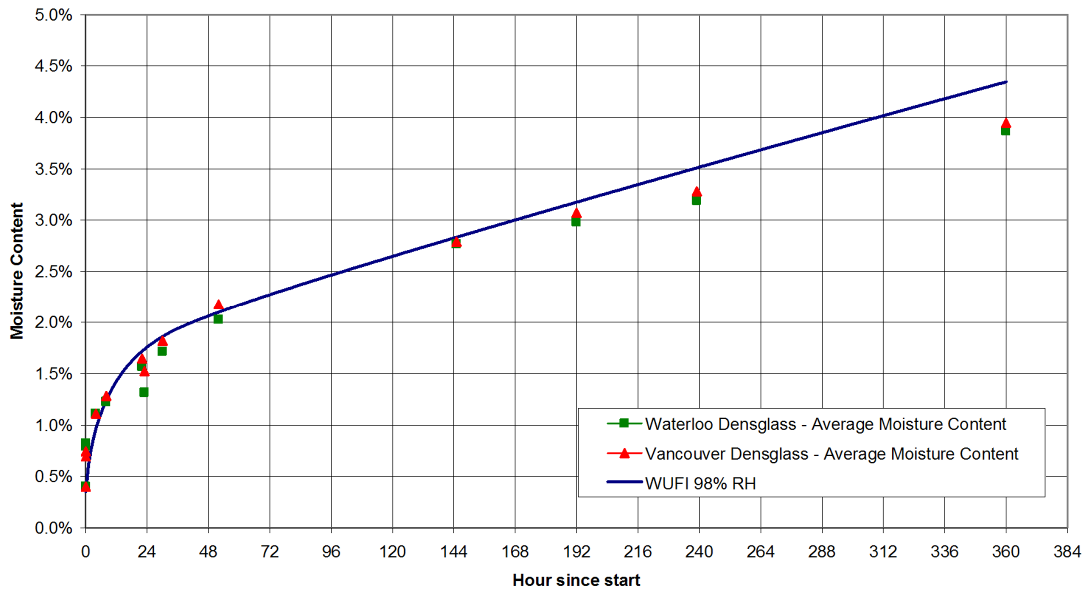


Figure 43: 97.9% RH modelled in WUFI compared to laboratory testing results

Here the modeled WUFI results more accurately reflect the laboratory conditions with only a minor 2.1% decrease in the relative humidity. It was shown that 98%, just 0.1% higher was not accurate in modeling the laboratory testing, showing the effect of the steep sorption isotherm at high relative humidity levels.

Even though the samples were placed over water, and supposedly exposed to 100% RH, air leakage through around container lid and testing wires, opening the container to perform measurements and slight fluctuations in laboratory temperature may have prevented the relative humidity in the chamber from achieving 100%. High levels of 100% RH also cannot be accurately measured using conventional instruments as the sensor error at high RH levels is large. It could therefore not be determined accurately if the RH in the chambers was in 100%, but likely was very close to it.

5.4 Comparison of Results to Literature

An equivalent wood moisture content was determined for each sample by plotting the relative humidity versus an equivalent (calculated) wood moisture content (based on the electrical resistance), similar to the NORDTEST plots discussed previously in Section 2.1.2. This provides a comparison of the developed gypsum moisture content electrical resistance correlation to compare to previous work and with other gypsum samples. The method to convert the data was as follows:

1. Using the correlation of moisture content with electrical resistance for gypsum, the relative humidity for each resistance was calculated by interpolating the validated sorption isotherm for gypsum. (ie. a resistance of 3.9 log kohms equals a gypsum MC of 0.54%, which from the sorption isotherm is interpolated to be 75% RH)
2. The resistance was then converted to a wood equivalent moisture content which would be read on a moisture meter (uncorrected for wood species or temperature). (ie. It can be calculated using methods in previous literature (Straube et al. 2002) that 3.9 log kohms gives 16.5% MC as the value that would be read on a Delmhorst Moisture Meter)
3. The equivalent wood moisture content is then plotted against the relative humidity which was determined in step #1.

The results of this analysis are presented in Figure 44, overlaid on top of the NORDTEST plots, which was discussed previously as the wood equivalent moisture content for gypsum samples exposed to different relative humidity levels.

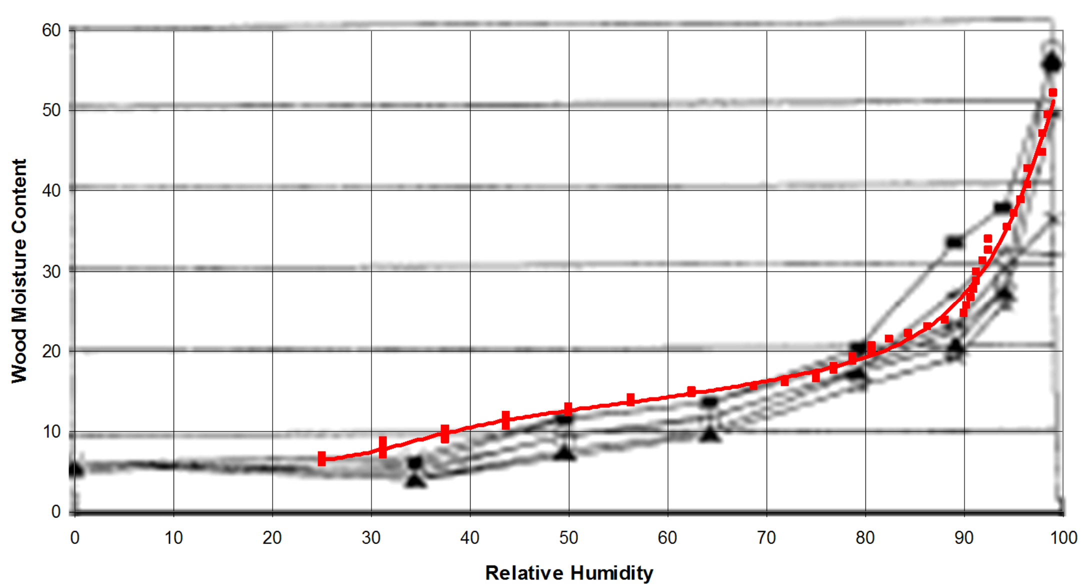


Figure 44: Equilibrium RH versus Gypsum MC Measured as Wood

It is shown that the lab results generally compare well to the NORDTEST data, following the same trend, and above 70% RH, the lab data falls within the range of values NORDTEST measured.

Below 70% RH the correlation reads wetter (or lower electrical resistance) than the NORDTEST results. This is shown in greater detail in Figure 45 which is similar to Figure 44 however instead of equivalent wood moisture content, log resistance (Mohms) is plotted against RH.

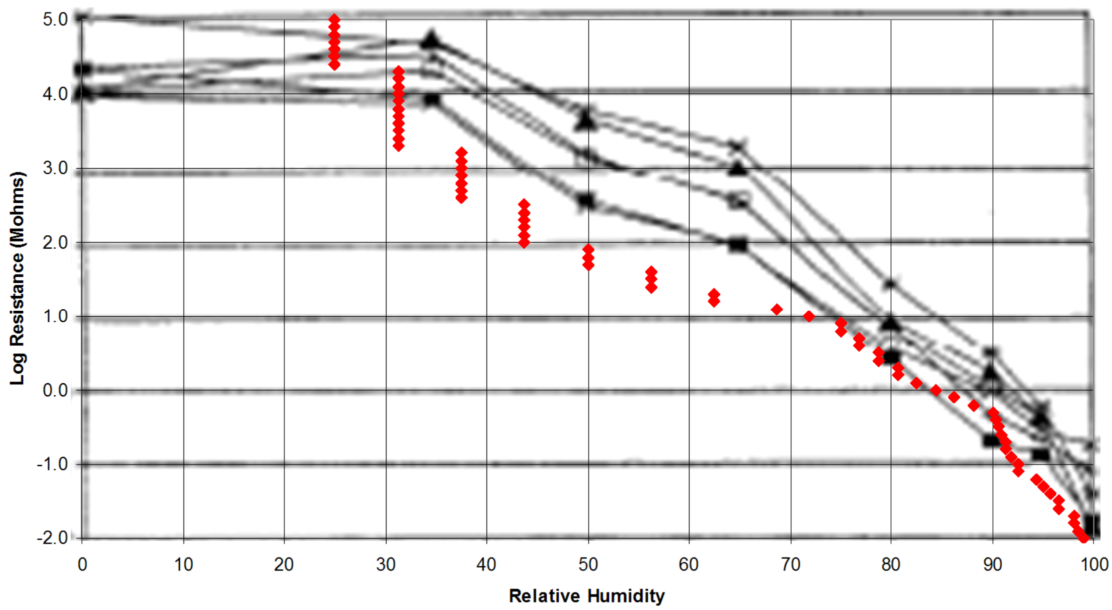


Figure 45: Gypsum equilibrium RH versus Log Resistance (Mohms)

This discrepancy is consistent with the lab results for DensGlass, as few data-points were recorded when the RH was below 70%. It is likely that the gypsum correlated moisture content reads wetter than actual moisture content below 70% RH. The data above 70% RH is generally consistent with the NORDTEST results.

It can be seen from comparing the correlation to the NORDTEST results, that the accuracy below 70% RH may be in question, however below 70% RH the gypsum board is below approximately 0.45% moisture content and its physical condition is generally not an issue. Moisture contents which we are generally concerned with, above 1% MC (>85% RH) are generally consistent with the published literature.

5.5 Wood Moisture Scale

It was determined that it would be useful to measure the approximate gypsum moisture content of DensGlass Gold sheathing using existing handheld meters typically calibrated for wood. As most wood meters (Delmhorst) are calibrated from for Douglas-Fir at 70F, it was felt that exploiting this similarity between different meters, a correlation for gypsum based on an equivalent wood scale could be developed.

Using the two relationships of moisture content with electrical resistance for wood and DensGlass Gold gypsum, a graph can be produced which plots the gypsum moisture content as it would read if measured using the wood moisture scale (on any model of Delmhorst, digital or analog).

It was attempted to use a wood calibrated moisture meter (Delmhorst Model J4) to measure the wood scale readings of the DensGlass sheathing during the laboratory tests, however the majority of moisture contents measured were above the scale of the meter. A few average measurements were recorded for DensGlass moisture contents in equilibrium with 50%, 75% and 85% RH and at 100% RH less than 1% gypsum moisture content. These average readings are summarized in Table 3.

Table 3: Gypsum MC and Wood Scale Reading

Relative Humidity	Gypsum MC (% by weight)	Wood Scale Reading
50	0.4	15
75	0.45	17
85	0.8	25
100% for <1 day	1.1	27
100% for <1 day	0.8	25
100% for <1day	1.5	>30
100% for <1 day	1.4	>30
100% for <1 day	1.2	30

While not statistically significant sample, the measurements provide some insight into the moisture scale of gypsum as compared to wood.

To complete the correlation of gypsum moisture content using the wood moisture scale, electrical resistance with gravimetric moisture content scales for wood (developed previously) and gypsum (developed in this report) are compared, and then plotted against each other to develop the relationship.

The wood moisture content is calculated from a known resistance, as it would be read on a handheld Delmhorst meter using the equation developed by the US Forest Products Lab as used by Straube et al (2002).

$$\text{Log10}(MCw) = 2.99 - 2.113\,(\log10(\log10(Rw))) \qquad \text{Equation 2}$$

Where Rw is the electrical resistance of wood in ohms (Ω), and MCw is the Douglas-Fir moisture content in mass, as would be read on all standard moisture meters.

Using the previously developed relationship of electrical resistance and MC for DensGlass gold we can determine the second relationship for gypsum.

Both gypsum and wood moisture contents are plotted versus electrical resistance (log-scale) in Figure 46.

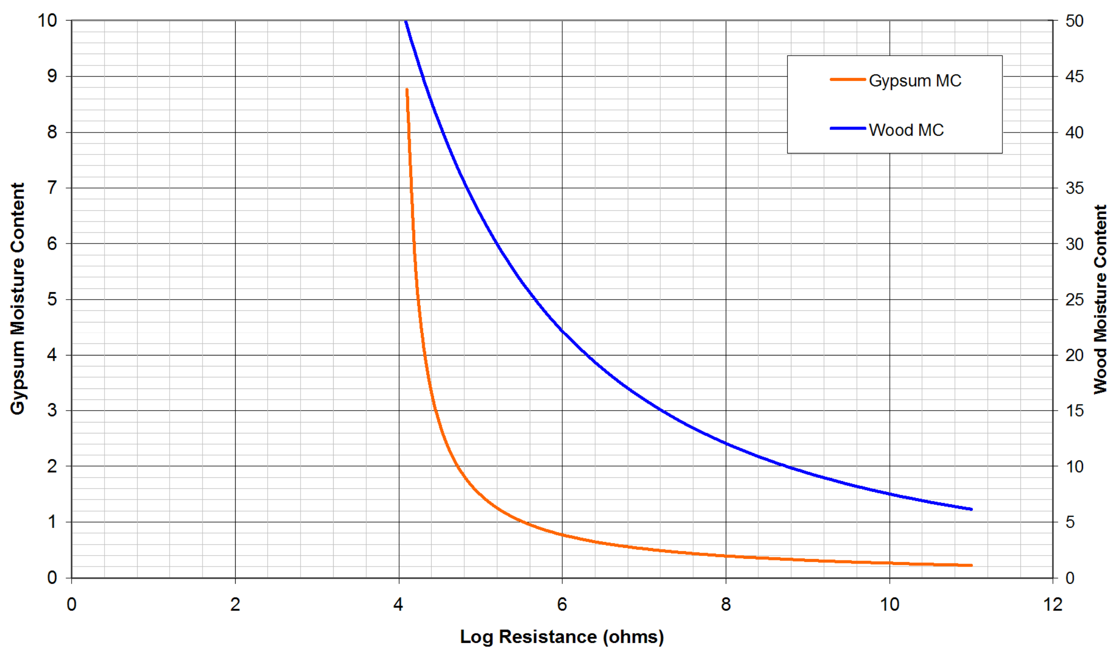


Figure 46: Wood and Gypsum MC versus Log Resistance (Ω)

As shown, wood and gypsum do not have the same curve relating the moisture contents with electrical resistance. However, the wood moisture content scale is then plotted (on the y-axis) against the gypsum moisture content (on the x-axis) in Figure 47.

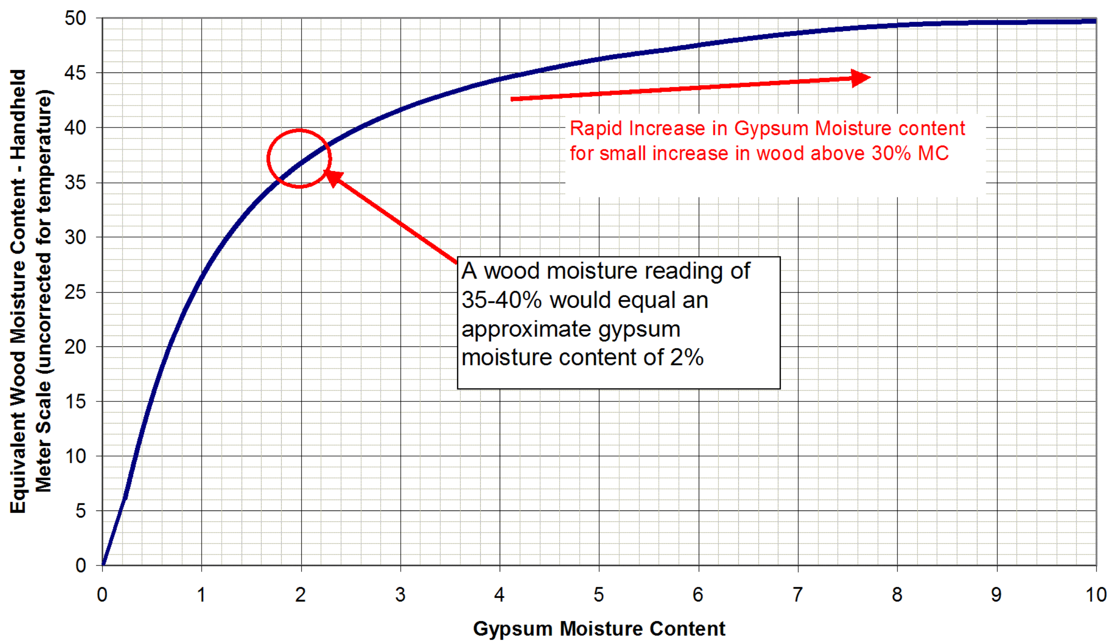


Figure 47: DensGlass Gold – Gypsum MC as read on a standard wood scale

The user would insert the moisture probes in gypsum sheathing and read the wood scale moisture content, and then using this plot, the approximate gypsum moisture content can be determined. Most wood meters read up to 30% and some up to 40% wood moisture content, limiting the evaluation of the gypsum moisture content to values below 1.5% or 2.5% correspondingly, for higher gypsum moisture contents up to 10% a wood moisture meter capable of reading up to 50% MC is required.

As a general rule, if gypsum is read on a handheld meter with a wood moisture content of 25% or greater, there is likely a moisture issue with the gypsum that should be addressed. On the contrary, "safe" levels for gypsum fall below 20% wood moisture content, showing the importance of accurate moisture meter readings when taken in gypsum.

For another comparison, the Delmhorst BD-10 Moisture meter provides two scales on the analog meter, the standard wood scale (6 to 40%) and a reference scale of 0-100 (for other materials). These scales are is plotted in Figure 48 for reference. Using the correlation developed in Figure 47, it is shown that relative scale readings of approximately 80 or above (>25% wood scale) are levels which would indicate that the gypsum was abnormally wet.

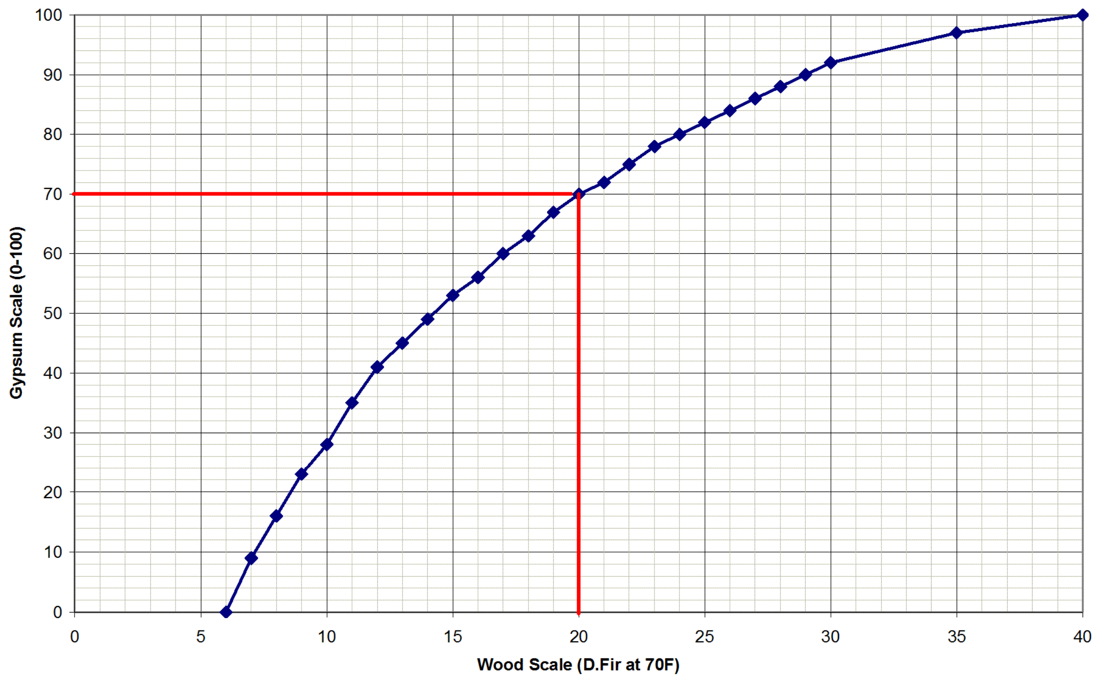


Figure 48: Delmhorst BD-10 Relative Scale (1-100) Compared to Wood Scale Reading

5.6 Field Correlation and Observations – Building 3

Building 3, as discussed in the body of the Thesis was constructed with DensGlass Gold sheathing in 2001. The same DensGlass Gold sample "Vancouver" which was tested in this laboratory experiment was taken from this job-site in 2001.

Field openings were made in January 2006, after 4 winters of repeated annual wetting cycles, and observed liquid water, staining and mould growth on the inside surface of the DensGlass Gold sheathing. Condensation droplets were observed on the inside surface, and the sheathing was also soft to touch and gave easily when probed with the moisture meter. Measurements using a Delmhorst BD-10 indicated relative moisture levels between 80 and 100, indicating elevated moisture contents of the DensGlass Gold sheathing. Correlation with measured data (from data-loggers) was performed and found that electrical resistance readings were returning valid data.

As the exterior of the DensGlass sheathing is covered with a self-adhered peel and stick membrane, drying is limited to the interior, and such moisture may accumulate in the sheathing when the vapour flow is towards the exterior (winter months).

The highest moisture levels were recorded at the base of the wall at a cold corner detail, and moisture levels likely are increased by air leakage condensation at this location. Potentially, gravity moisture flow was also increasing the moisture content at the bottom edge of this wall. In-place existing moisture content pins were located approximately 500 mm from this location (away from the corner) and were also reading wet (~80 relative moisture scale), however did not appear as wet as the corner location shown in Figure 49.

Figure 49: Mould/Mildew growth on DensGlass Gold Sheathing (Wall Cavity #8)

The recorded electrical resistance was then converted to a gypsum moisture content using the developed correlation and is plotted against measured relative humidity in the center of the stud space and calculated relative humidity at the sheathing. As the calculated value assumes the sensor is installed exactly in the middle of the insulation, and insulation was installed perfect without air-gaps, the actual relative humidity is likely between the two values.

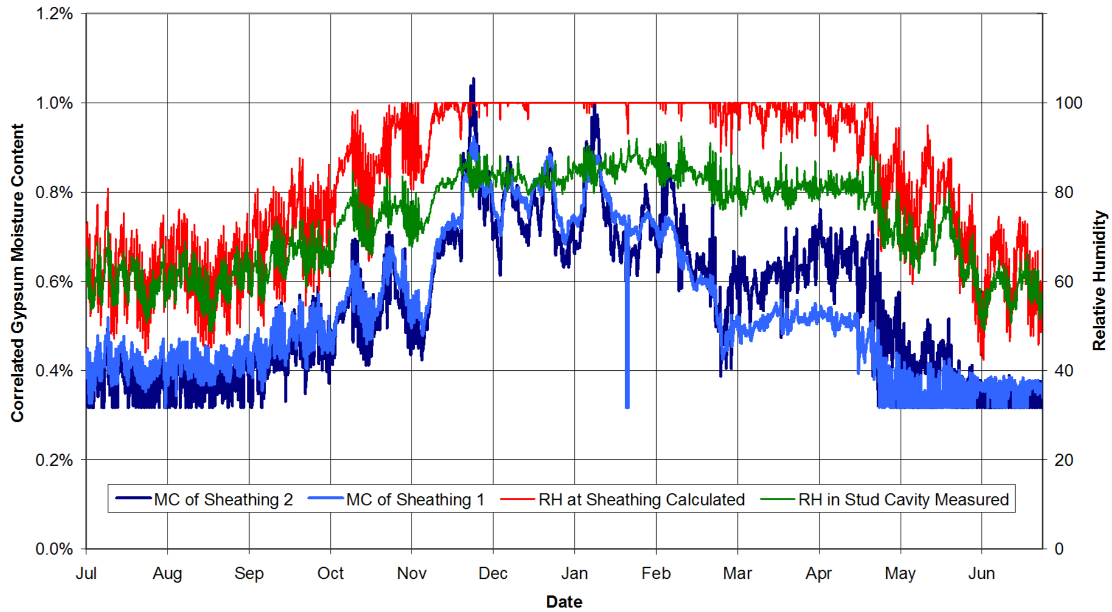


Figure 50: Building 3 – Wall Location 6 – Gypsum MC and RH in cavity (July 2002 to July 2003)

This same trend was observed for all eight monitored wall locations of the study.

Assuming the relative humidity at the sheathing is actually in between the measured and calculated value during the winter (85-95% RH), the moisture content (from the sorption isotherm) will be approximately 0.8% to 2.0%. As shown the moisture content on average during the winter is around 0.8% with peaks up to 1.0%. The readings indicate the RH at the sheathing may be closer to that measured by the sensors in the center of the insulated stud cavity, or an air gap causing convection loops between the insulation and sheathing may be reducing the RH at the sheathing.

From the presented data in Figure 50, when the wall cavity was opened up and observed in January 2006, extensive mould growth was not observed on the surface as in the corner shown in Figure 49. However the gypsum sheathing at the probes was soft and had readings of 80-90 on the Delmhorst BD-10 relative scale. It appears that the installed sensors are not located in the worst case locations for the building which were visually observed when the walls were opened up.

With this in mind, the lessons learned from this field study are that the exterior gypsum sheathing was exposed to high relative humidity levels above 80 to 90% for 5 to 6 months of the year, and was restricted from drying to the exterior by a vapour impermeable membrane. Prolonged moisture contents of greater than 0.8% and periods up to 1.0% were calculated. These prolonged humid conditions have lead to the softening of the gypsum sheathing and surface mould growth in areas of periodic condensation.

5.7 Field Correlation of results with BEGHUT Test Walls

As part of an existing BEGHut monitoring project, the performance of Spray Polyurethane Foams (SPUF) was monitored in which a few of the test walls were constructed with DensGlass Gold exterior sheathing. The walls were insulated on the exterior with 2″ (50 mm) closed cell sprayfoam, and insulated to the interior with 3 ½″ (89 mm) of fiberglass batt insulation between light gauge steel studs. Latex paint was used as the vapour control layer on the interior. The walls were exposed to Waterloo, Ontario exterior weather, and constant interior conditions of 50% RH/20°C (high wintertime interior relative humidity for this climate). The performance of the gypsum sheathing was monitored using insulated moisture pins to measure the electrical resistance at mid-depth of the samples.

The calculated gypsum moisture contents (eye and waist level) are plotted against the relative humidity measured within the center of the batt insulation and relative humidity calculated at the DensGlass sheathing (where sensor was not installed).

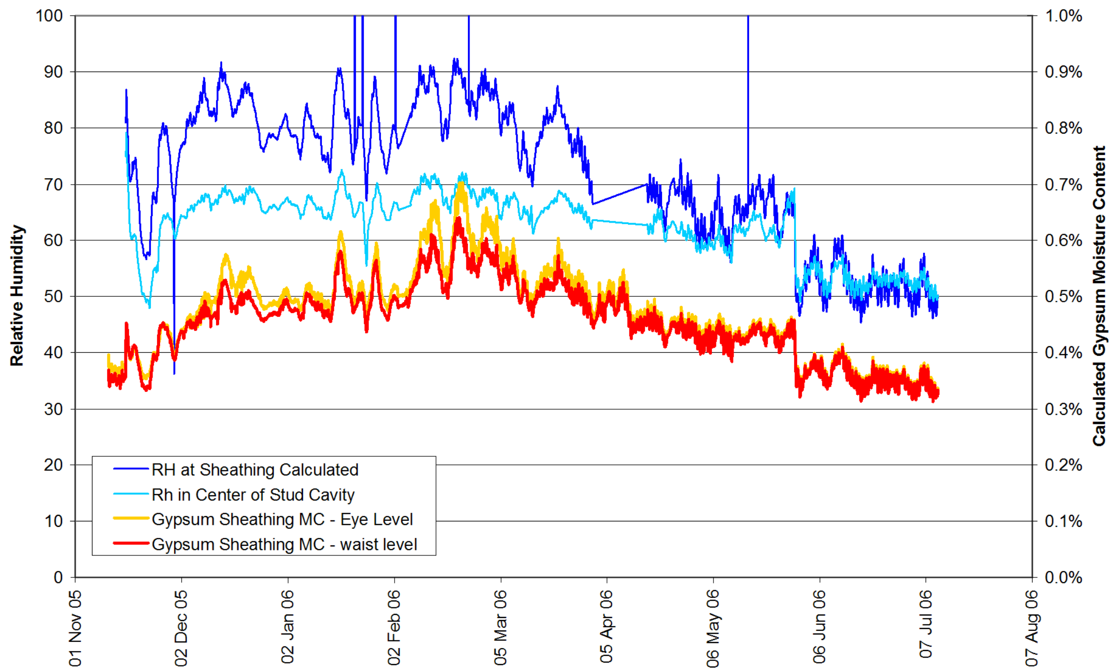


Figure 51: BEGHUT- SPUF North Wall 9 – DensGlass MC versus RH

The gypsum moisture content and relative humidity correlate well, as predicted, and shown with similar trends between the values. The moisture content of the gypsum sheathing remains below 0.7% for an average relative humidity of 80% during the winter. Peak relative humidity levels of 90% were calculated at the sheathing for up to a few days at a time.

A further comparison of the gypsum moisture content readings is made to surrogate wood wafer sensor readings which were installed in contact with the gypsum sheathing. Further information regarding the surrogate sensor calibration can be found in work by Ueno, 2007. Figure 52 compares the gypsum moisture contents to the surrogate wood moisture contents, with good agreement of the previously developed wood MC-gypsum MC correlation.

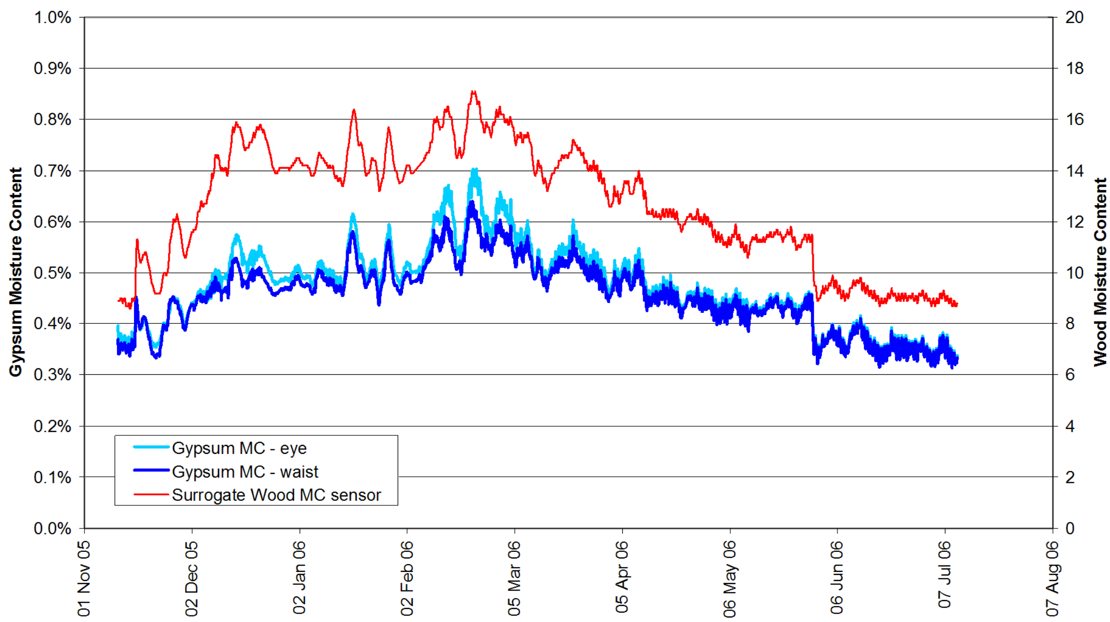


Figure 52: Comparison of Gypsum MC to Wood Surrogate Sensor MC

The closed cell SPUF to the exterior of the gypsum sheathing is vapour resistant (42 ng/Pa m^2 s); therefore some moisture is able to diffuse through the foam, potentially reducing the moisture content of the gypsum which is exposed to moderate to high relative humidity levels at the sheathing. Where as seen in Building 3, the moisture was trapped at the sheathing layer and likely resulted in the elevated moisture contents observed.

6 <u>CONCLUSIONS</u>

Structural testing by Levelton showed a significant strength loss in paper and fiberglass faced gypsum sheathing boards with as little as 1% moisture content. The sorption isotherm for gypsum indicates that between 80 and 90% RH, an equilibrium moisture content of 1% will be attained.

It was shown that 1% moisture content can be rapidly achieved in the laboratory testing in less than 24 hours, and potentially can be achieved in the field when exposed to exterior weather conditions or under circumstances such as in Building 3 where the moisture became trapped within the wall assembly during seasonal wetting.

Constructing walls with gypsum sheathing and steel studs does not allow the same safe storage capacity of comparable wood framed systems. 1% moisture content over 1 m^2 of 13 mm gypsum (density 850 kg/m^3 – 11.05 kg/m^2) means that approximately 111 g/m^2 of water can be safely stored in gypsum sheathing, where as 1% MC in 13 mm plywood sheathing (density 500 kg/m^3 – 6.5 kg/m^2) means that 65 g of water per 1%, however wood can safely store up to 20% moisture content or 1300 g/m^2 of water. In addition the wood studs also store some moisture, in the same order of magnitude as the wood sheathing. Steel studs do not have the capacity to store moisture, and high relative humidity environments will lead to corrosion. The difference to seasonally store between 111 g/m^2 of storage and 1300 g/m^2 of storage highlights the sensitivity of gypsum sheathing products to humid environments and the importance to keep walls constructed with moisture sensitive materials dry or able to dry quickly if they get wet.

While gypsum sheathing may be marketed at “water-resistant” it does not imply resistance to water-vapour (which would be detrimental in most conventional wall systems anyway). “Water resistant” gypsum behaves similar to untreated gypsum board when exposed to water vapour and exposed to 100% relative humidity. Water-vapour alone can and has been shown to damage walls sheathed with gypsum sheathings.

Gypsum sheathing will readily absorb moisture from the air; however will even more readily lose that moisture when exposed to drying conditions.

While fiberglass faced gypsum products such as DensGlass gold are “mould-resistant” under ASTM test standards, mould can grow on surface contaminants, accelerated by liquid water from condensation. As the moisture storage capacity of gypsum is low, condensation beads can potentially form at low moisture contents which can lead to surface mould and microbial growth.

There is some debate as to safe relative humidity levels which gypsum can be exposed to for extended periods. Many sources have recommended a maximum exposure of 80% RH. This will result in a moisture content of less than 1% and is conservative. Potentially this threshold could be increased to 90% RH for fiberglass faced gypsum, as long as condensation is avoided. 90% RH is the tipping point on the sorption isotherm where for small changes in RH the moisture content rapidly increases. 80% RH environments may be a conservative safe value, perhaps even 85% RH, however it is important to avoid extended periods of exposure above 90% RH for structural and also mould/microbial concerns.

The sorption isotherm for gypsum sheathing provided in WUFI (either North American or German database) is suitable to represent DensGlass Gold, provided the permeance values for DensGlass Gold are used.

The laboratory work was intended to demonstrate that gypsum moisture contents could be measured using electrical resistance, similar to that performed in the past for wood.

The following equation was developed from the laboratory testing of multiple samples exposed to varying moisture conditions from three different DensGlass Gold batches produced in 2001 and 2005.

$$GypsumMC(\%) = 1/((62.0693 * (\log(\mathrm{resistance}))) - 243.0790)$$

Figure 53 graphically shows this correlation plotted against measurements taken during Test #1 and #2. The gypsum moisture content correlation was further compared to an equivalent wood moisture content measurement. The relationship in Figure 54 was developed so that existing wood moisture meters could be used to approximately determine gypsum sheathing moisture contents in the field.

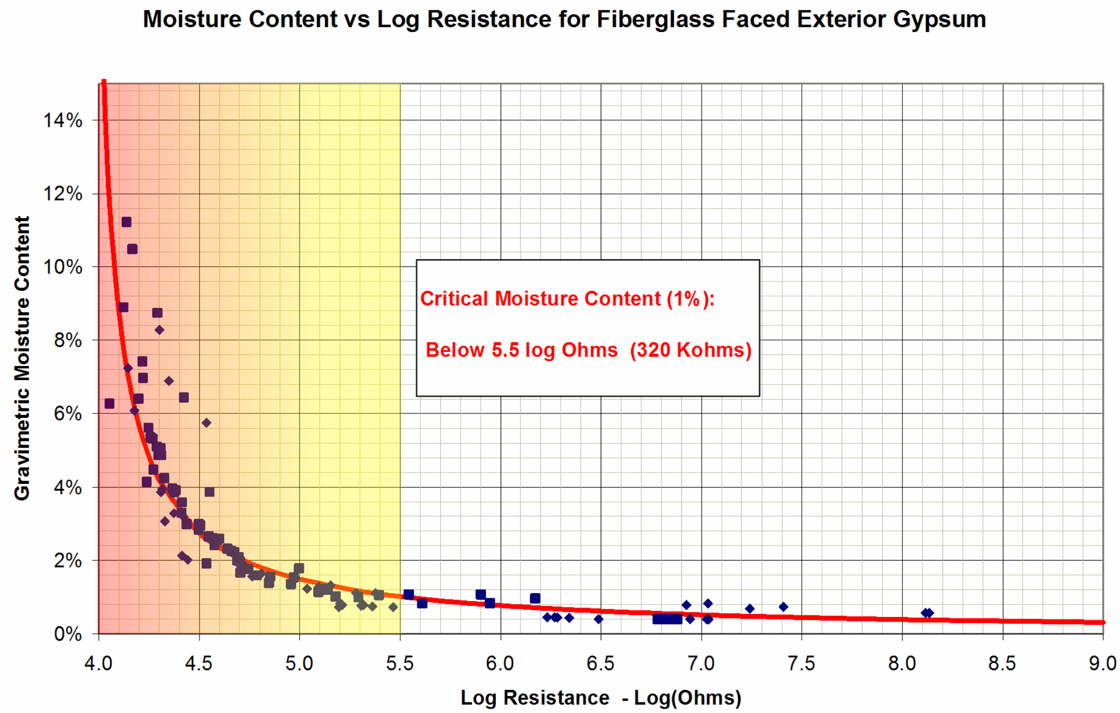


Figure 53: Moisture Content – Electrical Resistance Relationship for DensGlass Gold Exterior Gypsum Sheathing

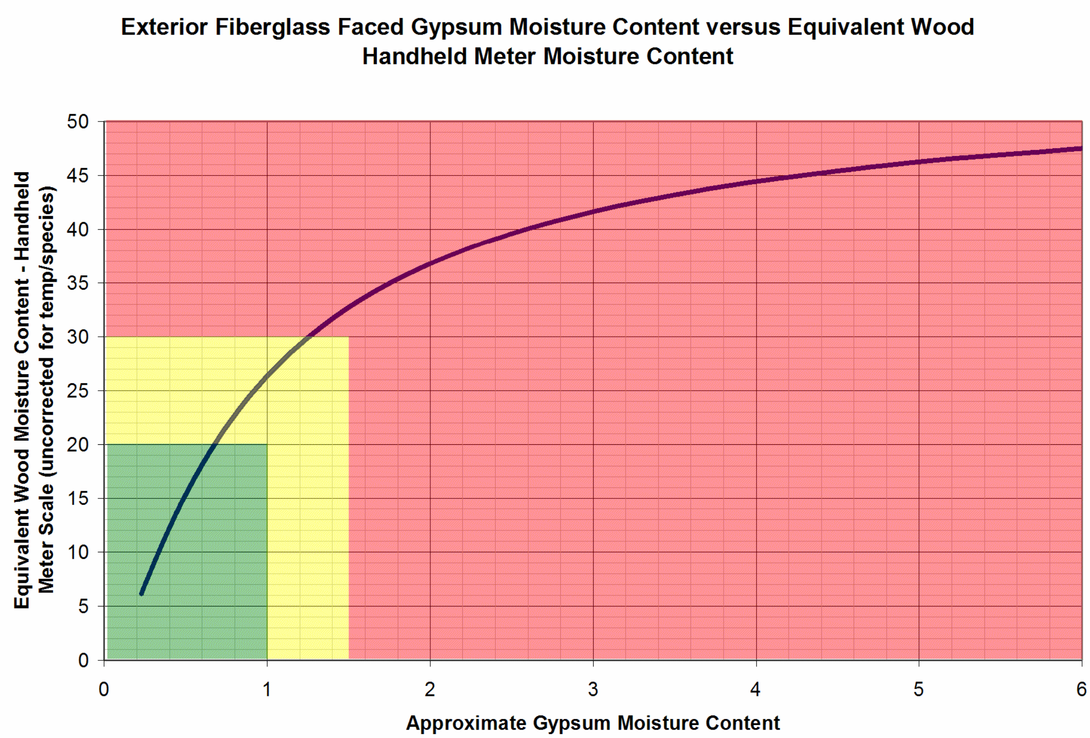


Figure 54: DensGlass Gold Moisture Content – Wood Scale Reading Relationship

7 RECOMMENDATIONS

It is important to know the moisture content of gypsum sheathing is such uses as field investigations, monitoring projects and for forensic use. As gypsum sheathing is extremely moisture sensitive, having a general understanding of whether the product is wet, dry or somewhere in between is required.

The test procedure is very simple and can be applied to other gypsum products easily if required. As gypsum sheathing board products differ somewhat chemically due to the natural materials and additives there may be some variance between brands, batches and thicknesses. For most practices however, simply measuring the moisture content using a handheld meter and referencing the wood scale measurement may be satisfactory.

It is recommended that further testing be carried to possibly fine tune the moisture content and electrical resistance correlation, specifically at low moisture contents (below 1% MC).

The distribution of moisture under gravity in gypsum sheathing panels could also be investigated.

It may also be of interest to develop an understanding of the gypsum properties chemically at different moisture contents to possibly develop a more water resistant gypsum core material.

While some gypsum sheathing products are marketed as “water-resistant”, they are often just as easily affected by moisture from humid environments as non water-resistant counterparts. It may be desirable to develop a gypsum sheathing board in the future which will safely store moisture at an order of magnitude similar to the safe storage capacity of wood.

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Appendix B: Hygrothermal Modeling

APPENDIX B: HYGROTHERMAL MODELING

Introduction

There are several needs for hygrothermal modeling of enclosures (wall, roof, and floor assemblies) in the building industry. Design professionals including architects and engineers use models to assist with new or retrofit design, but also for forensic and condition assessment analysis. Researchers use models to develop new products, establish code regulations, and further understand the real-time building physics or performance of the building enclosure.

Several hygrothermal models have been around for the past 20 years. Initially restricted to performing simple vapour diffusion or heat transfer analyses, models have developed in complexity to incorporate more parameters and able to model a wider range of assemblies and real-world situations. In the past few years, models have reached a stage where the ability to accurately re-create and model field performance has been shown (ie exposure to driving rain, air leakage, ventilation, and rain leaks etc).

Well established and benchmarked hygrothermal models are useful to the building industry as they allow for the analysis of enclosure assemblies without the time or economical constraints of performing full-scale field testing. Computer models also allow the quick comparison of several different variables, in a multitude of climates, which could not realistically be done elsewhere. Field and laboratory studies are however still useful and required to validate hygrothermal models, and provide comfort that the models are able to accurately model conditions in the field.

Hygrothermal model users still must use good judgement, and have an understanding of the building physics within the model and be aware of the potential impacts of those scenarios which the model cannot reproduce. Designing an entire building using modeling without consideration of other building knowledge is foolish, particularly if in a climate which the designer is unfamiliar with. Modeling is more effective as an enclosure designer’s tool to improve understanding of the building physics, and complement existing knowledge of enclosure systems.

The data collected in this thesis provides a three-fold purpose; one to compare field results and validate the widely used WUFI 1D model; two to develop potential wall improvements for industry; and three to better understand the performance of the wall assemblies in real-time.

The goal of a hygrothermal analysis is the evaluation of the moisture and thermal conditions that may occur through an enclosure at a specific location. To do this, the information required for a typical modeling exercise is shown in Figure 1 (Straube & Burnett 2005).

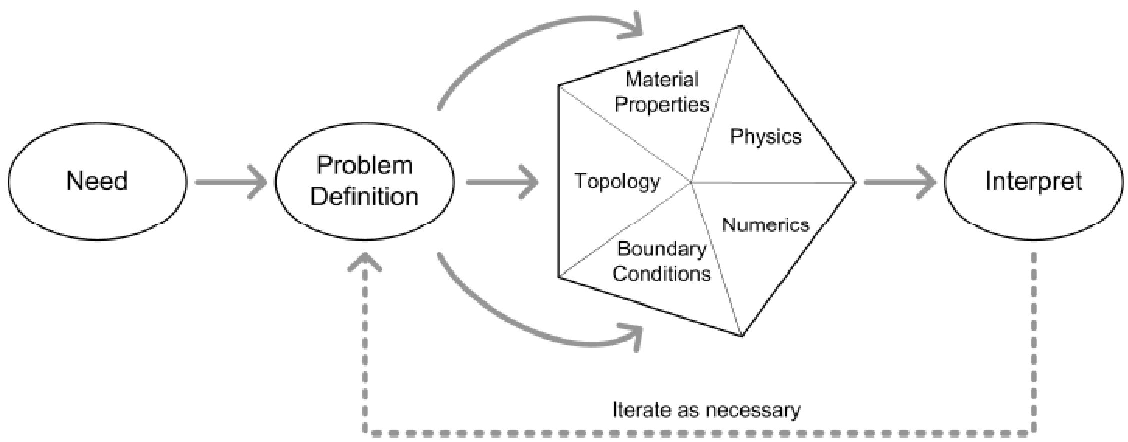


Figure 1: Modeling Approach (Straube & Burnett 2005)

In this thesis there is a need to further understanding wall performance by use of modeling, potentially validate an existing model and use to model potential wall improvements. The physics and numerics are embodied in the chosen computer modeling program. The boundary conditions and material properties in this case are the boundary conditions measured from the field study (Chapter 5 & 7), and the material properties within the program are used (collected from numerous laboratory studies). Finally the interpretation of the results requires engineering judgement and an understanding of the inner workings of the model and material behaviour.

Several hygrothermal models exist and are the strengths and weaknesses are summarized well by Hugo Hens in the IEA Annex 24 Project (1996) and more recently by the CMHC (2003).

Criteria for a selection of an appropriate hygrothermal model consisted of one that was well benchmarked against field studies (able to model rain, wind, solar, effects) and had the ability to model the effects of cladding ventilation in rainscreen walls. A one dimensional model was preferred for simplicity over a two-dimensional version if possible. In addition to be practically relevant to industry preference was given to a model that was widely used in North America. This limited the possibilities to WUFI (Fraunhofer-Institut für Bauphysik (IBP) in Germany and ORNL in the US), HygIRC (National Research Council of Canada), and potentially DELPHIN (University of Dresden, Germany).

While all models were briefly tested, WUFI was chosen because of its continued software development leading up to the ability to model ventilation and rain leaks in version 4.1. Results from WUFI versions 3.3 and 4.0 were also in the development of this thesis where relevant. It was beyond the scope to look at the validation with further one or two-dimensional models.

WUFI Hygrothermal Model

Commercially available hygrothermal software, WUFI 1D is often used by architects and engineers to perform design analyses or forensic simulations of wall and roof assemblies. To assist in making design decisions, several cases can be modeled together with different variables (including materials or boundary conditions) to develop an understanding of the performance range of a particular system.

The limitation of most current one-dimensional hygrothermal software includes the inability to model air leakage, cladding ventilation, or rain leaks. The latter ability is important if one is to meet the proposed ASHRAE Standard 160P requirement for 1% of the driving rain load to be modeled as a leak past the cladding.

To account for ventilation, IBP has introduced a new version of WUFI 4.1 which can model heat and moisture "sources and sinks" within wall assemblies at locations other than the exterior or interior boundary layers. In addition to ventilation, rain leaks, air leaks, or heat sources can be added to layers within the assembly and modeled. Different types of moisture and/or thermal sources or sinks can be modeled as follows (Kehrer 2006):

- Source from file (constant or at user defined interval)
- Source as fraction of boundary conditions (i.e. 1% driving rain load for ASHRAE SPC 160P)
- Source derived from air change rate in a ventilated gap (constant or user defined interval)

In the third option, WUFI 4.1 allows the user to ventilate airspaces by assigning either a fixed or hourly ventilation rate (in the form of air changes/hr). The moisture added to or extracted from the cavity is modeled as a well-mixed process:

$$Q_m = \frac{ACH}{3600} \cdot d_{cavity} \cdot (X_{out} - X_{cavity}) \qquad \text{(eqn. 1)}$$

where, Q_m is the moisture source/sink strength [kg/m²s]
X_{out} is water content of the outdoor air [kg/m³], and
X_{cavity} is water content of the cavity air [kg/m³]

The thermal source is calculated as follows:

$$Q_t = \rho_{out} \cdot \frac{ACH}{3600} \cdot d_{cavity} \cdot C_{p,Air} \cdot (T_{out} - T_{cavity}) \qquad \text{(eqn. 2)}$$

Where, Q_t is the thermal source term [W/m²], and
$C_{p,Air}$ is the specific heat capacity of dry air at constant pressure, moisture excluded.

When the simulation is complete, the user can check for errors and the balances to ensure the accuracy of the calculations.

Prior to WUFI 4.1 modeling of walls with cladding ventilation tended to yield inaccurate results unless modifications are made to the cladding materials or assembly to approximate the effects of ventilation (this is discussed in detail in the next section).

The accuracy of previous versions of WUFI have been verified against many full-scale field studies of enclosure performance (roofs, walls, foundations, parking garage decks, etc.) over a number of years (Karagiozis et al. 2001, Künzel 1998a, Künzel 1998b, Straube & Schumacher 2003). The source and sink model builds on the existing platform.

The use of a two-dimensional hygrothermal model may be more accurate at modeling the effects of ventilation or leaks. However 2D models may not be required in all situation or practical for some users. Modeling the impacts of leaks or ventilation in a two-dimensional model is currently time consuming. Therefore the ability to estimate some two-dimensional effects (heat and moisture sources, i.e. rain and air leaks or ventilation) in existing one-dimensional models which are fast, well benchmarked, and widely used is desirable for practitioners.

Past Approach to Modeling Cladding Ventilation

A number of modeling techniques have been used by practitioners in the past to model wall assemblies with ventilated claddings. These techniques have included the following:

1. <u>Ignoring Ventilation Effects</u> – The traditional approach has been to ignore the impact of ventilation by inserting a still air cavity behind the cladding and in some cases (where ventilation is very low, in dry climates, or with high permeance cladding) this may produce reasonable results. However for most climates and wall assemblies, this method will yield inaccurate results, highlighting the importance of ventilation and the cladding properties.
2. <u>Effective Cladding Permeance</u> – The user modifies the vapour permeance of the cladding material by an order of magnitude depending on the estimated ventilation rates. Effective permeance can be calculated using methods as shown by TenWolde and Carll (1992) and Straube and Burnett (1995, 2005) which typically results in an order of magnitude increase to the cladding vapour permeability. The cladding is left in the model as a screen to account for solar radiation heating and moisture storage from wetting events. The effective vapour permeance which is determined by the user has a significant impact on the results, and hence can be subjective based on the user's experience. A plot of equivalent vapour permeance versus cladding ventilation is shown in Figure 2.

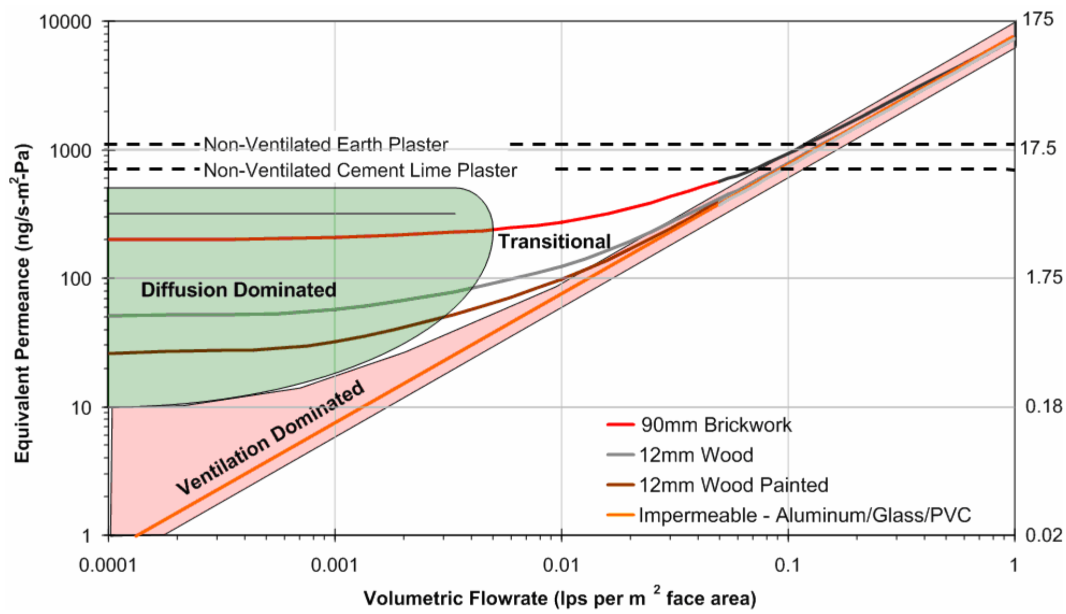


Figure 2: Equivalent Vapour Permeance of Claddings Based on Ventilation Flow rate (Straube et al. 2004).

3. Removal of Cladding – The user removes the cladding from the model, and at the same time, rain and solar radiation loads are typically turned off in the model, to prevent the sheathing from being directly wetted or solar heated. The impacts of solar radiation and rain have a significant result on the moisture distribution, wetting and drying and therefore this method tends to under-estimate the moisture loading.
4. Using Cavity Conditions as Exterior Boundary Conditions – Involves using measured cavity conditions (T/RH) as the exterior boundary conditions in a KLI file with the cladding and air cavity removed. This method has been shown to be accurate at capturing the wall performance to the interior of the cladding (Finch et al. 2007a, 2007b). However it can only be used if collected cavity data is available. It is not useful to the general user who uses a model to design and therefore is not discussed further here.

The sheathing moisture content of a stucco clad rainscreen wall (Building 2) modeled using the different techniques discussed above are reported in Figure 3 and Figure 4. The wall assembly is as described in Chapter 4, with materials properties in the WUFI database used. A “face-sealed” case (one in which the stucco is in direct contact with the water resistant barrier) was also modeled for comparison. Face-sealed assemblies have a poor record of performance in Vancouver due to sheathing rot and decay (Morrison Hershfield 1996).

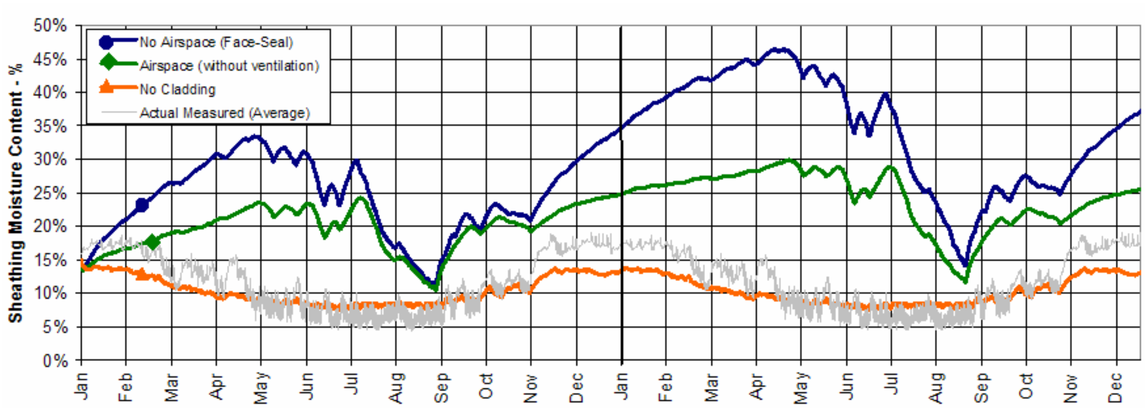


Figure 3: Hygrothermal Modeling Techniques – Comparison of Modeling Techniques (1&3)

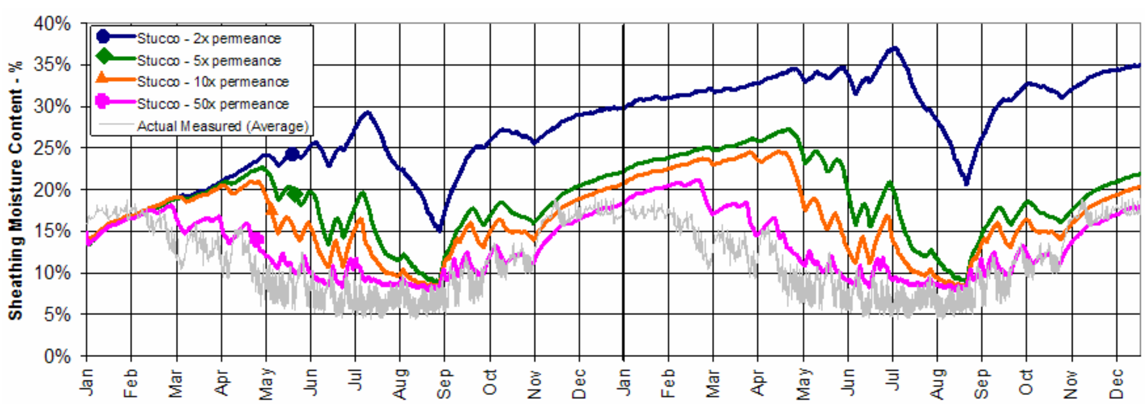


Figure 4: Hygrothermal Modeling Techniques – Comparison of Effective Cladding Permeance

Experience and moisture probe testing of wood frame buildings in Vancouver's coastal climate has shown a seasonal moisture trend from low in the summer (5-15% MC) to high in the winter (15-25% MC). The moisture content of the sheathing is at its highest during the wet winter months starting during the first significant rainfalls in fall (October-November) until the warmer and drier weather in spring (March-April). Similar trends are observed in ventilated rainscreen walls presented in Chapter 8. Not including accurate ventilation effects in the modeling, results in a significant (as much as 15%MC higher) over-prediction of the moisture content and a shift in the peak moisture levels until the summer months.

Therefore when the modeled results show skewed curves with peak moisture contents occurring in late spring-early summer, the user should be aware that the results are likely inaccurate. This occurs in the model as rain, coupled with higher exterior temperatures and solar radiation act to drive moisture into the wall (reverse vapour drive) which elevates sheathing moisture levels. Allowing this moisture to dissipate (less permeable cladding, or ventilation) shifts the peak to the wet winter months, as was observed in the field.

Source and Sink Approach to Modeling Ventilated Claddings

The impact of the ventilation rate was investigated with the model for the stucco rainscreen clad wall used in the previous example. Fixed ventilation rates of 1, 10, 50, 100, 140, and 200 ACH were considered as well as an hourly varying ventilation calculated from the buoyancy pressures alone (Refer to Chapter 2). From the results shown in Figure 5, it is again clear that the cladding ventilation rate can have an important effect on the modeled performance of rainscreen walls in Vancouver's climate. Lower ventilation rates will result in higher sheathing moisture contents for prolonged periods of time during the warm spring-summer months, which could allow mould growth and decay.

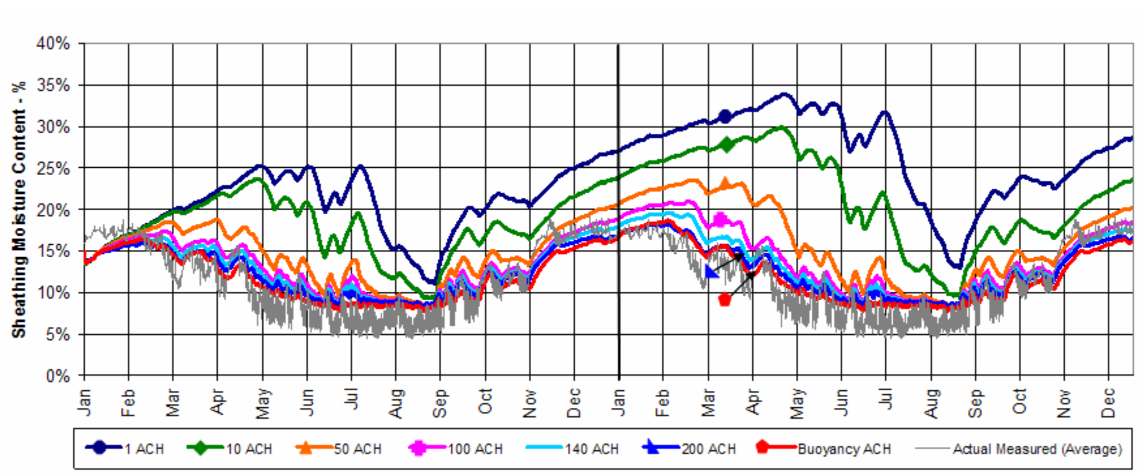


Figure 5: Effect of Cladding Ventilation on Moisture Content of Sheathing.

The use of the calculated ventilation rate for buoyancy only results in a close fit to the data. Higher ventilation flow rates likely occur in the field because of the flow induced by wind. Using a fixed (or annual average, (140 ACH in the case of Building 2) ventilation rate can predict field performance with reasonable accuracy and captures the trends of the sheathing moisture content. For these simulations the annual average rate is sufficient for most modeling purposes. Obviously using the actual hourly ventilation rate is more accurate; however it may not be worth the extra effort.

For the results shown above, the buoyancy pressures were calculated using the measured cavity temperature and RH. Without these field measurements, one can estimate the hourly ventilation rate iteratively by trial and error using the following method: 1. calculate the flow versus pressure relationship for the wall assembly and venting arrangement you wish to model, 2. choose an annual ventilation rate and run model, 3. export predicted hourly cavity temperature and RH, 4. calculate thermal/buoyancy and wind pressures to predict a new hourly ventilation rate, 5. run model with new calculated hourly ventilation rate, 6. compare cavity T/RH with previous, 8. repeat until T/RH from previous case is close enough to previous case. In experience convergence occurs within one or two iterations.

Future software versions could automate this iterative and time consuming process. Users could input the wall cavity and vent dimensions and details, and the software could apply the relationships and automatically determine the cladding ventilation based on wind and thermal/moisture buoyancy pressures.

Validation of Approach with Measured Field Data – Wood-frame Walls

The source and sink approach was applied to the stucco-clad wall of Building 2 the vinyl cladding of Building 1 and cement-board/brick clad wall of Building 4.

Three models were set up for each of the three rainscreen clad buildings (1, 2 & 4). Material properties were selected from the North American WUFI 4.1 database according to the wall construction. Ventilation was added to the airspace behind the cladding using the hourly calculated buoyancy flows determined in Chapter 2. Measured boundary conditions were input into the model using a TRY file for the exterior conditions and KLI file for the interior conditions. Solar radiation in the TRY file was calculated using the methodology described in *Appendix H: Solar Radiation Measurements and Calculations*. Driving rain was determined in the WUFI model using RDF and exposure factors for each building as discussed in Chapter 5.

It was necessary to add a small amount of moisture storage (about 0.7 kg/m^2 at saturation) to account for the liquid water that can be stored in the tracks of the vinyl cladding (Building 1). If this amount of storage is not added the relative humidity within the ventilated cavity and sheathing moisture content is under-predicted in the model.

The ability of the hygrothermal model to predict the moisture content of the plywood sheathing is shown for Building 1 for a year from January 1st 2002 and in detail from October to November during the wetting season (Figure 6).

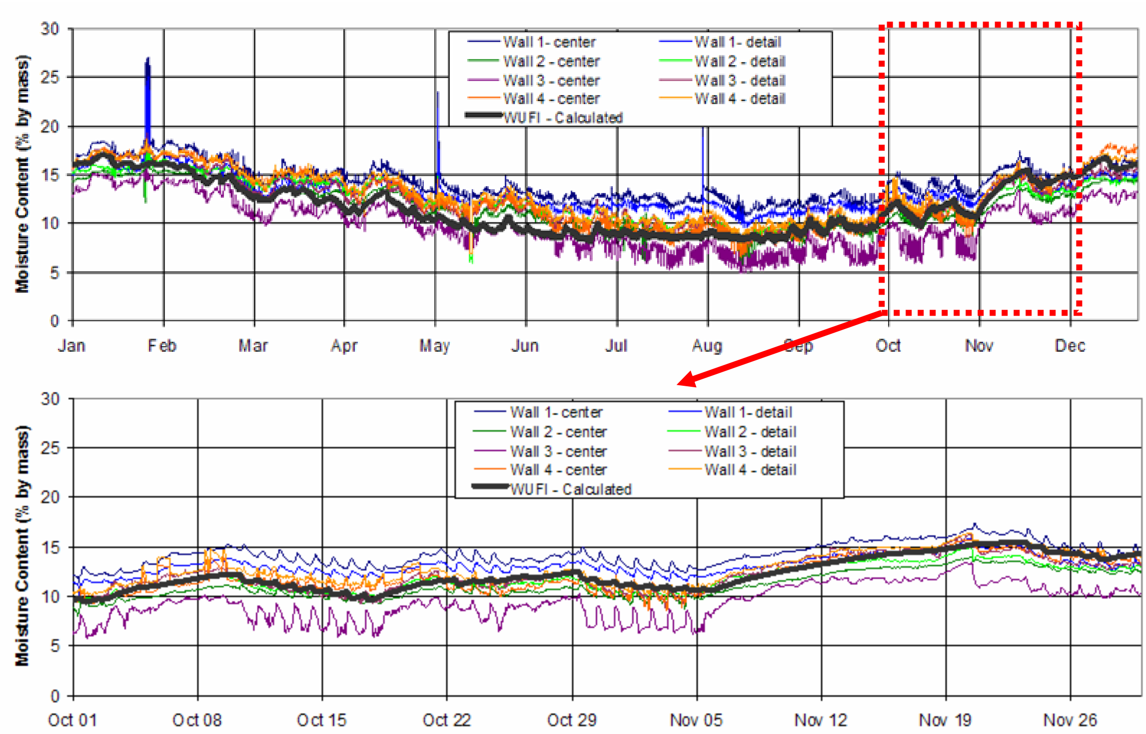
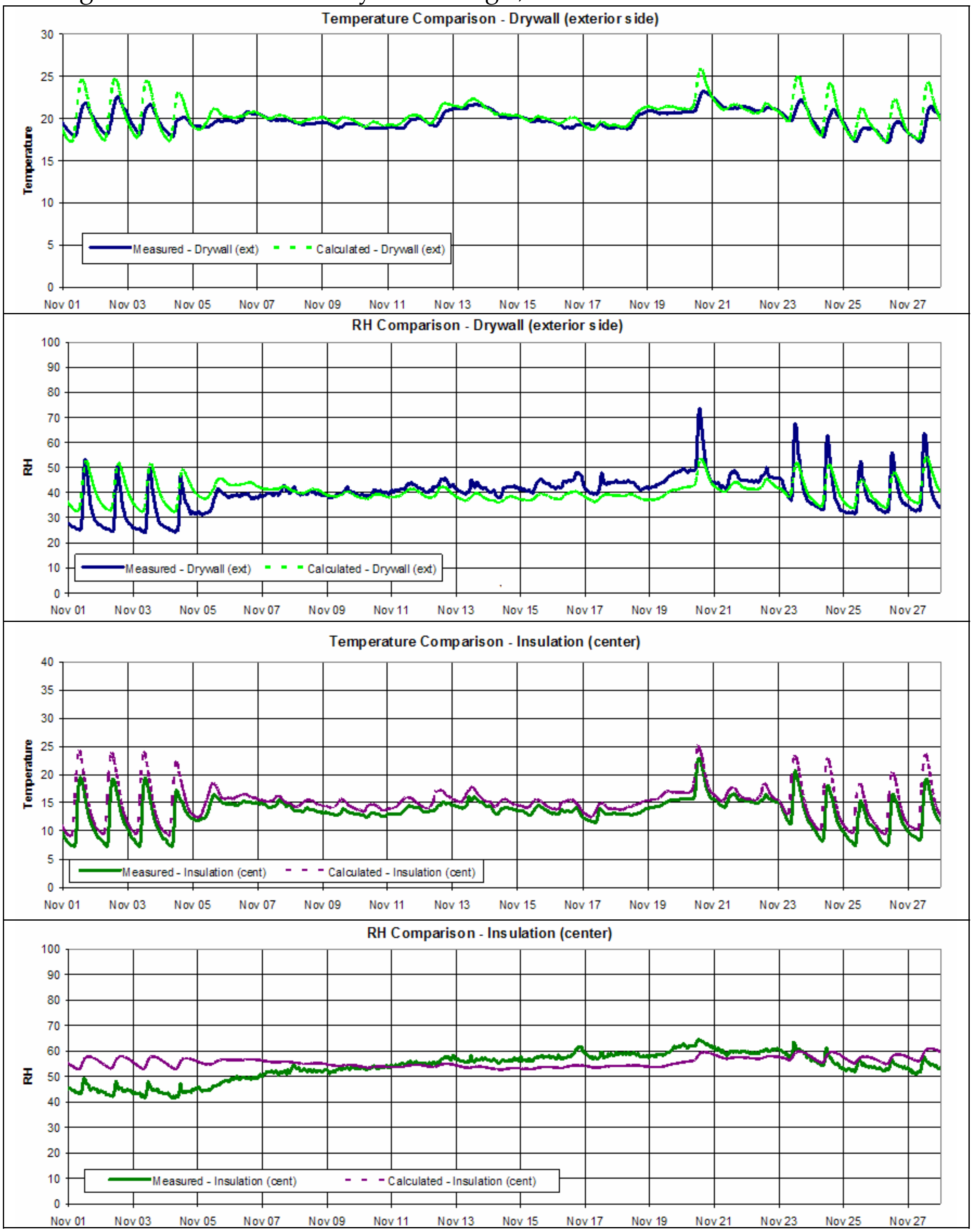


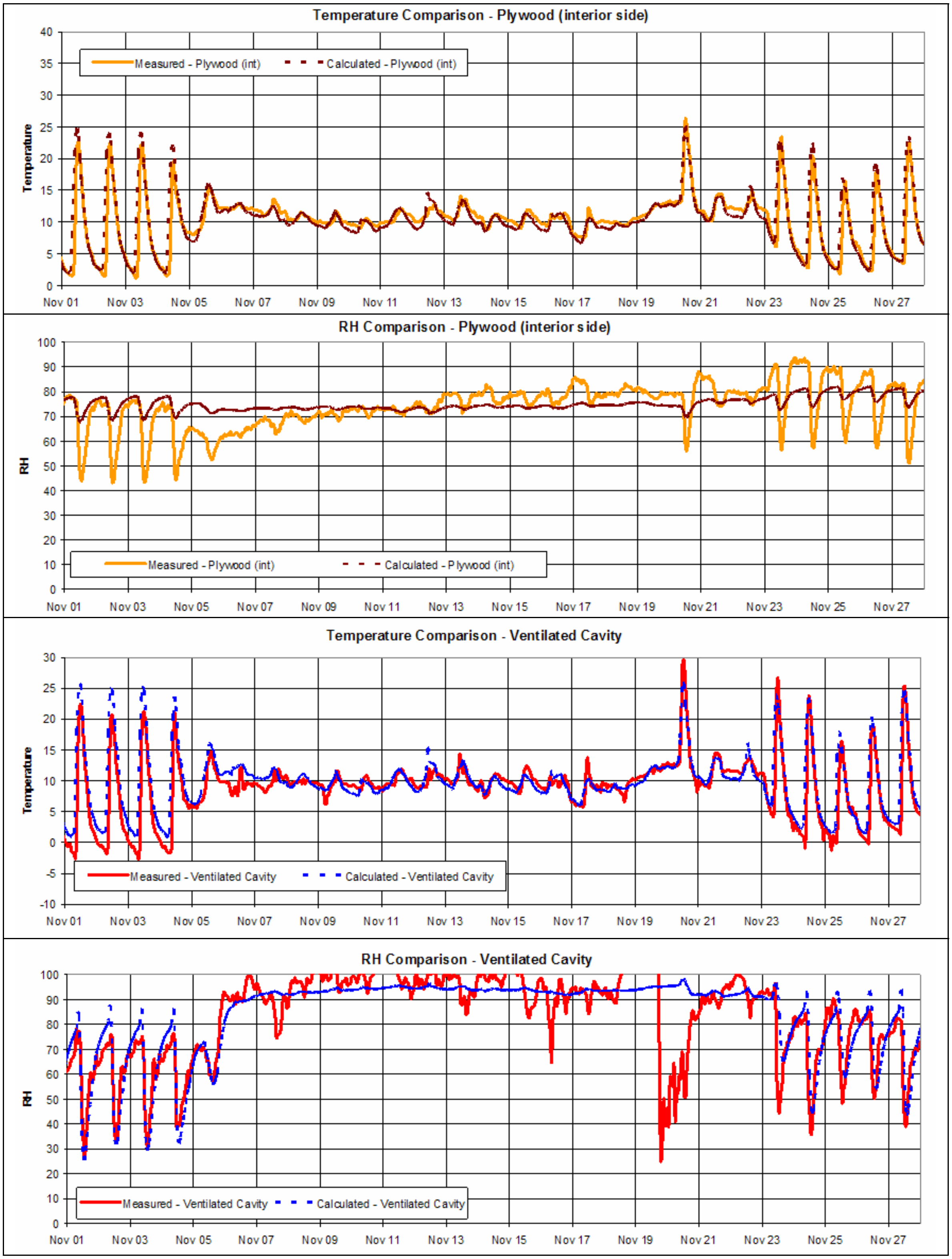
Figure 6: Comparison of WUFI Predicted to Measured Moisture Content

A relatively large scatter exists in the measured data; however the trends are consistent and captured accurately by WUFI and represent average conditions.

Other parameters including temperature, relative humidity, and dewpoint temperature are presented in Table 1 comparing the calculated WUFI values with the measured field data. Data is presented for one month from November 2002, for clarity, however similar correlations were observed over the entire year. Data from the two other buildings and models showed similar agreement.

Table 1: Comparison of WUFI to Measured Temperature, RH and Dewpoint throughout the Wall Assembly – Building 1, November 2002.




Temperature Comparison - Plywood (interior side)
Temperature
Measured - Plywood (int)
Calculated - Plywood (int)
0
5
10
15
20
25
30
35
40
Nov 01
Nov 03
Nov 05
Nov 07
Nov 09
Nov 11
Nov 13
Nov 15
Nov 17
Nov 19
Nov 21
Nov 23
Nov 25
Nov 27
RH Comparison - Plywood (interior side)
RH
Measured - Plywood (int)
Calculated - Plywood (int)
0
10
20
30
40
50
60
70
80
90
100
Nov 01
Nov 03
Nov 05
Nov 07
Nov 09
Nov 11
Nov 13
Nov 15
Nov 17
Nov 19
Nov 21
Nov 23
Nov 25
Nov 27
Temperature Comparison - Ventilated Cavity
Temperature
Measured - Ventilated Cavity
Calculated - Ventilated Cavity
-10
-5
0
5
10
15
20
25
30
Nov 01
Nov 03
Nov 05
Nov 07
Nov 09
Nov 11
Nov 13
Nov 15
Nov 17
Nov 19
Nov 21
Nov 23
Nov 25
Nov 27
RH Comparison - Ventilated Cavity
RH
Measured - Ventilated Cavity
Calculated - Ventilated Cavity
0
10
20
30
40
50
60
70
80
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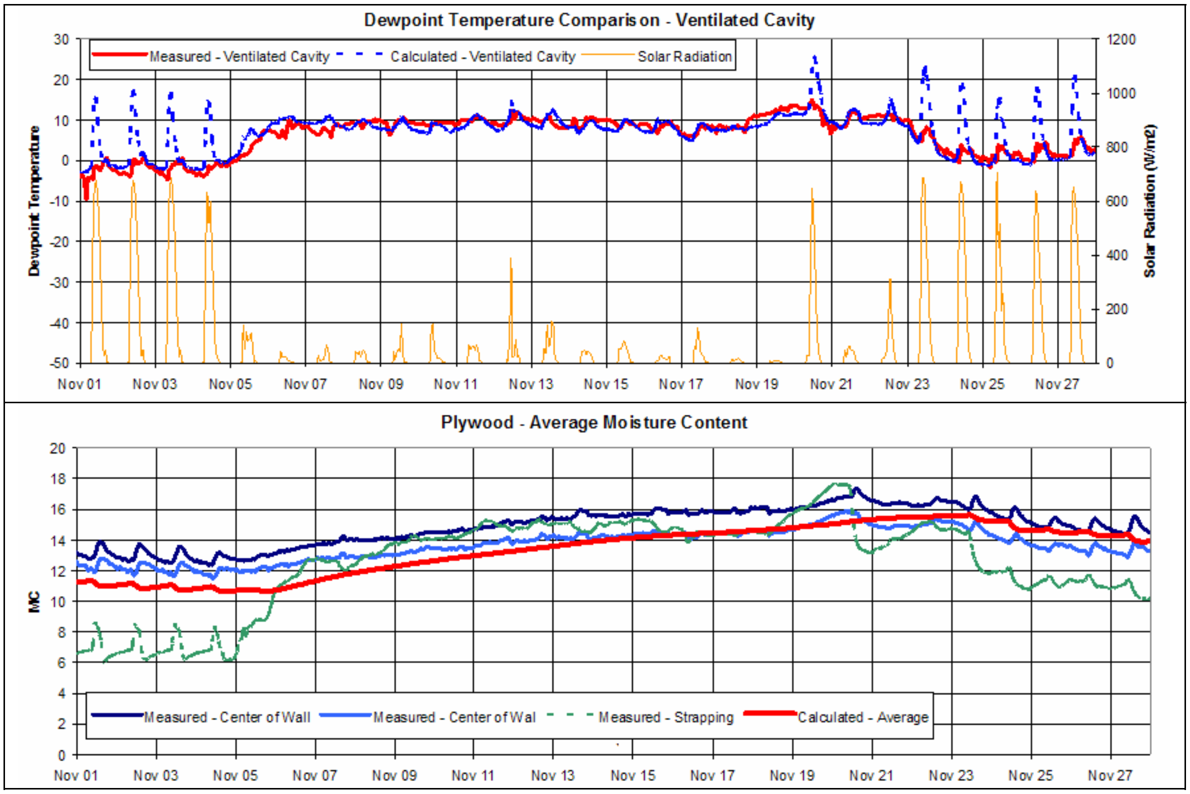

As shown the temperature and humidity profile through the wall predicted by WUFI closely represents the measured field conditions. The peaks or low points are not always captured but general agreement between trends is observed for the majority of the time. Differences between the measured and WUFI model are typically greatest at peaks under influence of direct solar radiation, where WUFI tends to predict drier or hotter conditions than are being recorded in the field.

Differences in sensor readings can also be accounted for by two-dimensional thermal effects or the location of the actual sensor in the field in relation to that represented in the model (i.e. sensor at middle of batt insulation may not be exactly half way through the insulation as assumed in the model). The effects of solar radiation may also be reduced in the field as a result of shading (from roof overhangs, balconies, adjacent buildings), and not captured in the model. On days with only diffuse radiation (i.e. November 7-19), the model correlation was most accurate.

Material properties also have an impact on the modeling accuracy. Results shown above are for "first-run" type simulations where materials from the WUFI database were used (with the exception of vinyl siding and cement board, which was modified to provide additional moisture storage to more accurately reflect measured results). Solar short-wave absorptivity and long-wave emissivity of the cladding were assumed based on published literature for common materials, and have an impact on the cladding surface temperatures and subsequently the rest of the wall.

As the sheathing moisture content is one of the critical performance measures different plywood sheathings were modeled and compared under the same boundary conditions (from German Fraunhofer-IBP, Generic North American, and Norwegian NTNU databases) and presented in Figure 6. The sorption isotherm for each of the plywoods is slightly different therefore for the same relative humidities at the material, different moisture contents will result.

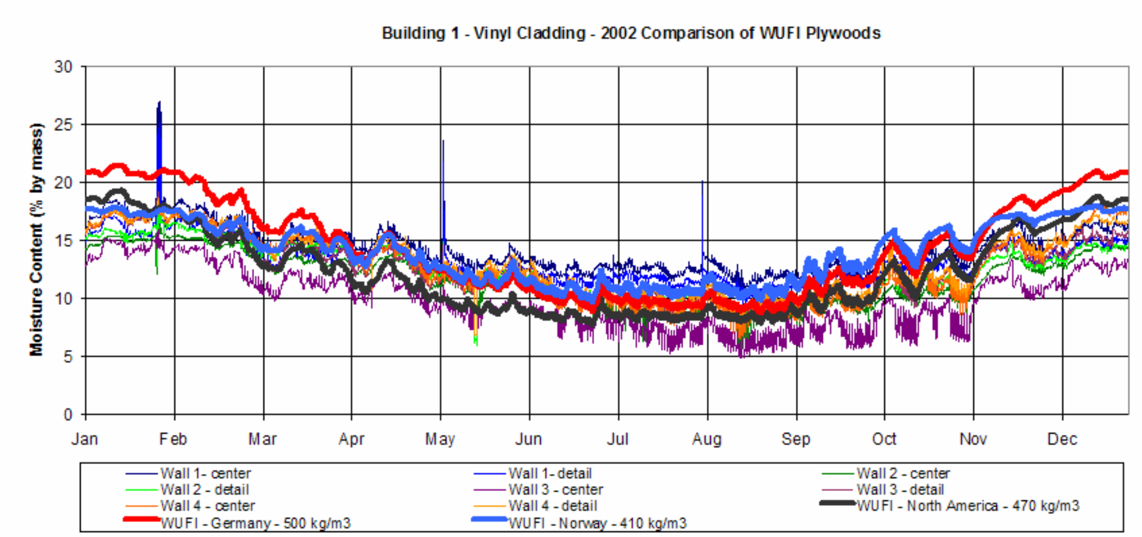

Figure 7: Comparison of Different Plywood Material Properties.

As shown up to a 4% difference in the calculated moisture content was observed between the different plywoods when similar boundary conditions were applied. Wood is a natural material and the sorption isotherm for each type of plywood is slightly different therefore a range of moisture contents were observed in the field when exposed to similar boundary conditions.

Validation with Building 3 Data

A model was set-up for the building 3 wall assembly. Material properties were selected from the North American WUFI 4.1 database according to the wall construction. Ventilation was added to the airspace behind the cladding using the hourly calculated buoyancy flows determined in Chapter 2. Measured boundary conditions were input into the model using a TRY file for the exterior conditions and KLI file for the interior conditions. Solar radiation in the TRY file was calculated using the methodology described in *Appendix H: Solar Radiation Measurements and Calculations*. Driving rain was determined in the WUFI model using RDF and exposure factors for the building as discussed in Chapter 5.

For this wall assembly, cladding ventilation was observed to have negligible impact on the performance on the materials inboard of the exterior insulation and impermeable air/vapour/moisture membrane outside of the gypsum sheathing. Therefore WUFI 3.3 and 4.0 (without source-sink terms) were both able to predict the performance for this assembly as well as the more advanced version 4.1.

The output from WUFI 4.1 is compared to the measured field results. Figure 8 plots the RH at the interior face of the exterior sheathing and Figure 9 plots the gypsum moisture content for the eight field wall cavities for the one year period from July 1st 2002 to 2003. The temperature at the gypsum sheathing is further plotted in Figure 10.

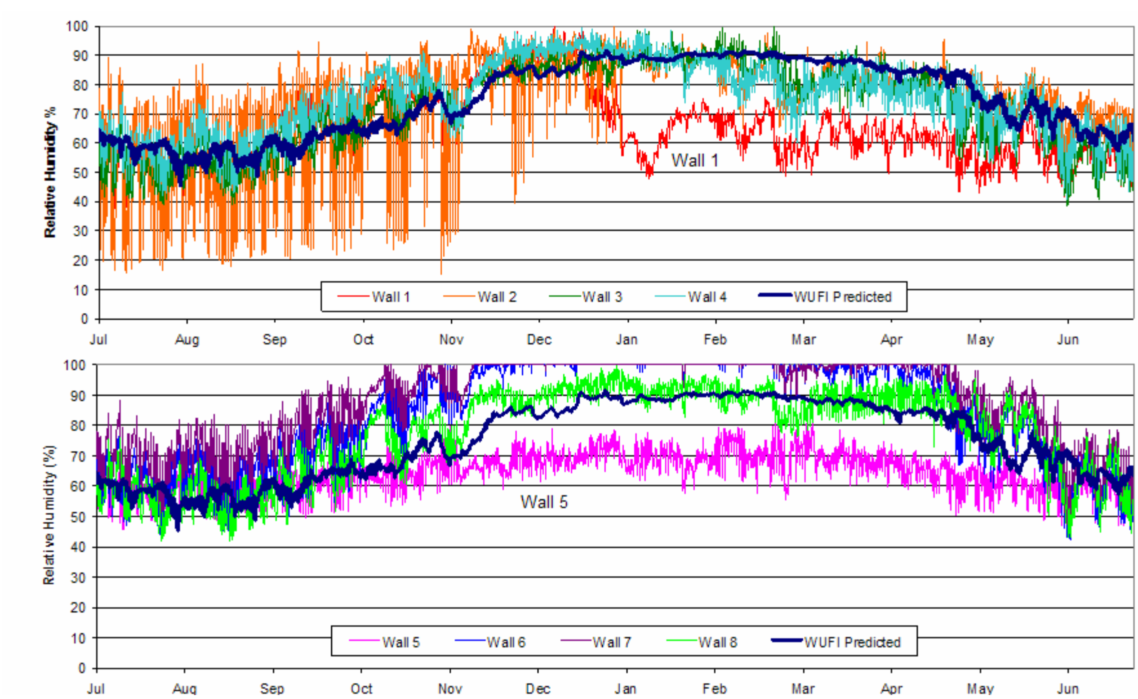

Figure 8: Comparison of RH at interior face of sheathing – Walls 1-8 compared to WUFI.

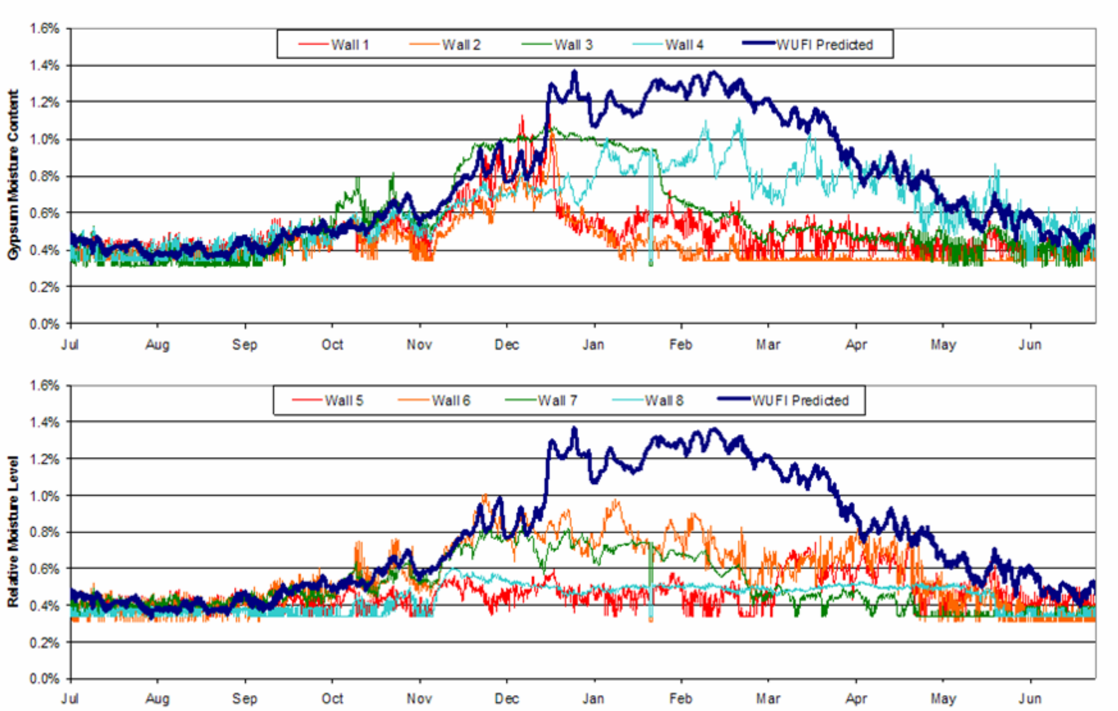

Figure 9: Comparison of Gypsum Moisture Content – Walls 1-8 compared to WUFI.

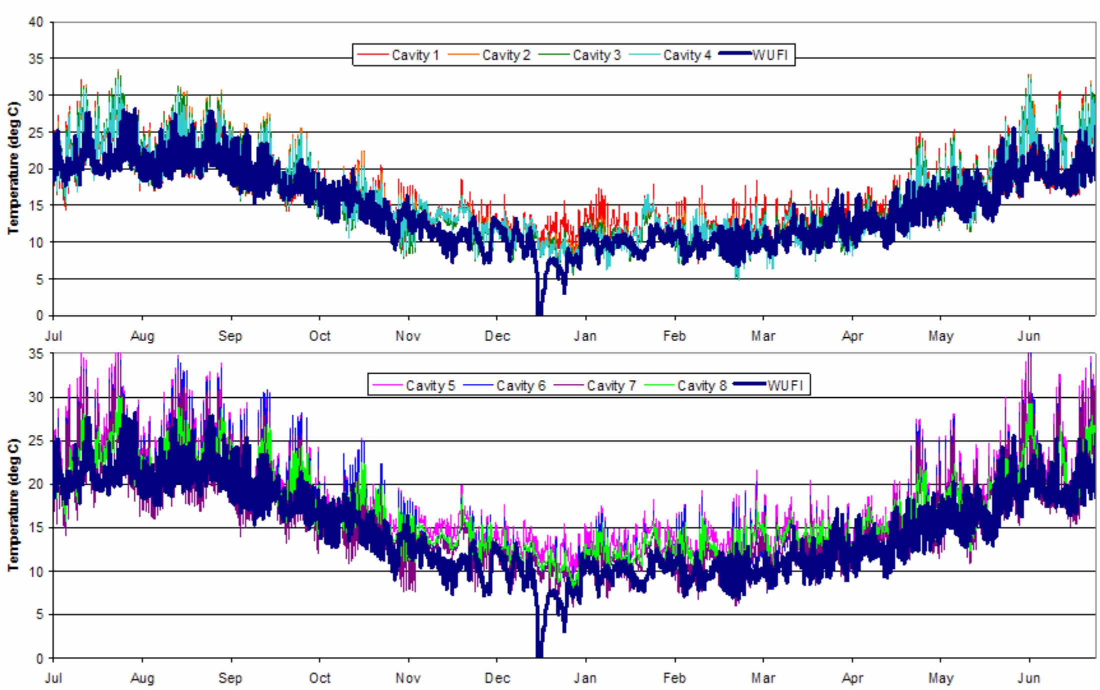

Figure 10: Comparison of Gypsum Temperature – Walls 1-8 compared to WUFI

From the results, it is shown that WUFI is able to model the observed field results for all eight walls with varying accuracy at predicting the absolute wetness. Temperature anomalies and variations between assemblies were evident which impacted the temperature of the sheathing, and thus RH and condensation at the surface. Walls 1 and 5, at the dryer vents showed lower than expected readings than WUFI; this is expected as these vents modified the thermal conditions. It should be noted that walls 3 and 8, located below windows compare closest to the WUFI model. The 3rd floor walls also compare closer to the WUFI results than the 6th floor, which were much wetter.

Similar trends were observed across the eight walls; however the absolute values were different. The sensors were located at different details (below window, near base of wall, or below vent at top of wall), and thus subject to interior temperature conditions. As shown in Chapter 9, the interior conditions had the greatest impact on the results; therefore if the interior temperature profile were modified (say at a colder corner compared to the center of the wall) the conditions within the wall assembly would also be different. As furniture or other interior items were sometimes placed at the monitored wall locations, differences in the measured results are expected.

The exterior sheathing relative moisture level and RH readings are generally higher on the 5th and 6th floors than the 2nd and 3rd floor walls. The neutral pressure plane for the building is near the 4th floor slab. Theoretically stack effect pressures during cold weather should be drawing outdoor air inward on the 2nd and 3rd floors and pushing indoor air outward at the 5th and 6th floor levels. If air leakage occurs through the monitored cavities, one would expect slightly higher RH in the upper floors, and slight lower RH in the lower floors.

The remaining differences between the field and simulated data could be from any number of potential sources, including:

- Air leakage is not accounted for in the WUFI model. Air leakage through electrical outlets, penetrations, and the base of wall will also increase the volume of air flow in the wall cavity and thus a higher risk of condensation. Air leakage condensation would result more frequently at colder sheathing locations than warm locations.
- Outward air leakage could be occurring and causing the higher relative humidities observed in the 5th and 6th floor wall cavities.
- The effect of thermal bridging is not modeled in WUFI 1D. The steel studs in the stud cavity and Z-girts in the strapping cavity are bridging the

insulation and resulting in different temperatures at the sheathing. This is particularly evident in Figure 10. Warmer temperatures result in drier conditions and cooler temperatures result in wetter conditions.

Validation with Building 5 Data

A model was set-up for the building 5 stucco rainscreen wall assembly. Material properties were selected from the North American WUFI 4.1 database according to the wall construction. Ventilation was added to the airspace behind the cladding using the hourly calculated buoyancy flows determined in Chapter 2. Measured boundary conditions were input into the model using a TRY file for the exterior conditions and KLI file for the interior conditions. Solar radiation in the TRY file was calculated using the methodology described in *Appendix H: Solar Radiation Measurements and Calculations*. Driving rain was determined in the WUFI model using RDF and exposure factors for the building as discussed in Chapter 5.

For this wall assembly, cladding ventilation was observed to have negligible impact on the performance on the materials inboard of the exterior insulation and impermeable air/vapour/moisture membrane outside of the gypsum sheathing.

The moisture sensitive components of this assembly are the gypsum sheathing and stud cavity. The relative humidity within the stud cavity and at the gypsum surface is used as a measure of the wall performance. The measured versus calculated RH within the stud cavity is shown in Figure 11 for monitored wall 5, at suite 3005. The corresponding gypsum moisture content is shown in Figure 12

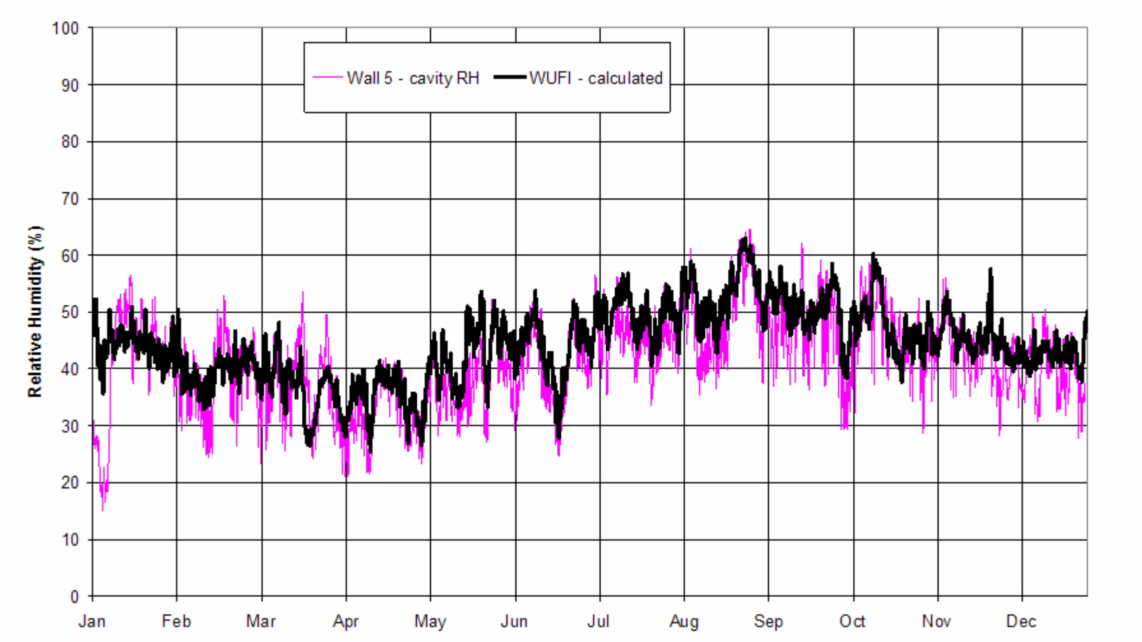

Figure 11: Measured RH within Stud Cavity compared to WUFI

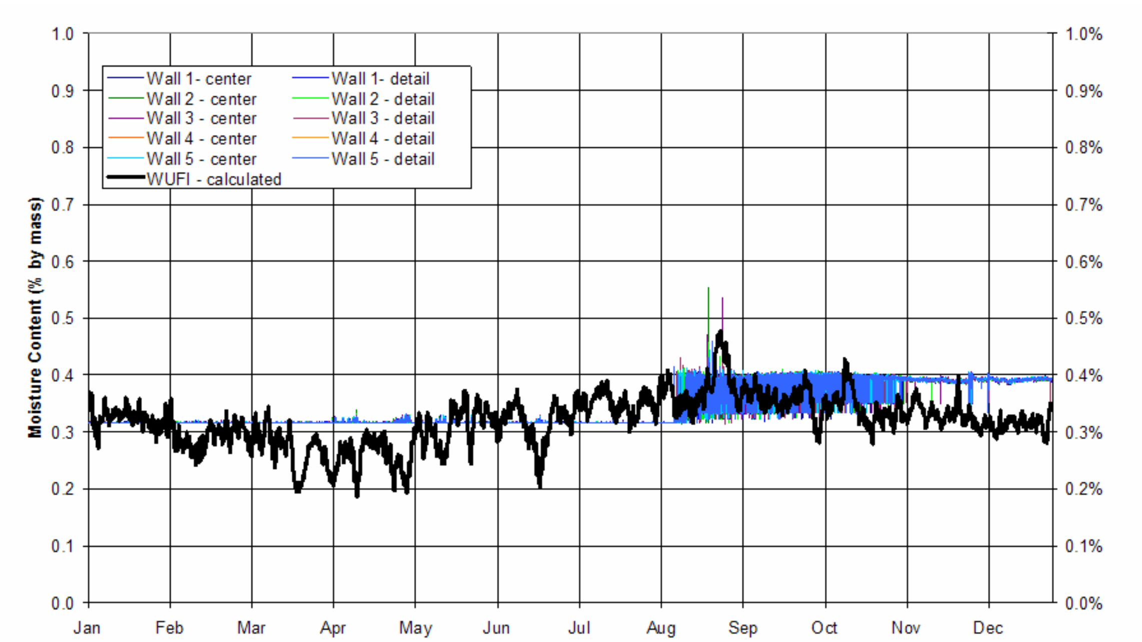

Figure 12: Measured Gypsum MC compared to WUFI.

As shown, the hygrothermal model is able to model the trends captured at wall 5. The gypsum moisture content is calculated from the recorded electrical resistance readings using the correlation in Appendix A, and has a lower limit of 0.32% MC which corresponds with 1 GΩ the maximum value recorded by the data logger. Therefore moisture readings below 0.32% were not recorded, where according the WUFI model, the sheathing spent the majority of time.

The one small spike in RH in late August corresponds with the jump in moisture content, as electrical resistances dropped below 1 GΩ.

Similar correlation was observed at walls 1-4 (at suite 506). Walls 6-8 are insulated metal spandrel panel assemblies, and were not modeled. As discussed in Chapter 9, the relative humidity at the sheathing closely follows the interior relative humidity, separated only by painted gypsum drywall.

Conclusions

It was shown that older and some current one-dimensional hygrothermal software programs have a limited ability to model the wetting and drying of walls with ventilated rainscreen claddings. Modeling "tweaks" were found to be limited in their accuracy for some ventilated cladding scenarios and either grossly overestimated or underestimated the response of the wall assembly to the applied boundary conditions. The new version of one-dimensional WUFI 4.1 which can model heat and moisture "sources and sinks" within wall assemblies can overcome many of the limitations of using 1-D models. This hygrothermal model was validated with measured field data from three wood-frame and two steel-stud/gypsum frame buildings.

Results from the new model highlight the importance of cladding ventilation for the interior insulated wood-frame wall assemblies. When hourly or annual average cladding ventilation rates are calculated using the theory outlined and ventilation modeled as a source/sink, the correlation between the field measured and modeled results is excellent.

Recommendations

The hygrothermal model could be updated to calculate flow versus pressure relationships for user defined wall assemblies and vent configurations. The hourly ventilation flow rates could then be determined by the software based on thermal and moisture buoyancy and wind pressures.

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Appendix C: Maximum Drying Potential Model

APPENDIX C:
SIMPLIFIED DRYING POTENTIAL MODEL

SUMMARY

The potential for exterior walls to dry in such coastal locations as Vancouver, BC is generally assumed to be relatively low because of the wet and temperate climate. The leaky condo crisis is often attributed to this lack of drying potential.

Most of the work in recent years to remediate the exterior walls of buildings has focused on preventing the penetration of rain water by the use of water resistant and often vapour impermeable membranes. However, experience has shown that moisture can still enter the building enclosure because of rain water leakage through small flaws, vapour diffusion (from the interior or rain wetted cladding) or air leakage (from humid interiors), or be built in during construction. Hence, the role of drying may still be important, and some material and assembly choices are provide less drying than others.

A model was developed to assess the drying potential for any wall assembly in any given location. The model uses monthly mean or more accurately hourly mean weather data for a given location. Interior data is assumed or calculated based on typical conditions for comfort. From the environmental conditions, net vapour pressure drives and a maximum net drying potential for a given wall assembly can be determined for a desired time period.

From the model a number of widely known facts regarding drying potentials are quantified. Exterior insulated walls in Vancouver's climate will always have a net annual drying rate higher than interior insulated walls. Walls which are not insulated will also dry faster than interior insulated walls. As the Interior relative humidity increases, the vapour pressure driving force and maximum drying potential is reduced. Ventilation is required to maintain indoor relative humidities to reasonable levels.

The south elevation has the highest drying potential; the North elevation has the lowest. The East and West elevations have similar drying potentials. Dark colored walls can increase the drying rate by up to 30% over light colored walls (solar absorptance of 0.9 for dark and 0.4 for light).

The drying potential for walls constructed during the 1980's and 1990's was significantly lower than that of the previous decades based on typical wall assemblies. This reduction in maximum potential drying could have contributed to the leaky condo crisis which includes buildings constructed in the 1980's and 1990's.

Currently most walls constructed today are being produced with materials and practice similar to those from the 1990's. These walls have a very low drying potential, which can

be improved by better material choice and configuration. Modern walls which are exterior insulated and use vapour semi-permeable materials throughout the wall assembly can achieve drying rates previously seen in the 1930's to 70's. At the same time these new modern walls will also be more energy efficient.

SIMPLIFIED DRYING POTENTIAL MODEL

1 INTRODUCTION

The potential for exterior walls to dry in such coastal locations as Vancouver, BC is generally assumed to be relatively low because of the wet and temperate climate. The leaky condo crisis is often attributed to this lack of drying potential.

Most of the work in recent years to remediate the exterior walls of buildings has focused on preventing the penetration of rain water by the use of water resistant and often vapour impermeable membranes. However, experience has shown that moisture can still enter the building enclosure because of rain water leakage through small flaws, vapour diffusion (from the interior or rain wetted cladding) or air leakage (from humid interiors), or be built in during construction. Hence, the role of drying may still be important, and some material and assembly choices are provide less drying than others.

The drying potential of a wall is a variable of the material variables, mainly the thermal resistance and vapour permeance and where they are situated in relation to the moisture sensitive materials.

Knowledge of potential drying forces and where they act from (interior or exterior) is therefore critical in the design of wall assemblies and to allow for seasonal storage from wetting events and to maximize drying potential should moisture enter the wall assembly at some future time.

A model was developed to assess the drying potential for any wall assembly in any given location. The model uses monthly mean or more accurately hourly mean weather data (Temperature, Relative Humidity, Solar Radiation) for a given location. Interior data can be assumed based on typical conditions observed in the Canadian climate. From the environmental conditions, net vapour pressure drives and a maximum net drying potential for a given wall assembly can be determined for a desired time period.

The maximum vapour diffusion wetting and drying potential is examined for a number of typical residential wall assemblies from the past 100 years in Vancouver's coastal climate. The ability for wall assemblies from the 1980's and 1990's to dry is analyzed as a possible contributor to the leaky condo crisis.

1.1 Objectives

The objective of this study was to review typical wall assemblies in Vancouver's climate from the past century and to determine the drying potential for such walls. Since the 1980's a significant number of exterior walls have failed catastrophically as a result of accumulated moisture, while at the same time several building code changes were made and new materials introduced that impacted construction practice.

Moisture problems have been well documented in the exterior walls of buildings and extend beyond Vancouver's coastal climate to other parts of North America as well. In the moisture failures observed through the 1980s and 1990s the wetting forces whether by air leakage condensation or rain penetration were greater than the diffusive or convective drying forces. An attempt to explain these moisture failures in terms of drying potential is made.

It is widely regarded that prior to the widespread use of insulation and vapour barriers, drying forces were greater and less moisture damage was typically observed under normal conditions. While the widespread use of insulation materials in exterior walls and roofs was pushed by government agencies in the 1970's and 80's in attempts to reduce energy consumption after the oil crisis of 1973, such trends had significant impact on the performance of walls from both energy and moisture standpoints. While the reduction in energy consumption is important from both a consumer and global standpoint, this should not come at the cost of wet and deteriorated walls. Proper placement of thermal and vapour resistive layers is critical to achieve both. Energy code standards will continue to increase the minimum allowable thermal resistance for walls as society drives towards reducing energy consumption and a more sustainable environment. Recommendations as to the best placement of insulation and vapour retarding layers are made. Typical uninsulated historical walls are compared to new modern walls.

The model will allow architects and engineers to better design wall assemblies and utilize available materials to maximize the drying potential in their given climate.

1.2 Scope and Limitations

While the developed model focuses on diffusion drying only, other drying mechanisms including convective transport (air leakage) and capillary transport will act within and around a material to redistribute moisture. Convective air transport can be accounted for by using effective permeance values for materials separated by intentional (ventilation cavities) or accidental (air leakage paths). Wet cup or inverted wet cup vapour permeance values were used when available which account for capillary transport within the material.

The model provides a simple analysis tool to analyze diffusion drying potentials. The model allows simultaneous comparison of different wall assemblies during the design phase and to compare such effects of interior environment, orientation, solar absorptance, and the degree of saturation. Since the model provides only the driving force in terms of vapour pressures and maximum drying or wetting potential in terms of vapour flow per unit area its use as a full design tool is limited.

This report focuses primarily on typical residential wall assemblies, the same model can also be applied to any other type of wall. The model can also be applied to roofs and below grade assemblies.

2 METHODOLOGY

2.1 Schematic and Model Setup

A simple model was developed to assess the drying potential for any type of wall assembly located in any climate.

In an ideal wall, if air leakage or rain water penetration is eliminated, the wetting and subsequent drying occurs by vapour diffusion. Vapour diffusion is driven by the difference in vapour concentration from high to low concentration of water vapour molecules.

The drying potential is determined based on the difference in vapour pressures from a wetted material within a wall assembly to the exterior and interior (drying out and drying in). The vapour pressure at the wetted material is dependant on the temperature at that location. It is assumed that the material be saturated, ie. 100% relative humidity and the vapour pressure is equal to the saturation vapour pressure, therefore the relationship is only temperature dependent. The material temperature is a simple function of the interior temperature, exterior surface temperature and thermal resistance of the wall inboard and outboard of the wetted material shown in equation 1.

$$T_{material} = T_{interior} - T_{exterior} * R_{in} / R_{total} \qquad \text{(Equation 1)}$$

Where R_{in} is the thermal resistance of the materials inboard of the wetted material.

It should be noted that in real conditions, as a result of drying, materials will rarely be saturated for at 100% RH all of the time, but at a lower relative humidity. A parametric analysis is performed on relative humidity conditions at the surface from 70% to 100%. Lower relative humidity levels at the surface i.e. 80% result in a reduction of the drying potential by a factor of 0.8. Therefore the maximum drying potential for a saturated material in a wall is calculated based on 100% RH or saturation and in the model this is used for comparative purposes.

In wood and wood based products 100% RH corresponds to 25-30% moisture content by weight, and at levels which will support mould growth and decay. Higher moisture levels can be achieved by capillary saturation. The isotherm for wood (taken from the US FPL Wood Handbook [1999]) at different temperatures is plotted in Figure 1.

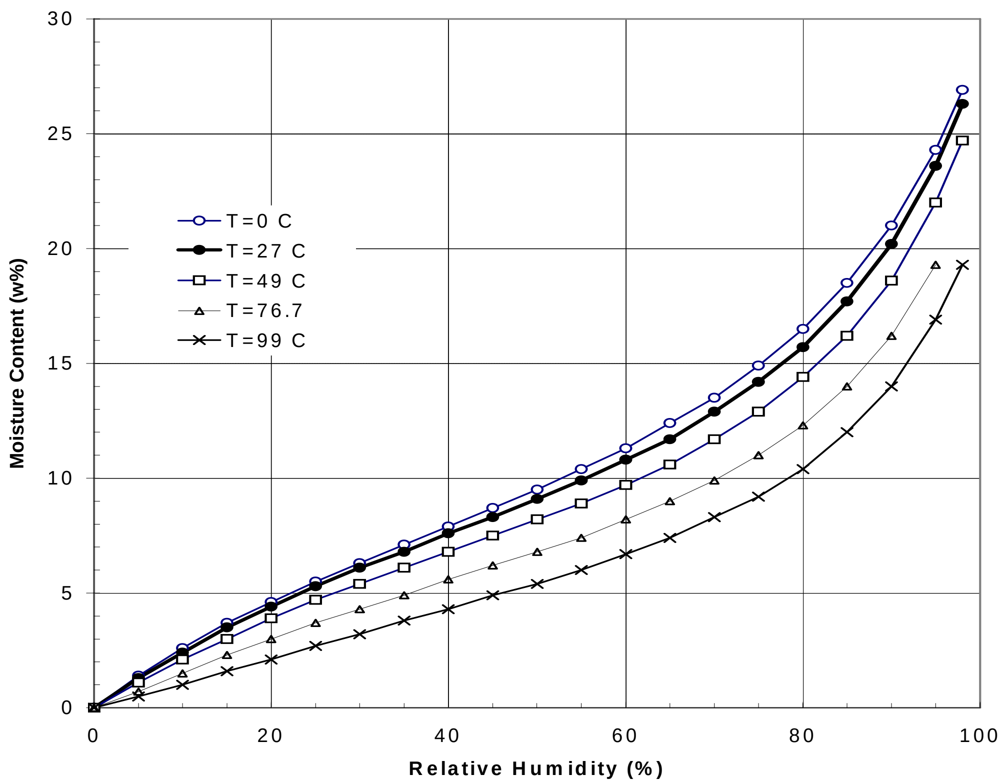


Figure 1: Average sorption isotherm for wood as a function of temperature (FPL 1999)

In a typical wood frame wall assembly the sheathing material and studs are moisture sensitive and prolonged exposure to high moisture levels will lead to mould and decay. In gypsum and steel stud walls, extended periods of moisture will lead to corrosion of fasteners and studs and deterioration of the gypsum. The exterior sheathing is usually the most moisture sensitive material in a stud wall assembly, the other being the studs. As seen in most moisture related wall failures, the exterior sheathing is the most severely deteriorated component, and is often used as an indicator of the wall condition. Wood stud and steel studs are also both affected by moisture, less uniform wetting than the sheathing however typically worse on the exterior face, where the temperature and thus vapour pressure conditions are similar to the sheathing.

Vapour pressures for the interior and exterior air can be calculated from the temperature and relative humidity. The model requires weather data (temperature, relative humidity, and solar radiation) for a given location. Interior values of temperature and relative humidity can be assumed based on typical seasonal conditions observed in the local climate. From the environmental conditions, vapour pressure differences can be determined.

A positive vapour pressure difference from the wetted material to the exterior or interior indicates drying will occur at a rate governed by the vapour resistance of the materials between the wet material and exterior. Figure 2 summarizes the approach followed by the model.

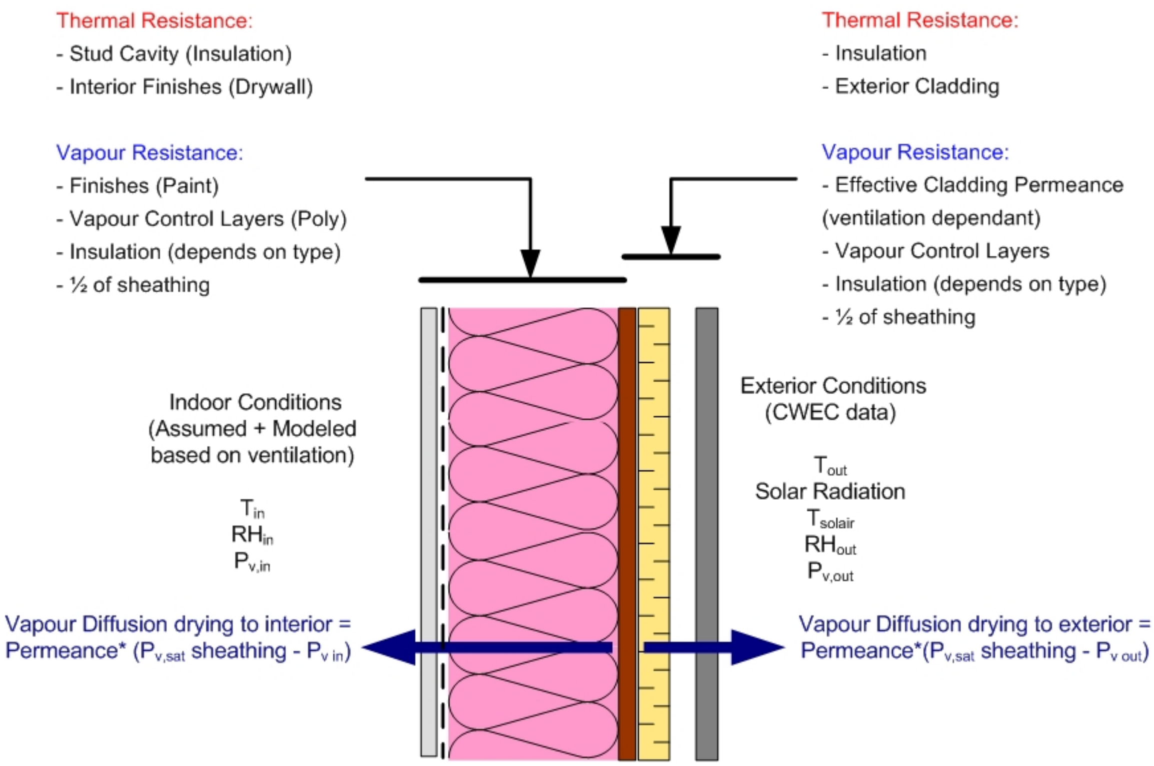


Figure 2: Model Wall Schematic

Only vapour diffusion was analyzed. Air leakage was not considered, however for the wetting and drying potentials noted, the inclusion of air leakage could be an order of magnitude different than the diffusion values. Air leakage condensation wetting or convective drying will act in the same direction as the vapour drive calculated. Air leakage can be accounted for using effective vapour permeance values and ventilation i.e. behind cladding is accounted for by use of effective permeance values.

2.2 Summary of Analysis

In summary, to develop the model the following steps were taken.

1. Extract exterior temperature and relative humidity data from CWEC weather files to determine exterior boundary conditions.
2. Extract the solar radiation data from CWEC weather files and convert to a vertical surface for a given orientation. Determine the sol-air surface temperature of the wall.
3. Assume or calculated interior temperature and relative humidity interior boundary conditions.
4. Determine the temperature and vapour pressure for the exterior sheathing assuming it is saturated.
5. Determine the vapour pressure difference between the exterior sheathing and interior (drying/wetting in) and difference between the exterior sheathing and exterior (drying/wetting out).
6. Sum the inward and outward pressures to get the total drying/wetting potential vapour pressure for each wall case.
7. Multiply the wetting/drying potential pressure inward and outward (Pa) by an assumed vapour permeance ($ng/Pa/s/m^2$) for the inward and outward portions of the wall to quantify the wetting and drying potentials in $g/s/m^2$. Multiply by the time period.
8. Repeat this analysis for multiple wall assemblies varying the insulation ratio and permeance of the wall materials.

Figure 3 shows a schematic of a generic wall assembly which summarizes the model analysis.

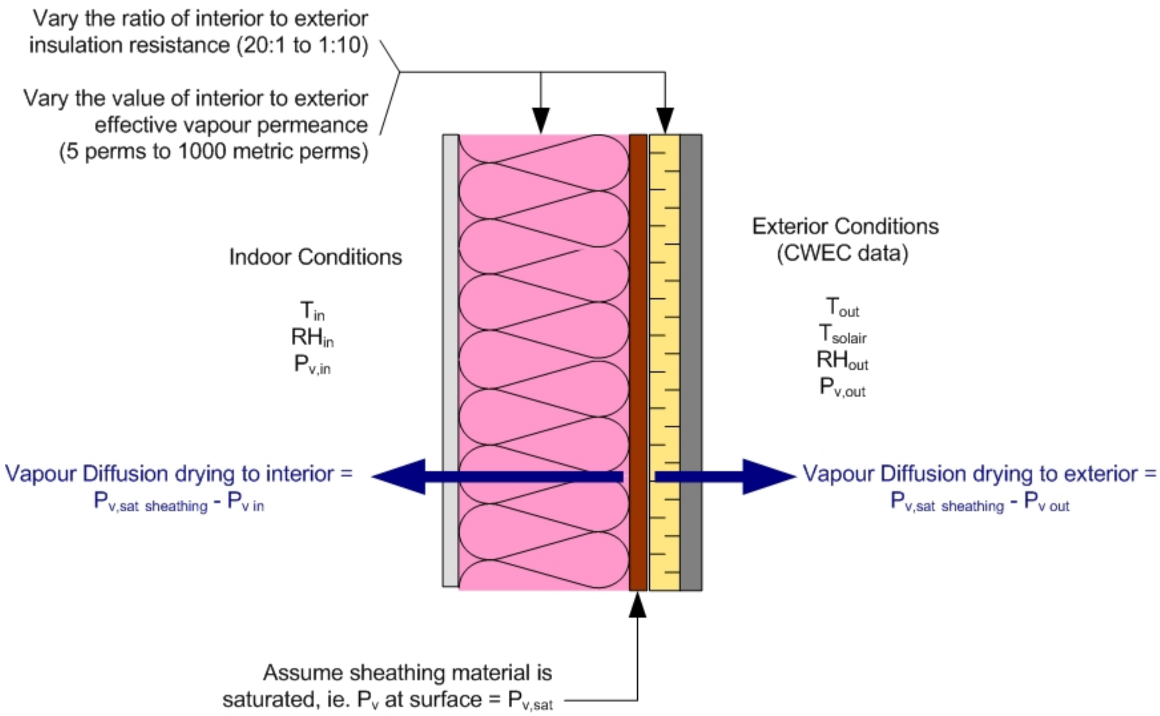


Figure 3: Model Wall Schematic Summary of Analysis

2.3 Environmental Data

The model was developed using annual hourly data (8760 hours) from CWEC weather files. As an attempt to simplify the model, monthly mean values were used to compare variables and determine the impact on results. A parametric analysis was performed and is discussed later on the accuracy of using monthly mean versus hourly values to simplify the analysis. Results from the hourly analysis are generally presented in this report; however monthly mean values were used for relative comparison.

2.3.1 Exterior Environmental Conditions

The model requires the use of readily available environmental data (temperature, relative humidity and solar radiation) for a given location. Historical Canadian climatic data is available from Environment Canada's Meteorological Centre web site (http://www.climate.weatheroffice.ec.gc.ca). Average weather data available from Environment Canada, also known as CWEC files (Canadian Weather Files for Energy Calculation) are available and are produced from average months in the past 30 years. CWEC files are representative of average conditions for a city and typically used for whole building energy simulations. This report uses CWEC data files for Vancouver with averages from the period of 1970-2000.

For below grade wall and floor assemblies, CWEC also provides mean monthly soil temperature values which could also be used with this model.

2.3.2 Interior Environmental Conditions

Interior temperature and relative humidity data can be assumed based on typical conditions for human comfort or can also be more accurately calculated using models which account for the exterior vapour pressure and ventilation rates. Three different indoor condition cases were analyzed.

1. Annual average conditions
    a. 21°C and 40% RH
    b. 21°C and 50% RH
    c. 21°C and 60% RH
    d. 21°C and 70% RH

2. Dynamic indoor conditions which approximate real seasonal conditions (sinusoidal relationship) cooler drier winter, warmer wetter summer conditions (Table 1)
    a. 20°C/30% RH winter 22°C/50% summer
    b. 20°C/35% RH winter 22°C/55% summer
    c. 20°C/40% RH winter 22°C/60% summer
    d. 20°C/45% RH winter 22°C/65% summer

Table 1: Dynamic Indoor Cases

	Interior Case A		**Interior Case B**		**Interior Case C**		**Interior Case D**	
Temp/RH	**21±1**	**40±10**	**21±1**	**45±10**	**21±1**	**50±10**	**21±1**	**55±10**
January	20.0	30.5	20.0	35.5	20.0	40.5	20.0	45.5
February	20.3	33.1	20.3	38.1	20.3	43.1	20.3	48.1
March	20.7	37.4	20.7	42.4	20.7	47.4	20.7	52.4
April	21.3	42.6	21.3	47.6	21.3	52.6	21.3	57.6
May	21.7	47.0	21.7	52.0	21.7	57.0	21.7	62.0
June	22.0	49.6	22.0	54.6	22.0	59.6	22.0	64.6
July	22.0	49.6	22.0	54.6	22.0	59.6	22.0	64.6
August	21.7	46.8	21.7	51.8	21.7	56.8	21.7	61.8
September	21.2	42.4	21.2	47.4	21.2	52.4	21.2	57.4
October	20.7	37.3	20.7	42.3	20.7	47.3	20.7	52.3
November	20.3	32.9	20.3	37.9	20.3	42.9	20.3	47.9
December	20.0	30.4	20.0	35.4	20.0	40.4	20.0	45.4
Annual	**21.0**	**40.0**	**21.0**	**45.0**	**21.0**	**50.0**	**21.0**	**55.0**

3. Assumed seasonal average temperature conditions (sinusoidal relationship) and relative humidity based on ventilation rate, moisture production, and exterior vapour pressure
   a. 5 ACH
   b. 3 ACH
   c. 1 ACH
   d. 0.5 ACH

The third relationship is based on a simple model to determine the interior vapour pressure knowing the exterior vapour pressure, moisture production rate, interior temperature, ventilation rate and volume of space (Straube 2005a). The model does not account for storage of moisture in hygrothermal materials which some more advanced indoor humidity models do.

$$P_{v,i} = P_{v,e} + (462*(t_i + 273) * G_w) / (n * V)$$

Equation 2

Where, $P_{v,i}$ and $P_{v,e}$ are the interior and exterior vapor pressures respectively (Pa),
G_w is the moisture production rate inside the space (kg/hr)
t_i is the interior temperature (°C)
n is the number of air changes per hour,
V is the volume of the space (m^3).

A sinusoidal temperature profile of 20°C in the winter (January 1st) and 24°C in the summer (July 1st) was assumed for typically accepted seasonal temperatures.

Figure 4 plots the relationship of the indoor relative humidity based on a ventilation rate and a moisture generation rate from 5 to 20 kg/day.

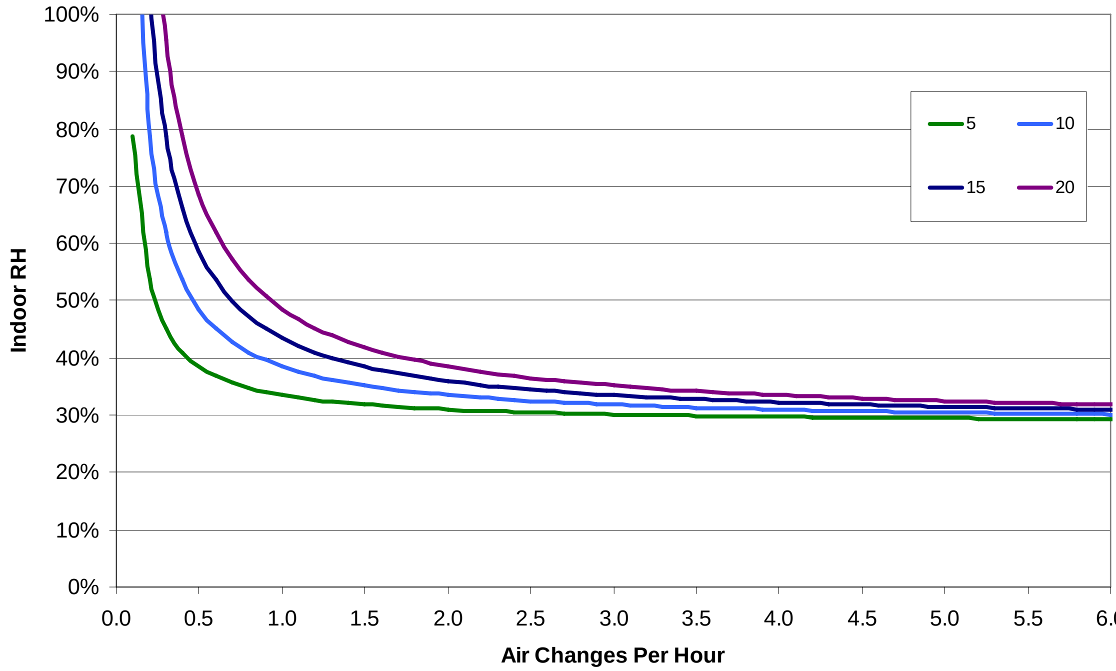


Figure 4: Indoor RH versus Ventilation for Average Vancouver Winter Conditions (4°C/87% RH)

This plot shows the importance of ventilation in achieving acceptable wintertime relative humidities for average conditions in Vancouver. Air-tight buildings <0.5 ACH will potentially suffer from high indoor relative humidities unless dehumidification is used based on this analysis.

Figure 5 shows the indoor RH and temperature for Vancouver based on a ventilation rate of 1 ACH.

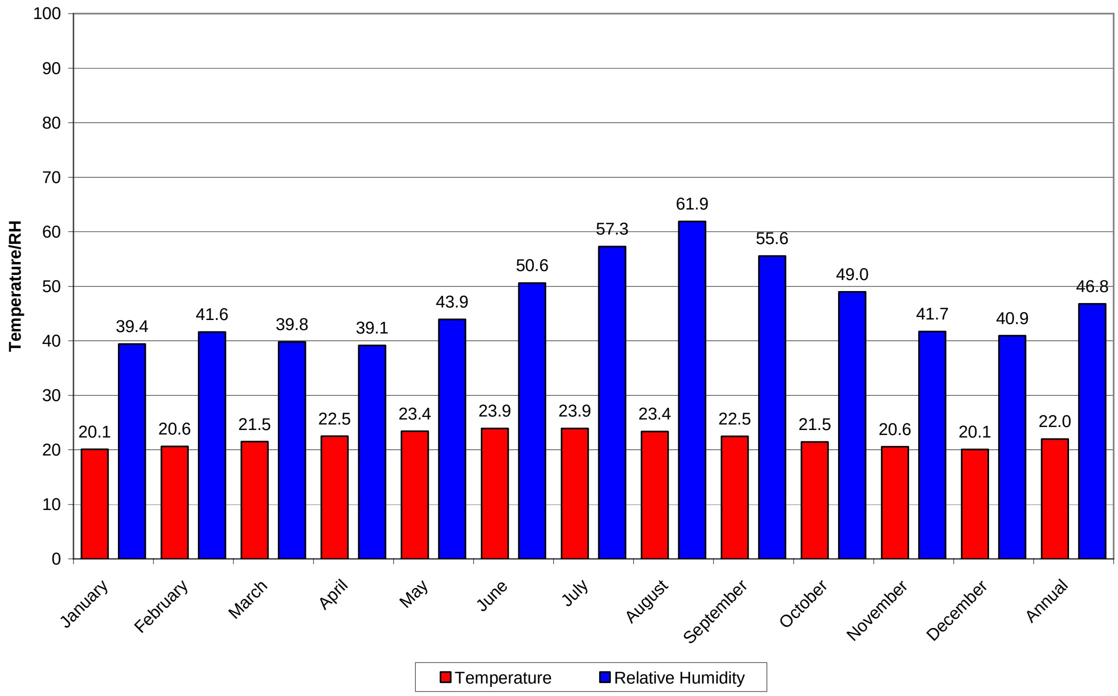


Figure 5: Indoor RH and T for Vancouver, ventilation at 1 ACH.

2.3.3 Vapour Pressures

The boundary conditions for this analysis consist of the interior and exterior vapour pressures. The saturation vapour pressure for air is a function the temperature and the vapour pressure is a simple function of the relative humidity as a proportion of the saturation vapour pressure. Saturation vapour pressure is calculated using formula 6.2 (5) and (6) in 2005 ASHRAE Book of Fundamentals and is shown in equation 3 below

If T >= 273.15

SatVP = Exp(-5800.2206 / T + 1.3914993 - 0.048640239 * T + 0.000041764768 * T ^ 2 - 0.000000014452093 * T ^ 3 + 6.5459673 * Logn(T))

If T < 273.15

SatVP = Exp(-5674.359 / T + 6.3925247 - 0.009677843 * T + 0.00000062215701 * T ^ 2 + 2.0747825E-09 * T ^ 3 - 9.484024E-13 * T ^ 4 + 4.1635019 * Logn(T))

Vapour pressure is determined from the relative humidity (decimal form 0.0 to 1.0) multiplied by the saturation vapour pressure.

2.4 Vancouver Weather

Monthly average exterior conditions from the CWEC files for Vancouver, BC are provided in Table 2. Seasonal (3 month) average exterior conditions are also used in the analysis and are provided in Table 3.

Table 2: Vancouver Monthly Averages (CWEC)

	Average Dry Bulb Temp (°C)	Average Wet Bulb Temp (°C)	Average RH (%)	Average atmospheric pressure (Pa)	$P_{v\ sat}$ (Pa)	P_v (Pa)	W_{abs} (kg/kg)
January	3.2	1.2	86.6	101372	773	669	0.0048
February	5.1	2.9	86.3	102063	883	762	0.0054
March	6.1	2.9	80.7	101572	946	763	0.0058
April	8.7	3.9	73.5	101661	1129	830	0.0070
May	11.8	7.0	73.2	101680	1393	1020	0.0086
June	15.1	10.1	73.5	101836	1719	1264	0.0106
July	17.0	12.4	76.2	101767	1944	1481	0.0121
August	17.1	13.2	79.1	101508	1955	1547	0.0122
September	13.8	10.2	80.1	101693	1583	1268	0.0098
October	9.8	6.6	81.9	101539	1220	999	0.0075
November	5.3	2.3	81.7	101330	894	730	0.0055
December	3.6	1.7	87.6	101628	797	698	0.0049
ANNUAL	**9.7**	**6.2**	**80.0**	**101634**	**1212**	**970**	**0.0075**

Table 3: Vancouver Seasonal Averages (CWEC)

SEASON	MONTHS	Average Dry Bulb Temp (°C)	Average Wet Bulb Temp (°C)	Average RH (%)	$P_{v\ sat}$ (Pa)	P_v (Pa)
WINTER	DEC - FEB	4.0	1.9	86.8	812	705
SPRING	MAR - MAY	8.9	4.6	75.8	1138	863
SUMMER	JUN - AUG	16.4	11.9	76.3	1862	1420
FALL	SEPT - NOV	9.6	6.4	81.2	1198	973

3 MATERIALS

3.1 Historical Trends

Insulation levels have increased as a result of building code changes, largely made to minimize heating energy use. Placement of insulation historically was in the stud space as a result of available materials and to reduce the overall wall thickness. As a result the temperature of the exterior sheathing has decreased proportionally to increasing insulation levels. A reduction in temperature results in a reduced vapour pressure and thus amount of diffusion drying. Typically in residential construction 2x4 stud framing was used without insulation prior to the 1930's, however as insulation products were introduced, insulation levels of R8 became common and further R12. Typically this was provided by fiberglass batt insulation in the stud space, however as a result of code changes in the 1980's and 1990's the minimum thermal resistance required for exterior walls, 2x6 stud framing became more popular with R20 batt insulation.

In more recent years as a result of new materials, construction practices, and industry research, the use of thermal insulation in board form placed to the exterior of the sheathing is becoming more common. In this case the temperature of the exterior sheathing is warmer in the cold winter months which results in increased wintertime drying, but cooler in the hot summer months, potentially reducing the summertime drying.

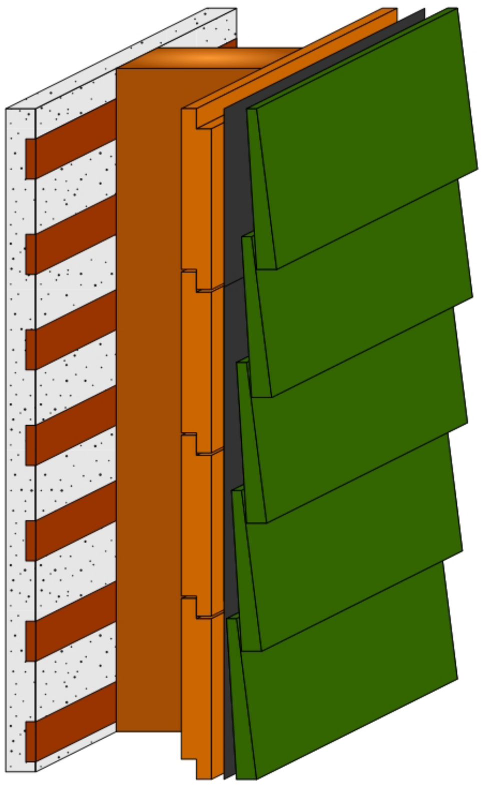
At the same time as insulation levels were increasing in the 1970's and 80's, less permeable materials were being introduced into the market and encouraged by building codes. Lower permeable materials such as polyethylene is typically used in the majority of wood stud frame buildings placed on the interior as a vapour retarder and if properly sealed an air flow retarder. While limiting the wintertime flow of vapour to the exterior, this reduces the drying potential of the wall assembly to the interior during warmer seasons. In recent years other low permeable membranes such as asphalt peel and stick membranes are becoming more common in construction. These however are placed on the exterior, typically in an exterior insulated system.

3.2 Historical Wall Assemblies

Nine different wall assemblies representative of changes in the past 100 years of wood frame construction in Canada were analyzed to determine appropriate insulation and permeance values for the analysis. These "typical" wall assemblies were developed with information presented in *Chapter 3: Through Progress and Failure – A Historical Development of the Wood Frame Wall in Canada*, and are meant to capture significant changes in construction practice between decades as new materials were introduced into the market and building code changes were made which impacted construction practice. Details pertaining to building code changes are not discussed within this report. Material properties (thermal and vapour) have been compiled in the *Appendix* the required wood frame materials, referenced from a number of published sources.

As discussed previously, half of the permeance value for the sheathing is included inboard and half is included outboard for purposes of this model. This assumes that the sheathing material is fully saturated and moisture sources for wetting can either be from the interior (air leakage condensation) or exterior (rain water penetration). Figures 6 through 14 present the nine typical wall assemblies from the 1930's to 2000's.

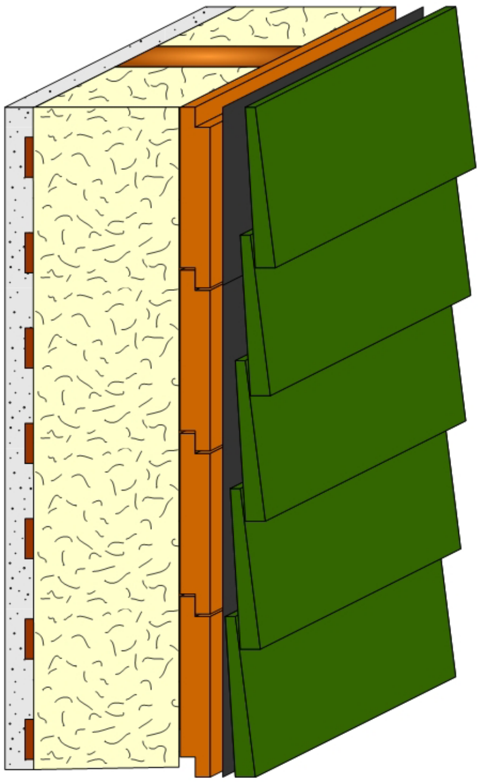
While not an absolute indicator of typical construction practice, these nine wall assemblies tell the story of how different materials came into common usage and impacted the drying potential of a typical residential wall. The changes discussed here were not made in all climates or locations. Each decade is meant to be different, capturing significant changes made during the decade to common materials used.



Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Plaster: 0.04 Airspace: 0.19 ½ sheath: 0.09 **Total: 0.32 (1.8)**	½ sheath: 0.09 Sheath Paper: 0 Wood siding: 0.1 **Total: 0.19 (1.1)**	Paint/Plaster: 150 Airspace: - ½ sheath: 2000 **Total: 140**	½ sheath: 2000 Sheath Paper: 1800 Wood siding: 2010 **Total: 650**

Figure 6: Typical Pre 1930's residential wall assembly.

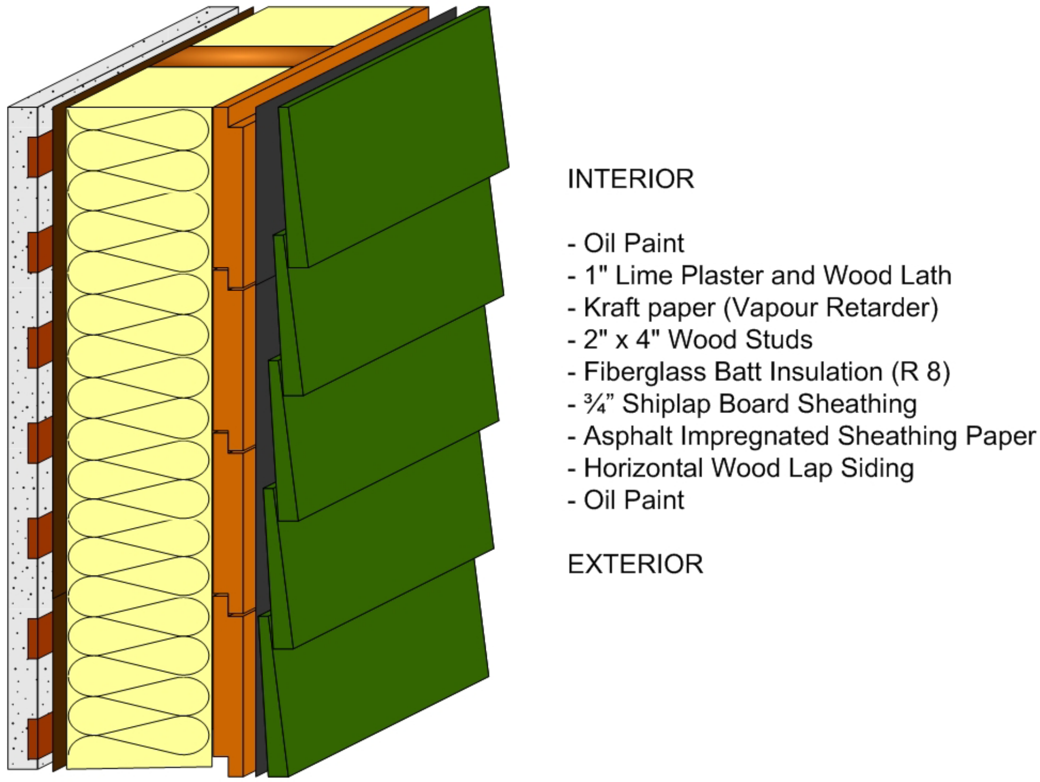
Although not widespread at the time, insulation typically consisted of materials such as sawdust, wood shavings, straw and grasses, seaweed, or mineral fibers. Mineral wool was available in some locations however not widely used. Typical cladding layers consisted of horizontal wood siding (shown), shingles, stucco, brick, or natural stone. Horizontal wood siding was chosen for consistency throughout this analysis and remains a common siding option today.



Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Plaster: 0.04 Mineral Insulation: 1.0 ½ sheath: 0.09 **Total: 1.2 (6.9)**	½ sheath: 0.09 Sheath Paper: 0 Wood siding: 0.1 **Total: 0.19 (1.1)**	Paint/Plaster: 150 Mineral Insulation: 1800 ½ sheath: 2000 **Total: 130**	½ sheath: 2000 Sheath Paper: 1800 Wood siding: 2010 **Total: 650**

Figure 7: Typical 1930's -1940's residential wall assembly.

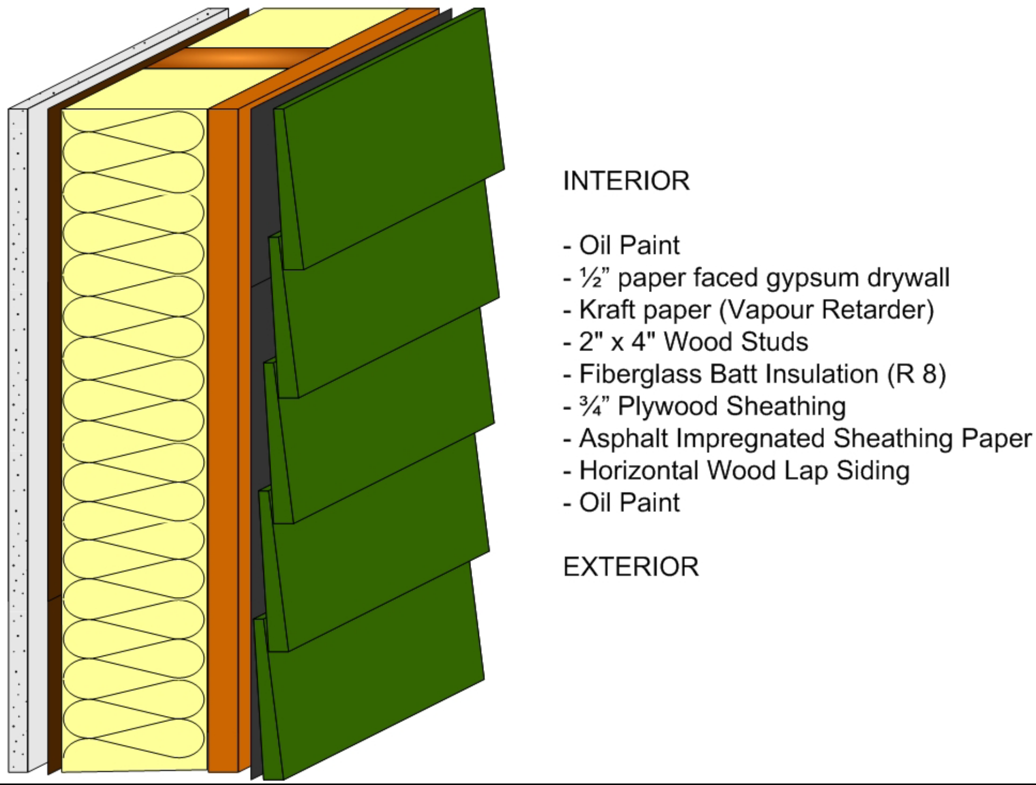
By the mid 1930's expanded mineral products such as perlite and vermiculite and mineral wool products such as slag wool, rock wool and glass fiber were available as insulating products. Mineral wool insulation was chosen for this analysis, however most products available at the time had similar vapour and thermal resistance properties. Typical cladding layers consisted of horizontal wood siding (shown), shingles, stucco, brick, or natural stone.



Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Plaster: 0.04 Kraft paper: 0 Fiberglass Insul: 1.4 ½ sheath: 0.09 **Total: 1.53 (8.7)**	½ sheath: 0.09 Sheath Paper: 0 Wood siding: 0.1 **Total: 0.19 (1.1)**	Paint/Plaster: 150 Kraft paper: 350 Fiberglass Insul: 1900 ½ sheath: 2000 **Total: 95**	½ sheath: 2000 Sheath Paper: 1800 Wood siding: 2010 **Total: 650**

Figure 8: Typical 1950's residential wall assembly.

Vapour retarding layers were introduced into insulated walls by the end of the 1940's. Vapour retarders typically consisted of asphalt impregnated or coated kraft paper installed to the interior of the insulation in cold climates. Typical cladding layers consisted of horizontal wood siding (shown), shingles, stucco, brick, or natural stone.

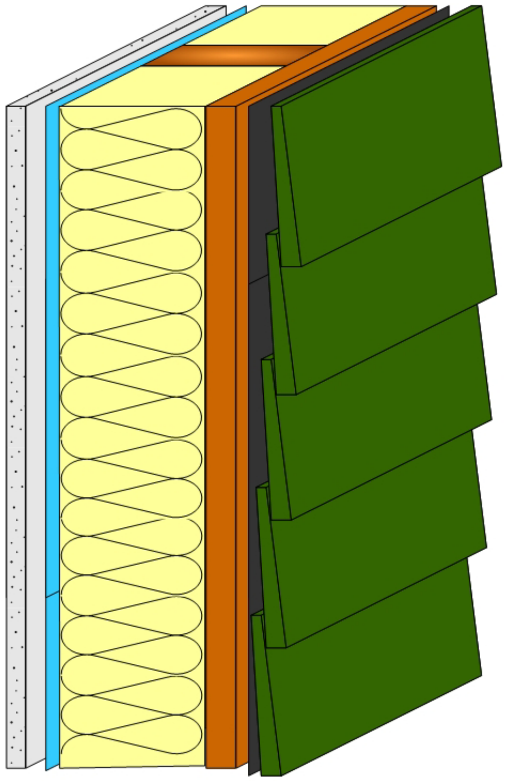


Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Drywall: 0.08 Kraft paper: 0 Fiberglass Insul: 1.4 ½ sheath: 0.09 **Total: 1.57 (8.9)**	½ sheath: 0.09 Sheath Paper: 0 Wood siding: 0.1 **Total: 0.19 (1.1)**	Paint/Drywall: 150 Kraft paper: 350 Fiberglass Insul: 1900 ½ sheath: 1400 **Total: 92**	½ sheath: 1400 Sheath Paper: 1800 Wood siding: 2010 **Total: 560**

Figure 9: Typical 1960's residential wall assembly.

Plaster and wood lath was replaced by paper-faced gypsum drywall in most homes by the late 1960's. During the 1960's Tongue and groove or shiplap wood sheathing was also replaced with panel-type sheathings such as plywood or fiberboard. Plywood is used here, as fiberboard was not used in all locations, particularly Vancouver. Wafer-board (OSB) was also introduced although not commonly during the 1960's.

Polyethylene film as an air/vapour retarder was introduced as a building practice as was friction-fit fiberglass batt insulation (not with attached building paper stapling strips). Typical cladding layers consisted of horizontal wood siding (shown), stucco, brick, aluminum, and wood-composite sidings.

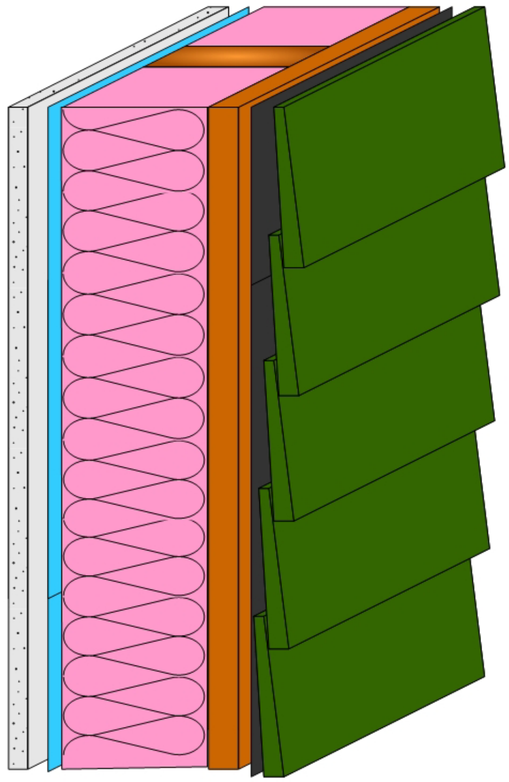


Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Drywall: 0.08 Poly: 0 Fiberglass Insul: 1.4 ½ sheath: 0.09 **Total: 1.57 (8.9)**	½ sheath: 0.09 Sheath Paper: 0 Wood siding: 0.1 **Total: 0.19 (1.1)**	Paint/Drywall: 150 Poly: 5 Fiberglass Insul: 1900 ½ sheath: 1400 **Total: 5**	½ sheath: 1400 Sheath Paper: 3060 Wood siding: 2010 **Total: 650**

Figure 10: Typical 1970's residential wall assembly.

The use of Polyethylene as an air/vapour retarder and friction-fit fiberglass batt insulation became common in late 1970's as part of energy conservation to increase wall R-values and reduce air-leakage. The polyethylene was typically installed loosely as the vapour barrier with little attention to sealing penetrations during this period. By virtue of the material properties and installation, this provided some resistance to air-flow, however also contributed to moisture problems at penetrations or discontinuities such as at electrical boxes and floor headers.

Typical cladding layers consisted of horizontal wood siding (shown), stucco, brick, aluminum, and wood-composite sidings.



INTERIOR

- Latex Paint
- ½" paper faced gypsum drywall
- Sealed 4 mil Polyethylene Vapour Retarder
- 2" x 4" Wood Studs
- Fiberglass Batt Insulation (R 12)
- ¾" Plywood Sheathing
- Asphalt Impregnated Sheathing Paper
- Horizontal Wood Lap Siding
- Oil Paint

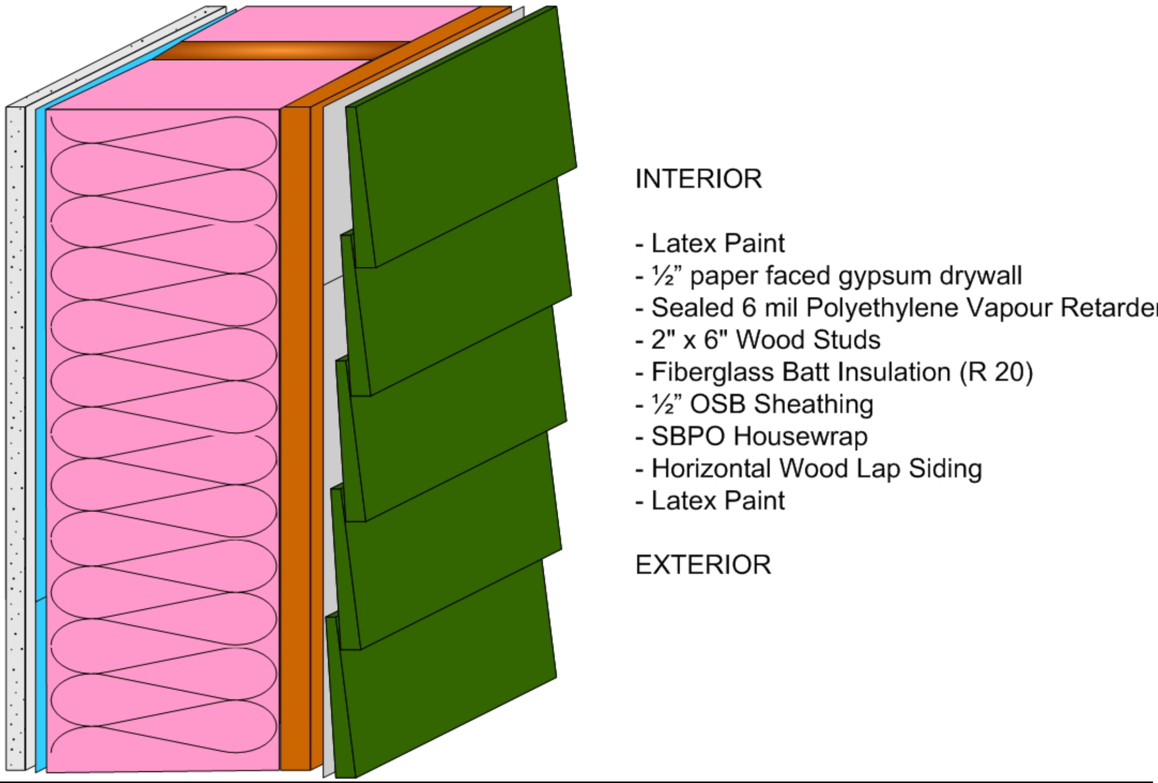
EXTERIOR

Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Drywall: 0.08 Poly: 0 Fiberglass Insul: 2.1 ½ sheath: 0.09 **Total: 2.28 (13.0)**	½ sheath: 0.09 Sheath Paper: 0 Wood siding: 0.1 **Total: 0.19 (1.1)**	Paint/Drywall: 360 Poly: 5 Fiberglass Insul: 1900 ½ sheath: 1400 **Total: 5**	½ sheath: 1400 Sheath Paper: 3060 Wood siding: 2010 **Total: 650**

Figure 11: Typical 1980's residential wall assembly.

The use of Polyethylene as an air/vapour retarder and friction-fit fiberglass batt insulation was common during the 1980's. Higher thermal insulation values were also typical (R-12 versus R-8) depending on the climate.

Typical cladding layers consisted of horizontal wood siding (shown), stucco, brick, aluminum, and wood-composite sidings. Vinyl siding was also introduced as an alternative to wood-siding

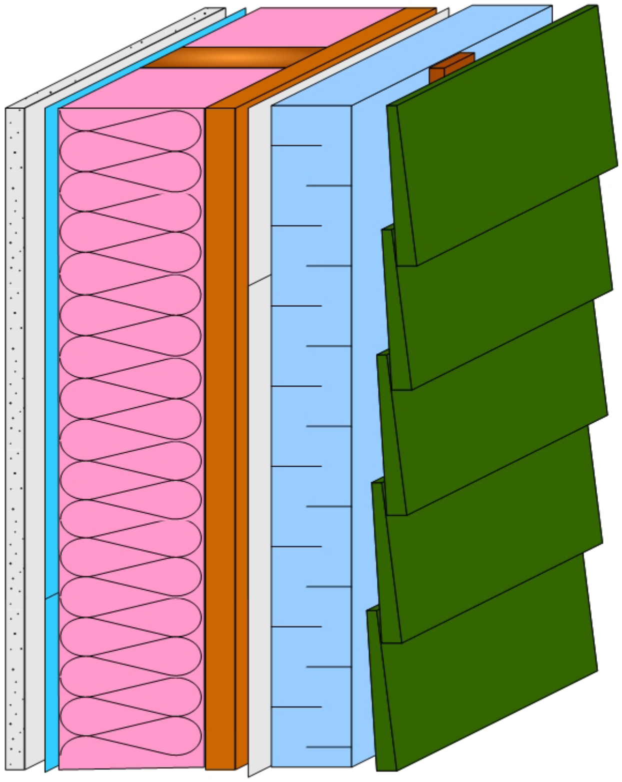


Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Drywall: 0.08 Poly: 0 Fiberglass Insul: 3.52 ½ sheath: 0.09 **Total: 3.7 (21.0)**	½ sheath: 0.09 SBPO: 0 Wood siding: 0.1 **Total: 0.19 (1.1)**	Paint/Drywall: 360 Poly: 5 Fiberglass Insul: 1900 ½ OSB sheath: 700 **Total: 5**	½ OSB sheath: 700 SBPO: 1800 Wood siding: 2010 **Total: 403**

Figure 12: Typical 1990's residential wall assembly.

By the 1990's minimum insulation requirements had further been increased. 2x6 framing filled with fiberglass batt insulation became typically used in place of 2x4 framing to achieve required thermal resistance (>R-12) required by building code. Spun bonded polyolefin (SBPO) house wraps were also more commonly used by the 1990's as was OSB sheathing as a replacement for plywood. These changes are reflected here and increased the thermal resistance, but also the vapour resistance.

Typical cladding layers consisted of horizontal wood siding (shown), stucco, brick, vinyl, aluminum, and wood-composite sidings, low permeability acrylic stucco is introduced.



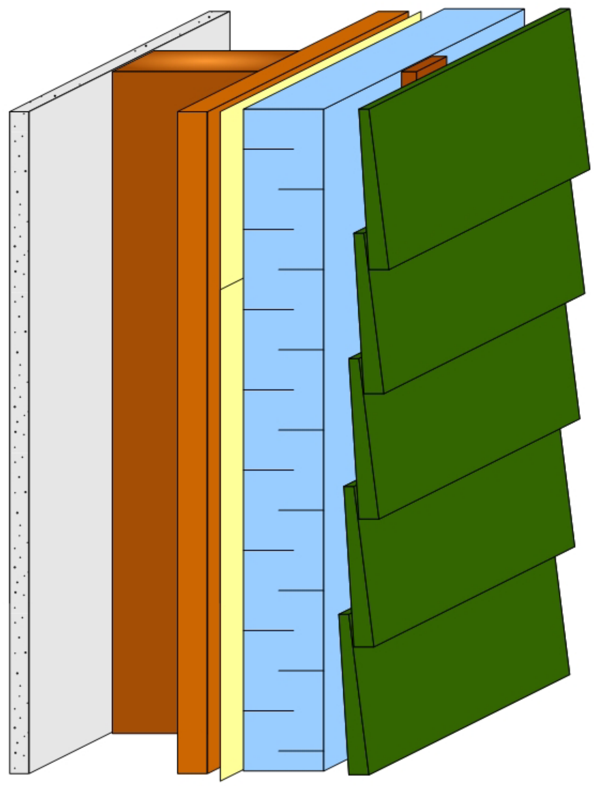
Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Drywall: 0.08 Poly: 0 Fiberglass Insul: 2.1 ½ sheath: 0.09 **Total: 2.3 (12.9)**	½ sheath: 0.09 SBPO: 0 Mineral wool: 1.4 Wood siding: 0.1 **Total: 1.5 (8.5)**	Paint/Drywall: 360 Poly: 5 Fiberglass Insul: 1900 ½ OSB sheath: 700 **Total: 5**	½ OSB sheath: 700 SBPO: 1800 Mineral wool: 2000 Wood siding: 2010 **Total: 335**

Figure 13: Typical 2000's residential wall assembly.

For the most part, wall assemblies for 2000-2007 closely resemble those used in the 1990s. However some changes have been made or are promoted which will increase the durability and drying potential of wall assemblies.

The use of insulation outboard of the sheathing membrane or as a replacement for the sheathing has become common in some residences as higher insulation values are required/desired. Insulation types for this application include expanded polystyrene (EPS), extruded polystyrene (XPS), semi-rigid mineral wool or semi-rigid fiberglass insulation to the outboard side of the stud wall. Within the stud wall, vapour open fiberglass, cellulose, or spray-foams are used.

A strapped cavity to provide drainage and ventilation is provided in wetter climates. This effectively negates the cladding layers vapour and thermal resistance, and can contribute to faster drying at the layers inboard of the cladding. Typical cladding layers consist of horizontal wood siding (shown), stucco, vinyl, brick veneer, hard-board, and cement board sidings.



Thermal Resistance Inboard of Sheathing - RSI (R value)	Thermal Resistance Outboard of Sheathing - RSI (R value)	Vapour Permeance Inboard of Sheathing - ng/m² Pa s	Vapour Permeance Outboard of Sheathing - ng/m² Pa s
Drywall: 0.08 Empty cavity: 0.19 ½ sheath: 0.09 **Total: 0.36 (2.0)**	½ sheath: 0.09 Semi-perm layer: 0 Mineral wool: 2.64 Wood siding: 0.1 **Total: 2.83 (16.1)**	Paint/Drywall: 360 Empty cavity: 0 ½ OSB sheath: 700 **Total: 240**	½ OSB sheath: 700 Semi-perm layer: 400 Mineral wool: 2000 Wood siding: 2010 **Total: 203**

Figure 14: Potential future residential wall assembly.

One potential wall assembly that is different than the 2000's wall is the use of an entirely exterior insulated wall, such as common for high-rise residential and some commercial buildings. Insulation types could include expanded polystyrene (EPS), extruded polystyrene (XPS), semi-rigid mineral wool or semi-rigid fiberglass insulation. Various semi-permeable materials could be used at the exterior of the sheathing as the water resistant barrier and the air/vapour retarder.

Table 4 summarizes the thermal resistance and vapour permeance for each of the historical walls.

Table 4: Summary of Thermal Resistance and Vapour Permeance

Time Period	Thermal Resistance Inboard of Sheathing (R-value)	Thermal Resistance Outboard of Sheathing (R-value)	Vapour Permeance Inboard of Sheathing Metric perms	Vapour Permeance Outboard of Sheathing Metric perms
Pre 1930's	1.8	1.1	140	650
1930's-1940's	6.9	1.1	130	650
1950's	8.9	1.1	95	650
1960's	8.9	1.1	92	560
1970's	8.9	1.1	5	650
1980's	13.0	1.1	5	650
1990's	21.0	1.1	5	403
2000's	12.9	8.5	5	335
Beyond 2000's	2.0	16.1	240	203

3.3 Walls for Analysis

For the model to be applicable a range of different wall systems the analysis was performed using six generic walls covering a range of typical insulation values shown in Table 6. The six different walls were analyzed by varying the ratio of insulation from interior to exterior. Interpolation/Extrapolation can be used to determine results not calculated in this report.

Table 6: Insulation Ratios used for the analysis.

Wall Case	Insulation Ratio (Interior/Exterior)	Description
1	0.1	1 to 10 (interior to exterior insulation)
2	0.2	1 to 5
3	1.0	1 to 1
4	5.0	5 to 1
5	10.0	10 to 1
6	20.0	20 to 1

The effect of vapour permeance values were used in conjunction with the thermal resistance values for the analyzed walls. The vapour permeance values were adjusted by an order of magnitude, and each vapour permeance can represent a range of potential materials. Four cases were analyzed and are summarized in Table 7.

Table 7: Permeance values used for the analysis

Wall	Vapour Permeance to interior	Vapour Permeance to exterior	Description, Potential Wall Materials
1	250	1000	Typical older Wall Assembly, Plaster/Oil Paint to interior, 1x8 board siding and building paper to exterior with ventilated cladding. Assuming some air leakage through the wall which increases effective permeance OR New wall, Gypsum drywall and vapour barrier paint to interior, exterior gypsum and Tyvek to exterior with ventilated cladding, vapour permeable insulation such as mineral wool or fiberglass are used
2	50	250	Gypsum drywall and oil or vapour barrier paint to interior, OSB or plywood and face applied cladding
3	5	250	Gypsum drywall and Poly to interior, OSB or Plywood with face applied cladding
4	250	50	Gypsum drywall and latex paint to interior, XPS and Plywood/OSB to exterior

Several other combinations could also be analyzed by varying the permeance. The historical wall permeance values are also analyzed in addition to these 4 cases.

4 RESULTS

Results are produced in graphical form to show the results from the hourly analysis. Monthly and seasonal mean values are graphically shown.

For the analysis an east facing wall with a solar absorptance of 0.4 (light colored cladding) with an annual average of 21°C and 40% RH indoors was assumed. Insulation ratio is shown, and typically used for comparison purposes.

Vapour pressure difference is independent of the vapour permeance of the chosen wall materials, based only the insulation ratio, the net maximum drying potential however is a function of the vapour permeance of the materials. For this analysis it was assumed that the vapour permeance to the interior of the sheathing was 250 metric perms and 1000 metric perms to the exterior.

Figure 15 shows the monthly mean exterior and interior boundary conditions and Figure 16 shows the monthly mean temperature at the saturated sheathing.

Figure 17 shows the temperature distribution of the saturated sheathing. This plot can be used to assess the potential for mould growth and or corrosion rates for the sheathing in a given climate, however is not discussed in this report.

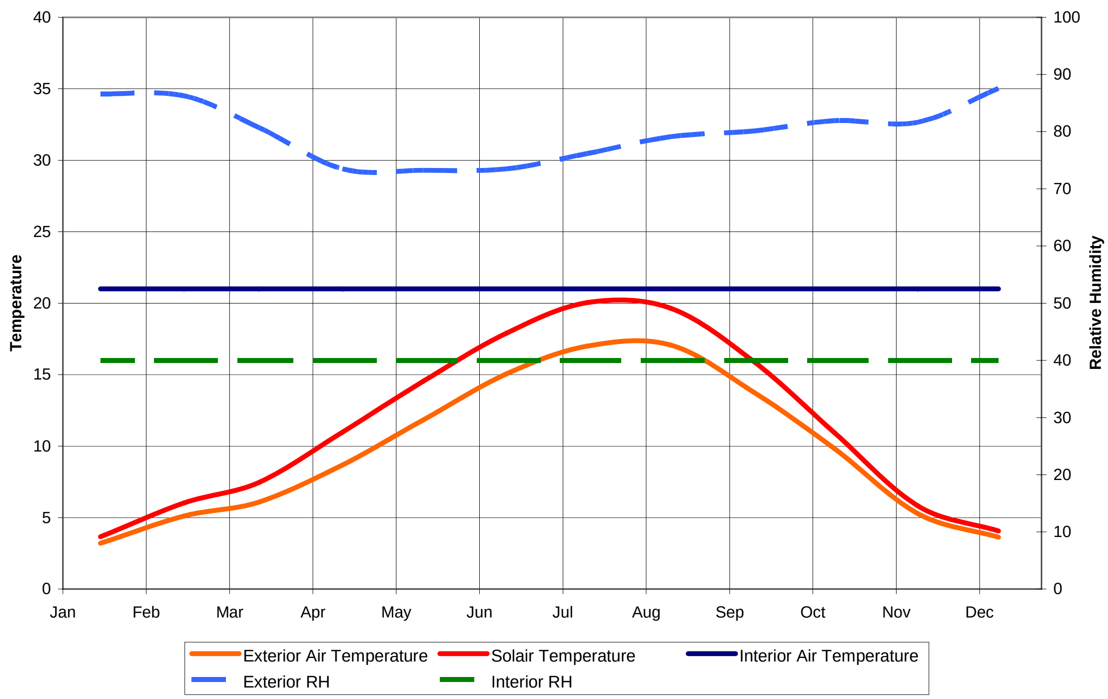


Figure 15: Monthly Mean Exterior and Interior Boundary Conditions

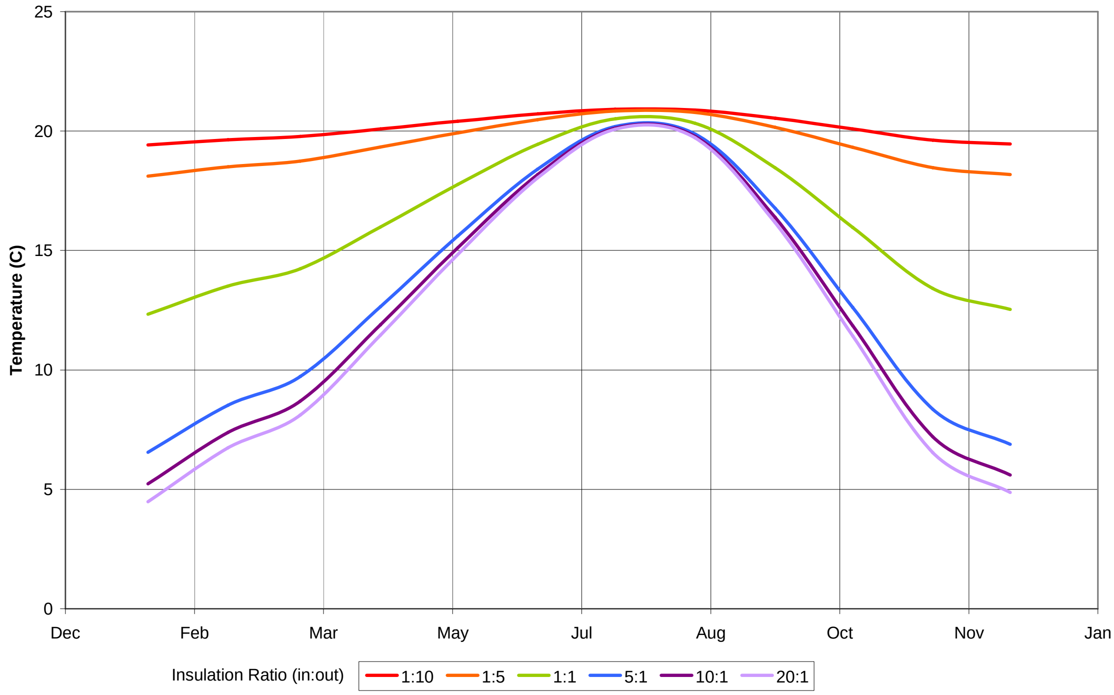


Figure 16: Monthly Mean Temperature at Saturated Sheathing.

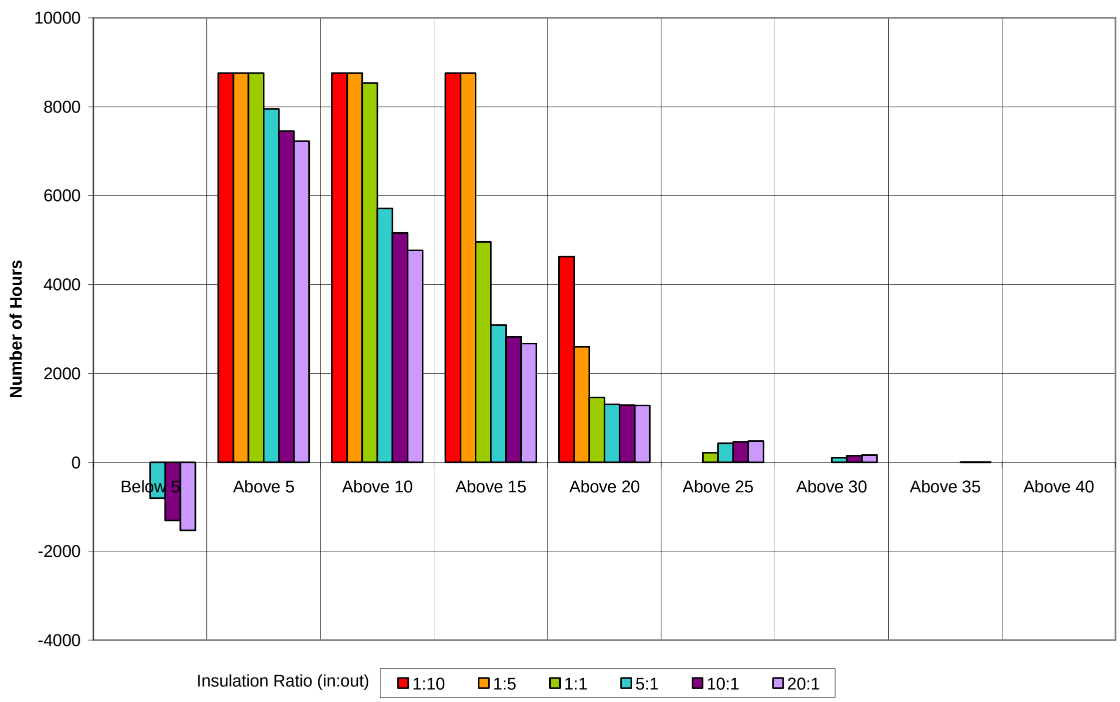


Figure 17: Annual Temperature distribution of Saturated Sheathing

Monthly and seasonal vapour pressure differences are provided in Figure 18 and 19 showing the effect of insulation ratio on a wall in Vancouver.

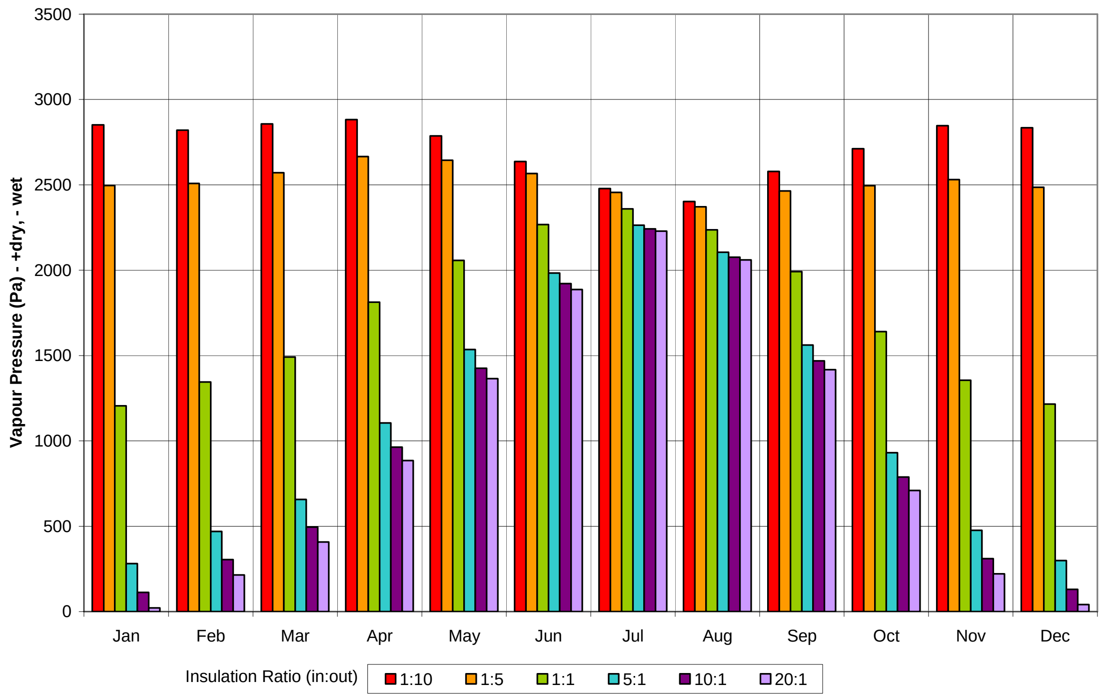


Figure 18: Monthly Average Vapour Pressure Difference

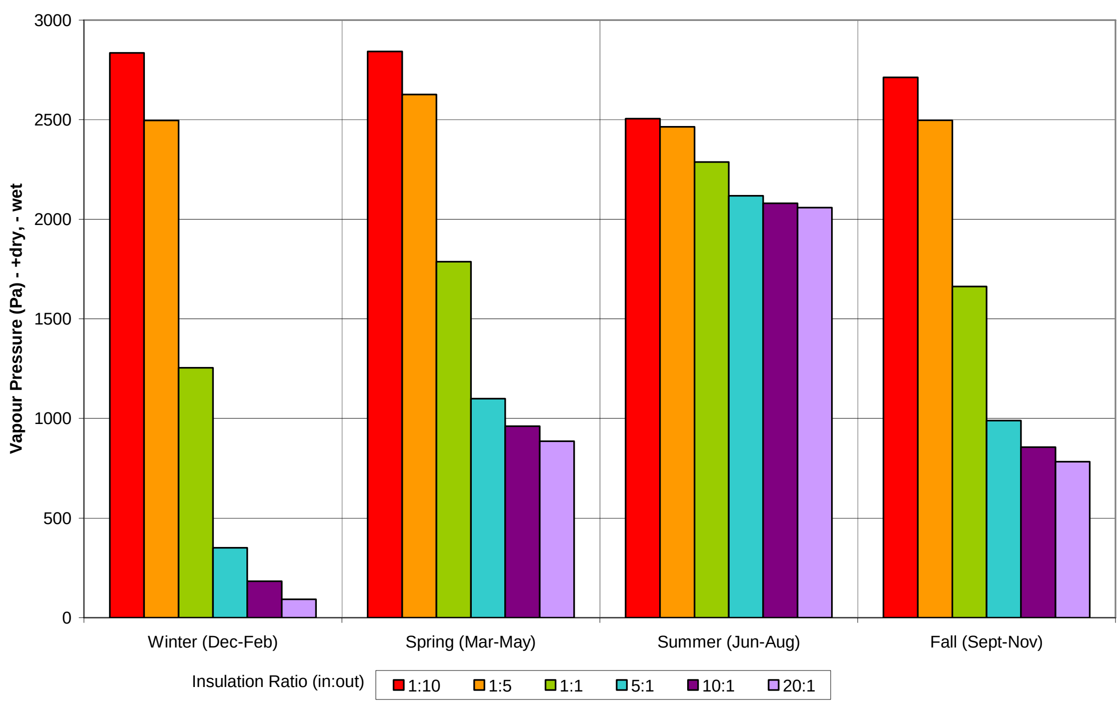


Figure 19: Seasonal Average Vapour Pressure Difference

The results show that while for a certain insulation ratio, and thus temperature at the sheathing, an annual average drying potential to the exterior exist in Vancouver. This potential is reduced by higher insulation levels, however remains positive (drying).

While being more energy efficient, additional insulation on the interior reduces the drying potential for the moisture sensitive sheathing (5:1, 10:1, 20:1). The more appropriate location would be to place the insulation to the exterior of the sheathing, thus increasing the sheathing temperature and drying potential (1:10, 1:5).

The four different wall cases are analyzed if Figures 20 through 23 to show the effect of material vapour permeance on the results. All graphical scales are the same, note the significant decrease from Wall 1 to Walls 2 through 4.

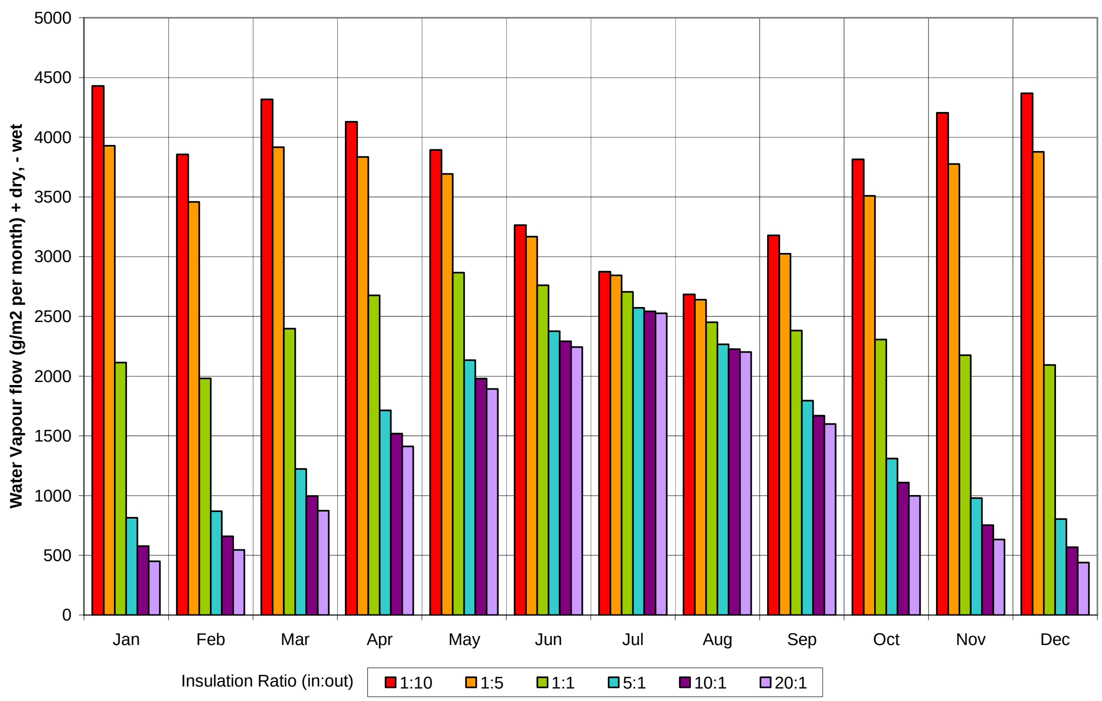


Figure 20 Wall 1 50/1000 perms - Vapour Diffusion Flow Rate Monthly Sum

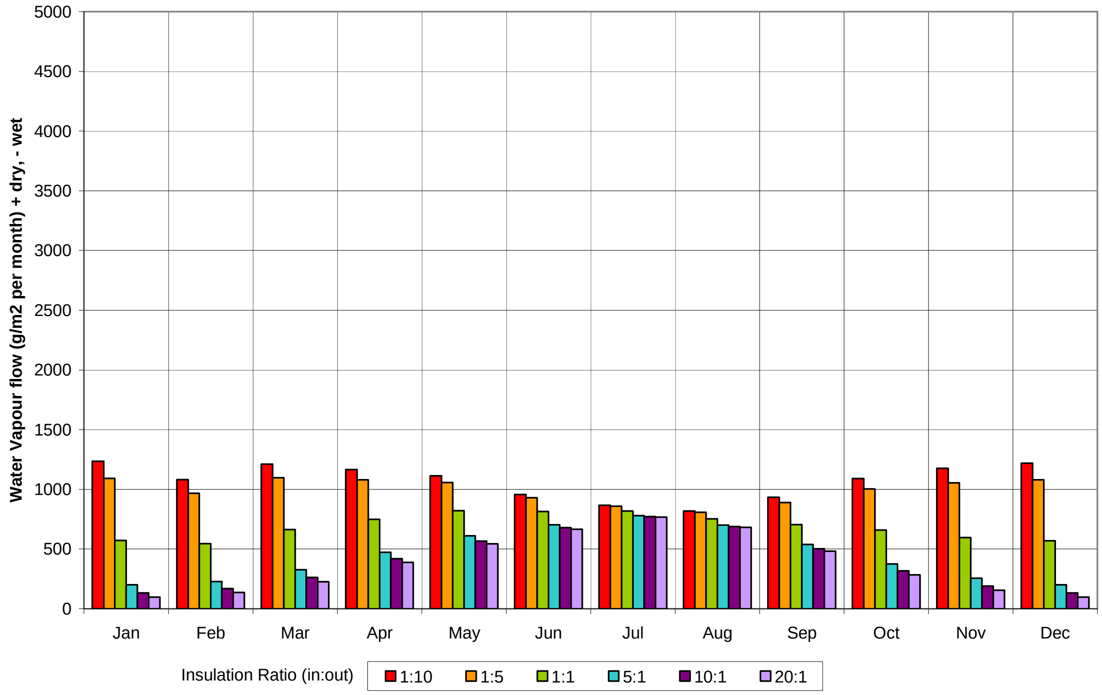


Figure 21: Wall 2 – 50/250 perms – Vapour Diffusion Flow Rate Monthly Sum

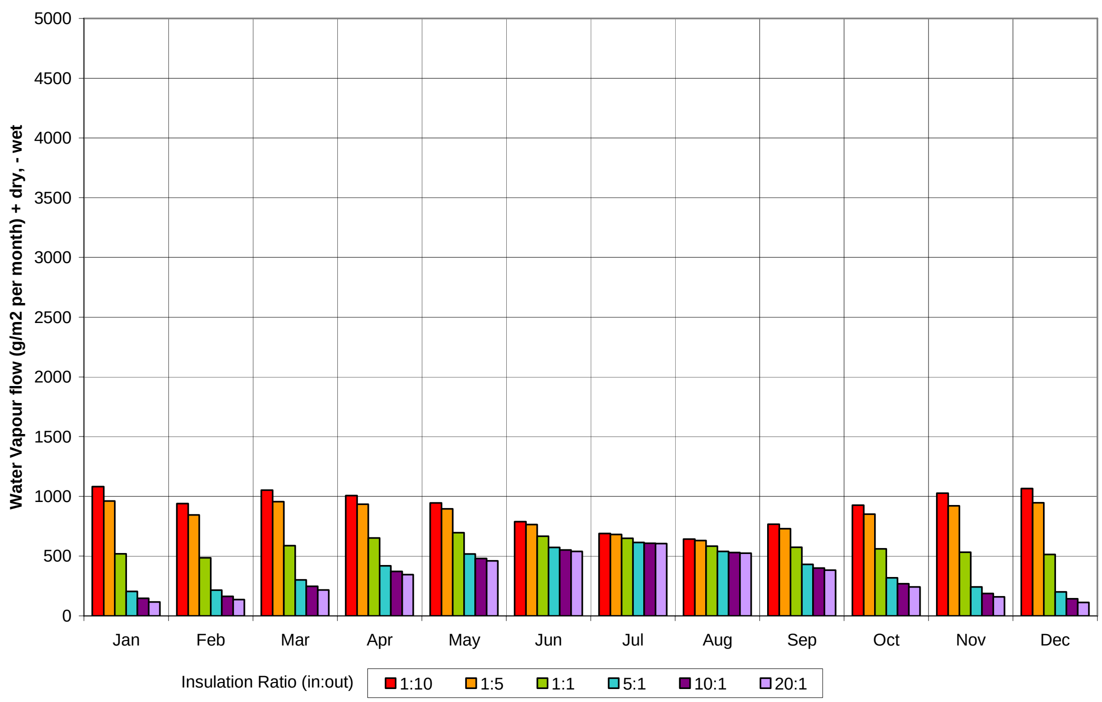


Figure 22: Wall 3 – 5/250 perms – Vapour Diffusion Flow Rate Monthly Sum

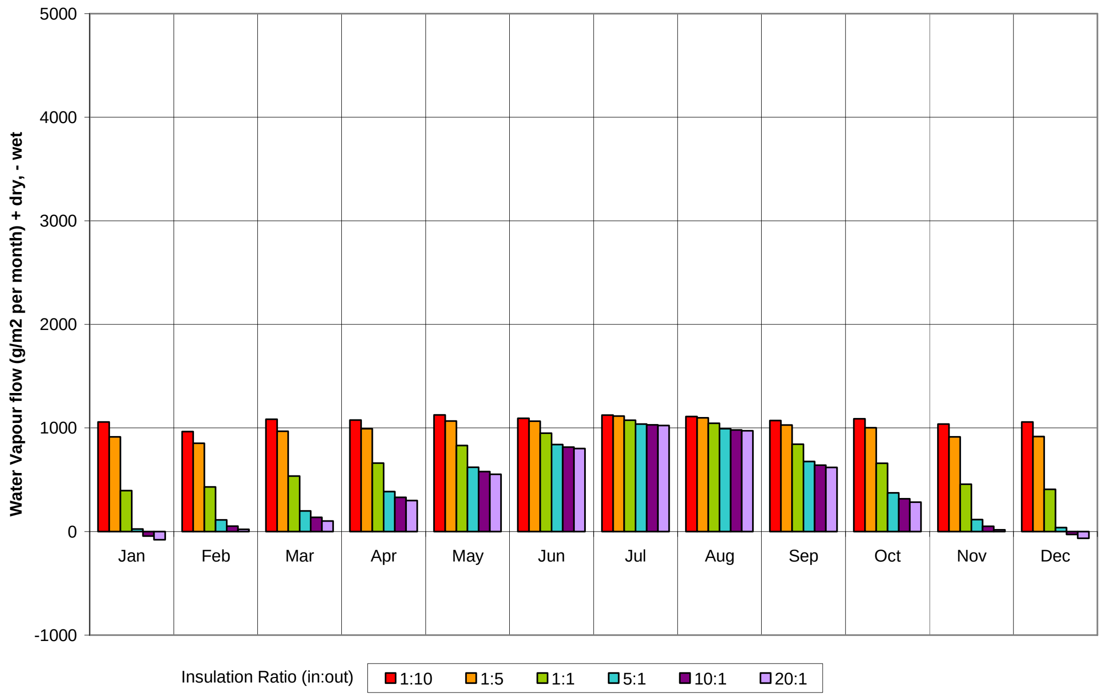


Figure 23: Wall 4 – 250/50 perms – Vapour Diffusion Flow Rate Monthly Sum

4.1 Parametric Analysis

A parametric analysis was performed on the variables for the analysis including:

1. Indoor Conditions
   a. Annual average conditions
      i. 21°C and 40% RH
      ii. 21°C and 50% RH
      iii. 21°C and 60% RH
      iv. 21°C and 70% RH
   b. Dynamic indoor conditions which approximate real seasonal conditions (sinusoidal relationship) cooler drier winter, warmer wetter summer conditions
      i. 20°C/30% RH winter 22°C/50% summer
      ii. 20°C/35% RH winter 22°C/55% summer
      iii. 20°C/40% RH winter 22°C/60% summer
      iv. 20°C/45% RH winter 22°C/65% summer
   c. Assumed seasonal average temperature conditions (sinusoidal relationship) and relative humidity based on ventilation rate, moisture production and exterior vapour pressure
      i. 5 ACH
      ii. 2 ACH

iii. 1 ACH
iv. 0.5 ACH

2. Orientation (North, East, South, West)
3. Solar absorptance (0.4, 0.6, 0.8, 0.9)
4. Degree of saturation of wetted layer (100% RH, 90% RH, 80% RH, 70% RH)
5. Hourly versus Monthly Period of Analysis

4.1.1 Indoor Conditions

The effect of annual average indoor temperature and humidity is compared in Figure 24. Humidity is increased as the interior temperature is kept constant.

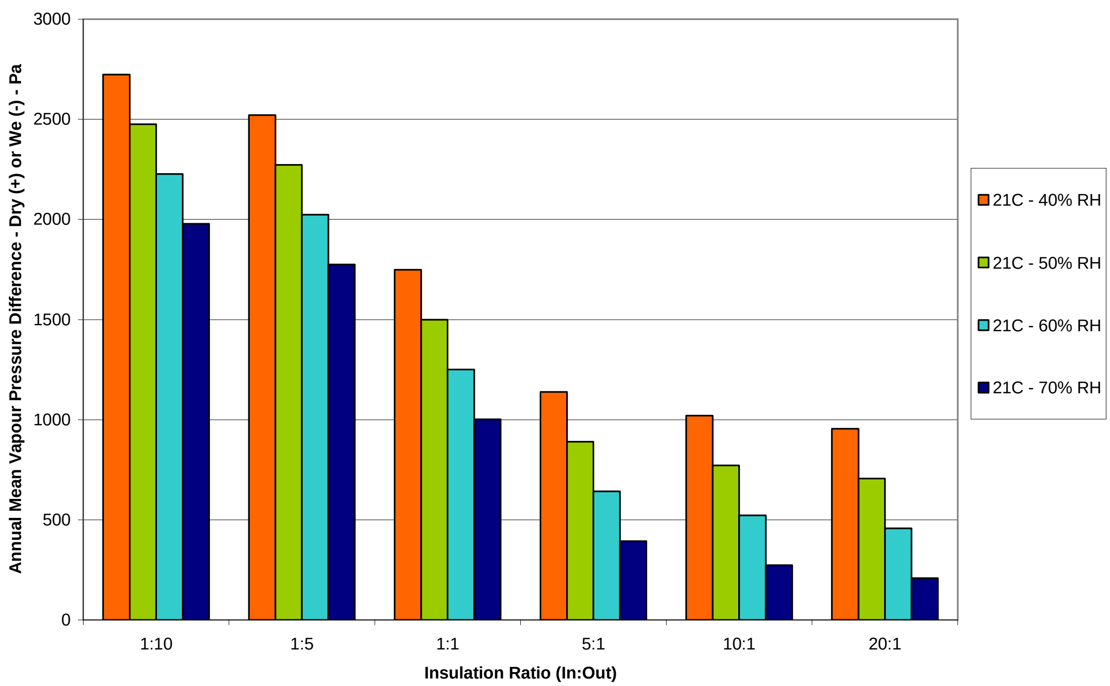


Figure 24: Effect of annual average indoor conditions on Vapour Pressure Difference

Increasing the relative humidity and thus vapour pressure indoors has a significant reduction on the vapour pressures as the drying to the interior is reduced significantly. Figure 25 shows the resulting net drying potential for Wall 1 250/1000 perms.

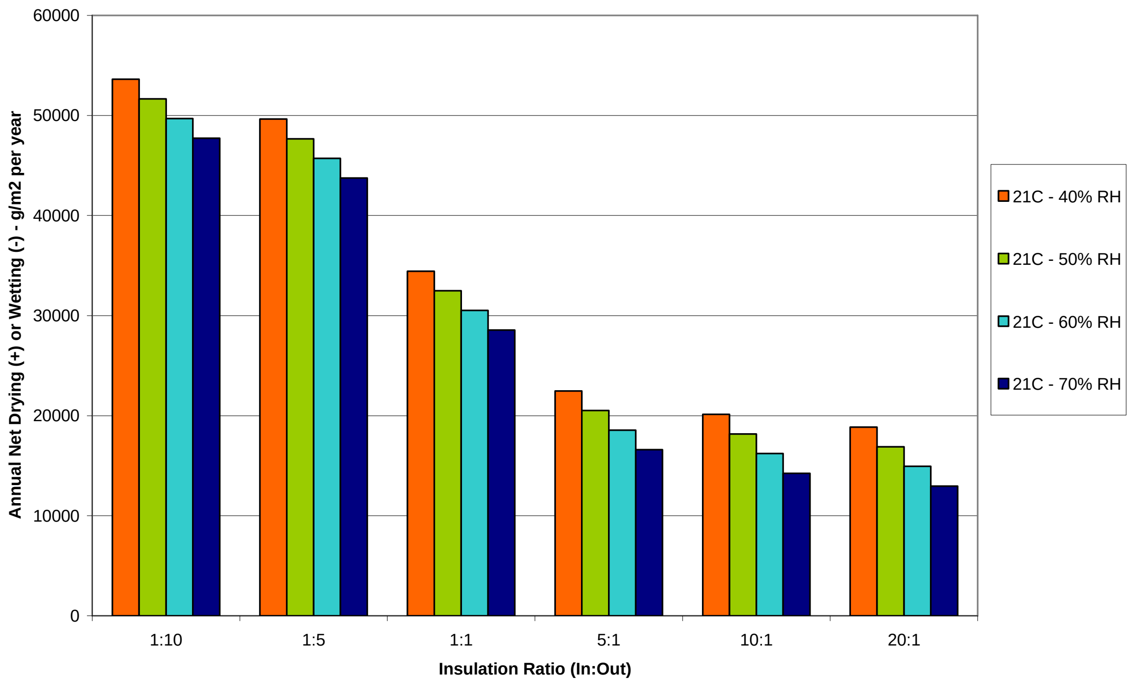


Figure 25: Effect of annual average indoor conditions on Net Annual Drying Potential

Similar results are produced with dynamic indoor conditions which approximate real seasonal conditions (sinusoidal relationship) simulating in a cooler drier winter and warmer wetter summer conditions as typically observed. These results are shown in Figure 26 and 27.

A further comparison was completed with assumed seasonal average temperature conditions (sinusoidal relationship) and relative humidity based on ventilation rate, moisture production and exterior vapour pressure. These results are shown in Figure 28 and 29.

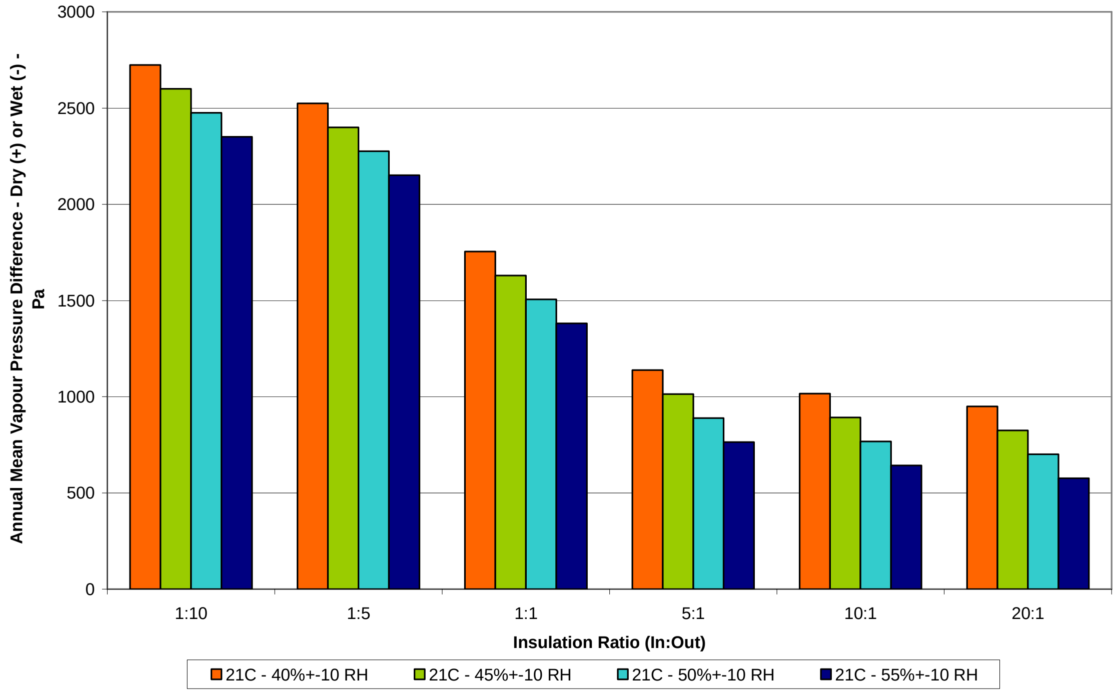


Figure 26: Effect of seasonal average indoor conditions on Vapour Pressure Difference

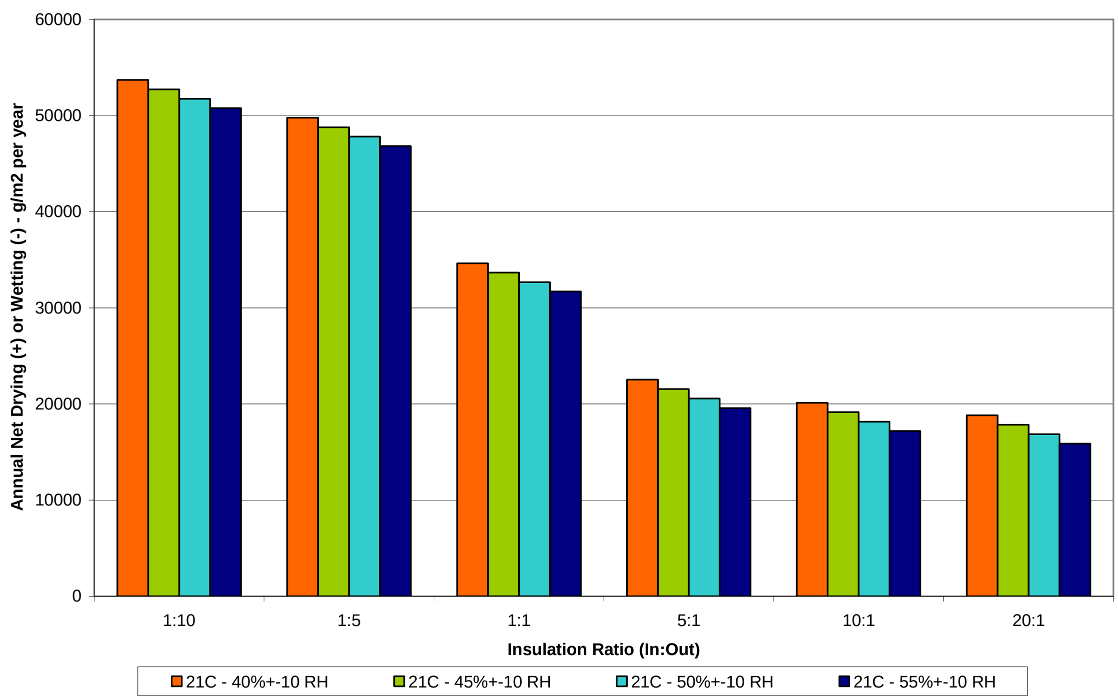


Figure 27: Effect of seasonal average indoor conditions on Net Drying Potential

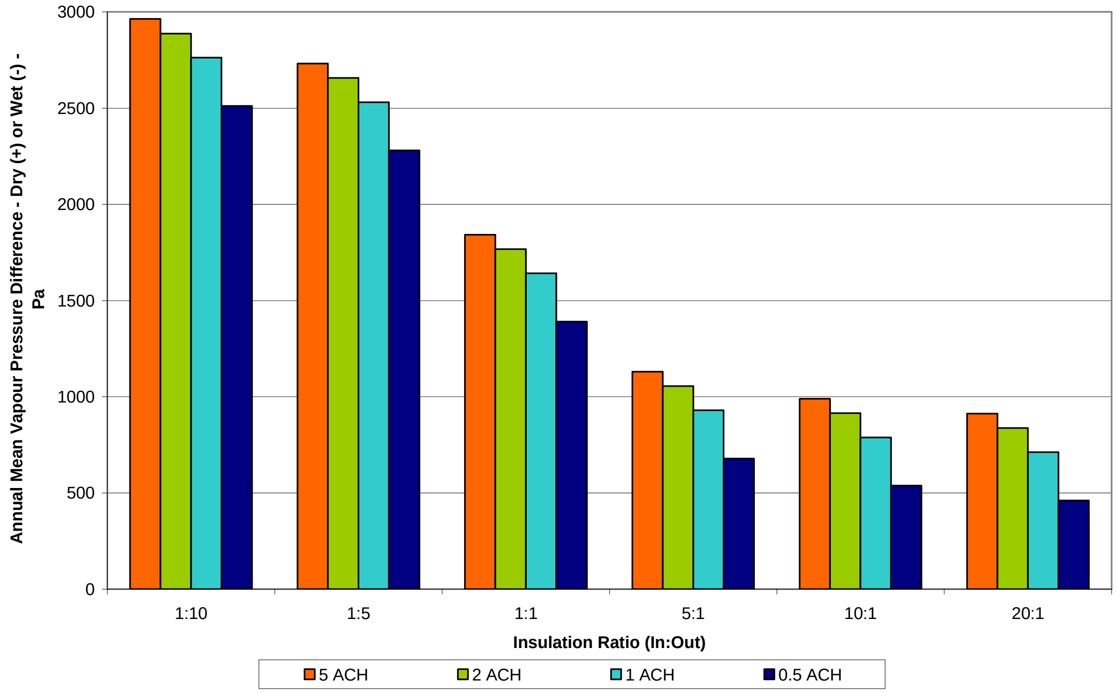


Figure 28: Effect of indoor ventilation rate on Vapour Pressure Difference

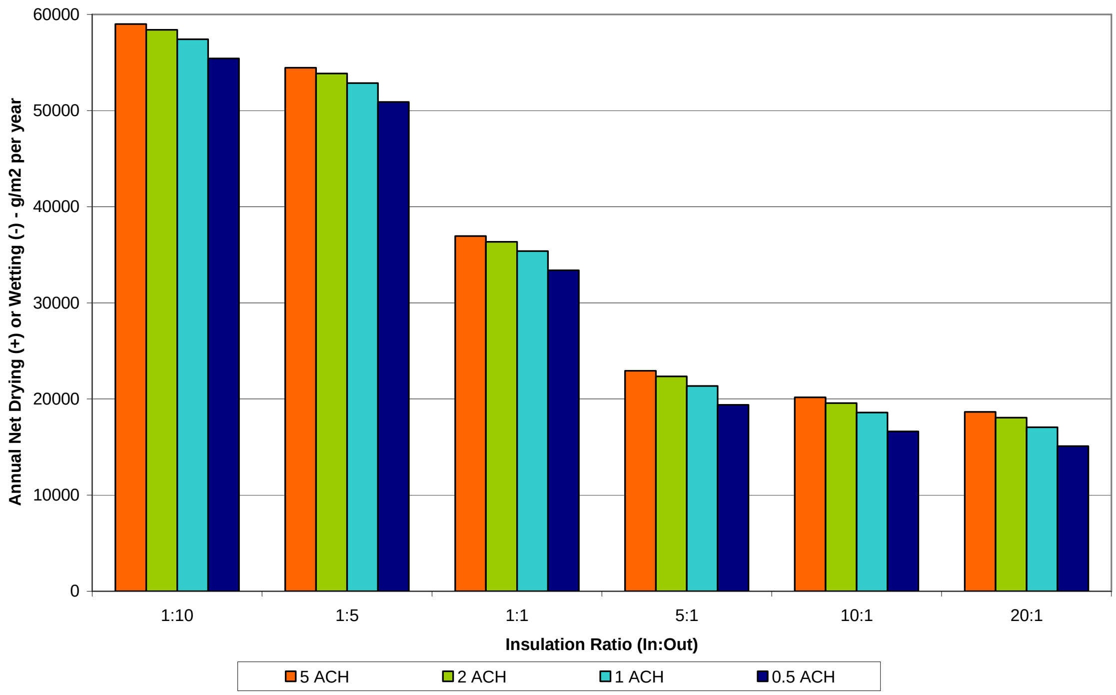


Figure 29: Effect of indoor ventilation rate on Net Drying Potential

4.1.2 Orientation

The monthly mean values of solar radiation (direct and diffuse) on a surface for each orientation is shown in Figure 30.

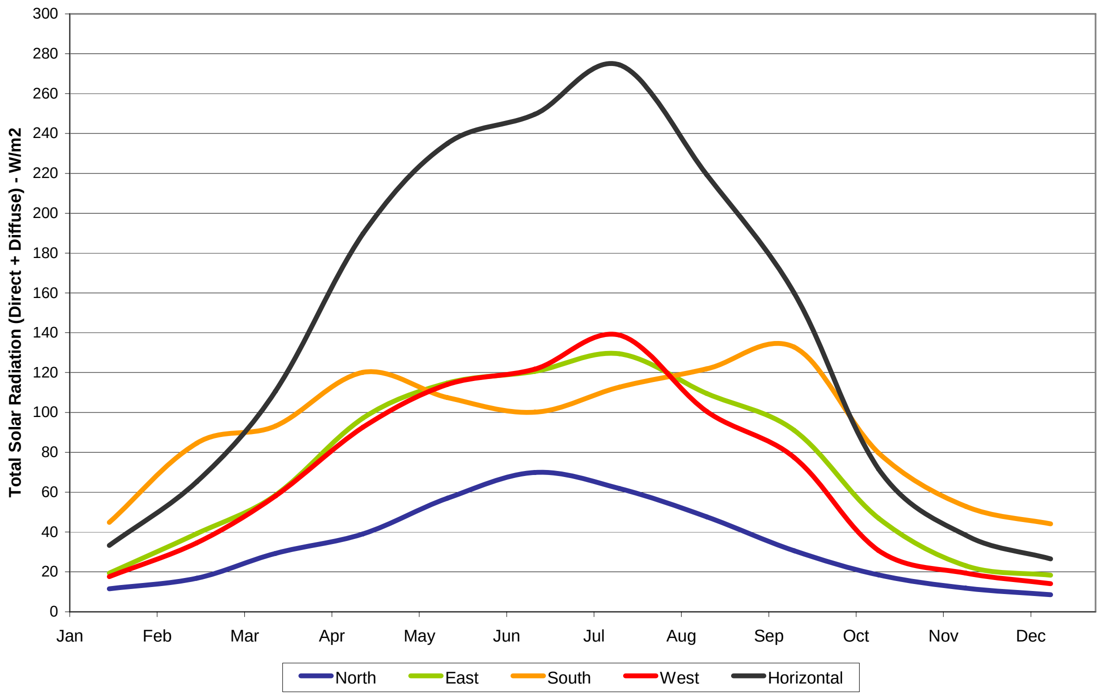


Figure 30: Monthly mean solar radiation on a surface

The corresponding sol-air surface temperatures on a vertical surface are calculated using the solar radiation, exterior air temperature and solar absorptance. The sol-air temperature and compared to ambient air temperature in Figure 31.

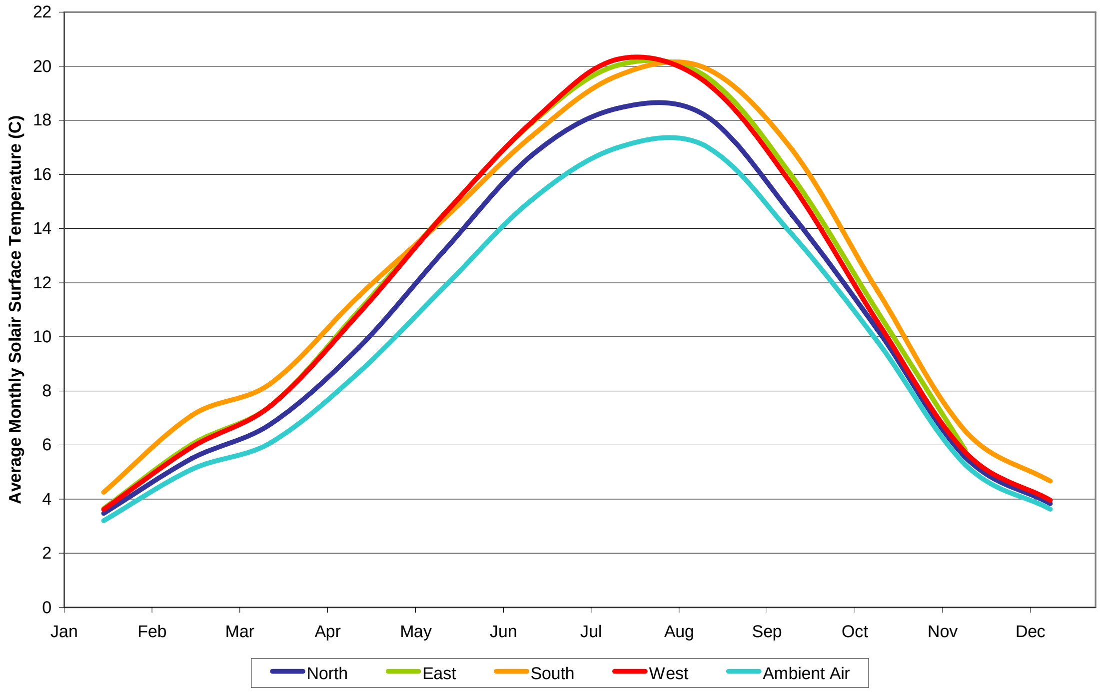


Figure 31: Monthly mean sol-air surface temperatures

As shown in Figure 31, sol-air temperatures on average increase the surface (solar absorptance 0.4) approximately 1°C in the winter and 2-3°C in the summer. Peaks are much higher up to 30-40°C depending on the orientation and incoming solar radiation.

Figure 32 shows the effect of the chosen elevation on the annual mean vapour pressure difference for a wall. Figure 33 shows the net annual drying potential.

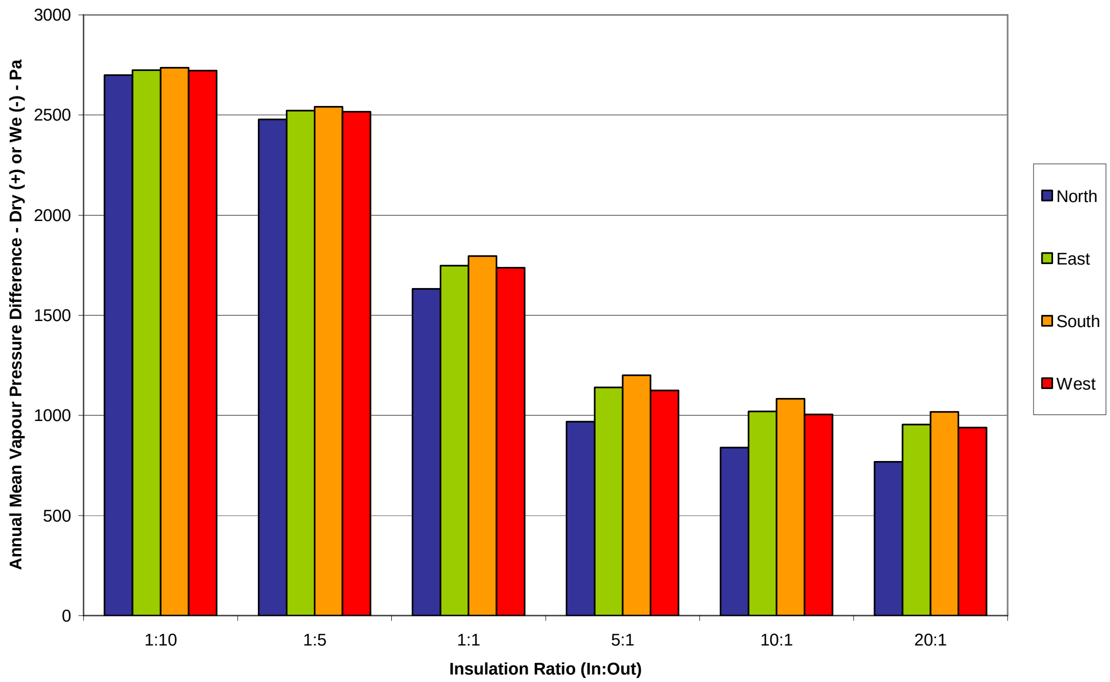


Figure 32: Annual Mean vapour Pressure Difference – Elevation Dependent

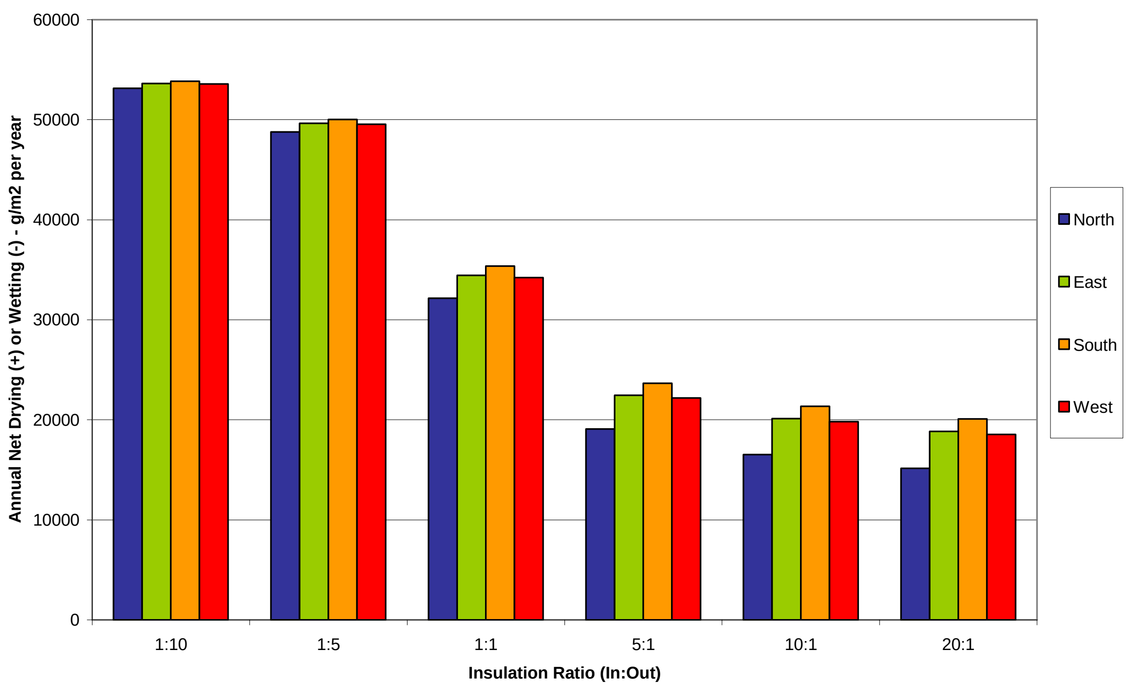


Figure 33: Annual Net Drying Potential – Elevation Dependent

The south elevation has the highest drying potential; the North elevation has the lowest. The difference in drying rates can be 20% lower on North elevations compared to the

South for interior insulated walls. The East and West elevations have similar drying potentials with the East elevation having a marginally higher drying rate.

4.1.3 Solar Absorptance

The solar absorptance value is adjusted from 0.4 (light coloured surface) to 0.9 (dark coloured surface to determine the impact on the results. The sol-air temperature is calculated and compared to the ambient air temperature in Figure 34.

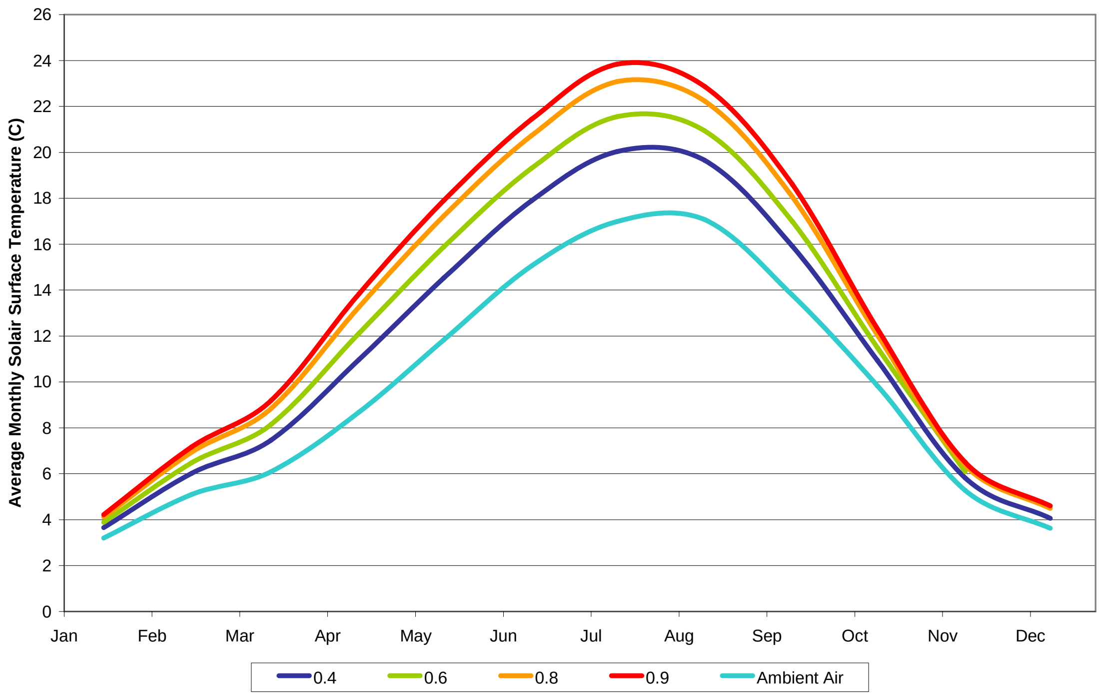


Figure 34: Monthly mean sol-air temperatures

As shown in Figure 31, the solar absorptance has a significant impact on the sol-air temperature of the cladding. A monthly mean increase of 4°C for a surface with absorptance of 0.4 compared to 0.9 is noted.

Figure 35 shows the effect of solar absorptance on the annual mean vapour pressure difference for a wall. Figure 36 shows the net annual drying potential.

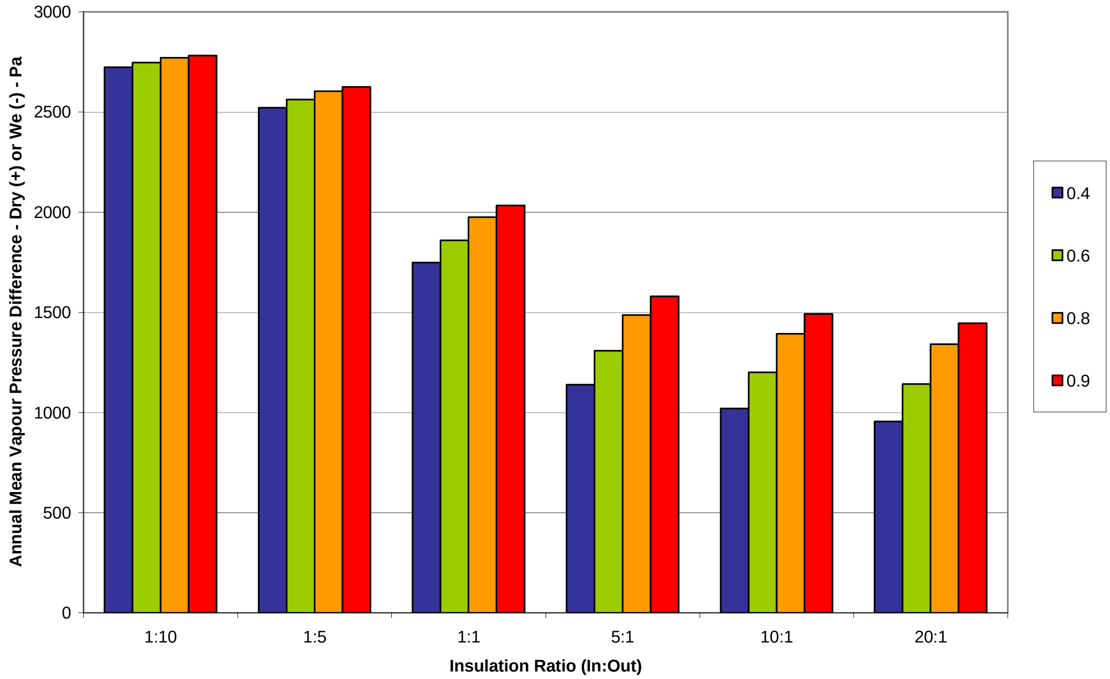


Figure 35: Annual Mean vapour Pressure Difference – Solar Absorptance Dependent

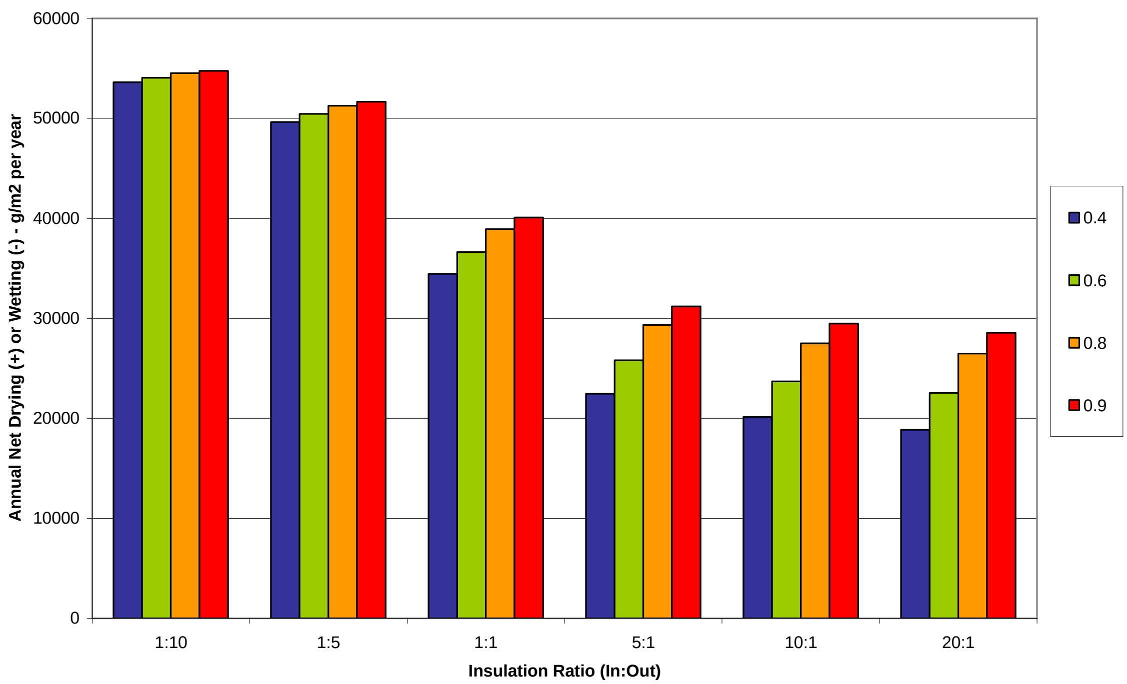


Figure 36: Annual Net Drying Potential – Solar Absorptance Dependent

Higher solar absorptance (dark materials) can increase the drying rate by up to 30% over light colored walls (solar absorptance of 0.9 for dark and 0.4 for light).

4.1.4 Degree of Saturation

Reducing the degree of saturation of the material can be compared by using the relative humidity at the surface of the material.

Figure 37 shows the effect of solar absorptance on the annual mean vapour pressure difference for a wall. Figure 38 shows the net annual drying potential.

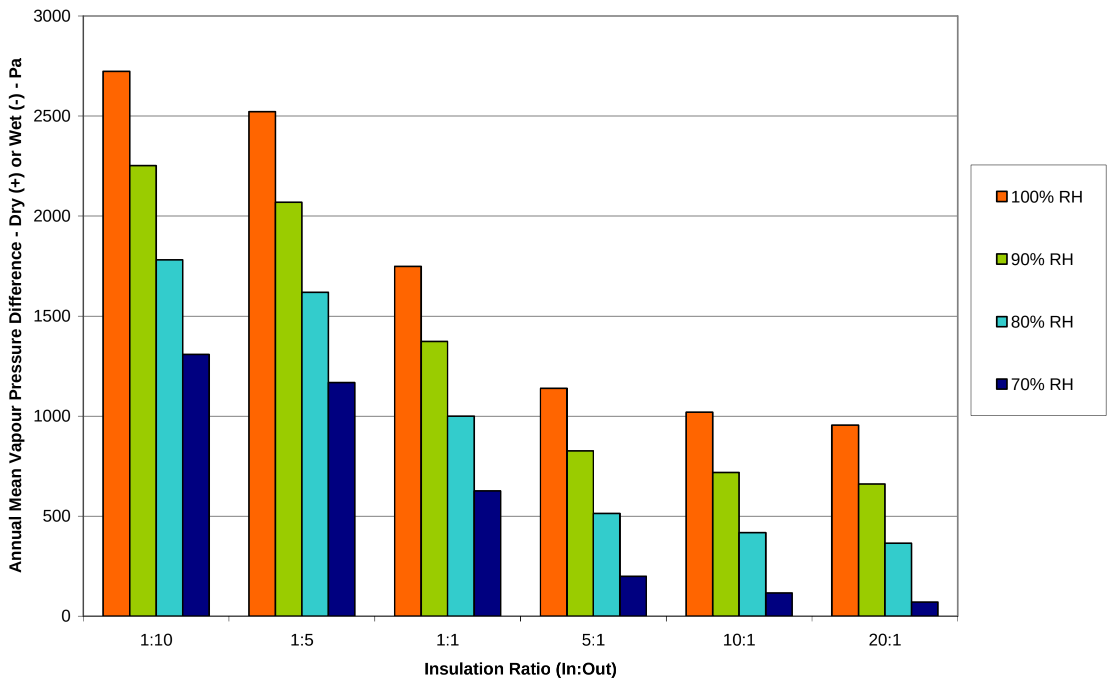


Figure 37: Impact of Degree of Saturation on Vapour Pressure difference

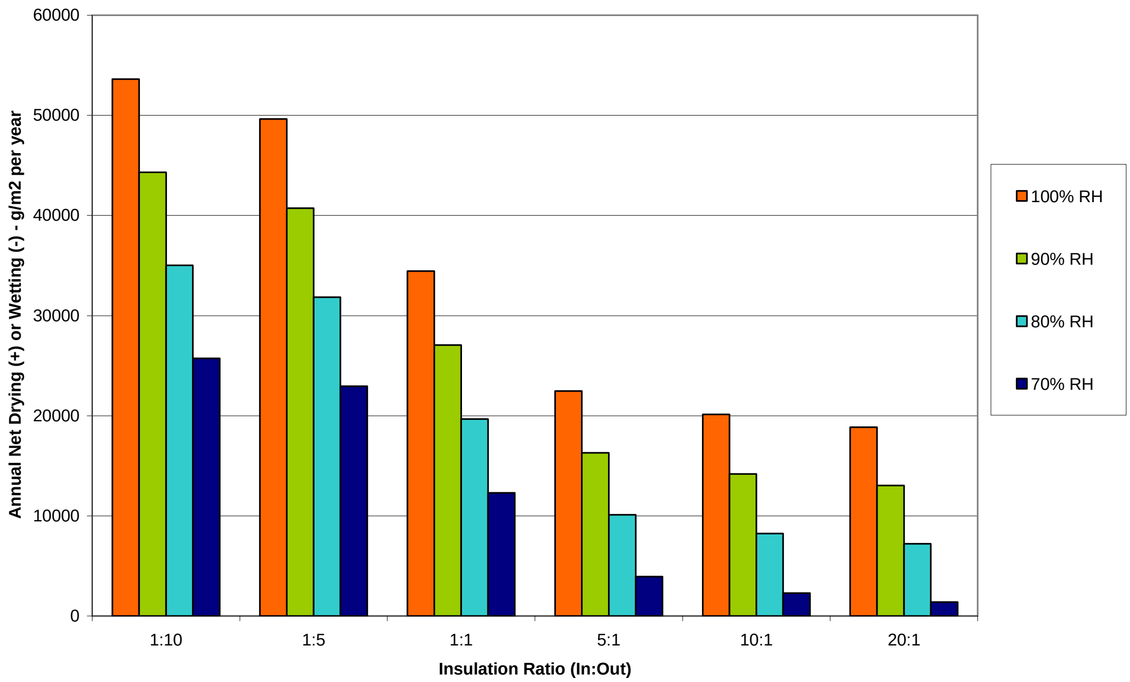


Figure 38: Impact of Degree of Saturation on Net Drying Potential.

As shown reducing the relative humidity at the wetted material surface significantly reduces the drying rate as the vapour pressure difference is reduced. The relationship is linear, 90% RH has a 90% drying rate, 80% RH has an 80% drying rate etc.

4.1.5 Differences between Monthly and Hourly Data

Differences between using monthly mean versus hourly mean values for analysis were compared.

Results from an hourly analysis were compared to an analysis using monthly means of the same data. It was found that for walls with high levels of insulation on the exterior (R1 in: R10 out) and subsequently sheathing temperatures close to interior the average vapour pressure driving rates ranged from -1.2% to +1.2% difference from the hourly values. Typically, the monthly means produced higher drying rates in the winter months and lower in the summer. On an annual basis there was a negligible 1 Pa difference (0.0%).

For the walls with high levels of insulation on the interior (R20 in: R 1 out) and subsequently sheathing temperature close to exterior the average vapour pressure driving rates ranged from -54.0% to -10.0% difference from the hourly values. Typically the monthly means produced lower drying rates in the winter months than the summer. On an annual basis there was a 13% difference, the hourly values allowed more drying than the monthly means. This can be explained by the more variable conditions the interior insulated wall will experience on a daily basis. Sol-air surface temperatures significantly increase the cladding surface and sheathing temperature, which increases the drying rates. This has a significant impact during the winter months and if not included the monthly rates would be lower. Table 8 compares these differences on a monthly and annual period, showing the relative importance of using hourly values with this model.

Table 8: Differences between Monthly and Hourly Data Accuracy.

R1:10 wall	Vapour Pressure Differences		R20:1 wall	Vapour Pressure Differences	
Monthly	Hourly	% diff to hourly	monthly	hourly	% diff to hourly
2852	2840.1	0.4%	22	47.1	-53.9%
2821	2818.8	0.1%	215	268.7	-20.0%
2857	2846.8	0.4%	408	499.2	-18.4%
2882	2893.7	-0.4%	884	1094.1	-19.2%
2788	2792.4	-0.2%	1364	1554.7	-12.2%
2637	2646.1	-0.4%	1887	2113.0	-10.7%
2479	2507.8	-1.2%	2230	2548.7	-12.5%
2402	2418.7	-0.7%	2060	2295.9	-10.3%
2578	2578.7	0.0%	1417	1638.8	-13.5%
2713	2704.7	0.3%	709	788.1	-10.0%
2847	2812.8	1.2%	221	259.0	-14.8%
2834	2816.8	0.6%	40	61.8	-35.3%
2724.09	2723.1	0.0%	954.67	1097.4	-13.0%

While an hourly analysis of the drying potential yields more accurate results, for purposes of a simple preliminary analysis an inaccuracy in the order of 10-15% when monthly mean values are used is acceptable, as long as the user is aware of these differences. The monthly mean analysis will underestimate the vapour pressure differences and thus produce more conservative results for interior insulated walls. When the walls are exterior insulated the monthly mean produces similar results within 1-2% of the hourly values as the impact of sol-air temperatures are dampened.

4.2 Walls through History

Typical wall assemblies developed in Section 3.2 (summarized in Table 4) are compared in Figures 39 through 46. A significant reduction in drying potential in walls from the 1980's and 1990's is shown.

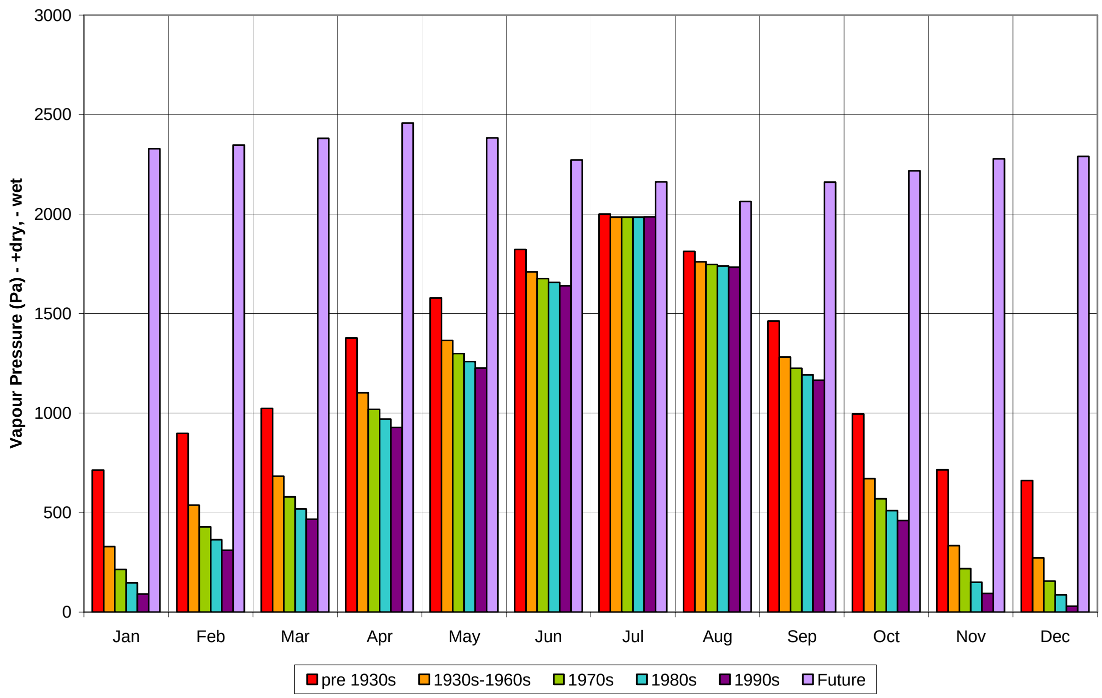


Figure 39: Monthly Average Vapour Pressure Difference – Historical Walls

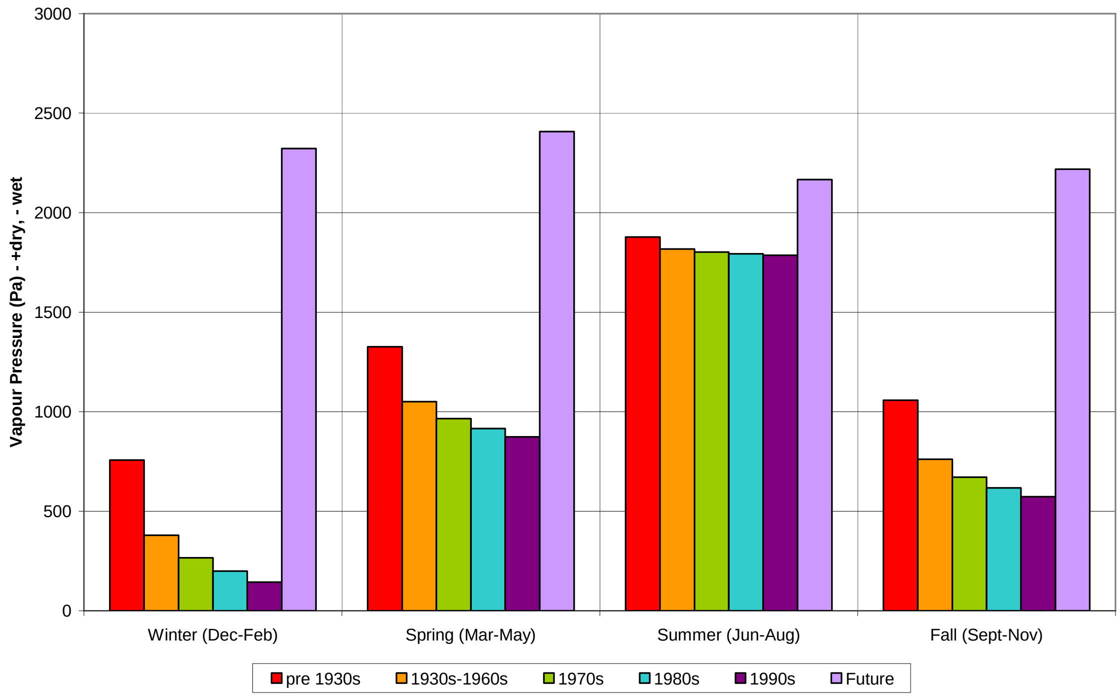


Figure 40: Seasonal Average Vapour Pressure Difference – Historical Walls

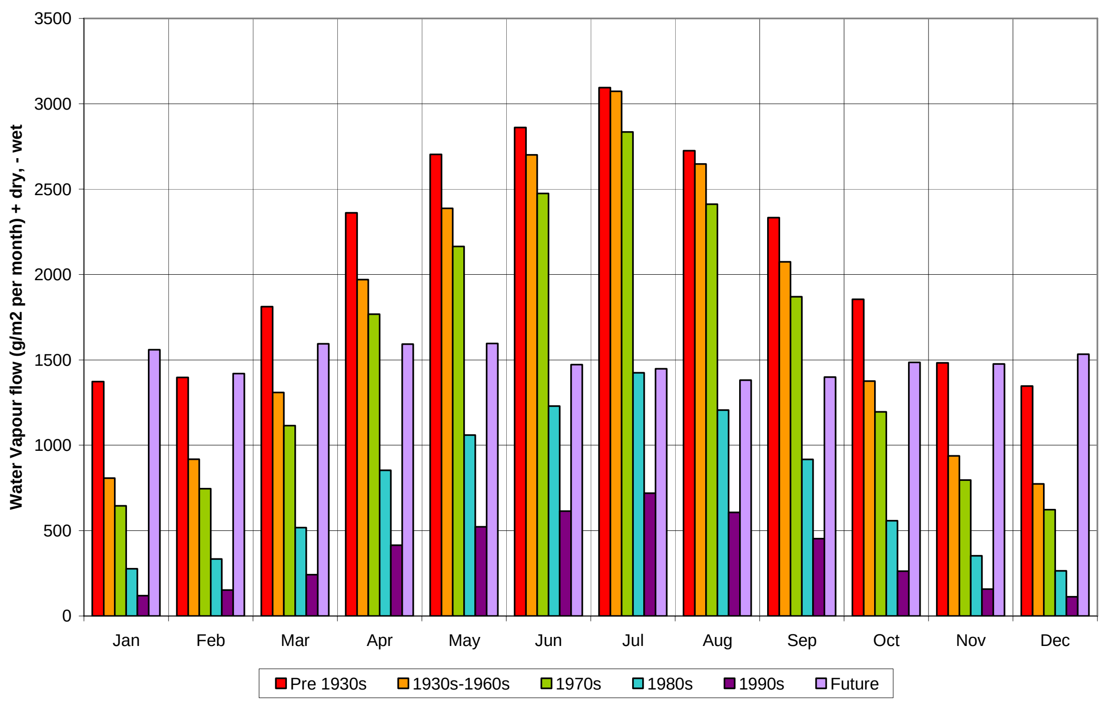


Figure 41: Monthly Net Drying Potential – Historical Walls

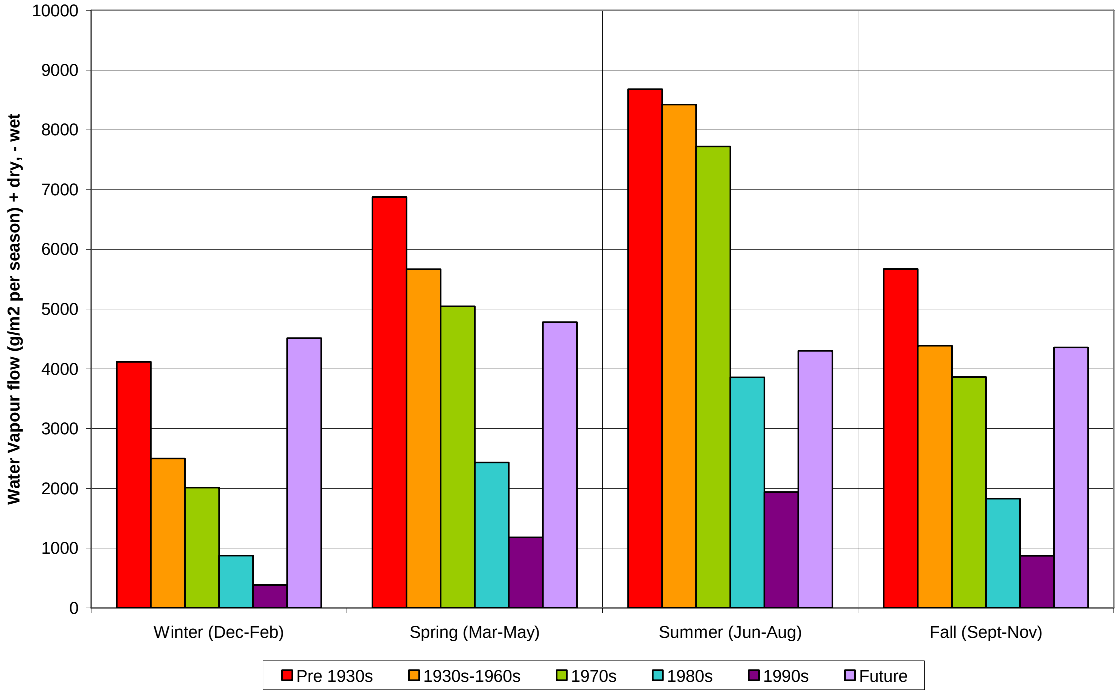


Figure 42: Seasonal Net Drying Potential – Historical Walls

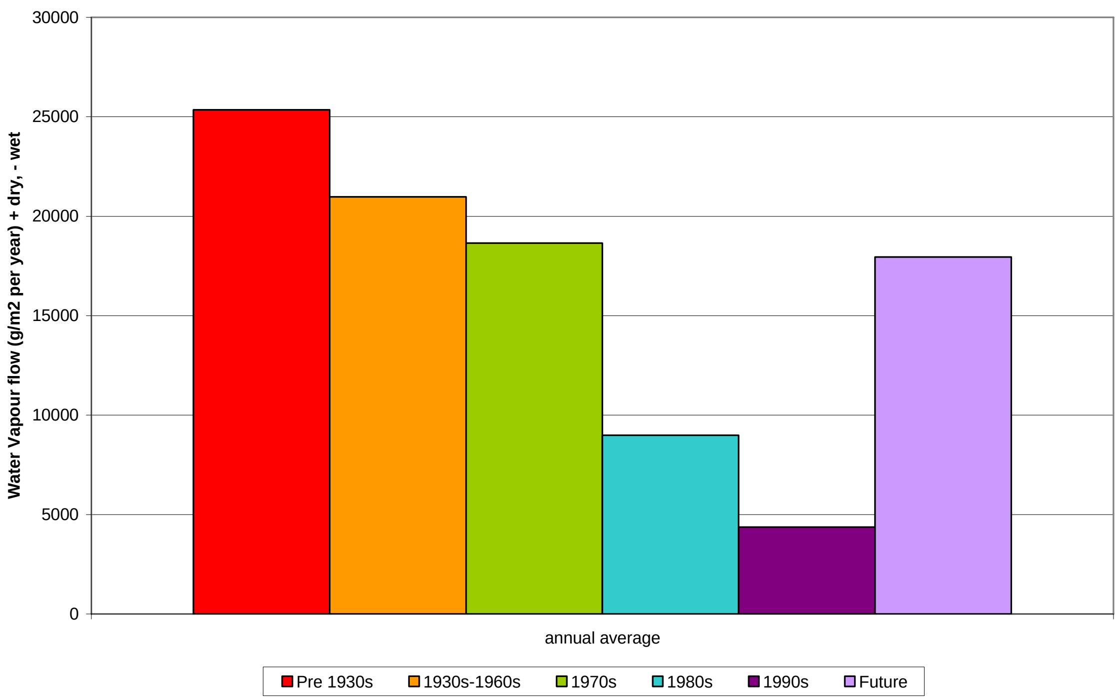


Figure 43: Seasonal Net Drying Potential – Historical Walls

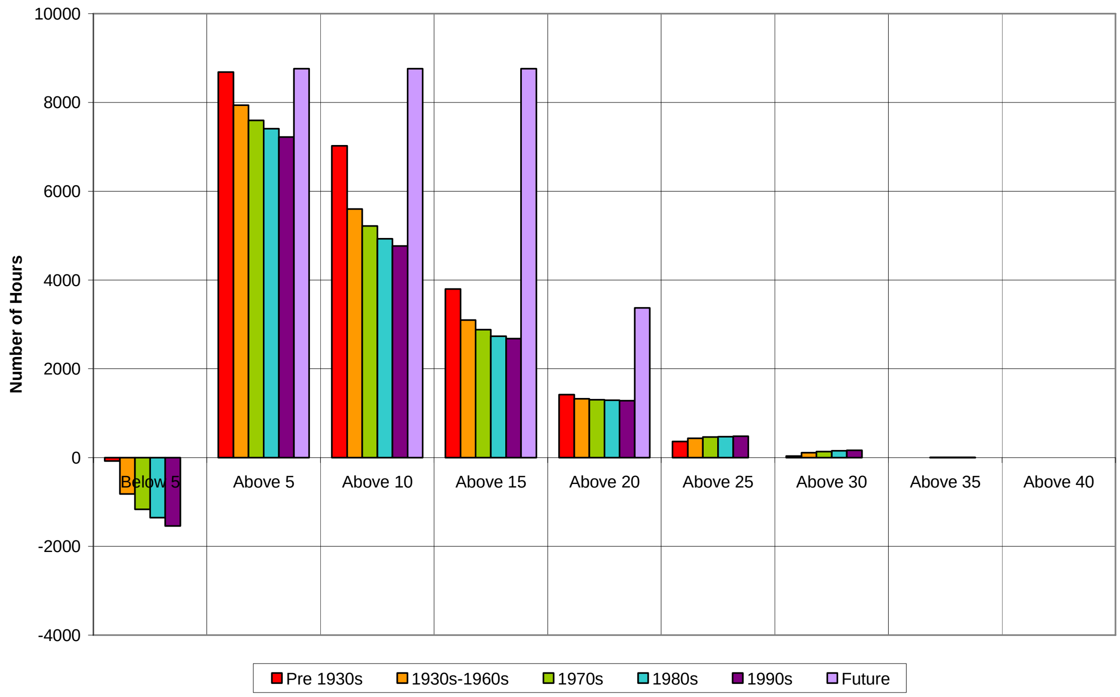


Figure 44: Annual Temperature Distribution – Historical Walls

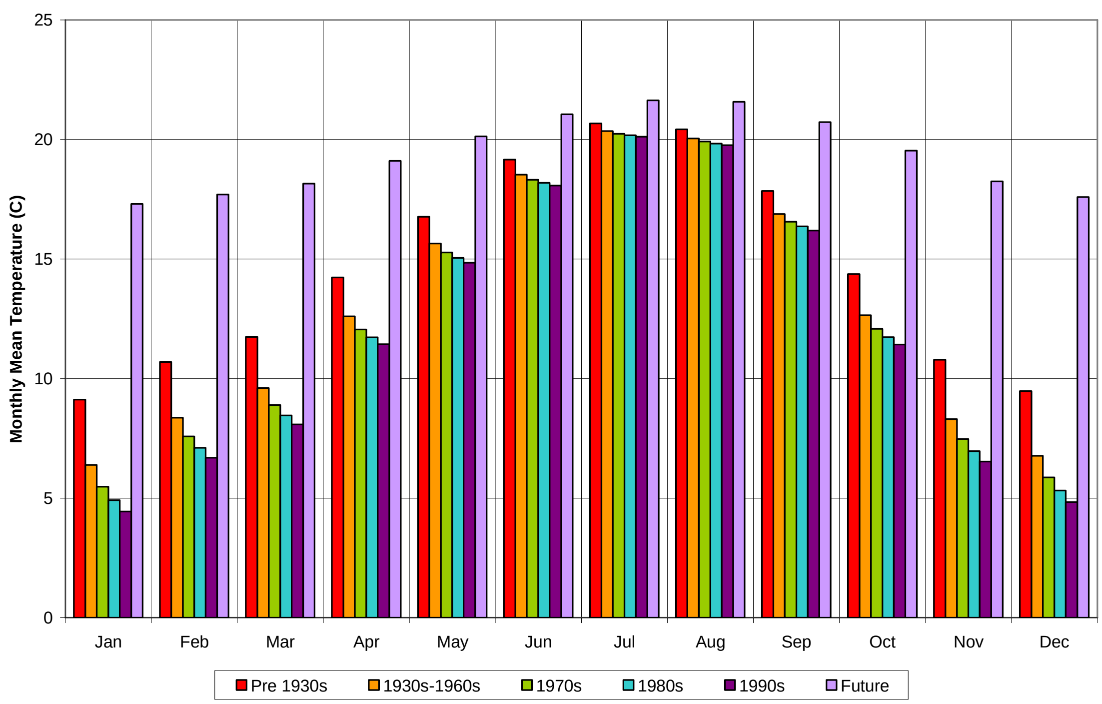


Figure 45: Monthly Average Temperature at Sheathing – Historical Walls

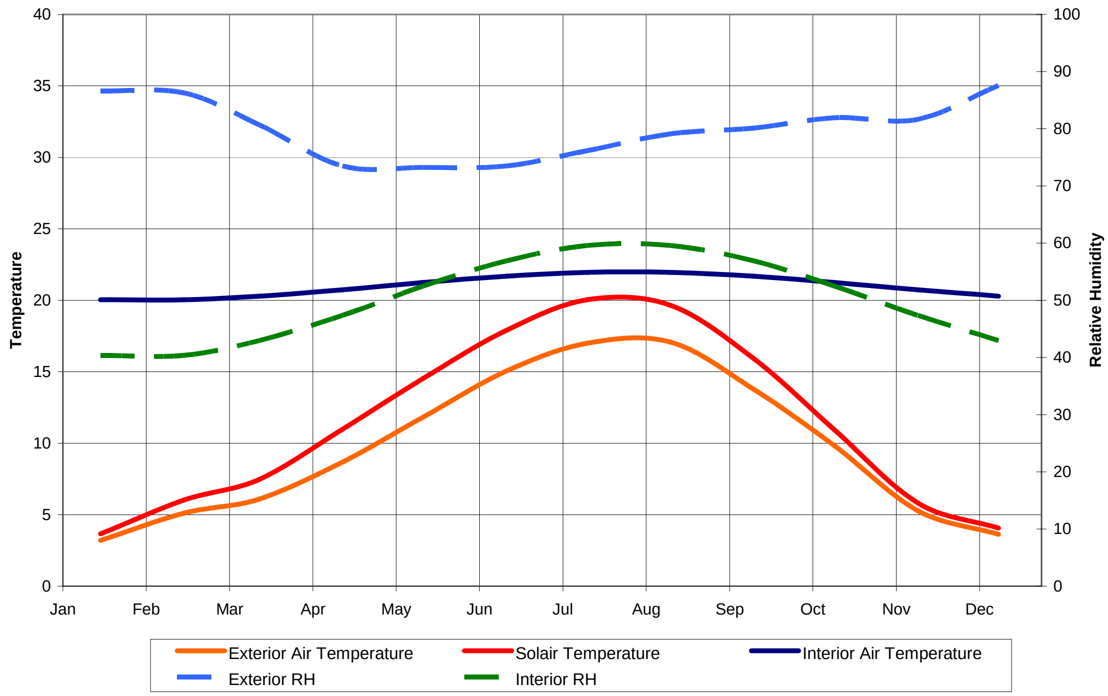


Figure 46: Monthly Average Exterior and Interior Boundary Conditions

5 SOURCES OF MOISTURE

As seen in the 1980's and 90's significant and catastrophic moisture damage can occur in Vancouver's climate. The damage occurs when there is a net accumulation of moisture and that moisture is sufficient and present for long enough to sustain mould growth followed by decay. Yet as shown all the walls above, there is a general drying potential provided that the interior relative humidity is kept below approximately 50% depending on the wall assembly. Yet there has been significant moisture damage, especially in walls with lower permeance materials. The moisture source must therefore be greater than the drying rate. Two other possible sources are air leakage condensation and rain water leakage.

Air leakage condensation is relatively well understood, and there have been a large number of documented moisture problems in Canada as a result of air leakage condensation. Air leakage condensation can occur when warm moist indoor air infiltrates the stud cavity under positive pressure from the interior. The warm moist air will potentially condense on the sheathing when the sheathing temperature is below the dewpoint temperature of the indoor air. Air leakage can be accounted for by increasing the effective permeance (by an order or two of magnitude) or by adding an effective convective permeance value in parallel with the diffusive permeance value calculated previously. Thus air leakage will not only cause wetting but also drying. Wetting is likely only to occur during the winter months, while drying will occur for the remainder of the year. Therefore air leakage will contribute to moisture but also increase the potential drying rate.

Driving Rain leakage may be assumed based on a percentage of the total driving rain which penetrates the cladding and moisture barrier. For Vancouver, a maximum annual driving rain load of 764 kg/m^2 is calculated for exposed east elevation from the CWEC weather file (Straube 2005b). Of this rain, we could assume that perhaps 1% of this rain manages to reach the exterior moisture sensitive cladding. 1% of 764 kg/m^2 is 7.6 kg/m^2, which can potentially exceed the drying amount for a number of the wall configurations discussed above. At a window sill or other poorly detailed penetration possibly 5% or 38 kg/m^2 of water per year can penetrate the wall into the sheathing. 38 kg/m^2 absorbing into 11 mm OSB of 600 kg/m^3 density (6.6 kg/m^2) would increase the moisture content significantly above fiber saturation. Even 1% of the maximum driving rain load increases the moisture content well above fiber saturation (30%). Depending on the annual drying rate, this moisture may accumulate every year until conditions for mould growth and decay are reached. Based on observations and numerous studies of failures in Vancouver's climate, the moisture source was typically rain and leaks at penetrations through the cladding typically provided the moisture source.

6 CONCLUSIONS

A model was developed to assess the drying potential for any wall assembly in any given location. From the environmental conditions, net vapour pressure drives and a maximum net drying potential for a given wall assembly are determined for a desired time period.

Exterior insulated walls in Vancouver's climate will always have a net annual drying rate higher than interior insulated walls. Walls which are not insulated will also dry faster than interior insulated walls.

Exterior insulated walls have mean annual monthly temperatures close to interior conditions, as a result drying during the summer months is reduced, however annually exterior insulated walls still have a higher drying rate than interior insulated or uninsulated walls

As the Interior relative humidity increases, the vapour pressure driving force and maximum drying potential is reduced. With high relative humidity rates and high permeance materials to the interior, the net annual drying potential could be negative, or net wetting will occur.

The south elevation has the highest drying potential; the North elevation has the lowest. The difference in drying rates can be 20% lower on North elevations compared to the

South for interior insulated walls. The East and West elevations have similar drying potentials with the East elevation having a marginally higher drying rate.

Higher solar absorptance (dark materials) can increase the drying rate by up to 30% over light colored walls (solar absorptance of 0.9 for dark and 0.4 for light).

Reducing the relative humidity at the wetted material surface significantly reduces the drying rate. This is observed in practice in materials that dry out in a non-uniform rate.

While an hourly analysis of the drying potential yields more accurate results, for purposes of a simple preliminary analysis an inaccuracy in the order of 10-15% when monthly mean values are used is acceptable, as long as the user is aware. The monthly mean analysis will underestimate the vapour pressure differences and thus produce more conservative results for interior insulated walls. When the walls are exterior insulated the monthly mean produces similar results within 1-2% of the hourly values.

The drying potential for historical walls from the 1980's and 1990's is significantly lower than that for the previous decades. The drying potential for walls constructed during the 1980's and 1990's is significantly lower than that of the previous decade as shown in Figure 47.

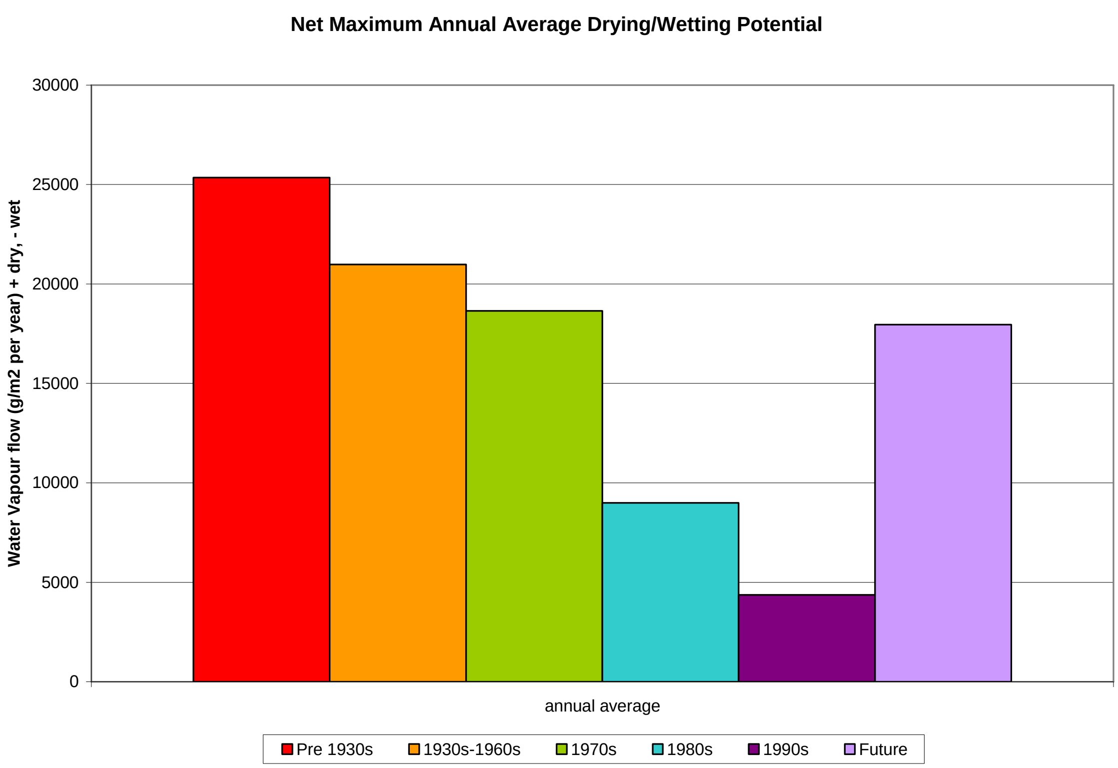


Figure 47: Net Annual Drying Potential for Historical Walls

Currently most walls constructed today are being produced with materials and practice similar to those from the 1990's. These walls have a very low drying potential, which can be improved by better material choice and configuration. Modern walls which are exterior insulated and use vapour semi-permeable materials throughout the wall assembly can achieve drying rates previously seen in the 1930's to 70's. At the same time these new modern walls will also be more energy efficient.

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8 MATERIAL PROPERTIES

Table A-1: Vapour Permeance of typical residential building materials

Material	Thickness (mm)	Permeability (ng/m s Pa)	Permeance (ng/m² s Pa)	Source	Comments – Test Type
Construction Materials – Wood					
Plywood	19	13.30	700	NRC	90% RH
Plywood	16	7.99	500	NRC	90% RH
Plywood	13	6.50	500	NRC	90% RH
Plywood, 400-600 kg/m³	19	20 – 30	1052 – 1579	Straube	Saturated
OSB	13	2.75	212	NRC	90% RH
OSB	11	4.08	371	NRC	90% RH
OSB	9.5	3.83	403	NRC	90% RH
OSB, 575-725 kg/m³	11	4 – 5	364 – 455	Straube	Saturated
Wood Fiber Board, 320 kg/m²	11	18.1	1645	NRC	90% RH
Fibreboard – asphalt coated, 300 kg/m³	11	22	2000	Straube	
Fibreboard, untreated	12.5		2520	H&H	Wet Cup
Fibreboard, sheathing grade	12.5		1780	H&H	Wet Cup
Wood, sugar pine	19	0.58-7.8	30 – 411	ASHRAE	Other
Construction Materials – Plaster and Gypsum					
Plaster on Wood Lath	19		860	ASHRAE	Other
Plaster on Wood Lath	19		630	H&H	Wet cup
Plaster on Metal Lath	19		630	ASHRAE	Wet cup
Plaster on plain gypsum lath	19		1140	ASHRAE	Other
Plaster on plain gypsum lath on studs			1150	H&H	Other
Gypsum plaster	19	12 – 22	630 - 1160	Straube	Lath

Material	**Thickness** **(mm)**	**Permeability** **(ng/m s Pa)**	**Permeance** **(ng/m² s Pa)**	**Source**	**Comments – Test Type**
on gypsum lath					dependent
Gypsum wall board	9.5		2860	ASHRAE	Other
Gypsum wall board	9.5		2870	H&H	Other
Gypsum wall board 625 kg/m³	13		3190	NRC	50% RH
Gypsum wall board with one coat primer	13		2200	NRC	50% RH
Gypsum wall board with one coat primer and two coats latex paint	13		400	NRC	50% RH
Gypsum wall board 700-900 kg/m³	13	25	1923	Straube	Wet cup
Exterior Gypsum wall board, 900 kg/m³	13	25	1923	Straube	Wet cup
Fiberglass faced exterior gypsum, Densglass Gold	13		1320	Georgia Pacific	Dry cup
Regular Gypsum wall board	13		2296	Georgia Pacific	Dry cup
Construction Materials – Cladding					
Hardboard Siding 740 kg/m²	11	5.58	507	NRC	90% RH
Clay Brick 1980 kg/m³	100	5.50	55	NRC	90% RH
Brick Masonry	100		46	H&H	Other
Face Brick	100	2.5 – 20	25 – 200	Straube	Other

Material	**Thickness** **(mm)**	**Permeability** **(ng/m s Pa)**	**Permeance** **(ng/m² s Pa)**	**Source**	**Comments – Test Type**
Cement Stucco	19	5 – 12	263 – 632	Straube	Wet cup
Cement-Lime Stucco	19	9.7 – 26	511 – 1368	Straube	Other
Portland Stucco 1985 kg/m³	19	3.26	172	NRC	90% RH
Fiber cement board 1380 kg/m³	8	14.80	1850	NRC	90% RH
Cement Board 1130 kg/m³	13	16.10	1238	NRC	90% RH
Synthetic Stucco	3		200 – 300	Straube	Other
Siloxane Sealers			500 – 1500	Straube	Other
Wood Siding, painted, ventilation at joints	13		2010	ASHRAE	Other
Thermal Insulations					
Air (still)		174		ASHRAE	All conditions
Air		185		WUFI	
Mineral Wool, Rockwool	50	245	4900	ASHRAE	All conditions
Semi-rigid mineral wool insulation, Roxul	50		1807	Roxul	All conditions
Expanded Polystyrene (XPS)		1.7		ASHRAE	All conditions
XPS, 28.6 kg/m³	50	1.22	24	NRC	All conditions
Expanded Polystyrene (EPS)	50	2.9 – 8.4	58 - 168	ASHRAE	Dry cup
EPS, 14.8 kg/m³	50	5.50	110	NRC	90% RH
EPS	50	3 – 8.5	60 - 170	H&H	Dry cup
Glass Fiber Batt	89	172	1932	NRC	All Conditions

Material	Thickness (mm)	Permeability (ng/m s Pa)	Permeance (ng/m² s Pa)	Source	Comments – Test Type
11.5 kg/m³					
Cellulose Fiber, dry blown 30 kg/m³	89	168	1888	NRC	70% RH
Spray Polyurethane Foam, closed cell 39 kg/m³	50	3.22	64.4	NRC	90% RH
Spray polyurethane foam, closed cell 40					
Spray Polyurethane Foam, open cell 6.5 to 8.5 kg/m³	89	87.50	983	NRC	All conditions
Polyisocyanurate	50	6.55	131	NRC	90% RH
Plastic and Metal Foils					
Aluminium Foil	0.025		0	ASHRAE	All conditions
Polyethylene (4 mil)	0.1		4.6	ASHRAE	All conditions
Polyethylene (6 mil)	0.15		3.4	ASHRAE	All conditions
Peel and Stick Bituminous Membranes	2		2.8	Sto, Bakor, Grace	All Conditions
Building Paper, Felts, Roofing Papers					
Asphalt laminated, aluminium foil one side			10	ASHRAE	Wet cup
Kraft paper and asphalt laminated,			103	ASHRAE	Wet cup

Material	**Thickness** **(mm)**	**Permeability** **(ng/m s Pa)**	**Permeance** **(ng/m² s Pa)**	**Source**	**Comments – Test Type**
reinforced					
Blanket thermal insulation backup paper, asphalt coated			34 – 240	ASHRAE	Wet cup
Asphalt-saturated but not coated, sheathing paper			1160	ASHRAE	Wet cup
Asphalt-saturated sheathing paper (15lb)			480	H&H	Wet cup
Asphalt-saturated building paper (25lb)			370	H&H	Wet cup
Asphalt-saturated building paper (heavy weight)			360	H&H	Wet cup
Asphalt-saturated roofing felt (15lb)			680	H&H	Wet cup
Tar-infused sheathing paper			1770	H&H	Wet cup
Asphalt-infused sheathing paper			1080	H&H	Wet cup
Asphalt-coated building paper			63	H&H	Wet cup
Perforated Asphalt Coated sheathing paper			800	H&H	Wet cup
Asphalt Sheathing paper			400 – 1800	Straube	RH dependent
Single Kraft, double			2400	ASHRAE	Wet cup
Bituminous Paper (#15 felt), 515 g/m²	0.72		1170	NRC	90% RH
Asphalt Impregnated Paper, 10 min. rating 170 g/m²	0.2		3060	NRC	90% RH

Material	**Thickness** **(mm)**	**Permeability** **(ng/m s Pa)**	**Permeance** **(ng/m² s Pa)**	**Source**	**Comments – Test Type**
Asphalt Impregnated Paper, 30 min. rating 200 g/m²	0.22		4670	NRC	90% RH
Asphalt Impregnated Paper, 60 min. rating 280 g/m²	0.34		4240	NRC	90% RH
Spun Bonded Polyolefin (SPBO)	0.15		4370	NRC	All conditions
Tyvek (Canada)			1800	Dupont	All conditions
Tyvek (USA)			3330	Dupont	All conditions
Vinyl Wallpaper	0.21		210	NRC	50% RH
Stucco Breather Board	3		300-400	Hal-Tex Industries	Wet Cup
Liquid Applied Coating Materials					
Vapour Retarder Paint			26	ASHRAE	Other
Latex Primer-Sealer			360	ASHRAE	Other
Vinyl Acrylic Primer			491	ASHRAE	Other
Exterior Acrylic House and Trim			313	ASHRAE	Other
Various Primers plus 1 coat flat oil paint on plaster			91 – 172	ASHRAE	Other
Exterior Paint, white lead and oil on wood siding			17-57	ASHRAE	Dry cup
Polyvinyl Acetate Latex Coating			315	ASHRAE	Dry cup
Enamels on Smooth plaster			29 – 86	ASHRAE	Other

Sources: **ASHRAE** = (ASHRAE Handbook of Fundamentals 2005), **NRC** = (National Research Council MEWS), **H&H** = (Building Science for a Cold Climate Hutcheon and Handegord, from ASHRAE HOF 1981 and from NRCC #8838, 1963), **Straube** (Building Science for Building Enclosures, 2005)

Table A-2: Thermal Properties of typical wood frame building materials.

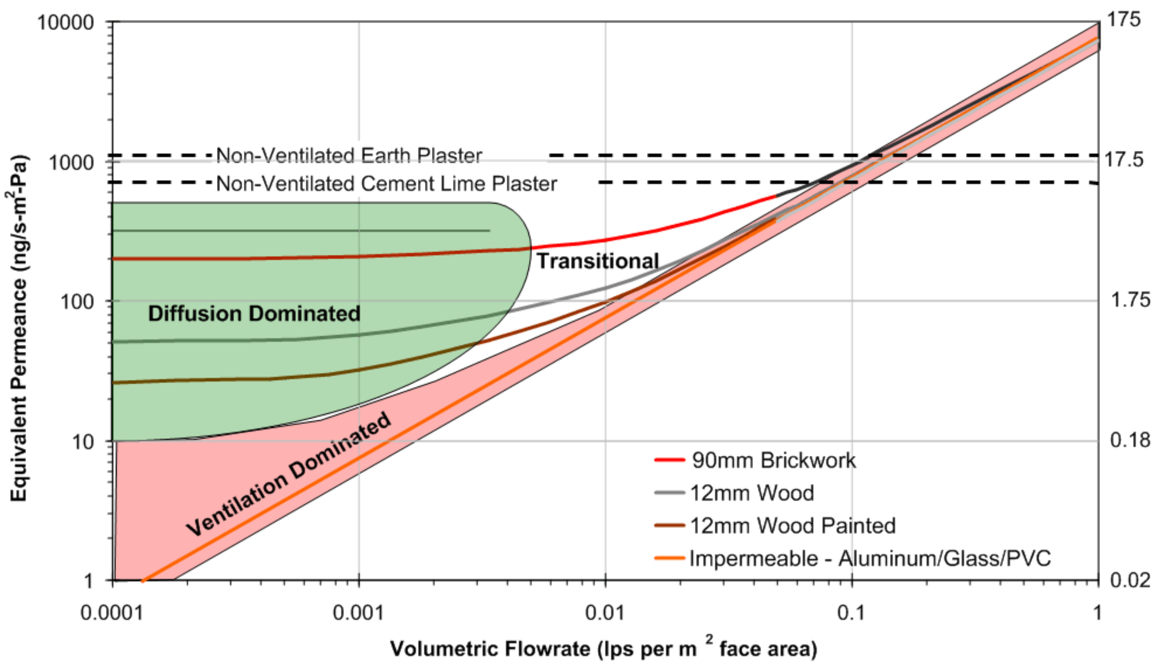
Material	Thickness (mm)	Conductivity k – (W/m K)	Conductance C = k/t (W/m² K)	Thermal Resistance RSI = 1/C (K m²/W)	Source
Construction Materials					
Plywood	19	0.08 – 0.11	4.2 – 5.8	0.24 – 0.17	Straube
OSB	11	0.09 – 0.12	8.2 – 10.9	0.12 – 0.09	Straube
Gypsum Board	13	0.16	12.3	0.08	Straube
Gypsum Plaster and Lath	19	0.16 – 0.35	8.4 – 18.4	0.12 – 0.05	Straube
Sand cement plaster	19	0.53	27.9	0.04	Straube
Concrete	200	1.4 – 2.6	7 – 13	0.14 – 0.08	Straube
Lightweight concrete block			2.84	0.35	Straube
Fiberboard, 270 kg/m³	13	0.052	4	0.25	Straube
Cladding Materials					
Hardboard Siding	12	0.094	7.83	0.13	Straube
Face Brick – clay	100	1.3	13	0.08	Straube
Wood Siding – Lap	12	0.1 – 0.12	8.3 – 10	0.12 – 0.1	Straube
Cement Stucco	19	0.7 – 1.4	36 – 74	0.03 – 0.01	Straube
Thermal Insulations					

EPS type 1, 16 kg/m^3	25	0.039	1.56	0.64 (R 3.6 per inch)	Straube
EPS type 2, 24-32 kg/m^3	25	0.034	1.36	0.74 (R 4.2 per inch)	Straube
XPS type 3 and 4	25	0.029	1.16	0.86 (R 4.9 per inch)	Straube
Mineral wool, Rockwool	25	0.034	1.36	0.74 (R 4.2 per inch)	Straube
Fiberglass Batt Insulation	25	0.036 – 0.048	1.44 – 1.92	0.69 – 0.52 (R 4 to R 3 per inch)	Straube
Rigid polyurethane	25	0.024	0.96	1.04 (R 5.9 per inch)	Straube
Cellulose Fiber, 37-51 kg/m^3	25	0.039 – 0.046	1.56 – 1.84	0.64 – 0.54 (R 3.6 to 3.1 per inch)	Straube
Sawdust	25	0.05 – 0.08	2 – 3.2	0.5 – 0.31 (R 2.8 to 1.8 per inch)	Straube
Vermiculite, exfoliated, 64-130 kg/m^3	25	0.06 – 0.07	2.4 – 2.8	0.42 – 0.36 (R 2.4 to 2.0 per inch)	Straube
Perlite, expanded, 320 kg/m^3	25	0.07 – 0.08	2.8 – 3.2	0.36 – 0.31 (R 2 to R 1.8 per inch)	Straube
Perlite, bonded expanded, 16 kg/m^3	25	0.052	2.1	0.48 (R 2.7 per inch)	Straube
Eel Grass Batt, 145-215 kg/m^3	25	0.043 – 0.049	1.7 – 2.0	0.59 – 0.51 (R 3.3 to R 2.9 per inch)	Straube
Plane Air Spaces – See Table 3, pg 25.4 ASHRAE 2005					
Heat flow Horizontal, Effective Emittance 0.82, 10 mean, 5 diff	13			0.16	
Heat flow	20			0.18	

Horizontal, Effective Emittance 0.82, 10 mean, 5 diff					
Heat flow Horizontal, Effective Emittance 0.82, 10 mean, 5 diff	90			0.19	

Sources: **ASHRAE** = (ASHRAE Handbook of Fundamentals 2005), **NRC** = (National Research Council MEWS), **H&H** = (Building Science for a Cold Climate Hutcheon and Handegord, from ASHRAE HOF 1981 and from NRCC #8838, 1963), **Straube** (Building Science for Building Enclosures, 2005)

Effect of Ventilated Cavities – Convective Vapour Transport (Straube 2005)



Source: Straube et al, ASHRAE 1091 Report #1, 2004

Appendix D: Monitoring Equipment and Sensor Information

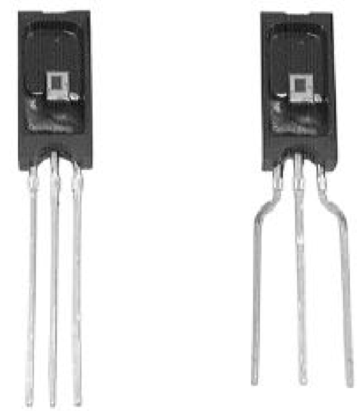
Relative humidity sensors – Honeywell HIH-3610-002

Humidity Sensors
Humidity Sensor

HIH-3610 Series

FEATURES
- Molded thermoset plastic housing with cover
- Linear voltage output vs %RH
- Laser trimmed interchangeability
- Low power design
- High accuracy
- Fast response time
- Stable, low drift performance
- Chemically resistant

TYPICAL APPLICATIONS
- Refrigeration
- Drying
- Metrology
- Battery-powered systems
- OEM assemblies



The HIH-3610 Series humidity sensor is designed specifically for high volume OEM (Original Equipment Manufacturer) users. Direct input to a controller or other device is made possible by this sensor's linear voltage output. With a typical current draw of only 200 µA, the HIH-3610 Series is ideally suited for low drain, battery operated systems. Tight sensor interchangeability reduces or eliminates OEM production calibration costs. Individual sensor calibration data is available.

The HIH-3610 Series delivers instrumentation-quality RH (Relative Humidity) sensing performance in a low cost, solderable SIP (Single In-line Package). Available in two lead spacing configurations, the RH sensor is a laser trimmed thermoset polymer capacitive sensing element with on-chip integrated signal conditioning. The sensing element's multilayer construction provides excellent resistance to application hazards such as wetting, dust, dirt, oils, and common environmental chemicals.

⚠WARNING
PERSONAL INJURY
- DO NOT USE these products as safety or emergency stop devices, or in any other application where failure of the product could result in personal injury.

Failure to comply with these instructions could result in death or serious injury.

⚠WARNING
MISUSE OF DOCUMENTATION
- The information presented in this product sheet is for reference only. Do not use this document as system installation information
- Complete installation, operation, and maintenance information is provided in the instructions supplied with each product.

Failure to comply with these instructions could result in death or serious injury.

Humidity Sensors

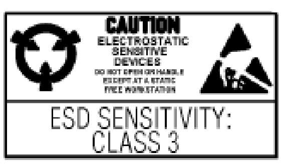
Humidity Sensor *HIH-3610 Series*

TABLE 1: PERFORMANCE SPECIFICATIONS

Parameter	Condition
RH Accuracy[1]	±2% RH, 0-100% RH non-condensing, 25 °C, V_{supply} = 5 Vdc
RH Interchangeability	±5% RH, 0-60% RH; ±8% @ 90% RH typical
RH Linearity	±0.5% RH typical
RH Hysteresis	±1.2% RH span maximum
RH Repeatability	±0.5% RH
RH Response Time, 1/e	15 sec in slowly moving air at 25 °C
RH Stability	±1% RH typical at 50% RH in 5 years
Power Requirements	
Voltage Supply	4 Vdc to 5.8 Vdc, sensor calibrated at 5 Vdc
Current Supply	200 µA at 5 Vdc
Voltage Output	$V_{out} = V_{supply}$(0.0062(Sensor RH) + 0.16), typical @ 25 °C (Data printout option provides a similar, but sensor specific, equation at 25 °C.)
V_{supply} = 5 Vdc	0.8 Vdc to 3.9 Vdc output @ 25 °C typical
Drive Limits	Push/pull symmetric; 50 µA typical, 20 µA minimum, 100 µA maximum Turn-on ≤ 0.1 sec
Temperature Compensation	True RH = (Sensor RH)/(1.093-0.0012T), T in °F True RH = (Sensor RH)/(1.0546-0.00216T), T in °C
Effect @ 0% RH	±0.007 %RH/°C (negligible)
Effect @ 100% RH	-0.22% RH/°C (<1% RH effect typical in occupied space systems above 15 °C (59 °F))
Humidity Range	
Operating	0 to 100% RH, non-condensing[1]
Storage	0 to 90% RH, non-condensing
Temperature Range	
Operating	-40 °C to 85 °C (-40 °F to 185 °F)
Storage	-51 °C to 125 °C (-60 °F to 257 °F)
Package[2]	Three pin, solderable SIP in molded thermoset plastic housing with thermoplastic cover
Handling	Static sensitive diode protected to 15 kV maximum

Notes:

1. Extended exposure to ≥90% RH causes a reversible shift of 3% RH.
2. This sensor is light sensitive. For best results, shield the sensor from bright light.



Humidity/Moisture Sensors
Humidity Sensor
HIH-3610 Series

FACTORY CALIBRATION

HIH-3610 sensors may be ordered with a calibration and data printout (Table 2). See order guide on back page.

TABLE 2: EXAMPLE DATA PRINTOUT

Model	HIH-3610-001
Channel	92
Wafer	030996M
MRP	337313
Calculated values at 5 V V_{out} @ 0% RH V_{out} @ 75.3% RH	 0.958 V 3.268 V
Linear output for 2% RH accuracy @ 25 °C Zero offset Slope RH	 0.958 V 30.680 mV/%RH (V_{out}-zero offset)/slope (V_{out}-0.958)/0.0307
Ratiometric response for 0 to 100% RH V_{out}	 V_{supply} (0.1915 to 0.8130)

FIGURE 1: RH SENSOR CONSTRUCTION

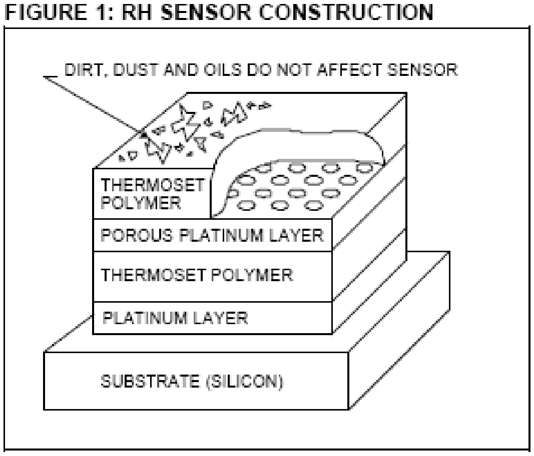


FIGURE 2: OUTPUT VOLTAGE VS RELATIVE HUMIDITY AT 0 °C

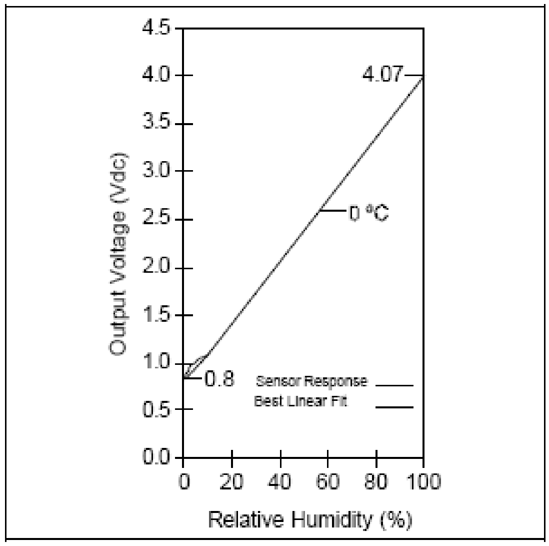
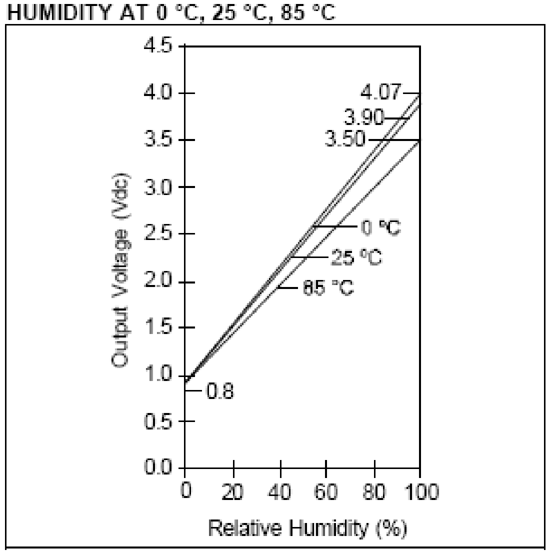


FIGURE 3: OUTPUT VOLTAGE VS RELATIVE HUMIDITY AT 0 °C, 25 °C, 85 °C



Humidity/Moisture Sensors

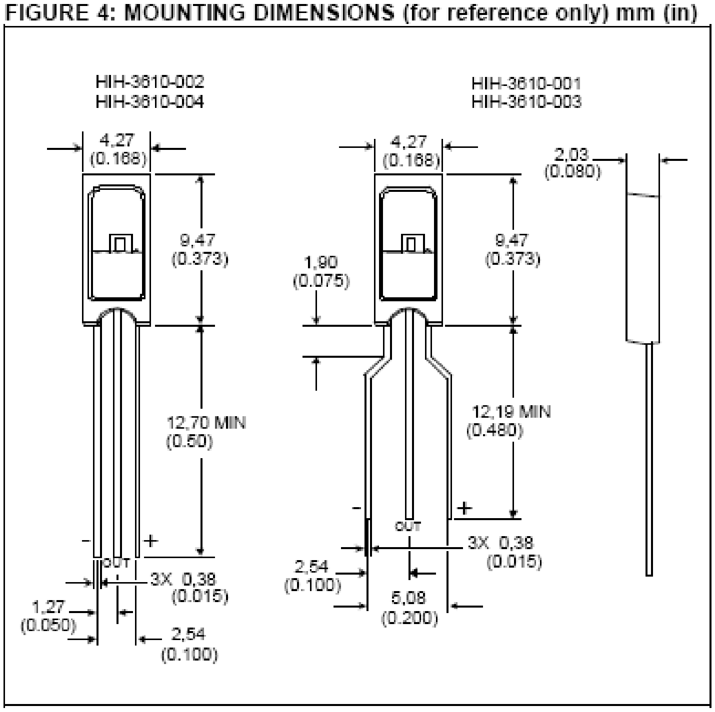
Humidity Sensor

HIH-3610 Series

ORDER GUIDE

Catalog Listing	Description
HIH-3610-001	Integrated circuit humidity sensor, 0.100 in lead pitch SIP
HIH-3610-002	Integrated circuit humidity sensor, 0.050 in lead pitch SIP
HIH-3610-003	Integrated circuit humidity sensor, 0.100 in lead pitch SIP with calibration and data printout
HIH-3610-004	Integrated circuit humidity sensor, 0.050 in lead pitch SIP with calibration and data printout

FIGURE 4: MOUNTING DIMENSIONS (for reference only) mm (in)



WARRANTY/REMEDY

Honeywell warrants goods of its manufacture as being free of defective materials and faulty workmanship. Contact your local sales office for warranty information. If warranted goods are returned to Honeywell during the period of coverage, Honeywell will repair or replace without charge those items it finds defective. The foregoing is Buyer's sole remedy and is **in lieu of all other warranties, expressed or implied, including those of merchantability and fitness for a particular purpose.**

Specifications may change without notice. The information we supply is believed to be accurate and reliable as of this printing. However, we assume no responsibility for its use.

While we provide application assistance personally, through our literature and the Honeywell web site, it is up to the customer to determine the suitability of the product in the application.

For application assistance, current specifications, or name of the nearest Authorized Distributor, check the Honeywell web site or call:
1-800-537-6945 USA
1-800-737-3360 Canada
1-815-235-6847 International

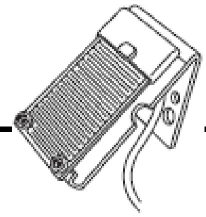
FAX
1-815-235-6545 USA

INTERNET
www.honeywell.com/sensing
info.sc@honeywell.com

WETNESS SENSORS – Davis 6420

Leaf Wetness Sensor

For the Wireless Leaf & Soil Moisture/
Temperature Station (# 6345)



6420

Vantage Pro2™ Accessories

The Leaf Wetness Sensor detects the presence of surface moisture. The sensor is an artificial-leaf electrical-resistance type. It consists of a sensing grid, low-voltage bi-polar excitation circuit, and conductivity-sensing circuit. The Vantage Pro2 console measures the conductivity across the grid and displays the result as a moisture level, scaled from 0 to 15. The user may select the threshold level at and above which moisture-hour totals are accumulated.

The sensing grid is a gold-plated etched circuit on an epoxy-glass substrate; the excitation and sense circuits are encapsulated in black epoxy. The included mounting bracket holds the sensor at a 45° angle to simulate a typical leaf position and to permit runoff of excess moisture; it may be mounted on a vertical post, pipe, or stake, or on the Sensor Mounting Arm.

General

Sensor Type	Artificial leaf electrical resistance
Excitation	Bipolar (3V nominal) built-in
Time Constant	2 seconds
Attached Cable Length	40' (12 m)

Note: Increasing the cable length above the recommended maximum cable length causes measurement error in the form of lower leaf wetness readings.

Cable Type	4-conductor, 26 AWG
Connector	Modular connector (RJ-11)
Recommended Maximum Cable Length (see Note 1)	200' (61 m) using 4-conductor 26 AWG cable
Material	
Substrate	Glass-reinforced, ceramic-filled laminate
Grid	1 oz. copper, nickel, and 50 μ inch gold plate
Mounting Bracket	White powder-coated aluminum
Dimensions (length x width x height)	
Leaf Wetness Sensor	4.00" x 2.25" x 2.25" (102 mm x 58 mm x 58 mm)
Sensor Area	4.4 in^2 (28 cm^2)
Weight	13 oz. (.4 kg)

Sensor Output

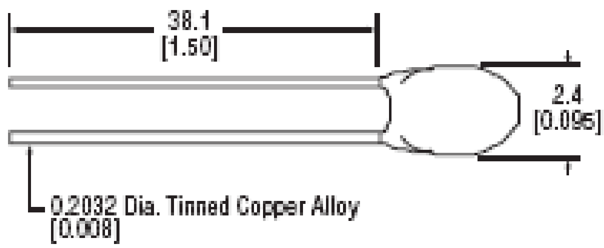
Resolution	1
Range	0 to 15
Dry/Wet Threshold	User-selectable
Accuracy	±0.5
Update Interval	62.5 to 75 seconds

Input/Output

Supply Voltage and Current	100 μA (typical) @ 3 VDC
Output	2.5 to 3 VDC
Connections	
Yellow	3 VDC
Red	Ground
Green	Output

Temperature Thermistors – Fenwal uni-curve 192-103LET-A01

192 Series Unicurve® R-T Matched Interchangeable NTC Thermistors



UNI-CURVE® INTERCHANGEABLE THERMISTORS are high quality, low cost resistance temperature matched interchangeable thermistors. They offer additional cost savings by eliminating the need for individual resistance temperature calibration, as well as standardization of circuit components and simplification of design and replacement problems. They are particularly well suited for use in applications such as temperature measurement, indication and control. Other applications include: compensation of ambient temperature effects on copper coils, transistors, integrated circuits and other semiconductor devices.

Features

- Applications: Temperature Measurement, Indication, and Control Accuracy
- High Stability; High Reliability; Long Life
- Small Size
- Epoxy Coated; Lead Material = Tinned Copper Alloy
- Dissipation Constant = 0.75 mW/°C In Still Air Minimum
- Time Constant = 15 Sec. In Still Air Maximum
- Resistance Range = 1K Ohm to 100K Ohm
- Maximum Temperature = 150°C

Stock No.	Mfr.'s Type	Ohms @ 25°C	Tolerance ± °C	Resistance Ratio	EACH
254-0064	192-501DET-A01	500	0.2	6.35	3.81
254-0065	192-102DEW-A01	1K	1.0	6.35	1.74
254-0066	192-222LET-A01	2.2K	0.2	9.10	3.81
254-0067	192-222LEV-A01	2.2K	0.5	9.10	3.13
254-0068	192-302LET-A01	3K	0.2	9.10	2.47
254-0069	192-502LET-A01	5K	0.2	9.10	3.81
254-0070	192-103LET-A01	10K	0.2	9.10	3.81
254-0071	192-103LEV-A01	10K	0.5	9.10	3.13
254-0072	192-103LEW-A01	10K	1.0	9.10	2.58
254-0073	192-103LFW-A01	10K	1.0	9.10	2.58
254-0074	192-303KET-A01	30K	0.2	8.72	3.81
254-0076	192-303QET-A01	30K	0.2	8.72	3.81
254-0075	192-303KET-A02	30K	0.2	8.72	3.81
254-0077	192-503QET-A01	50K	0.2	8.72	3.81
254-0078	192-104QET-A01	100K	0.2	8.72	2.47

PRESSURE – SETRA MODEL 265

INSTALLATION GUIDE
SETRA SYSTEMS MODEL 265
DIFFERENTIAL PRESSURE TRANSDUCER

1.0 GENERAL INFORMATION
Every Model 265 has been tested and calibrated before shipment. Specific performance specifications are shown on page 3 of this Guide.

Setra Systems 265 pressure transducers sense differential or gage (static) pressure and convert this pressure difference to a proportional high level analog output for both unidirectional and bidirectional pressure ranges. Two standard output versions are offered: A voltage output of 0 to 5 VDC or a current output of 4 to 20mA. Optional voltage outputs are available. Check the label on the unit to confirm the excitation and output.

2.0 MECHANICAL INSTALLATION

2.1 Media Compatibility
Model 265 transducers are designed to be used with air or nonconducting gases. **Use with liquids or corrosive gases will damage the unit.**

2.2 Environment
The operating and compensated temperature limits of the 265 are 0∞F to +150∞F (-18∞C to +65∞C).

2.3 Pressure Fittings
The Model 265 is supplied with two factory installed 1/4" O.D. pressure fittings for the pressure signal connection and typically installed with 1/4" push-on tubing. Both the positive (high) pressure port and the reference (low) pressure port are located on the front of the unit, labeled "HIGH" and "LOW" respectively. For best results (shortest response times), 3/16" I.D. tubing is suggested for tubing lengths up to 100 feet long, 1/4" I.D. for tubing is suggested for tubing lengths up to 100 feet long, 1/4" I.D. for tubing lengths up to 300 feet, and 3/8" I.D. for tubing lengths up to 900 feet.

3.0 ELECTRICAL INSTALLATION
If the Model 265 is supplied with the optional Conduit Enclosure, access the electrical terminations by removing the cover.

3.1 Voltage Output Units
The Model 265 voltage output is a 3-wire circuit, with three terminals available for wiring. These terminals have the designation COM, OUT and EXC (see Diagram 1).
[Note: The "–" designation above COM and the "+" designation above EXC are designations for the current output terminals.] The -Excitation and -Output are commoned on the circuit (see Diagram 2). The 265 voltage output can operate from 9-30 VDC excitation. The 265 has a 0-5 output.

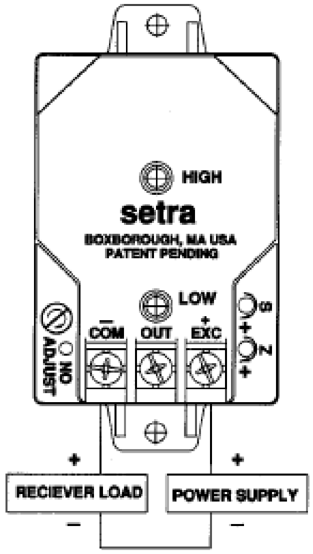


Diagram 1

Voltage Circuit Diagram

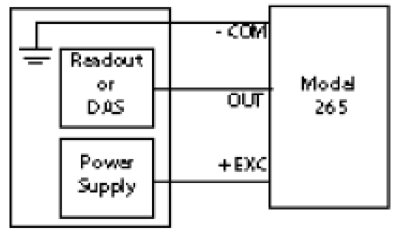


Diagram 2

+EXC Connected to positive terminal of DC power supply.
GND Connect as the reference for power supply and output signal.
+SIG Connect to positive terminal of control or pressure monitor.

3.2 **Current Output Units**

The Model 265 is a two-wire loop-powered 4 to 20mA current output unit (see Diagram 3). The current flows into + terminal and returns back to the power supply through the -terminal (see Diagram 3). The power supply must be a DC voltage source with a voltage range between 9 and 30 measured between terminal + and - terminals. The unit is calibrated at the factory with a 24 VDC loop supply voltage and a 250 ohm load.

Current Circuit Diagram

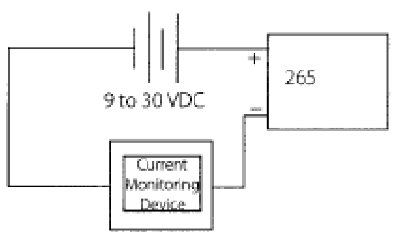


Diagram 3

4.0 CALIBRATION

The 265 transducer is factory calibrated and should require no field adjustment. Generally, the mounting position will have a zero shift effect on ranges below 1" WC. Whenever possible, any zero and/or span offsets should be corrected by software adjustment in the user's control system. However, both zero and span adjustments are accessible either on the front of the unit or by removing the optional conduit enclosure. The 265 transducer is calibrated in the vertical position at the factory.

4.1 Voltage Output Zero Adjustment

While monitoring the voltage between the positive output (OUT) and common (COM), and with both pressure ports open to atmosphere, the zero may be adjusted by turning the zero adjustment screw. (See Diagram 1 for location of zero adjustment.) For 0-5 VDC output units, the factory settings are 0.0 VDC (±50mV) for unidirectional pressure ranges and 2.5 VDC (±50mV) for bidirectional pressure ranges. Optional outputs are set at the same ±1% factory setting.

4.2 Voltage Output Span Adjustment (Complete the zero adjustment before setting span.) Span or full scale output adjustments should only be performed by using an accurate pressure standard (electronic manometer, digital pressure gage, etc.), with at least comparable accuracy to the 265 transducer (<±1% FS). With full range pressure applied to the high pressure port (reference port open to atmosphere), the span may be adjusted by turning the SPAN adjustment screw. (See Diagram 1 for location of the SPAN adjustment.) For 0-5 VDC output units, the factory settings are 5.0 VDC (±50mV) for unidirectional and bidirectional ranges. Optional outputs are set at the same ±1% factory setting.

4.3 Current Output Zero Adjustment
While monitoring the current output between +EXC and OUT, and with both pressure ports open to atmosphere, the zero may be adjusted by turning the zero adjustment screw (See Diagram 1 for location of zero adjustment.) The factory settings are 4mA (0.16mA) for unidirectional pressure ranges and 12mA (0.16mA) for bidirectional ranges.

4.4 Current Output Span Adjustment
Span or full scale output adjustments should only be performed by using an accurate pressure standard (electronic manometer, digital pressure gage, etc.) with at least comparable accuracy to the 265 transducer (<±1% FS). With full range pressure applied to the high pressure port (reference port open to atmosphere), the span may be adjusted by turning the SPAN adjustment screw. (See Diagram 1 for location of SPAN adjustment.) The factory settings are 20mA (0.16mA) for unidirectional and bidirectional pressure ranges.

5.0 MODEL 265 PERFORMANCE SPECIFICATIONS

Accuracy RSS*		<u>Thermal Effects</u>	
(at constant temperature)	±1.0% FS	Compensated Range ∞F(∞C)	0 to +150 (-18 to+65)
Non-Linearity, BFSL	±0.98% FS	Zero/Span Shift %FS/∞F(∞C)	0.033 (0.06)
Hysteresis	0.1% FS	Maximum Line Pressure	10 psi
Non-Repeatability	0.05% FS	Overpressure	10 psi in positive or negative direction
		Warm-up Shift	±0.1% FS total
*RSS of Non-Linearity, Non-Repeatability and Hysteresis			

<u>Positive Effects</u>
(Unit is factory calibrated at Og effect in the vertical position)

Range	**Zero Offset (%FS/G)**
0 to 1" WC	.22
0 to 5" WC	.14
0 to 30" WC	.06

6.0 RETURNING PRODUCTS FOR REPAIR
Please contact a Setra application engineer (800-257-3872, 978-263-1400) before returning unit for repair to review information relative to your application. Many times only minor field adjustments may be necessary. When returning a product to Setra, the material should be carefully packaged and shipped prepaid to:

Setra Systems, Inc.
159 Swanson Road
Boxborough, MA 01719-1304
Attn: Repair Department

To assure prompt handling, please supply the following information and include it inside the package of returned material:

1. Name and phone number of person to contact.
2. Shipping and billing instructions.
3. Full description of the malfunction.
4. Identify any hazardous material used with product.

Notes: Please remove any pressure fittings and plumbing that you have installed and enclose any required mating connectors and wiring diagrams.

Allow approximately 3 weeks after receipt at Setra for the repair and return of the unit. Non-warranty repairs will not be made without customer approval and a purchase order to cover repair charges.

Calibration Services

Setra maintains a complete calibration facility that is traceable to the National Institute of Standards & Technology (NIST). If you would like to recalibrate or recertify your Setra pressure transducers or transmitters, please call our Repair Department at 800-257-3872 (978-263-1400) for scheduling.

7.0 LIMITED WARRANTY AND LIMITATION OF LIABILITY

SETRA warrants its products to be free from defects in materials and workmanship, subject to the following terms and conditions: Without charge, SETRA will repair or replace products found to be defective in materials or workmanship within the warranty period; provided that:

a) the product has not been subjected to abuse, neglect, accident, incorrect wiring not our own, improper installation or servicing, or use in violation of instructions furnished by SETRA;
b) the product has not been repaired or altered by anyone except SETRA for its authorized service agencies;
c) the serial number or date code has not been removed, defaced, or otherwise changed; and
d) examination discloses, in the judgment of SETRA, the defect in materials or workmanship developed under normal installation, use and service;
e) SETRA is notified in advance of and the product is returned to SETRA transportation pre-paid.

Unless otherwise specified in a manual or warranty card, or agreed to in a writing signed by a SETRA officer, SETRA pressure and acceleration products shall be warranted for one year from date of sale.

The foregoing warranty is in lieu of all warranties, express, implied or statutory, including but not limited to, any implied warranty of merchantability for a particular purpose.

SETRA's liability for breach of warranty is limited to repair or replacement, or if the goods cannot be repaired or replaced, to a refund of the purchase price. SETRA's liability for all other breaches is limited to a refund of the purchase price. In no instance shall SETRA be liable for incidental or consequential damages arising from a breach of warranty, or from the use or installation of its products.

No representative or person is authorized to give any warranty other than as set out above or to assume for SETRA any other liability in connection with the sale of its products.

159 Swanson Road, Boxborough, MA 01719-1304; 800-257-3872;
(978) 263-1400; Fax. 978-264-0292; WEB; www.setra.com;
E-mail: transducer.sales@setra.com
Rev. E 4/06/99

WINDSPEED/DIRECTION – OMEGA – WMS-22

Wind Monitor Stations with Arm or Analog Outputs

WMS-21, dual setpoint wind station, $690, shown smaller than actual size.

WMS-23S, wind speed and direction module, $675, shown smaller than actual size.

WMS-23, wind speed and direction module, $730, shown smaller than actual size.

WMS Series Starts at **$675**

The WMS-20 Series consist of 3 individual wind monitor stations. The WMS-21 is a microprocessor-based wind alarm station. It sounds an alarm buzzer and controls the operation of 2 electrical circuits whenever wind speed reaches either of 2 independent setpoints. An LCD display provides a readout of the measured wind speed and is also used to set the value of the setpoints which are stored in non-volatile memory. Self-contained relays for each alarm point can be used to actuate external devices such as air samplers or sirens. The WMS-23 Series monitors wind speed and direction. Two versions are offered; WMS-23S measures wind speed only, while the WMS-23 measures both wind speed and direction. Each parameter is converted into a 4 to 20 mA signal for use by process controllers or monitoring systems.

Specifications
WMS-21
Wind Speed

Measurement Range: 0 to 100 mph
Transducer Type: Reed switch
Avg Speed Resolution: 0.1 mph
Threshold Speed: 0.8 mph
Measurement Accuracy: 1 mph or 3%
Controls: Protected push-button for run, or set variables, select menu items, increment and decrement alarm values
Alarm On/Off Delay Range: 0 to 99 sec
Contact Ratings: 3 A SPDT @ 24 Vdc
Display: 2 line x 16 character LCD
Character Size: 3 x 8 mm
Setpoint 1 and 2: LED
Supply Voltage: 12 Vac or Vdc
Supply Current: 50 mA, 5 mA nominal
Operating Temperature: -20 to 50°C (-4 to 122°F)
Dimensions:
- **Anemometer:** 114.3 H x 215.9 W mm (4.5 x 8.5")
- **Sensor Cable Length:** 12 m (40'), supplied
- **Electronics Enclosure Size:** 119.3 H x 198.1 W x 88.9 D mm (4.7 x 7.8 x 3.5")

WMS-23 (Wind Speed and Direction) WMS-23S (Wind Speed)

Measurement Range: 0 to 100 mph
Transducer Type: Reed switch
Threshold Speed: 0.8 mph
Measurement Accuracy: 1 mph or 3%

WMS-23 Only (Wind Direction)

Azimuth Accuracy: ± 3%
Mechanical Range: 0 to 360°
Potentiometer Gap: 5°
Threshold: 1.2 mph
Measurement Range: 0 to 360°
Current Loop:
- **Output Span:** 4 to 20 mA
- **Proportioned:** 0 to 100 mph, 0 to 360°
- **Circuit Time Constant:** 1 sec
- **2-Wire Loop Interface:** Screw terminal block
- **Supply Voltage:** 8 to 30 Vdc
- **Operating Temperature:** -40 to 40°C (-40 to 104°F)

Dimensions:
- **Anemometer and Vane:** 305 H x 254 W mm (12 x 10")
- **Anemometer Only:** 114.3 H x 215.9 W mm (4.5 x 8.5")
- **Sensor Cable Length:** 12 m (40'), supplied
- **Electronics Enclosure Size:** 114.3 H x 114.3 W x 63.5 D mm (4.5 x 4.5 x 2.5")

MOST POPULAR MODELS HIGHLIGHTED!

To Order *(Specify Model Number)*

Model No.	Price	Description
WMS-21	$725	Dual setpoint wind station
WMS-23S	675	Wind speed only 4 to 20 mA output
WMS-23	730	Wind speed/direction 4 to 20 mA output
WMS-EC-40	40	12 m (40') extension cable

Comes with sensor cable and operator's manual.
Ordering Example: WMS-23, wind speed/direction wind station with 4 to 20 mA output and cable, $730, and WMS-EC-40, 12 m (40') extra extension cable, $40, $730 + 40 = $770.

Hu-73

OMEGA Engineering
Model WMS-22 and WMS-22A Current Loop WindStations

Instruction Manual

1.0 INTRODUCTION

The WMS-22 Current Loop WindStation measures wind speed and direction and converts each paramenter into 4-20 mA output signals for use by process control or monitoring systems. No external power is required since the encoding electronics for wind speed and for wind direction are isolated and powered from their respective 2-wire current loops.

The WMS-22 wind sensor includes a three-cup anemometer and wind vane. The sensor is ruggedly constructed of UV-resistant ABS plastic and anodized aluminum parts. The cable that connects the pole-mounted wind sensor to the encoder electronics package may be extended up to a total of 250 feet. The encoded current loops signals may be transmitted over distances of up to several miles. The electronics package, which is typically mounted in an indoor locations, is supplied in a gasketed, wall-mounted NEMA-4X enclosure.

The measurement time base for the wind speed-to-current conversion in the encoder is crystal controlled for stable long-term accuracy. Likewise, ratiometric signal conditioning is used to the direction measurement circuitry to minimize drift and non-linerity.

Two versions are offered; the WMS-22A measures wind speed only, while the WMS-22 measures both wind speed and direction. The WMS-22 systems consist of two subassemblies: a wind sensor and a signal conditioning electronics assembly.

2.0 PHYSICAL DESCRIPTION

2.1 The Wind Sensor

The rotating assembly containing the three-cup anemometer and wind vane for sensing wind speed and directional information is called the wind sensor. The wind vane is mounted on a common axis with the anemometer and includes a tail fin with a nose weight that provides balance. The wind vane is coupled to an angular encoder which is housed within the cylindrical weather skirt.

2.2 The Encoder

The encoder electronics package is housed in a sealed NEMA enclosure and contains two independent 4-20 mA data channels, one for wind speed and the second for wind direction. Each is powered from its respective 2-wire measurement loop.

2.3 Specifications

Wind Speed	
Measurement Range	0-100 mph
Averaging Interval	2.1 Seconds
Resolution	1 mph
Threshold	≤1 mph
Measurement Accuracy	±3% F.S.
Wind Direction	
Range	0-360° Mechanical 350° Electrical
Resolution	2 Degrees
Accuracy	±5 Degrees
Threshold	≤1 Mph
Current Loop	
Output Span	4 to 20 mA
Supply Voltage Range	10 to 48 Vdc
2-Wire Loop Interface	Screw Terminal Block

3.0 GENERAL DESCRIPTION

3.1 Wind Speed Measurement

The WMS-22 wind sensor is designed to be mounted on the end of a 1" outside diameter pole. It is supplied with 40 feet of cable for connection to the electronics housing. The anemometer's precision ball bearing is protected from the weather and has lifetime lubrication. The counterweight at the end of the wind vane balances the weight of the moving mass over its supporting bearing. It is important that the wind sensor be installed in a location free from any obstructions that would distort the natural flow of air across the sensor.

The full-scale (20 mA) output of the wind speed channel represents a measured 100 mph wind speed. The full-scale span of the direction channel represents a full 360 degree swing of the wind vane. The potentiometer used as a direction sensor for wind direction has a small arc of resistance discontinuity (typically 5-10°) straddling the North direction (indicated by the set screw in the mounting base). When the wind vane is pointing in this region, the loop current will be encoded as an underscale value of approximately 3.6 mA.

Wind Direction	Wind Speed (mph)	Loop Current (mA)	V_{1000} (Volts)
N+	0.0	4.0	0.4
NE = 45°	12.5	6.0	0.6
E = 90°	25	8.0	0.8
SE = 135°	37.5	10.0	1.0
S = 180°	50	12.0	1.2
SW = 225°	62.5	14.0	1.4
W = 270°	75	16.0	1.6
NW = 315°	87.5	18.0	1.8
N-	100	20.0	2.0

WINDSPEED/DIRECTION – RM YOUNG MODEL 05103 wind monitor

YOUNG Model 05103 **Wind Monitor**

The Wind Monitor is a high performance, rugged wind sensor. Its simplicity and corrosion-resistant construction make it ideal for a wide range of wind measuring applications.

The wind speed sensor is a four blade helicoid propeller. Propeller rotation produces an AC sine wave voltage signal with frequency directly proportional to wind speed. Slip rings and brushes are eliminated for increased reliability.

The wind direction sensor is a rugged yet lightweight vane with a sufficiently low aspect ratio to assure good fidelity in fluctuating wind conditions. Vane angle is sensed by a precision potentiometer housed in a sealed chamber. With a known excitation voltage applied to the potentiometer, the output voltage is directly proportional to vane angle. A mounting orientation ring assures correct realignment of the wind direction reference when the instrument is removed for maintenance.

The instrument is made of UV stabilized plastic with stainless steel and anodized aluminum fittings. Precision grade, stainless steel ball bearings are used. Transient protection and cable terminations are in a convenient junction box. The instrument mounts on standard 1 inch pipe.

For offshore and marine use, **Model 05106, Wind Monitor-MA** features special waterproof bearing lubricant and a sealed, heavy duty cable pigtail in place of the standard junction box. Separate signal conditioning for voltage or current outputs is available.

The Wind Monitor is available with two additional output signal options. **Model 05103V** offers calibrated 0-5 VDC outputs, convenient for use with many dataloggers. **Model 05103L** provides a calibrated 4-20 mA current signal for each channel, useful in high noise areas or for long cables (up to several kilometers). Signal conditioning electronics are integrated into the sensor junction box.

Ordering Information

WIND MONITOR	MODEL
WIND MONITOR	05103
WIND MONITOR 0-5 VDC OUTPUTS	05103V
WIND MONITOR 4-20 mA OUTPUTS	05103L
WIND MONITOR-MA (MARINE MODEL)	05106
WIND SENSOR INTERFACE (FOR USE WITH 05106) 0-5 VDC	05603C
WIND LINE DRIVER (FOR USE WITH 05106) 4-20 mA	05631C

Specifications

Range:
Wind speed: 0-100 m/s (224 mph)
Azimuth: 360° mechanical, 355° electrical (5° open)

Accuracy:
Wind speed: ±0.3 m/s (0.6 mph) or 1% of reading
Wind direction: ±3 degrees

Threshold:*
Propeller: 1.0 m/s (2.2 mph)
1.1 m/s (2.4 mph) 05106
Vane: 1.1 m/s (2.4 mph) 05103

Dynamic Response:*
Propeller distance constant (63% recovery) 2.7 m (8.9 ft)
Vane delay distance (50% recovery) 1.3 m (4.3 ft)
Damping ratio: 0.3
Damped natural wavelength: 7.4 m (24.3 ft)
Undamped natural wavelength: 7.2 m (23.6 ft)

Signal Output:
Wind speed: magnetically induced AC voltage, 3 pulses per revolution. 1800 rpm (90 Hz) = 8.8 m/s (19.7 mph)
Azimuth: analog DC voltage from conductive plastic potentiometer – resistance 10K Ω, linearity 0.25%, life expectancy – 50 million revolutions

Power Requirement:
Potentiometer excitation: 15 VDC maximum

Dimensions:
Overall height: 37 cm (14.6 in)
Overall length: 55 cm (21.7 in)
Propeller: 18 cm (7 in) diameter
Mounting: 34 mm (1.34 in) diameter (standard 1 inch pipe)

Weight:
Sensor weight: 1.0 kg (2.2 lbs)
Shipping weight: 2.3 kg (5 lbs)

**Nominal values, determined in accordance with ASTM standard procedures.*

MODEL 05103V 0-5 VDC outputs

Power Requirement:
8-24 VDC (5 mA @ 12 VDC)

Operating Temperature:
-50 to 50° C

Output Signals:
0-5.00 VDC full scale

MODEL 05103L 4-20 mA outputs

Power Requirement:
8-30 VDC (40 mA max.)

Operating Temperature:
-50 to 50° C

Output Signals:
4-20 mA full scale

CE *Complies with applicable CE directives.*
Specifications subject to change without notice.

R.M. YOUNG COMPANY
2801 Aero Park Drive
Traverse City, Michigan 49686 USA
TEL: (231) 946-3980 FAX: (231) 946-4772
E-mail: met.sales@youngusa.com
Web Site: www.youngusa.com

2. Specifications

	05103 ***05103-10***	***05106*** ***05106-10*** ***05106C*** ***05106C-10***	***05305*** ***05305-10***
Wind Speed			
Range:	0-100 m/s (0-224 mph)	0-100 m/s (0-224 mph)	0-50 m/s (0-112 mph)
Accuracy:	±0.3 m/s (±0.6 mph)	±0.3 m/s (±0.6 mph)	±0.2 m/s (±0.4 mph)
Starting Threshold:	1.0 m/s (2.2 mph)	1.1 m/s (2.4 mph)	0.4 m/s (0.9 mph)
Distant Constant (63% Recovery):	2.7 m (8.9 ft)	2.7 m (8.9 ft)	2.1 m (6.9 ft)
Output:	A/C Voltage (3 pulses per revolution) 1800 RPM 90 Hz = 8.8 m/s (19.7 mph)	A/C Voltage (3 pulses per revolution) 1800 RPM 90 Hz = 8.8 m/s (19.7 mph)	A/C Voltage (3 pulses per revolution) 1800 RPM 90 Hz = 9.2 m/s (20.6 mph)
Wind Direction			
Range:	0-360° Mechanical, 0-355° Electrical (5° Open)	0-360° Mechanical, 0-355° Electrical (5° Open)	0-360° Mechanical, 0-355° Electrical (5° Open)
Accuracy:	±3°	±3°	±3°
Starting Threshold at 10° Displacement:	1.1 m/s (2.2 mph)	1.1 m/s (2.2 mph)	0.5 m/s (1.0 mph)
Delay Distance (50% Recovery):	1.3m (4.3 ft)	1.3m (4.3 ft)	1.2m (3.9 ft)
Damping Ratio:	0.25	0.25	0.45
Damped Natural Wavelength:	7.2m (23.6 ft)	7.2m (23.6 ft)	4.4m (14.4 ft)
Output:	Analog D/C Voltage from 10kohm Potentiometer	Analog D/C Voltage from 10kohm Potentiometer	Analog D/C Voltage from 10kohm Potentiometer
Power	Switched Excitation supplied by the Datalogger	Switched Excitation supplied by the Datalogger	Switched Excitation supplied by the Datalogger

	05103 ***05103-10***	***05106*** ***05106-10*** ***05106C*** ***05106C-10***	***05305*** ***05305-10***
Operating Temperature	-50°C to 50°C, assuming non-riming conditions	-50°C to 50°C, assuming non-riming conditions	-50°C to 50°C, assuming non-riming conditions
Dimensions			
Overall:	37 cm H by 55 cm L (14.6 " H by 21.7 " L)	37 cm H by 55 cm L (14.6 " H by 21.7 " L)	38 cm H by 65 cm L (15.0 " H by 25.6 " L)
Main Housing Diameter:	5 cm (2.0 ")	5 cm (2.0 ")	5 cm (2.0 ")
Propeller Diameter:	18 cm (7.1 ")	18 cm (7.1 ")	20 cm (7.9 ")
Mounting Pipe:	34 mm (1.34 ") OD; Standard 1.0 " IPS Schedule 40	34 mm (1.34 ") OD; Standard 1.0 " IPS Schedule 40	34 mm (1.34 ") OD; Standard 1.0 " IPS Schedule 40
Weight			
Sensor:	1.5 kg (3.2 lbs)	1.5 kg (3.2 lbs)	1.1 kg (2.5 lbs)
Shipping (Approximate):	2.3 kg (5.5 lbs)	2.3 kg (5.5 lbs)	2.3 kg (5.5 lbs)
Cable	Supplied by CSC Standard Length 3.3m (10 ft) Custom Lengths Available	Supplied by RMY / CSC Standard Length 3.3m* (10 ft) Custom Lengths Available * 05106C Standard Length 1m (3.3 ft) + Custom Length (with Connectors)	Supplied by CSC Standard Length 3.3m (10 ft) Custom Lengths Available

Table 5-1 Wind Speed Multipliers (With Configuration Code 21*)				
Model	**m/s**	**kmph**	**mph**	**knots**
05103-10	0.0980	0.3528	0.2192	0.1904
05106-10	0.0980	0.3528	0.2192	0.1904
05106C	0.0980	0.3528	0.2192	0.1904
05305-10	0.1024	0.3686	0.2290	0.1989
* If Configuration Code 11 is used, the multiplier above is divided by the execution interval in seconds.				

5.2 Wind Direction

The wind vane is coupled to a 10K potentiometer. The potentiometer has a 5 degree dead band between 355 and 360 degrees, therefore the maximum signal is 355 degrees. The potentiometer is measured with a half bridge measurement instruction, which applies an excitation voltage and makes a Single-Ended voltage measurement. The multiplier converts the measurement result to degrees.

The EX-DEL-SE measurement instruction is used for dataloggers that are programmed with Edlog (e.g. CR10X, CR23X) and the CR200. The measurement result is mV; the multiplier to convert mV to degrees is 355deg/excitation mV.

The BRHalf measurement instruction is used for dataloggers that are programmed with CRBasic (e.g. CR1000, CR3000). The measurement result is the measured mV/excitation mV; the multiplier to convert mV/excitation mV to degrees is 355.

The excitation voltage, range codes, and multipliers for the different datalogger types are listed in Table 5-2.

TABLE 5-2. Parameters for Wind Direction

	CR10(X), CR510, CR200	**CR7, 21X, CR23X**	**CR800 CR1000**	**CR5000, CR3000**
Measurement Range	2500 mV, slow	5000 mV, slow/60 Hz	2500 mV, 60 Hz, reverse excitation	5000 mV, 60 Hz, reverse excitation
Excitation Voltage	2500 mV	5000 mV	2500 mV	5000 mV
Multiplier	0.142 deg/mV	0.071 deg/mV	355 deg excitation (mV/mV)	355 deg excitation (mV/mV)
Offset	0	0	0	0

MODEL 05103
WIND MONITOR

YOUNG

WIND SPEED SPECIFICATION SUMMARY

Range	0 to 60 m/s (130 mph), gust survival 100 m/s (220 mph)
Sensor	18 cm diameter 4-blade helicoid propeller molded of polypropylene
Pitch	29.4 cm air passage per revolution
Distance Constant	2.7 m (8.9 ft.) for 63% recovery
Threshold Sensitivity	1.0 m/s (2.2 mph)
Transducer	Centrally mounted stationary coil, 2K Ohm nominal DC resistance
Transducer Output	AC sine wave signal induced by rotating magnet on propeller shaft. 80 mV p-p at 100 rpm. 8.0 V p-p at 10,000 rpm.
Output Frequency	3 cycles per propeller revolution (0.0980 m/s per Hz)

WIND DIRECTION (AZIMUTH) SPECIFICATION SUMMARY

Range	360° mechanical, 355° electrical (5° open)
Sensor	Balanced vane, 38 cm (15 in) turning radius.
Damping Ratio	0.3
Delay Distance	1.3 m (4.3 ft) for 50% recovery
Threshold Sensitivity	1.1 m/s (2.5 mph) at 10° displacement
Damped Natural Wavelength	7.4 m (24.3 ft)
Undamped Natural Wavelength	7.2 m (23.6 ft)
Transducer	Precision conductive plastic potetiometer, 10K ohm resistance (±20%), 0.25% linearity, life expectancy 50 million revolutions, rated 1 watt at 40° C, 0 watts at 125° C
Transducer Excitation Requirement	Regulated DC voltage, 15 VDC max
Transducer Output	Analog DC voltage proportional to azimuth angle with regulated excitation voltage applied across potentiometer.

GENERAL

Operating Temperature: -50 to 50°C (-58 to 122°F)

INTRODUCTION

The Wind Monitor measures horizontal wind speed and direction. Originally developed for ocean data buoy use, it is rugged and corrosion resistant yet accurate and light weight. The main housing, nose cone, propeller, and other internal parts are injection molded U.V. stabilized plastic. Both the propeller and vertical shafts use stainless steel precision grade ball bearings. Bearings have light contacting teflon seals and are filled with a wide temperature range grease to help exclude contamination and moisture.

Propeller rotation produces an AC sine wave signal with frequency proportional to wind speed. This AC signal is induced in a stationary coil by a six pole magnet mounted on the propeller shaft. Three complete sine wave cycles are produced for each propeller revolution.

Vane position is transmitted by a 10K ohm precision conductive plastic potentiometer which requires a regulated excitation voltage. With a constant voltage applied to the potentiometer, the output signal is an analog voltage directly proportional to wind direction angle.

The instrument mounts on standard one inch pipe, outside diameter 34 mm (1.34"). An orientation ring is provided so the instrument can be removed for maintenance and reinstalled without loss of wind direction reference. Both the mounting post assembly and the orientation ring are secured to the mounting pipe by stainless steel band clamps. Electrical connections are made in a junction box at the base. A variety of devices are available for signal conditioning, display, and recording of wind speed and direction.

INITIAL CHECKOUT

When the Wind Monitor is unpacked it should be checked carefully for any signs of shipping damage.

Remove the plastic nut on the propeller shaft. Install the propeller on the shaft so the serial number on the propeller faces forward (into the wind). Engage the propeller into the molded ribs on the propeller shaft hub. The instrument is aligned, balanced and fully calibrated before shipment, however, it should be checked both mechanically and electrically before installation. The vane and propeller should easily rotate 360° without friction. Check vane balance by holding the instrument base so the vane surface is horizontal. It should have near neutral torque without any particular tendency to rotate. A slight imbalance will not degrade performance.

The potentiometer requires a stable DC excitation voltage. Do not exceed 15 volts. When the potentiometer wiper is in the 5° deadband region, the output signal is "floating" and may show varying or unpredictable values. To prevent false readings, signal conditioning electronics should clamp the signal to excitation or reference level when this occurs. **NOTE: Young signal conditioning devices clamp the signal to excitation level.** Avoid a short circuit between the wind direction signal line and either the excitation or reference lines. Although there is a 1K ohm current limiting resistor in series with the wiper for protection, damage to the potentiometer may occur if a short circuit condition exists.

Before installation, connect the instrument to an indicator as shown in the wiring diagram and check for proper wind speed and wind direction values. To check wind speed, temporarily remove the propeller and connect the shaft to an Anemometer Drive. Details appear in the CALIBRATION section of this manual.

INSTALLATION

Proper placement of the instrument is very important. Eddies from trees, buildings, or other structures can greatly influence wind speed and wind direction observations. To get meaningful data for most applications locate the instrument well above or upwind from obstructions. As a general rule, the air flow around a structure is disturbed to twice the height of the structure upwind, six times the height downwind, and up to twice the height of the structure above ground. For some applications it may not be practical or necessary to meet these requirements.

FAILURE TO PROPERLY GROUND THE WIND MONITOR MAY RESULT IN ERRONEOUS SIGNALS OR TRANSDUCER DAMAGE.

Grounding the Wind Monitor is vitally important. Without proper grounding, static electrical charge can build up during certain atmospheric conditions and discharge through the transducers. This discharge can cause erroneous signals or transducer failure. To direct the discharge away from the transducers, the mounting post assembly is made with a special antistatic plastic. It is very important that the mounting post be connected to a good earth ground. There are two ways this may be accomplished. First, the Wind Monitor may be mounted on a metal pipe which is connected to earth ground. The mounting pipe should not be painted where the Wind Monitor is mounted. Towers or masts set in concrete should be connected to one or more grounding rods. If it is difficult to ground the mounting post in this manner, the following method should be used. Inside the junction box the terminal labeled EARTH GND is internally connected to the antistatic mounting post. This terminal should be connected to an earth ground (Refer to wiring diagram).

Initial installation is most easily done with two people; one to adjust the instrument position and the other to observe the indicating device. After initial installation, the instrument can be removed and returned to its mounting without realigning the vane since the orientation ring preserves the wind direction reference. Install the Wind Monitor following these steps:

1. MOUNT WIND MONITOR
   a) Place orientation ring on mounting post. Do Not tighten band clamp yet.
   b) Place Wind Monitor on mounting post. Do Not tighten band clamp yet.

2. CONNECT SENSOR CABLE
   a) Refer to wiring diagram located at back of manual.

3. ALIGN VANE
   a) Connect instrument to an indicator.
   b) Choose a known wind direction reference point on the horizon.
   c) Sighting down instrument centerline, point nose cone at reference point on horizon.
   d) While holding vane in position, slowly turn base until indicator shows proper value.
   e) Tighten mounting post band clamp.
   f) Engage orientation ring indexing pin in notch at instrument base.
   g) Tighten orientation ring band clamp.

CALIBRATION

The Wind Monitor is fully calibrated before shipment and should require no adjustments. Recalibration may be necessary after some maintenance operations. Periodic calibration checks are desirable and may be necessary where the instrument is used in programs which require auditing of sensor performance.

Accurate wind direction calibration requires a Model 18112 Vane Angle Bench Stand. Begin by connecting the instrument to a signal conditioning circuit which has some method of indicating wind direction value. This may be a display which shows wind direction values in angular degrees or simply a voltmeter monitoring the output. Orient the base so the junction box faces due south. Visually align the vane with the crossmarkings and observe the indicator output. If the vane position and indicator do not agree within 5°, adjust the potentiometer coupling inside the main housing. Details for making this adjustment appear in the MAINTENANCE, POTENTIOMETER REPLACEMENT, outline, step 7.

It is important to note that, while the sensor mechanically rotates through 360°, the full scale wind direction signal from the signal conditioning occurs at 355°. The signal conditioning electronics must be adjusted accordingly. For example, in a circuit where 0 to 1.000 VDC represents 0° to 360°, the output must be adjusted for 0.986 VDC when the instrument is at 355°. (355°/360° X 1.000 volts = 0.986 volts)

Wind speed calibration is determined by propeller pitch and the output characteristics of the transducer. Calibration formulas showing wind speed vs. propeller rpm and output frequency are included below. Standard accuracy is ± 0.3 m/s (0.6mph). For greater accuracy, the sensor must be individually calibrated in comparison with a wind speed standard. Contact the factory or your supplier to schedule a NIST (National Institute of Standards & Technology) traceable wind tunnel calibration in our facility.

To calibrate wind system electronics using a signal from the instrument, temporarily remove the propeller and connect an Anemometer Drive to the propeller shaft. Apply the appropriate calibration formula to the calibrating motor rpm and adjust the electronics for the proper value. For example, with the propeller shaft turning at 3600 rpm adjust an indicator to display 17.6 meters per second [3600 rpm X 0.00490 (m/s)/rpm =17.6 m/s]

Details on checking bearing torque, which affects wind speed and direction threshold, appear in the following section.

CALIBRATION FORMULAS

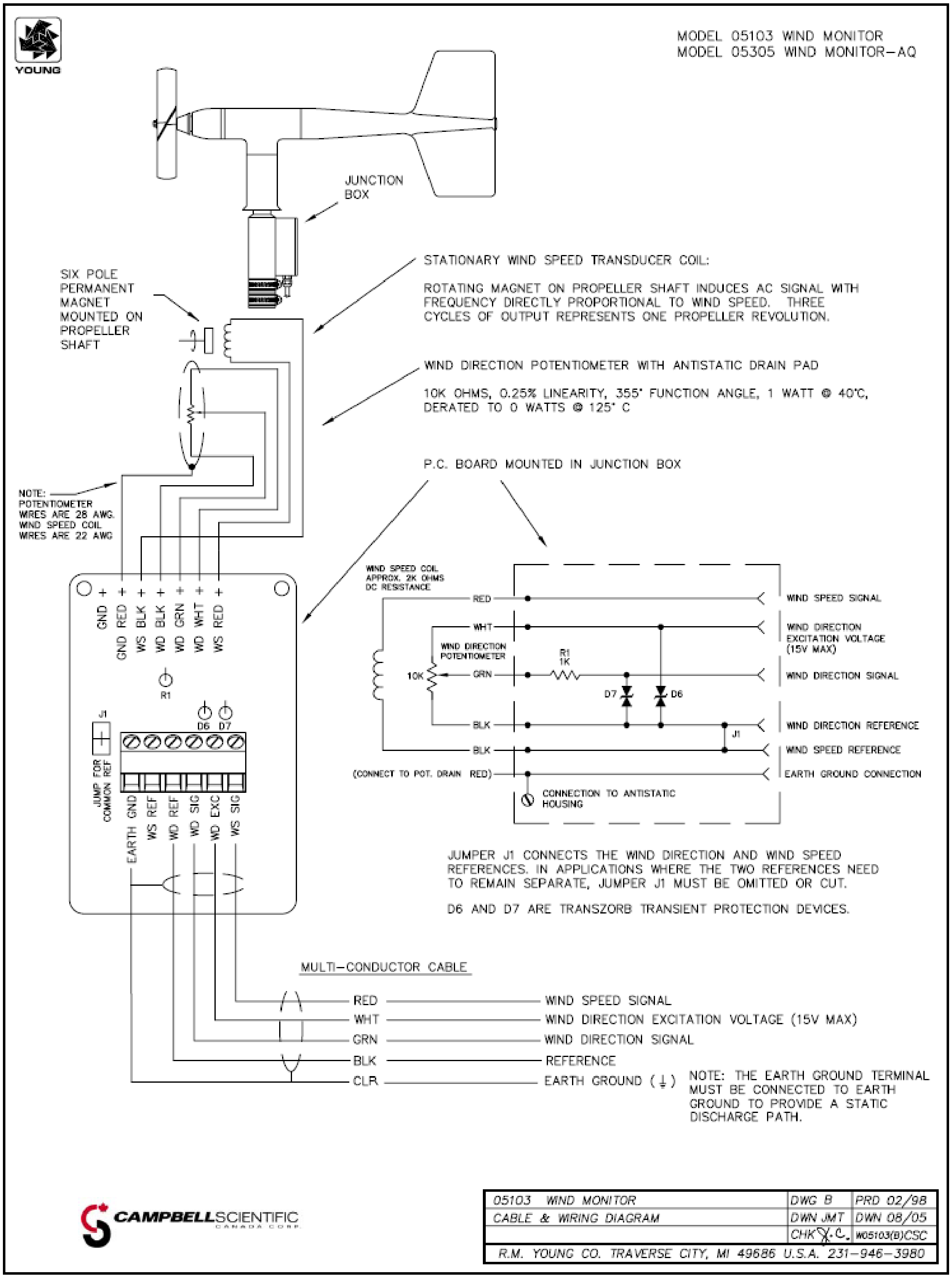
Model 05103 Wind Monitor w / 08234 Propeller

WIND SPEED vs PROPELLER RPM

m/s	=	0.00490 x rpm
knots	=	0.00952 x rpm
mph	=	0.01096 x rpm
km/h	=	0.01764 x rpm

WIND SPEED vs OUTPUT FREQUENCY

m/s	=	0.0980 x Hz
knots	=	0.1904 x Hz
mph	=	0.2192 x Hz
km/h	=	0.3528 x Hz



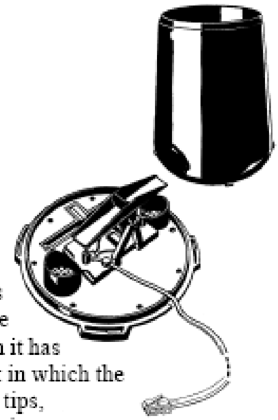
YOUNG
MODEL 05103 WIND MONITOR
MODEL 05305 WIND MONITOR–AQ
JUNCTION BOX
STATIONARY WIND SPEED TRANSDUCER COIL:
ROTATING MAGNET ON PROPELLER SHAFT INDUCES AC SIGNAL WITH FREQUENCY DIRECTLY PROPORTIONAL TO WIND SPEED. THREE CYCLES OF OUTPUT REPRESENTS ONE PROPELLER REVOLUTION.
SIX POLE PERMANENT MAGNET MOUNTED ON PROPELLER SHAFT
WIND DIRECTION POTENTIOMETER WITH ANTISTATIC DRAIN PAD
10K OHMS, 0.25% LINEARITY, 355° FUNCTION ANGLE, 1 WATT @ 40°C, DERATED TO 0 WATTS @ 125° C
P.C. BOARD MOUNTED IN JUNCTION BOX
NOTE: POTENTIOMETER WIRES ARE 28 AWG. WIND SPEED COIL WIRES ARE 22 AWG
GND RED BLK BLK GRN WHT RED
GND WS WD WD WD WS
R1
J1
D6 D7
JUMP FOR COMMON REF
EARTH GND
WS REF
WD REF
WD SIG
WD EXC
WS SIG
WIND SPEED COIL APPROX. 2K OHMS DC RESISTANCE
RED
WHT
WIND DIRECTION POTENTIOMETER
10K
GRN
R1 1K
D7
D6
BLK
BLK
J1
(CONNECT TO POT. DRAIN RED)
CONNECTION TO ANTISTATIC HOUSING
WIND SPEED SIGNAL
WIND DIRECTION EXCITATION VOLTAGE (15V MAX)
WIND DIRECTION SIGNAL
WIND DIRECTION REFERENCE
WIND SPEED REFERENCE
EARTH GROUND CONNECTION
JUMPER J1 CONNECTS THE WIND DIRECTION AND WIND SPEED REFERENCES. IN APPLICATIONS WHERE THE TWO REFERENCES NEED TO REMAIN SEPARATE, JUMPER J1 MUST BE OMITTED OR CUT.
D6 AND D7 ARE TRANSZORB TRANSIENT PROTECTION DEVICES.
MULTI–CONDUCTOR CABLE
RED — WIND SPEED SIGNAL
WHT — WIND DIRECTION EXCITATION VOLTAGE (15V MAX)
GRN — WIND DIRECTION SIGNAL
BLK — REFERENCE
CLR — EARTH GROUND (⏚)
NOTE: THE EARTH GROUND TERMINAL MUST BE CONNECTED TO EARTH GROUND TO PROVIDE A STATIC DISCHARGE PATH.
CAMPBELLSCIENTIFIC CANADA CORP
05103 WIND MONITOR
CABLE & WIRING DIAGRAM
DWG B
PRD 02/98
DWN JMT
DWN 08/05
CHK
W05103(B)CSC
R.M. YOUNG CO. TRAVERSE CITY, MI 49686 U.S.A. 231–946–3980

Tipping Rain Gauge – Davis Rain Collector II

Rain Collector

0.01" or 0.2 mm Increments

7852



Perception and Wizard Sensors

The Rain Collector is designed to meet the guidelines of the World Meteorological Organization. Rain enters the collector cone, passes through a debris-filtering screen, and collects in one chamber of the tipping bucket. The bucket tips when it has collected an amount of water equal to the increment in which the collector measures (0.01" or 0.2 mm). As the bucket tips, it causes a switch closure and brings the second tipping bucket chamber into position. The rain water drains out through the screened drains in the base of the collector.

The collector is designed for years of accurate, trouble-free service. The body and base of the collector are constructed of tough, UV resistant plastic; the tipping bucket pivots on bearings that minimize friction and wear. Stainless steel adjustment screws under each chamber of the tipping bucket allow you to fine-tune the calibration of the Rain Collector.

The rain collector comes with an optional metric adapter for converting the rain collector to take 0.2 mm rain measurements for every tip of the bucket. The rain collector comes with mounting holes pre-drilled in the base and a built-in leveling trough to aid you in installing the rain collector. The Rain Collector Heater is available for use with either of the Rain Collector units. This heater allows the Rain Collector to measure the moisture content of snowfall and protects the internal components from freezing rain. If mounted according to instructions, the Rain Collector is wind tunnel tested to be stable in winds up to 140 MPH (224 kph).

General

Sensor Type	Tipping bucket with magnetic reed switch
Output	Contact closure
Attached Cable Length	40' (12 m)
Cable Type	4-conductor, 26 AWG
Connector	Modular connector (RJ-11)
Recommended Maximum Cable Length	900' (270 m)
Housing Material	UV-stabilized ABS plastic
Dimensions	
Rain Collector	8.75" diameter x 9.5" high (16.5 cm diameter x 24 cm high)
Collection Area	33.2 in^2 (214 cm^2)
Weight	2 lbs. 3 oz. (1 kg)

Console Data

Note: (These specifications apply to sensor output as converted by Davis Instruments weather station consoles.)

Weather Monitor/Wizard Range

Daily Rainfall	0.00" to 99.99" (0.0 mm to 999.8 mm)
Total Rainfall	0.00" to 99.99" (0.0 mm to 9999 mm)
Accuracy	
Rainfall	±4%, ±1 rainfall count between 0.01" and 2.00" per hour (0.2 mm and 50.0 mm per hour); ±5%, ±1 rainfall count between 2.00" and 4.00" per hour (50.0 mm and 100.0 mm per hour)
Resolution	0.01" (0.2 mm)
Sample and Display Update Interval	16 seconds (max)

2

Perception and Wizard Sensors

WeatherLink® Data

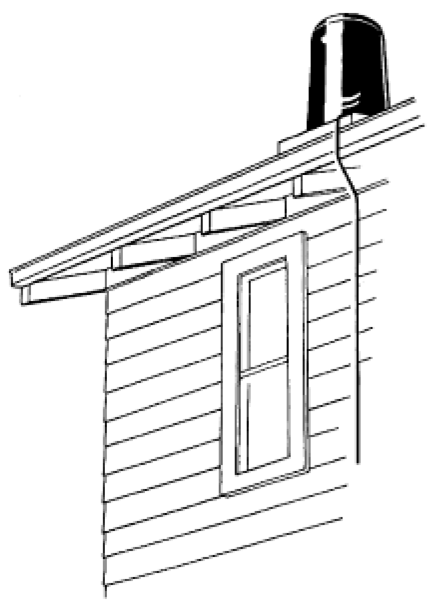
Note: (These specifications apply to sensor output as logged and displayed by the WeatherLink.)

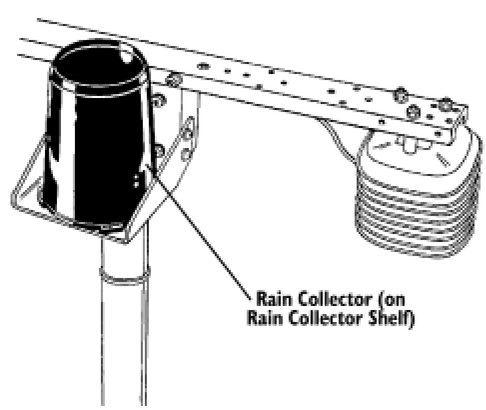
Daily Rainfall . . . . Total during archive interval
Total Rainfall . . . . Total during archive interval
Rate of Rainfall . . . . Maximum value during archive interval (For Vantage Pro and Pro2 models only)

Note: Input/Output Connections

Black & Red. . . . . Switch terminal
Green & Yellow . . . . Switch terminal

Installation Options





Package Dimensions

Product #	Package Dimensions (Length x Width x Height)	Package Weight	UPC Codes
7852	8.63" x 8.75" x 11.00" (219 mm x 223 mm x 280 mm)	3.3 lbs. (1.5 kg)	011698 78520 9

DATALOGGER/MULTIPLEXER – CAMBELL SCIENTIFIC CR10X/AM16

CR10X Specifications

Electrical specifications are valid over a -25° to +50°C range unless otherwise specified; non-condensing environment required. To maintain electrical specifications, yearly calibrations are recommended.

PROGRAM EXECUTION RATE

Program is synchronized with real-time up to 64 Hz. One measurement with data transfer is possible at this rate without interruption. Burst measurements up to 750 Hz are possible over short intervals.

ANALOG INPUTS

NUMBER OF CHANNELS: 6 differential or 12 single-ended, individually configured. Channel expansion provided by AM416 Relay Multiplexers and AM25T Thermocouple Multiplexers.

ACCURACY: ±0.1% of FSR (-25° to 50°C);
±0.05% of FSR (0° to 40°C);
e.g., ±0.1% FSR = ±5.0 mV for ±2500 mV range

RANGE AND RESOLUTION:

Full Scale Input Range (mV)	Resolution (µV) Differential	Single-Ended
±2500	333	666
±250	33.3	66.6
±25	3.33	6.66
±7.5	1.00	2.00
±2.5	0.33	0.66

INPUT SAMPLE RATES: Includes the measurement time and conversion to engineering units. The fast and slow measurements integrate the signal for 0.25 and 2.72 ms, respectively. Differential measurements incorporate two integrations with reversed input polarities to reduce thermal offset and common mode errors.

Fast single-ended voltage:	2.6 ms
Fast differential voltage:	4.2 ms
Slow single-ended voltage:	5.1 ms
Slow differential voltage:	9.2 ms
Differential with 60 Hz rejection:	25.9 ms
Fast differential thermocouple:	8.6 ms

INPUT NOISE VOLTAGE (for ±2.5 mV range):
Fast differential: 0.82 µV rms
Slow differential: 0.25 µV rms
Differential with 60 Hz rejection: 0.18 µV RMS

COMMON MODE RANGE: ±2.5 V

DC COMMON MODE REJECTION: >140 dB

NORMAL MODE REJECTION: 70 dB (60 Hz with slow differential measurement)

INPUT CURRENT: ±9 nA maximum

INPUT RESISTANCE: 20 Gohms typical

ANALOG OUTPUTS

DESCRIPTION: 3 switched, active only during measurement, one at a time.

RANGE: ±2.5 V

RESOLUTION: 0.67 mV

ACCURACY: ±5 mV; ±2.5 mV (0° to 40°C);

CURRENT SOURCING: 25 mA

CURRENT SINKING: 25 mA

FREQUENCY SWEEP FUNCTION: The switched outputs provide a programmable swept frequency, 0 to 2.5 V square wave for exciting vibrating wire transducers.

RESISTANCE MEASUREMENTS

MEASUREMENT TYPES: The CR10X provides ratiometric bridge measurements of 4- and 6-wire full bridge, and 2-, 3-, and 4-wire half bridges. Precise dual polarity excitation using any of the switched outputs eliminates dc errors. Conductivity measurements use a dual polarity 0.75 ms excitation to minimize polarization errors.

ACCURACY: ±0.02% of FSR plus bridge resistor error.

PERIOD AVERAGING MEASUREMENTS

DEFINITION: The average period for a single cycle is determined by measuring the duration of a specified number of cycles. Any of the 12 single-ended analog input channels can be used. Signal attenuation and AC coupling are typically required.

INPUT FREQUENCY RANGE:

Signal peak-to-peak[1] Min.	Max.	Min. Pulse w.	Max Freq.[2]
500 mV	5.0 V	2.5 µs	200 kHz
10 mV	2.0 V	10 µs	50 kHz
5 mV	2.0 V	62 µs	8 kHz
2 mV	2.0 V	100 µs	5 kHz

[1]Signals centered around datalogger ground
[2]Assuming 50% duty cycle

RESOLUTION: 35 ns divided by the number of cycles measured

ACCURACY: ±0.03% of reading

TIME REQUIRED FOR MEASUREMENT: Signal period times the number of cycles measured plus 1.5 cycles + 2 ms

PULSE COUNTERS

NUMBER OF PULSE COUNTER CHANNELS: 2 eight-bit or 1 sixteen-bit; software selectable as switch closure, high frequency pulse, and low level AC.

MAXIMUM COUNT RATE: 16 kHz, eight-bit counter; 400 kHz, sixteen-bit counter. Channels are scanned at 8 or 64 Hz (software selectable).

SWITCH CLOSURE MODE
Minimum Switch Closed Time: 5 ms
Minimum Switch Open Time: 6 ms
Maximum Bounce Time: 1 ms open without being counted

HIGH FREQUENCY PULSE MODE
Minimum Pulse Width: 1.2 µs
Maximum Input Frequency: 400 kHz
Voltage Thresholds: Count upon transition from below 1.5 V to above 3.5 V at low frequencies. Larger input transitions are required at high frequencies because of input filter with 1.2 µs time constant. Signals up to 400 kHz will be counted if centered around +2.5 V with deviations ≥ ± 2.5 V for ≥ 1.2 µs.
Maximum Input Voltage: ±20 V

LOW LEVEL AC MODE
(Typical of magnetic pulse flow transducers or other low voltage, sine wave outputs.)

Input Hysteresis: 14 mV

Maximum AC Input Voltage: ±20 V

Minimum AC Input Voltage: (Sine wave mV RMS)	Range (Hz)
20	1.0 to 1000
200	0.5 to 10,000
1000	0.3 to 16,000

DIGITAL I/O PORTS

8 ports, software selectable as binary inputs or control outputs. 3 ports can be configured to count switch closures up to 40 Hz.

OUTPUT VOLTAGES (no load): high 5.0 V ±0.1 V; low < 0.1 V

OUTPUT RESISTANCE: 500 ohms

INPUT STATE: high 3.0 to 5.5 V; low -0.5 to 0.8 V

INPUT RESISTANCE: 100 kohms

SDI-12 INTERFACE STANDARD

DESCRIPTION: Digital I/O Ports C1-C8 support SDI-12 asynchronous communication; up to ten SDI-12 sensors can be connected to each port. Meets SDI-12 Standard version 1.2 for datalogger and sensor modes.

CR10XTCR THERMOCOUPLE REFERENCE

POLYNOMIAL LINEARIZATION ERROR: Typically <±0.5°C (-35° to +50°C), <±0.1°C (-24° to +45°C).

INTERCHANGEABILITY ERROR: Typically <±0.2°C (0° to +60°C) increasing to ±0.4°C (at -35°C).

EMI and ESD PROTECTION

EMISSIONS: Meets or exceeds following standards:
Radiated: per EN 55022:1987 Class B
Conducted: per EN 55022:1987 Class B

IMMUNITY: Meets or exceeds following standards:
ESD: per IEC 801-2;1984 8 kV air discharge
RF: per IEC 801-3;1984 3 V/m, 27-500 MHz
EFT: per IEC 801-4;1988 1 kV mains, 500 V other

CE COMPLIANCE (as of 01/98)

APPLICATION OF COUNCIL DIRECTIVE(S): 89/336/EEC as amended by 89/336/EEC and 93/68/EEC

STANDARD(S) TO WHICH CONFORMITY IS DECLARED:
ENC55022-1: 1995 and ENC50082-1: 1992

CPU AND INTERFACE

PROCESSOR: Hitachi 6303

PROGRAM STORAGE: Up to 16 kbytes for active program; additional 16 kbytes for alternate programs. Operating system stored in 128 kbytes Flash memory.

DATA STORAGE: 128 kbytes SRAM standard (approximately 60,000 data values). Additional 2 Mbytes Flash available as an option.

OPTIONAL KEYBOARD DISPLAY: 8-digit LCD (0.5" digits)

PERIPHERAL INTERFACE: 9 pin D-type connector for keyboard display, storage module, modem, printer, card storage module, and RS-232 adapter.

BAUD RATES: Selectable at 300, 1200, 9600 and 76,800 for synchronous devices. ASCII communication protocol is one start bit, one stop bit, eight data bits (no parity).

CLOCK ACCURACY: ±1 minute per month

SYSTEM POWER REQUIREMENTS

VOLTAGE: 9.6 to 16 Vdc

TYPICAL CURRENT DRAIN: 1 mA quiescent, 13 mA during processing, and 46 mA during analog measurement.

BATTERIES: Any 12 V battery can be connected as a primary power source. Several power supply options are available from Campbell Scientific. The Model CR2430 lithium battery for clock and SRAM backup has a capacity of 270 mAhr.

PHYSICAL SPECIFICATIONS

SIZE: 7.8" x 3.5" x 1.5" - Measurement & Control Module; 9" x 3.5" x 2.9" - with CR10WP Wiring Panel. Additional clearance required for serial cable and sensor leads.

WEIGHT: 2 lbs

WARRANTY

Three years against defects in materials and workmanship.

We recommend that you confirm system configuration and critical specifications with Campbell Scientific before purchase.

CAMPBELL SCIENTIFIC, INC.
815 W. 1800 N. • Logan, Utah 84321-1784 • (435) 753-2342 • FAX (435) 750-9540
Offices also located in: Australia • Brazil • Canada • England • France • South Africa

Relay Multiplexer

Model AM416

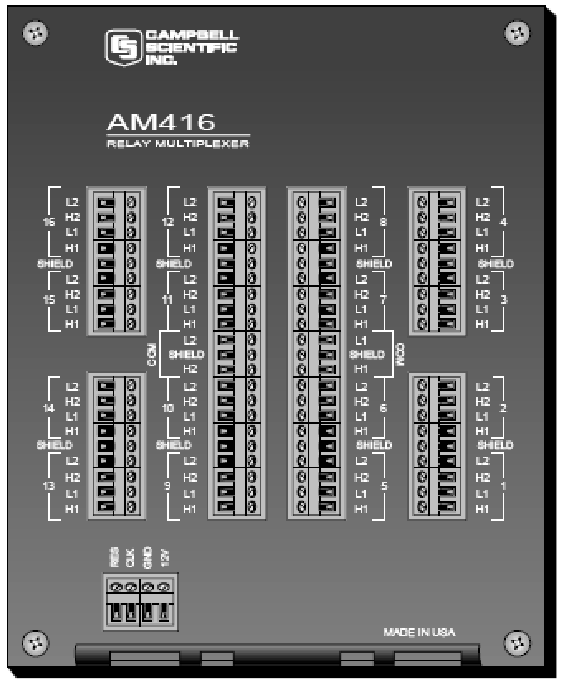
The AM416 Multiplexer increases the number of sensors that can be scanned by a CR10(X), 21X, CR23X, or CR7 datalogger. The AM416 sequentially multiplexes sixteen groups of four lines at a time (a total of sixty-four lines) through four common (COM) terminals. Compatible sensors include thermistors, thermocouples, potentiometers, load cells, strain gages, vibrating wires, and gypsum soil moisture blocks.

Number of Sensors Scanned

The maximum number of sensors multiplexed through one AM416 depends on the type(s) of sensors scanned. Examples, assuming identical sensors, are:

- Up to 32 single-ended or differential sensors that require two wires (e.g., thermistors, thermocouples, half bridges)
- Up to 16 single-ended or differential sensors that require four wires (e.g., full bridges, four-wire half bridges)
- Up to 32 vibrating wire sensors, in conjunction with the CR10(X) or CR23X and the AVW1 or AVW4 Vibrating Wire Sensor Interface
- Up to 32 gypsum soil moisture blocks. The AM416 eliminates the requirement for DC blocking capacitors on gypsum soil moisture blocks, significantly reducing sensor cost (Models 223 or 253).

Mixing sensor types may require special considerations. Contact Campbell Scientific for application assistance.



Datalogger Connections

A four- or five-conductor cable connects the measurement/excitation channels of the datalogger with the COM terminals of the multiplexer. This reduces the cost of cabling individual sensors on long wire runs. The maximum distance between the datalogger and the AM416 depends on the sensors, the scan rate, and the cable type used in the application.

Datalogger control and power to the AM416 are supplied via a four-conductor cable. The AM416 requires one datalogger control port to enable a scan (reset terminal), and a second control port or an excitation channel to "clock" through the channels (clock terminal). Either the datalogger's power supply or a separate 12 VDC supply is used to power the multiplexer.

Scanning Multiple AM416's

Several AM416's may be connected to the same datalogger; usually up to three AM416's with a CR10(X), four with a 21X, and six with a CR23X. Sequential scanning requires a common clock line and separate reset lines. Simultaneous scanning is possible when the reset and clock lines are common.

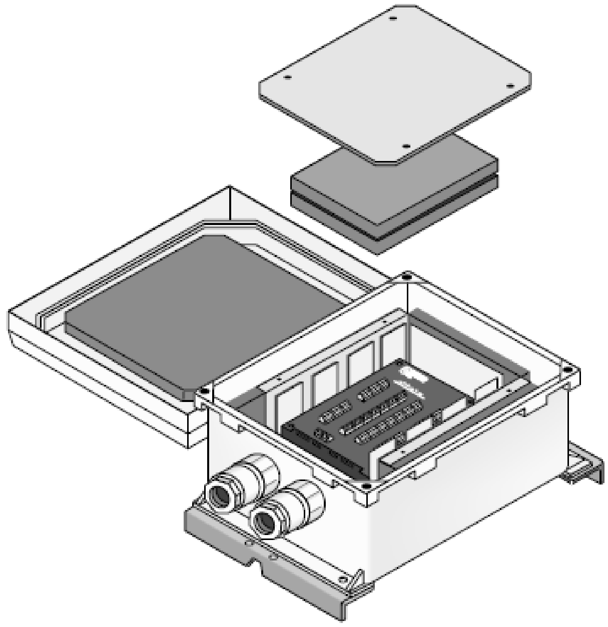
CAMPBELL SCIENTIFIC, INC.
815 W. 1800 N. • Logan, Utah 84321-1784 • (435) 753-2342 • FAX (435) 750-9540 • www.campbellsci.com

Environmental Enclosures

The AM416 operates in most field conditions but requires a non-condensing environment. A weather-resistant enclosure equipped with desiccant is required for field use.

The AM-ENC Multiplexer Enclosure is recommended for non-thermocouple applications. The AM-ENCT (shown at right) has foam insulation (dark gray) and internal aluminum plates. These components aid in reducing temperature gradients. Thermocouple wires should be routed around the aluminum plates to dissipate conducted heat. The AM-ENCT has a thermal time constant (τ) of 1 hour 25 minutes (10%) at 2 m/s wind speeds.

Each enclosure houses one AM416 and has conduit bushings for cable entry. The white fiberglass enclosures can be attached to a 1.25" IPS pipe (1.660" OD) or lag-bolted to a flat surface.



Specifications

Electrical

- Power: 9.6 to 16 VDC (under load), unregulated
- Current drain: < 100 µA-quiescent; 17 mA-active (average)
- Reset levels: < 0.9 V-inactive; 3.5 to 16 V-active
- Clock levels: Scan advance occurs on the leading edge of the clock pulse (from below 1.5 V to above 3.5 V)
- Minimum clock pulse width: 5 ms
- Initial relay resistance, closed: 0.1 ohm
- Maximum switching current: 500 mA switching currents greater than 30 mA (occasional 50 mA, acceptable) degrades the suitability of that channel for switching low-voltage signals.
- Minimum contact life: 10^7 closures

Physical

- Operating temperature: -25° to +50°C (typical)
- Operating humidity: 0 to 95%, non-condensing
- AM416
Size: 6.5"W x 8.2"L x 1.5"D
Weight/shipping: 1.5 lbs/6.0 lbs
- AM416 (with AM-ENC)
Size: 11.3"W x 13.5"L x 5.6"D
Weight/shipping: 12.0 lbs/16.0 lbs
- AM416 (with AM-ENCT)
Size: 11.3"W x 13.5"L x 5.6"D
Weight/shipping: 12.6 lbs/18.0 lbs

If you have questions concerning the use of the AM416 in your application, please call Campbell Scientific.

CAMPBELL SCIENTIFIC, INC.
815 W. 1800 N. • Logan, Utah 84321-1784 • (435) 753-2342 • FAX (435) 750-9540
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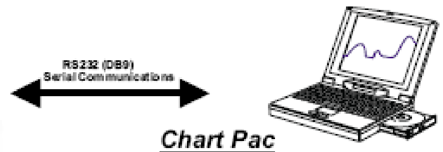
Printed November, 1996

DATALOGGER – Lakewood Chart Pac CP-X

LAKEWOOD SYSTEMS LTD.
Remote Data Recording Products

Chart Pac CPXK
IBM/PC Based Data Recording Module

NRTL /C
Class 1
Div. 2



This self-powered datalogger provides a highly reliable means of recording field data. Lakewood's Chart Pacs make it easy to record conditions such as temperatures, pressures, fluid levels, humidity, rainfall, voltages, and alarm conditions for fast graphical and tabular analysis on laptop or desktop computers. When used with a remote modem, Chart Pacs can operate on cellular or standard phone lines.

Chart Pacs can be programmed to record data ranging from once a day to once per second. With Lakewood's Dataview Windows software, you can view graphs within seconds or quickly move the data to standard spreadsheet programs such as Excel.

Chart Pacs also offer the convenience of interchanging modules in remote field applications through the use of unique input plugs. Recorded data is always protected by a five year memory battery. A standard 9 volt alkaline battery can power the module for up to 4 months. ULB lithium batteries provide 1 to 5 years of continuous power for Chart Pac.

SPECIFICATIONS

ANALOG INPUT (CPXA)

Quantity	1 to 4 Channel
Range	0 to 2.5 volts D.C.
Storage Res.	1/16383
A/D Resolution	1/8191
A/D Accuracy	1/2047
Impedance	1 Megohm

CONTACT STATUS INPUT (CPXS)

Quantity	1 to 4 (Dry or Wet)
Type	Switch to Ground TTL Compatible
Range	0-99,999,999-0 Count Cycle
Speed	20 C.P.S. Count Rate
Conditioning	Soft Debounce

OUTPUT POWER SWITCHING

Voltage Ref.	2.5 Volts 10 mA. Source
Soft Control	35 to 835 mSec. Warm-up
Current Switch	1.6 amp. max.

COMMUNICATION

Data Transfer	Up to 12X Compression 64K/160 Sec.(Direct)
Error Handling	CRC Multiple Retry
Type	RS232C (UCB may be req'd)
Interface	9 Pin Male/D (CC10S Cable Female/Female)

DATA STORAGE

Data Samples	32K(high resolution) 64K (low resolution)
Type	Non-volatile RAM (5 Year Lithium Battery)
Interval Mode	1 Sec. to 1 Day/1 Sec. Definition
Time Accuracy	.0015% (1min/month)
Time Format	Month/Day/Year Hour/Minute/Second Hardware Calendar Clock
Time Tag	Midnight Day# Marker

ELECTRICAL

Memory Battery	Lithium (3 Yr. / Powered)
Datalogger Bat.	9V Standard Lithium Battery Inc. (~4 months @ 5min. samples) ULB5 Lithium Opt. (~3 to 5 yrs. @ 1 min. samples)
Sleep Mode	100 Micro Amp. Draw
Wake Mode	6 ma-Sec Power Pulse
Communication	6 ma-Sec Power Pulse

PHYSICAL

Dimensions	~200 x 57 x 110 mm (7.8 x 2.2 x 4.3 in.)
Weight	~.68 kg.(1.5 lbs)

ENVIRONMENTAL

Operating Temp.	-40°C to +75°C (-40°F to +170°F) Non-Certified
Storage Temp.	-50°C to +90°C (-60°F to +200°F)
Humidity	0% to 95% Non-Condensing (Protected By Silicon Conformal Coating)

Chart Pac

- ☐ **CPXKA** *$649.00*
  1 channel analog input 0 to 2.5 volt D.C c/w 64K memory.
- ☐ **CPXKS** *$649.00*
  1 channel status event/recording accumulation 0-99,999,999-0 cycle c/w 64K memory

Chart Pac Accessories

- ☐ **ULB1** Lithium Battery . . *$14.00*
  1 Amp.Hr battery
- ☐ **ULB5** Lithium Battery . . *$149.00*
  5.2 Amp.Hr. battery
- ☐ **CC10S** Comm. Cable . . . *$49.00*
  RS232 cable,10' long, surge protected
- ☐ **URB700** Inst. Battery . . . *$89.00*
  700 mA-hrs. 12 V Rechargeable Internal
- ☐ **ULAC500** Adaptor *$29.00*
  for AC power/URB700CP Charging
- ☐ **CSA12** Certification. . . *$149.00*
  for Class 1 Div. 2 Groups A,B,C,D
- ☐ **CPC** Expansion Plug. . . *$50.00*
  for each additional channel
- ☐ **LS4** IBM/PC Software. *$149.00*
  DOS version, c/w manual
- ☐ **DV1** Dataview *$89.00*
  Windows Graphing Software for LS4
- ☐ **DV+** Dataview Plus . . . *$199.00*
  Win95/98/NT Software - for downloading, monitoring and & graphing data,eval. download from www.lakewood.com

- ☐ **IPX** Input Plug *$29.00*
  (standard) 4 screw terminals
- ☐ **IP2V** Input Plug *$29.00*
  0 to 2.5 volt input range
- ☐ **IP10V** Input Plug *$29.00*
  0 to 10 volt input range
- ☐ **IP420F** Input Plug *$39.00*
  4 to 20 milliamp input range
- ☐ **IP25MV** Input Plug *$89.00*
  0 to 25 millivolt input range
- ☐ **IP250MV** Input Plug *$89.00*
  0 to 250 millivolt input range

www.lakewood.com   PRINTED IN CANADA   NOV. 14/2000   CM054R   e-mail mail@lakewood.com

DATALOGGER – HOBO H8 Pro 2 Channel T/RH

The above times are intended only as guidelines. For critical field applications of long duration we recommend installing a fresh battery before each deployment. We recommend replacing the HOBO's battery and O-rings simultaneously (Onset battery/service kit part #HP-BK includes battery, O-ring, stainless steel self-sealing screw with O-ring, O-ring lubricant and jack cap.)

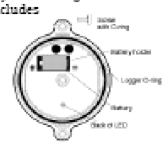


Diagram B- HOBO Pro Series back with cover removed

Changing or Accessing the Battery

If you can, offload the logger before changing the battery. This will ensure that no data will be lost (See Non-Volatile Memory below). To change the battery, open the case by removing the Phillips screw in the center of the back of the logger and removing the stainless steel back plate. Remove the old battery and install the new one. Be careful to put the battery in the battery holder with the correct polarity (Diagram B). The logger's red LED will blink three times after the battery has been installed. If you have difficulty seeing the LED flash, use the battery check in the Launch dialog box of the logger software to verify the battery status. **Warning: Do not cut open, incinerate, heat above +185°F (+85°C) or recharge the removed lithium battery. Dispose per local regulations.**
Note: Before replacing the back plate, check that the logger seals (O-ring, screw, jack cap) are not contaminated by dust, dirt or other materials. All components must be cleaned of any contaminants to ensure a weathertight seal. Make sure the back plate O-ring has a light film of lubricant (Dow Corning DC 111 or Nye Lubricants NYOGEL). Insert the O-ring in the groove and replace the back plate using the screw with O-ring. The screw should be tightened until it is snug (10 inch-pounds). Do not use lubricant on jack cap.

Non-Volatile Memory

The HOBO Pro uses a high-capacity Flash EEPROM to store data. This storage is non-volatile and will retain the data even if the battery is removed. To save power and maximize the life of the flash memory device, 32 bytes of data are buffered in RAM prior to writing to the flash memory. In the case of a dead battery, or the unlikely event that power is interrupted during logging, the data in this RAM buffer will be lost. For example, if the sample interval was set to one half hour and one channel with low resolution, then up to 16 hours of data could be lost.

Service and Support

HOBO® products are easy to use and reliable. In the unlikely event that you have a problem with the hardware or software, please read the following.

Who do I contact?

Contact the company that you bought the loggers from: Onset Computer Corporation or an Onset Authorized Dealer.

Before calling, you can evaluate and often solve your problem if you try the following:

1. Read this manual and the ReadMe file on the software disk. It may only take a few moments to get the answers you need.

2. Write down the events that led to the problem. Have you changed anything in your computer recently? Are you doing anything differently?

When contacting Onset Computer Corporation, please indicate that you need Technical Support for HOBO® products.

Be prepared to:
1. Provide the product number which is found on the side of the logger, the software version and serial number if present on the disk.
2. Provide details on the hardware and software configuration of your computer including: manufacturer, model number, peripherals, and version of operating system.
3. Completely describe the problem or question. The more information you provide, the faster and more accurately we will be able to respond.

NOTE: Onset provides technical support to one person for each software license.

Onset Technical Support
Onset Computer Corporation
470 MacArthur Blvd.
Bourne, MA 02532
Mailing: PO Box 3450
Pocasset, MA 02559-3450
1-800-LOGGERS (1-800-564-4377)
Phone: (508) 759-9500
Fax: (508) 759-9100
E-mail: loggerhelp@onsetcomp.com
www.onsetcomp.com

Warranty

The HOBO® products are warranted to be free from defects in material and workmanship for a period of one year from the date of original purchase. During the warranty period Onset will, at its option, either repair or replace products that prove to be defective. This warranty is void if the Onset products have been damaged by customer error or negligence or if there has been an unauthorized modification.

Returning Products to Onset

Direct all warranty claims to place of purchase. Before returning a failed unit, you must obtain a Return Merchandise Authorization (RMA) number from Onset. You must provide proof that you purchased the Onset product(s) directly from Onset (purchase order number or Onset invoice number). Onset will issue an RMA number that is valid for 30 days. You must ship the product(s), properly packaged against further damage, to Onset (at your expense) with the RMA number marked clearly on the outside of the package. Onset is not responsible for any package that is returned without a valid RMA number or for the loss of the package by any shipping company. Loggers must be clean and free of any toxins before they are sent back to Onset or they may be returned to you.

Repair Policy

Products that are returned after the warranty period or that are damaged by the customer as specified in the warranty provisions can be returned to Onset with a valid RMA number for evaluation.

Please contact Onset for more information and prices on:

ASAP Repair Policy

Onset will expedite the repair of a returned product.

Data-back™ Service

HOBO® data loggers store data in nonvolatile EEPROM memory. Onset will, if possible, recover your data to a disk.

Tune Up™ Service

Onset will examine and retest any HOBO® data logger.

2669-J MAN-H08-03x-08

HOBO® H8 Pro Series User's Manual

Requires Onset Computer Corporation's BoxCar® Pro 3.5 or BoxCar® 3.6 or later software and PC interface cable for operation.

The CE mark identifies this product as complying with all relevant directives in the European Union (EU).

Inside this package

The HOBO H8 Pro Series is shipped with:

1. One HOBO H8 Pro Series logger (part numbers H08-030-08, H08-031-08, or H08-032-08)

2. Mounting Accessories:
Two self-tapping screws
Hook and loop tape

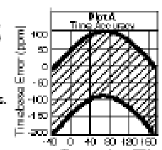
Thank you for buying a HOBO H8 Pro Series data logger. With proper care it will give you years of accurate and reliable measurements.

This manual covers all of the HOBO H8 Pro Series products. All products share a common feature set, store up to 65,291 time-stamped measurements, and are compatible with the HOBO Shuttle (Part number H09-002-08) and HandCar software for Palm™ handhelds allowing for convenient retrieval of data. The measurements available on each model are:

Model	Part Number	Temp	RH	External Temp
HOBO Pro Temp	H08-030-08	✓		
HOBO Pro Temp/External Temp	H08-031-08	✓		✓
HOBO Pro RH/Temp	H08-032-08	✓	✓	

Unlike most other HOBOs, the HOBO Pro does not have the wrap-around-when-full option for storing data; its large memory capacity eliminates the need for this function in most cases.

Common Specifications



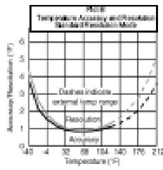
Operating range (logger): -30°C to +50°C (-22°F to +122°F), 0 - 100% RH, HOBO Pro RH/Temp should be mounted so that water does not impact or collect in the RH sensor.
RH Sensor operating environment: 0°C to +50°C (+32°F to +122°F) in intermittent condensing environments up to +30°C; and above +30°C in non-condensing environments. Sensor requires protection from rain, splashing, mist, dust, and airborne chemicals such as salt and ammonia.
Time accuracy: approx. ±1 minute per week (±100 ppm at +20°C or +68°F), full dependance shown in Plot A.
Measurement capacity: 65,291 standard-resolution (8-bit) measurements, 32,645 high-resolution (12-bit) measurements or 21,763 measurements if one channel uses standard-resolution and the other channel uses high-resolution. RH measurements use standard resolution only. All measurements are stored in nonvolatile memory, with seven levels of data archiving (See Non-Volatile Memory).
Data offload time: 1 minute typical
Size: 4.0" H x 3.2" W x 2.0" D
Weight: Temp and RH/Temp are approx. 3.7 oz. and Temp/Temp External is 5.1 oz.
Battery: ½ AA, lithium, 3.6V, user-replaceable (Use only Onset part # HP-B)
Battery life (continuous use): 3 years
Storage temperature: -30°C to +75°C (-22°F to +167°F)

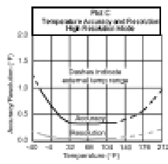
NOTE: The logger software's absolute humidity calculation does not use an actual pressure measurement but assumes an ambient pressure of 1 atmosphere (14.7 PSI.)

2669-J MAN-H08-03x-08 2 11/6/03, 2:16 PM

Measurement Specifications

Temperature - Each HOBO Pro Series logger has an internal temperature sensor mounted inside the front of the logger's case (Diagram A). The sensor measures ambient air temperature over the operating range of the logger; -30°C to +50°C (-22°F to +122°F) with a response time of less than thirty-five minutes (typical to 90%) in still air. The HOBO Pro Series loggers have a standard and a high-resolution mode which are selectable in the logger's software. For temperature accuracy and resolution specifications, please refer to Plot B for standard-resolution mode and Plot C for high-resolution mode. See "Selecting Channels and Resolutions" for more information.





External Temperature - The HOBO Pro Temp/Ext Temp is equipped with a 6' external temperature sensor which measures temperature from -40°C to +100°C (-40°F to +212°F) with a response time of less than 3 minutes typical to 90% in air moving 1 m/sec (2.2 mph). See plot B and C for accuracy and resolution specifications in the two resolution modes. For loggers with serial numbers greater than 593938 the sensor tip and cable can be buried in soil or immersed in fresh water up to +50°C (+122°F) for up to one year.

Relative Humidity - The HOBO's relative humidity sensor has an accuracy of ±3% over the range of 0 to 50°C (32° to 122°F). The relative humidity sensor range is 0 to 100% RH. It can read up to 104.1% in a condensing environment. While the sensor is saturated, you will not get accurate readings. In general, the RH response time is less than 5 minutes typical to a 90% change (independent of temp). Drift is less than 1% per year in normal operating conditions (non-corrosive, non-condensing). An additional temporary drift of up to 3% can occur when the average humidity is above 70%. Factory verification and tune-up service available. White RH sensor case may yellow with exposure to light. This is not a problem.

Connecting the Communications Cable and Launching

A Starter Kit, which includes the appropriate PC interface cable and software, is required to operate your logger. Unscrew the jack cap from the logger. You can store it temporarily by pushing it onto the cap holder (Diagram A). Connect the interface cable into the 3.5 mm jack on the logger and into a working serial port on your computer. Install and start the logger's software. Select **Launch...** under **Logger** on the menu bar and a launch dialog box will be provided. For a complete explanation on installing the software and launching your logger, please refer to the logger software manual.

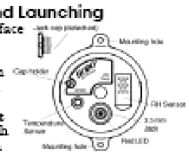


Diagram A - HOBO Pro Series Front

When launching a logger, the software defaults to the parameters specified the last time the logger was launched. The factory default is to select all channels with high-resolution mode for temperature measurements. See "Selecting Channels and Resolutions" for details.

Operation Indicator

The HOBO data loggers have a red LED that blinks while they are logging. The blinking LED is located inside the 3.5 mm jack and is only visible when the PC interface cable and jack cap are removed (Diagram A). The LED blinks brightly at every measurement, and weakly every two seconds if the interval between measurements is longer than two seconds. Once you have verified the operation of the logger, rescrew the jack cap, making sure there is no dust or dirt on the cap that might compromise the integrity of the weatherproof seal. Hand tighten lightly. The cap only needs to be snug. If it is overtightened it may require a pair of pliers to unscrew.

Operation on Computers Equipped with a Power Conservation Mode

Many newer computers, especially laptops, have a power conservation feature which shuts the serial port off after a short period of time. If a HOBO or StowAway logger is still connected to the serial port when this happens, the logger will shut off. To resolve power conservation shut off of the serial port, BoxCar Pro 4.0, 4.1, and 4.2.x customers should download the BoxCar Pro 4.2.10.1 or later upgrade patch. Similarly, BoxCar 3.6 and 3.7.1 customers should download the BoxCar 3.7.3 or later upgrade patch. Both are available for free on our website under Support and Upgrades, Software Upgrades and Utilities. If you have an earlier version of BoxCar and you would like to test to see if you will be affected by the power conservation feature do the following. Using BoxCar, launch your logger from the computer that you are testing. If you are using a laptop, it may behave differently when running off battery versus running off the power plug; please test both. After launch, leave the logger attached to the PC interface cable and watch the LED to see if it remains blinking. When a logger is actively logging, the LED will blink faintly every 2 seconds. If the power conservation is causing a problem, the LED will stop blinking within one minute.

When you are using a HOBO Pro logger, the LED is located under the PC interface cable, and is not visible when the cable is plugged in. To test a HOBO Pro, launch the logger to take readings at 10 second intervals. Leave the logger attached to the interface cable for one minute. You can either remove the interface cable at this point and check the LED status, or download the datafile to see how many points were collected. If power conservation is causing the logger to shut off, you will only see one data point in the file. If your computer has the power conservation feature, you should download an upgrade patch as noted above.

Mounting Options

The HOBO Pro Series data loggers have mounting tabs. Be careful not to stress the case when using the screws to mount the logger to an uneven surface, as this may crack the tabs. The supplied hook and loop tape can be stuck on the back of your HOBO for mounting. Do not use double sided tape on the back of the logger for mounting, as this could disturb the weatherproof seal when the logger is removed.

HOBO Pro RH Sensor Should not get Saturated

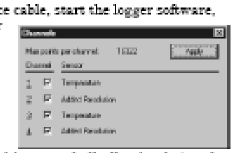
The RH sensor used on the HOBO Pro is among the best in its price range. It is designed for normal outdoor environments with cyclical high and low humidity levels. Saturation of the sensor is evident when the logger reads values of 100% RH or greater. Like all RH sensors, repeated saturation from exposure to condensing environments will lead to irreversible drift and eventually destroy the RH sensor. If this happens, the logger will need to be returned to Onset Computer Corp. for sensor replacement. The rate at which this degradation of the sensor occurs depends on the harshness of the environment to which the sensor is exposed. Condensing environments with temperatures above 30°C (86°F), exposure to salt spray, ammonia vapor, or some other chemicals will accelerate the sensor degradation.

Mounting considerations in wet environments

The RH/Temp version should be mounted so that the RH sensor is protected from water saturation. To prolong the life of your RH sensor, Onset strongly recommends mounting the HOBO Pro logger (H08-032-08) face down in a protective housing such as the Solar Radiation Shield (Onset part # RS1) or the Rain Shield (Onset part # RS2).

Readout

Reconnect the HOBO data logger to the interface cable, start the logger software, select **Readout** under **Logger** on the menu bar and the data will be displayed in a graphical or tabular form. For a complete explanation on reading out your logger, please refer to the logger software manual. The optional HOBO Shuttle can also be used to readout and relaunch the HOBO Pro loggers.



Selecting Channels and Resolutions

The three HOBO Pro Series loggers covered by this manual all offer the choice of standard-resolution (8-bit) or high-resolution (12-bit) operation for their temperature channel(s). High-resolution mode doubles the amount of memory required by each measurement, reducing the deployment time for each interval setting, but dramatically improving the temperature resolution and accuracy. The high-resolution mode is not available for the RH channel. For high-resolution mode select the sensor and "Added Resolution" on the channel that follows it. For standard-resolution select only the temperature channel. *"Added Resolution" should not be enabled unless the corresponding temperature channel is enabled, otherwise the data will be invalid*. If you are using the Temp/Ext Temp version, the internal temperature sensor is Channel 1 and the external temperature probe is Channel 3.

Data Archiving

HOBO Pro Series loggers preserve the data from up to seven deployments preceding the current deployment. You will be able to retrieve data from all eight deployments by using the archive reader function in the logger software. (In some versions of the software it is a separate utility for windows 95/98/NT on the installation disk.) The reader will contact your logger, readout the last eight deployments, display information such as the deployment number, start time, end time, number of points and the description, and then allow you to select which file(s) you would like to save. For more information on the archive reader function, consult your logger software manual or the Archive Reader Utility readme.txt file. This archiving feature provides backup of your measurements in the logger, giving you another level of protection from accidental data loss.

Battery Life Specifications and Battery Level Indication

The battery level is displayed on the host computer during Launch. For the HOBO Pro Logger this will display one of two states: 98% or 20%. The lowest battery level that will be shown is 20%. Thus if the battery status indicates 20%, the battery is effectively dead and should be replaced immediately. **Launching the logger when the battery level reads 20% risks data corruption and/or data loss.**

In normal usage the HOBO Pro's battery can last up to three years when used with an interval of 1 minute or greater. Battery life is very dependent upon the sample interval and service temperature. See Table **1** for approximate run times at various intervals and service temperatures.

Table 1. Approximate Operational Battery Life for the HOBO Pro

	Logging Interval		
Operating Temperature	**< 10 seconds**	**10 secs - 1 minute**	**1 minute – 1 hour**
-40 - +122°F (-40 - +50°C)	~ 3 - 6 months	½ - 1½ years	1½ - 2 years
+77 - +102°F (+25 - +39°C)	~ 3 - 6 months	½ - 2 years	2 - 3 years
< +77°F (< +25°C)	~ 3 - 6 months	½ - 2½ years	2½ - 3+ years

Appendix E: Supplemental Building Information and Photographs

APPENDIX E: SUPPLEMENTAL BUILDING INFORMATION

i Building 1

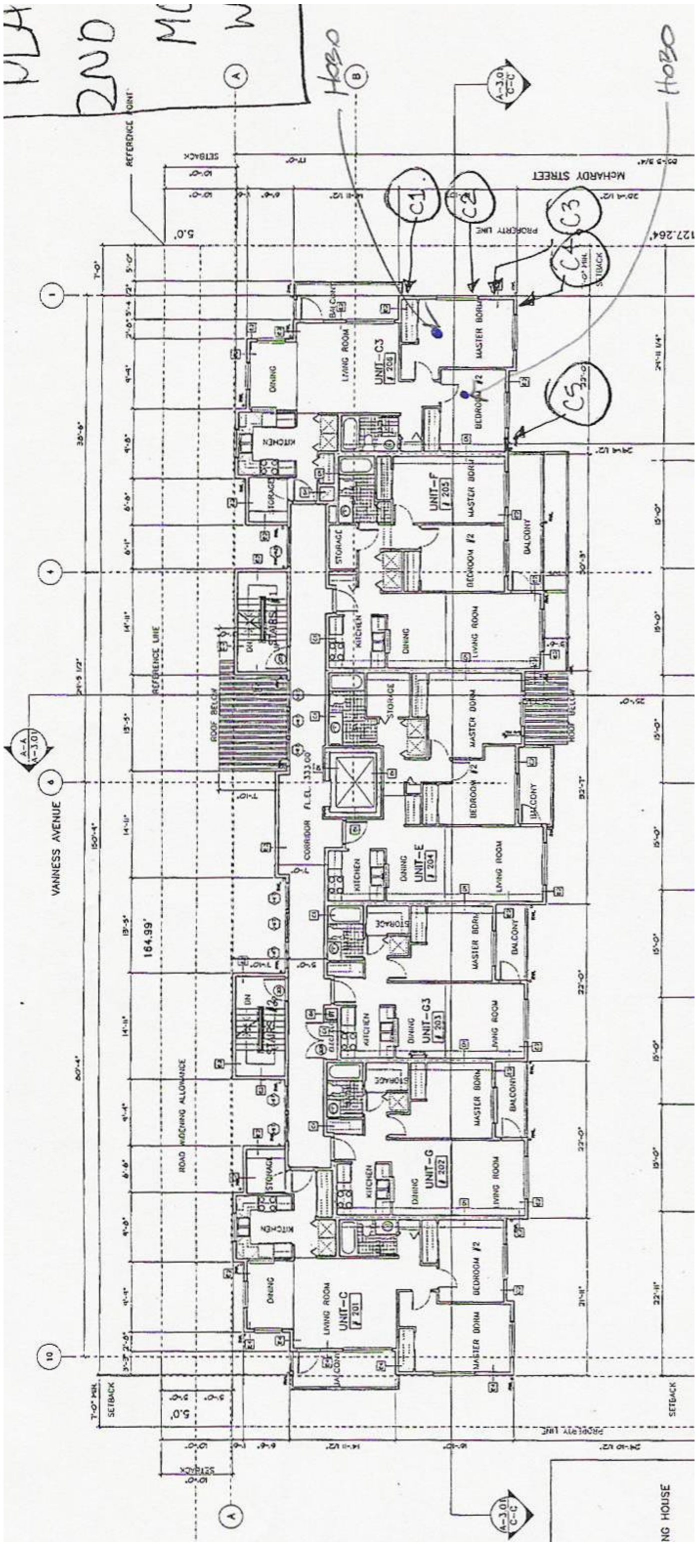
ii Building 2

iii Building 3

iv Building 4

v Building 5

I . BUILDING 1



Building 1 Floor Plan

Building 1- 1: Overview showing adjacent buildings and Sky-train tracks to northeast

Building 1- 2: Northeast elevation, showing adjacent neighbourhood

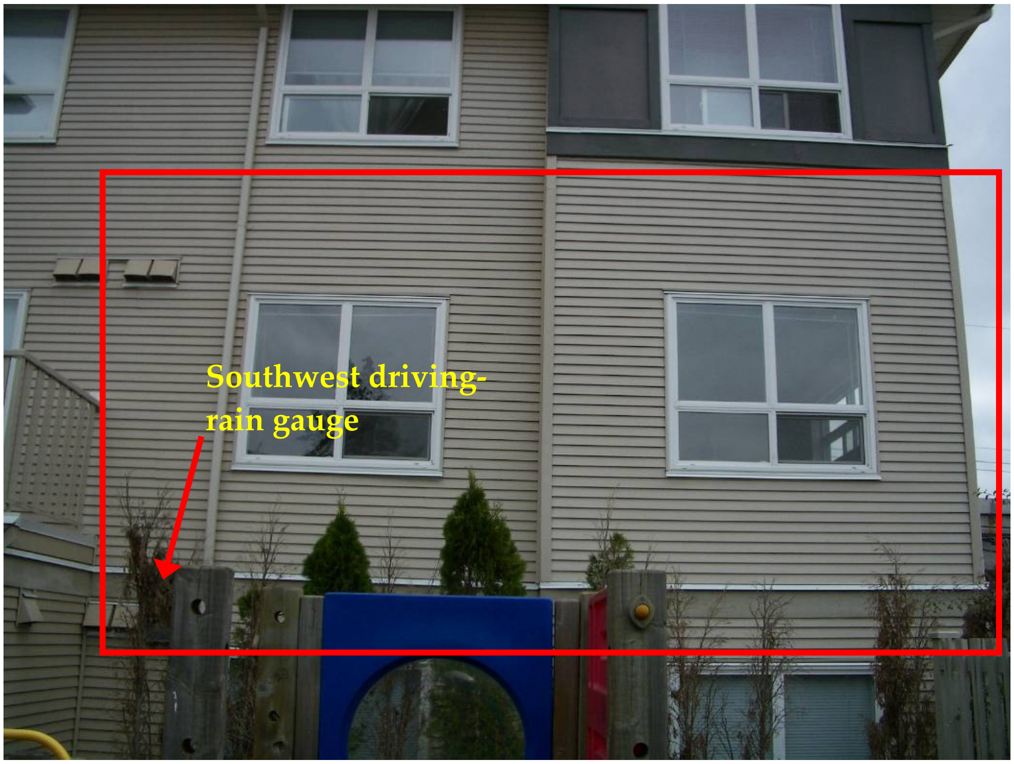
Building 1- 3: Southwest and southeast corner of building, suite 206 @ corner with monitored wall locations marked (red)

Building 1- 4: Wall monitoring locations 1 through 5 outside suite 206 & driving rain gauge locations

Building 1- 5: View of northeast (right side) and southeast elevation

Building 1- 6: Southeast elevation, suite 206 highlighted, driving rain gauge bottom left corner

Building 1- 7: Southeast and southwest elevation, corner of suite, note south-east note driving rain gauge (july 2005) appears to be obstructed behind foliage



Building 1- 8: Southwest elevation, suite 206 highlighted, note southwest driving rain gauge bottom left corner, view obstructed by foliage

Building 1- 9: Southwest elevation, driving rain gauge shown, view obstructed by foliage, and balcony obstructing capture from west

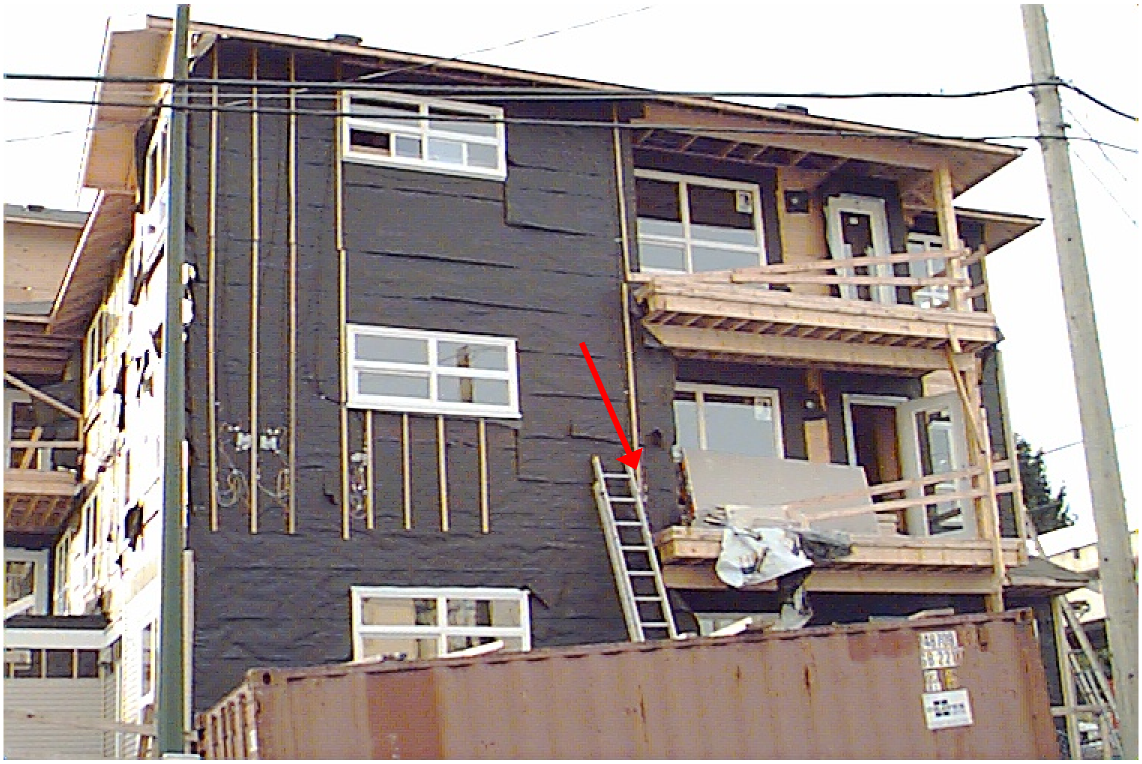

Building 1- 10: Southwest driving rain gauge

Building 1- 11: Southeast driving rain gauge

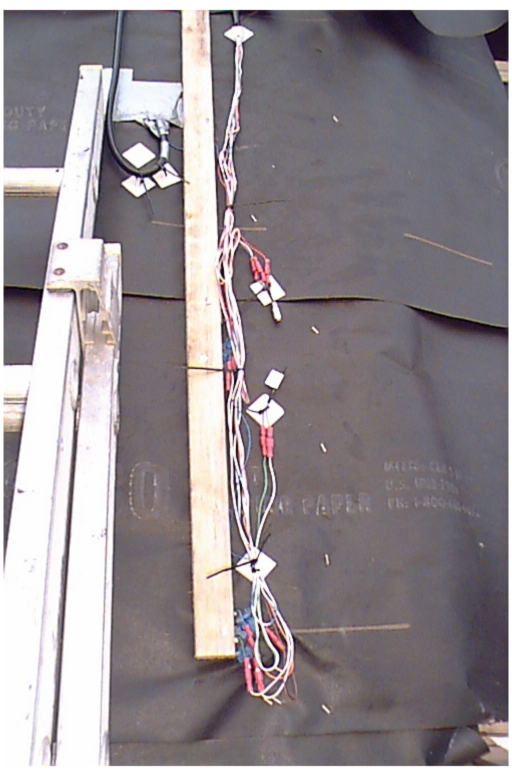
Building 1- 12: Interior of master bedroom, looking at future location of southeast wall monitor locations 2, 3, and 4.

Building 1- 13: Wall monitor location #5 from interior adjacent to driving rain gauge on exterior

Building 1- 14: Wall monitor locations 2 (far right), 3 (middle), and 4 (left wires between strapping) on southeast elevation

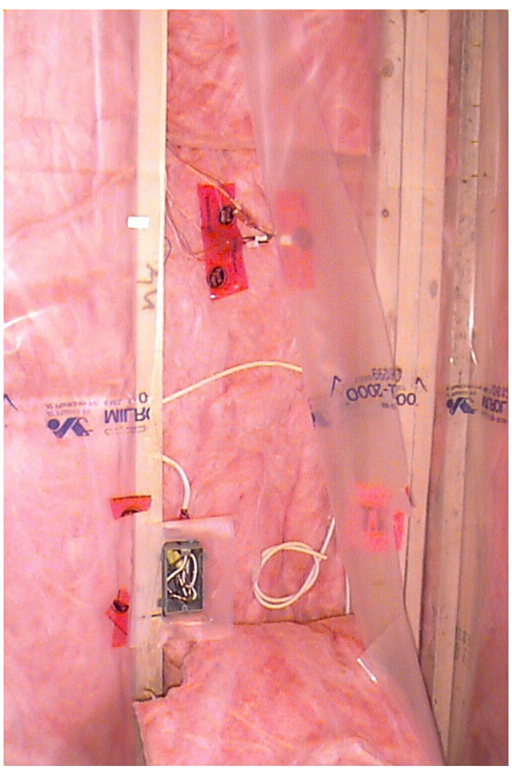


Building 1- 15: Southeast elevation during construction, note wall monitor location #1 at balcony on right



Building 1- 16: Wall monitor location #1 close-up of sensors

Building 1- 17: Wall monitor location #2 (below window), insulation cavity sensors 18” above floor



Building 1- 18: Wall monitor location 4, adjacent to electrical box

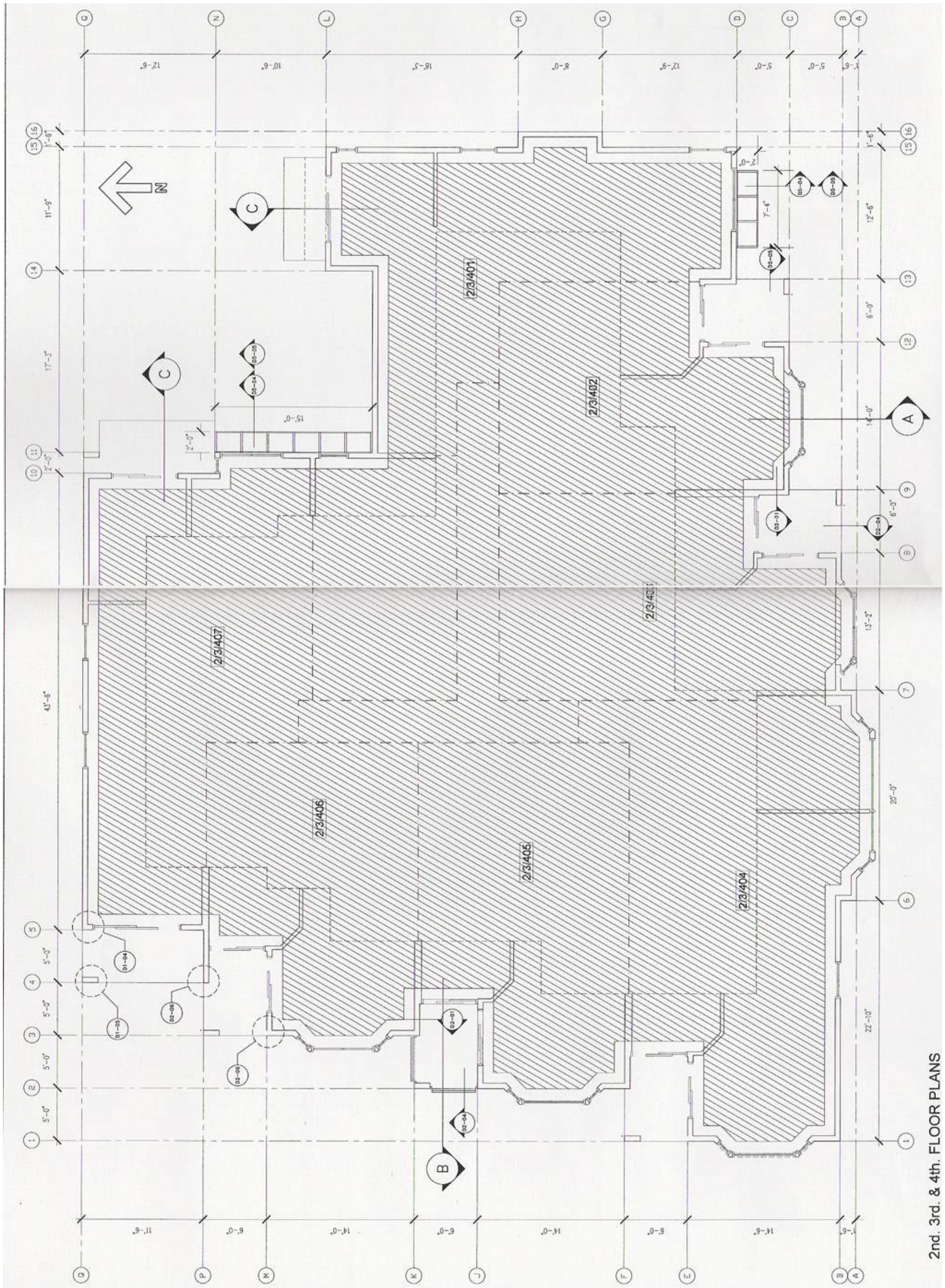
Building 1- 19: Wall monitor location 1, interior is inside closet of master bedroom

Building 1- 20: Wall monitor location 5, below exhaust vent, investigation of high MC readings in January 2001, close-up under vinyl siding in next photo

Building 1- 21: Close-up of MC (with blue liquid electrical insulation), RH, and T sensors at monitored location #5

Building 1- 22: Weather station on roof looking east

II. BUILDING 2



Building 2: Floor Plan

Building 2- 1: View showing surrounding neighbourhood

Building 2- 2: South view showing adjacent building to east

Building 2- 3: Wall monitoring locations 1 through 5 outside suite 401 & driving rain gauge locations, south elevation (left)

Building 2- 4: Overview of southwest corner

Building 2- 5: Southeast corner, suite 401 top floor, note driving rain gauges on south above window and east.

Building 2- 6: South east corner, suite 401

Building 2- 7: North elevation, suite 401 at balcony on left

Building 2- 8: Building prior to rehabilitation in 2000, southeast corner

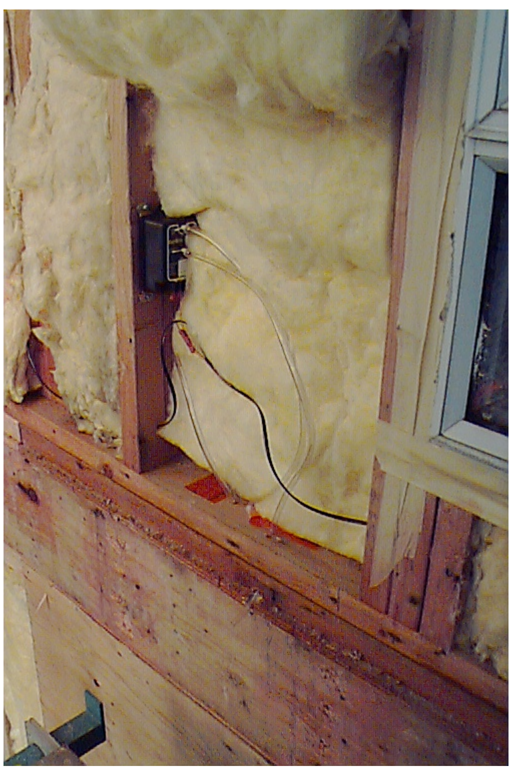
Building 2- 9: Suite 401, southeast corner window during exterior wall rehabilitation

Building 2- 10: Suite 401, balcony area on north elevation during rehabilitation

Building 2- 11: Suite 401 at sloped roof at cathedral ceiling. To be covered with roofing paper and slope metal roofing.

Building 2- 12: Rooftop weather station

Building 2- 13: Monitored wall location 5, temperature sensors installed mid-insulation adjacent to fireplace and chimney



Building 2- 14: Pressure sensor on south elevation adjacent to monitored wall location 5

Building 2- 15: Monitored wall location 3

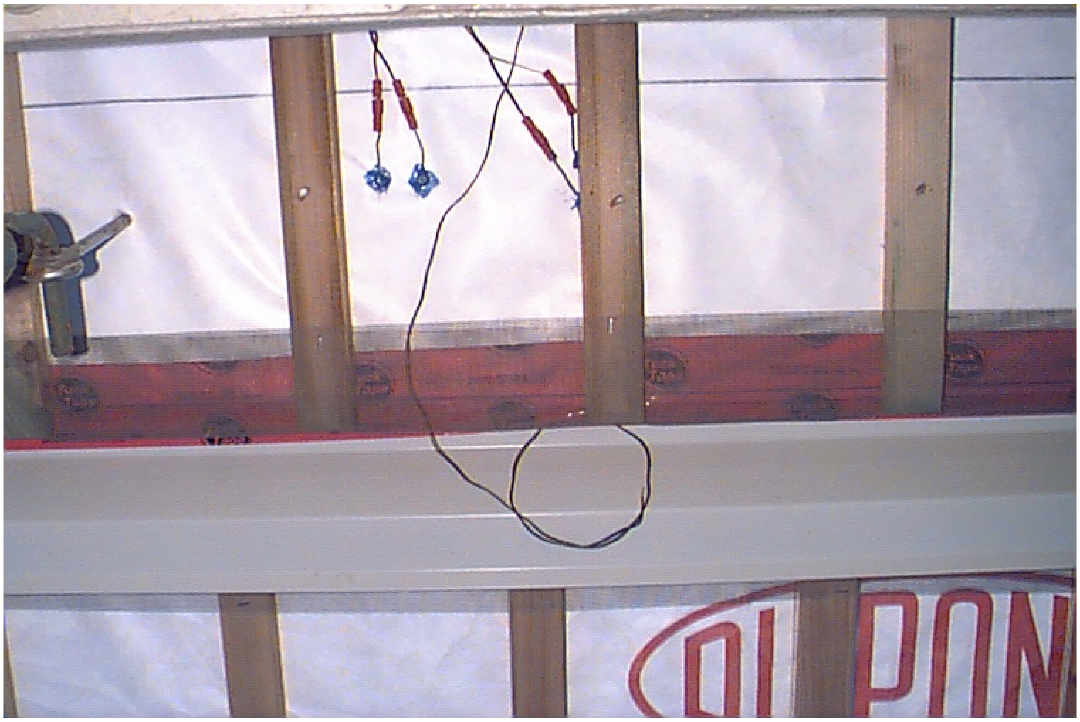
Building 2- 16: Monitored wall location 4 below window corner, new window frame in place

Building 2- 17: Monitored wall location 2, electrical box to interior, framing sensors in place

Building 2- 18: Monitored wall location 1, below drying vent (not shown) and adjacent to window jamb (mid-height of window)

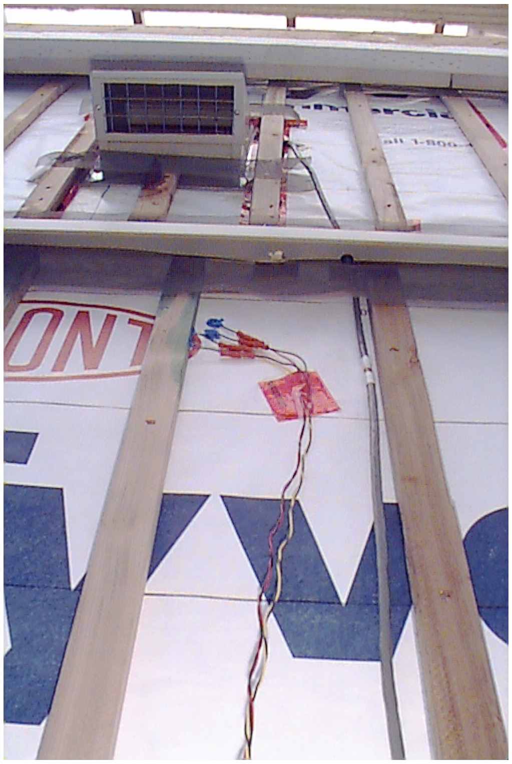
Building 2- 19: Monitored wall location 4, east elevation below window corner, strapping/sheathing and cavity sensors in place

Building 2- 20: Monitored wall location 3, middle of wall, strapping/sheathing and cavity sensors in place



Building 2- 21: Monitored wall location 3, worst case moisture sensors at bottom of wall cavity

Building 2- 22: Monitored wall location 2 cavity sensors in place



Building 2- 23: Monitored wall location 1, below dryer exhaust vent on east elevation

Building 2- 24: Monitored wall locations 2 (right), 3 (middle) and 4 (below window)

Building 2- 25: Monitored wall location 5, south elevation adjacent to balcony at suite 402

Building 2- 26: Monitored wall location 5, south elevation prior to installation of balcony guardrail at suite 402

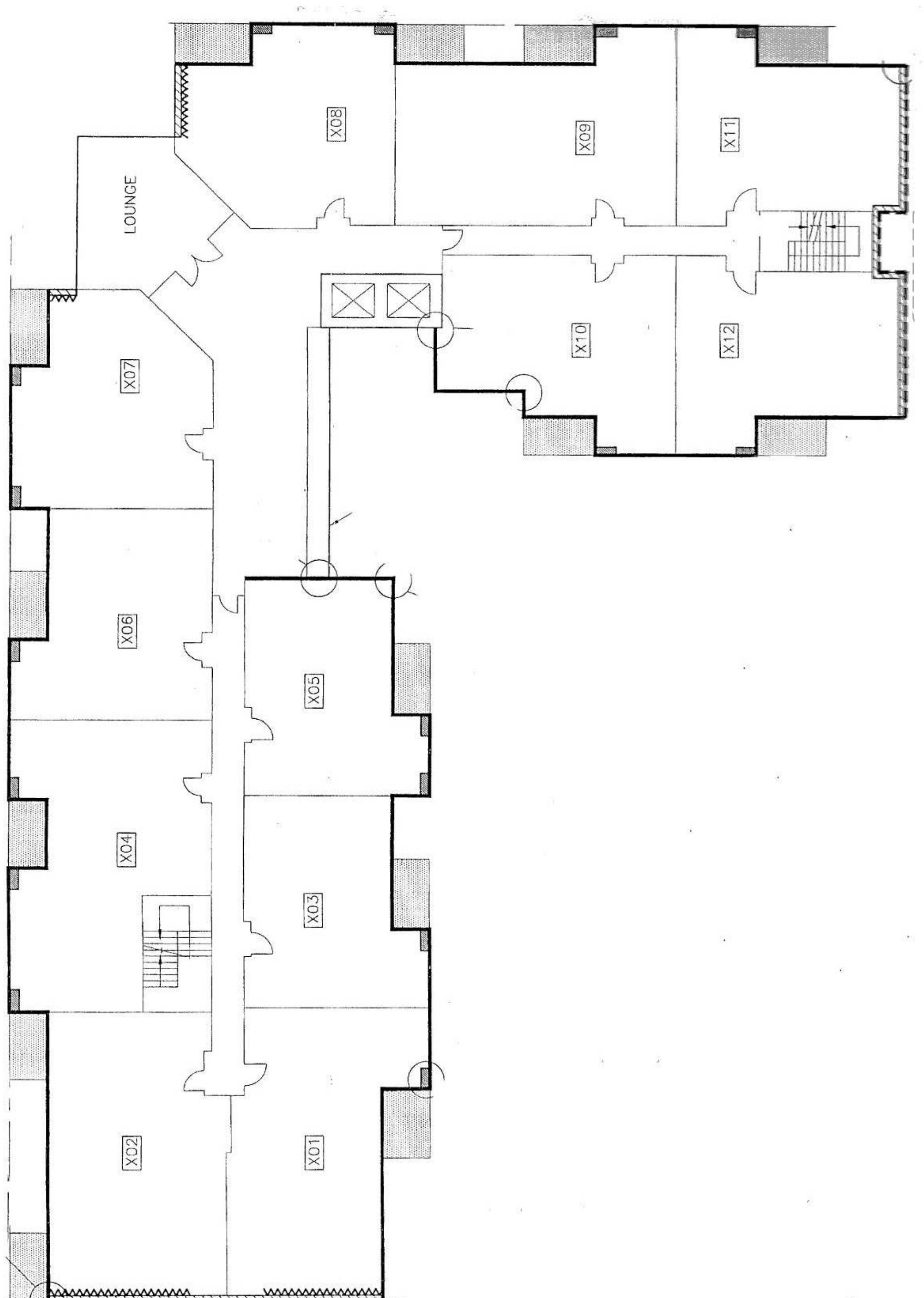
Building 2- 27: Suite 401 (top) after installation of stucco cladding

Building 2- 28: Interior of suite 401, living room at southeast corner

Building 2- 29: Interior of suite 401, location of monitored wall location 5 behind fireplace/chimney to right

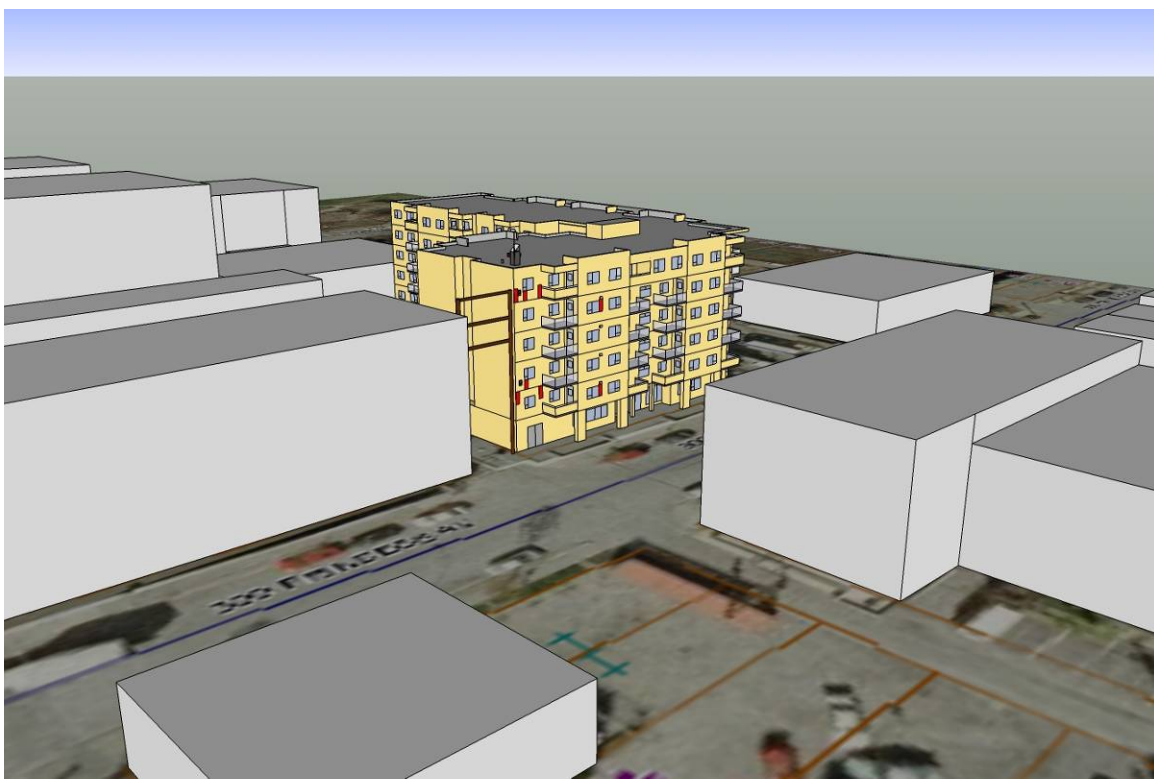
Building 2- 30: South Driving Rain Gauge, note minimal overhang protection

III. BUILDING 3



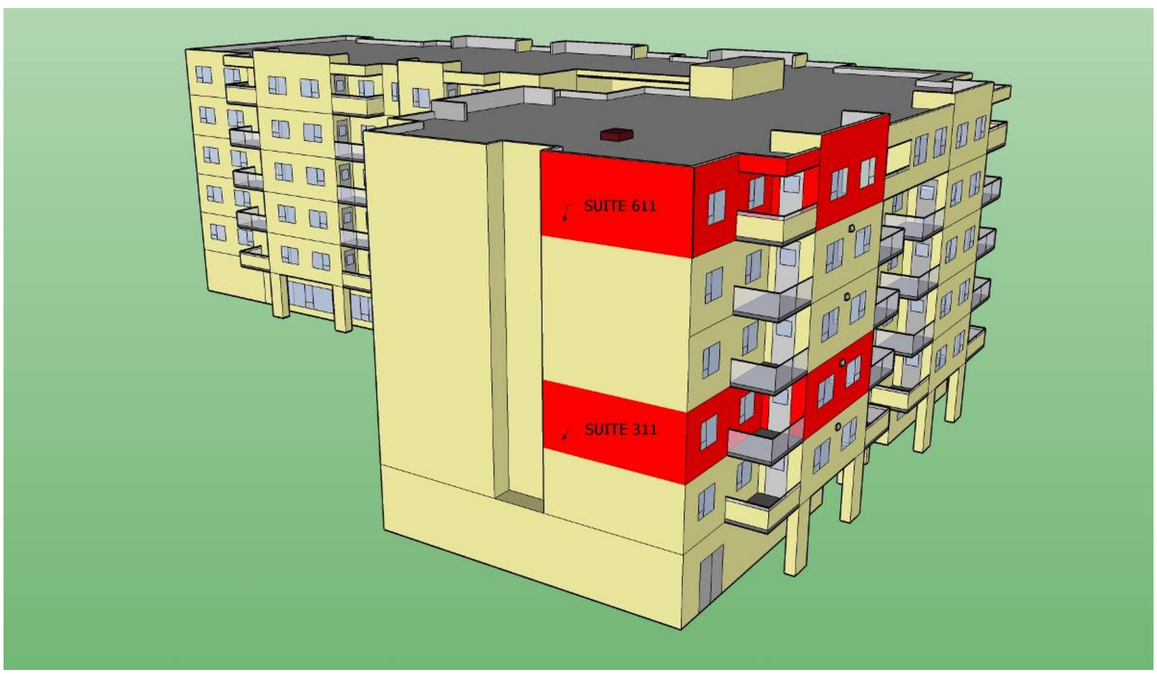
Building 3 – Floor Plan

Building 3_1: Northeast overview of building and surrounding neighbourhood



Building 3_ 2: Southeast overview of building and surrounding neighbourhood

Building 3_ 3: Wall monitoring locations 1 through 8 & driving rain gauge locations, east elevation



Building 3_ 4: Suite 611 and 311, highlighted

Building 3_ 5: East elevation (right), south at alleyway (concrete shear wall)

Building 3_ 6: East elevation, location of driving rain gauges on 3rd and 6th floors

Building 3_ 7: North elevation

Building 3_ 8: South elevation at interior courtyard (note open corridor at right)

Building 3_ 9: Rooftop weather station

Building 3_ 10: Suite 611 interior at living room looking east

Building 3_ 11: Suite 611 interior at storage room, location of interior Hobo

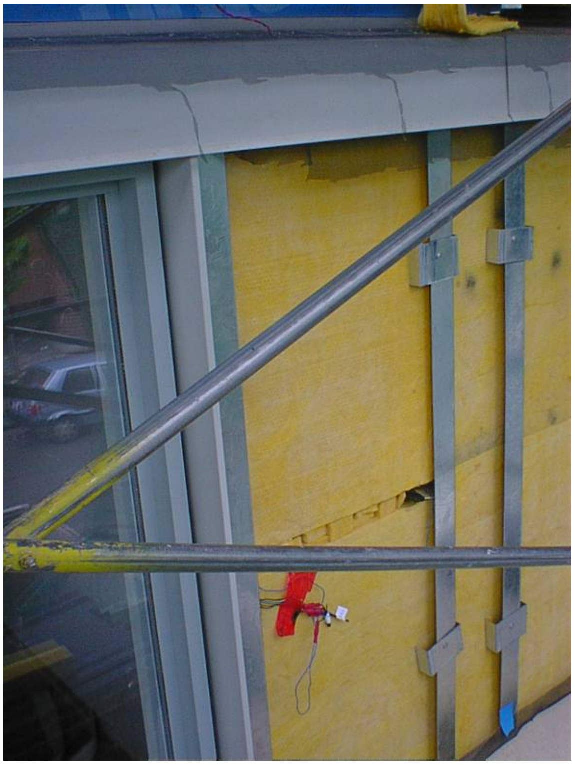

Building 3_ 12: 6th floor driving rain gauge outside suite 611

Building 3_ 13: 3rd floor driving rain gauge outside suite 311

Building 3_ 14: Suite 311, interior at bedroom 2, location of interior Hobo

Building 3_ 15: Wall monitoring location 1, below in-slab exhaust vent (3rd floor), during rehabilitation

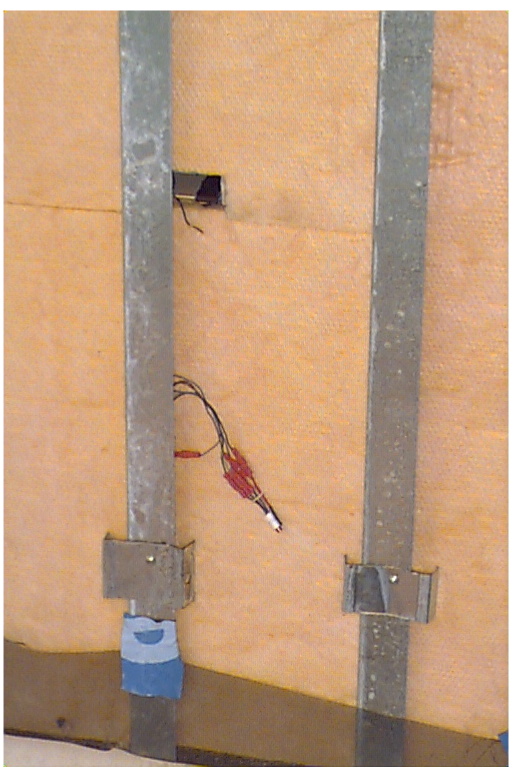
Building 3_ 16: Wall monitoring location 1, below exhaust vent, location of sensors



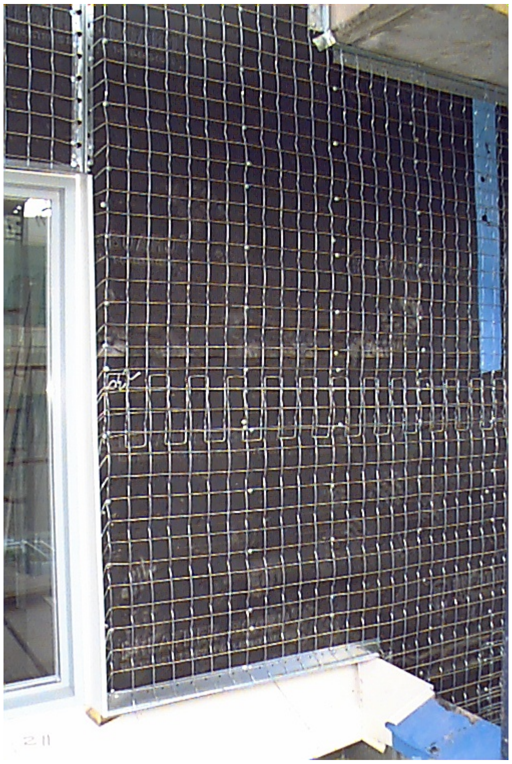
Building 3_ 17: Wall monitoring location 1, below exhaust vent, location of cavity sensors 36” below vent in cavity

Building 3_ 18: Wall monitoring location 2, below balcony outside suite 211

Building 3_ 19: Wall monitoring location 2, below balcony edge (suite 211)



Building 3_ 20: Wall monitoring location 2, after cavity insulation installed, location of cavity T/RH sensors

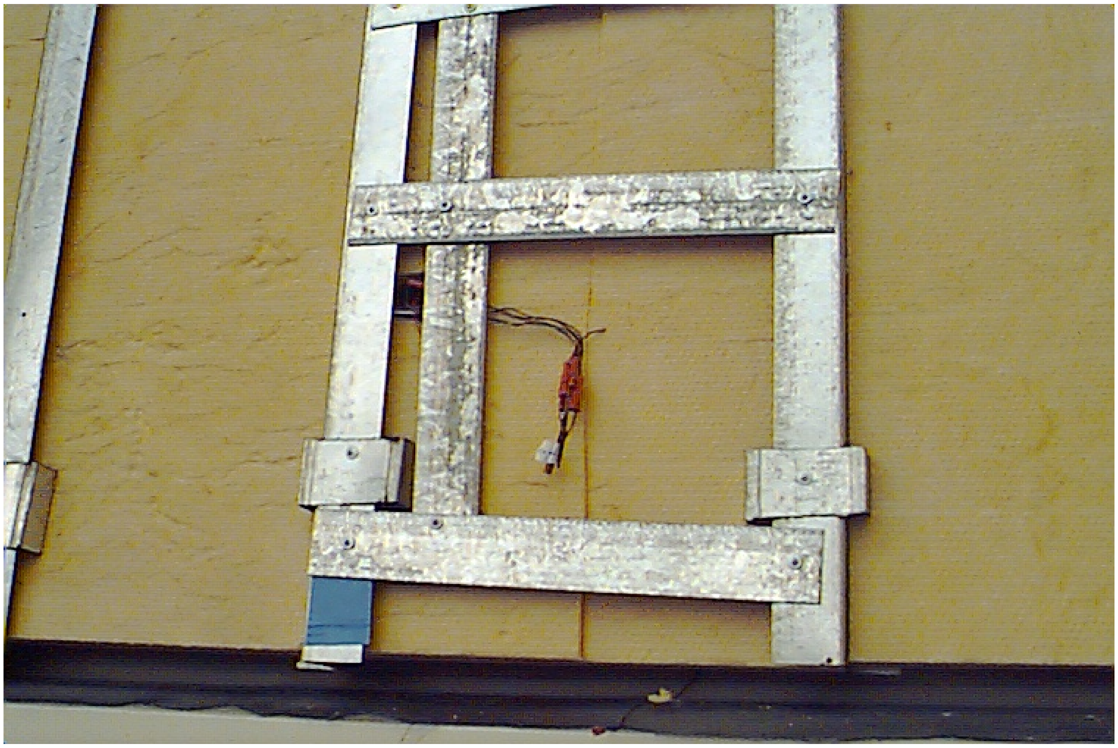


Building 3_ 21: Wall monitoring location 2, after stucco backer-board and wire mesh installed

Building 3_ 22: Wall monitoring location 2, after stucco installed below balcony corner

Building 3_ 23: Wall monitoring location 3, below 3rd floor window prior to insulation install

Building 3_ 24: Wall monitoring location 3, gypsum sheathing MC pins installed



Building 3_ 25: Wall monitoring location 3, cavity insulation and T/RH sensors installed, note unnecessary use of additional steel strapping around sensor

Building 3_ 26: Wall monitoring location 3, below suite 311 bedroom window corner adjacent to 3rd floor driving rain gauge

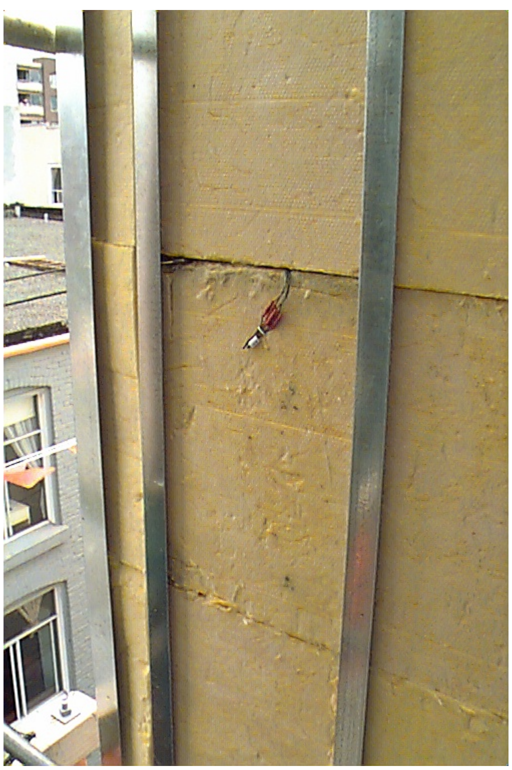
Building 3_ 27: Wall monitoring location 4, at suite 211 corner of wall

Building 3_ 28: Wall monitoring location 4, gypsum sheathing sensors through peel and stick membrane

Building 3_ 29: Wall monitoring location 5, below 6th floor in-slab exhaust vent prior to rehabilitation

Building 3_ 30: Wall monitoring location 5, cavity RH/T sensors installed

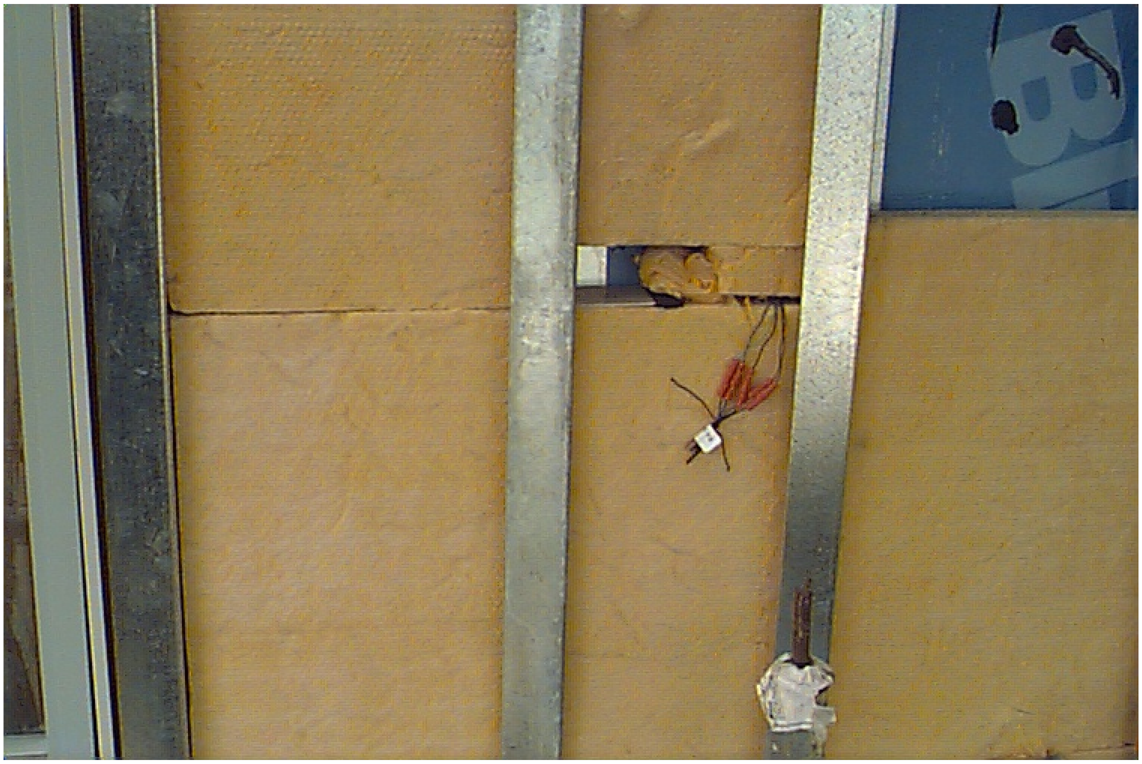
Building 3_ 31: Wall monitoring location 6, during rehabilitation, prior to removal of insulation and polyethylene



Building 3_ 32: Wall monitoring location 6, installation of cavity T/RH sensors

Building 3_ 33: Wall monitoring location 6, adjacent to driving rain gauge

Building 3_ 34: Wall monitoring location 7 at balcony guardrail prior to rehabilitation

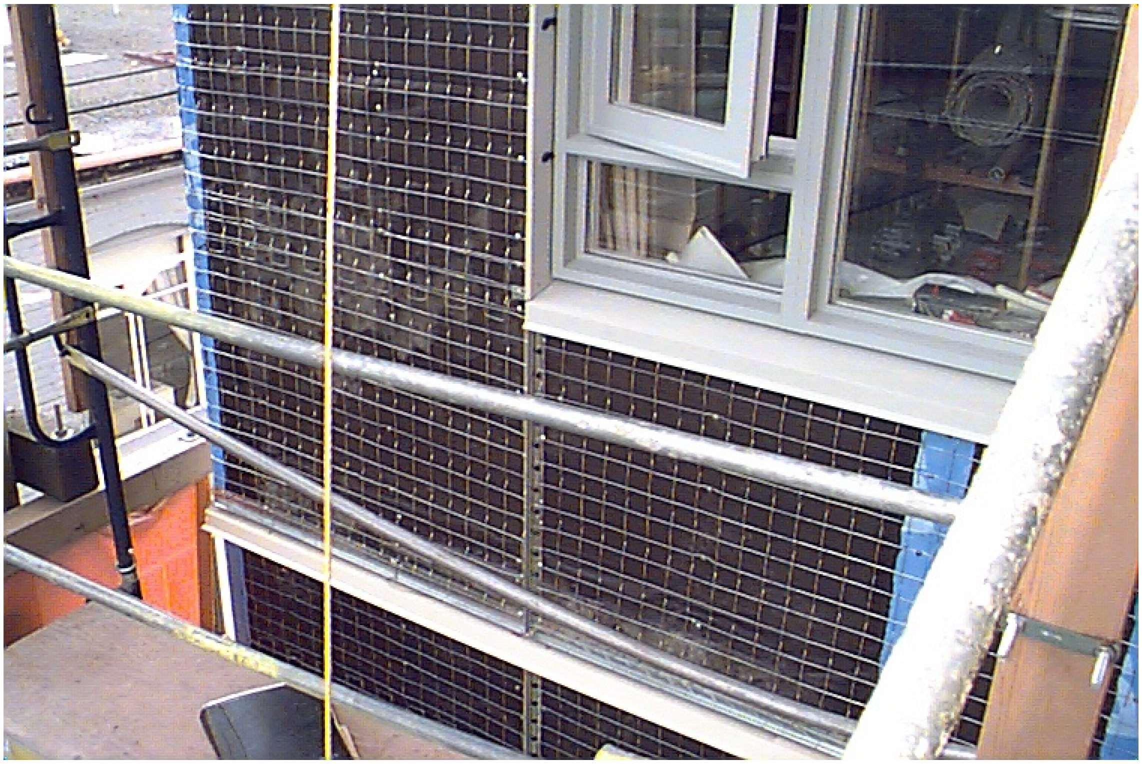


Building 3_ 35: Wall monitoring location 7, at balcony guardrail interface

Building 3_ 36: Wall monitoring location 7 after installation of stucco cladding

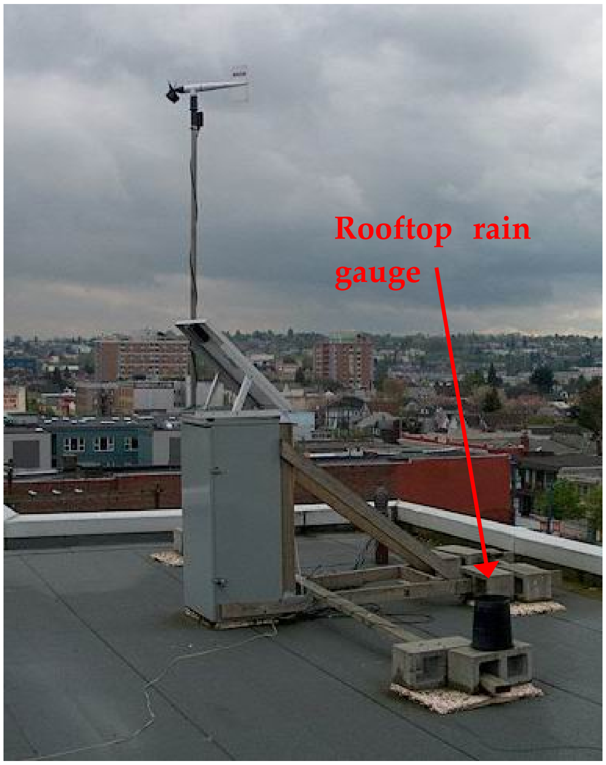
Building 3_ 37: Wall monitoring location 8, below window prior to rehabilitation

Building 3_ 38: Wall monitoring location 8, below window, Cavity T/RH sensors in place

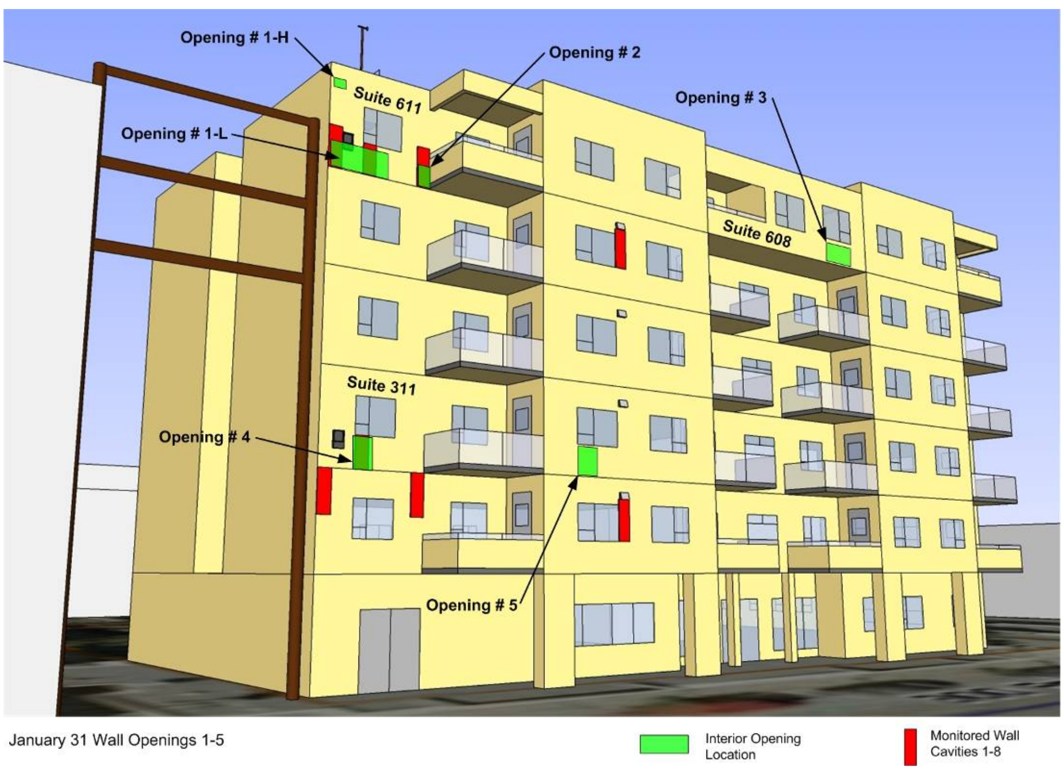


Building 3_ 39: Wall monitoring location 8, after installation of stucco backer-board and wire mesh

Building 3_ 40: view from roof looking at 6th floor driving rain gauge on east elevation – no overhang



Building 3_ 41: Rooftop weather station and rain gauge

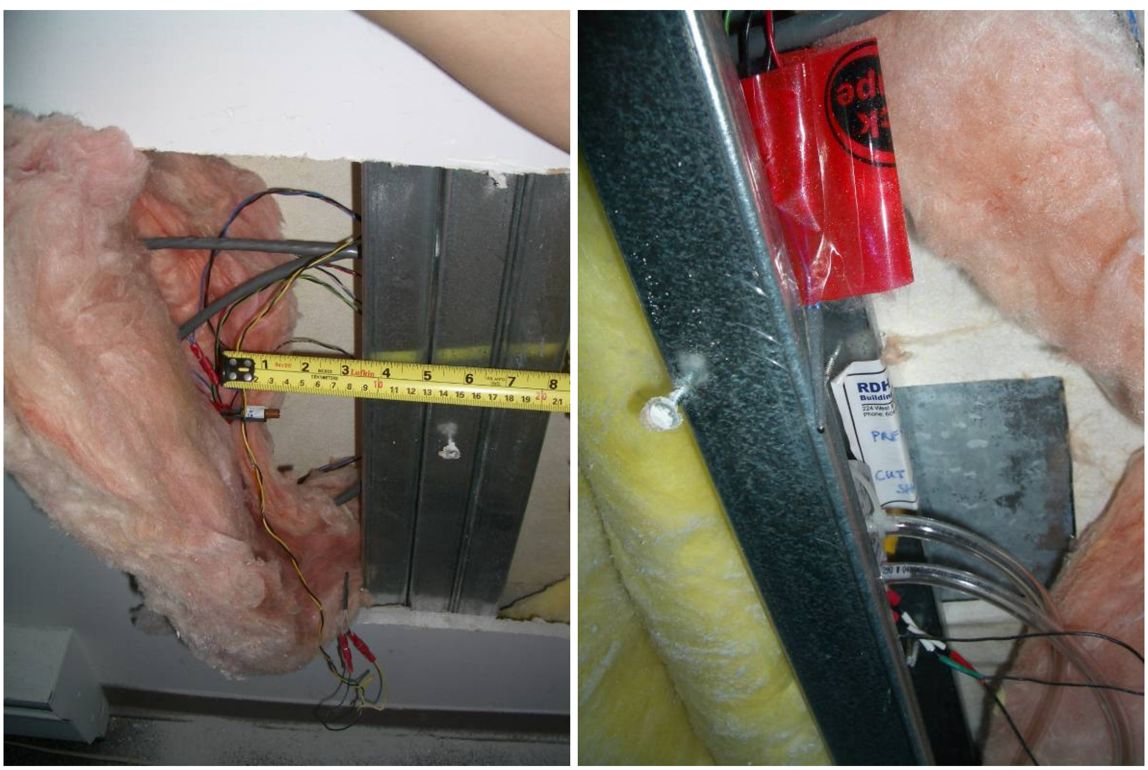


Building 3_ 42: Jan 31/06 Openings 1 through 5 location on exterior walls

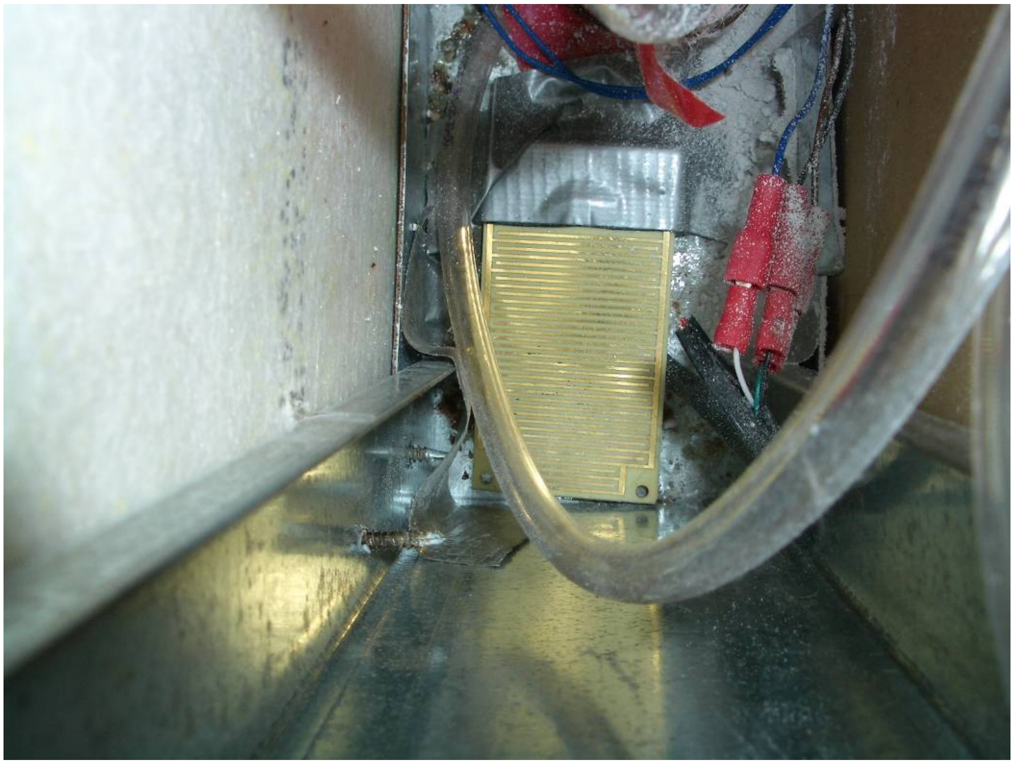
Building 3_ 43: Jan 31/06 Openings – Suite 611 bedroom 2, note foam insulation rolls piled against the exterior walls

Building 3_ 44: Jan 31/06 Openings – Suite 611 opening 1 – prior to removal of drywall

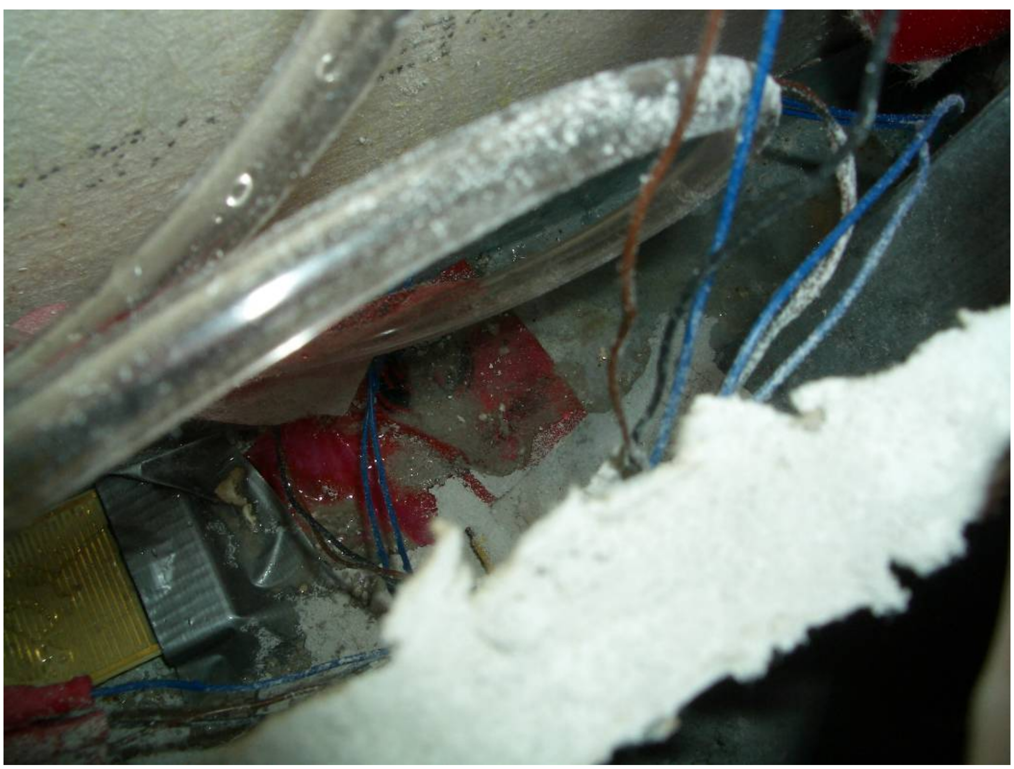
Building 3_ 45: Jan 31/06 Openings – Suite 611 opening 1 after drywall removed



Building 3_ 46: Jan 31/06 Openings – Suite 611 opening 1 – stud cavity sensors. T/RH (left) and pressure sensor (right)

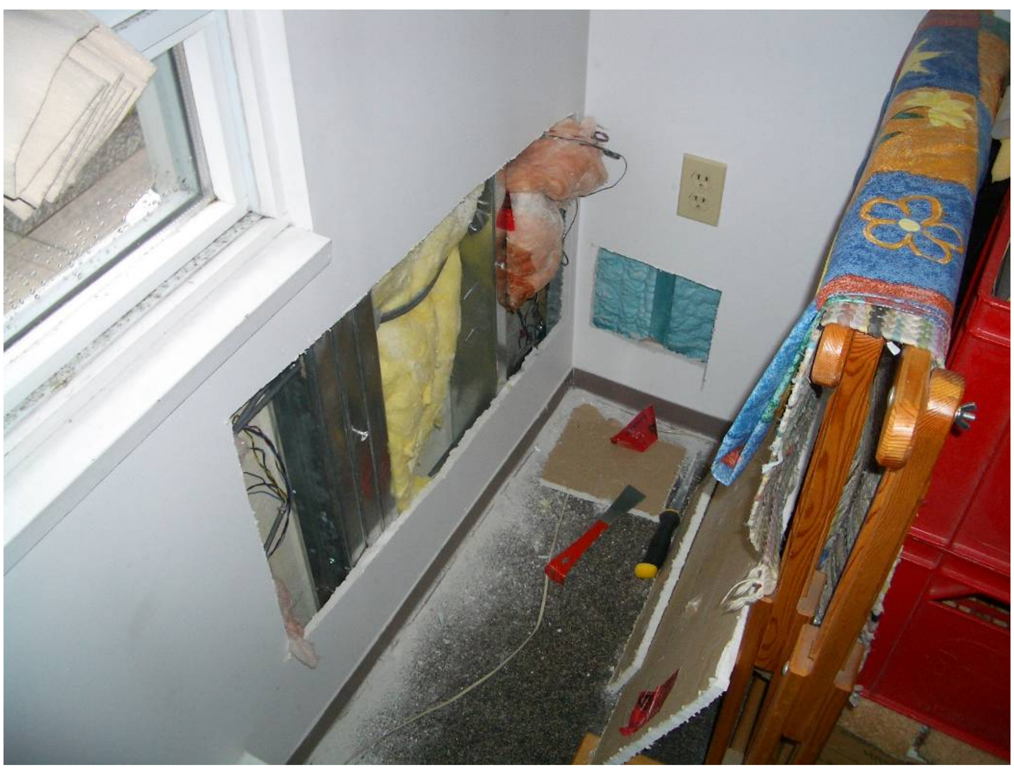


Building 3_ 47: Jan 31/06 Openings – Suite 611 opening 1 – wetness sensor at bottom of sill track, monitored wall location 8



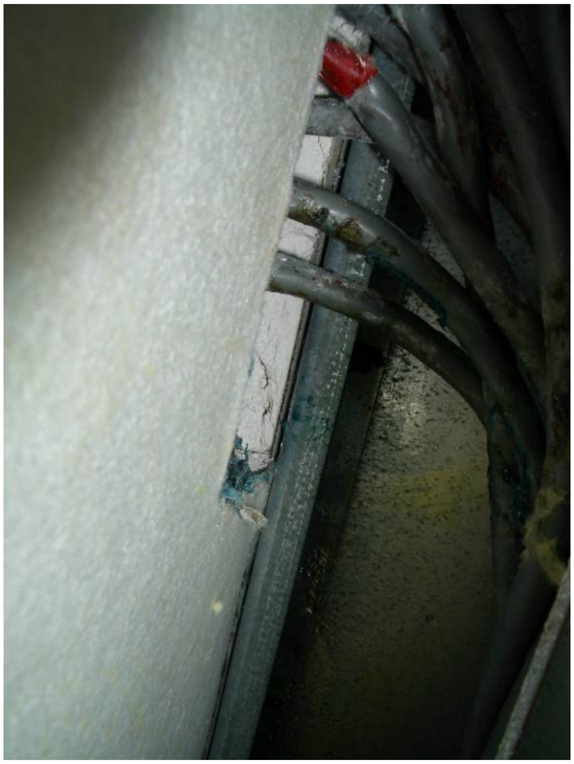
Building 3_ 48: Jan 31/06 Openings – Suite 611 opening 1 –note liquid water at sill track at bottom of monitored wall location 6

Building 3_ 49: Jan 31/06 Openings – Suite 611 opening 1 – liquid water in sill track, condensation on gypsum, mould growth and light corrosion of studs



Building 3_ 50: Jan 31/06 Openings – Suite 611 opening 1 – further opening of south wall (note blue closed cell polyurethane sprayfoam)

Building 3_ 51: Jan 31/06 Openings – Suite 611 opening 1 – corner of stud cavity at monitored wall location 6



Building 3_ 52: Jan 31/06 Openings – Suite 611 opening 1 – additional opening at top of wall (opening 1-H). View of sensor cables passing through wall (dry)

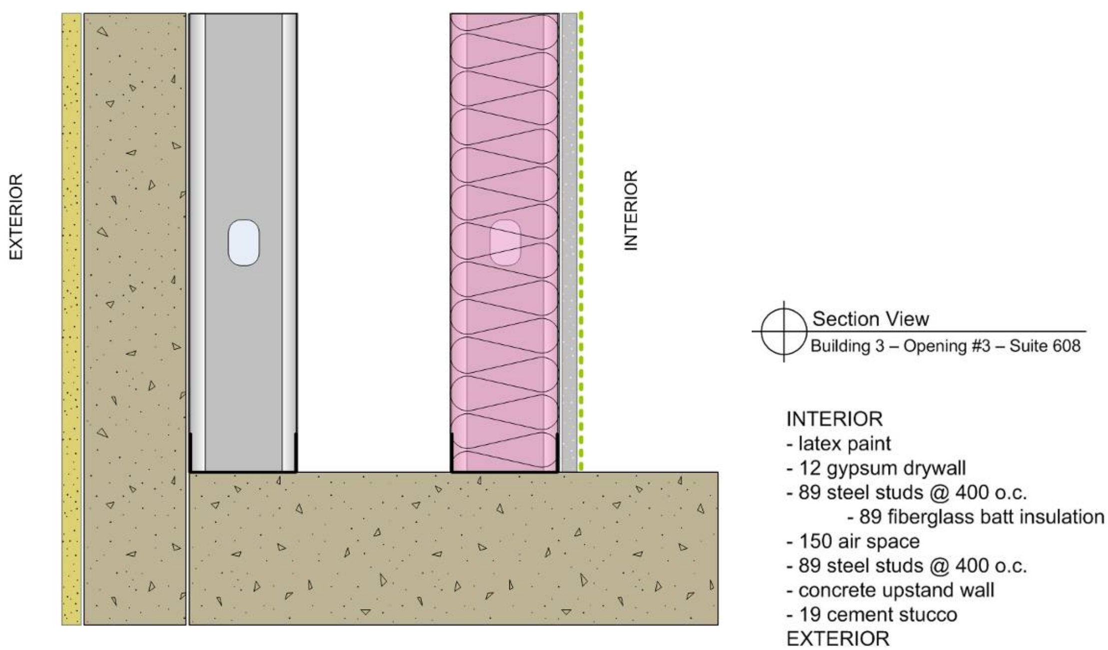
Building 3_ 53: Jan 31/06 Openings – Suite 611 opening 2 – wall monitoring location 7 (balcony guardrail)

Building 3_ 54: Jan 31/06 Openings – Suite 611 opening 2 – wall monitoring location 7, leaf wetness sensor in stud cavity (insulation pulled back)

Building 3_ 55: Jan 31/06 Openings – Suite 611 – condensation and mildew on window frame (typical for apartment)

Building 3_ 56: Jan 31/06 Openings – Suite 608 opening 3 – location of opening below window

Building 3_ 57: Jan 31/06 Openings – Suite 609 opening 3 – below window at pre-cast concrete spandrel, alternate wall configuration



Building 3_ 58: Jan 31/06 Openings – Suite 609 opening schematic

Building 3_ 59: Jan 31/06 Openings – Suite 602 mould at ceiling, condensation on sliding glass door frame

Building 3_ 60: Jan 31/06 Openings – Suite 311 – condensation on window frame (typical for suite)

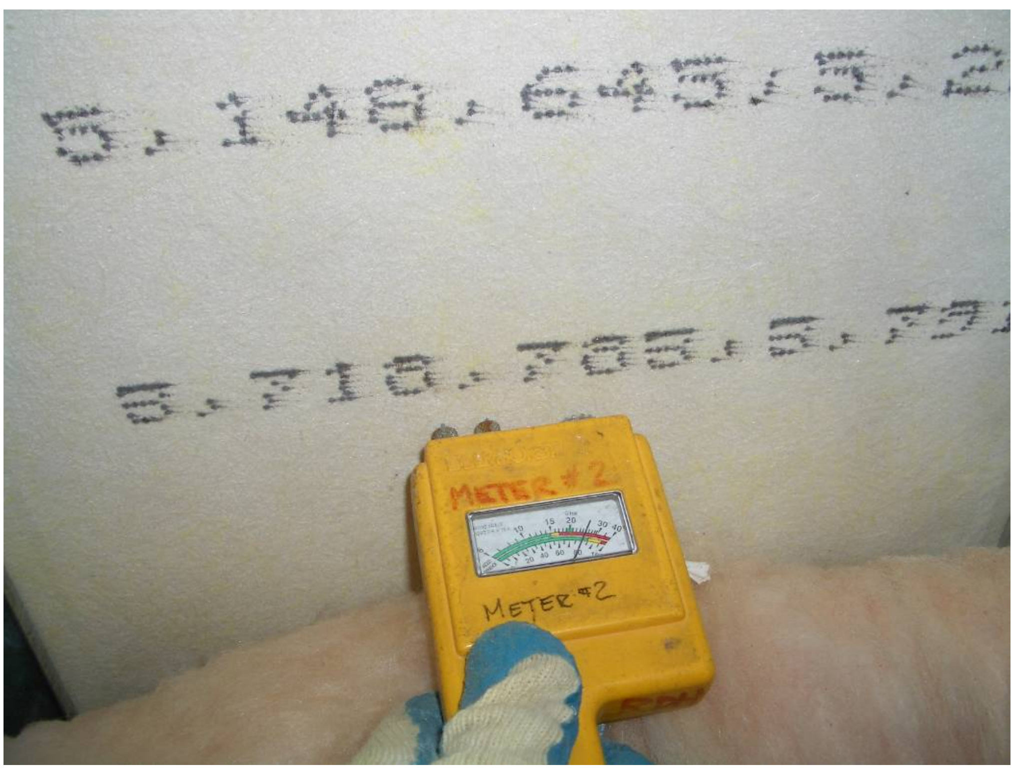
Building 3_ 61: Jan 31/06 Openings – Suite 311 opening 4 – below window at monitored wall location 3

Building 3_ 62: Jan 31/06 Openings – Suite 311 opening 4 – below window, note gypsum moisture content >30% wood scale and staining on gypsum interior side

Building 3_ 63: Jan 31/06 Openings – Suite 311 opening 4 – below window inside stud cavity insulation removed. Corroded fasteners noted

Building 3_ 64: Jan 31/06 Openings – Suite 311 opening 5 – below living room window on east elevation

Building 3_ 65: Jan 31/06 Openings – Suite 311 opening 5 – below living room window on east elevation, cavity dry.



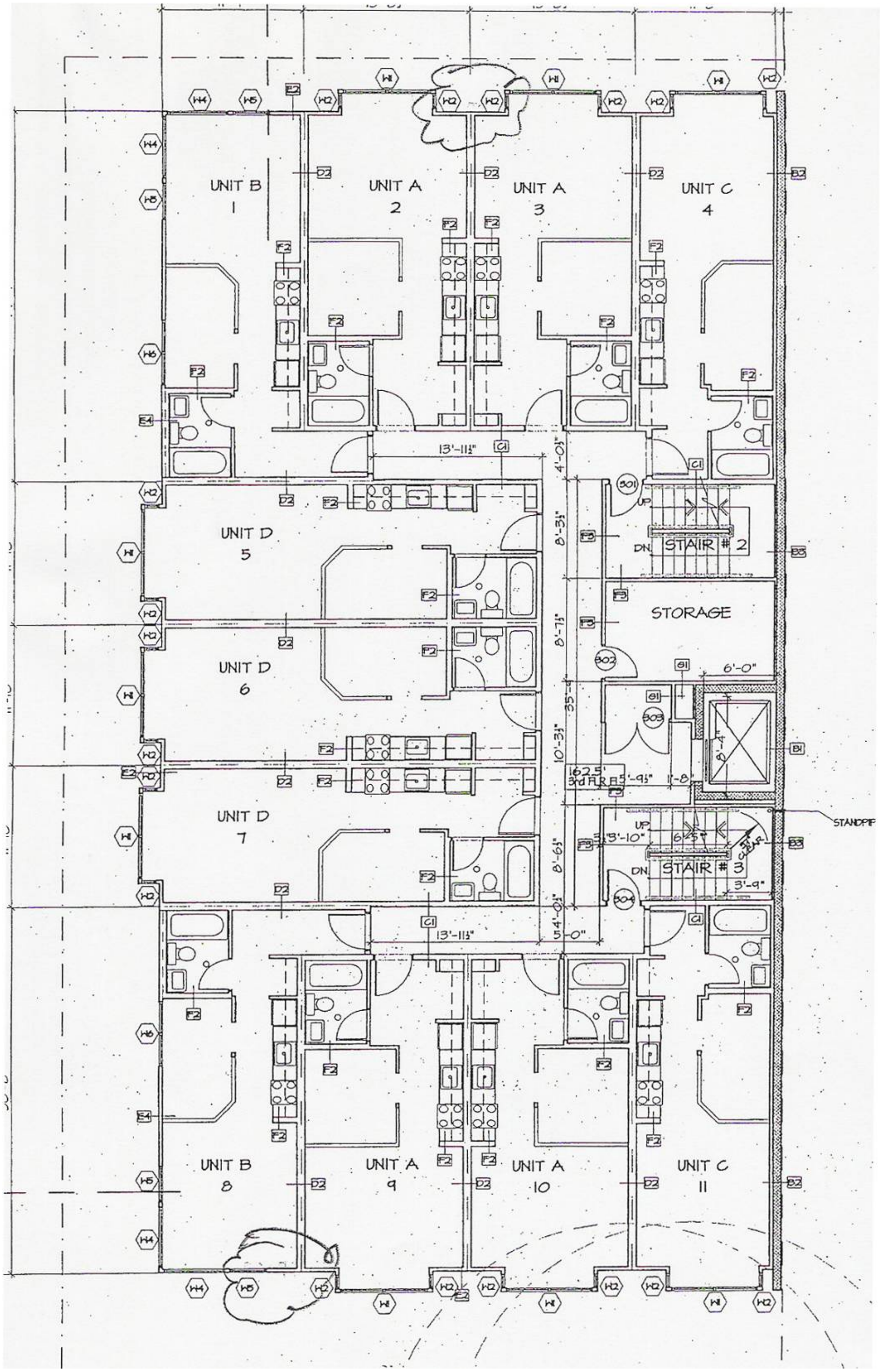
Building 3_ 66: Jan 31/06 Openings – Suite 311 opening 5 – below living room window on east elevation, gypsum had wood moisture content of 25% all over

Building 3_ 67: Interior of suite in Building 3 Prior to Rehabilitation in 2001 (MH Photo)

Building 3_ 68: Interior of suite in Building 3 Prior to Rehabilitation in 2001 (MH Photo)

Building 3_ 69: Exterior of Building 3 Prior to Rehabilitation in 2001 (MH Photo)

IV. BUILDING 4



Building 4 – Plan view of floors 2 through 4

Building 4. 1: West overview of building and surrounding neighbourhood

Building 4. 2: top view of building in relation to neighbourhood

Building 4. 3: Southwest overview (south elevation at right)

Building 4. 4: South Elevation Sensor Locations 3, 4, and 5, South Driving Rain

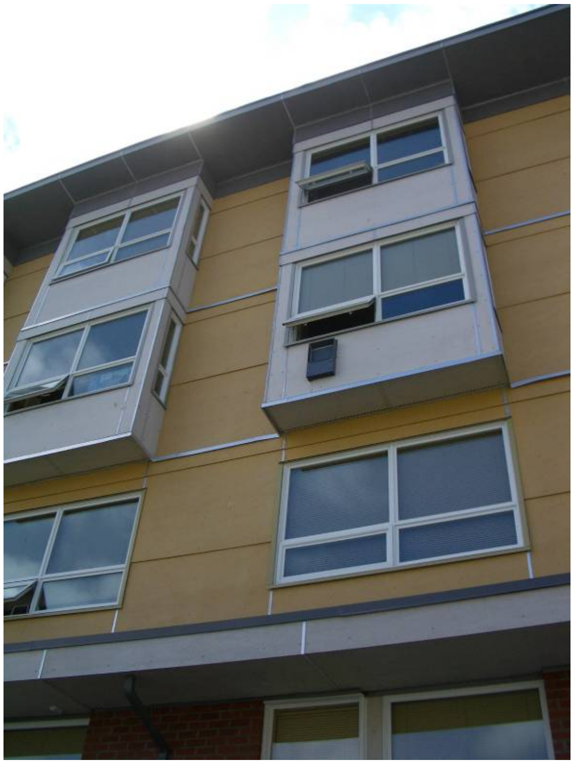
Building 4 North Elevation

Building 4. 5: North Elevation Sensor Locations 1 and 2, North Driving Rain at window build-out

Building 4. 6: Northwest overview (north at left)

Building 4. 7: Southeast elevation, note east elevation consists of solid concrete-block fire-wall

Building 4. 8: South elevation, note 4' wide overhangs above main wall, 2' over window build-outs

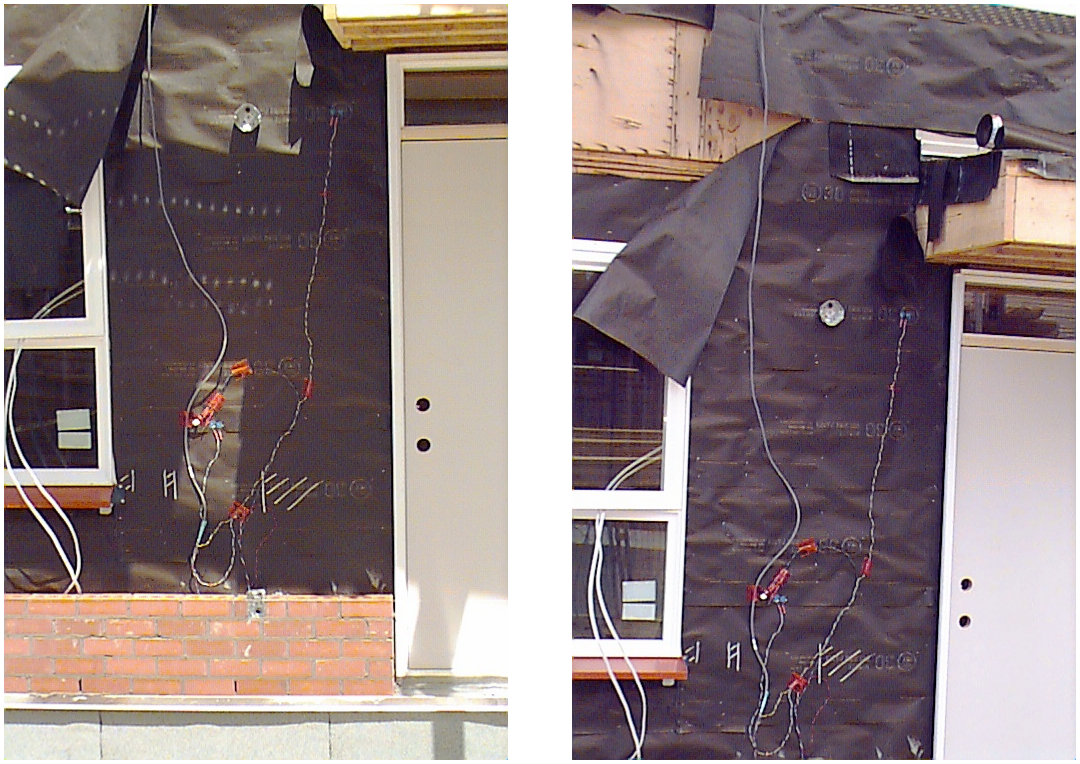


Building 4. 9:North elevation, note driving rain gauge below operable window

Building 4. 10: Rooftop weather station (rain gauge behind)

Building 4. 11: Southwest elevation (south at right)

Building 4. 12: Northwest elevation during construction in 2001



Building 4. 13: Wall monitoring location 5, south elevation at ground floor behind brick veneer, installation of cavity sensors behind brickwork

Building 4. 14: Wall monitoring location 2, north elevation at suite 303 adjacent to suite 302 at left

Building 4. 15: Wall monitoring location 2, north elevation, suite 303 at pressure sensor and stud cavity sensors

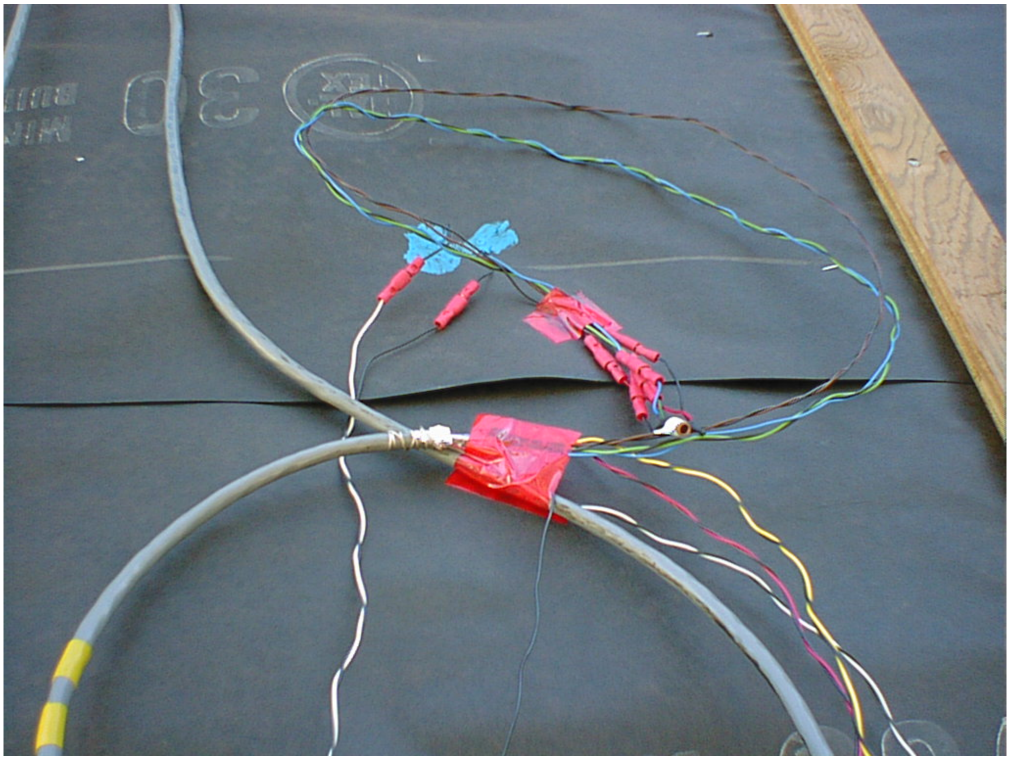
Building 4. 16: Wall monitoring location 1, north elevation at bay window, suite 302. Stud cavity sensors prior to insulation install

Building 4. 17: Wall monitoring location 4, south elevation at suite 308 (corner unit). Sensors below window corner

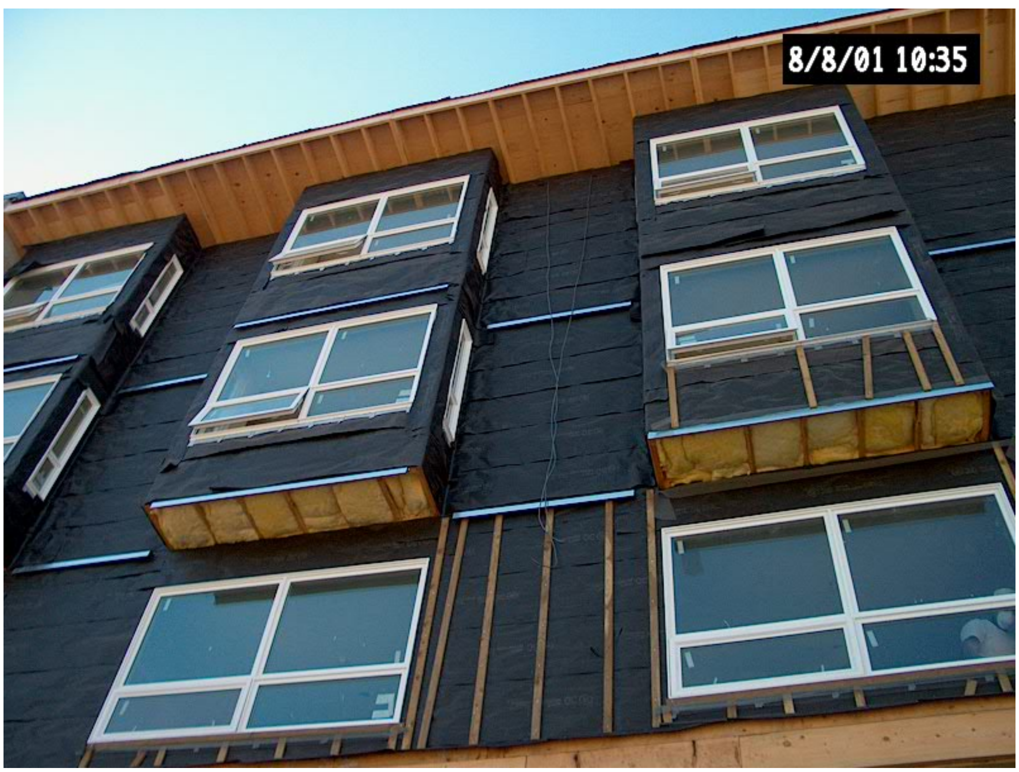
Building 4. 18: Wall monitoring locations 4 (right) and 3 (at left) on south elevation in suite 308

Building 4. 19: Wall monitoring location 3, south elevation, suite 308, driving rain gauge to exterior

Building 4. 20: Wall monitoring location 4 below window and triple strapping

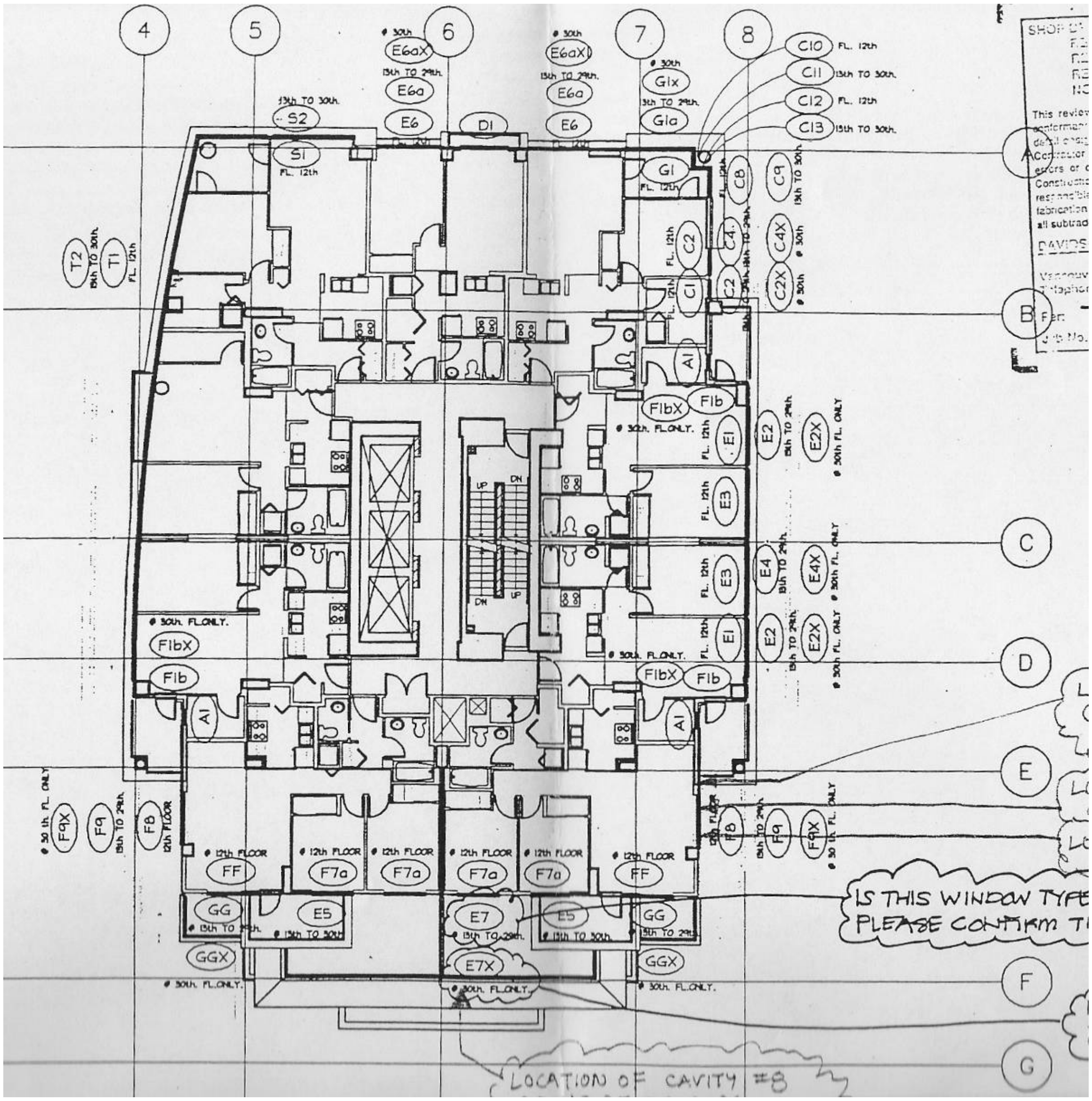


Building 4. 21: Wall monitoring location 3 cavity sensors installed



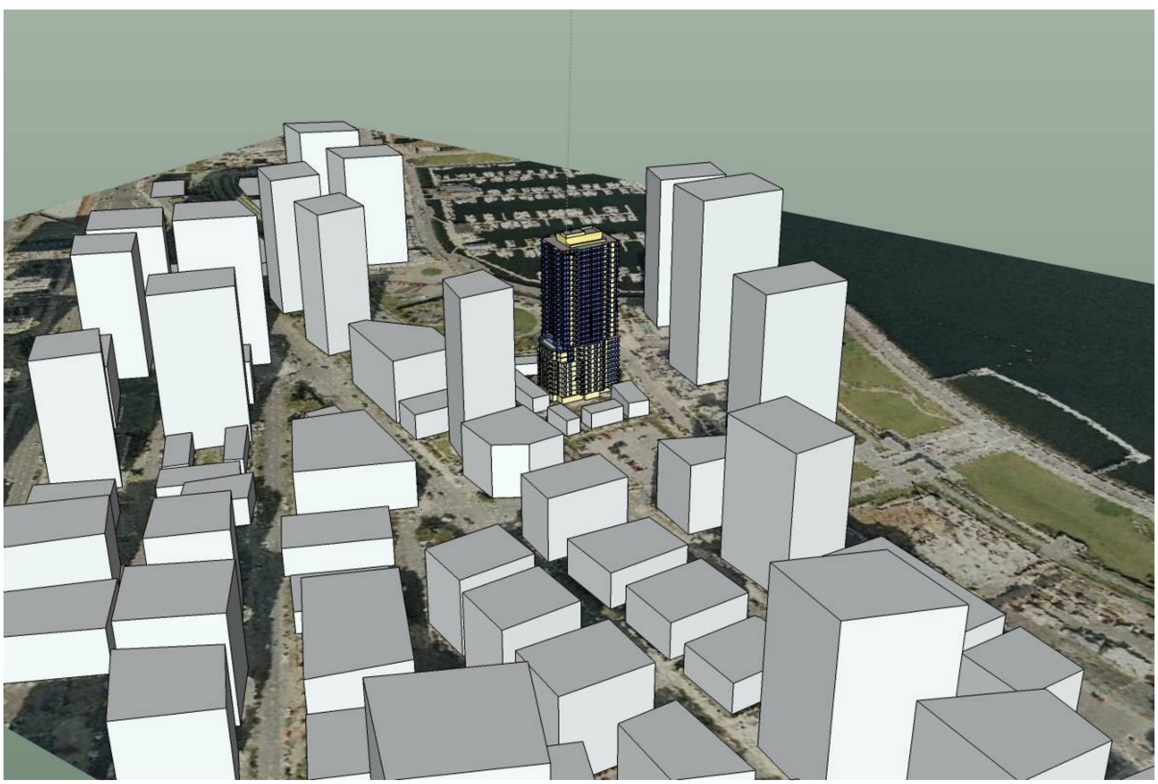
Building 4. 22: North elevation, wall monitoring locations 1 & 2 after building paper and partial strapping installed.

V. BUILDING 5

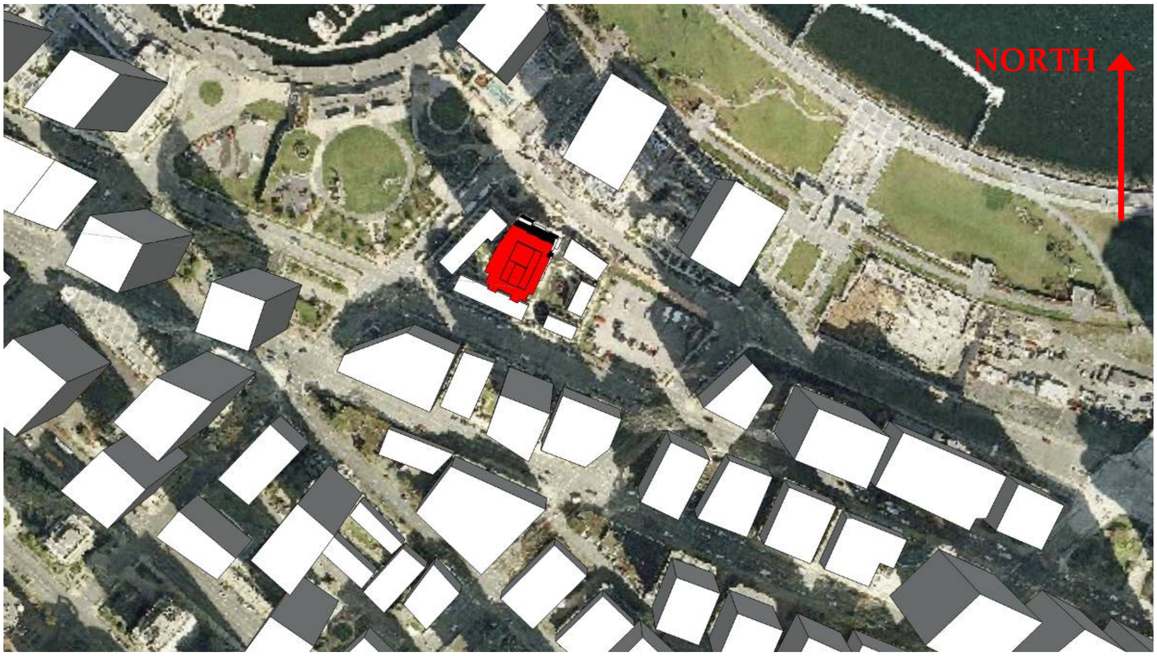


Building 5 – Floor Plan 12th to 30th floors

Building 5- 1: Northwest overview (2002)

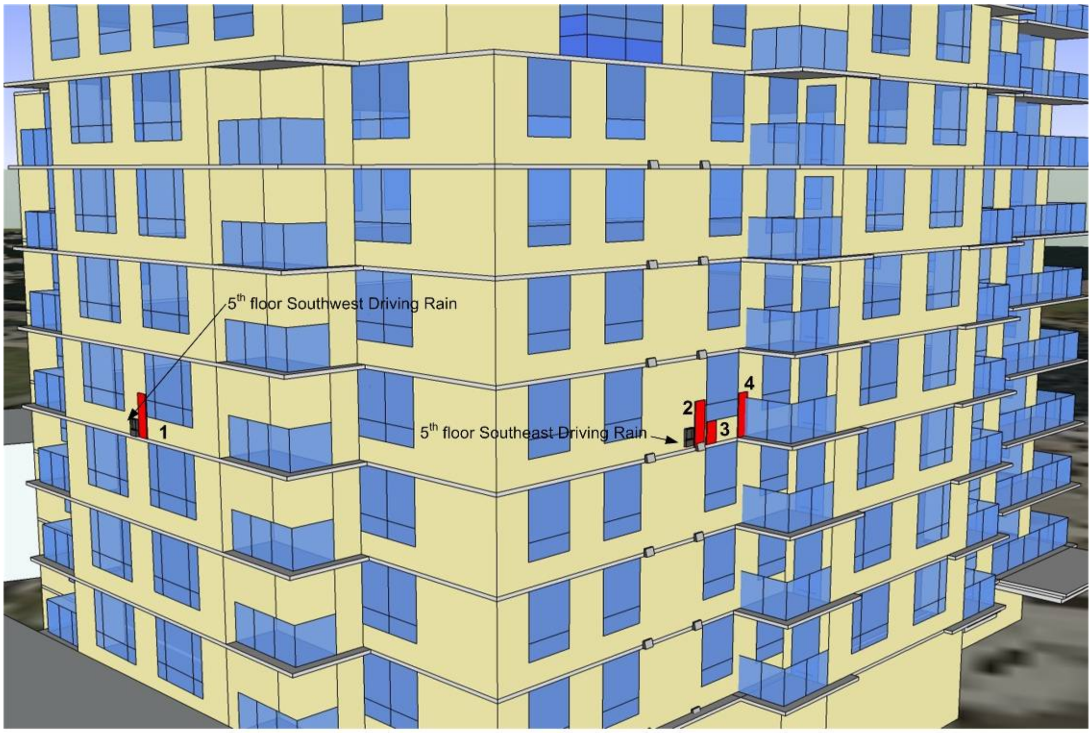


Building 5- 2: Southeast overview (2002)



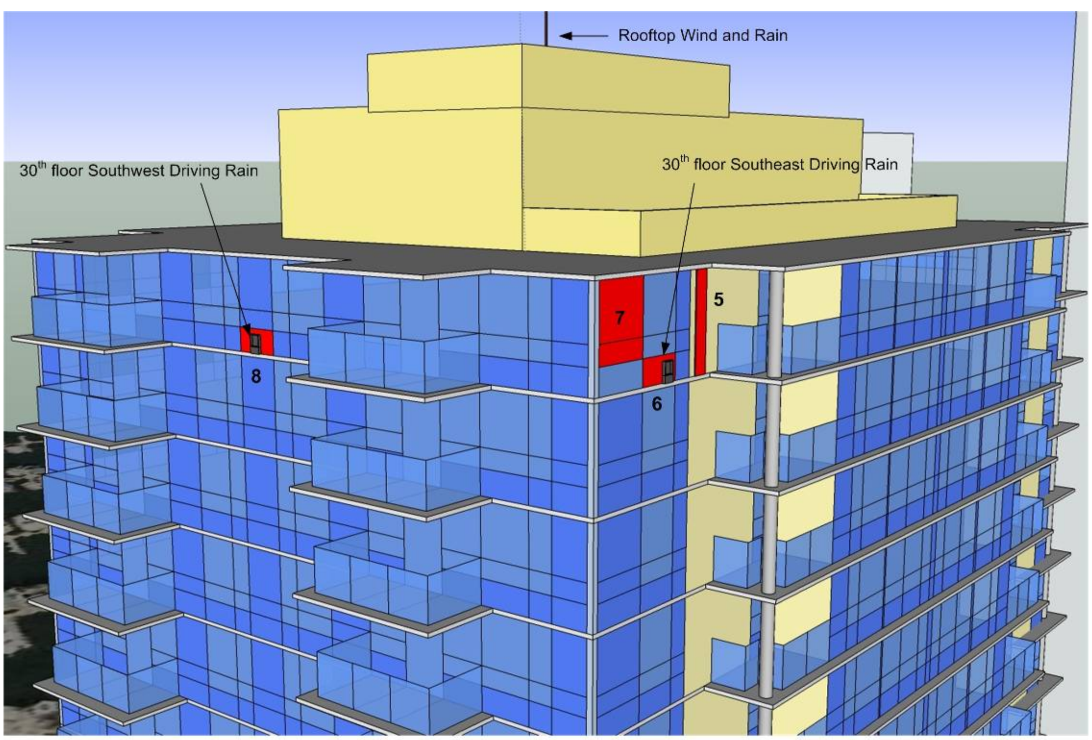
Building 5- 3: Top view, building 5 highlighted (red)

Building 5- 4: Southeast close-up of entire tower (southeast elevation at right)



Building 5 – 5th Floor Wall Cavities – Southeast view

Building 5- 5: 5th floor monitored wall locations 1 (southwest), 2, 3, and 4 (southeast). 5th floor driving rain gauges do not work



Building 5 – 30th Floor Wall Cavities – Southeast view

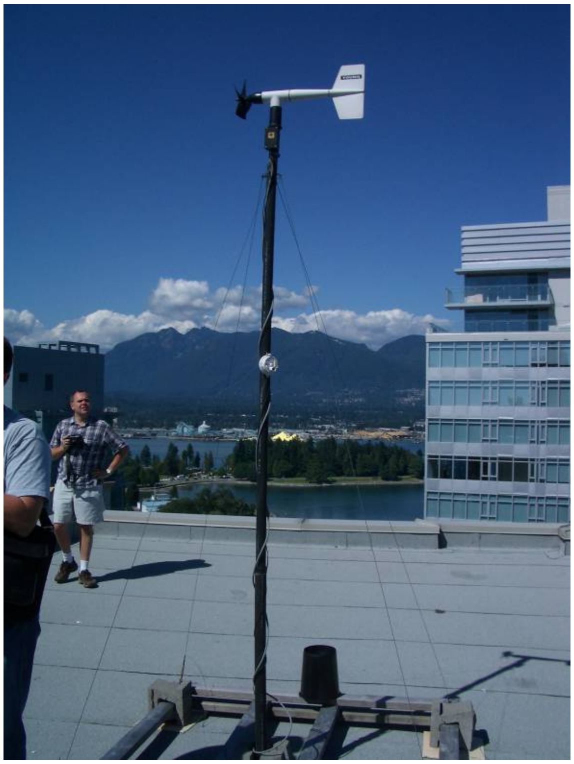
Building 5- 6: 30th floor monitored wall locations 5, 6, 7 (southeast), and 8 (southwest). Also 30th floor driving rain gauges

Building 5- 7: Northeast elevation (left), northwest (right)

Building 5- 8: 5^{th} floor southeast monitored wall locations 2, 3 and 4.

Building 5- 9: Southeast elevation 5th floor, monitored wall locations 2, 3, and 4


Building 5- 10: Southeast and southwest elevation



Building 5- 11: Penthouse Rooftop weather station and rain gauge

Building 5- 12: view to south

Building 5- 13: view to northwest, note this is the tallest building in this direction

Building 5- 14: view to east, note buildings of same height few blocks away

Building 5- 15: southeast elevation, 5th floor location of wall monitoring locations 2, 3 and 4.

Building 5- 16: southeast elevation, 30th floor, location of wall monitoring locations 5, 6, and 7.

Building 5- 17: 5th floor southeast, wall monitoring locations 2 (left), 3 (middle below window), and 4 (far right at balcony)

Building 5- 18: 5th floor southeast, wall monitoring locations 2 (left), 3 (middle below window), and 4 (right)

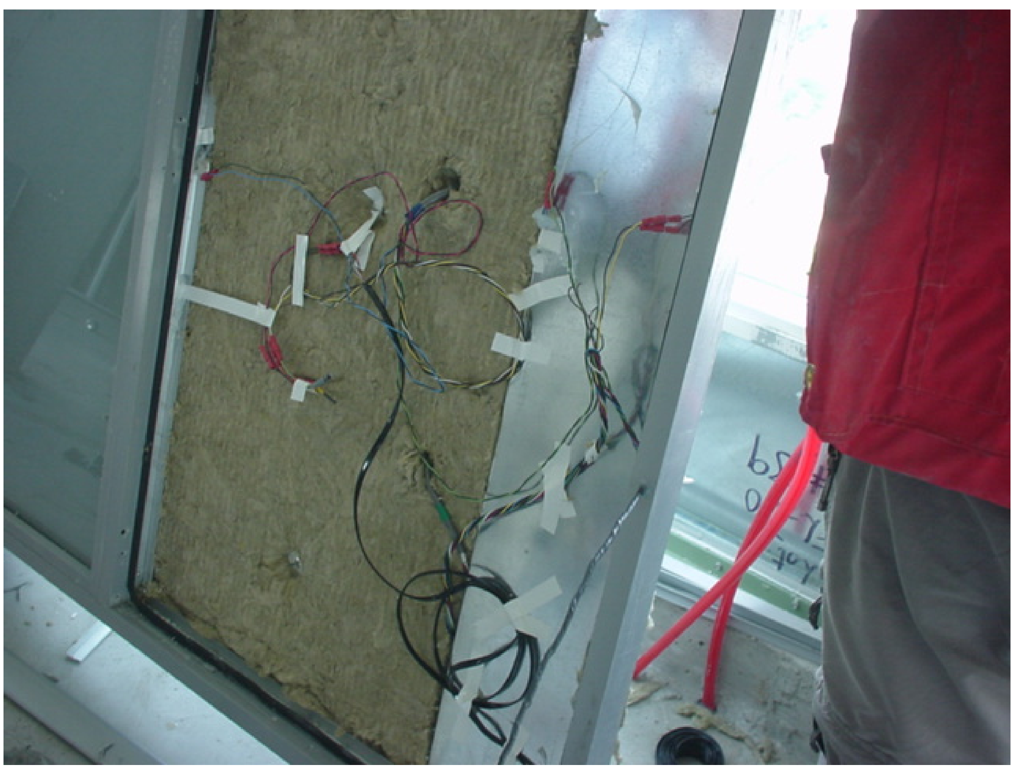
Building 5- 19: Wall monitoring location 4, 5th floor southeast, after cavity insulation installed. T/RH sensors installed outside of XPS

Building 5- 20: interior view of 5th floor (suite 504), wall monitoring location (2 at right), 3 (below window) and 4 (to left of window)

Building 5- 21: Wall monitoring location 4 (to left of window) at balcony guardrail interface

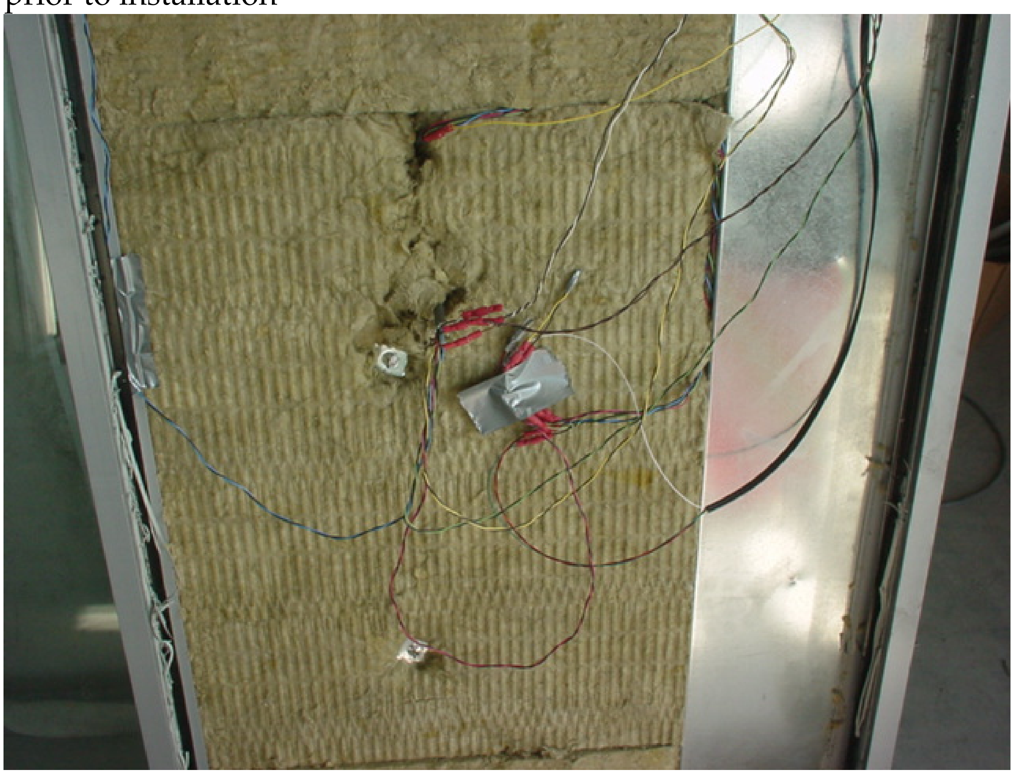
Building 5- 22: Interior of suite 504 after installation of interior drywall, wall monitoring location 2 (at right) and 3 (below window)

Building 5- 23: Wall monitoring location 8, southwest elevation, spandrel panel prior to installation



Building 5- 24: Wall monitoring location 8, southwest elevation, spandrel panel prior to installation

Building 5- 25: Wall monitoring location 7, southeast elevation, spandrel panel prior to installation



Building 5- 26: Wall monitoring location 7, southeast elevation, spandrel panel prior to installation after wiring

Building 5- 27: Wall monitoring location 5, at stucco clad wall, 30th floor south east elevation, after cavity insulation installed

Building 5- 28: Interior of wall monitoring locations 5 (left side of window at stucco clad wall and 6 (spandrel panel below window)

Building 5- 29: Interior of wall monitoring locations (6 below window at left) and 7 to right side of window at spandrel panel)

Building 5- 30: Wall monitoring location 6, southeast elevation below window

Appendix F: Supplemental Measured Data

APPENDIX F: DATA PLOTS

1. Monthly Data Summary of Exterior Climate Data – Buildings 1- 5 & YVR
2. Comparison of Monthly Climate Data 2001-2004 – Buildings 1-5 & YVR
3. YVR Climate Normals
4. Interior Climate Data

1. Monthly Data Summary of Exterior Climate Data – Buildings 1- 5 & YVR

	Vancouver Airport						
	RH	Temperature	Rain	Snow	Total Precip	Wind	
	Exterior	Exterior	mm	cm	mm	Direction	Speed
Month:Year	YVR-RH	YVR-T	YVR-RAIN	YVR-SNOW	YVR-PRECIP	YVR-WDIR	YVR-WSPD
Jan 2001	83.7	5.2	130.3	0	130.3	156	11.4
Feb 2001	75.2	4	25.8	15.2	39	173	11.2
Mar 2001	80.3	6.8	120.2	0	120.2	192	14.2
Apr 2001	74.6	8.8	107.7	0	107.7	175	13.5
May 2001	70.4	12.4	47.6	0	47.6	204	13.9
Jun 2001	71.9	14.6	60.4	0	60.4	164	12.5
Jul 2001	72.8	17.1	39.3	0	39.3	178	13
Aug 2001	79.7	17.3	88.4	0	88.4	174	12.6
Sep 2001	82.2	14.7	43.6	0	43.6	189	11.5
Oct 2001	85.1	9.9	146.1	0	146.1	187	14.8
Nov 2001	84.8	7.8	141.9	0	141.9	156	14.5
Dec 2001	84.4	3.9	211	3	214	154	15.9
Jan 2002	87.3	4.3	133.4	36.9	161.5	137	14.1
Feb 2002	79.1	4.8	103.3	0	103.3	172	13.7
Mar 2002	74.1	4.4	55.6	12	67.1	168	14.1
Apr 2002	74.6	8.8	82.3	0	82.3	184	15
May 2002	71	11.7	51.5	0	51.5	178	12.8
Jun 2002	67.7	16.4	30.8	0	30.8	185	13.9
Jul 2002	68.4	17.9	15.2	0	15.2	195	13.2
Aug 2002	68.7	17.7	5.8	0	5.8	214	13.4
Sep 2002	80.6	14.8	34.6	0	34.6	201	13.9
Oct 2002	87	9.7	18.3	0	18.3	205	9.3
Nov 2002	91.3	7.7	147.7	0	147.7	166	12.2
Dec 2002	89.2	5.5	139.5	0	139.5	141	14.6
Jan 2003	91.5	6.1	150.5	0	150.5	148	12.2
Feb 2003	86.3	4.7	27.1	0	27.1	174	10.1
Mar 2003	82.2	7.3	130	3.7	133.7	148	16.2
Apr 2003	79.6	9.2	139.6	0.2	139.8	157	14.5
May 2003	74	12.4	49.3	0	49.3	172	13.7
Jun 2003	70.5	16.6	12.8	0	12.8	202	15.1
Jul 2003	69.1	19	19.8	0	19.8	198	13.3
Aug 2003	70.9	18.4	4.1	0	4.1	187	13.2
Sep 2003	77.7	15.6	40.2	0	40.2	200	13.1
Oct 2003	84.3	10.9	248.2	0	248.2	173	13.3
Nov 2003	86.5	6.9	167.4	0	167.4	144	12.5
Dec 2003	86.2	5	97.2	14.6	113.2	143	13.3
Jan 2004	86.6	4.2	151.6	8.1	161.4	135	11.8
Feb 2004	86.3	5.9	83.4	0	83.4	165	11.5
Mar 2004	80.1	8	101.2	0	101.2	178	15.4
Apr 2004	72.4	11.2	15	0	15	191	13.3
May 2004	75.1	14	60.8	0	60.8	160	12.2
Jun 2004	69.4	17.3	22.8	0	22.8	184	13.4
Jul 2004	71.1	19.5	16.6	0	16.6	206	15.4
Aug 2004	74.5	19.1	75	0	75	158	12.9
Sep 2004	81.9	14.3	169.4	0	169.4	177	13.6
Oct 2004	82.9	10.9	117.2	0	117.2	175	13.3
Nov 2004	86.6	6.9	199.6	0	199.6	147	12.5
Dec 2004	85.9	5.5	188.2	0	188.2	161	12.7

	Building 1										
	Relative Humidity			Temperature			Wind		Rain		
	Exterior	Interior - Bed 2	Interior - M Bed	Exterior	Interior - Bed 2	Interior - M Bed	Direction	Velocity	Horizontal	SE Driving	SW Driving
Month:Year	B1-RH-EXT	B1-RH-INT-BED2	B1-RH-INT-MBED	B1-T-EXT	B1-T-INT-BED2	B1-T-INT-MBED	B1-WINDDIR	B1-WINDSPEED	B1-RAIN-HOR-INST	B1-RAIN-SE-INST	B1-RAIN-SW-INST
Jan 2001											
Feb 2001											
Mar 2001											
Apr 2001		37.6	39.5		24.8	24.2					
May 2001		35.0	36.8		25.5	24.9					
Jun 2001		37.6	39.5		25.7	25.0					
Jul 2001		40.5	42.3		26.0	25.3			48.8	0.75	0.9
Aug 2001		43.7	46.0		26.7	25.9			93.4	2.65	0.8
Sep 2001		42.3	44.3		26.0	25.3			39.2	1.2	0.85
Oct 2001		38.5	41.6		24.6	23.7			173	2.9	0.8
Nov 2001		39.0	42.6		24.6	23.5			141.8	6.65	1.7
Dec 2001		36.6	39.2		24.7	23.8			203.6	9.55	4.8
Jan 2002		41.3	43.9		23.7	23.0	125.3	4.8	154.8	4.45	2.5
Feb 2002		34.3	36.7		24.8	24.2	136.4	4.8	110.2	3.15	1
Mar 2002		33.7	35.4		24.8	24.3	144.7	6.8	86.8	2.65	1.45
Apr 2002		35.1	37.5		25.2	24.5	163.0	6.4	83	2.65	0.95
May 2002		35.0	37.3		25.4	24.7	160.7	7.1	42.2	0.5	0.35
Jun 2002		37.4	39.0		25.9	25.2	175.3	9.1	33.4	1.1	0.5
Jul 2002		41.0	42.3		26.2	25.7	180.6	1.8	15.4	0	0.05
Aug 2002		39.6	40.8		26.6	26.1	186.4	3.7	13.6	0.75	0
Sep 2002	78.1	40.9	42.3	15.1	25.7	25.2	178.0	6.0	51.4	1.45	1.05
Oct 2002	85.1	39.7	41.8	10.1	24.9	24.4	146.2	3.4	16	0	0
Nov 2002	90.8	42.8	45.3	8.1	24.6	23.9	112.1	4.8	197.6	8.3	1.95
Dec 2002	93.8	41.7	44.4	5.2	24.0	23.3	96.2	6.2	109.6	5.35	3.45
Jan 2003	93.0	39.9	42.8	6.7	24.9	24.2	101.9	5.4	129.2	6.6	2.15
Feb 2003	87.6	39.4	41.8	5.0	24.5	23.8	134.4	3.9	37	0.6	0.2
Mar 2003	88.4	39.1	41.5	7.1	24.4	23.7	106.4	8.4	131.2	6.3	1.45
Apr 2003	83.6	40.1	42.3	9.2	24.5	24.0			110.8	2.95	0.45
May 2003	72.9	35.4	37.1	13.1	25.6	25.1			54.4	0.25	0.35
Jun 2003	66.8	35.7	37.1	18.1	26.6	26.0			16.2	0.15	0.1
Jul 2003	66.5	37.6	39.2	20.6	27.8	27.1	153.6	8.3	13.6	0	0.3
Aug 2003	68.8	37.3	39.7	19.7	27.6	26.7	143.6	9.0	5.6	0	0
Sep 2003	76.0			17.0			146.2	10.0	27.6	0.2	0.35
Oct 2003	88.4			11.7			124.1	11.2	232	16.1	8.7
Nov 2003	84.2	35.0	38.1	4.8	25.1	24.0	114.7	12.5	193.8		0.55
Dec 2003	96.1	41.1	45.7	4.5	23.8	22.9	90.4	13.4	78		1.9
Jan 2004	94.9	40.4	44.2	4.1	24.1	23.3					
Feb 2004	92.3	37.5	40.3	6.4	23.5	23.3	111.7	12.6			
Mar 2004	84.6	37.9	41.4	8.5	23.8	23.3	128.6	11.4	137.6	2.45	1.45
Apr 2004	68.3	32.9	35.6	12.8	24.5	23.8	145.6	9.2	26	0.45	0
May 2004	76.0	38.3	40.7	14.5	24.6	24.0	127.8	8.1	92.8	0.8	0.1
Jun 2004	63.9	38.3	39.6	18.7	25.9	25.5	144.5	8.3	19.2	0	0
Jul 2004	66.4	40.3	41.0	21.0	27.4	27.1					
Aug 2004	76.3	45.9	46.6	20.1	26.8	26.5					
Sep 2004	87.0	45.0	46.2	14.5	24.9	24.5					
Oct 2004	88.4	43.3	44.9	11.1	24.6	24.3					
Nov 2004	95.7	41.6	42.3	6.6	24.1	23.8					
Dec 2004	96.0	39.5	41.7	5.3	24.2	23.8					

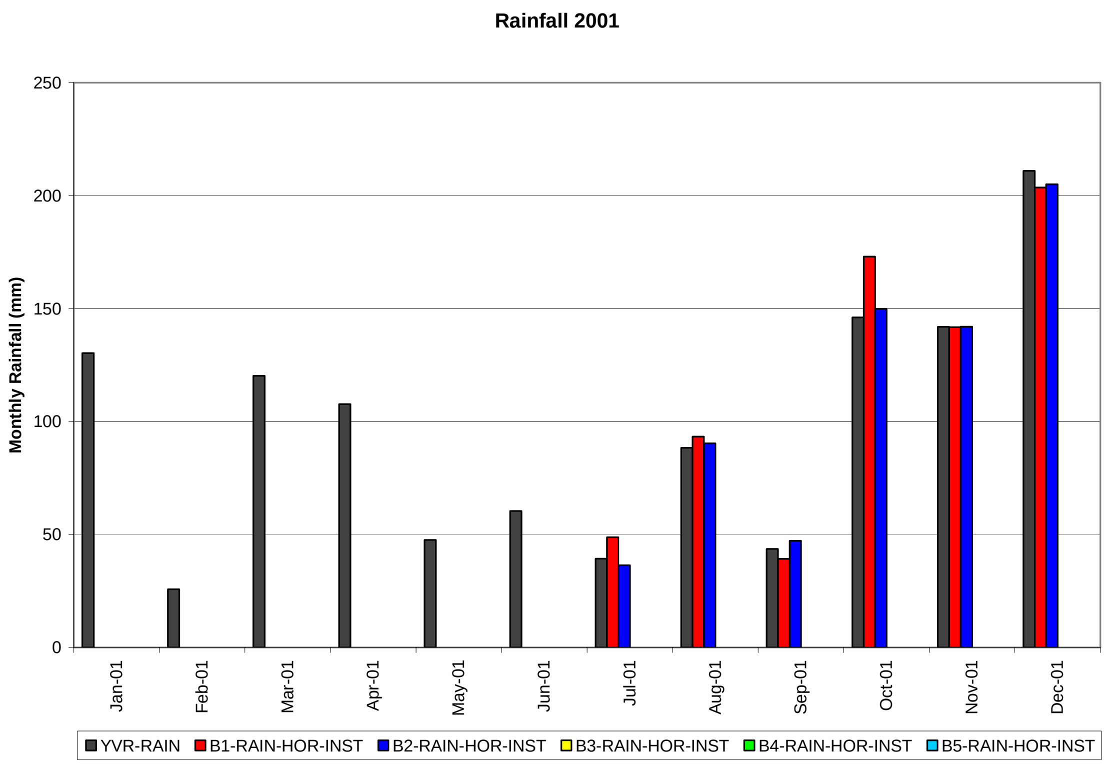
	Building 2								
	Relative Humidity		Temperature		Wind		Rain		
	Exterior	Interior	Exterior	Interior	Direction	Velocity	East Driving	Horizontal	South Driving
Month:Year	B2-RH-EXT	B2-RH-INT	B2-T-EXT	B2-T-INT	B2-WINDDIR	B2-WINDSPEED	B2-RAIN-E-INST	B2-RAIN-HOR-INST	B2-RAIN-S-INST
Jan 2001		36.1		19.1					
Feb 2001		34.0		19.9					
Mar 2001		29.9		20.1					
Apr 2001									
May 2001									
Jun 2001									
Jul 2001					178.5	8.7	2.85	36.4	0.85
Aug 2001					169.4	7.6	7.3	90.4	4.1
Sep 2001					181.9	6.5	2.25	47.2	4
Oct 2001					170.6	6.8	16.35	150	1.85
Nov 2001		40.4		19.9	148.5	5.2	21.95	142	7.05
Dec 2001		34.5		19.2	146.0	8.6	38	205	15.65
Jan 2002		36.1		19.1			15.25	142.4	5.85
Feb 2002		34.0		20.0			10.35	102.6	3.35
Mar 2002		29.9		20.1			12.2	86.6	4.95
Apr 2002		34.8		21.7	172.3	5.2	9.3	77.6	4.25
May 2002		35.9		23.1	172.3	5.4	2.7	56.8	2.6
Jun 2002		37.0		25.6	176.1	7.9	3.1	33.2	1.5
Jul 2002		44.8		24.8	197.3	7.6	1.1	26	1.1
Aug 2002		44.4		25.1	221.6	7.3	0.2	2.6	0.05
Sep 2002	73.6	43.9	16.2	24.0	189.2	7.3	3.35	44.6	1.05
Oct 2002	82.9	44.7	10.9	20.8	209.7	3.8	0.85	17.4	0
Nov 2002	90.5	45.1	8.5	20.9	161.0	2.2	5.35	186.4	5.8
Dec 2002	92.7		5.8		142.9	4.5	0.55	128.2	13.1
Jan 2003	92.4		7.0		153.3	6.0	0.5	130	4.2
Feb 2003	85.6	40.4	5.7	19.2	175.5	5.4	0.3	30.8	0.7
Mar 2003	85.7	43.3	7.7	19.1	151.7	9.9	1.05	131	7.6
Apr 2003	80.3	43.9	9.8	21.2	157.6	7.6	0.3	120.4	3.4
May 2003	67.8	37.4	13.9	23.2	174.3	8.3	1.9	42.6	0.65
Jun 2003	65.8	39.6	18.0	24.6	156.5	8.3	0.55	12.6	0.3
Jul 2003	64.0	39.7	20.6	27.5	207.9	7.6	0.4	22.4	0.8
Aug 2003	65.4	40.9	19.9	26.5	201.9	7.0	0.3	4	0.1
Sep 2003	76.6		16.6		203.5	5.6	1.25	29.2	0.3
Oct 2003	87.1		12.0		172.8	5.7	26.1	234.6	15.95
Nov 2003	81.6	39.8	5.3	18.4	159.0	4.7	12.45	187.2	5.1
Dec 2003	94.1	42.6	4.9	18.2	129.2	4.0	10.05	122.6	7.65
Jan 2004	93.9	44.7	4.6	17.7	136.5	5.6			
Feb 2004	90.4	44.3	6.7	18.5	157.8	6.7			
Mar 2004	81.0	41.8	8.8	19.9	168.2	7.9		108.6	4.9
Apr 2004	58.7	35.0	13.2	22.1	179.1	7.9	0.8	14.8	0.5
May 2004	67.1	39.2	15.3	23.4	167.8	8.0	7.55	79	1.4
Jun 2004	54.3	36.7	19.0	26.1	183.3	8.2	1.6	19.6	0.05
Jul 2004		40.7		26.9					
Aug 2004		49.0		25.5					
Sep 2004									
Oct 2004									
Nov 2004									
Dec 2004									

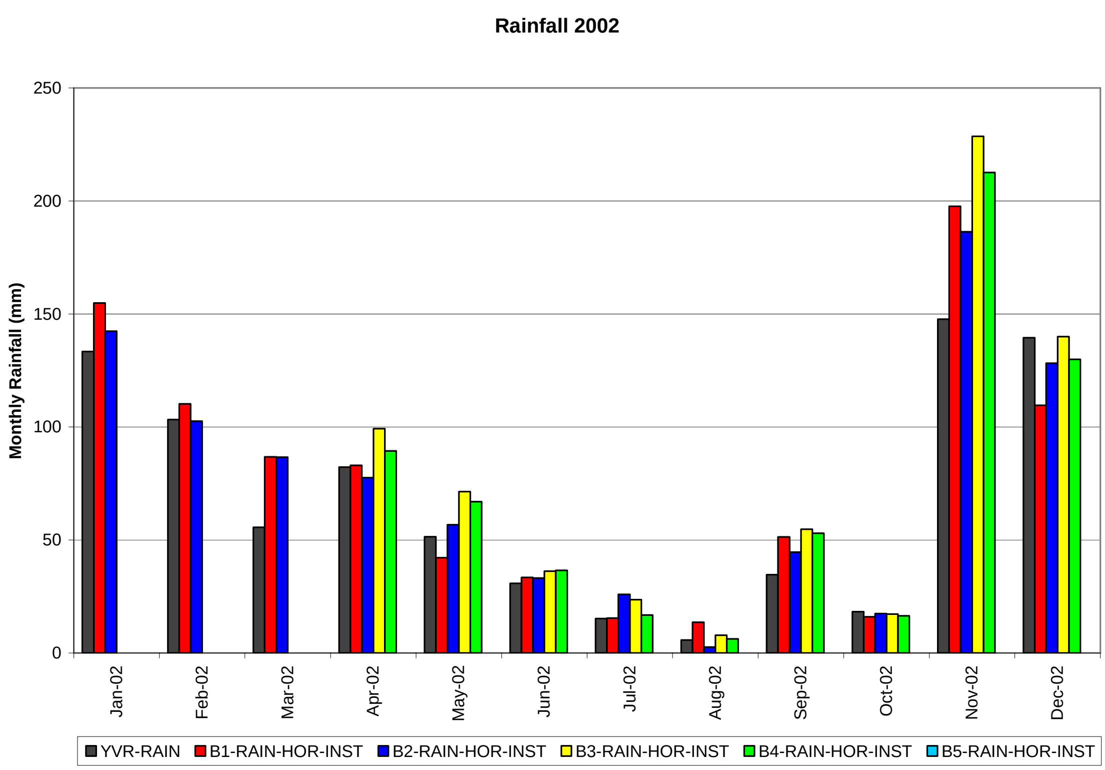
	Building 3										
	Relative Humidity			Temperature			Wind		Rain		
	Exterior	Interior - 311	Interior - 611	Exterior	Interior - 311	Interior - 611	Direction	Velocity	East 3rd Driving	East 6th Driving	Horizontal
Month:Year	B3-RH-EXT	B3-RH-INT-311	B3-RH-INT-611	B3-T-EXT	B3-T-INT-311	B3-T-INT-611	B3-WINDDIR	B3-WINDSPEED	B3-RAIN-3RD-INST	B3-RAIN-6TH-INST	B3-RAIN-HOR-INST
Jan 2001											
Feb 2001											
Mar 2001											
Apr 2001											
May 2001											
Jun 2001											
Jul 2001											
Aug 2001											
Sep 2001											
Oct 2001											
Nov 2001											
Dec 2001											
Jan 2002											
Feb 2002											
Mar 2002		47.2	51.6		17.0	18.4					
Apr 2002		47.9	48.1		19.6	20.1	163.6	7.3	6.4	15.6	99.2
May 2002		46.3	42.7		21.6	21.5	162.1	7.0	1.7	4.3	71.4
Jun 2002		43.5	41.5		24.8	23.5	175.9	7.5	2.2	5.5	36.2
Jul 2002	59.1	42.5	44.4	19.8	26.1	24.7	183.3	6.3	1.25	3.15	23.6
Aug 2002	58.2	43.8	45.3	20.1	26.1	24.5	190.6	5.5	0.45	1.1	7.8
Sep 2002	67.6	47.5	47.7	16.7	23.5	22.8	154.8	6.0	2.8	7.4	54.8
Oct 2002	75.6	52.1	52.9	11.5	19.9	20.5	164.4	4.2	0.55	1.85	17.2
Nov 2002	83.8	56.9	59.0	8.9	17.9	18.8	130.2	6.1	17.45	40.65	228.6
Dec 2002	87.7	56.8	58.3	5.8	16.3	17.8	119.6	7.8	11.85	25.85	140
Jan 2003	86.3	62.4	61.2	7.2	16.6	18.2	125.9	6.3	14.4	30.8	146.2
Feb 2003	78.3	59.1	55.6	6.1	16.1	18.4	145.8	5.1	2.2	5.2	33
Mar 2003	79.1	58.8	54.2	7.7	16.6	18.9	139.4	8.5	14.85	29.5	149.2
Apr 2003	74.4	58.1	53.6	9.9	17.9	19.5	132.5	8.0	10.3	22.55	112.6
May 2003	63.9	50.8	46.2	14.0	21.4	21.6	157.6	6.9	1.95	5.1	64.8
Jun 2003	59.2	45.3	40.9	18.7	25.1	24.1	182.5	6.4	0.55	1.35	14.4
Jul 2003							182.7	6.3	0.25	0.7	25.4
Aug 2003							175.3	5.8	0.15	0.35	5.8
Sep 2003		46.6	45.7		24.4	23.5	165.8	5.2	0.95	2.85	36.2
Oct 2003		57.9	58.6		20.5	20.5	146.7	7.1	22	41.95	258
Nov 2003	78.1	53.7	56.3	5.9	16.3	17.0	143.5	6.5	28.5	49.55	217.2
Dec 2003	90.2	59.4	64.9	5.0	16.6	15.6	122.6	7.7	10.2	20.25	124.2
Jan 2004	89.9	62.3	63.6	4.6	15.7	16.1	124.3	6.9	10.65	20.65	165.6
Feb 2004	83.2	56.7	58.5	7.4	17.2	19.2	139.7	6.5	7.05	14	70
Mar 2004	77.1	65.0	55.3	9.2	18.2	19.4	153.9	7.4	8.25	17.4	126.4
Apr 2004	61.6			13.8			166.3	6.4	1	2.2	17
May 2004	69.1	58.9	43.8	15.5	22.6	22.3	160.7	6.6	5.2	10.8	81.2
Jun 2004	60.0	53.4	41.7	19.4	24.8	24.1	179.3	6.5	0.8	2.1	18.2
Jul 2004	61.8	48.8	43.4	21.9	27.0	25.8	185.3	6.5	0.4	0.8	12
Aug 2004	70.9	53.2	48.7	21.2	26.4	25.4	164.7	6.1	3.95	7.65	88.4
Sep 2004	80.2			16.0			153.9	6.1	5.05	11.75	91.6
Oct 2004	85.9			12.2			147.4	6.0	7.2	15.9	115.8
Nov 2004	93.8			7.4			130.2	6.4	14.65	30.55	188.6
Dec 2004	94.5			5.8			133.7	6.2	15.15	27.15	175.8

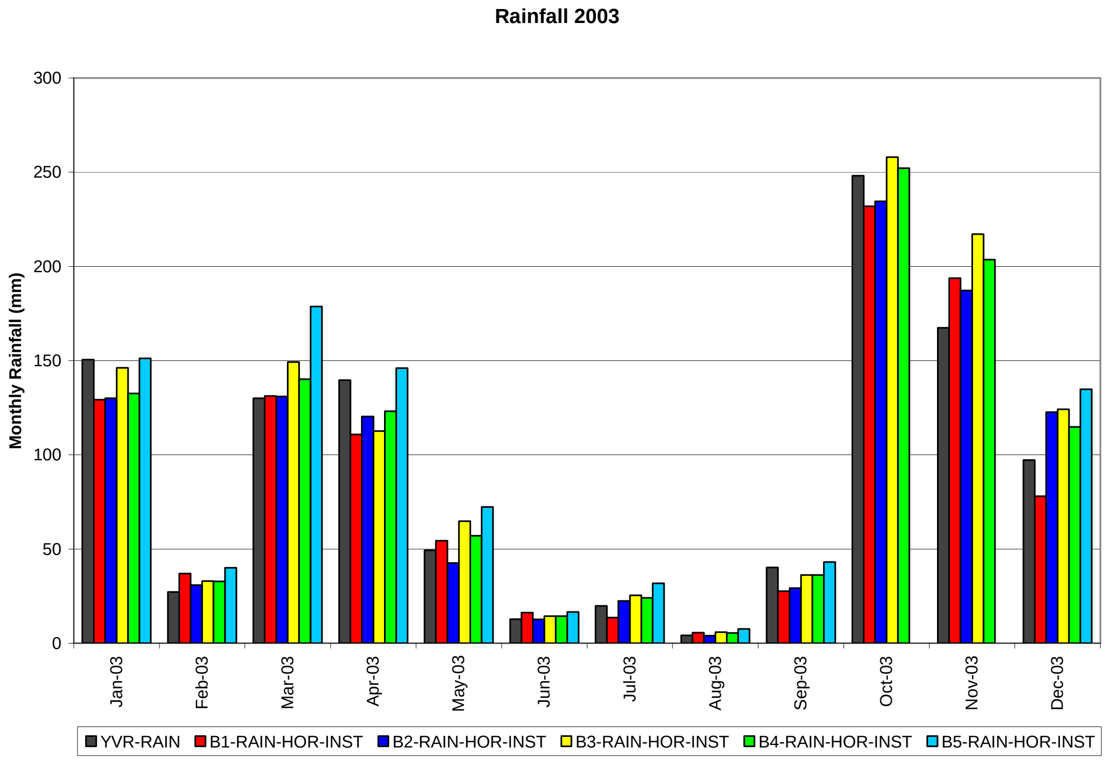
	Building 4										
	Relative Humidity			Temperature			Wind		Rain		
	Exterior	Interior - North	Interior - South	Exterior	Interior - North	Interior - South	Direction	Velocity	Horizontal	North Driving	South Driving
Month:Year	B4-RH-EXT	B4-RH-INT-NORTH	B4-RH-INT-SOUTH	B4-T-EXT	B4-T-INT-NORTH	B4-T-INT-SOUTH	B4-WINDDIR	B4-WINDSPEED	B4-RAIN-HOR-INST	B4-RAIN-NORTH-INST	B4-RAIN-SOUTH-INST
Jan 2001											
Feb 2001											
Mar 2001											
Apr 2001											
May 2001											
Jun 2001											
Jul 2001											
Aug 2001											
Sep 2001											
Oct 2001											
Nov 2001											
Dec 2001											
Jan 2002											
Feb 2002											
Mar 2002		26.5			23.9						
Apr 2002		33.1			23.9		181.4	3.5	89.4	0	0.5
May 2002		34.3			23.9		180.2	3.1	67	0	0.4
Jun 2002		37.3	37.7		26.1	25.3	196.1	4.0	36.6	0	0.4
Jul 2002		39.6	41.3		27.8	26.6	206.5	3.1	16.8	0	0.15
Aug 2002		42.7	39.5		26.1	26.8	223.6	2.7	6.2	0	0
Sep 2002	79.2	42.2	39.3	15.2	25.0	26.2	193.8	2.6	53	0.35	0.7
Oct 2002	88.1		39.0	9.9		22.9	191.8	1.3	16.4	0	0.05
Nov 2002	95.6		36.9	7.8		21.7	160.3	2.1	212.6	0	0.8
Dec 2002			34.4			21.1	142.6	3.1	130	0.1	0.25
Jan 2003				6.5			151.7	2.1	132.6	0	0.7
Feb 2003				4.8			169.9	1.5	32.8	0	0.35
Mar 2003		31.9		7.4	24.0		160.4	4.3	140.2	0.05	0.2
Apr 2003		32.6		9.6	23.7		154.3	3.7	123.2	0	0.45
May 2003		35.4		13.8	23.2		178.5	3.2	57	0.45	0.25
Jun 2003		36.7		19.1	25.9		212.6	3.7	14.4	0	0
Jul 2003		41.8		21.4	26.7		208.1	3.4	24	0	0.05
Aug 2003		43.3		20.1	26.2		202.5	3.0	5.4	0	0
Sep 2003		44.8	43.3		25.0	26.5	195.6	2.4	36.2	0.3	0.2
Oct 2003		44.4	39.9		23.8	24.7	171.9	3.4	252.2	2.2	0.85
Nov 2003		30.2	26.5	4.5	23.5	23.6	163.3	2.4	203.6	0.2	2.8
Dec 2003		30.6	28.3	4.5	24.3	23.8	141.6	2.8	114.8	0.4	0.2
Jan 2004		33.1	29.1	4.4	22.7	23.6	139.9	2.2	171.4	0	0.65
Feb 2004		30.7	26.4	6.3	24.4	24.0	158.3	2.3	78.2	0	0.3
Mar 2004				8.3			173.4	3.7	130.6	0.3	0.9
Apr 2004				12.7			189.3	3.4	18.6	0	0
May 2004		36.6	34.3	15.5	24.2	24.8	182.3	3.0	94	0	0.4
Jun 2004		37.3	34.8	19.9	26.2	26.7	200.3	3.5	19.2	0	0
Jul 2004		41.1	34.7	22.0	27.4	29.3	212.2	3.7	16.2	0	0
Aug 2004		47.1	40.0	20.8	26.5	28.7	190.6	2.6	73	0.05	0.6
Sep 2004		45.1	40.5	14.8	24.4	25.7	185.1	2.4	97.6	1.2	0.9
Oct 2004		41.3	37.4	11.0	24.1	24.2	173.0	2.2	121.4	0.6	0
Nov 2004		35.0	32.6	6.9	24.0	24.1	151.5	2.0	210.2	1.4	0.3
Dec 2004		32.9	30.1	5.5	22.5	24.5	157.4	2.3	193	0.95	0.2

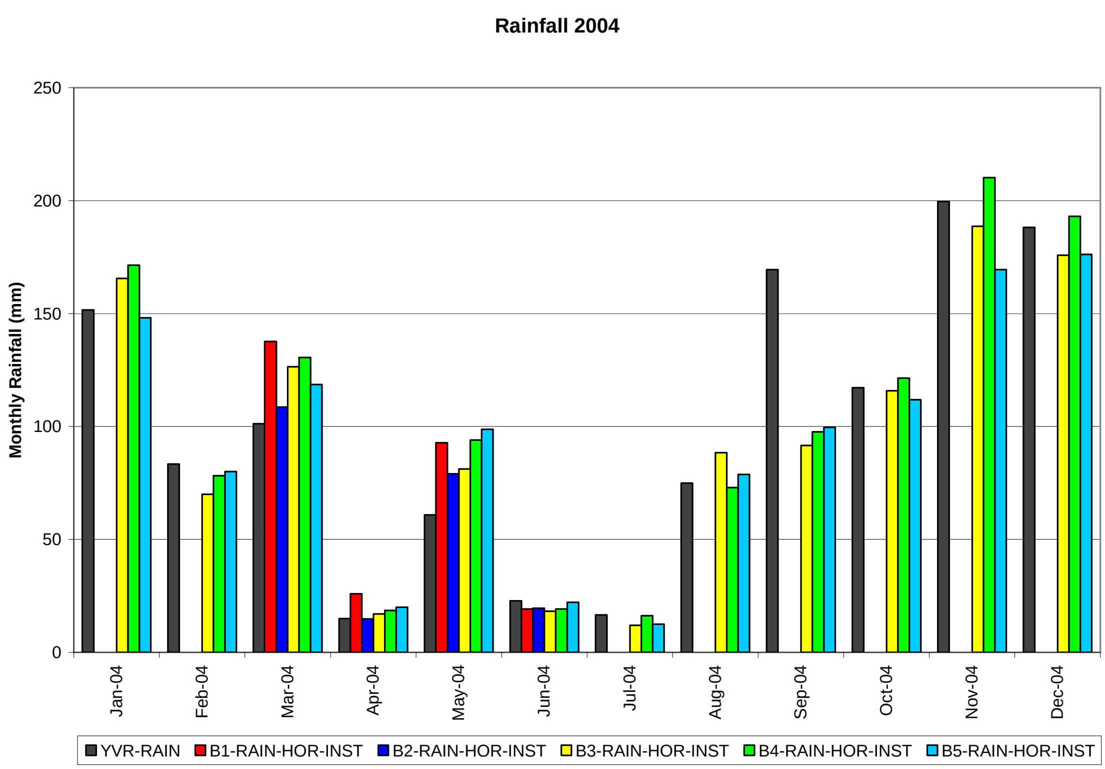
	Building 5										
	Relative Humidity			Temperature			Wind		Rain		
	Exterior	Interior - 30th	Interior 5th	Exterior	Interior 30th	Interior 5th	Direction	Velocity	East Driving	Horizontal	South Driving
Month:Year	B5-RH-EXT	B5-RH-INT-30TH	B5-RH-INT-5TH	B5-T-EXT	B5-T-INT-30TH	B5-T-INT-5TH	B5-WINDDIR	B5-WINDSPEED	B5-RAIN-EAST-INST	B5-RAIN-HOR-INST	B5-RAIN-SOUTH-INST
Jan 2001											
Feb 2001											
Mar 2001											
Apr 2001											
May 2001											
Jun 2001											
Jul 2001											
Aug 2001											
Sep 2001											
Oct 2001											
Nov 2001											
Dec 2001											
Jan 2002											
Feb 2002											
Mar 2002											
Apr 2002											
May 2002											
Jun 2002											
Jul 2002											
Aug 2002											
Sep 2002											
Oct 2002											
Nov 2002											
Dec 2002											
Jan 2003							145.4	8.5	2.3	151.2	15.9
Feb 2003		36.5	37.1		19.8	24.4	114.8	6.9	0.5	40	1.55
Mar 2003		37.4	35.8		20.4	24.8	102.7	10.1	1.85	178.8	13.15
Apr 2003		40.2	37.6		20.8	25.2	95.3	9.6	1.3	146	7.75
May 2003		46.4	46.1		22.2	24.9	121.2	8.9	0.65	72.4	2.75
Jun 2003		49.7	47.9		23.7	25.5	141.0	8.4	0.1	16.6	0.5
Jul 2003		50.0	48.8		23.4	25.0	150.4	7.9	0.85	31.8	0.25
Aug 2003		48.9	47.8		22.5	24.2	132.2	7.7	0	7.6	0.3
Sep 2003							128.8	7.7	0.3	43	0.7
Oct 2003											
Nov 2003	78.9	30.7	34.0	5.2	19.5	23.2					
Dec 2003	91.2	30.6	37.9	4.8	20.7	23.5	86.1	11.5	3	134.8	
Jan 2004	92.3	32.1	37.5	4.4	20.3	23.7	90.0	9.9	1.4	148.2	
Feb 2004	87.4	32.5	34.2	6.6	20.6	23.8	108.1	9.7	0.25	80	
Mar 2004		28.6	33.1	8.3	23.1	23.3	120.0	10.9	1.6	118.6	
Apr 2004		29.1	32.0	12.3	23.8	24.4	130.7	9.7	0.05	20	
May 2004		35.0	40.1		24.8	24.3	122.1	9.5	0.35	98.8	
Jun 2004		37.1	41.8		25.4	24.9	138.5	9.3	0	22.2	
Jul 2004		44.9	48.6		25.6	25.3	145.3	9.5	0	12.4	
Aug 2004		48.1	51.8		25.9	25.5	118.4	8.6	0.8	78.8	
Sep 2004		43.0	48.3		24.5	24.3	119.9	9.2	0.9	99.6	
Oct 2004		36.0	42.7	11.5	24.8	24.3	109.1	9.5	0.95	111.8	
Nov 2004		32.2	40.3	7.0	23.2	23.8	95.6	10.1	2.05	169.4	
Dec 2004		30.5	37.0	5.7	23.0	23.7	98.1	9.8	1.85	176.2	

2. Comparison of Monthly Data 2001-2004 – Buildings 1-5 & YVR



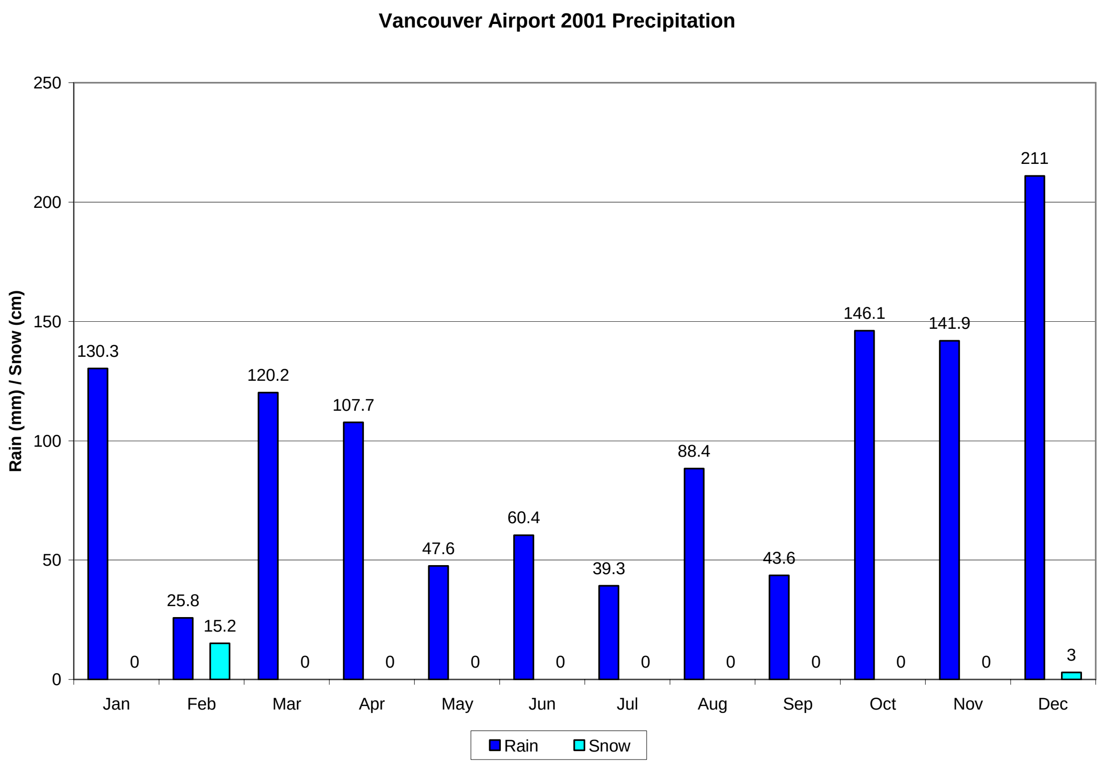


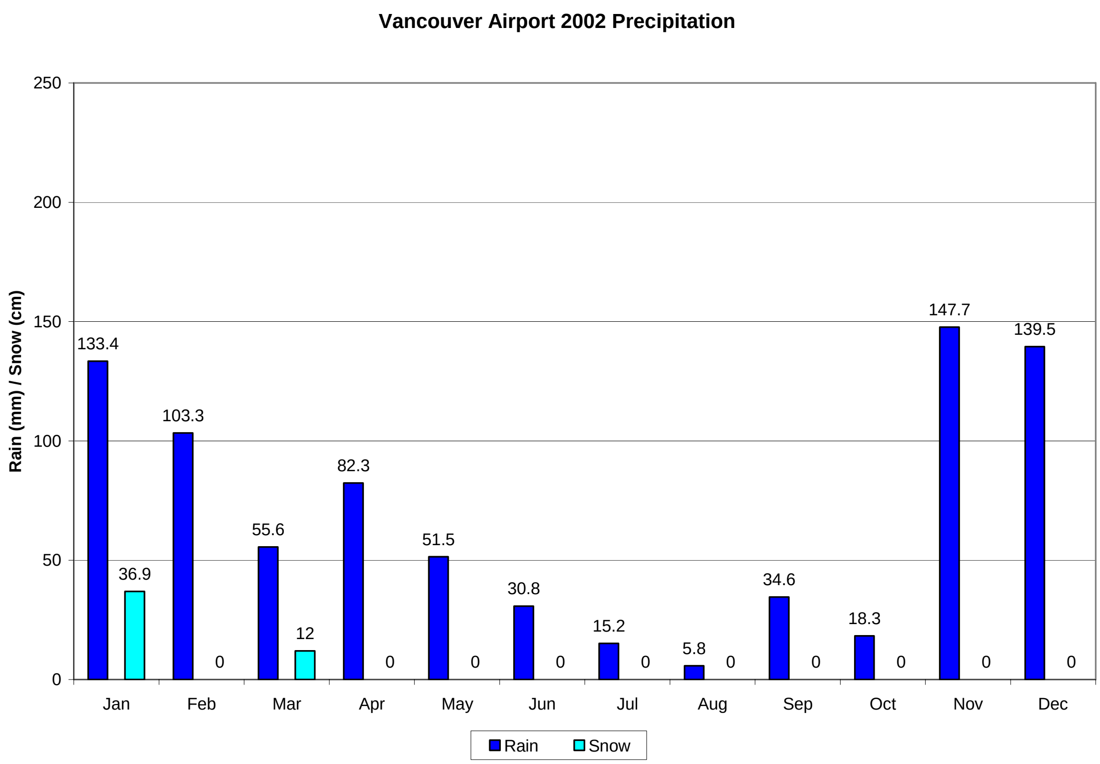

Rainfall 2003
Monthly Rainfall (mm)
300
250
200
150
100
50
0
Jan-03
Feb-03
Mar-03
Apr-03
May-03
Jun-03
Jul-03
Aug-03
Sep-03
Oct-03
Nov-03
Dec-03
YVR-RAIN
B1-RAIN-HOR-INST
B2-RAIN-HOR-INST
B3-RAIN-HOR-INST
B4-RAIN-HOR-INST
B5-RAIN-HOR-INST

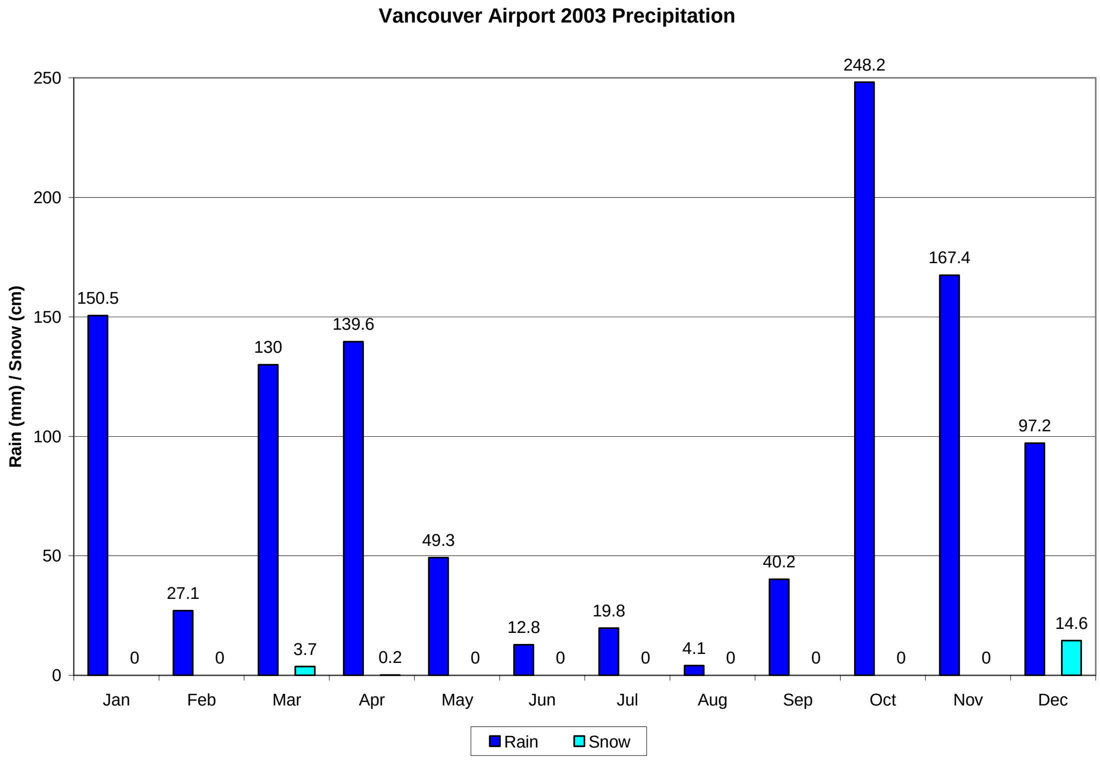

Rainfall 2004
Monthly Rainfall (mm)
250
200
150
100
50
0
Jan-04
Feb-04
Mar-04
Apr-04
May-04
Jun-04
Jul-04
Aug-04
Sep-04
Oct-04
Nov-04
Dec-04
YVR-RAIN
B1-RAIN-HOR-INST
B2-RAIN-HOR-INST
B3-RAIN-HOR-INST
B4-RAIN-HOR-INST
B5-RAIN-HOR-INST

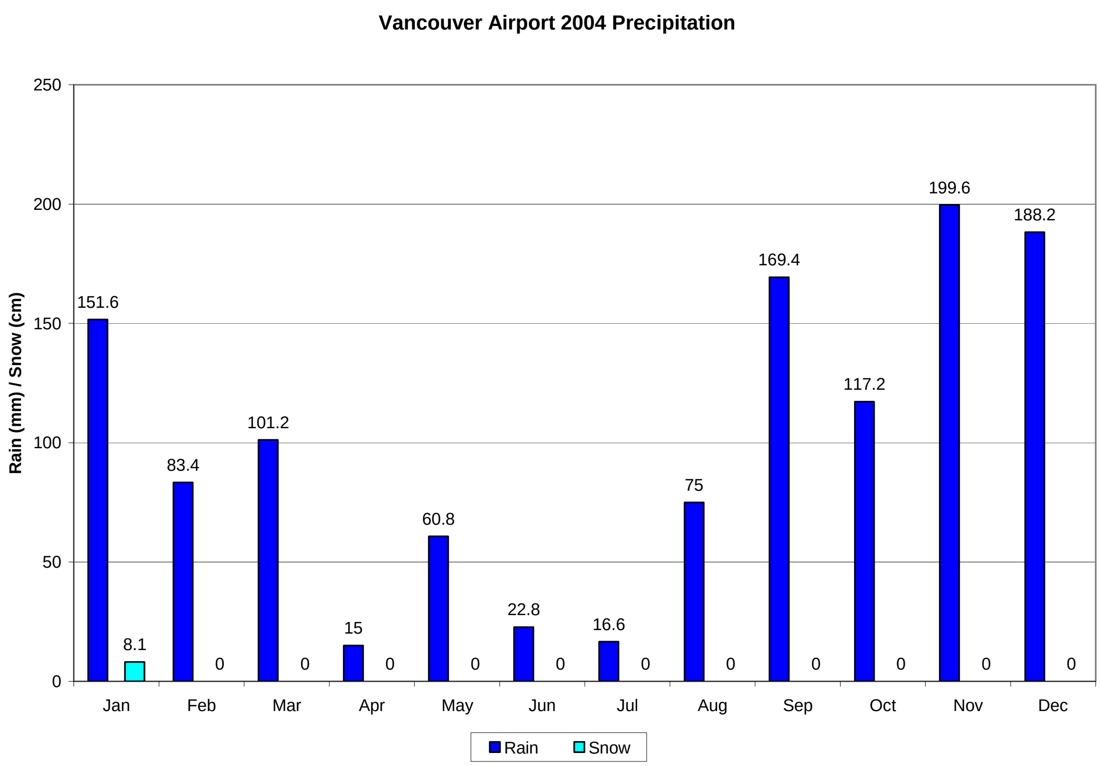
RAINFALL on HORIZONTAL

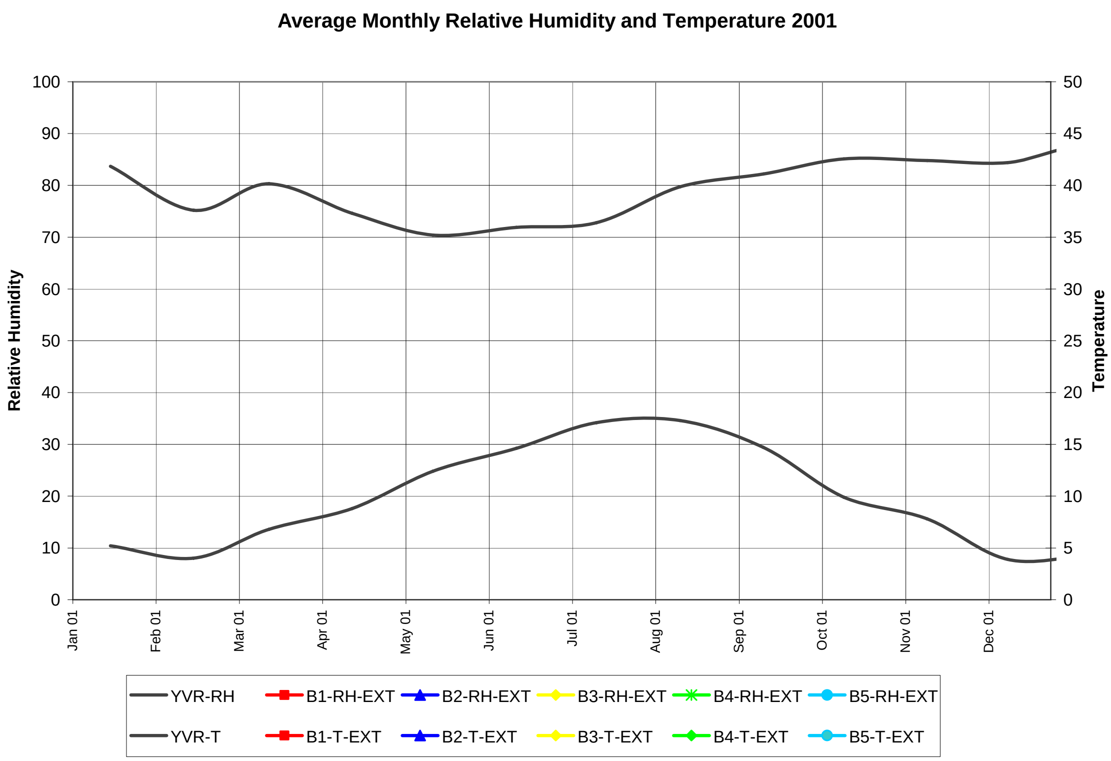
	YVR	Building 1	Building 2	Building 3	Building 4	Building 5
	Rain on Horizontal (mm)					
Jan 2001	130.3					
Feb 2001	25.8					
Mar 2001	120.2					
Apr 2001	107.7					
May 2001	47.6					
Jun 2001	60.4					
Jul 2001	39.3	48.8	36.4			
Aug 2001	88.4	93.4	90.4			
Sep 2001	43.6	39.2	47.2			
Oct 2001	146.1	173	150			
Nov 2001	141.9	141.8	142			
Dec 2001	211	203.6	205			
total jul-dec	**670.3**	**699.8**	**671**			
total annual	**1162.3**	-	-			
Jan 2002	133.4	154.8	142.4			
Feb 2002	103.3	110.2	102.6			
Mar 2002	55.6	86.8	86.6			
Apr 2002	82.3	83	77.6	99.2	89.4	
May 2002	51.5	42.2	56.8	71.4	67	
Jun 2002	30.8	33.4	33.2	36.2	36.6	
Jul 2002	15.2	15.4	26	23.6	16.8	
Aug 2002	5.8	13.6	2.6	7.8	6.2	
Sep 2002	34.6	51.4	44.6	54.8	53	
Oct 2002	18.3	16	17.4	17.2	16.4	
Nov 2002	147.7	197.6	186.4	228.6	212.6	
Dec 2002	139.5	109.6	128.2	140	130	
total apr-dec	**525.7**	**562.2**	**572.8**	**678.8**	**628**	
total annual	**818**	**914**	**904.4**	-	-	
Jan 2003	150.5	129.2	130	146.2	132.6	151.2
Feb 2003	27.1	37	30.8	33	32.8	40
Mar 2003	130	131.2	131	149.2	140.2	178.8
Apr 2003	139.6	110.8	120.4	112.6	123.2	146
May 2003	49.3	54.4	42.6	64.8	57	72.4
Jun 2003	12.8	16.2	12.6	14.4	14.4	16.6
Jul 2003	19.8	13.6	22.4	25.4	24	31.8
Aug 2003	4.1	5.6	4	5.8	5.4	7.6
Sep 2003	40.2	27.6	29.2	36.2	36.2	43
Oct 2003	248.2	232	234.6	258	252.2	
Nov 2003	167.4	193.8	187.2	217.2	203.6	
Dec 2003	97.2	78	122.6	124.2	114.8	134.8
total jan-sep	**573.4**	**525.6**	**523**	**587.6**	**565.8**	**687.4**
total	**1086.2**	**1029.4**	**1067.4**	**1187**	**1136.4**	-
Jan 2004	151.6			165.6	171.4	148.2
Feb 2004	83.4			70	78.2	80
Mar 2004	101.2	137.6	108.6	126.4	130.6	118.6
Apr 2004	15	26	14.8	17	18.6	20
May 2004	60.8	92.8	79	81.2	94	98.8
Jun 2004	22.8	19.2	19.6	18.2	19.2	22.2
Jul 2004	16.6			12	16.2	12.4
Aug 2004	75			88.4	73	78.8
Sep 2004	169.4			91.6	97.6	99.6
Oct 2004	117.2			115.8	121.4	111.8
Nov 2004	199.6			188.6	210.2	169.4
Dec 2004	188.2			175.8	193	176.2
total mar-jun	**199.8**	**275.6**	**222**	**242.8**	**262.4**	**259.6**
total annual	**1200.8**	-	-	**1150.6**	**1223.4**	**1136**

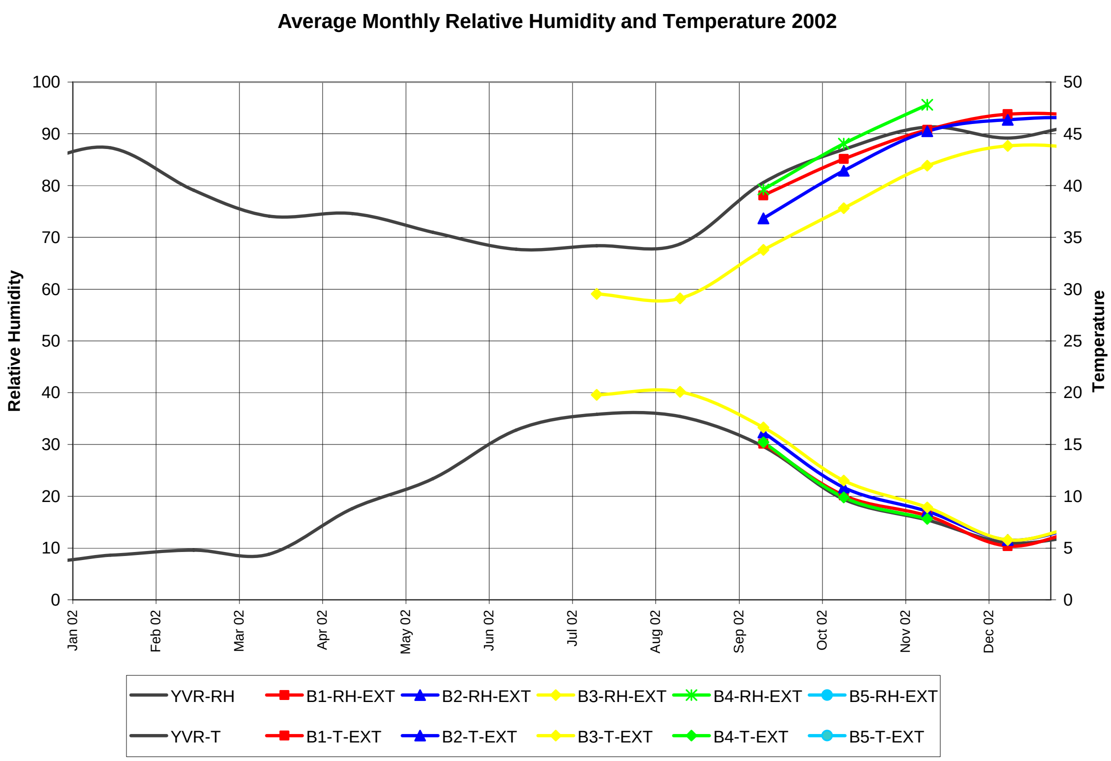

Vancouver Airport 2001 Precipitation
Rain (mm) / Snow (cm)
250
200
150
100
50
0
130.3
0
25.8
15.2
120.2
0
107.7
0
47.6
0
60.4
0
39.3
0
88.4
0
43.6
0
146.1
0
141.9
0
211
3
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Rain
Snow


Vancouver Airport 2002 Precipitation
Rain (mm) / Snow (cm)
250
200
150
100
50
0
133.4
36.9
103.3
0
55.6
12
82.3
0
51.5
0
30.8
0
15.2
0
5.8
0
34.6
0
18.3
0
147.7
0
139.5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Rain
Snow

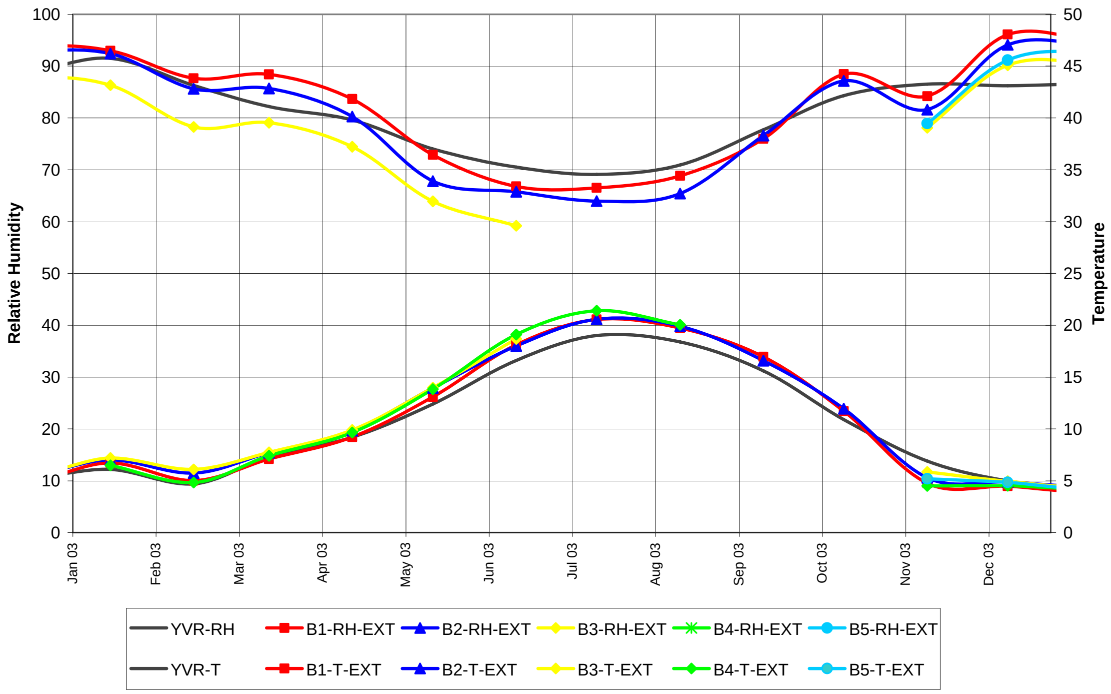

Vancouver Airport 2003 Precipitation
Rain (mm) / Snow (cm)
250
200
150
100
50
0
150.5
0
27.1
0
130
3.7
139.6
0.2
49.3
0
12.8
0
19.8
0
4.1
0
40.2
0
248.2
0
167.4
0
97.2
14.6
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Rain
Snow


Vancouver Airport 2004 Precipitation
Rain (mm) / Snow (cm)
250
200
150
100
50
0
151.6
8.1
83.4
0
101.2
0
15
0
60.8
0
22.8
0
16.6
0
75
0
169.4
0
117.2
0
199.6
0
188.2
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Rain
Snow

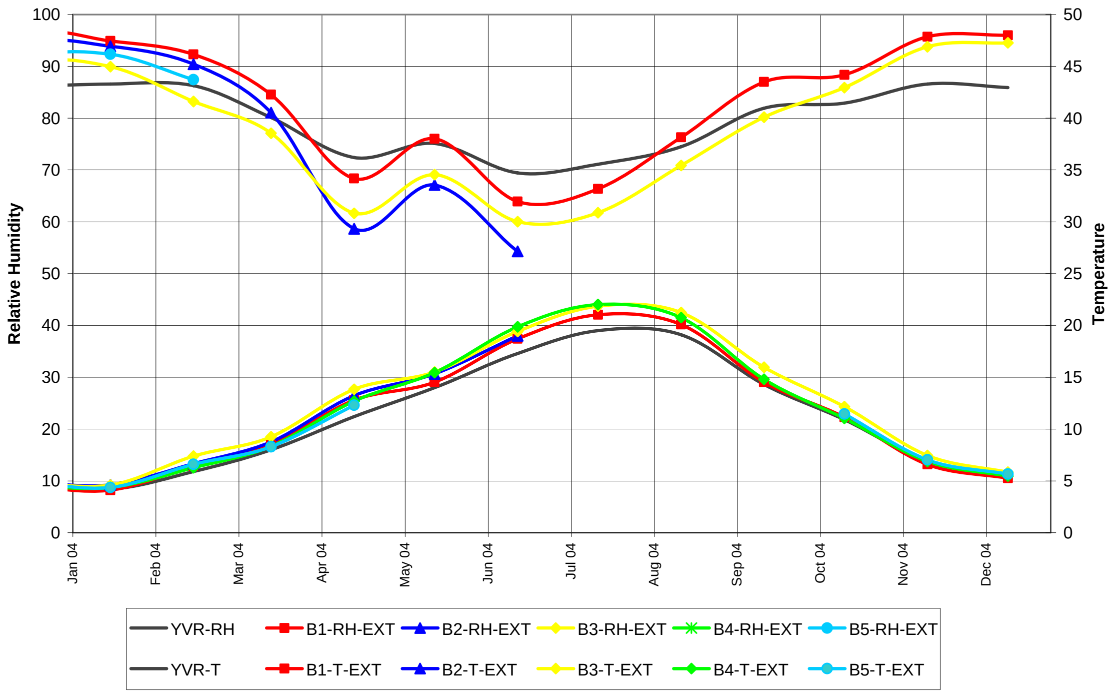

Average Monthly Relative Humidity and Temperature 2001
Relative Humidity
Temperature
100
90
80
70
60
50
40
30
20
10
0
50
45
40
35
30
25
20
15
10
5
0
Jan 01
Feb 01
Mar 01
Apr 01
May 01
Jun 01
Jul 01
Aug 01
Sep 01
Oct 01
Nov 01
Dec 01
YVR-RH
B1-RH-EXT
B2-RH-EXT
B3-RH-EXT
B4-RH-EXT
B5-RH-EXT
YVR-T
B1-T-EXT
B2-T-EXT
B3-T-EXT
B4-T-EXT
B5-T-EXT

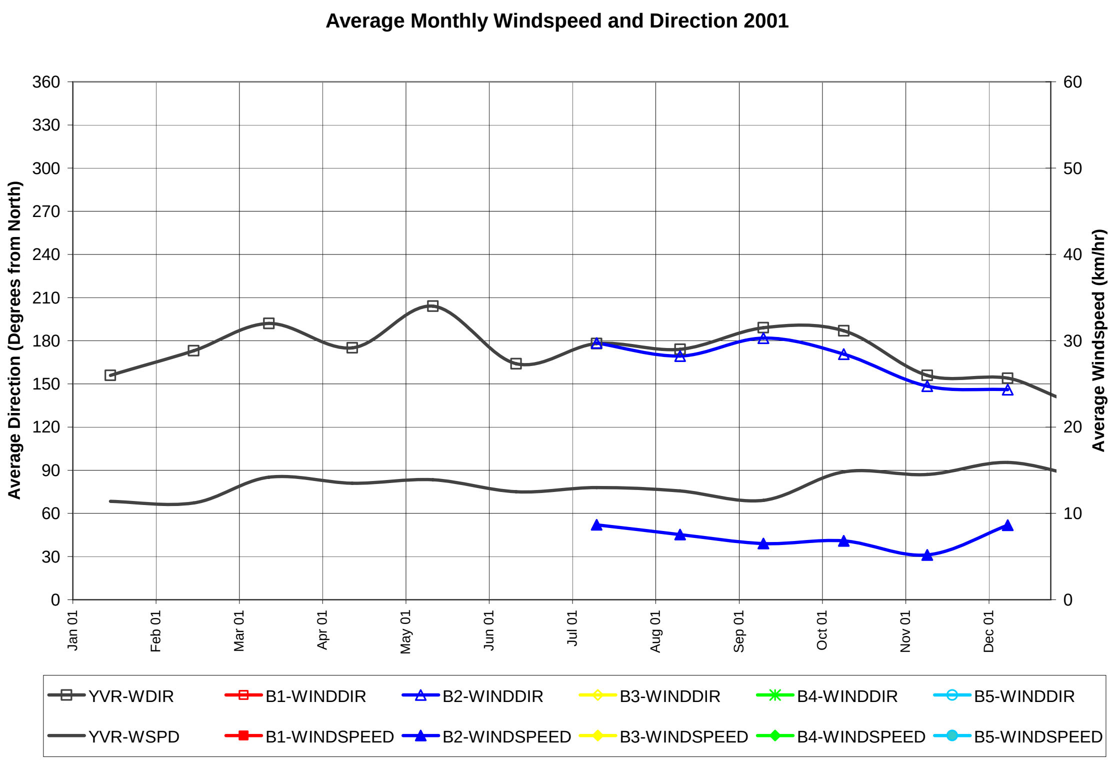

Average Monthly Relative Humidity and Temperature 2002
Relative Humidity
Temperature
100
90
80
70
60
50
40
30
20
10
0
50
45
40
35
30
25
20
15
10
5
0
Jan 02
Feb 02
Mar 02
Apr 02
May 02
Jun 02
Jul 02
Aug 02
Sep 02
Oct 02
Nov 02
Dec 02
YVR-RH
B1-RH-EXT
B2-RH-EXT
B3-RH-EXT
B4-RH-EXT
B5-RH-EXT
YVR-T
B1-T-EXT
B2-T-EXT
B3-T-EXT
B4-T-EXT
B5-T-EXT

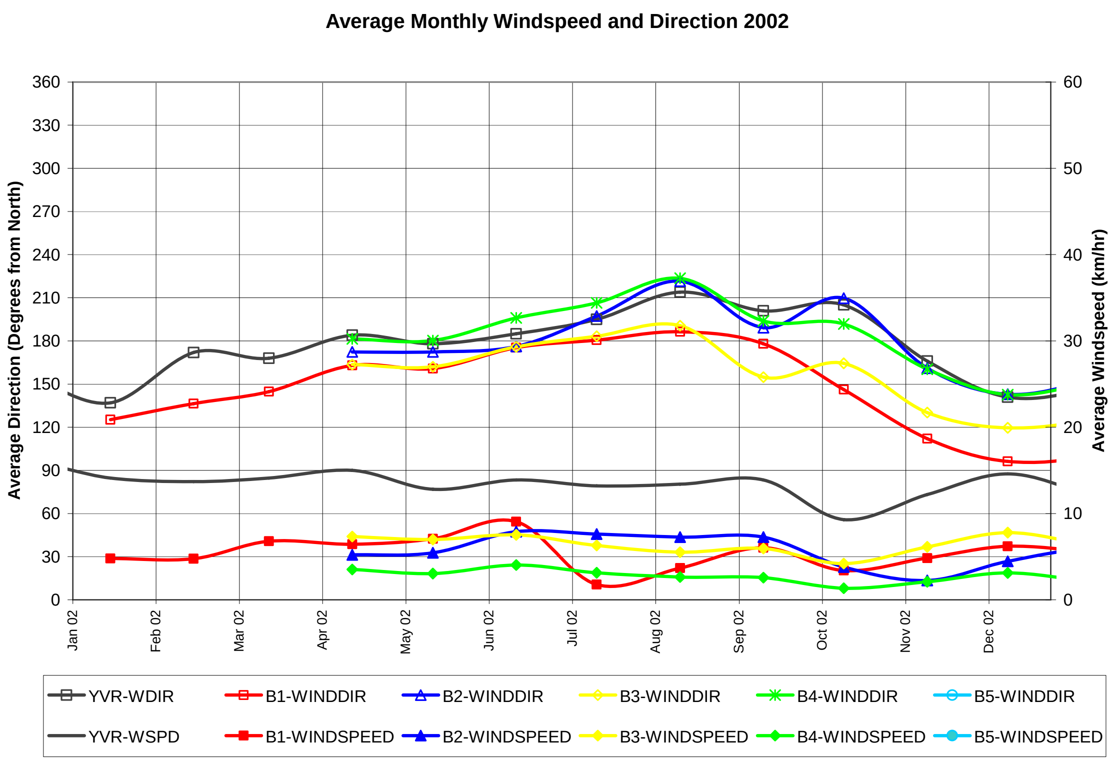
Average Monthly Relative Humidity and Temperature 2003

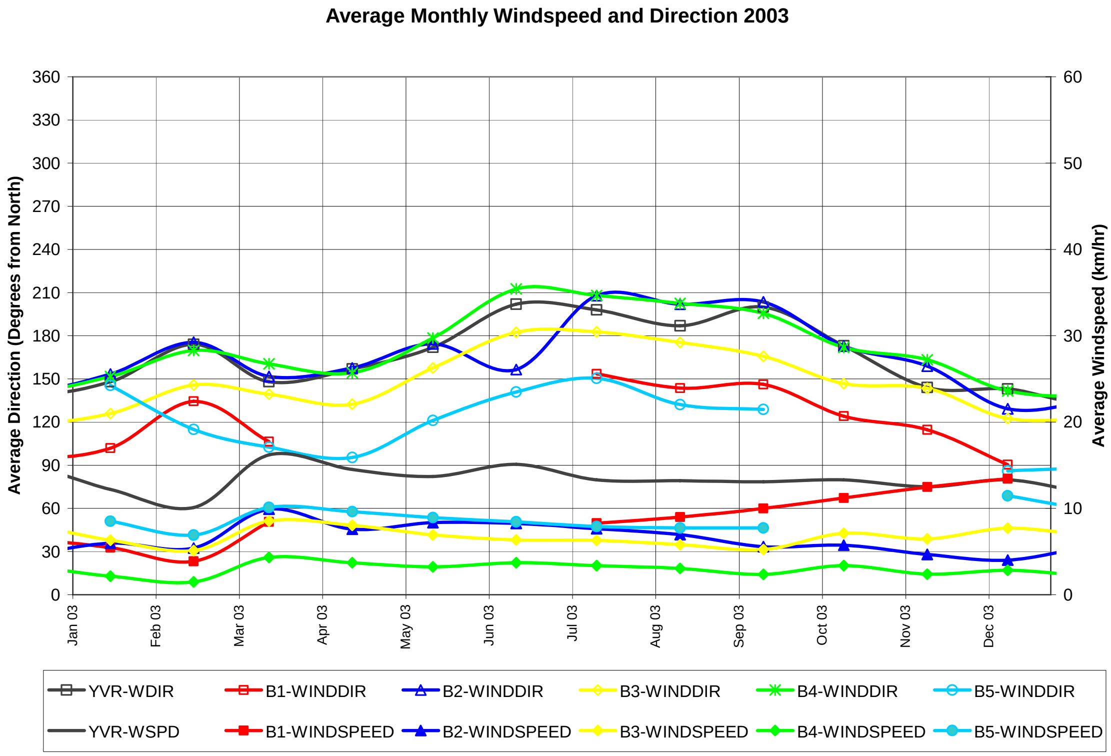


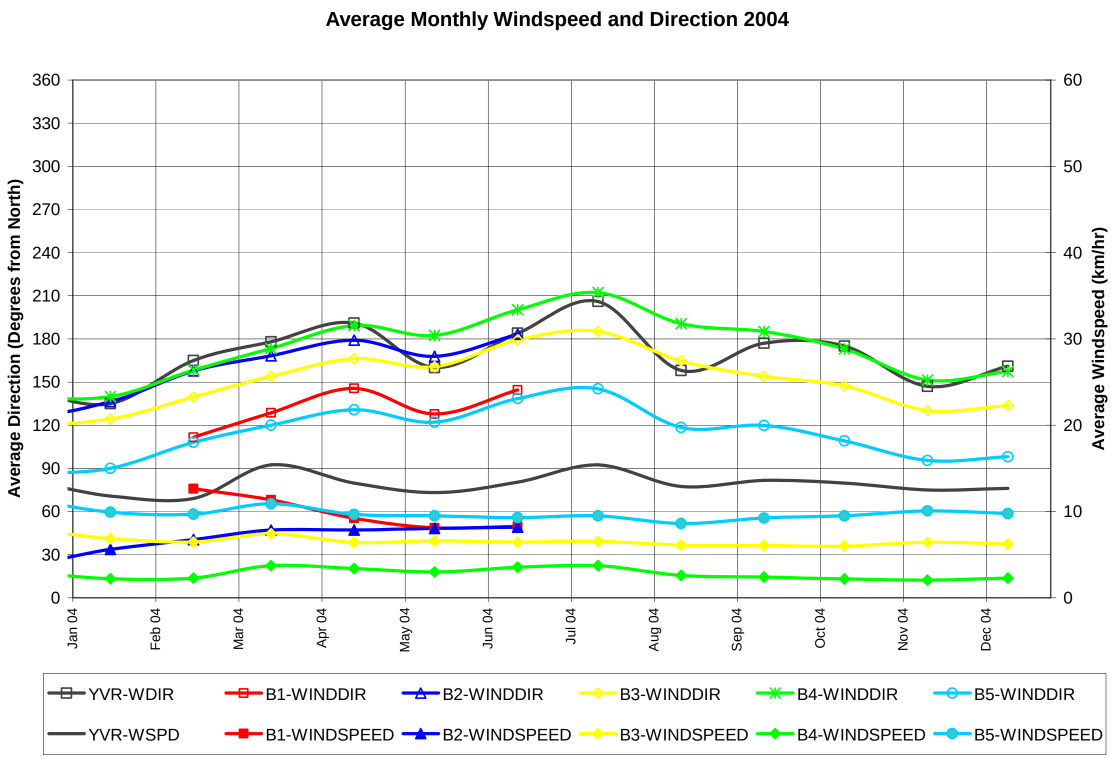
Average Monthly Relative Humidity and Temperature 2004




Average Monthly Windspeed and Direction 2001
Average Direction (Degrees from North)
Average Windspeed (km/hr)
360
330
300
270
240
210
180
150
120
90
60
30
0
60
50
40
30
20
10
0
Jan 01
Feb 01
Mar 01
Apr 01
May 01
Jun 01
Jul 01
Aug 01
Sep 01
Oct 01
Nov 01
Dec 01
YVR-WDIR
B1-WINDDIR
B2-WINDDIR
B3-WINDDIR
B4-WINDDIR
B5-WINDDIR
YVR-WSPD
B1-WINDSPEED
B2-WINDSPEED
B3-WINDSPEED
B4-WINDSPEED
B5-WINDSPEED


Average Monthly Windspeed and Direction 2002
Average Direction (Degrees from North)
Average Windspeed (km/hr)
360
330
300
270
240
210
180
150
120
90
60
30
0
60
50
40
30
20
10
0
Jan 02
Feb 02
Mar 02
Apr 02
May 02
Jun 02
Jul 02
Aug 02
Sep 02
Oct 02
Nov 02
Dec 02
YVR-WDIR
B1-WINDDIR
B2-WINDDIR
B3-WINDDIR
B4-WINDDIR
B5-WINDDIR
YVR-WSPD
B1-WINDSPEED
B2-WINDSPEED
B3-WINDSPEED
B4-WINDSPEED
B5-WINDSPEED


Average Monthly Windspeed and Direction 2003
Average Direction (Degrees from North)
Average Windspeed (km/hr)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
10
20
30
40
50
60
Jan 03
Feb 03
Mar 03
Apr 03
May 03
Jun 03
Jul 03
Aug 03
Sep 03
Oct 03
Nov 03
Dec 03
YVR-WDIR
B1-WINDDIR
B2-WINDDIR
B3-WINDDIR
B4-WINDDIR
B5-WINDDIR
YVR-WSPD
B1-WINDSPEED
B2-WINDSPEED
B3-WINDSPEED
B4-WINDSPEED
B5-WINDSPEED


Average Monthly Windspeed and Direction 2004
Average Direction (Degrees from North)
Average Windspeed (km/hr)
0
30
60
90
120
150
180
210
240
270
300
330
360
0
10
20
30
40
50
60
Jan 04
Feb 04
Mar 04
Apr 04
May 04
Jun 04
Jul 04
Aug 04
Sep 04
Oct 04
Nov 04
Dec 04
YVR-WDIR
B1-WINDDIR
B2-WINDDIR
B3-WINDDIR
B4-WINDDIR
B5-WINDDIR
YVR-WSPD
B1-WINDSPEED
B2-WINDSPEED
B3-WINDSPEED
B4-WINDSPEED
B5-WINDSPEED

3. Monthly Data Summary of Exterior Climate Data – Buildings 1- 5 & YVR

YVR – 1971-2000 Data Normals

Temperature: Temperature:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Code
Daily Average (°C)	3.3	4.8	6.6	9.2	12.5	15.2	17.5	17.6	14.6	10.1	6	3.5	10.1	A
Standard Deviation	1.9	1.5	1.1	1	1	0.9	0.9	1	1	0.8	1.7	1.7	0.7	A
Daily Maximum (°C)	6.1	8	10.1	13.1	16.5	19.2	21.7	21.9	18.7	13.5	9	6.2	13.7	A
Daily Minimum (°C)	0.5	1.5	3.1	5.3	8.4	11.2	13.2	13.4	10.5	6.6	3.1	0.8	6.5	A
Extreme Maximum (°C)	15.3	18.4	19.4	25	30.4	30.6	31.9	**33.3**	29.3	23.7	18.4	14.9		
Date (yyyy/dd)	1981/20+	1986/27	1960/25	1987/27	1983/29	1970/02	1998/28	**1960/09**	1988/03	1991/11	1980/04	1980/26		
Extreme Minimum (°C)	**-17.8**	-16.1	-9.4	-3.3	0.6	3.9	6.7	6.1	0	-5.9	-14.3	-17.8		
Date (yyyy/dd)	**1950/14**	1950/01	1951/10+	1951/19	1954/01	1976/01	1949/02	1937/28	1950/29	1984/31	1985/27	1968/29		
Precipitation: Precipitation:														
Rainfall (mm)	139.1	113.8	111.8	83.5	67.9	54.8	39.6	39.1	53.5	112.5	178.5	160.6	1154.7	A
Snowfall (cm)	16.6	9.6	2.6	0.4	0	0	0	0	0	0.1	2.5	16.3	48.2	A
Precipitation (mm)	153.6	123.1	114.3	84	67.9	54.8	39.6	39.1	53.5	112.6	181	175.7	1199	A
Average Snow Depth (cm)	1	1	0	0	0	0	0	0	0	0	0	1	0	A
Median Snow Depth (cm)	0	0	0	0	0	0	0	0	0	0	0	0	0	A
Snow Depth at Month-end (cm)	0	1	0	0	0	0	0	0	0	0	0	3	0	A
Extreme Daily Rainfall (mm)	68.3	64.2	49.3	44.5	35.2	47.6	45.2	39.4	49.5	60.7	65	**89.4**		
Date (yyyy/dd)	1968/18	1982/13	1974/09	1946/10	1998/27	1992/29	1972/12	1991/30	1959/24	1975/29	1989/03	**1972/25**		
Extreme Daily Snowfall (cm)	29.7	28.6	25.9	3.8	0	0	0	0	0	2	22.1	**41**		
Date (yyyy/dd)	1971/13	1990/15	1962/02	1981/12+	1937/01+	1937/01+	1937/01+	1937/01+	1937/01+	1991/28	1975/30	**1996/29**		
Extreme Daily Precipitation (mm)	68.3	64.2	49.3	44.5	35.2	47.6	45.2	39.4	49.5	60.7	65	**89.4**		
Date (yyyy/dd)	1968/18	1982/13	1974/09	1946/10	1998/27	1992/29	1972/12	1991/30	1959/24	1975/29	1989/03	**1972/25**		
Extreme Snow Depth (cm)	**61**	32	33	3	0	0	0	0	0	1	10	48		
Date (yyyy/dd)	**1971/15**	1990/16	1962/02	1972/09	1955/01+	1955/01+	1955/01+	1955/01+	1955/01+	1989/14+	1955/18	1964/31		
Days with Maximum Temperature: Days with Maximum Temperature:														
<= 0 °C	1.8	0.37	0.03	0	0	0	0	0	0	0	0.34	1.9	4.5	A
> 0 °C	29.2	27.9	31	30	31	30	31	31	30	31	29.7	29.1	360.8	A
> 10 °C	3.5	6.9	15.3	25.8	30.9	30	31	31	30	28.5	10.8	3.3	246.9	A
> 20 °C	0	0	0	0.6	4	10.1	22	22.9	9	0.53	0	0	69.1	A
> 30 °C	0	0	0	0	0.03	0	0.07	0.1	0	0	0	0	0.2	A
> 35 °C	0	0	0	0	0	0	0	0	0	0	0	0	0	A
Days with Minimum Temperature: Days with Minimum Temperature:														
> 0 °C	18.7	19.3	26.3	29.5	31	30	31	31	30	30.2	23.7	18.7	319.4	A
<= 2 °C	18.7	15	11	3	0.03	0	0	0	0.03	2.6	10.5	17.8	78.6	A
<= 0 °C	12.3	9	4.7	0.5	0	0	0	0	0	0.8	6.3	12.3	45.9	A
< -2 °C	8	4.2	1.1	0.03	0	0	0	0	0	0.13	2.9	7	23.3	A
< -10 °C	0.63	0.2	0	0	0	0	0	0	0	0	0.24	0.83	1.9	A
< -20 °C	0	0	0	0	0	0	0	0	0	0	0	0	0	A
< - 30 °C	0	0	0	0	0	0	0	0	0	0	0	0	0	A
Days with Rainfall: Days with Rainfall:														
>= 0.2 mm	16.9	15.4	16.7	13.9	13	11.2	6.9	6.8	8.6	14.2	19.5	18.2	161.3	A
>= 5 mm	9.1	7.6	7.4	6	4.7	3.3	2.5	2.6	3.7	7	10.7	9.7	74.2	A
>= 10 mm	5.3	4	3.7	2.6	2.2	1.6	1.2	1.5	1.8	4	6.7	6	40.7	A
>= 25 mm	0.87	0.6	0.43	0.3	0.2	0.2	0.27	0.1	0.2	0.73	1.4	1.1	6.4	A
Days With Snowfall: Days With Snowfall:														
>= 0.2 cm	3.7	1.9	0.9	0.2	0	0	0	0	0	0.1	0.8	3.3	10.9	A
>= 5 cm	1	0.7	0.2	0	0	0	0	0	0	0	0.17	0.97	3	A
>= 10 cm	0.57	0.27	0.07	0	0	0	0	0	0	0	0.03	0.55	1.5	A
>= 25 cm	0.03	0.03	0	0	0	0	0	0	0	0	0	0.1	0.16	A
Days with Precipitation: Days with Precipitation:														
>= 0.2 mm	18.5	16.3	17	13.9	13	11.2	6.9	6.8	8.6	14.3	19.7	19.8	166.1	A
>= 5 mm	10.1	8.3	7.6	6	4.7	3.3	2.5	2.6	3.7	7	10.8	10.7	77.3	A
>= 10 mm	5.9	4.4	3.8	2.6	2.2	1.6	1.2	1.5	1.8	4	6.8	6.5	42.4	A
>= 25 mm	0.9	0.63	0.43	0.3	0.2	0.2	0.27	0.1	0.2	0.73	1.4	1.2	6.6	A
Days with Snow Depth: Days with Snow Depth:														
>= 1 cm	3.7	2	0.6	0.03	0	0	0	0	0	0.07	0.6	3.5	10.4	A
>= 5 cm	2.4	1.3	0.43	0	0	0	0	0	0	0	0.27	2.3	6.7	A
>= 10	1.4	0.63	0.3	0	0	0	0	0	0	0	0	1.7	4	A
>= 20	0.37	0.1	0	0	0	0	0	0	0	0	0	0.31	0.78	A

YVR – 1971-2000 Data Normals cont.

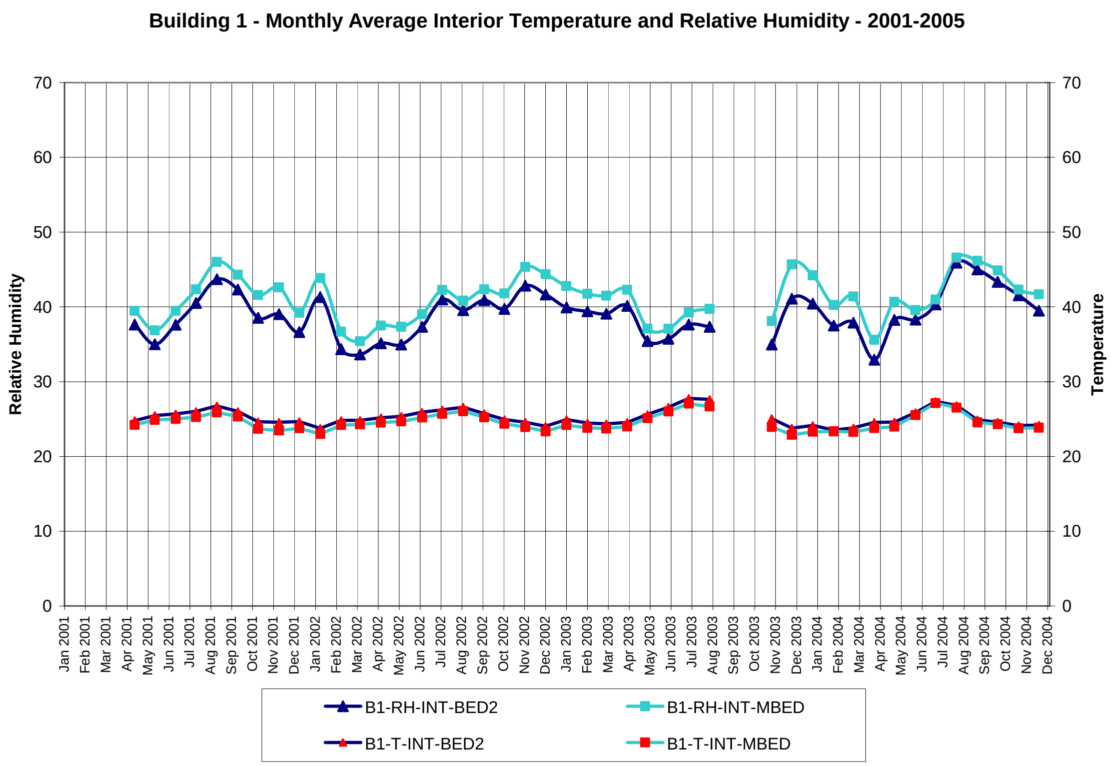
Wind: Wind:														
Speed (km/h)	11.5	12.1	12.9	12.6	12	11.7	11.5	11	10.6	11	12.3	12	11.8	A
Most Frequent Direction	E	E	E	E	E	E	E	E	E	E	E	E	E	A
Maximum Hourly Speed	69	**89**	77	72	61	52	48	50	64	76	89	82		
Date (yyyy/dd)	1963/09+	**1960/20**	1975/30	1961/03	1982/25	1979/06+	1960/07+	2002/14	1968/26+	1962/13	1961/01	2001/14		
Maximum Gust Speed	97	119	108	100	90	70	71	85	91	126	**129**	100		
Date (yyyy/dd)	1964/19	1961/21	1975/30	1961/03+	1955/07	1992/02	1960/07	1980/17	1999/25	1962/13	**1957/25**	1957/23+		
Direction of Maximum Gust	SW	W	W	W	W	W	W	W	W	SE	W	SE	W	
Days with Winds >= 52 km/hr	1.2	0.7	0.9	0.5	0.3	0.1	0	0	0.2	0.6	1.2	1.3	7	A
Days with Winds >= 63 km/hr	0.1	0.2	0.3	0.2	0.1	0	0	0	0.1	0.1	0.2	0.4	1.8	A
Degree Days: Degree Days:														
Above 24 °C	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.1	A
Above 18 °C	0	0	0	0	0.4	3.8	18.2	19.6	2.2	0	0	0	44.2	A
Above 15 °C	0	0	0	0.2	6.3	27.6	80	83.6	21.5	0.6	0	0	219.8	A
Above 10 °C	0.3	0.5	1.8	17.1	81.1	156.3	231.8	236.4	139.2	32.6	3.4	0.3	900.8	A
Above 5 °C	22.6	30.8	60.6	125.7	232.6	306.3	386.8	391.4	288.6	158.6	56.8	24	2084.8	A
Above 0 °C	118.3	139.3	205.7	275.5	387.6	456.3	541.8	546.4	438.6	312.3	186.4	123.1	3731.2	A
Below 0 °C	15.1	4.5	0.4	0	0	0	0	0	0	0.1	4	14.5	38.6	A
Below 5 °C	74.5	37.4	10.3	0.3	0	0	0	0	0	1.4	24.4	70.4	218.6	A
Below 10 °C	207.2	148.4	106.4	41.6	3.5	0.1	0	0	0.7	30.4	121	201.7	860.9	A
Below 15 °C	361.9	289.2	259.6	174.7	83.7	21.3	3.2	2.2	33	153.4	267.6	356.4	2006.3	A
Below 18 °C	454.9	374	352.6	264.5	170.9	87.5	34.3	31.2	103.7	245.8	357.6	449.4	2926.5	A
Bright Sunshine: Bright Sunshine:														
Total Hours	60.4	84.6	134.1	182.4	230.7	229.1	294.5	267.9	199.1	124.8	64.3	56.1	1928	A
Days with measureable	17.5	19.2	24.6	26.6	28.5	27.8	29.3	29.4	27.5	23.6	18.3	16.1	288.5	A
% of possible daylight hours	22.4	29.6	36.5	44.4	48.7	47.3	60.2	60	52.5	37.2	23.4	21.8	40.3	A
Extreme Daily	9.1	10.5	11.8	14.1	15	15.7	15.4	14.7	13	10.5	9.4	8.1		A
Date (yyyy/dd)	1996/30	1996/29	1998/28	1989/30	1993/24+	1989/23	1996/07	1987/02	1972/01	1971/16+	1995/01	1972/07		
Humidex: Humidex:														
Extreme Humidex	17.2	18	19.1	23.9	33.7	33.9	**37.9**	35.9	33	27.2	21.1	15.7		
Date (yyyy/dd)	1981/21	1986/27	1972/16	1957/30	1983/29	1969/18	**1998/28**	1990/12	1987/01	1991/11	1980/04	1980/25		
Days with Humidex >= 30	0	0	0	0	0	0.4	1.9	2	0.2	0	0	0	4.5	A
Days with Humidex >= 35	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.2	A
Days with Humidex >= 40	0	0	0	0	0	0	0	0	0	0	0	0	0	A
Wind Chill: Wind Chill:														
Extreme Wind Chill	-22.6	-21.2	-14.5	-5.4	-1.5	2.4	5	5.1	-0.8	-11.4	-21.3	**-27.8**		
Date (yyyy/dd)	1969/23	1956/15	1955/04	1976/02	1954/01	1976/01	1979/01	1973/18	1972/25	1984/31	1985/27	**1964/16**		
Days with Wind Chill < -20	0	0	0	0	0	0	0	0	0	0	0	0	0.1	A
Days with Wind Chill < -30	0	0	0	0	0	0	0	0	0	0	0	0	0	A
Days with Wind Chill < -40	0	0	0	0	0	0	0	0	0	0	0	0	0	A
Humidity: Humidity:														
Average Vapour Pressure (kPa)	0.7	0.7	0.8	0.9	1.1	1.3	1.5	1.5	1.3	1.1	0.8	0.7	1	A
Average Relative Humidity - 0600LST (%)	87.8	87	85.9	84.7	83.9	83	83.5	86.1	89.4	89.9	87.9	88.1	86.4	A
Average Relative Humidity - 1500LST (%)	79.8	75.3	70.2	65.4	63.9	63.6	62.4	63.1	67.8	75.8	78.9	80.8	70.6	A
	83.8	81.15	78.05	75.05	73.9	73.3	72.95	74.6	78.6	82.85	83.4	84.45	78.5	
Pressure: Pressure:														
Average Station Pressure (kPa)	101.7	101.6	101.5	101.7	101.6	101.6	101.7	101.6	101.7	101.8	101.6	101.8	101.7	A
Average Sea Level Pressure (kPa)	101.7	101.6	101.6	101.7	101.7	101.7	101.7	101.6	101.7	101.8	101.6	101.8	101.7	A
Visibility (hours with): Visibility (hours with):														
< 1 km	30.8	11.5	2.8	0.3	0.1	0.2	0.2	0.4	4.7	27	14.1	25		A
1 to 9 km	134.4	81	46.4	26.7	18	19.1	13.2	23.4	50.7	111.4	94.5	122.7		A
> 9 km	578.8	584.6	694.8	693	725.9	700.7	730.6	720.2	664.6	605.7	611.5	596.3		A
Cloud Amount (hours with): Cloud Amount (hours with):														
0 to 2 tenths	103.6	101.4	136.4	140.6	157.6	138.1	274	289.4	256.1	164.4	99.6	106.6		A
3 to 7 tenths	88.1	99.6	127.9	142.3	170.9	161.9	161	158.4	151.4	132.7	96	93		A
8 to 10 tenths	552.3	476.1	479.6	437.1	415.5	420	309	296.2	312.5	446.9	524.4	544.4		A

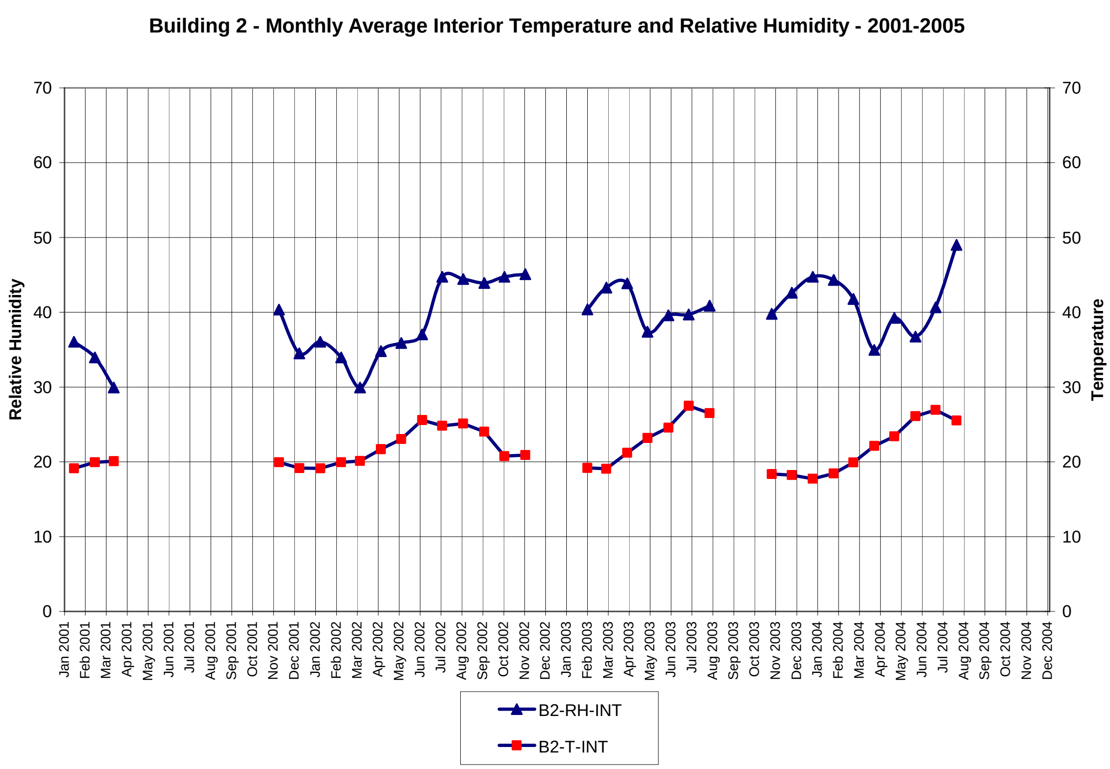
Appendix F: Supplemental Measured Data

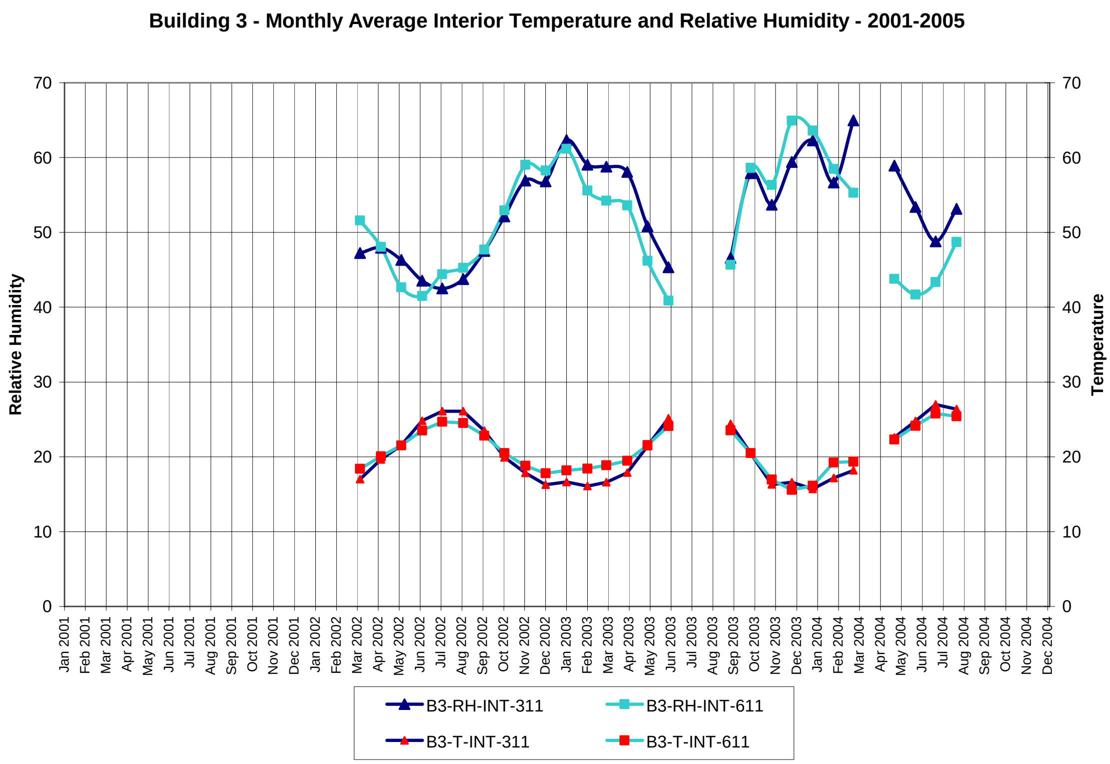
data from YVR hourly data 2001-2006													UBC	
Month	**Mean Temp**	**Mean RH**	**Mean SatVP**	**Mean VP**	**Mean DP**	**Rainfall**	**Snow**	**Precip**	**Wind Dir**	**Wind Speed**	**Visibility**	**Pressure**	**Solar on**	**Approx.**
	C	**%**	**Pa**	**Pa**	**C**	**mm**	**cm**	**mm**	**Degrees 0 north**	**km/hr**	**km**	**kPa**	**Horizontal**	**cloud cover**
Jan 2001	5.2	83.7	885	741	2.7	130.3	0	130.3	156	11.4	30.4	101.9	40.2	4.7
Feb 2001	4	75.2	813	612	0.0	25.8	15.2	39	173	11.2	36.2	101.8	85.9	3.5
Mar 2001	6.8	80.3	988	794	3.7	120.2	0	120.2	192	14.2	33.6	101.8	109.2	4.3
Apr 2001	8.8	74.6	1133	845	4.6	107.7	0	107.7	175	13.5	35.8	101.5	176.8	4.1
May 2001	12.4	70.4	1440	1014	7.2	47.6	0	47.6	204	13.9	41	101.9	232.9	3.8
Jun 2001	14.6	71.9	1662	1195	9.6	60.4	0	60.4	164	12.5	39.4	101.8	247.8	3.8
Jul 2001	17.1	72.8	1950	1420	12.2	39.3	0	39.3	178	13	41.1	101.7	257.2	2.6
Aug 2001	17.3	79.7	1975	1574	13.8	88.4	0	88.4	174	12.6	34.1	101.6	197.8	3.3
Sep 2001	14.7	82.2	1673	1375	11.7	43.6	0	43.6	189	11.5	38.4	101.6	159	3.4
Oct 2001	9.9	85.1	1220	1038	7.5	146.1	0	146.1	187	14.8	32.8	101.7	87.2	4.4
Nov 2001	7.8	84.8	1058	897	5.4	141.9	0	141.9	156	14.5	31	101.2	44.3	5.2
Dec 2001	3.9	84.4	808	682	1.5	211	3	214	154	15.9	29	101.3	32.6	4.8
average	**10.2**	**78.8**	**1300.4**	**1015.5**	**6.7**	**96.9**	**1.5**	**98.2**	**175.2**	**13.3**	**35.2**	**101.7**	**139.2**	**4.0**
sum						**1162.3**	**18.2**	**1178.5**						
Jan 2002	4.3	87.3	831	725	2.4	133.4	36.9	161.5	137	14.1	24.1	101.7	30.8	5.4
Feb 2002	4.8	79.1	860	681	1.5	103.3	0	103.3	172	13.7	33.1	102.2	72.8	4.4
Mar 2002	4.4	74.1	837	620	0.2	55.6	12	67.1	168	14.1	32.3	101.8	107.6	4.9
Apr 2002	8.8	74.6	1133	845	4.6	82.3	0	82.3	184	15	36.6	101.7	183.7	3.7
May 2002	11.7	71	1375	976	6.6	51.5	0	51.5	178	12.8	38.1	101.7	223.1	4
Jun 2002	16.4	67.7	1865	1263	10.5	30.8	0	30.8	185	13.9	42.7	101.6	280.1	2.9
Jul 2002	17.9	68.4	2051	1403	12.0	15.2	0	15.2	195	13.2	43	101.8	272.1	2.4
Aug 2002	17.7	68.7	2026	1392	11.9	5.8	0	5.8	214	13.4	44.4	101.8	254.4	2
Sep 2002	14.8	80.6	1684	1357	11.5	34.6	0	34.6	201	13.9	41.6	101.6	182.9	2.5
Oct 2002	9.7	87	1204	1047	7.7	18.3	0	18.3	205	9.3	26.3	102.1	98.3	4
Nov 2002	7.7	91.3	1051	960	6.4	147.7	0	147.7	166	12.2	25.1	101.8	47.8	4.8
Dec 2002	5.5	89.2	903	806	3.9	139.5	0	139.5	141	14.6	24.5	101.1	27	5.4
average	**10.3**	**78.3**	**1318.3**	**1006.2**	**6.6**	**68.2**	**4.1**	**71.5**	**178.8**	**13.4**	**34.3**	**101.7**	**148.4**	**3.9**
sum						**818**	**48.9**	**857.6**						
Jan 2003	6.1	91.5	942	862	4.8	150.5	0	150.5	148	12.2	25.3	101.9	37.5	5.2
Feb 2003	4.7	86.3	854	737	2.6	27.1	0	27.1	174	10.1	32.2	101.9	78.9	3.8
Mar 2003	7.3	82.2	1023	841	4.5	130	3.7	133.7	14.8	16.2	27.1	101.2	91.8	5
Apr 2003	9.2	79.6	1164	926	5.9	139.6	0.2	139.8	157	14.5	32.1	101.2	153.8	5.1
May 2003	12.4	74	1440	1066	7.9	49.3	0	49.3	172	13.7	36.4	101.7	219.2	4.1
Jun 2003	16.6	70.5	1889	1332	11.3	12.8	0	12.8	202	15.1	37.3	101.5	274.4	2.9
Jul 2003	19	69.1	2198	1519	13.2	19.8	0	19.8	198	13.3	43	101.7	299.4	2.1
Aug 2003	18.4	70.9	2117	1501	13.1	4.1	0	4.1	187	13.2	36.1	101.7	256.7	1.9
Sep 2003	15.6	77.7	1772	1377	11.8	40.2	0	40.2	200	13.1	31.9	101.7	184.5	2.4
Oct 2003	10.9	84.3	1304	1099	8.4	248.2	0	248.2	173	13.3	22.5	101.3	76.1	5
Nov 2003	6.9	86.5	995	861	4.8	167.4	0	167.4	144	12.5	20.7	102.2	63.9	5.4
Dec 2003	5	86.2	872	752	2.9	97.2	14.6	113.2	143	13.3	21.8	101.6	25.7	5.3
average	**11.0**	**79.9**	**1380.9**	**1072.7**	**7.6**	**90.5**	**1.5**	**92.2**	**159.4**	**13.4**	**30.5**	**101.6**	**146.8**	**4.0**
sum						**1086.2**	**18.5**	**1106.1**						
Jan 2004	4.2	86.6	825	714	2.2	151.6	8.1	161.4	135	11.8	20.5	101.6	31.5	5.7
Feb 2004	5.9	86.3	929	802	3.8	83.4	0	83.4	165	11.5	24.8	101.6	75.2	4.5
Mar 2004	8	80.1	1073	859	4.8	101.2	0	101.2	178	15.4	25.6	101.9	130.7	4.5
Apr 2004	11.2	72.4	1330	963	6.4	15	0	15	191	13.3	33.5	101.8	241.9	2.7
May 2004	14	75.1	1599	1201	9.7	60.8	0	60.8	160	12.2	28.5	101.5	248.1	3.7
Jun 2004	17.3	69.4	1975	1371	11.7	22.8	0	22.8	184	13.4	33.5	101.6	300.5	2.8
Jul 2004	19.5	71.1	2267	1612	14.2	16.6	0	16.6	206	15.4	35.3	101.5	301.1	2.3
Aug 2004	19.1	74.5	2212	1648	14.5	75	0	75	158	12.9	33.2	101.4	229.6	3.2
Sep 2004	14.3	81.9	1630	1335	11.3	169.4	0	169.4	177	13.6	26.3	101.5	158.7	4
Oct 2004	10.9	82.9	1304	1081	8.1	117.2	0	117.2	175	13.3	26.2	101.3	90.5	4.5
Nov 2004	6.9	86.6	995	862	4.8	199.6	0	199.6	147	12.5	20.7	102.2	43.9	5.3
Dec 2004	5.5	85.9	903	776	3.3	188.2	0	188.2	161	12.7	22.4	101.7	29.9	5.6
average	**11.4**	**79.4**	**1420.2**	**1101.9**	**7.9**	**100.1**	**0.7**	**100.9**	**169.8**	**13.2**	**27.5**	**101.6**	**156.8**	**4.1**
sum						**1200.8**	**8.1**	**1210.6**						
Average 2001-2005														
Jan	5.0	87.3	871	760	3.0	141.5	11.3	150.9	144.0	12.4	25.1	101.8	35.0	5.3
Feb	4.9	81.7	864	708	2.0	59.9	3.8	63.2	171.0	11.6	31.6	101.9	78.2	4.1
Mar	6.6	79.2	980	778	3.3	101.8	3.9	105.6	138.2	15.0	29.7	101.7	109.8	4.7
Apr	9.5	75.3	1190	895	5.4	86.2	0.1	86.2	176.8	14.1	34.5	101.6	189.1	3.9
May	12.6	72.6	1463	1064	7.9	52.3	0.0	52.3	178.5	13.2	36.0	101.7	230.8	3.9
Jun	16.2	69.9	1848	1290	10.8	31.7	0.0	31.7	183.8	13.7	38.2	101.6	275.7	3.1
Jul	18.4	70.4	2117	1488	12.9	22.7	0.0	22.7	194.3	13.7	40.6	101.7	282.5	2.4
Aug	18.1	73.5	2082	1529	13.3	43.3	0.0	43.3	183.3	13.0	37.0	101.6	234.6	2.6
Sep	14.9	80.6	1690	1361	11.6	72.0	0.0	72.0	191.8	13.0	34.6	101.6	171.3	3.1
Oct	10.4	84.8	1258	1066	7.9	132.5	0.0	132.5	185.0	12.7	27.0	101.6	88.0	4.5
Nov	7.3	87.3	1025	895	5.4	164.2	0.0	164.2	153.3	12.9	24.4	101.9	50.0	5.2
Dec	5.0	86.4	872	754	2.9	159.0	4.4	163.7	149.8	14.1	24.4	101.4	28.8	5.3
YEAR	10.7	79.1	1355.0	1049.1	7.2	88.9	2.0	90.7	170.8	13.3	31.9	101.7	147.8	4.0
						1066.8								
Avg 1971-2000														
Jan	3.3	90.4	774	700		139.1	16.6	153.6						
Feb	4.8	81.4	860	700		113.8	9.6	123.1						
Mar	6.6	82.1	975	800		111.8	2.6	114.3						
Apr	9.2	77.3	1164	900		83.5	0.4	84						
May	12.5	75.9	1450	1100		67.9	0	67.9						
Jun	15.2	75.3	1728	1300		54.8	0	54.8						
Jul	17.5	75.0	2000	1500		39.6	0	39.6						
Aug	17.6	74.5	2013	1500		39.1	0	39.1						
Sep	14.6	78.2	1662	1300		53.5	0	53.5						
Oct	10.1	89.0	1236	1100		112.5	0.1	112.6						
Nov	6	85.5	935	800		178.5	2.5	181						
Dec	3.5	89.1	785	700		160.6	16.3	175.7						
YEAR	10.1	81.1	1298.5	1033		96	4	100						
						1154.7	48.1	1199.2						

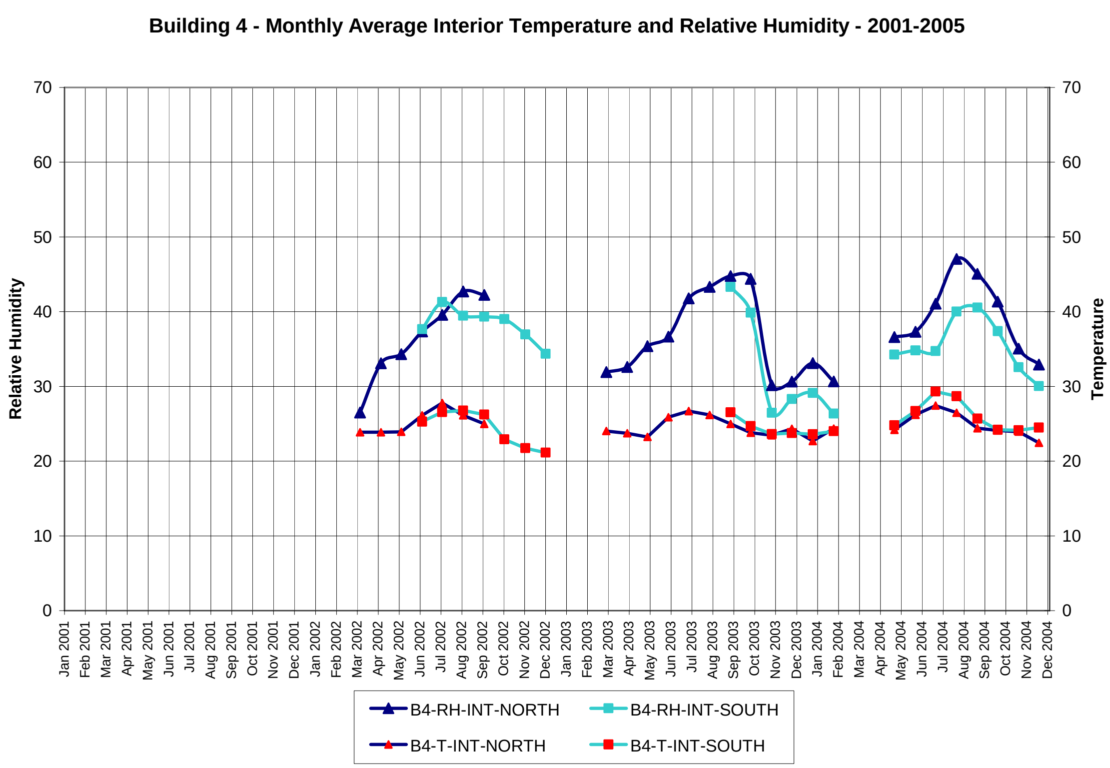
Difference between 2001 - 2005 to 1971-200 data								
Month	**Mean Temp**	**Mean RH**	**Mean SatVP**	**Mean VP**	**Mean DP**	**Rainfall**	**Snow**	**Precip**
	C	**%**	**Pa**	**Pa**	**C**	**mm**	**cm**	**mm**
Jan	1.7	-3.1	96.3	60.5	3.0	2.4	-5.4	-2.7
Feb	0.0	0.4	3.9	7.8	2.0	-53.9	-5.8	-59.9
Mar	0.0	-2.9	5.4	-21.6	3.3	-10.1	1.3	-8.8
Apr	0.3	-2.0	26.1	-5.1	5.4	2.7	-0.4	2.2
May	0.1	-3.3	13.9	-35.9	7.9	-15.6	0.0	-15.6
Jun	1.0	-5.4	120.4	-9.9	10.8	-23.1	0.0	-23.1
Jul	0.9	-4.6	116.4	-11.6	12.9	-16.9	0.0	-16.9
Aug	0.5	-1.1	69.4	28.6	13.3	4.2	0.0	4.2
Sep	0.3	2.4	27.7	61.1	11.6	18.5	0.0	18.5
Oct	0.3	-4.2	21.6	-33.6	7.9	20.0	-0.1	19.9
Nov	1.3	1.8	89.7	94.9	5.4	-14.4	-2.5	-16.9
Dec	1.5	-2.7	86.4	53.9	2.9	-1.6	-11.9	-12.0

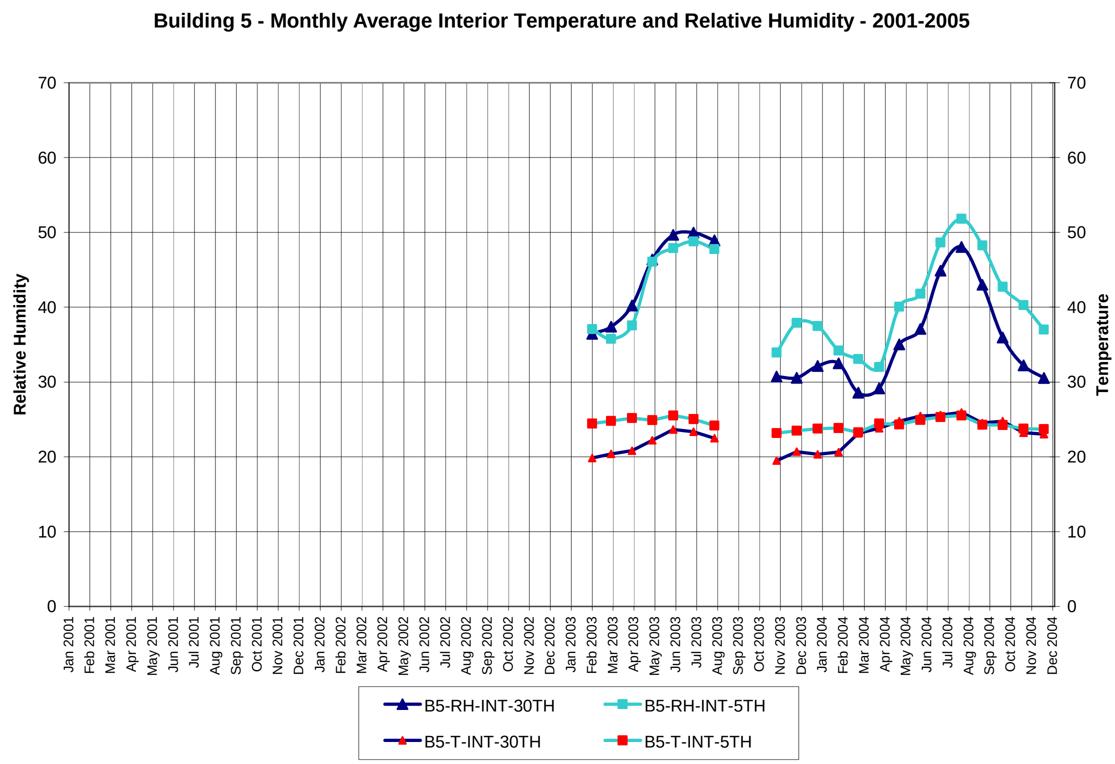
4. Interior Measured Conditions 2001-2005

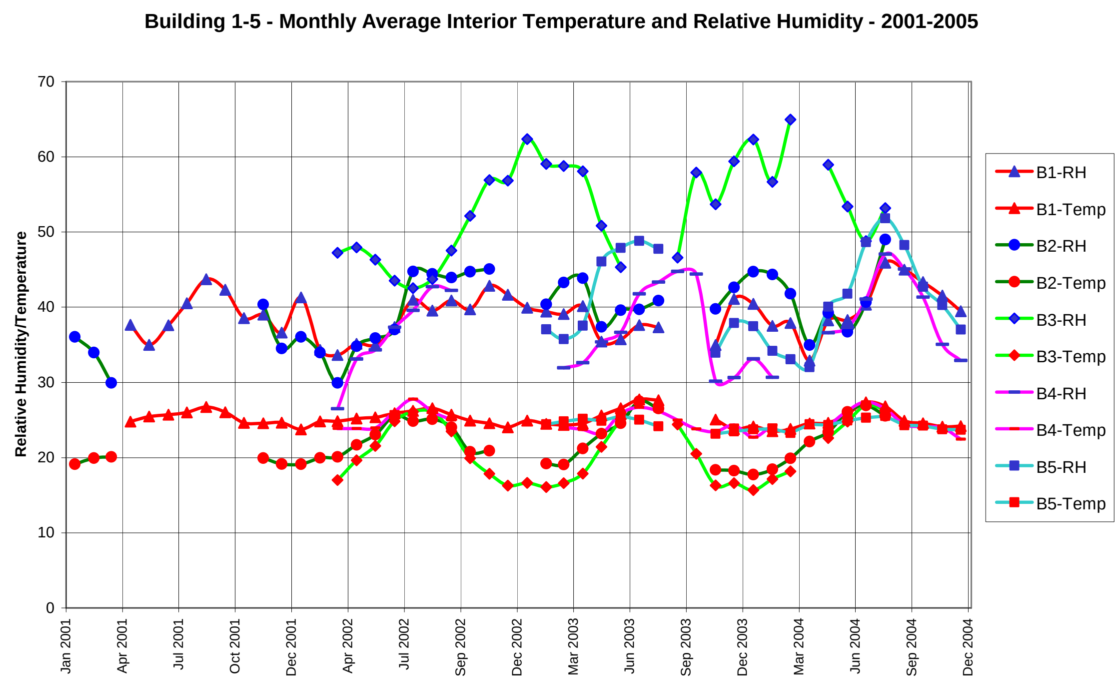




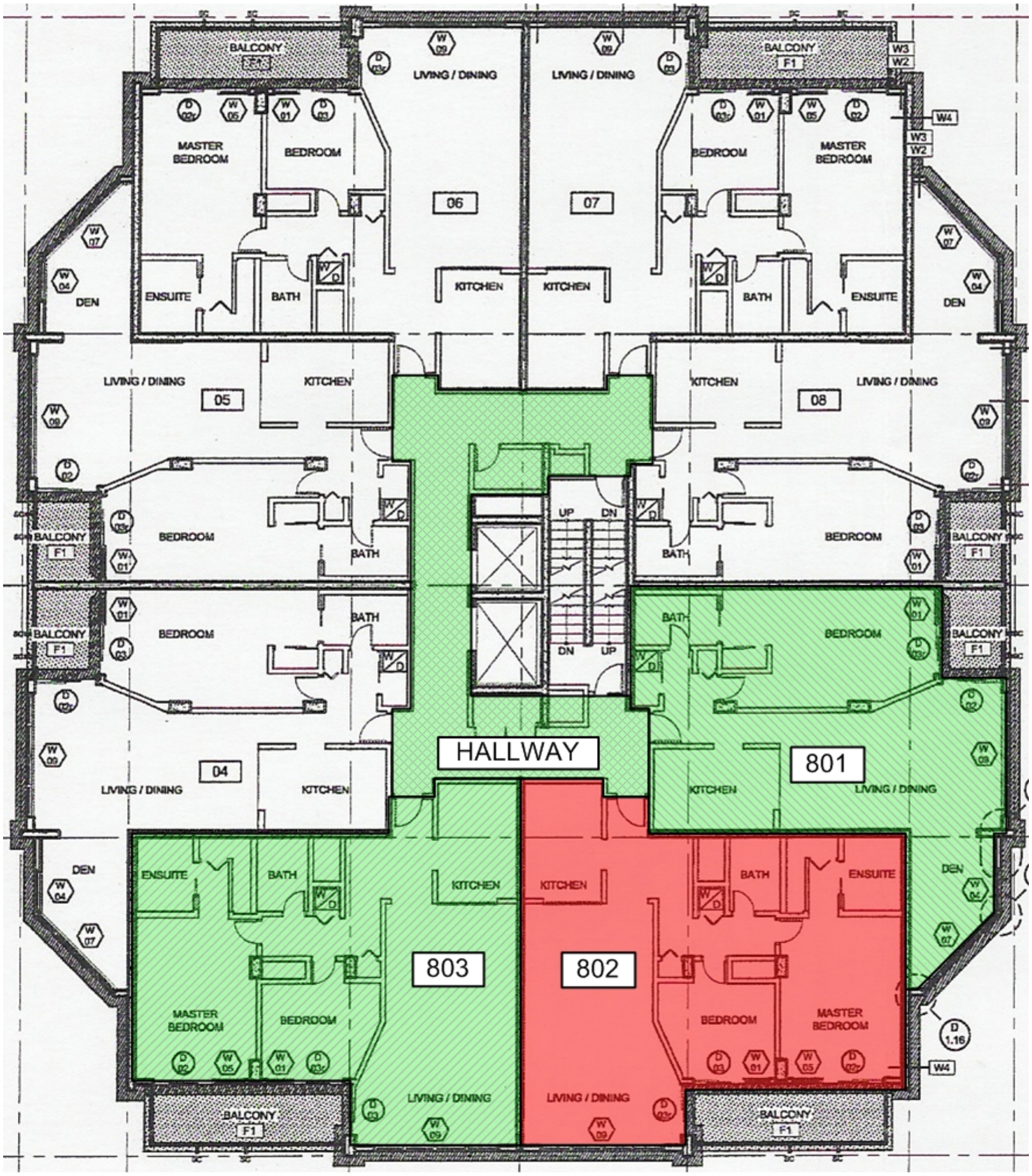

Building 3 - Monthly Average Interior Temperature and Relative Humidity - 2001-2005
Relative Humidity
Temperature
B3-RH-INT-311
B3-RH-INT-611
B3-T-INT-311
B3-T-INT-611


Building 4 - Monthly Average Interior Temperature and Relative Humidity - 2001-2005
Relative Humidity
Temperature
B4-RH-INT-NORTH
B4-RH-INT-SOUTH
B4-T-INT-NORTH
B4-T-INT-SOUTH


Building 5 - Monthly Average Interior Temperature and Relative Humidity - 2001-2005
Relative Humidity
Temperature
B5-RH-INT-30TH
B5-RH-INT-5TH
B5-T-INT-30TH
B5-T-INT-5TH


Building 1-5 - Monthly Average Interior Temperature and Relative Humidity - 2001-2005
Relative Humidity/Temperature
B1-RH
B1-Temp
B2-RH
B2-Temp
B3-RH
B3-Temp
B4-RH
B4-Temp
B5-RH
B5-Temp

Appendix G: Air Leakage Testing – Floor Plans and Supplemental Information

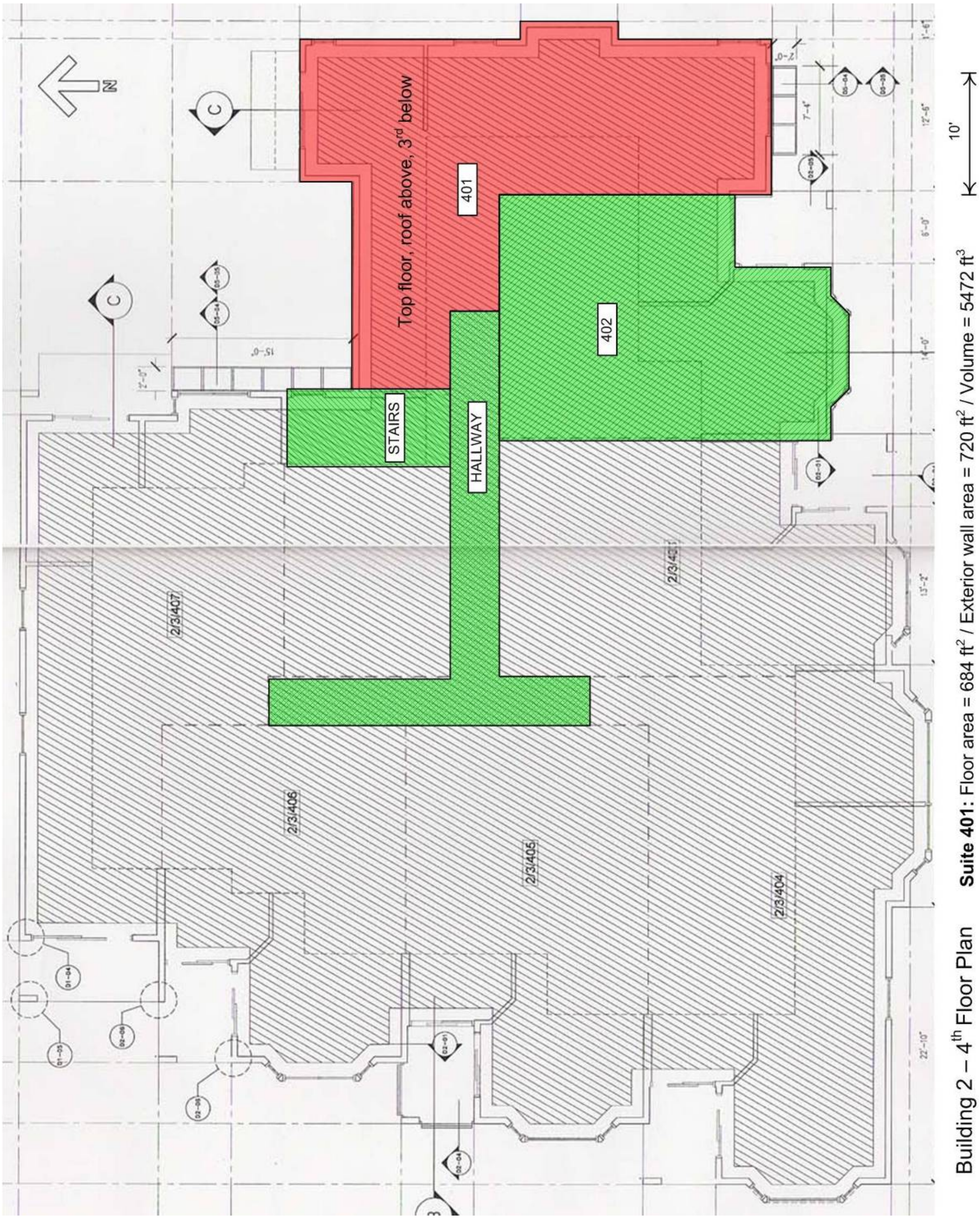


Building A – 8th Floor Plan

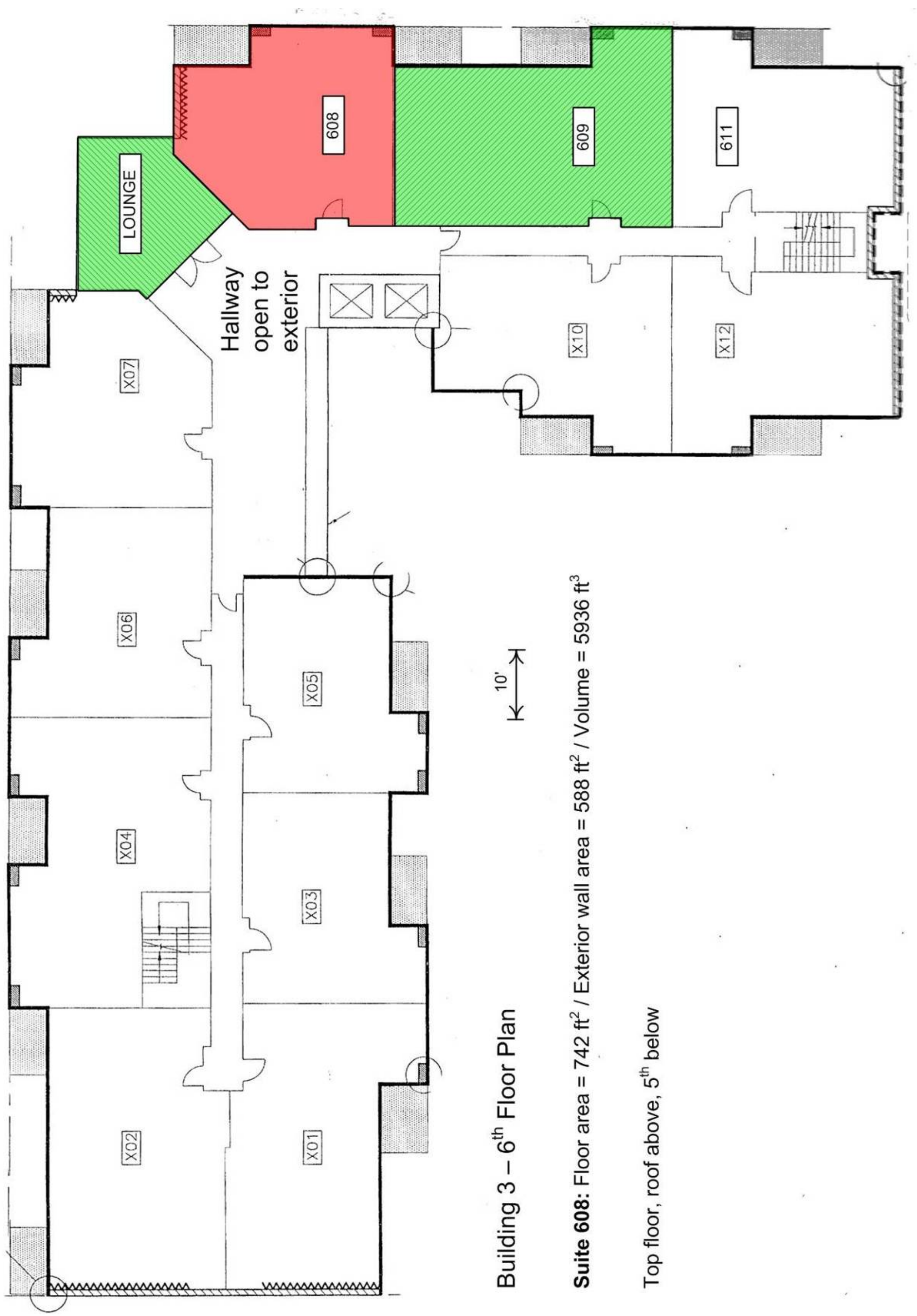
Suite 802:
Floor area = 1085 ft^2
Exterior wall area = 450 ft^2
Volume = 8680 ft^3

10'

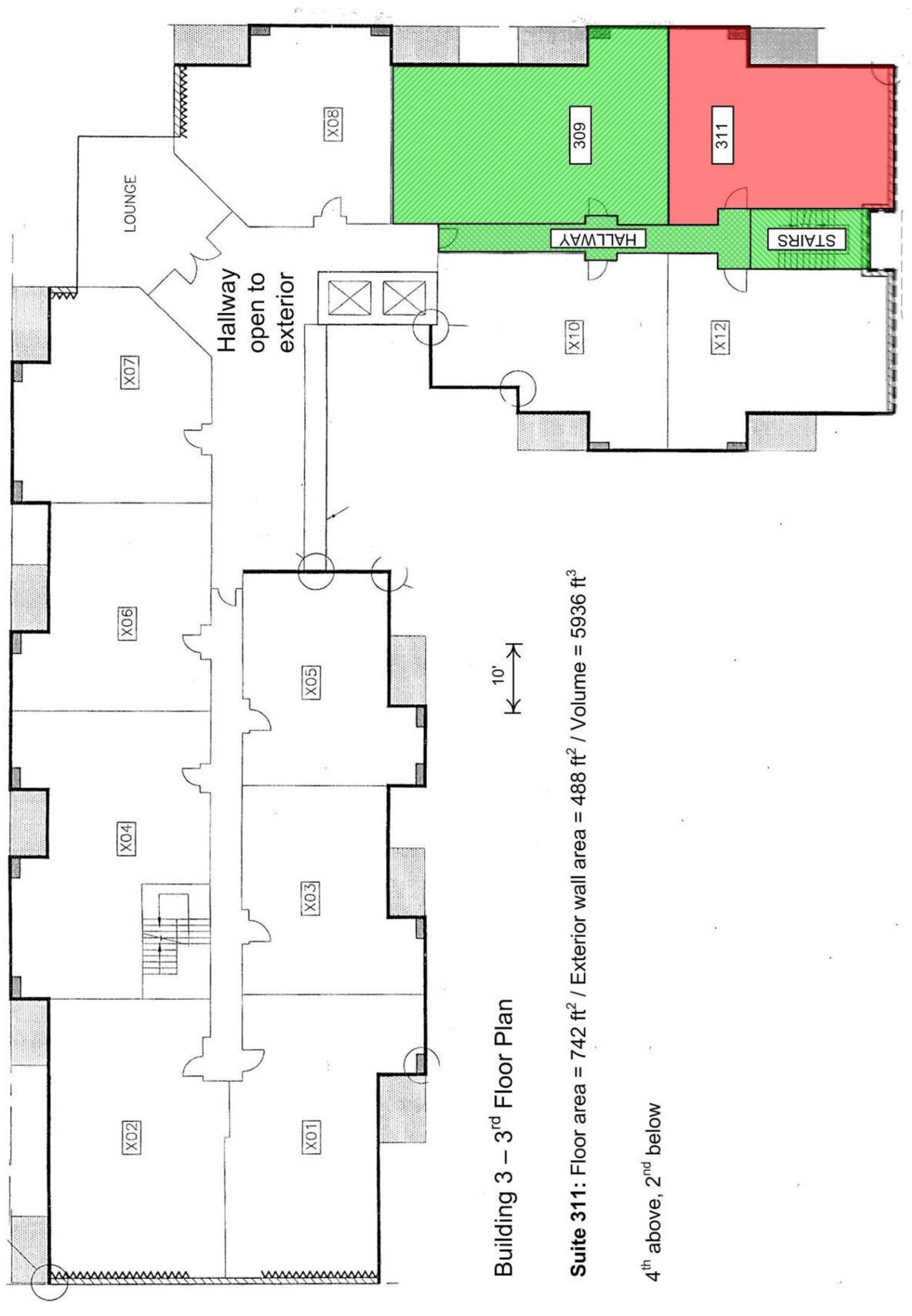
BUILDING A – SUITE 802 TEST



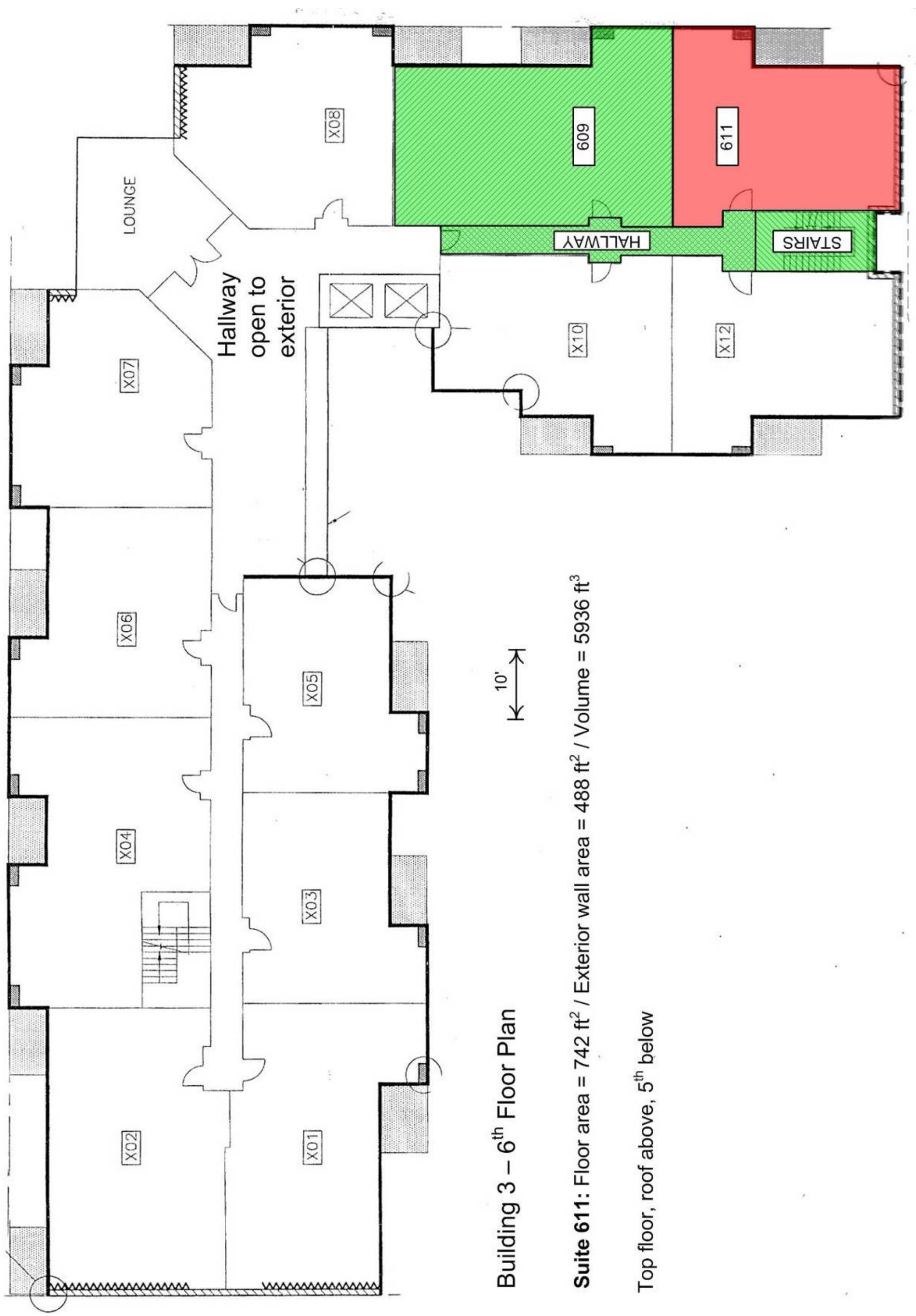
BUILDING 2 – SUITE 401 TEST



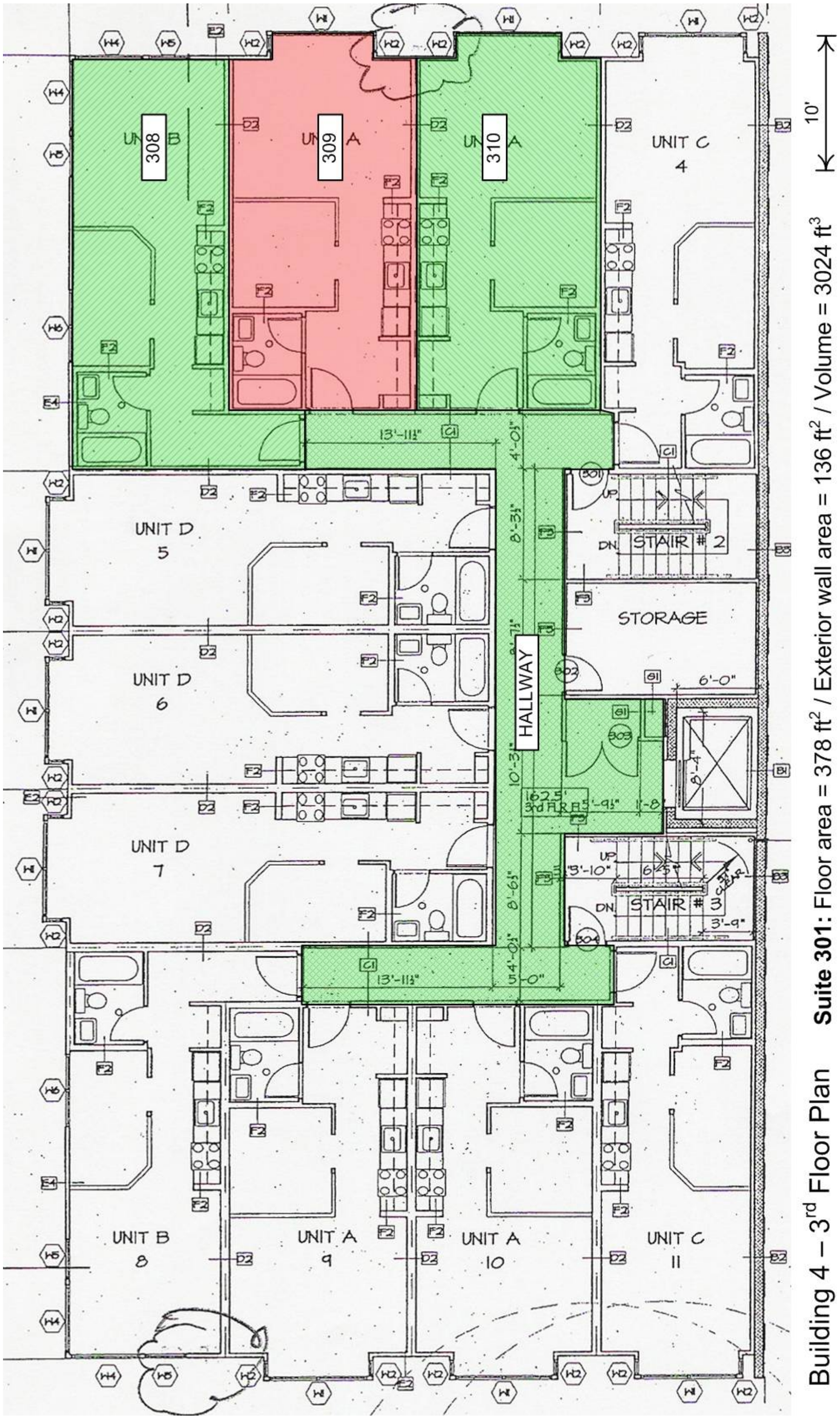
BUILDING 3 – SUITE 608 TEST



BUILDING 3 – SUITE 611 TEST

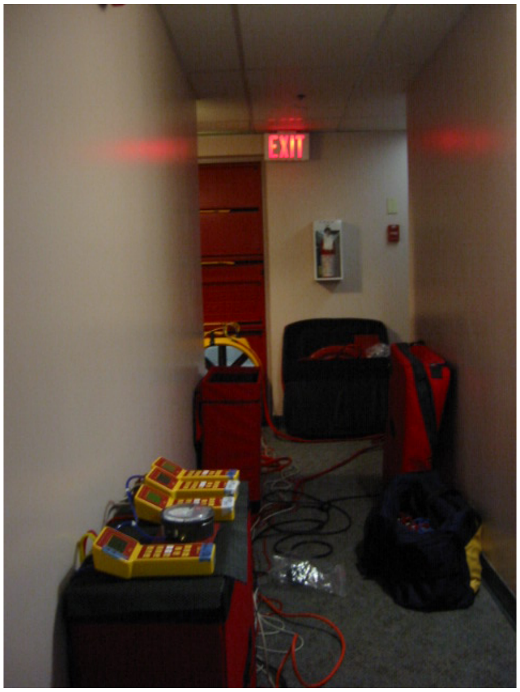


BUILDING 3 – SUITE 311 TEST



BUILDING 4 – SUITE 309 TEST

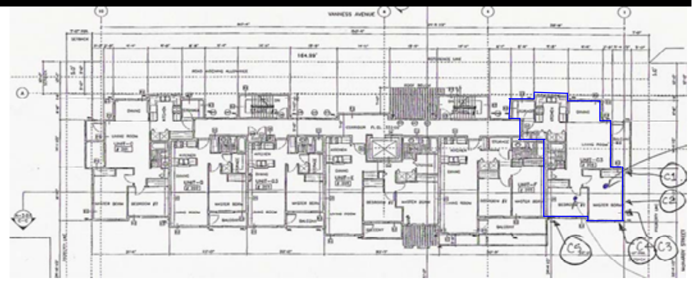
Photographs from Test Procedure:




retrotec

Building Calculations:

BUILDING 1



Building Type:	4 storey wood frame apartment building (21 units), with reinforced concrete Parking Garage below grade Social Housing
Year Constructed:	2000 - New construction
Monitored Suites:	1 - #206, 2bed
Additional Access:	3 - #205, #106, #306, Amenity Space
Notes:	Monitored Suite #206 is corner unit, one suite adjacent #205 Exterior balconies on suites 206, 205 and 306 Floor 1, corridors open to exterior, covered by floor 2 above 9 ft floor to floor, assume 8' ceilings for volume calculations
Mechanical System:	Bath/Kitchen exhaust fans only, Electrical baseboard Heat, Supply air to corridor floors 2,3,&4 No dryers in suites - laundry in amenity space
Floor Access:	1 elevator, plus two stairwells at each end of corridor, door to exterior and parkade, roof hatch on 4th floor

MEASUREMENTS

	Plan - Areas/Volumes				**Elevation - Wall Areas**					
					Exterior Walls			**Interior Walls**		
	Area sq.ft	**Height F-C ft**	**Volume ft3**	**m3**	**Length linear ft.**	**height F-F ft**	**Surface Area ft2**	**Length linear ft.**	**height F-C ft**	**Surface Area ft2**
Suite #206	859.1	8	6873	194.6	102	9	918	40.875	8	327
Suite #205	828.1	8	6625	187.6						
Suite #106	855.5	8	6844	193.8						
Suite #306	859.1	8	6873	194.6						
Floor 1 (5 units)		8								
Floor 2 (6 units)	5377	8	43016	1218.1	this is the volume that a fan door would need to pressurize for entire floor					
Floor 3 (6 units)	5377	8	43016	1218.1						
Floor 4 (4 units)	3139	8	25112	711.1						
Building Total	17755.5	8	142044	4022.2						

PRESSURES

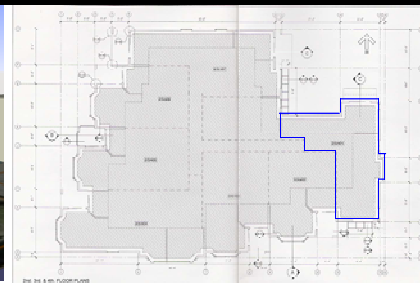
Design Temp	**IN**	21 C	
	OUT	5 C	
Bldg Height		40 ft	to peak of roof

Stack Effect Across Shaft:

Total ΔP	8.26 Pa	
per foot	0.21 Pa	
N.P.P	20 ft	assume mid-height, no mech penthouse, distributed openings
P top	4.13 w.r.t outside	
P bottom	-4.13 w.r.t outside	

Level	Elevation (ft)	Pressure
Roof	40	4.13 Pa
4th ceiling	36	3.31 Pa
4th	27	1.45 Pa
3rd	18	-0.41 Pa
2nd	9	-2.27 Pa
Ground	0	-4.13 Pa

BUILDING 2



Building Type:	4 storey wood frame apartment building (27 units), with reinforced concrete Parking Garage below grade Private Condominium
Year Constructed:	1987 - Original Construction, 2000 - Exterior Wall Rehabilitation
Monitored Suites:	1 - #401, 1bed
Additional Access:	2 - #402, #301
Notes:	Monitored Suite #401 is corner unit, one suite adjacent #402 Cathedral ceiling over portion of suite #401, approx 950 cu.ft added to total volume for suite 9 ft floor to floor, assume 8' ceilings for volume calculations Exterior balconies on all suites
Mechanical System:	Bath/Kitchen exhaust fans only, Electrical baseboard heat, supply air to corridor floors 1,2,3,&4 Washer and Dryer within suites
Floor Access:	1 elevator, plus one stairwell at elevator core,stairwell door opens to roof and parkade, stairs to roof door

MEASUREMENTS

	Plan - Areas/Volumes				**Elevation - Wall Areas**					
					Exterior Walls			**Interior Walls**		
	Area	**Height F-C**	**Volume**		**Length**	**height F-F**	**Surface Area**	**Length**	**height F-C**	**Surface Area**
	sq.ft	**ft**	**ft3**	**m3**	**linear ft.**	**ft**	**ft2**	**linear ft.**	**ft**	**ft2**
Suite #401	684	8	6422	181.9	90	9	810	45	8	360
Suite #402	492	8	3936	111.5				28	8	360
Suite #301	684	8	5472	154.9				shared w/ 401		
Floor 1 (6 units)	4995	8	39960	1131.5						
Floor 2 (7 units)	4995	8	39960	1131.5						
Floor 3 (7 units)	4995	8	39960	1131.5						
Floor 4 (7 units)	4995	8	39960	1131.5	this is the volume that a fan door would need to pressurize for entire floor					
Building Total	19980	8	159840	4526.2						

PRESSURES

Design Temp	**IN**	21 C	
	OUT	5 C	
Bldg Height		44.5 ft	to peak of roof

Stack Effect Across Shaft:

Total ΔP	9.19 Pa	
per foot	0.21 Pa	
N.P.P	22.25 ft	assume mid-height, no mech penthouse, distributed openings
P top	4.60 w.r.t outside	
P bottom	-4.60 w.r.t outside	

Level	Elevation (ft)	Pressure
Roof	44.5	4.60 Pa
4th ceiling	36	2.84 Pa
4th	27	0.98 Pa
3rd	18	-0.88 Pa
2nd	9	-2.74 Pa
Ground	0	-4.60 Pa

BUILDING 3

Building Type:	6 storey reinforced concrete frame apartment building (60 units), with parking garage below grade Social Housing
Year Constructed:	1990 - Original Construction, 2001 - Exterior Wall Rehabilitation
Monitored Suites:	2 - #611, 2bed - #311, 2bed
Additional Access:	6 - #211, #309, #411, #511, #608, #609
Notes:	Monitored Suites #311 and #611 are corner units, one suite adjacent #309/609, concrete stairwell also adjacent 10ft ground level, 9 ft floor to floor, assume 8' ceilings for volume calculations Balconies on all suites
Mechanical System:	Bath/Kitchen exhaust fans only, Electrical baseboard heat, supply air to corridors of suites except #08 and #07 which are open to exterior Corridor not continuous between suites, Amenity space, #07 and #08 suites are exposed to exterior at open corridor No dryers in suites - laundry in amenity space
Floor Access:	2 elevators in central core, plus two stairwells at either end of floor, stairwells open to exterior and parkade, hatch to roof

MEASUREMENTS

	Plan - Areas/Volumes				**Elevation - Wall Areas**					
					Exterior Walls			**Interior Walls**		
	Area	**Height F-C**	**Volume**		**Length**	**height F-F**	**Surface Area**	**Length**	**height F-C**	**Surface Area**
	sq.ft	**ft**	**ft3**	**m3**	**linear ft.**	**ft**	**ft2**	**linear ft.**	**ft**	**ft2**
Suite #311	682	8	5456	154.5	61	9	549	57	8	456
Suite #611	682	8	5456	154.5	61	9	549	57	8	456
Suite #211	682	8	5456	154.5	(24' of 61' is concrete shear wall)			(16' of 57' is to concrete stairwell)		
Suite #411	682	8	5456	154.5						
Suite #511	682	8	5456	154.5						
Suite #309	894	8	7152	202.5						
Suite #608	742	8	5936	168.1						
Suite #609	894	9	8046	227.8						
Floor 2-6 (contained)	3341	10	33410	946.1	this is the volume that a fan door would need to pressurize for entire floor					
Floor 2-6 (each)	10354	8	82832	2345.5						
Building Total	62124	8	496992	14073.2						

PRESSURES

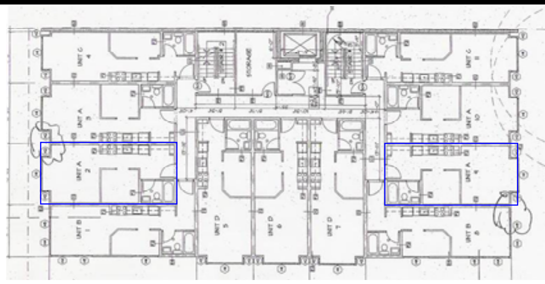
Design Temp	**IN**	21 C	
	OUT	5 C	
Bldg Height		55 ft	to peak of roof

Stack Effect Across Shaft:

Total ∆P	11.36 Pa	
per foot	0.21 Pa	
N.P.P	27.5 ft	assume mid-height, no mech penthouse, distributed openings
P top	5.68 w.r.t outside	
P bottom	-5.68 w.r.t outside	

Level	Elevation (ft)	Pressure
Roof	55	5.68 Pa
6th	46	3.82 Pa
5th	37	1.96 Pa
4th	28	0.10 Pa
3rd	19	-1.76 Pa
2nd	10	-3.62 Pa
Ground	0	-5.68 Pa

BUILDING 4



Building Type:	4 storey wood frame apartment building (40 units), with reinforced concrete Parking Garage below grade Social Housing
Year Constructed:	2001 - New Construction
Monitored Suites:	2 - #303, bach - #309, bach
Additional Access:	8 - #302, #304, #203, #403, #308, #310, #209, #409
Notes:	Monitored Suites #303 (north) and #309 (south) are middle units, with two suites adjacent #303/304 and #308/310 11.5ft ground level, 9 ft floor to floor, assume 8' ceilings for volume calculations
Mechanical System:	Bath/Kitchen exhaust fans only, Electrical baseboard heat, supply air to corridors of suites No dryers in suites - laundry in amenity space
Floor Access:	1 elevator, plus two stairwells on north and south of elevator, stairwells open to ground floor and parkade, hatch to roof

MEASUREMENTS

	Plan - Areas/Volumes				**Elevation - Wall Areas**					
					Exterior Walls			**Interior Walls**		
	Area	**Height F-C**	**Volume**		**Length**	**height F-F**	**Surface Area**	**Length**	**height F-C**	**Surface Area**
	sq.ft	**ft**	**ft3**	**m3**	**linear ft.**	**ft**	**ft2**	**linear ft.**	**ft**	**ft2**
Suite #303	378	8	3024	85.6	17	9	153	66.5	8	532
Suite #309	378	8	3024	85.6	17	9	153	66.5	8	532
Suite #302	378	8	3024	85.6						
Suite #304	390	8	3120	88.3						
Suite #308	390	8	3120	88.3						
Suite #310	378	8	3024	85.6						
Suite #203/403	378	8	3024	85.6						
Suite #209/309	378	9	3402	96.3						
Floors 1-4 (Each)	4900	8	39200	1110.0	this is the volume that a fan door would need to pressurize for entire floor					
Building Total	19600	8	156800	4440.1						

PRESSURES

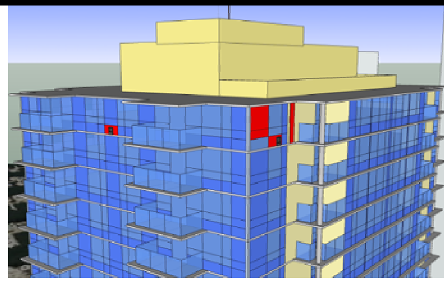
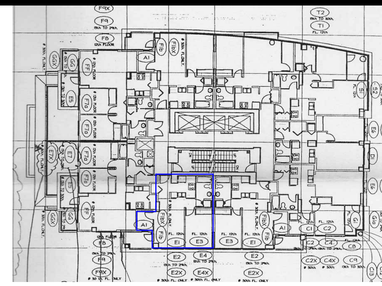
Design Temp	**IN**	21 C	
	OUT	5 C	
Bldg Height		39.5 ft	to peak of roof

Stack Effect Across Shaft:

Total ΔP	8.16 Pa	
per foot	0.21 Pa	
N.P.P	19.75 ft	assume mid-height, no mech penthouse, distributed openings
P top	4.08 w.r.t outside	
P bottom	-4.08 w.r.t outside	

Level	Elevation (ft)	Pressure
Roof	39.5	4.08 Pa
4th	29.5	2.01 Pa
3rd	20.5	0.15 Pa
2nd	11.5	-1.70 Pa
Ground	0	-4.08 Pa

BUILDING 5

Building Type:	30 storey concrete frame apartment building (284 units), with multilevel reinforced concrete Parking Garage below grade Mixed Social Housing/Rental Aparments
Year Constructed:	2002 - New Construction
Monitored Suites:	2 - #3005 2bed, #504 2bed
Additional Access:	7 - #3004, #3006, #503, #505, #2905, #404, #604
Notes:	Monitored Suites #3005 and #504 (south) are corner units, two suites adjacent #3004/3006 and #503/505 10ft ground level, 8.5'ft floor to floor, assume 8' ceilings for volume calculations
Mechanical System:	Bath/Kitchen exhaust fans only, Electrical baseboard heat, supply air to corridors of suites Washer and dryers in suites exhaust through slab duct
Floor Access:	3 elevators in core, plus one dual stairwell in corer, stairwells open to ground floor and parkade, and roof

MEASUREMENTS

	Plan - Areas/Volumes				**Elevation - Wall Areas**					
					Exterior Walls			**Interior Walls**		
	Area	**Height F-C**	**Volume**		**Length**	**height F-F**	**Surface Area**	**Length**	**height F-C**	**Surface Area**
	sq.ft	**ft**	**ft3**	**m3**	**linear ft.**	**ft**	**ft2**	**linear ft.**	**ft**	**ft2**
Suite #3005	541	8	4328	122.6	31	9	279	76	8	608
Suite #405	541	8	4328	122.6	31	9	279	76	8	608
Floors 1-8	8485	8	67880	1922.1				(15' of 76' concrete shearwall)		
Floors 13-30	7260	9	65340	1850.2	this is the volume that a fan door would need to pressurize for entire floor					
Building Total	232500	8	1860000	52669.2						

PRESSURES

Design Temp	**IN**	21 C	
	OUT	5 C	
Bldg Height		280 ft	to peak of roof

Stack Effect Across Shaft:

Total ∆P	57.84 Pa	
per foot	0.21 Pa	
N.P.P	140 ft	assume mid-height, no mech penthouse, distributed openings
P top	28.92 w.r.t outside	
P bottom	-28.92 w.r.t outside	

Level	Elevation (ft)	Pressure
Pent. Roof	280	28.92 Pa
Main Roof	260	24.79 Pa
30th	251.5	23.03 Pa
29th	243	21.28 Pa
6th	44.5	-19.73 Pa
5th	36	-21.48 Pa
4th	27.5	-23.24 Pa
Ground	0	-28.92 Pa

Raw Testing Data:

Multi-Unit Residential Air Leakage Testing - Quantitatively Determining Air Leakage Paths between Suites and to the exterior

Building:	**Building 2**	**Suite**			Floor 4 - 4995 sq.ft
Test Suite:	**401**	Area	684	ft2	
Date/Time:	**Tuesday December 5th, 9am - 2pm**	Volume	5472	ft3	
Weather:	**Overcast/Clear, Calm Winds, 5 degC**				
Test by:	Colin Genge (Retrotec), Graham Finch (U. Waterloo), Hua Ge (BCIT), Wendy Ye (BCIT)				
Notes:	stack effect at 4th floor range approximately 4-5 Pa exfiltration, woodframe building - stucco rainscreen, tyvek (taped), 2x6 batt, polyethylene, drywall				

Incremental Leakage Test Results

Test # (p)-pressurize, (d)-depressurize	**1p**	**1d**	**2p**	**2d**	**3p**	**3d**	**4p**	**4d**	**5p**	**5d**	**6p**	**6d**	**-**	**-**
test order	1	7	2	8	3	9	4	10	5	11	6	12	-	-
Test to Measure:	all 6 sides		hallway below only		floor below (hallway and adjacent suites)		hallway wall		left wall, south stairwell		right wall, suite 402		exterior walls/windows/ducts	
50 Pa Neutralization Pressure applied to:	none		floor hallway below only		floor below		floor and hallway		floor, hallway and left stairwell wall		floor, hallway, left stairwell wall, right suite 402		all 4 interior sides	
Testing Notes			door to suite 301 closed, hallway leaks only		door to suite 301 opened						ceiling space and cathedral ceiling not able to neutralize		end result of testing	
Test Suite Pressure *pressures all with respect to exterior	+50	-50	+50	-50	+50	-50	+50	-50	+50	-50	+50	-50		
Test Flow (cfm)														
Fan Range Configuration (A,B,C)	C8	C8	C8	C8	C8	C8	C8	C8	C8	C8	C8	C8		
ELA @50Pa - cm^2	1070	1060	1015	-	1006	976	890	910	850	889	840	879		
Average ELA @50Pa - cm^2	1065		1015		991		900		870		860			
Difference (Pressurize-Depressurize) - cm^2	10		-		30		-20		-39		-39			
Summary	**all 6 sides**		**hallway on floor below**		**Apartment below**		**4th floor hallway wall (also attic)**		**left wall, south stairwell**		**right wall, suite 402**		**exterior walls, roof, windows, ducts, fireplace**	
Average Surface Leakage Area (ELA) - cm^2	**1065**		**50**		**74**		**91**		**30.5**		**10**		**860**	
in^2	**165.1**		**7.8**		**11.5**		**14.1**		**4.7**		**1.6**		**133.2**	
% of total	**100%**		**5%**		**7%**		**9%**		**3%**		**1%**		**81%**	
CFM 50	**1256.6**		**59.0**		**87.3**		**107.4**		**36.0**		**11.8**		**1014.1**	
ACH 50	13.78		0.65		0.96		1.18		0.39		0.13		**11.12**	
Wall/Floor Surface Area (ft^2)	1777.60				684.00		82.40		64.00		227.20		**720.00**	
(m^2)	165.14				63.55		7.66		5.95		21.11		**66.89**	
Normalized Leakage Area (in^2/100sqft)	9.29				1.68		17.12		7.39		0.68		**18.50**	
(cm^2/m^2)	6.45				1.16		11.89		5.13		0.47		**12.85**	
m^3/hr per m^2 @50Pa	12.93				2.33		23.83		10.28		0.95		**25.76**	
L/s/m2 50	3.59				0.65		6.62		2.86		0.26		7.16	

Additional Flows Measured

Bathroom Exhaust Fan flow — tested with 2" circular sharpedged orifice "flow meter", pressure drop 53Pa = 25cfm, with plastic diffuser on, Suite 402 fan only 21 Pa = 16 cfm
likely some leakage into drop plenum bypassing opening, should be 50cfm fan?

Multi-Unit Residential Air Leakage Testing - Quantitatively Determining Air Leakage Paths between Suites and to the exterior

Building:	**Building A**	**Suite**		Floor 8 - 8920 square ft
Test Suite:	**802**	Area	1085 ft2	
Date/Time:	**Thursday December 6th, 10am-4pm**	Volume	8680 ft3	
Weather:	**Overcast, Calm Winds, 8 degC**			
Test by:	Colin Genge (Retrotec), Graham Finch (U. Waterloo), Matt Mulleray (RDH), Chris Black (RDH), Shen Huang(RDH)			
Notes:	stack effect at 8th floor range varied 10-15 Pa infiltration prior to fan door neutralization, minimal wind +-5Pa building under rehabilitation however suite 802 complete interior finishes and exterior cladding/sealants etc. concrete frame, concrete walls between suites, steel-stud/gypsum elsewhere, large area of glazing			

Incremental Leakage Test Results

Test # (p)-pressurize, (d)-depressurize	**1p**	**1d**	**2p**	**2d**	**3p**	**3d**	**4p**	**4d**	**5p**	**5d**	**6p**	**6d**	**-**	**-**
test order	1	7	2	8	3	9	4	10	5	11	6	12	-	-
Test to Measure:	all 6 sides		ceiling (9th floor)		floor		hallway wall		left wall, suite 801 - concrete shear wall		right wall, suite 803 - concrete shear wall		exterior walls/windows/ducts	
50 Pa Neutralization Pressure applied to:	none		ceiling		ceiling and floor		ceiling, floor and hallway		ceiling, floor, hallway and left suite 801		all 5 interior sides		all 5 interior sides	
Testing Notes	retested three times to confirm large difference in +/- pressures		open/closed door at suite 902 upstairs had no impact on results				retested three times to confirm sudden drop in delta +/- pressures						end result of testing	
Test Suite Pressure *pressures all with respect to exterior	+50	-50	+50	-50	+50	-50	+50	-50	+50	-50	+50	-50		
Test Flow (cfm)	410	340	330	280	320	270	150	155	145	132	136	126		
Fan Range Configuration (A,B,C)	C2	C2	C2	C2	C2	C1	C1	C1	C1	C1	C1	C1		
ELA @50Pa - cm^2	347	290	286	236	270	220	125	132	120	112	115	108		
Average ELA @50Pa - cm^2	319		261		245		129		116		112		112	
Difference (Pressurize-Depressurize) - cm^2	57		50		50		-7		8		7			

Summary	**all 6 sides**	**ceiling (9th floor)**	**floor (7th floor)**	**hallway wall**	**left wall, suite 801**	**right wall, suite 803**	**exterior walls, windows & ducts, (53% window area)**
Average Surface Leakage Area (ELA) - cm^2	**319**	**58**	**16**	**117**	**13**	**5**	**112**
in^2	**49.4**	**8.9**	**2.5**	**18.1**	**1.9**	**0.7**	**17.4**
% of total	**100%**	**18%**	**5%**	**37%**	**4%**	**1%**	**35%**
CFM 50	**375.8**	**67.8**	**18.9**	**137.5**	**14.7**	**5.3**	**132.1**
ACH 50	2.60	0.47	0.13	0.95	0.10	0.04	**0.91**
Wall/Floor Surface Area (ft^2)	3380.67	1085.00	1085.00	114.00	358.67	288.00	**450.00**
(m^2)	314.07	100.80	100.80	10.59	33.32	26.76	**41.81**
Normalized Leakage Area (in^2/100sqft)	1.46	0.82	0.23	15.84	0.54	0.24	**3.86**
(cm^2/m^2)	1.01	0.57	0.16	11.00	0.38	0.17	**2.68**
m^3/hr per m^2 @50Pa	2.03	1.14	0.32	22.05	0.75	0.34	**5.37**
L/s/m2 50	0.56	0.32	0.09	6.13	0.21	0.09	1.49

Additional Flows Measured

Bathroom Exhaust Fan flow	tested with 2" circular sharpedged orifice "flow meter", pressure drop 50Pa = 24cfm, with plastic diffuser on, typical slot type 10" square (noisy) likely some leakage into drop plenum, 50cfm fan
Kitchen Range Hood	tested with 2" circular sharp edged orifice "flow meter", pressure drop 160Pa = 43cfm over each side, when measured separately on high speed setting

Impact of Ducts — Effect of taping bathroom fan/kitchen range hood during all six sides of leakage

Test # (p)-pressurize, (d)-depressurize	**7p**	**7d**	**8p**	**8d**	**9p**	**9d**
test order	13	14	15	16	17	18
Test to Measure:	recheck 1p/1d		bathroom ducts		kitchen ducts	
50 Pa Neutralization Pressure applied to:	n/a		n/a		n/a	
Testing Notes			taped bathroom fan cover opening		taped kitchen fan openings	
Test Suite Pressure *pressures all with respect to exterior	+50	-50	+50	-50	+50	-50
Fan Range Configuration (A,B,C)	C2	C2	C2	C2	C2	C2
ELA @50Pa - cm^2	347	290	311	290	325	290
Average ELA @50Pa - cm^2	319		301		308	
Difference (Pressurize-Depressurize) - cm^2	57		21		35	
Impact on Results - ELA cm^2			18		11	
			bath duct		both ducts double checked	

Multi-Point Test

6 side leakage, depressurizing 802
"depressurizing from inside

Room Pres:	Flow Pressure
49	230
45	196
31	106
29	89
27	73
24	56
22	46
20	37
17	25
14.5	19

Multi-Unit Residential Air Leakage Testing - Quantitatively Determining Air Leakage Paths between Suites and to the exterior

Building:	**Building 3**		**Suite**	
Test Suite:	**608**		Area	742 ft2
Date/Time:	**Wednesday December 7th, 9am-11am**		Volume	5936 ft3
Weather:	**Cloudy, Calm Winds, 6-8 degC**			
Test by:	Colin Genge (Retrotec), Graham Finch (U. Waterloo), Anik Teesdale St.Hillaire (MH), Wendy Ye (BCIT)			
Notes:	608 exposed to exterior on east(princess ave) and west (open hallway) concrete slabs/columns, steel stud and gypsum party walls, exterior stucco rainscreen over blueskin and densglass gold			

Incremental Leakage Test Results

Test #	**1p**	**1d**	**2p**	**2d**	**3p**	**3d**	**4p**	**4d**	**5p**	**5d**	**6p**	**6d**	**-**	**-**
(p)-pressurize, (d)-depressurize test order	1	6	-	-	-	-	-	-	2	5	3	4	-	-
Test to Measure:	all 6 sides		-		-		-		left wall (common room)		right wall (suite 609)		exterior walls/windows/ducts	
50 Pa Neutralization Pressure applied to:	none								left wall (common room)		right wall (609) and hallway		both 2 interior sides	
Testing Notes			roof above		floor below was not tested		no hallway(open to exterior corridor)						end result of testing	
Test Suite Pressure *pressures all with respect to exterior	+50	-50							+50	-50	+50	-50		
Test Flow (cfm)														
Fan Range Configuration (A,B,C)	C4	C4							C4	C4	C4	C2		
ELA @50Pa - cm^2	341	330							323	308	280	243		
Average ELA @50Pa - cm^2	336								316		262			
Difference (Pressurize-Depressurize) - cm^2	11								15		37			
Summary	**all 6 sides**		**roof**		**5th floor**		**exterior corridor**		**left wall, common room**		**right wall, suite 609**		**exterior walls, roof, windows & ducts**	
Average Surface Leakage Area (ELA) - cm^2	**336**								**20**		**54**		**262**	
in^2	**52.0**								**3.1**		**8.4**		**40.5**	
% of total	**100%**								**6%**		**16%**		**78%**	
CFM 50	**395.9**								**23.6**		**63.7**		**308.5**	
ACH 50	4.00								0.24		0.64		**3.12**	
Wall/Floor Surface Area (ft^2)	2532.00		742.00		742.00		176.00		108.00		176.00		**588.00**	
(m^2)	235.23								10.03		16.35		**54.63**	
Normalized Leakage Area (in^2/100sqft)	2.05								2.87		4.76		**6.89**	
(cm^2/m^2)	1.43								1.99		3.30		**4.79**	
m^3/hr per m^2 @50Pa	2.86								4.00		6.62		**9.60**	
L/s/m2 50	0.79								1.11		1.84		2.67	

Additional Flows Measured

Bathroom Exhaust Fan flow — tested with 2" circular sharpedged orifice "flow meter", pressure drop 22Pa = 16cfm, with plastic diffuser on, typical slot type 10" square (noisy)
likely some leakage into drop plenum bypassing opening, 50cfm fan?

Impact of Ducts — Effect of taping bathroom fan/kitchen range hood during all six sides of leakage

Test #	**7p**	**7d**	**8p**	**8d**	**9p**	**9d**
(p)-pressurize, (d)-depressurize test order	7		8		9	
Test to Measure:	recheck 1p/1d		bathroom ducts		kitchen ducts	
50 Pa Neutralization Pressure applied to:	n/a		n/a		n/a	
Testing Notes			taped bathroom fan cover		taped kitchen range hood opening	
Test Suite Pressure *pressures all with respect to exterior	+50	-50	+50	-50	+50	-50
Fan Range Configuration (A,B,C)	C4		C4		C4	
ELA @50Pa - cm^2	340		314		308	
Average ELA @50Pa - cm^2	340		314		308	
Difference (Pressurize-Depressurize) - cm^2	340		314		308	
Impact on Results - ELA cm^2			26		32	
			bath duct		both ducts	

Multi-Unit Residential Air Leakage Testing - Quantitatively Determining Air Leakage Paths between Suites and to the exterior

Building:	**Building 3**	**Suite**		
Test Suite:	**311**	Area	742	ft2
Date/Time:	**Wednesday December 7th, 3pm-5pm**	Volume	5936	ft3
Weather:	**Cloudy, Calm Winds, 6-8 degC**			
Test by:	Colin Genge (Retrotec), Graham Finch (U. Waterloo), Anik Teesdale St.Hillaire (MH), Wendy Ye (BCIT)			
Notes:	311 corner unit concrete slabs/columns, steel stud and gypsum party walls, exterior stucco rainscreen over blueskin and densglass gold			

Incremental Leakage Test Results

Test #	1p	1d	2p	2d	3p	3d	4p	4d	5p	5d	6p	6d	-	-
(p)-pressurize, (d)-depressurize test order	1	12	2	11	3	10	4	9	5	8	6	7	-	-
Test to Measure:	all 6 sides		ceiling above (4th floor)		floor below (2nd)		hallway wall		left wall (suite 309)		-		exterior walls/windows/ducts	
50 Pa Neutralization Pressure applied to:	none		-		floor below (5th)		floor below, hallway wall		floor below, hallway, suite 609		-		all 4 interior sides	
Testing Notes											right wall concrete shear wall at stairs		end result of testing	
Test Suite Pressure *pressures all with respect to exterior **Test Flow (cfm)**	+50	-50	+50	-50	+50	-50	+50	-50	+50	-50				
Fan Range Configuration (A,B,C)	C4	C4	C4	C2	C4	C2	C2	C1/2	C2	C1/2				
ELA @50Pa - cm^2	392	302	389	296	380	288	211	93	165	63.5				
Average ELA @50Pa - cm^2	347		343		334		152		114				114	
Difference (Pressurize-Depressurize) - cm^2	90		93		92		118		101.5					

Summary	**all 6 sides**	**ceiling above (4th floor)**	**floor below (2nd floor)**	**hallway wall**	**left wall (suite 309)**	**right wall - stairwell**	**exterior walls, roof, windows & ducts**
Average Surface Leakage Area (ELA) - cm^2	**347**	**5**	**9**	**182**	**38**		**114**
in^2	**53.8**	**0.7**	**1.3**	**28.2**	**5.9**		**17.7**
% of total	**100%**	**1%**	**2%**	**52%**	**11%**		**33%**
CFM 50	**409.4**	**5.3**	**10.0**	**214.7**	**44.5**		**134.8**
ACH 50	4.14	0.05	0.10	2.17	0.45		**1.36**
Wall/Floor Surface Area (ft^2)	2422.66	742.00	742.00	106.66	216.00	128.00	**488.00**
(m^2)	225.07	68.93	68.93	9.91	20.07	11.89	**45.34**
Normalized Leakage Area (in^2/100sqft)	2.22	0.09	0.18	26.45	2.71		**3.63**
(cm^2/m^2)	1.54	0.07	0.12	18.37	1.88		**2.52**
m^3/hr per m^2 @50Pa	3.09	0.13	0.25	36.82	3.77		**5.05**
L/s/m2 50	0.86	0.04	0.07	10.23	1.05		1.40

Additional Flows Measured

Bathroom Exhaust Fan flow — tested with 2" circular sharpedged orifice "flow meter", pressure drop 54Pa = 25cfm, with plastic diffuser on, typical slot type 10" square (noisy) likely some leakage into drop plenum bypassing opening, 50cfm fan?

Impact of Ducts — Effect of Fan running and taped shut

Test #	7p	7d	8p	8d	9p	9d	
(p)-pressurize, (d)-depressurize test order	13		14		15		
Test to Measure:	recheck 1p/1d		fan taped		fan running		
50 Pa Neutralization Pressure applied to:	n/a		n/a		n/a		
Testing Notes			fan cover taped		fan cover open and fan running		
Test Suite Pressure *pressures all with respect to exterior	+50	-50	+50	-50	+50	-50	
Fan Range Configuration (A,B,C)	C4		C4		C4		
ELA @50Pa - cm^2	392	302	392	302	290	206	cfm @50Pa
Average ELA @50Pa - cm^2	347		347		248		
Difference (Pressurize-Depressurize) - cm^2	90		90		84		
Impact on Results - ELA cm^2			0		99		
			bath duct		both ducts		

Multi-Unit Residential Air Leakage Testing - Quantitatively Determining Air Leakage Paths between Suites and to the exterior

Building:	**Building 3**	**Suite**		
Test Suite:	**611**	Area	742	ft2
Date/Time:	**Wednesday December 7th, 11am-2pm**	Volume	5936	ft3
Weather:	**Cloudy, Calm Winds, 6-8 degC**			
Test by:	Colin Genge (Retrotec), Graham Finch (U. Waterloo), Anik Teesdale St.Hillaire (MH), Wendy Ye (BCIT)			
Notes:	611 corner unit, on top floor, 609 adjacent concrete slabs/columns, steel stud and gypsum party walls, exterior stucco rainscreen over blueskin and densglass gold			

Incremental Leakage Test Results

Test #	**1p**	**1d**	**2p**	**2d**	**3p**	**3d**	**4p**	**4d**	**5p**	**5d**	**6p**	**6d**	**-**	**-**
(p)-pressurize, (d)-depressurize test order	1	8	-	-	2	7	3	6	4	5			-	-
Test to Measure:	all 6 sides		-		floor below (5th)		hallway wall		left wall (suite 609		-		exterior walls/windows/ducts	
50 Pa Neutralization Pressure applied to:	none		-		floor below (5th)		floor below, hallway wall		floor below, hallway, suite 609		-		all 3 interior sides	
Testing Notes			roof above		including suite 511						right wall concrete shear wall at stairs		end result of testing	
Test Suite Pressure *pressures all with respect to exterior	+50	-50			+50	-50	+50	-50	+50	-50				
Test Flow (cfm)														
Fan Range Configuration (A,B,C)	C4	C4			C4	C4	C4	C2	C2	C1				
ELA @50Pa - cm^2	540	492			532	487	328	217	240	135				
Average ELA @50Pa - cm^2	516				510		273		188				188	
Difference (Pressurize-Depressurize) - cm^2	48				45		111		105					

Summary	**all 6 sides**	**ceiling**	**floor below (5th)**	**hallway wall**	**left wall (suite 609)**	**right wall - stairwell**	**exterior walls, roof, windows & ducts**
Average Surface Leakage Area (ELA) - cm^2	**516**		**7**	**237**	**85**		**188**
in^2	**80.0**		**1.0**	**36.7**	**13.2**		**29.1**
% of total	**100%**		**1%**	**46%**	**16%**		**36%**
CFM 50	**608.8**		**7.7**	**279.6**	**100.3**		**221.2**
ACH 50	6.15		0.08	2.83	1.01		**2.24**
Wall/Floor Surface Area (ft^2)	2422.66	742.00	742.00	106.66	216.00	128.00	**488.00**
(m^2)	225.07		68.93	9.91	20.07		**45.34**
Normalized Leakage Area (in^2/100sqft)	3.30		0.14	34.44	6.10		**5.96**
(cm^2/m^2)	2.29		0.09	23.92	4.24		**4.14**
m^3/hr per m^2 @50Pa	4.60		0.19	47.94	8.49		**8.29**
L/s/m2 50	1.28		0.05	13.32	2.36		2.30

Multi-Unit Residential Air Leakage Testing - Quantitatively Determining Air Leakage Paths between Suites and to the exterior

Building:	**Building 4**		**Suite**	
Test Suite:	**309**		Area	378 ft2
Date/Time:	**Friday December 8th, 10am-1pm**		Volume	3024 ft3
Weather:	**Overcast, Calm Winds, 8 degC**			
Test by:	Colin Genge (Retrotec), Graham Finch (U. Waterloo), Wendy Ye (BCIT)			
Notes:	Each Floor pressurized to 8Pa, makeup air one fan per floor, suppply from roof top unit/ Radiant heated floors (conc topped) - 25C indoors woodframe building - cement board over strapping, 2layers building paper over plywood, 2x4 batt, polyethylene (pimary air barrier), drywall			

Incremental Leakage Test Results

Test #	**1p**	**1d**	**2p**	**2d**	**3p**	**3d**	**4p**	**4d**	**5p**	**5d**	**6p**	**6d**	**-**	**-**
(p)-pressurize, (d)-depressurize test order	1	6	2	7	3	8	4	9	5	10	-	-	-	-
Test to Measure:	all 6 sides		ceiling (4th floor)		floor (2nd floor)		hallway wall		left wall, suite 308		right wall, suite 310		exterior walls/windows/ducts	
50 Pa Neutralization Pressure applied to:	none		ceiling		ceiling and floor		ceiling, floor and hallway		ceiling, floor, hallway and left suite 308		ceiling, floor, hallway and left suite 308		all 5 interior sides	
Testing Notes	no access to 310, door closed (1/2" undercut)										no access to suite 310		end result of testing	
Test Suite Pressure *pressures all with respect to exterior	+50	-50	+50	-50	+50	-50	+50	-50	+50	-50				
Test Flow (cfm)	540	430					414		395					
Fan Range Configuration (A,B,C)	C4	C4	C4	C4	C4	C4	C4	C2	C4	C2				
ELA @50Pa - cm²	470	360	470	360	470	360	350	220	335	215				
Average ELA @50Pa - cm²	415		415		415		285		275				275	
Difference (Pressurize-Depressurize) - cm²	110		110		110		130		120				116 consistent +poly pushe	

Summary	**all 6 sides**	**ceiling (4th floor)**	**floor (2nd floor)**	**hallway wall**	**left wall, suite 308**	**right wall, suite 310**	**exterior walls, windows & ducts**
Average Surface Leakage Area (ELA) - cm²	**415**	**0**	**0**	**130**	**10**		**275**
in²	**64.3**	**0.0**	**0.0**	**20.2**	**1.6**		**42.6**
% of total	**100%**	**0%**	**0%**	**31%**	**2%**		**66%**
CFM 50	**489.7**	**0.0**	**0.0**	**153.4**	**11.8**		**324.5**
ACH 50	9.72	0.00	0.00	3.04	0.23		**6.44**
Wall/Floor Surface Area (ft²)	1428.00	378.00	378.00	68.00	256.00	212.00	**136.00**
(m²)	132.67	35.12	35.12	6.32	23.78	19.70	**12.63**
Normalized Leakage Area (in²/100sqft)	4.50	0.00	0.00	29.63	0.61		**31.34**
(cm²/m²)	3.13	0.00	0.00	20.58	0.42		**21.77**
m³/hr per m² @50Pa	6.27	0.00	0.00	41.25	0.84	0.00	**43.63**
L/s/m2 50	1.74	0.00	0.00	11.46	0.23	0.00	12.12

Additional Flows Measured

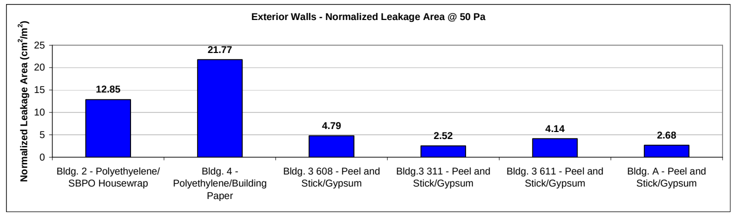
Bathroom Exhaust Fan flow: tested with 2" circular sharpedged orifice "flow meter", pressure drop 67Pa = 28cfm, with plastic diffuser on, typical slot type 10" square likely some leakage into drop plenum, 90cfm fan, Quiet 1.5 sones

Impact of Ducts: Effect of taping bathroom fan/kitchen range hood during all six sides of leakage

Test #	**7p**	**7d**	**8p**	**8d**
(p)-pressurize, (d)-depressurize test order	11		12	
Test to Measure:	recheck 1p/1d		fan taped	
50 Pa Neutralization Pressure applied to:	n/a		n/a	
Testing Notes			taped bathroom fan cover opening	
Test Suite Pressure *pressures all with respect to exterior	+50	-50	+50	-50
Fan Range Configuration (A,B,C)	C2	C2	C2	C2
ELA @50Pa - cm²	420		420	430
Average ELA @50Pa - cm²	420		425	
Difference (Pressurize-Depressurize) - cm²	420		-10	
Impact on Results - ELA cm²			-5	
negligible impact			bath duct	

Exterior Walls

ACH 50	cm2/m2	
11.12	12.85	Bldg. 2 - Polyethylene/ SBPO Housewrap
6.44	21.77	Bldg. 4 - Polyethylene/Building Paper
3.12	4.79	Bldg. 3 608 - Peel and Stick/Gypsum
1.36	2.52	Bldg.3 311 - Peel and Stick/Gypsum
2.24	4.14	Bldg. 3 611 - Peel and Stick/Gypsum
0.91	2.68	Bldg. A - Peel and Stick/Gypsum



Concrete Demising Walls

cm2/m2		
0.38	La Mirage 802-801	Concrete - Bldg. A - 802-801
0.17	La Mirage 802-803	Concrete - Bldg. A - 802-803

Wood Demising Walls

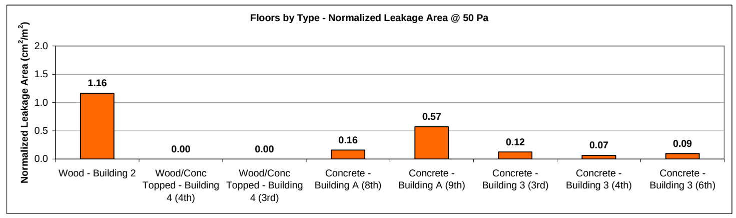
cm2/m2		
5.13	Building 2 - 401-Stairw	Wood Frame - Bldg. 2 - 401-Stair
0.47	Building 2 - 401-402	Wood Frame - Bldg. 2 - 401-402
0.42	Building 4 - 309-308	Wood Frame - Bldg. 4 - 309-308

Wood Hallway Walls

cm2/m2		
20.58	Building 4 - Hallway	Wood Frame - Bldg. 4 - 401
11.89	Building 2 - Hallway	Wood Frame - Bldg. 2 - 309

Wood Floors

cm2/m2		
1.16	Building 2 - 401 floor	Wood - Building 2

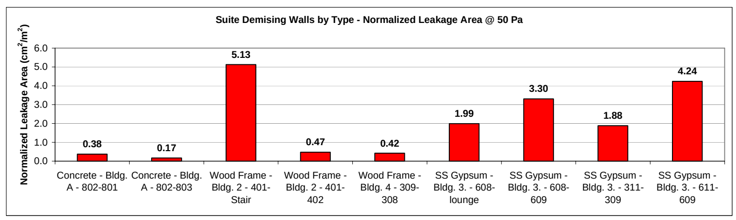


Wood-Concrete topped floors

cm2/m2		
0.00	Building 4 - 3nd	Wood/Conc Topped - Building 4 (4th)
0.00	Building 4 - 4th	Wood/Conc Topped - Building 4 (3rd)

Concrete Floors

cm2/m2		
0.16	Building A - 8th	Concrete - Building A (8th)
0.57	Building A - 9th	Concrete - Building A (9th)
0.12	Building 3 - 3rd	Concrete - Building 3 (3rd)
0.07	Building 3 - 4th	Concrete - Building 3 (4th)
0.09	Building 3 - 6th	Concrete - Building 3 (6th)

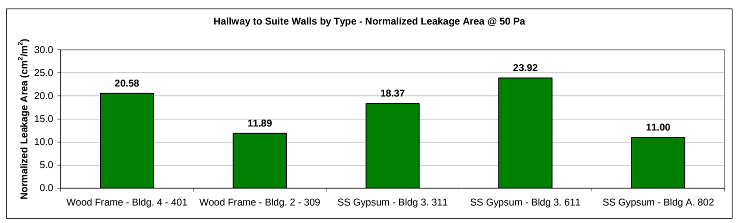


Gypsum-Steel Stud Demising Walls

cm2/m2		
1.99	Building 3 - 608-lounge	SS Gypsum - Bldg. 3. - 608-lounge
3.30	Building 3 - 608-609	SS Gypsum - Bldg. 3. - 608-609
1.88	Building 3 - 311-309	SS Gypsum - Bldg. 3. - 311-309
4.24	Building 3 - 611-609	SS Gypsum - Bldg. 3. - 611-609

Gypsum-Steel Stud Hallway Walls

cm2/m2		
18.37	Building 3 - 311-hall	SS Gypsum - Bldg 3. 311
23.92	Building 3 - 611-hall	SS Gypsum - Bldg 3. 611
11.00	Building A - 802-hall	SS Gypsum - Bldg A. 802



Appendix H: Solar Radiation Measurements and Calculations

APPENDIX H: SOLAR RADIATION MEASUREMENTS AND CALCULATIONS

INTRODUCTION

Solar radiation data was not collected as part of the monitoring study however is useful in the determination of wall performance. Solar radiation data is required for certain hygrothermal modeling applications; therefore it was of interest to find data from a local source close to the five buildings.

In the past, Environment Canada has collected solar radiation data as part of the climatic data it records at the Vancouver International Airport (YVR). However for recent years (including from 2000 onwards), hourly solar radiation data has not been collected at this location, therefore another local source was required.

Measured hourly solar radiation data for Vancouver was provided by Andrew Black at the University of British Columbia (UBC), Biometeorology and Soil Physics Group for the four year period from January 1, 2000 to December 31, 2004. The UBC Weather station records hourly solar radiation data (total radiation on horizontal in W/m^2) and is situated in the middle of a large field on campus. UBC is on average 10 km to the west of the five buildings (ranging from a minimum of 7 km to Building 2 and 16 km to Building 1).

The raw solar radiation data from UBC was provided at 15 minute intervals which were further averaged to hourly measurements. The hourly data was checked with corresponding temperature data against hourly YVR data and data from the five buildings and found to be time synched and in good agreement. The monthly solar radiation data was further checked against climate normals for total, diffuse, and direct radiation as described in this section and also found to be in good agreement.

Solar radiation data was measured using a pyranometer, which measures the total solar radiation on a horizontal surface in W/m^2. To apply this measurement onto the surface of the buildings, the components of direct and diffuse radiation must be determined from the singular reading using empirical methods. When direct and diffuse solar radiation components are determined, mathematical relationships for sun location and angle can be used to apply measurements to a vertical surface at any given orientation. This procedure is critical when generating annual weather files (KLI or TRY) using measured data for simulations in WUFI.

This appendix describes the methodology used to convert hourly measured solar radiation on a horizontal surface into diffuse and direct components and eventually onto a vertical surface at any given orientation. The methodology referenced published sources including ASHRAE Handbook of Fundamentals and Duffie and Beckman (1991). Methodology was developed in correlation with work by Straube and Schumacher at the University of Waterloo for work with ongoing research.

The calculations were developed in a spreadsheet to cover the complex hourly calculations. Portions of the spreadsheet are provided here in operational order, defining the variables as required to explain the procedure and allow others to reproduce the calculations. The spreadsheet cells are presented first followed by a discussion of the calculations for those cells.

1. Defining the Location

City	Vancouver, BC	
Latitude, L	49.2	North
Longitude, LON	123.18	West
Elevation, A	0.001	km (0.001km = 1m)
Local Standard Time Zone	-8	
Local Standard Meridian	120	
Wall Inclination, sigma	0	0 horiz, 90 vert
Wall Azimuth, psi	0	0 s, 90 w, -90e, 180n

- Latitude (**L**) and Longitude, (**LON**) are required in decimal form
- Elevation (**A**) above sea level of the site in kilometers (A= m/1000).
- Local Standard Time zone is the number of meridians found every 15° from 0° at Greenwich Meridian. For example Vancouver is -8, Toronto -5.
- Local Standard Meridian (**LSM**) is the meridian at the location -8*15°= 120° where west is positive. As a check, Vancouver is at 123°W, which is 3° west of 120°.
- Wall Inclination (**sigma**), 0 for horizontal, 90 for vertical, for which the measured solar radiation was *measured* on. Ie 0° for flat roof, or 90° if pyranometer was placed on a vertical wall. Adjustments to *determine* solar radiation on a wall surface are performed later.

- Wall Azimuth (**psi**), is used if the pyranometer was on a wall at a certain orientation. Where 0° is south 180° is north. On the horizontal, orientation does not matter, however 0° is used here for simplicity.
- Calculations are performed using **radians** unless noted to use decimal degrees. Formulae presented may convert from degree input into radians
- West is assumed as positive, East as negative for directions.
- PI (3.14159…) is defined as PI() in excel notation in the equations.

2. Setting the Time

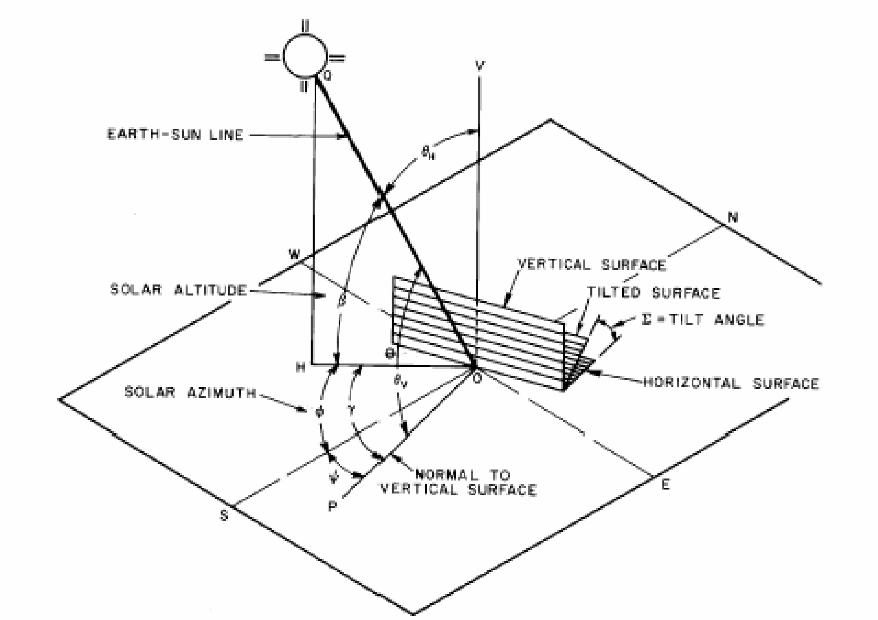
Hour	Date	Time	Day Number	equation of time	Local Standard Time	Apparent Standard Time
			eta	ET	LST	AST
1	01 Jan 2001 00:00	0.00	1.00	-4.57	0.00	0.14
2	01 Jan 2001 01:00	1.00	1.04	-4.59	1.00	1.14
3	01 Jan 2001 02:00	2.00	1.08	-4.61	2.00	2.14
4	01 Jan 2001 03:00	3.00	1.12	-4.62	3.00	3.13
5	01 Jan 2001 04:00	4.00	1.17	-4.64	4.00	4.13
6	01 Jan 2001 05:00	5.00	1.21	-4.66	5.00	5.13
7	01 Jan 2001 06:00	6.00	1.25	-4.68	6.00	6.13
8	01 Jan 2001 07:00	7.00	1.29	-4.69	7.00	7.13
9	01 Jan 2001 08:00	8.00	1.33	-4.71	8.00	8.13
10	01 Jan 2001 09:00	9.00	1.37	-4.73	9.00	9.13
11	01 Jan 2001 10:00	10.00	1.42	-4.75	10.00	10.13
12	01 Jan 2001 11:00	11.00	1.46	-4.76	11.00	11.13

- *Hour* is the hour of the year from 1-8760. (used as cell marker, not in calculations)
- *Date* is in YY/MM/DD hh:mm (used as cell marker, not in calculations)
- **Time** is the hour of the day from 0:00 (midnight) to 23:00 (11pm). This is required, and can be put on the half hour or every 15 minutes if such resolution was required.
- Day Number (**ETA**) is the decimal number that represents a day plus the hour portion (1/24 fractions). Each whole day is 1.0, starting at 1.0 on January 1st. Therefore January 2nd at 12 noon would be 2.5. Using decimals improves accuracy of calculation; otherwise whole numbers for the day could be used. Continues from 1.0 to 366.0
- Equation of Time (**ET**) (Reference: Whitman, Villanova University, PA)
    - **ET**= 229.18 * (-0.0334 * SIN(2 * PI() / 365.24 * **ETA**) + 0.04184 * SIN(4 * PI() / 365.24 * **ETA** + 3.5884))
    - Other ET formulas were tested, ie ASHRAE 2005, Duffie and Beckman and provide similar results, +- a few decimal points. End accuracy has negligible impact on solar radiation results.

- Local Standard Time (**LST**) – uses the input time (above). Also can refer to Local Solar Time, however for hourly calculations is the same here.
- Apparent Standard Time (**AST**) (Reference: ASHRAE 2005)
    - **AST** = **LST** +(**ET** / 60) - ((**LSM**- **LON**) / 15)

3. Positioning the Sun

The suns angle in relation to the wall is well established and can be easily calculated using methods outlined in the ASHRAE Handbook of Fundamentals.



Source: ASHRAE 2005

Hour	Date	Hour Angle		Declination	
		H -rads	degrees	delta -rads	degrees
1	01 Jan 2001 00:00	-3.11	-177.96	-0.40	-23.01
2	01 Jan 2001 01:00	-2.84	-162.97	-0.40	-23.01
3	01 Jan 2001 02:00	-2.58	-147.97	-0.40	-23.01
4	01 Jan 2001 03:00	-2.32	-132.98	-0.40	-23.00
5	01 Jan 2001 04:00	-2.06	-117.98	-0.40	-23.00
6	01 Jan 2001 05:00	-1.80	-102.98	-0.40	-23.00
7	01 Jan 2001 06:00	-1.54	-87.99	-0.40	-22.99
8	01 Jan 2001 07:00	-1.27	-72.99	-0.40	-22.99
9	01 Jan 2001 08:00	-1.01	-58.00	-0.40	-22.99
10	01 Jan 2001 09:00	-0.75	-43.00	-0.40	-22.98
11	01 Jan 2001 10:00	-0.49	-28.01	-0.40	-22.98
12	01 Jan 2001 11:00	-0.23	-13.01	-0.40	-22.98

- Hour Angle (**H**) (Reference: ASHRAE 2005)
  - **H**=15*(**AST**-12)*(PI()/180)
- Declination (**delta**) (Reference: ASHRAE 2005)
  - **delta**= (23.45 * SIN(2 * **PI**() * (284 + **ETA**) / 365)) * PI() / 180

Hour	Date	Solar Altitude		Solar Azimuth	
		beta - rads	degrees	phi - rads	degrees
1	01 Jan 2001 00:00	-1.11	-63.76	-3.07	-175.75
2	01 Jan 2001 01:00	-1.06	-60.57	-2.56	-146.72
3	01 Jan 2001 02:00	-0.94	-53.68	-2.17	-124.49
4	01 Jan 2001 03:00	-0.78	-44.90	-1.89	-108.07
5	01 Jan 2001 04:00	-0.62	-35.31	-1.66	-95.04
6	01 Jan 2001 05:00	-0.45	-25.52	-1.46	-83.72
7	01 Jan 2001 06:00	-0.28	-15.94	-1.28	-73.09
8	01 Jan 2001 07:00	-0.12	-6.88	-1.09	-62.46
9	01 Jan 2001 08:00	0.02	1.33	-0.90	-51.34
10	01 Jan 2001 09:00	0.14	8.30	-0.69	-39.39
11	01 Jan 2001 10:00	0.24	13.63	-0.46	-26.41
12	01 Jan 2001 11:00	0.29	16.90	-0.22	-12.51

- Solar Altitude (**beta**) (Reference: ASHRAE 2005), angle from the horizontal to the sun.
  - **beta**= ASIN(COS(**L**) * COS(**delta**) * COS(**H**) + SIN(**L**) * SIN(**delta**))
- Solar Azimuth (**phi**) (Reference: ASHRAE 2005)
  - **phi**= ACOS((SIN(**beta**) * SIN(**L**) - SIN(**delta**)) / (COS(**beta**) * COS(**L**))) * IF(**H**<0,-1,IF(**H**=0,0,1))
  - IF statement is added to keep sign direction correct.
  - Typically negative values before solar noon (0°), and positive after until solar midnight (180°).

Hour	Date	Wall Solar Azimuth gamma, rads	degrees	Angle of Incidence theta, rads	degrees	Number Daylight Hours hrs
1	01 Jan 2001 00:00	-3.07	-175.75	2.68	153.76	8.07
2	01 Jan 2001 01:00	-2.56	-146.72	2.63	150.57	8.07
3	01 Jan 2001 02:00	-2.17	-124.49	2.51	143.68	8.07
4	01 Jan 2001 03:00	-1.89	-108.07	2.35	134.90	8.07
5	01 Jan 2001 04:00	-1.66	-95.04	2.19	125.31	8.07
6	01 Jan 2001 05:00	-1.46	-83.72	2.02	115.52	8.07
7	01 Jan 2001 06:00	-1.28	-73.09	1.85	105.94	8.07
8	01 Jan 2001 07:00	-1.09	-62.46	1.69	96.88	8.07
9	01 Jan 2001 08:00	-0.90	-51.34	1.55	88.67	8.08
10	01 Jan 2001 09:00	-0.69	-39.39	1.43	81.70	8.08
11	01 Jan 2001 10:00	-0.46	-26.41	1.33	76.37	8.08
12	01 Jan 2001 11:00	-0.22	-12.51	1.28	73.10	8.08

- Wall Solar Azimuth (**gamma**), a correction if pyranometer was placed and measured on a vertical wall surface instead of horizontal. No correction here from Solar Azimuth in last step.
  - **gamma** = **phi** - **psi**
- Angle of Incidence (**theta**) (Reference: ASHRAE 2005)
  - **theta** = ACOS(COS(**beta**) * COS(**gamma**) * SIN(**sigma**) + SIN(**beta**) * COS(**sigma**))
  - If no correction **gamma=phi**
- Number of daylight hours – can be used to check calculations.
  - Hrs daylight = (2/15)*ACOS(-TAN(**L**)*TAN(**delta**))*180/PI()

Hour	Date	Sun Zenith Angle thetaH-rads	degrees
1	01 Jan 2001 00:00	2.68	153.76
2	01 Jan 2001 01:00	2.63	150.57
3	01 Jan 2001 02:00	2.51	143.68
4	01 Jan 2001 03:00	2.35	134.90
5	01 Jan 2001 04:00	2.19	125.31
6	01 Jan 2001 05:00	2.02	115.52
7	01 Jan 2001 06:00	1.85	105.94
8	01 Jan 2001 07:00	1.69	96.88
9	01 Jan 2001 08:00	1.55	88.67
10	01 Jan 2001 09:00	1.43	81.70
11	01 Jan 2001 10:00	1.33	76.37
12	01 Jan 2001 11:00	1.28	73.10

- Sun Zenith Angle (**thetaH**) – is the angle from the vertical to the sun.
    - o **thetaH** = PI()/2 - **beta**

3. Estimating Clear Sky Radiation Values to Determine Diffuse and Direct Components of Radiation

Cloud cover causes scatter and the ratio of diffuse and beam radiation to change. However the ratios in absence of clouds must first be determined using empirical methods. Maximum clear sky beam radiation is determined which the measured values can be applied to.

Hottels Clear Sky Radiation Model is used to determine the clear sky beam radiation values. Methodology is followed from Duffie and Beckman (1991) as presented in this section. Hottel's model to estimate clear sky radiation uses 6 constants based on climate type and elevation (**A**) above sea level which account for measurements based on air density and relative clearness:

Constants:

Climate type	**r0**	**r1**	**rk**
Tropical	0.95	0.98	1.02
Mid-latitude summer	0.97	0.99	1.02
Sub-arctic summer	0.99	0.99	1.01
Mid-latitude winter	1.03	1.01	1.00

a0 = r0 * (0.4237 - 0.00821 * (6 - **A**) ^ 2)
a1 = r1 * (0.5055 + 0.00595 * (6.5 - **A**) ^ 2)
k = rk * (0.2711 + 0.01858 * (2.5 - **A**) ^ 2)

Mid-latitude summer values were chosen for Vancouver, BC (winter values not used as found to have negligible impact on results): r0 = 0.97, r1 = 0.99, rk = 1.02 and a0, a1 and k were calculated.

coefficients for hottel	
ro	0.97
r1	0.99
rk	1.02
ao	0.12
a1	0.75
k	0.39

Solar constant	
Gsc	1353

Once the coefficients are calculated the remainder of the calculation continues.

Hour	Date	hottel clear sky radiation	atm trans for beam radiation	Outer atm normal radiation	clear sky horizontal beam radiation
		if <pi/2	Taub	Ion	Icb
1	01 Jan 2001 00:00	0	0.000	1397.6	0.00
2	01 Jan 2001 01:00	0	0.000	1397.6	0.00
3	01 Jan 2001 02:00	0	0.000	1397.6	0.00
4	01 Jan 2001 03:00	0	0.000	1397.6	0.00
5	01 Jan 2001 04:00	0	0.000	1397.6	0.00
6	01 Jan 2001 05:00	0	0.000	1397.6	0.00
7	01 Jan 2001 06:00	0	0.000	1397.6	0.00
8	01 Jan 2001 07:00	0	0.000	1397.6	0.00
9	01 Jan 2001 08:00	1	0.124	1397.6	4.03
10	01 Jan 2001 09:00	1	0.173	1397.6	34.91
11	01 Jan 2001 10:00	1	0.265	1397.6	87.12
12	01 Jan 2001 11:00	1	0.317	1397.6	128.77

- The first step is a check to ensure the sun is above the horizon with a 0 or 1 multiplier to eliminate erroneous data, 1 being the sun is up.
    - =IF(ABS(**theta**)<=PI()/2,1,0)
- Atmospheric Transmittance for Beam Radiation (**Taub**) (τ_b)
    - **TauB** = a0 + a1 * e ^ (-k / COS(**thetaH**))
- Solar Constant (**Gsc**) (W/m²)
    - Gsc = 1353 W/m²
- Outer Atmosphere Normal Radiation (**Ion**)
    - **Ion** = **GSC** * (1 + 0.033 * COS(2 * PI() * **ETA** / 365))
- Clear Sky Horizontal Beam Radiation (**Icb**)
    - **Icb** = **Ion** * **TauB** * COS(**thetaH**) : calculate only if sun is up

Hour	Date	tran coeff for beam and diffuse	clear sky horizontal diffuse radiation	Total horizontal clear sky radiation
		Taud	Icd	Ic
1	01 Jan 2001 00:00	0.00	0.00	0.00
2	01 Jan 2001 01:00	0.00	0.00	0.00
3	01 Jan 2001 02:00	0.00	0.00	0.00
4	01 Jan 2001 03:00	0.00	0.00	0.00
5	01 Jan 2001 04:00	0.00	0.00	0.00
6	01 Jan 2001 05:00	0.00	0.00	0.00
7	01 Jan 2001 06:00	0.00	0.00	0.00
8	01 Jan 2001 07:00	0.00	0.00	0.00
9	01 Jan 2001 08:00	0.23	7.60	11.63
10	01 Jan 2001 09:00	0.22	44.42	79.33
11	01 Jan 2001 10:00	0.19	63.63	150.76
12	01 Jan 2001 11:00	0.18	72.25	201.01

To determine the relationship between the transmission coefficients for beam (direct) and diffuse radiation (**TauD**) (τ_d), Liu and Jordan's empirical relationship for clear days is used (Duffie and Beckman 1991).

- Coefficient for beam and diffuse radiation (**TauD**)
  - **TauD** = 0.271 - 0.2939 * **TauB**

Using these coefficients for the portion of diffuse radiation, the total beam (direct) and diffuse components can be determined.

- Total Clear Sky Horizontal DIFFUSE Radiation (**Icd**)
  - **Icd** = **Ion** * **TauD** * COS(**thetaH**)
- Therefore the Total Horizontal clear sky radiation (**Ic**)
  - **Ic** = **Icb** + **Icd**

4. Inputting the Measured Data

At this step the hourly measured data is input into the calculation. Measured data consists of total solar radiation on a horizontal surface in W/m^2 (or vertical if corrections made as described).

Hour	Date	Measured Radiation I	I/Ic ratio	Id/I - stauter klein	Id/I corrected for low sun angles
1	01 Jan 2001 00:00	0	0.00	1.00	1.00
2	01 Jan 2001 01:00	0	0.00	1.00	1.00
3	01 Jan 2001 02:00	0	0.00	1.00	1.00
4	01 Jan 2001 03:00	0	0.00	1.00	1.00
5	01 Jan 2001 04:00	0	0.00	1.00	1.00
6	01 Jan 2001 05:00	0	0.00	1.00	1.00
7	01 Jan 2001 06:00	0	0.00	1.00	1.00
8	01 Jan 2001 07:00	1	0.00	1.00	1.00
9	01 Jan 2001 08:00	15	1.29	0.20	0.98
10	01 Jan 2001 09:00	82	1.03	0.31	0.42
11	01 Jan 2001 10:00	160	1.06	0.26	0.26
12	01 Jan 2001 11:00	241	1.20	0.20	0.20
13	01 Jan 2001 12:00	261	1.21	0.20	0.20
14	01 Jan 2001 13:00	193	1.01	0.34	0.34
15	01 Jan 2001 14:00	99	0.74	0.70	0.70
16	01 Jan 2001 15:00	60	0.99	0.37	0.62
17	01 Jan 2001 16:00	13	0.00	1.00	1.00
18	01 Jan 2001 17:00	1	0.00	1.00	1.00
19	01 Jan 2001 18:00	0	0.00	1.00	1.00
20	01 Jan 2001 19:00	0	0.00	1.00	1.00
21	01 Jan 2001 20:00	0	0.00	1.00	1.00
22	01 Jan 2001 21:00	0	0.00	1.00	1.00
23	01 Jan 2001 22:00	0	0.00	1.00	1.00
24	01 Jan 2001 23:00	0	0.00	1.00	1.00

Stauter and Klein's correlation is used to determine components of diffuse and direct solar radiation from the total horizontal (Duffie and Beckman 1991). The correlation was developed from average readings of several North American cities.

- Measured solar radiation on a horizontal surface (**I**) is input
- Ratio of **I/Ic** is determined (**IICratio**) – Ratio of measured radiation to estimated clear sky radiation
- **Id/I** ratio of diffuse to measured radiation (**IIDratio**)– ratio of actual horizontal diffuse radiation to measured total radiation.
    - o =IF(AE13<=0.48,(1-0.1***IICratio**),IF(**IICratio** >=1.1,0.2,((1.11+(0.0396***IICratio**)-(0.789*(**IICratio**)^2)))))
- **Id/I** ratio is corrected for low sun angles to eliminate erroneous readings. For angles below 10° then is equal to cos(7.84*beta) – (**IIDCorr**)
    - o =IF(OR(**beta**(deg)>10,**beta**(deg)<0),**IIDratio**,COS(7.84***beta**))

5. Results for Diffuse and Direct Components of Solar Radiation

The diffuse and direct (beam) components of the horizontal are determined using the empirical ratio relationships which were developed.

Hour	Date	Predicted Id - diffuse W/m2	Predicted Ib - direct W/m2	Global Horizontal
1	01 Jan 2001 00:00	0.00	0.00	0
2	01 Jan 2001 01:00	0.00	0.00	0
3	01 Jan 2001 02:00	0.00	0.00	0
4	01 Jan 2001 03:00	0.00	0.00	0
5	01 Jan 2001 04:00	0.00	0.00	0
6	01 Jan 2001 05:00	0.00	0.00	0
7	01 Jan 2001 06:00	0.00	0.00	0
8	01 Jan 2001 07:00	1.00	0.00	1
9	01 Jan 2001 08:00	14.75	0.25	15
10	01 Jan 2001 09:00	34.55	47.45	82
11	01 Jan 2001 10:00	42.13	117.87	160
12	01 Jan 2001 11:00	48.20	192.80	241

- Calculated Diffuse component (**Id**)
  - **Id** = **IIDCorr * I**
- Calculated Direct (beam) component (**Ib**)
  - **Ib** = **I - Id**

6. Conversion to Vertical Orientation

This section describes the methodology to convert the horizontal radiation to a vertical surface at any orientation. Degrees instead of radians are typically used here for ease of user input, however are converted in the calculations. The methodology here was developed with reference to the WUFI 4.0 users manual (WUFI 2006).

The following is a summary of the data measured and calculated is shown.

Hour	Global Horizontal	Diffuse Horizontal	Direct Horizontal	Actual Direct Normal Radiation - altitude dependent
1	0	0	0	0.0
2	0	0	0	0.0
3	0	0	0	0.0
4	0	0	0	0.0
5	0	0	0	0.0
6	0	0	0	0.0
7	0	0	0	0.0
8	1	1	0	0.0
9	15	15	0	10.7
10	82	35	47	328.7
11	160	42	118	500.3
12	241	48	193	663.3

- Where Global horizontal (**I**) was measured and diffuse (**Id**) and direct (**Ib**) were calculated previously.
- Direct normal radiation (**Idn**) is determined from:
    - **Idn**=(**Ib**)/SIN(**beta**)

Change Wall Tilt and Rotation Here				
Wall Tilt		*90*	*0 horiz, 90 vert*	
Wall Rotation		*0*	*0 s, 90 w, -90e, 180n*	
Ground Reflectivity		*0.25*	*0.1 to 0.3*	

- Wall **tilt** is input, 90° tilt for vertical wall, and 0° for south facing.
- Wall **rotation** is also entered, 0° for south as previous convention.
- Ground reflectivity (**Gref**) depends on surface material short-wave albedo. Typical values are provided in the following table (ASHRAE 2005).

Foreground Surface	Incident Angle 20°	30°	40°	50°	60°	70°
New concrete	0.31	0.31	0.32	0.32	0.33	0.34
Old concrete	0.22	0.22	0.22	0.23	0.23	0.25
Bright green grass	0.21	0.22	0.23	0.25	0.28	0.31
Crushed rock	0.20	0.20	0.20	0.20	0.20	0.20
Bitumen and gravel roof	0.14	014	0.14	0.14	0.14	0.14
Bituminous parking lot	0.09	0.09	0.10	0.10	0.11	0.12

Adapted from Threlkeld (1962)

Corrections are made for wall direction and tilt here.

Hour	Solar Altitude	Wall Solar Azimuth	Wall Angle of Incidence
1	-63.76	-175.75	153.76
2	-60.57	-146.72	150.57
3	-53.68	-124.49	143.68
4	-44.90	-108.07	134.90
5	-35.31	-95.04	125.31
6	-25.52	-83.72	115.52
7	-15.94	-73.09	105.94
8	-6.88	-62.46	96.88
9	1.33	-51.34	88.67
10	8.30	-39.39	81.70
11	13.63	-26.41	76.37
12	16.90	-12.51	73.10

- Solar Altitude (**beta**) as previously calculated
- Wall solar azimuth (**alpha**) (degrees)
  - **Wall azimuth** = **phi** (degrees) – **wall rotation**
- Wall angle of incidence (**chi**) (degrees)
  - = (ACOS(COS(**beta**) * COS(**alpha***PI()/180) * SIN(**tilt***PI()/180) + SIN(**beta**) * COS(**tilt***PI()/180)))*180/PI()

Hour	Direct Radiation Incident to surface W/m²	Diffuse Radiation on Surface W/m²	Reflected Radiation on Surface W/m²	Total Radiation on Surface W/m²
1	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0
8	0.0	0.5	0.1	0.6
9	6.7	7.4	1.9	15.9
10	251.4	17.3	10.3	278.9
11	435.5	21.1	20.0	476.5
12	619.6	24.1	30.1	673.8

- Direct Radiation incident to surface (W/m^2) (**Ibv**)
  - **Ibv**=IF((**Idn***COS(**chi***PI()/180))>0,(**Idn***COS(**chi***PI()/180)),0)
  - IF statement used to eliminate erroneous readings with negative/zero values
- Diffuse Radiation on Surface (**Idv**)
  - **Idv**=**Id** * COS((**tilt**/2)*PI()/180)^2
- Reflected Radiation on Surface (**Irv**)
  - **Irv**=**Gref** * **I** * (SIN((**tilt**/2)*PI()/180))^2
- Total Radiation on Vertical Surface **(Iv)**
  - **Iv = Ibv + Idv + Irv**

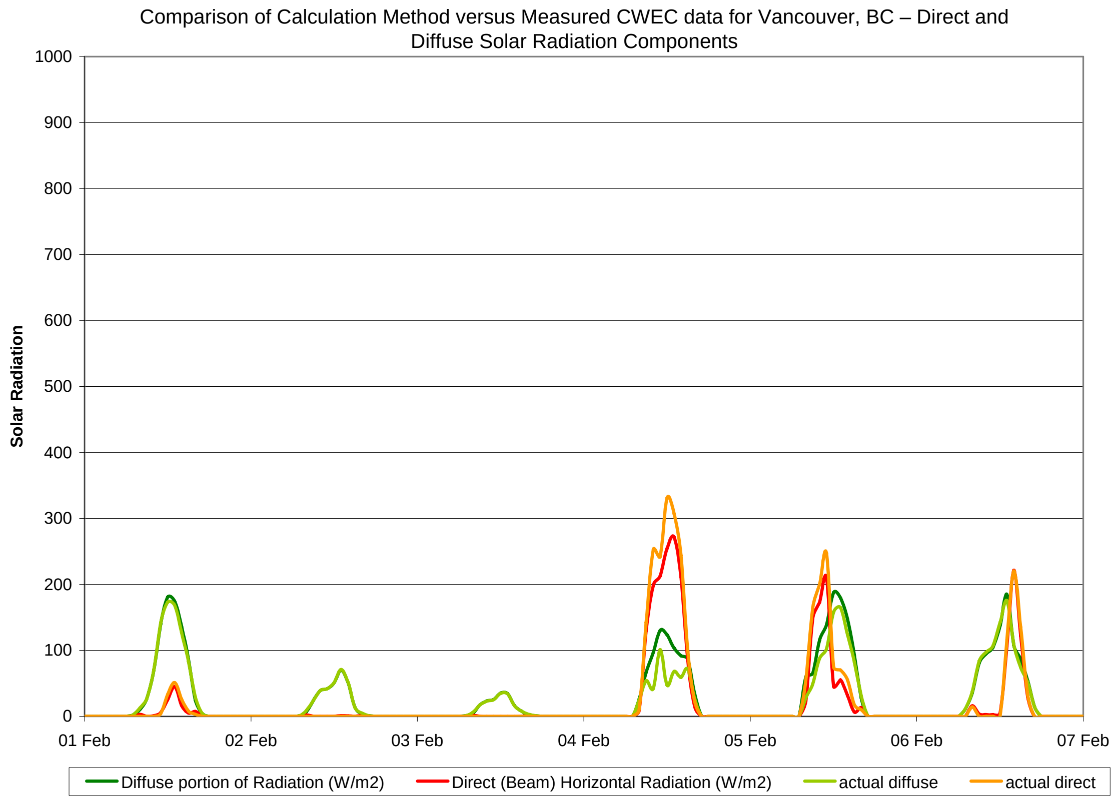
7. Accuracy of Calculated Results

The calculations are setup in a spreadsheet, and calculated for the entire year. Annual and monthly averages have been produced for comparison to previous published data and presentation.

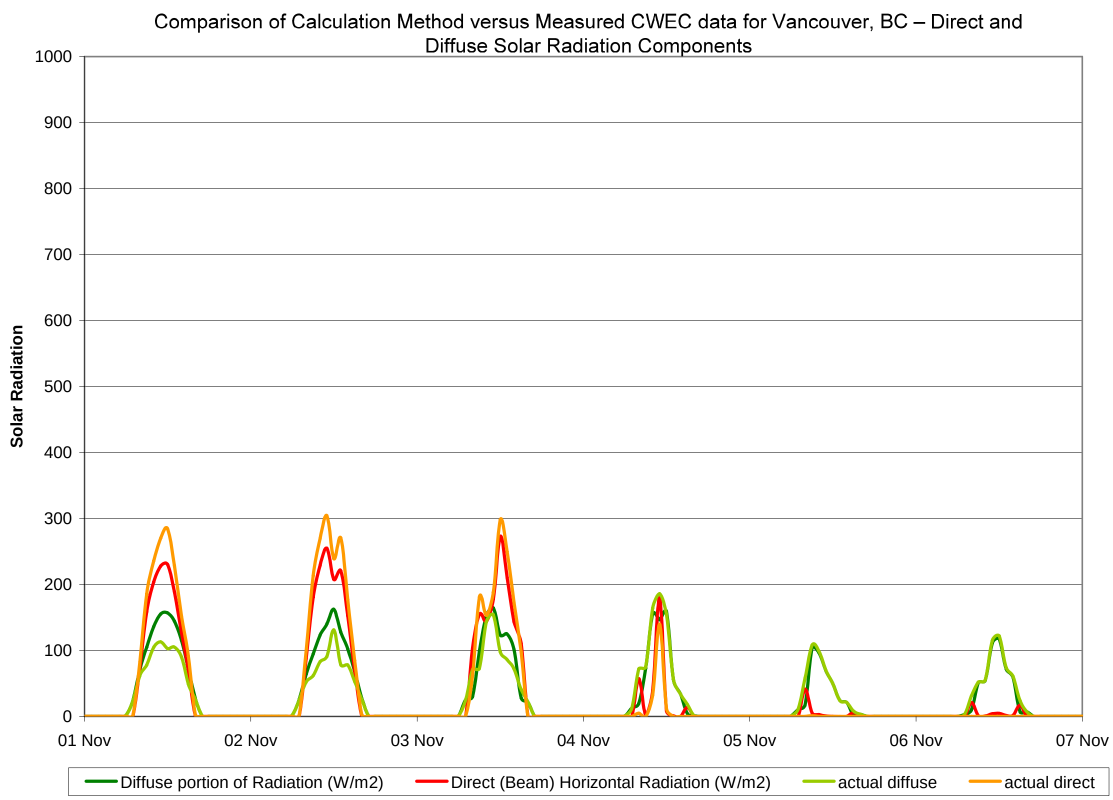
The calculation methodology was validated with measured CWEC data for Vancouver and CWEC/IWEC data for several other North American and worldwide climates. CWEC/IWEC data provides hourly direct, diffuse and total solar radiation values for most cities which allows predicted versus measured diffuse and direct components of horizontal radiation to be analyzed. The methodology presented was found to be in good agreement with the CWEC and IWEC measured data. While the precise direct and diffuse components of radiation may not be able to be calculated for every given hour, daily trends were captured and monthly averages equal and for purposes of hygrothermal modeling provides sufficient accuracy. Other calibration models are available (such as Reindl et al. 1990 or Perez et al. 1990), and will calculate slightly different diffuse/direct ratios with varying accuracy. However the accuracy may not always be required nor provide any improved end results on the hygrothermal simulations.

Using the Vancouver CWEC data as a benchmark, the calculation method provided (using Hottels clear sky and Stauter and Klein's direct/diffuse coefficients) was able to determine diffuse and direct radiation components with satisfactory accuracy. The average error in prediction was ±18.8 W/m^2 with a standard deviation of 21.1 W/m^2. Average values were measured to be 118.7 W/m^2 of diffuse and 161.5 W/m^2 for direct solar radiation (only hours of radiation). Therefore the accuracy of the results can be estimated at ±10-20% for calculating the correct diffuse/direct components (or as CWEC presents as correct values).

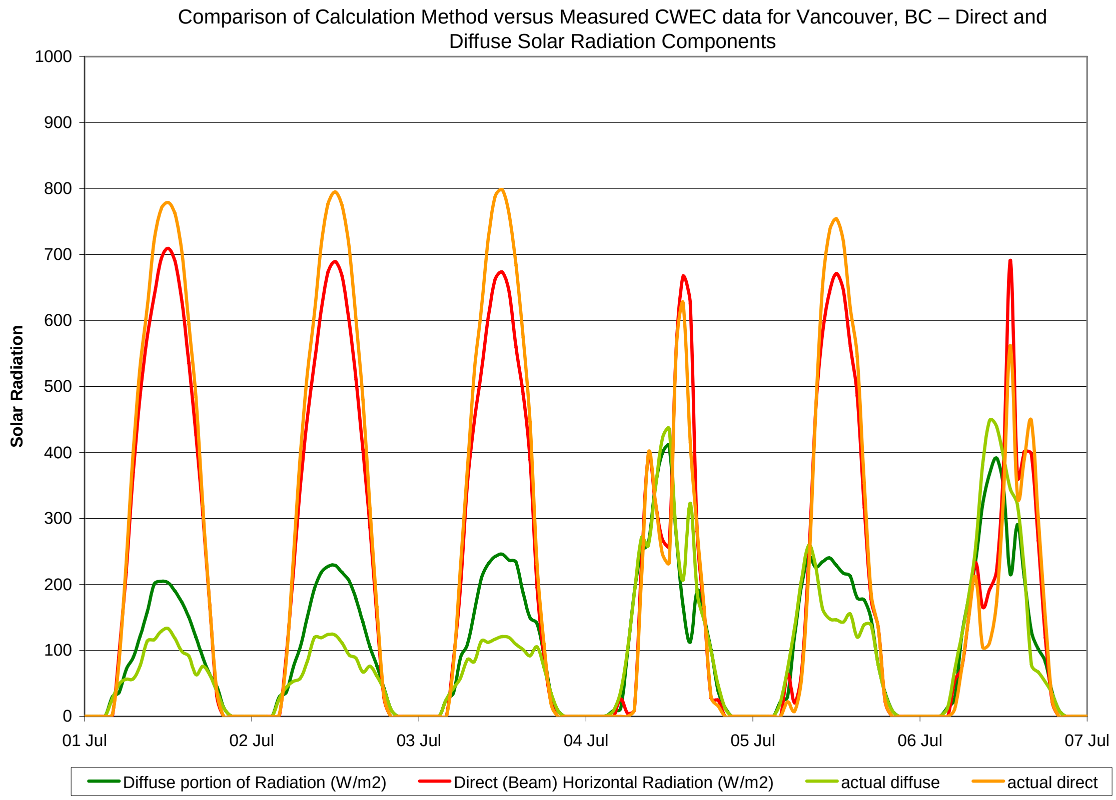
Plots of 3 weeks in February, July, and November are shown comparing calculated to measured data for Vancouver CWEC data. On several instances the model was able to capture the exact trends (days with complete cloud or no cloud). Partially cloudy days appear to result in errors which the model does not completely capture, resulting in different peaks. It appears that the model for this case under predicts the beam and over predicts the diffuse by a small margin.



Comparison of Calculation Method versus Measured CWEC data for Vancouver, BC – Direct and Diffuse Solar Radiation Components
Solar Radiation
1000
900
800
700
600
500
400
300
200
100
0
01 Feb
02 Feb
03 Feb
04 Feb
05 Feb
06 Feb
07 Feb
Diffuse portion of Radiation (W/m2)
Direct (Beam) Horizontal Radiation (W/m2)
actual diffuse
actual direct



Comparison of Calculation Method versus Measured CWEC data for Vancouver, BC – Direct and Diffuse Solar Radiation Components
Solar Radiation
1000
900
800
700
600
500
400
300
200
100
0
01 Nov
02 Nov
03 Nov
04 Nov
05 Nov
06 Nov
07 Nov
Diffuse portion of Radiation (W/m2)
Direct (Beam) Horizontal Radiation (W/m2)
actual diffuse
actual direct



As shown the calculated and measured results generally are in good agreement using the empirical models.

To attempt to improve the hourly accuracy, a new model was developed which incorporated an approximate cloud cover index to attempt to determine more accurate I/Ic and Id/I ratios (similar to what was performed to develop empirical values by Hottel or Stauter and Klein). However it was found that this method was less accurate as that previously developed as it required hourly cloud cover data which was not consistently nor accurately recorded in Vancouver.

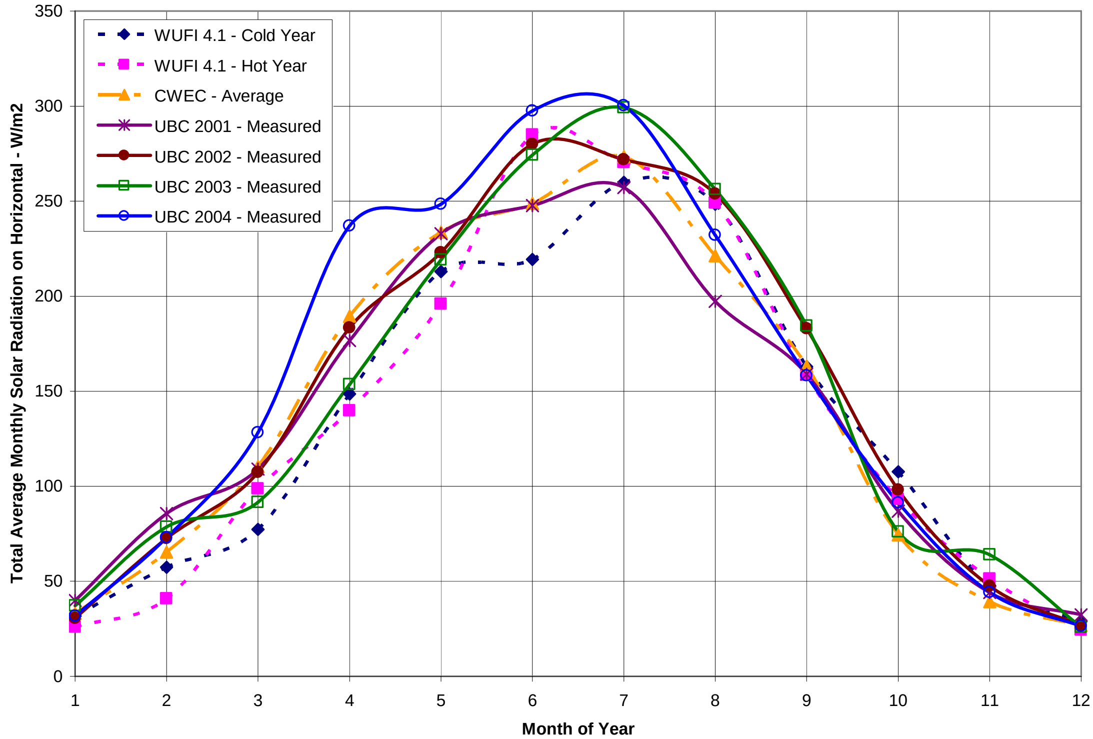
The method outlined in this Appendix allows for general use when converting solar radiation for use with modeling programs. The user only requires measured solar radiation on the horizontal and the building location and the calculations can determine the rest.

7. Summary of Data

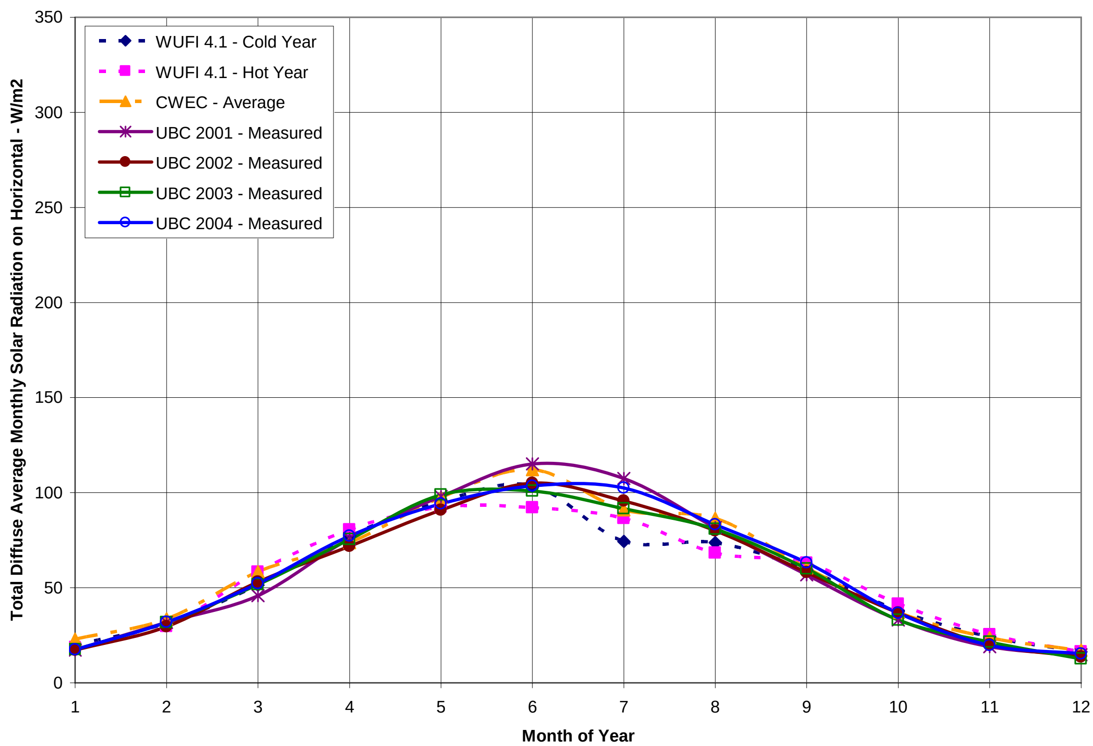
Monthly averages have been calculated and presented in the body of the thesis and as shown in the following table for Vancouver CWEC data. The monthly direct to diffuse ratio changes throughout the year as sunny months would see a higher proportion of direct radiation, where as cloudy winter months see more diffuse radiation. Averages are for all hours (8760 per year)

Monthly Averages W/m^2	Direct Solar	Diffuse Solar	Reflected Solar	Total Solar	Ratio dir/diff
January	14.2	18.9	0.0	33.1	0.75
February	36.0	29.4	0.0	65.4	1.23
March	56.5	54.0	0.0	110.4	1.05
April	118.2	71.3	0.0	189.6	1.66
May	140.1	93.7	0.0	233.8	1.50
June	138.9	109.9	0.0	248.8	1.26
July	179.8	93.7	0.0	273.5	1.92
August	139.5	81.5	0.0	220.9	1.71
September	106.7	56.8	0.0	163.5	1.88
October	43.4	31.0	0.0	74.4	1.40
November	20.6	18.6	0.0	39.3	1.10
December	13.3	13.5	0.0	26.8	0.98
Annual	84.2	56.2	0.0	140.4	1.50

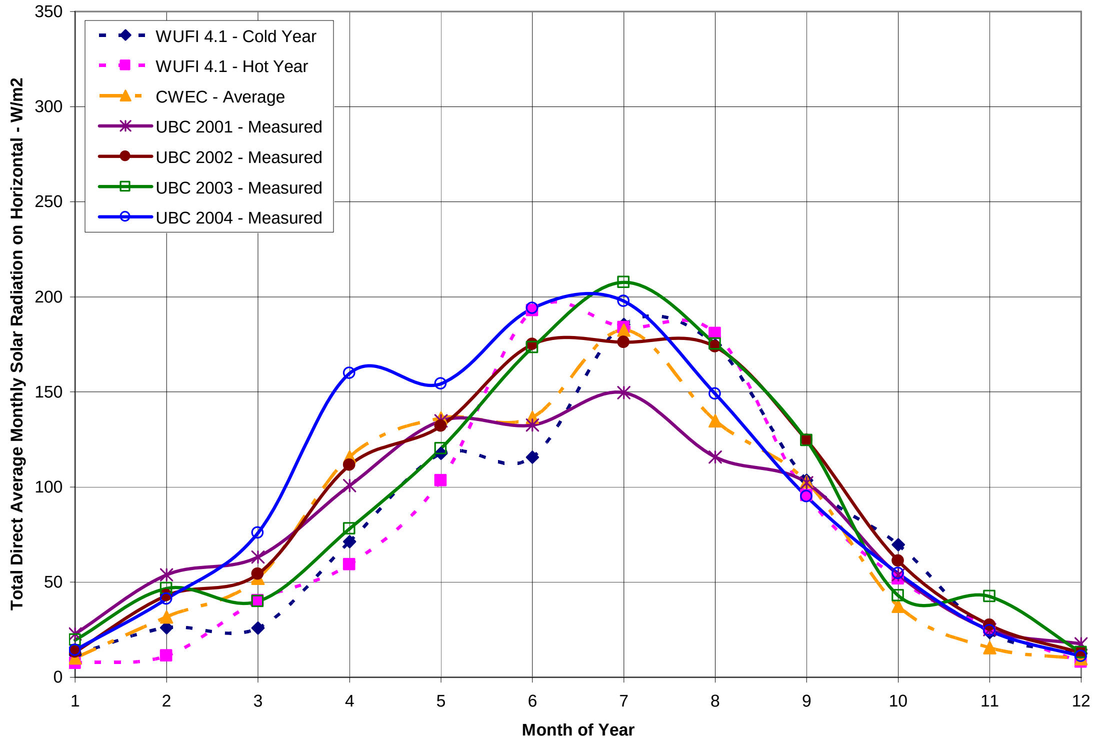
The calculation procedure was applied to the measured UBC solar radiation data (years 2001, 2002, 2003 and 2004) and is compared to CWEC and WUFI hot/cold year data for validation. All of the data sources were found in good agreement for monthly averages providing further confidence of the calculation procedure. The data is compared in the following plots.



Total Radiation



Diffuse Radiation



Direct Radiation

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Perez, R., Ineichen, P., Seals, R., Michalsky, J., Stewart, R. 1990. "Modeling Daylight Availability and Irradiance Components from Direct and Global Irradiance". *Solar Energy Jounal*. Vol 44, No. 5, pp 271-289. Permagon Press. 1990.

Reindl, D. Beckman, J., Duffie, W. 1990. "Diffuse Fraction Correlations". *Solar Energy Journal*. Vol 45, No 1, pp1-7. Permagon Press. 1990.

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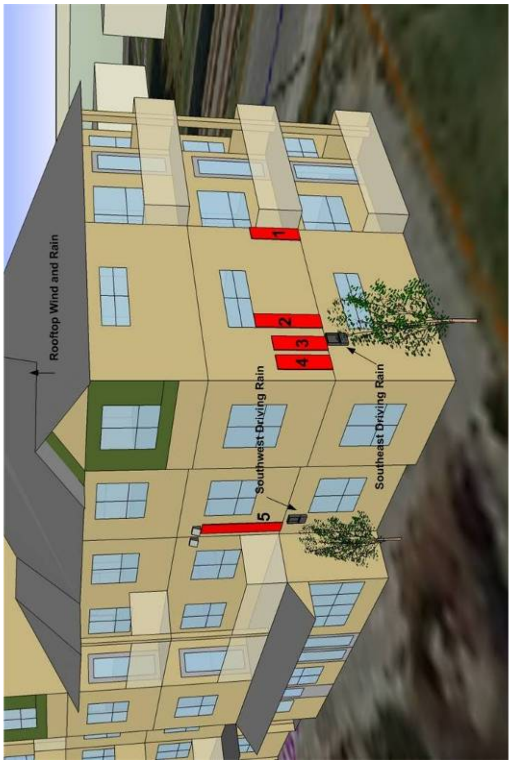
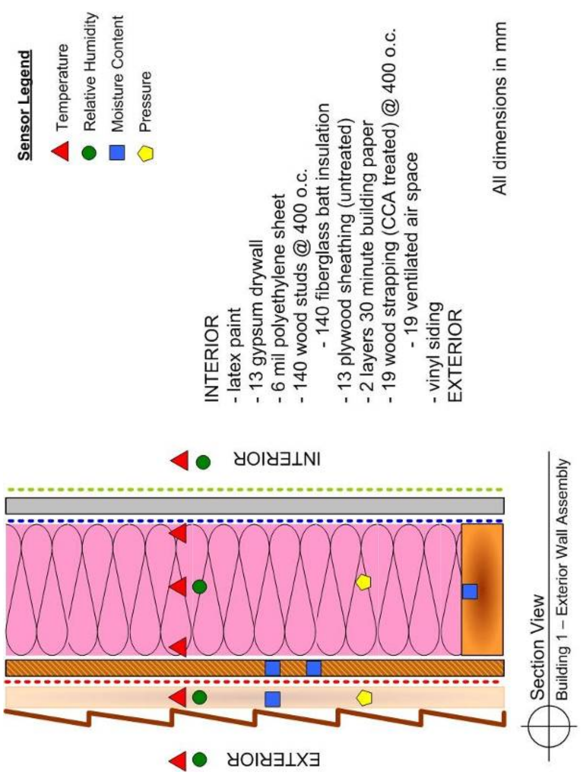
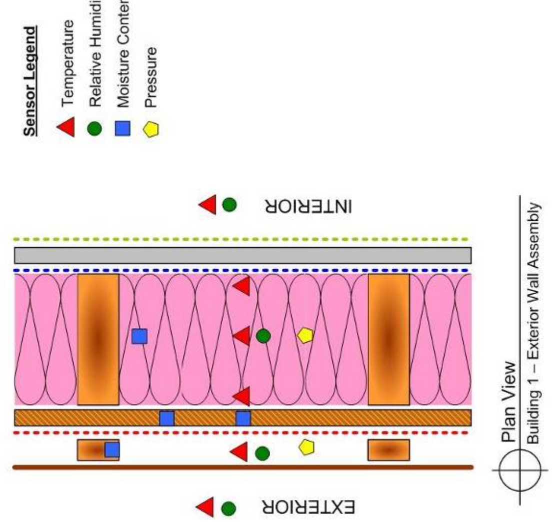
Appendix I: Quick Reference

BUILDING 1


Rooftop Wind and Rain
Southwest Driving Rain
Southeast Driving Rain
1
2
3
4
5


Sensor Legend
Temperature
Relative Humidity
Moisture Content
Pressure
INTERIOR
- latex paint
- 13 gypsum drywall
- 6 mil polyethylene sheet
- 140 wood studs @ 400 o.c.
- 140 fiberglass batt insulation
- 13 plywood sheathing (untreated)
- 2 layers 30 minute building paper
- 19 wood strapping (CCA treated) @ 400 o.c.
- 19 ventilated air space
- vinyl siding
EXTERIOR
All dimensions in mm
INTERIOR
EXTERIOR
Section View
Building 1 – Exterior Wall Assembly


Sensor Legend
Temperature
Relative Humidity
Moisture Content
Pressure
INTERIOR
EXTERIOR
Plan View
Building 1 – Exterior Wall Assembly

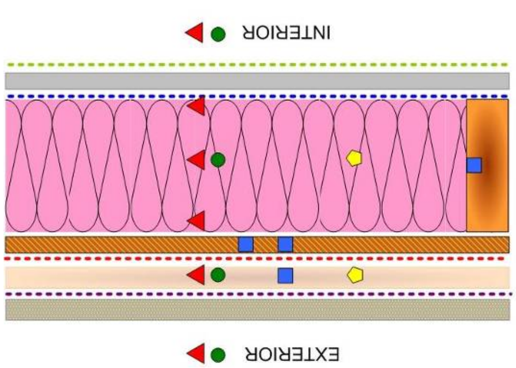
BUILDING 2

Sensor Legend
- Temperature
- Relative Humidity
- Moisture Content
- Pressure

INTERIOR
- latex paint
- 13 gypsum drywall
- 4 mil polyethylene sheet
- 140 wood studs @ 400 o.c.
  - 140 fiberglass batt insulation
- 13 plywood sheathing (Borate treated)
- 1 layer SBPO Housewrap
- 19 wood strapping (CCA treated) @ 400 o.c.
  - 19 ventilated air cavity
- 3-Ply semi-rigid asphalt breather board
- 19 cement stucco

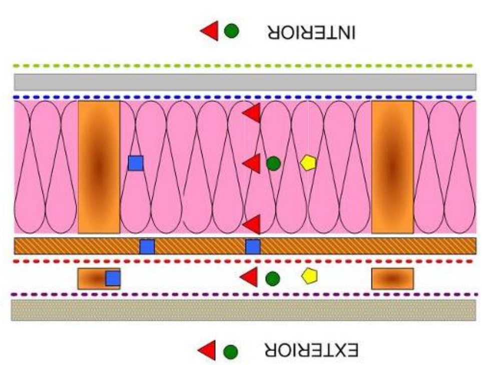
EXTERIOR

All dimensions in mm



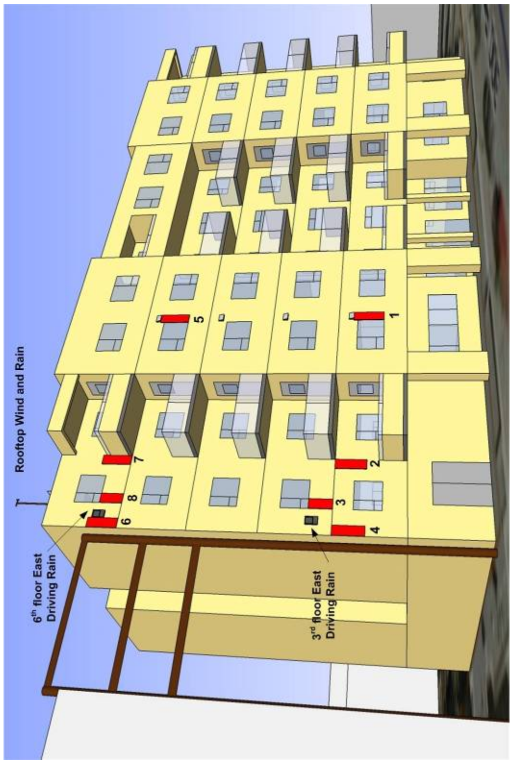
Section View
Building 2 – Exterior Wall Assembly

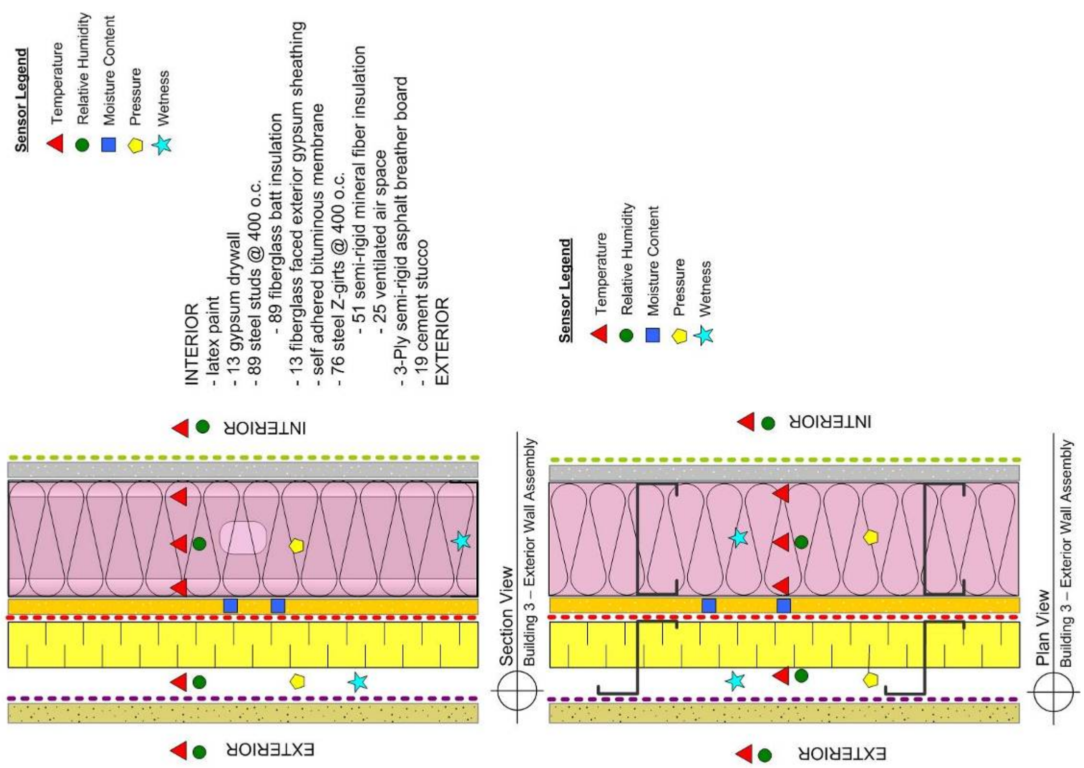
Sensor Legend
- Temperature
- Relative Humidity
- Moisture Content
- Pressure



Plan View
Building 2 – Exterior Wall Assembly

BUILDING 3

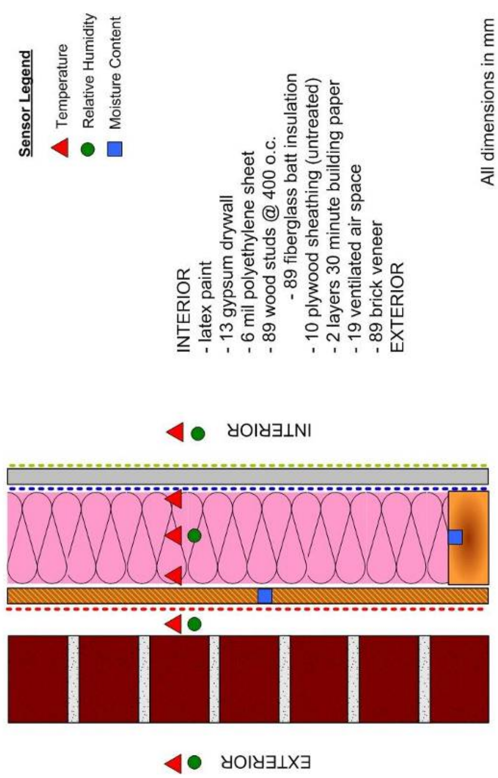

Rooftop Wind and Rain
6th floor East Driving Rain
3rd floor East Driving Rain


Sensor Legend
Temperature
Relative Humidity
Moisture Content
Pressure
Wetness
INTERIOR
- latex paint
- 13 gypsum drywall
- 89 steel studs @ 400 o.c.
- 89 fiberglass batt insulation
- 13 fiberglass faced exterior gypsum sheathing
- self adhered bituminous membrane
- 76 steel Z-girts @ 400 o.c.
- 51 semi-rigid mineral fiber insulation
- 25 ventilated air space
- 3-Ply semi-rigid asphalt breather board
- 19 cement stucco
EXTERIOR
INTERIOR
EXTERIOR
Section View
Building 3 – Exterior Wall Assembly
Sensor Legend
Temperature
Relative Humidity
Moisture Content
Pressure
Wetness
INTERIOR
EXTERIOR
Plan View
Building 3 – Exterior Wall Assembly

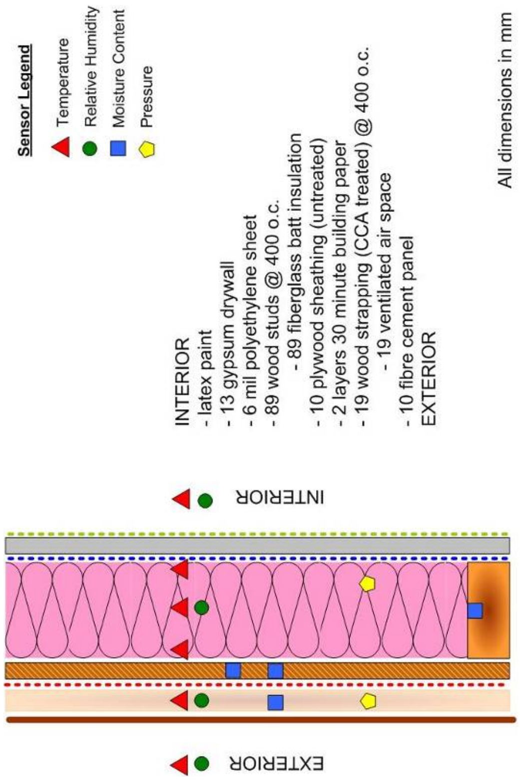
BUILDING 4


Rooftop Wind and Rain
3
4
5
South Driving Rain
Building 4 South Elevation

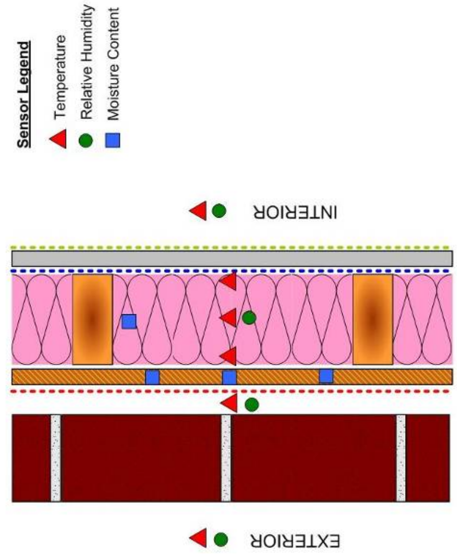

Rooftop Wind and Rain
1
2
North Driving Rain
Building 4 North Elevation



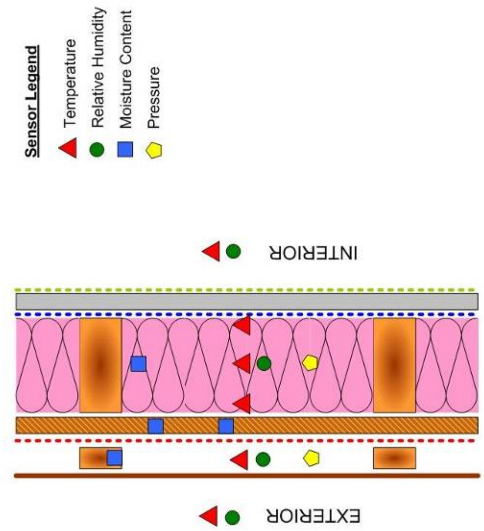
Section View
Building 4 – Exterior Wall Assembly – Cavity 5



Section View
Building 4 – Exterior Wall Assembly – Cavities 1-4

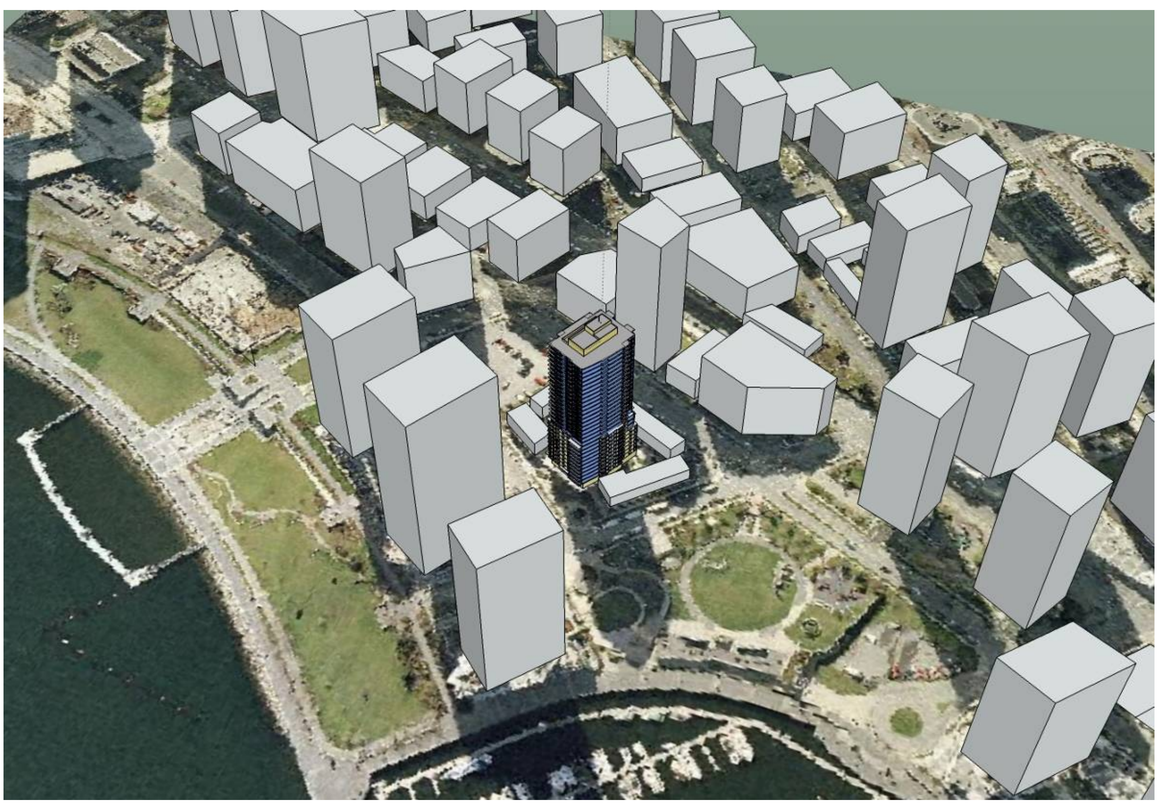


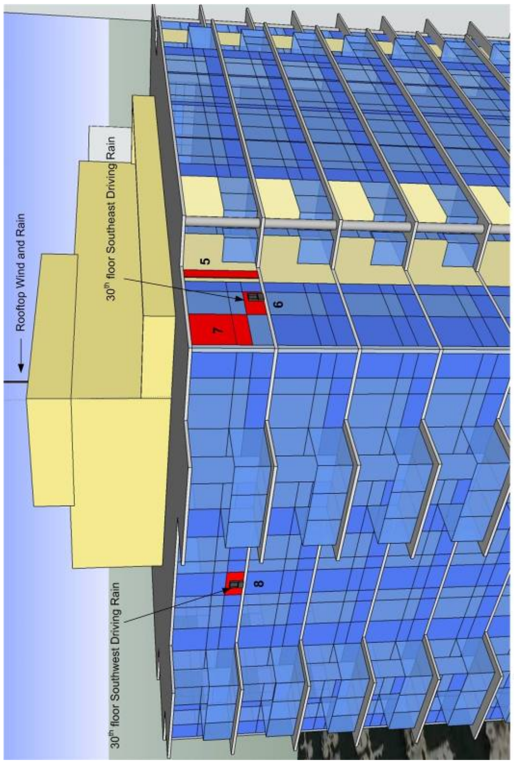
Plan View
Building 4 – Exterior Wall Assembly – Cavity 5



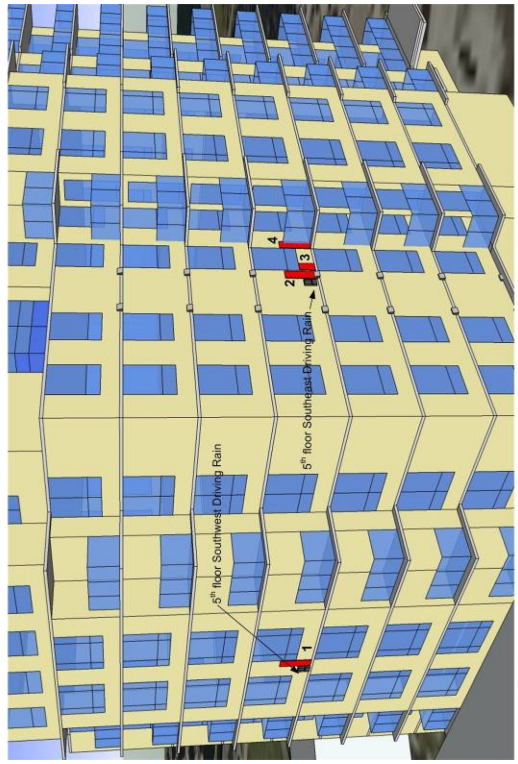
Plan View
Building 4 – Exterior Wall Assembly – Cavities 1-4

BUILDING 5

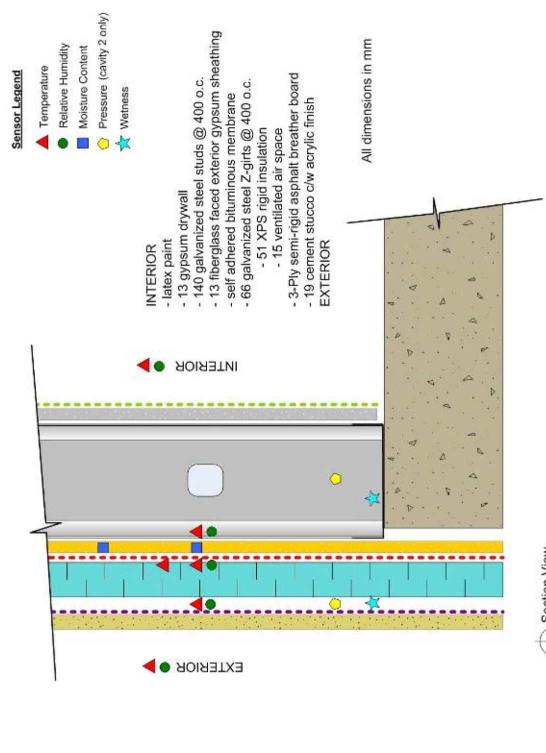




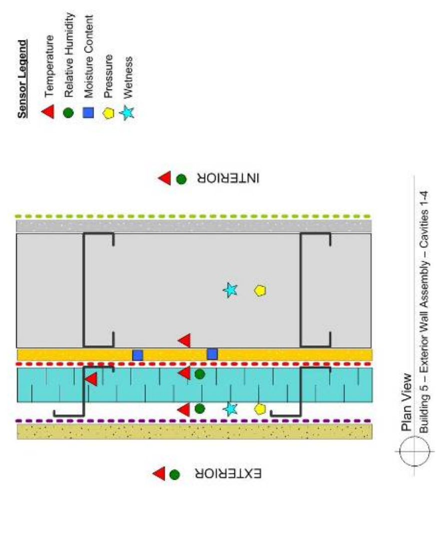
Building 5 – 30th Floor Wall Cavities – Southeast view



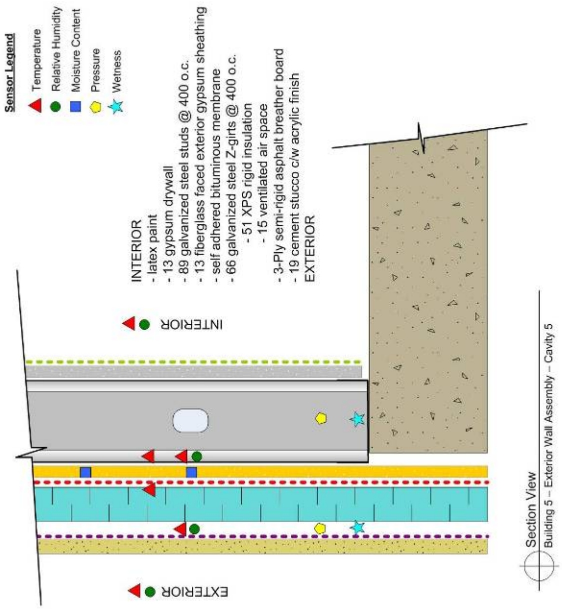
Building 5 – 5th Floor Wall Cavities – Southeast view



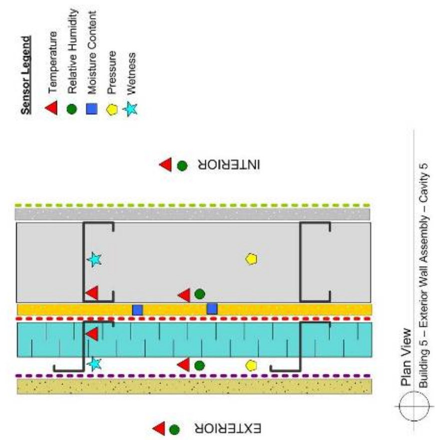
Section View
Building 5 – Exterior Wall Assembly – Cavities 1-4



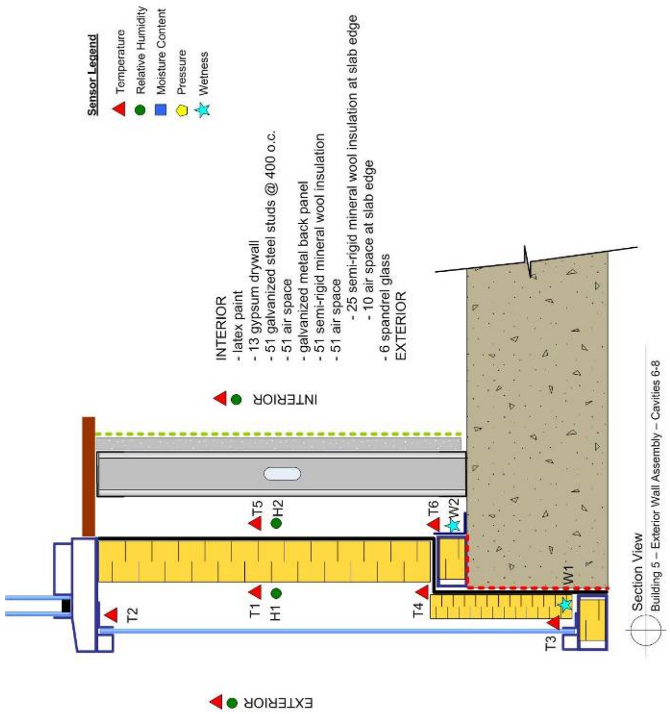
Plan View
Building 5 – Exterior Wall Assembly – Cavities 1-4



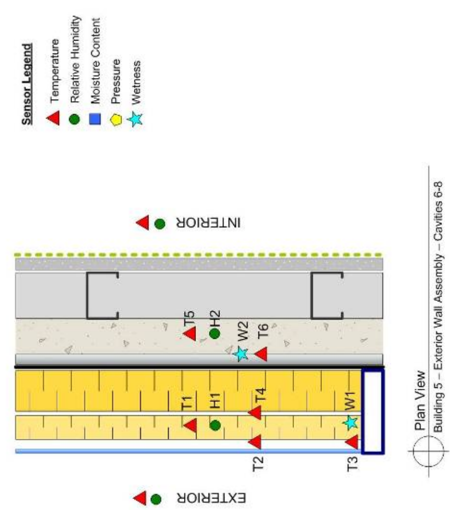
Section View
Building 5 – Exterior Wall Assembly – Cavity 5



Plan View
Building 5 – Exterior Wall Assembly – Cavity 5



Section View
Building 5 – Exterior Wall Assembly – Cavities 6-8



Plan View
Building 5 – Exterior Wall Assembly – Cavities 6-8

MONITORED BUILDING LOCATIONS, VANCOUVER, BC