

Moisture Management in VIP Retrofitted Walls

by

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Bachelor of Technology, Punjab Technical University, 2012

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of

Master of Applied Science

In the Mechanical Engineering

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University of Victoria

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Supervisory Committee

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Supervisory Committee

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Abstract

Thermal resistance per unit thickness for Vacuum Insulation Panel (VIP) is 5 to 10 times higher than conventional insulation materials. This makes VIP an attractive option for retrofitting exterior building envelopes. Insulation can be added in an exterior wall either on the interior side, exterior side or in the available stud cavity. VIP has high vapor diffusion resistance factor and could lead to moisture management risk in the wall layers because of the steep temperature gradient in the wall generated due to very high thermal resistance of VIP. VIP is a relatively new insulation material for building envelope construction, thus the hygrothermal or moisture management performance of VIP-insulated exterior building envelopes need to be critically analyzed before its application. This study aims to evaluate the moisture management risk associated with wood-frame stucco-cladded exterior walls retrofitted with VIP using a 2-D hygrothermal simulation tool WUFI-2D. Eight North American locations were considered, based on Moisture Index (MI) which varied between 0.13 and 1.17, and two different indoor hygrothermal loading conditions as prescribed by the ASHRAE 160P and EN 13788, respectively. The outputs from hygrothermal simulations (water content, relative humidity and temperature) were critically analysed and expressed further using freeze-thaw cycles and RHT indices. The results show that the appropriately designed VIP retrofitted walls can have superior moisture management performance as compared to conventional stucco-cladded wall.

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Dedication

This work is dedicated to my late father Mr. Sushil Sharma
and beloved mother Mrs. Anju Sharma

Acknowledgements

I would like this opportunity to thank the people who have always shown confidence in my potential and possibilities.

I would first like to thank my supervisor Dr. Phalguni Mukhopadhyaya. This thesis was only possible because of his support and exceptional guidance. He always steered me in the right direction and was available whenever I had any doubt regarding my thesis. I would also like to thank my co-supervisor Dr. Caterina Valeo, it is because of her that I was accepted in this university and was able to write this thesis.

Finally I would like to thank my parents, my sister Ankita Sharma, my uncle Vipin Sharma, friends and relatives for providing me constant support throughout this emotional journey.

1. Introduction

Building construction practices have evolved a long way, with designs ranging from medieval stone houses to modern skyscrapers. Today buildings are more comfortable, durable and energy efficient by virtue of the new building materials being used and improved construction practices. Occupants spend the majority of their lifetimes in buildings either for living or working. Thus thermal comfort inside the buildings is of utmost importance to the inhabitants. Depending on the climatic conditions, buildings require heating in the winters and air conditioning in the summers with a well-designed ventilation system (i.e. heating, ventilation and air conditioning (HVAC) system) for the comfort of the building occupants. HVAC systems tend to draw a lot of energy from the electricity grid which majorly contributes to the overall energy consumption in the households. It has been observed that a significant amount of the energy consumption is utilized for space heating and cooling. Energy used for air conditioning, space and water heating in the USA in the year 2009 accounted for 65% of the total household energy consumption [1] whereas for Canada in the year 2013 about 81% of the total energy consumption was for HVAC systems, out of the 63% that was used for space heating and cooling [2]. Average household energy consumption distribution for both Canada and the USA are as shown in Figure 1. The International Energy Association (IEA) aims for the world to be carbon neutral by 2040 and reduce the consumption and reliance on non-renewable sources of energy such as coal and petroleum for the energy generation [3]. Increasing the energy efficiency in the households and specifically older buildings could significantly impact the overall energy consumption and could potentially help in decreasing the level of greenhouse gases in the atmosphere. Modern buildings are designed with stringent guidelines described within the building codes and thus are more efficient and durable as compared to the older and historical buildings. The poor energy performance of the older buildings could significantly impact the average energy consumption and thus improved retrofitting measures for older buildings are always needed.

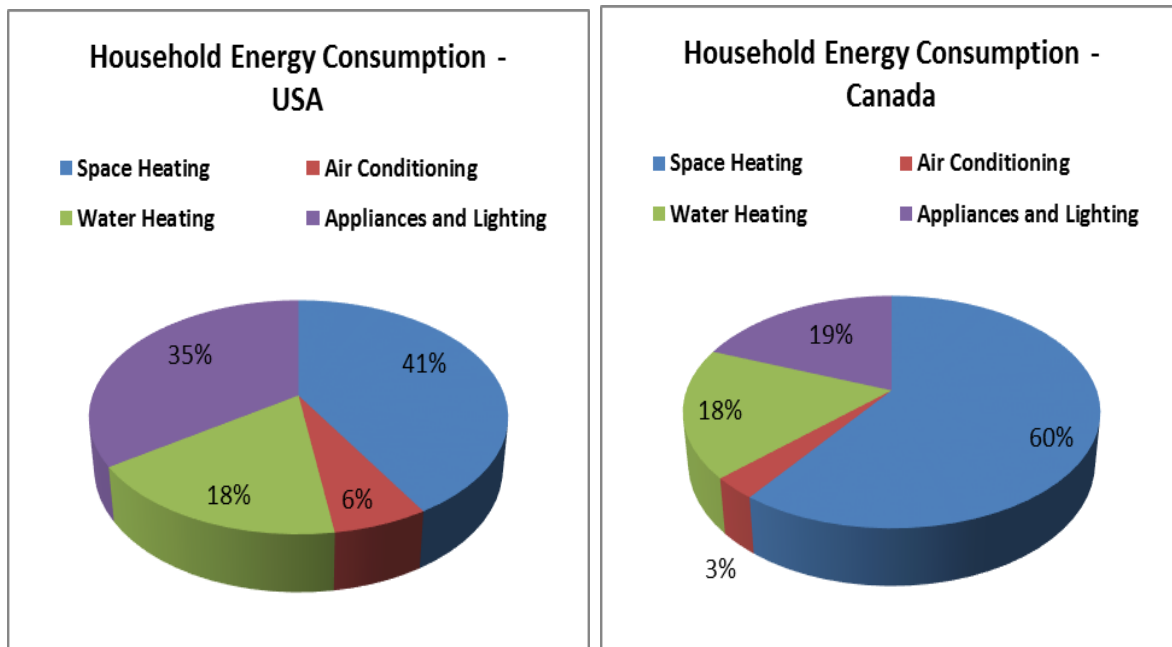


Figure 1: Household energy consumption comparison for USA [1] and Canada [2]

The energy efficiency of building envelopes can be improved in many ways including recovering heat from the ventilated air, by using solar panels to generate their own electricity, or by making buildings more airtight and insulated, to name a few. Adding extra insulation and thus increasing the effective thermal resistance per inch (R-Value) is one of the most prevalent methods of retrofitting a building. Increasing insulation levels in a building could significantly alter the building performance and could potentially result in increased moisture risks if the retrofitting measures are not evaluated carefully.

The overall R-Value, or insulation, in the building envelope could be increased by several ways; by adding insulation on the exterior side of the wall, inside the stud cavity, or on the interior side of the wall. The amount of insulation that could be added in the stud cavity is limited by the amount of insulation already present in it. Exterior retrofitting has been a widely used and studied method of retrofitting and offers many advantages, for example the building can be retrofitted without moving out the inhabitants from the inside. It also results in lower chances of interstitial condensation inside the wall assembly as the inside layers of the wall are kept at a higher temperature [4]. However, older and historical buildings cannot be retrofitted from the exterior side because of their façade appearance or limited space available for adding insulation, thus the only option left is to retrofit the building from the inside. Increased interior insulation could result in steep temperature gradients in the wall layers, which could potentially lead to interstitial condensation, provided the building climatic conditions and location inhibit the drying of the building over the time. This could also lead to a decreased inside floor area as the thickness of conventional insulation materials required for retrofitting is generally higher.

Vacuum Insulation Panels (VIP) is one of the breakthrough insulation materials which have a very high R-Value per inch (5 to 10 times higher) as compared with conventional insulation materials, thus making it useful for both interior and exterior retrofitting measures [5]. Even though VIP has many advantages over the conventional insulation materials, the improvement in the overall energy efficiency and the resultant impacts on the hygrothermal performance of the retrofitted buildings need to be carefully evaluated and validated in order to facilitate the usage of VIP as a standard insulation material in the building envelope constructions.

1.1. Brief Outline of the Research

The aim of this thesis was to assess the applicability of the VIP as a retrofitting measure and evaluate its hygrothermal performance for both interior and exterior applications in the external walls. A wood frame stucco cladded wall was used as the base wall and was retrofitted with VIP. The modelling for the wall was done using WUFI-2D for both the interior and exterior configuration around eight different North American climatic locations. The Relative Humidity (RH), Water Content (WC) and Temperature results were used as the criterion for the hygrothermal evaluation. The minimum thickness of VIP required for retrofitting was evaluated from the hygrothermal performance of the wall retrofitted with 8mm, 13mm and 25mm thick VIP. The exterior stucco wall was then retrofitted on the interior and exterior side using VIP and simulated for a period of three years. The third year results from the simulations were used to assess the hygrothermal performance of the retrofitted walls in comparison to the regular stucco wall. Higher indoor moisture loadings as per the ASHRAE 160P and EN 13788 conditions were used in simulations to assess effect of increased interior moisture loading on the performance of the retrofitted wall. Results using the steady state dew point method were used further to justify the

results obtained from the WUFI-2D calculations. RHT index and Freeze-Thaw cycles for the regular wall and retrofitted walls were used to assess the hygrothermal performance of the retrofitted walls further.

1.2. Limitations

The conclusions drawn in this thesis are based on the hygrothermal simulation results obtained from the WUFI-2D, with the available weather conditions and material database. VIPs are manufactured in definite sizes and are arranged in single or multiple layers throughout the length of the wall, however in this study a single layer of VIP with length 2400mm was used in the model. The thermal conductivity of the VIP used in this study was 0.007 W/mK, which corresponds to the aged design thermal conductivity of VIP. The thermal conductivity for pristine VIP lies in the range of 0.001-0.005 W/mK [4]. Further field studies are required to validate the results obtained from the WUFI-2D simulations.

2. Background

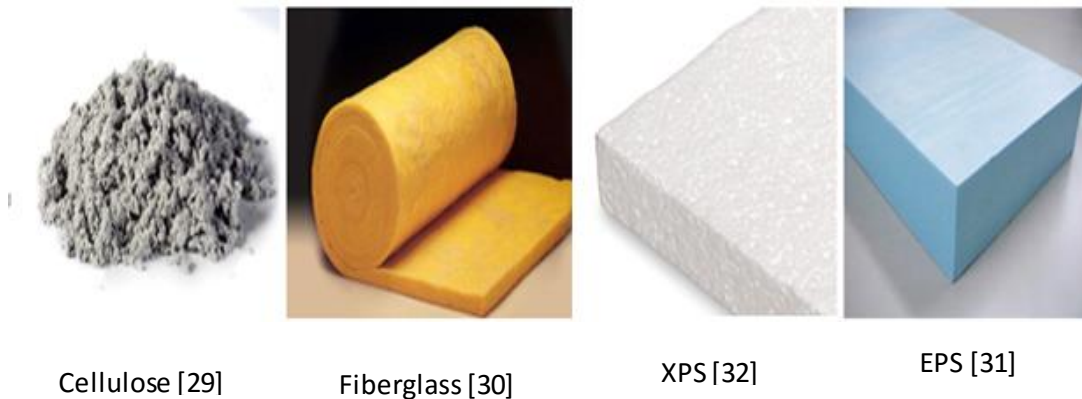
Old and historic buildings need to be consistently upgraded using retrofitting measures to keep them on par with the energy performance of new buildings. Damages to the building envelope and poor insulation measures used in the older buildings could result in increased energy consumption. The building construction is strictly controlled by the Building Codes of the region and defines the measures required in the building envelope to improve the overall building performance. Installing extra insulation either on the interior side of the wall or exterior side of the wall could be one of the several possible methods of retrofitting. A variety of insulation materials are available in the market, which can be easily installed and modified based on their application. Addition of extra insulation on the exterior and interior side could increase the overall R-Value of the wall with significantly increased wall thickness. Increased wall thickness could lead to decrease in the effective inside floor area or could interfere with the zoning laws on the exterior side. Thus a need of high performance insulation material has always been present, which have an increased effective R-Value whilst maintaining a thin profile. The sections given below provides a brief introduction to the various available insulation materials, the VIP and the tools required for an effective hygrothermal evaluation of the retrofitted walls.

2.1 Insulation Materials

Insulation inside the building envelope is used to retain or preserve the heating or cooling over a longer time and thus minimize the loading on the HVAC system which eventually results in the overall improvement in the energy performance. A variety of insulation materials in different shapes and sizes are available in the market. The R-Value per inch and the application method to be used decides the type of insulation material used in construction. Based on the application, they could be applied as a spray, in the form of blocks and batts, or could be applied as a loose fill. Table 1, outlines some of the insulation material available in the market and lists out their respective R-Value and application methods. Some of the insulation materials discussed in the Table 1 are as shown in Figure 2. The conventional insulation materials because of their lower R-Value per inch results in increased wall thickness if used for retrofitting and reduce the floor area or land for the inhabitants. Thus, a need of developing new insulation materials is always present.

Table 1: Types of insulation materials [6]

Material	R- Value	Application Method
Cellulose Insulation	3.0-3.7	Loose fill/Spray
Fibreglass Insulation	3.0-3.7	Batt/Board/Loose fill
Mineral Wool Insulation	2.8-3.7	Batt
Expanded Polystyrene insulation	3.6-4.4	Board
Extruded Polystyrene Insulation	4.5-5.0	Board
Polyurethane Insulation	3.6-6.0	Spray
Polyisocyanurate Insulation	5.6-6.7	Spray



Cellulose [29]

Fiberglass [30]

XPS [32]

EPS [31]

Figure 2: Types of insulation materials

The main requirement in the development of new insulation materials is that they should have a lower thermal conductivity, higher R-Value per inch, lightweight and durable, and should cost if not less than at least similar to conventional insulation materials available. One such novel insulation material is Vacuum Insulation Panel (VIP) which by virtue of its low thermal conductivity and high R-Value per inch is being proposed as the breakthrough insulation material. VIP would increase the effective R-Value of the retrofitted building while still occupying less space in the wall cavity because of its thin profile as compared to the conventional insulation materials. VIPs are suitable for both interior and exterior retrofitting projects. A study conducted by Dow Corning [7] compared the thermal properties of their VIP with the other conventional insulation materials and the results obtained are as shown in Table 2.

Table 2: Thermal comparison of conventional insulation with VIP [7]

Insulation Material	Thermal Conductivity (W/mK)	U- Value (W/m ² K)	Thickness required for Passive houses (mm)
Mineral Wool	0.038	1.27	253
XPS and EPS	0.035	1.17	233
PUR and PF	0.024	0.8	160
Aerogel	0.019	0.63	127
VIP	0.0046	0.15	25

The results given in Table 2 clearly show that the thermal performance of a building envelope could be significantly improved (~by a factor of 10) by replacing the conventional insulation materials with VIP. The study also compares the thickness of the VIP required for a passive house application. It was observed that the thickness required for the insulation with using VIP was only 25mm whereas the other insulation materials required thicknesses in the range of 127mm-253mm. The graph shown in Figure 3 outlines the comparative difference between the transmittance value (U- Value) of the conventional insulation materials and the VIP.

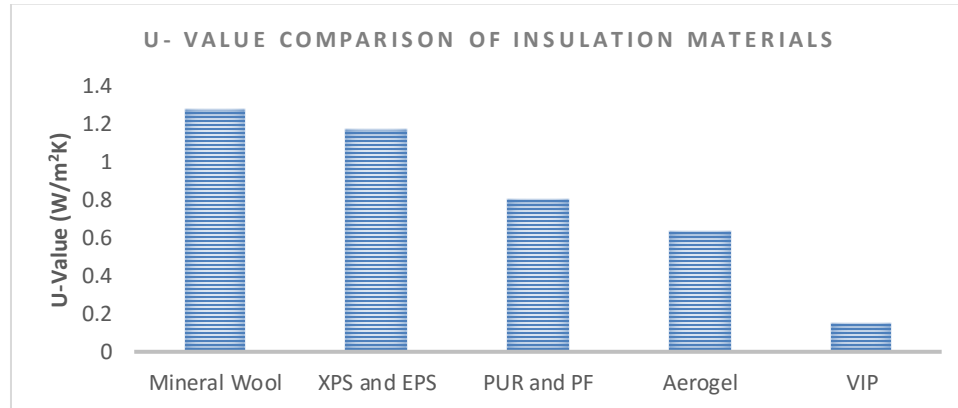


Figure 3: U-Value comparison of conventional insulation materials with VIP [7]

2.2. Vacuum Insulation Panels (VIPs) – Construction and Performance

Vacuum Insulation Panels (VIPs) have long been used in the cryogenic application in refrigerators and shipping cold storages [8]. Because of their high R-Values, VIPs are capable of minimizing the temperature fluctuations inside a building to a minimum and could maintain the temperature inside the building envelope for a longer time period. VIP consists of an open pore core material encapsulated inside a core bag containing getter and desiccants and is wrapped inside a multilayer barrier layer which maintains the low pressure inside the panel. The Figure 4, outlines the basic construction of the VIP. Several studies have been undertaken to evaluate the performance and life

cycle assessment of VIP in building envelope applications [9]. A detailed study about the VIP construction has been discussed in the ECBCS Annex 39 [10].

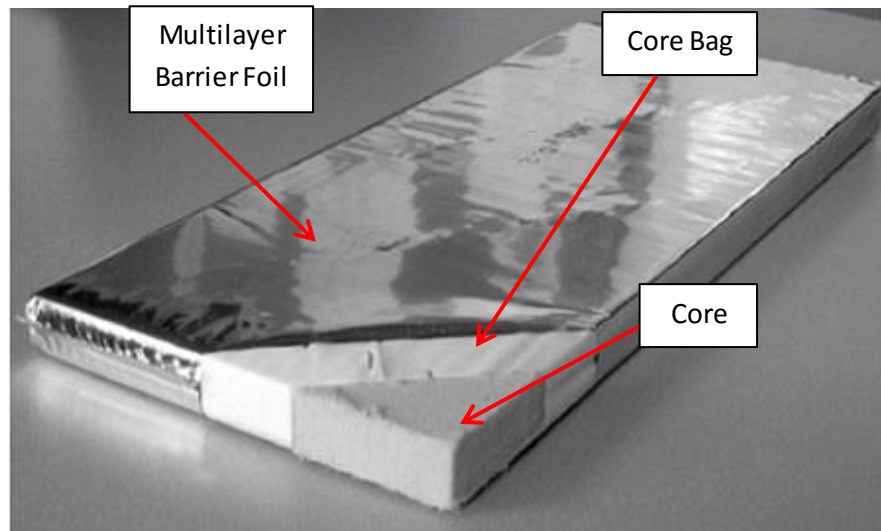


Figure 4: VIP construction [10]

The porous core material used in the VIP when vacuumed results in a decreased gas conduction component in the overall conduction, and results in reduced thermal conductivity. The multilayer barrier foil should be resistant to the air and moisture permeability from the atmosphere to maintain the thermal performance of the VIP [10].

Apart from the advantages of having a thin profile, low thermal conductivity and low U-value, VIP do have some major drawbacks. VIP has a fragile construction, thus considerable care is required in their handling and application. VIPs are manufactured in standard shapes and sizes and the vacuum inside them restricts any required modifications at the construction site. Therefore, the selection of the VIP should be based on the available standard sizes during the wall design phase. Long term performance evaluation studies need to be done for the applicability of VIP in the buildings. The thermal conductivity of the VIP increases over time as the vacuum inside the VIP lowers due to the increased air permeation from the environment with aging. Major problems with the applicability of VIP is there is a relatively higher cost of production whereas the majority of conventional insulation materials are available in various shapes and sizes and are cheap when compared to VIP. Several projects are being carried out to reduce the cost of VIP production and to make them affordable and readily available. One such project is VIP4ALL [11] which aims to modify the existing core materials and propose new core materials for the VIP instead of the regularly used silica to decrease the overall cost for the manufacturing. A brief comparison between the regular VIP and VIP from VIP4ALL is as shown in Figure 5.

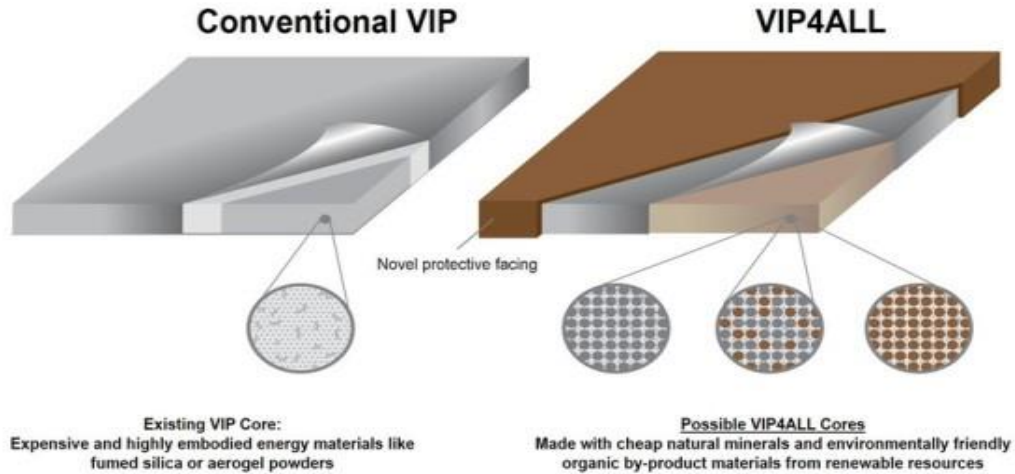


Figure 5: Different VIP core constructions [11]

One of the major drawbacks of the VIP is their rigid and fragile construction, which requires the design to be carefully studied before applying the VIP in construction. Recent advances in the manufacturing techniques have led to fabrication of VIP in different shapes and sizes as shown in Figure 6 and thus could be used to install at locations having asymmetric geometry, but the cost associated with customized VIPs is generally higher when compared to the regular VIP.

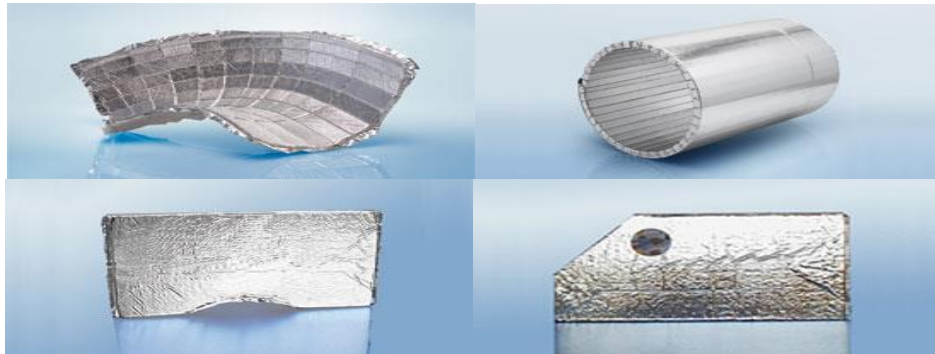


Figure 6: VIP shapes [25]

VIPs can also be used in variety of applications apart from their use in retrofitting applications. They can be used to insulate doors by applying VIP in the door cavity, they can also be used for the construction of dormer windows and roofs which require high insulating capacity in thinner profiles. VIP provides an opportunity to be used as an out of the store retrofitting measure similar to EIFS, wherein the VIP product could be directly placed on the exterior or interior side of the external wall with minimum supervision. Advanced manufacturing processes are now capable of manufacturing VIP virtually in any complex shape as shown in Figure 6. Continuous effort and research needs to be carried out in order to make the application of VIP more accessible and convenient.

VIP by virtue of their high R-Value per inch could be used as a retrofitting measure either on the interior or exterior side. The VIP can be placed in the exterior or interior retrofitting measures as shown in Figure 7. In exterior retrofitting VIP is applied before the stucco layer in the wall assembly. Exterior retrofitting first requires the old exterior façade to be removed for the

installation of the insulation material or VIP before reinstalling the exterior façade, thus making it a rather expensive method for retrofitting. Exterior retrofitting has been widely studied and is considered to have lesser moisture problems. Similarly VIP could also be used as an interior retrofitting option. In interior retrofitting the VIP is placed before the gypsum board or the drywall layer in the building envelope. The interior retrofit is less expensive than the exterior retrofit as only the drywall layer needs to be replaced after installing the insulation of VIP, however interior retrofitting has some drawbacks. The inhabitants need to be moved out while retrofitting and interior retrofitting could also lead to increase in moisture problems. VIP also has a very high vapor diffusion resistance factor, which could reduce the water vapour diffusion to the inside and outside of the wall construction layers. This could lead to interstitial moisture condensation as the outer wall layers after interior retrofitting would be at lower temperatures. Thus retrofitting on the exterior or the interior side needs to be critically analyzed before using VIP as a retrofitting measure.

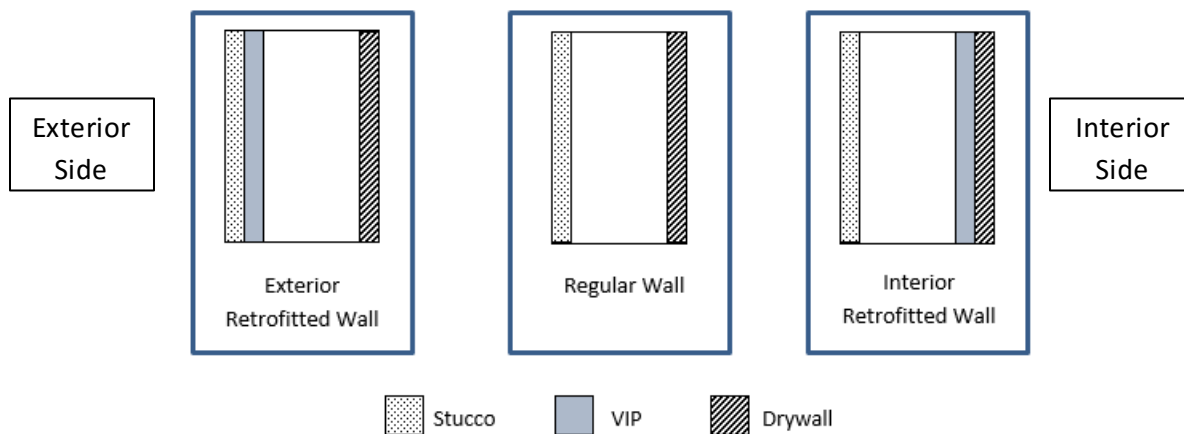


Figure 7: Interior and exterior retrofitting using VIP

2.3. WUFI-2D

To analyze the hygrothermal performance of the retrofitted assembly a numerical simulation tool WUFI-2D was used. WUFI is a German acronym for “Warme Und Feuchte Instationar”, which translates to transient heat and moisture transport [12]. WUFI was used to model, simulate and analyze the real life hygrothermal performance of the building envelope. Transient boundary and climatic conditions were applied to the model and was simulated over a time period. WUFI is developed by Fraunhofer Institute for Building Physics (IBP) and has been optimised for the North American database by Oak Ridge National Laboratory (ORNL).

WUFI helps in calculating the transient Heat, Air and Moisture (HAM) loads in the building envelope within the specified boundary conditions while iterating it over specified time. The results obtained from WUFI can be used to estimate the drying time with the entrapped moisture, the impact of the driving rain and effect of solar radiation absorptivity and emissivity [12]. WUFI can be used to design new buildings or retrofit designs by analyzing the performance of the prototype model. This saves considerable time and effort in terms of building and monitoring the results over a time period for the model design. Table 3 outline the transport mechanism and the cause and potential of transport as described by Kunzel [13]

Table 3: Transport mechanism, cause and potential of transport [13]

Transport Mechanism		Cause and potential of transport
Heat Transport	Heat conduction	Temperature
	Heat radiation	Temperature in 4 th power
	Air flow	Total pressure
Vapour Transport	Gas diffusion	Vapour pressure
	Solution Diffusion	Vapour pressure
	Convection	Total pressure gradient
Liquid Transport	Capillary conduction	Capillary suction process
	Surface diffusion	Relative humidity
	Seepage flow	Gravitation
	Hydraulic flow	Total pressure differentials
	Osmosis	Ion concentration

WUFI uses the equations defined below to iteratively find the results for the simultaneous heat and moisture transport in a building element under consideration. The equation for the heat transport used in WUFI is as given in Equation 1 [13]

$$\frac{dH}{d\theta} \cdot \frac{\partial \theta}{\partial t} = \nabla \cdot (\lambda \nabla \theta) + h_v \nabla \cdot (\delta_p \nabla (\varphi p_{sat})) \quad (1)$$

Similarly the equation for moisture transport in WUFI is as given in Equation 2 [13].

$$\frac{dw}{d\varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla \cdot (D_\varphi \nabla \varphi + \delta_p \nabla (\varphi p_{sat})) \quad (2)$$

Where,

$\frac{dH}{d\theta}$ = Heat storage capacity of the moist building material

$\frac{dw}{d\varphi}$ = Moisture storage capacity of the building material

λ = Thermal conductivity of the moist building material

D_ϕ = Liquid conduction coefficient of the building material

δ_p = Water vapour permeability of the building material

h_v = Evaporation enthalpy of the water

p_{sat} = Water vapor saturation pressure

θ = Temperature

ϕ = Relative humidity

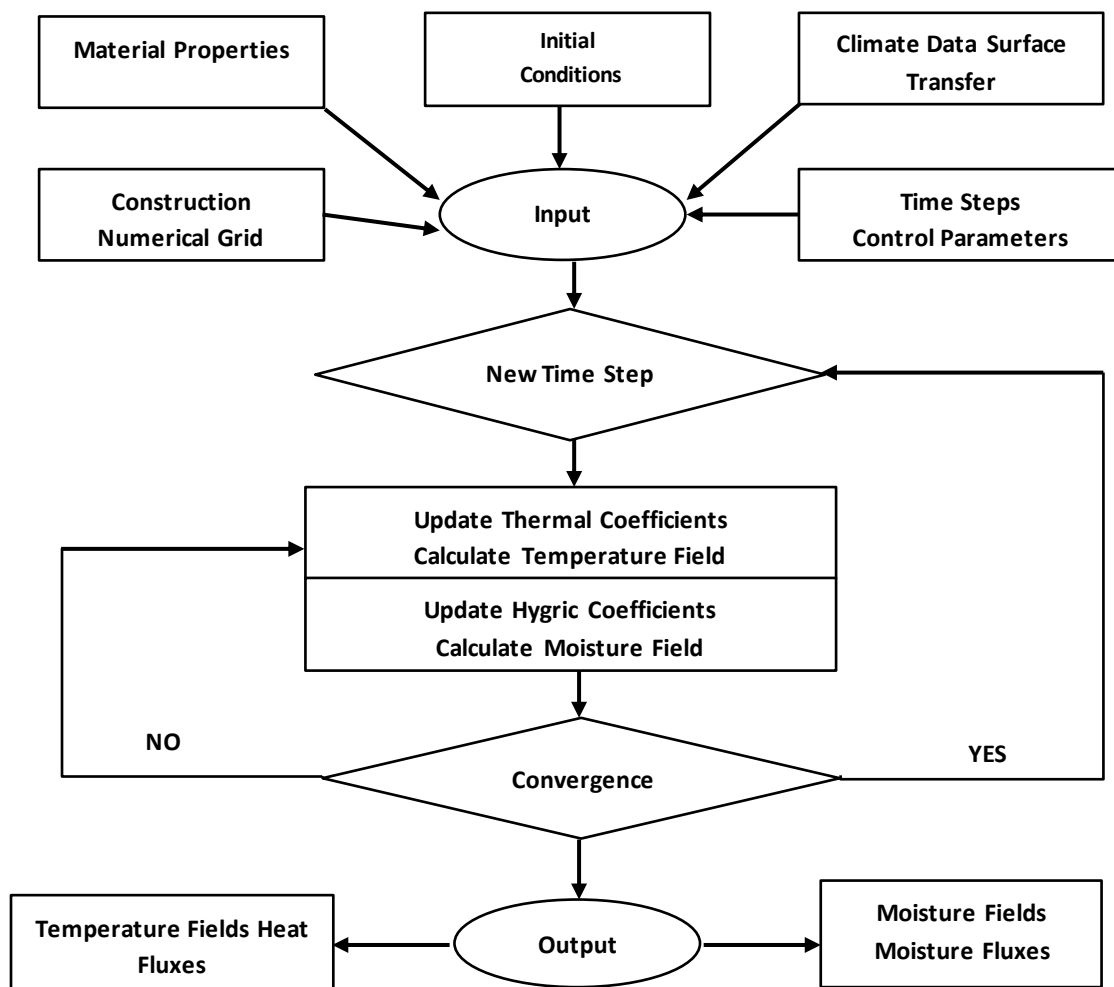


Figure 8: WUFI simulation overview [10]

WUFI simultaneously iterates the heat and moisture equations for each of the discrete elements described in the geometry. Figure 8 gives the flow diagram outline for the process.

2.4. Moisture Index

The eight locations used in the simulations were selected based on their moisture index. The concept of classifying locations based on the moisture index was suggested in MEWS consortium [14]. Moisture Index is defined as the function of Drying Index (DI) and Wetting Index (WI). Wetting component is defined as the fraction of the driving rain absorbed by the wall from the amount of rainfall received on the ground. The equation for wetting potential is as given below [14].

$$\Delta w(h) = w_{\text{saturation}}(\text{hourly temperature}) - w_{\text{out}}(\text{hourly temperature}) \text{ kg water/kg air} \quad (3)$$

The drying Index (DI) could be defined as the difference between the humidity ratio at saturation and the humidity ratio of the ambient air [14]. The drying index could be defined as given in Equation 4 [14].

$$DI = \left(\frac{1}{n}\right) \sum_{i=1}^n \sum_{h=1}^k \Delta w(h) \text{ kg water/kg air-year} \quad (4)$$

Where,

DI is the Drying Index in kg water/kg air-year

w is humidity ratio

n is the number of years under consideration, and

k is the number of hours in a particular year

The Moisture Index (MI) could then be defined as the ratio of WI to the DI. The higher the MI value, the higher the risk for moisture related risk for the building envelope for that location. The Equation for the MI is as shown below [14].

$$MI = \frac{WI}{DI} \quad (5)$$

MI classification was used to define the zoning map for the North America as shown in Table 4. The MI can be used as a parameter for assessing the moisture performance of the buildings in that climatic zone.

Table 4: MI classification and North America climate zoning map [14]

Moisture Index	Zone	Classification w.r.t. Moisture Problems
$MI \geq 1$	Zone 5	Severe
$0.9 \leq MI < 1$	Zone 4	High
$0.8 \leq MI < 0.9$	Zone 3	Moderate
$0.7 \leq MI < 0.8$	Zone 2	Limited
$MI < 0.7$	Zone 1	Low

2.5. RHT Index

Increased RH level with varying temperature loads could lead to varying degrees of damage to the building envelope and significantly affect the performance and lifetime of a building. NRC Canada set up a task force specifically for evaluating the Moisture Management for Exterior Wall Systems (MEWS), in which they studied moisture performance of stucco clad wall, EIFS wall, masonry wall and wood frame wall [8]. They developed a novel concept being the RHT index wherein they computed an RHT number by taking the summation of the product of the RH and Temperature for the given time period and evaluated the moisture problem risks, based on the RHT index. Equation 6 [8] gives the mathematical representation of the RHT index as defined in MEWS consortium.

$$\text{Cumulative RHT} = \sum (RH - RH_x)(T - T_x) \quad (6)$$

If the $RH \leq RH_x\%$ and $T \leq T_x$, the RHT value for that time stamp is zero. Two RHT indices of RHT (80-5) and RHT (80-0) were used to evaluate the moisture performance of the wood frame stucco clad wall used for the analysis. Although the RH and temperature limit defined in the MEWS report was RHT (95-5) lower limits of RHT (80-5) and RHT (80-0) were used to assess if there is moisture risk at lower values.

2.6. Dew Point Method

Insulation materials having low permeance when used in new or retrofitted buildings could often lead to condensation risks and result in poor performance of the building envelope, thus there is always a need to assess the moisture performance of the building envelope before using the insulation material. Dew point method is a widely used condensation analysis method in North America by the building consulting companies and calculates the condensation potential by comparing the vapor pressure with the saturation pressure [15].

The dew point method utilizes the vapour pressure inside the building envelope as a condensation evaluation criterion. The vapour pressure inside the envelope is calculated using the simple vapour diffusion equations and then compared with the calculated saturation vapour pressure. A condensation risk is observed whenever the vapour pressure at the interface is above the associated saturation vapour pressure. The building performance could be significantly deteriorated by mold and mildew, spalling, or freeze thaw damages which are not necessarily associated with increased condensation and is one of the major limitations of using the dew point method. Also, the dew point method does not consider the effect of moisture storage, air movement, liquid water movement or rain [16] and thus limits the usefulness of dew point method for moisture performance evaluation.

For dew point calculations the material data for each of the layer in the wall section was taken from the WUFI North American material database. The calculation method as explained by TenWolde [16] was used and vapour pressure at each of the interface was calculated as shown in the Appendix E.

2.7. Moisture Problems

High moisture content in the building envelope could adversely affect the building performance and in extreme cases could lead to building failures. Mold formation and freeze thaw damage are one of the major moisture problems in the building envelope. Mold and mildew can adversely affect the building environment and pose a serious health issue for the inhabitants. The Freeze-Thaw damage on the other hand could significantly affect the appearance of the façade and result in decreased energy performance and lifetime of the building envelope.

2.7.1. Freeze-Thaw

Water expands on freezing. This phenomenon when applied on the façade of buildings in the colder climates could explain the unwanted cracks and spalling observed in those buildings. Buildings in colder climates with high MI, pose a considerable risk for damage to the façade of the building. The weather in some locations during winters could go significantly lower than the freezing point of water i.e. 0°C, thus making the moisture present in the façade to either change its phase to frost or ice. When water changes its phase from liquid to ice, it expands and thus makes the material expand. As the temperature increases back again the ice thus formed inside the material changes back to its liquid phase, thus leaving a void inside the material. This cycle repeats itself over time and results in damage to the façade of the building. Assessing freeze thaw damage is rather a complex mechanism. Thus calculating freeze thaw cycles can predict the potential extent of damage from the freeze thaw phenomenon. A freeze thaw cycle for a material can be calculated

whenever the water content in the material increases beyond a certain factor of the free water saturation and temperature in the material goes above and below 0°C.

2.7.2. Mold Growth

Mold and mildew are a type of fungi which can grow practically on any surface provided the conditions required for their growth are met [17]. Mold and mildew require a threshold RH level and temperature level to grow and affect the building environment. Molds can grow in a building if the moisture management measures incorporated in the building are not sufficient to keep the moisture from accumulating in the building. Mold and mildew growth in the building could also lead to some severe health issues like respiratory problems, skin, eye, and throat irritation. They can also have an adverse effect on the mental state of the occupant and could lead to mood swings, headaches and in severe cases even memory loss [18], thus the mold growth in the building envelope should be critically assessed and analyzed by taking in consideration all the potential moisture locking scenarios in the building. The mold growth generally require a RH level of above 80% for their growth, thus increased RH and WC levels in the building envelope could potentially provide a potent environment for the mold growth. Thus while retrofitting any building with low vapour permeable materials, the moisture performance needs to be critically evaluated to reduce any potential of moisture accumulation and resulting in mold and mildew growth.

3. Related Work

VIP has long been used in the fields of cryogenics, but their use as an insulating material in the building envelope has been proposed and used recently. VIP research can broadly be categorised in material development, application and evaluation. Figure 9 shows the breakdown of the VIP research used in this study. This chapter outlines the literature survey and the related work conducted throughout the world to develop VIP as a breakthrough insulation material.

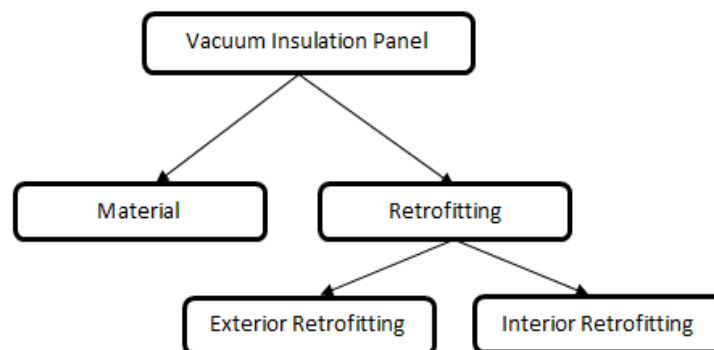


Figure 9: VIP research flow chart

Mukhopadhyaya et al [5] in their study at National Research Council Canada investigated the VIP performance with various core materials. They compared the thermal conductivity and the internal pore pressure for various materials and deduced that for inexpensive and high performing VIP further research needs to be conducted for using composite core materials, powder insulation materials and fibrous insulation materials.

Alam et al [18] in their study discussed about the potential materials to be used for the commercial production of VIP, which can increase the performance of the VIP and at the same time decrease the production cost for them. They also highlighted the limitations of using silica as the core material and the cost reduction potential by changing the silica core to other porous materials. They also discussed about the need of developing newer adhesive materials which have lower permeance than water vapor as water vapour has 30000 times faster transmission rate than air.

Fricke et al [19] in their study discussed about the potential of using vacuum insulation panels in the buildings which have very less or no space to install the conventional insulation in the buildings. They also discussed about the development of better laminates and development of RFID sensors to measure the temperature profile without requiring a thermal contact with the VIP.

VIPs, if handled and installed carefully can be used as insulation material in the new building construction. Apart from being used in the new construction VIP have a tremendous potential to be used as insulation in retrofitting older buildings. By virtue of their thin profile they could either be used for interior retrofitting or exterior retrofitting. Various parametric simulation studies and field tests for different wall constructions have been conducted by various researchers around the world for assessing the performance of the VIP in retrofitted buildings.

Mukhopadhyaya et al [20] in their study at National Research Council, Canada discussed about the application of hygrothermal modelling tool to assess the performance of a retrofitted and regular wall assembly. The wall performance could be correctly assessed provided the input parameters are well defined. The RHT index thus developed in the study could be used to compare and verify the effect of retrofitting on the moisture and thermal performance of the wall assemblies.

Johansson et al [21] in their study discussed about the application of VIP as a retrofitting option in the exterior wall section in Austria and the results for the field tests for the reference wall and retrofitted wall were recorded and compared. The results from the field tests were compared with the numerical simulation results generated from WUFI. A significant improvement in the thermal performance of the retrofitted wall was observed when compared with the results from the regular wall. A small deviation in the hygrothermal results from the field tests and simulation results was observed which was attributed to the air leakage path in the wall section.

Saber et al [22] in their study evaluated the thermal performance of three 2X6 wall frame wall system one retrofitted with VIP using Tongue and Groove configuration, second retrofitted using VIP in Clip On configuration and the third retrofitted using XPS. The walls were kept in the field exposure of wall facility at NRC and the results were monitored over a period of one year. The field results and simulation results were then analyzed and compared and no discrepancy in the results was observed. The hygrothermal performance of the wall using VIP was significantly better than the XPS configuration. The performance of the T&G configuration was slightly better than the C-O configuration.

Mukhopadhyaya et al [23] in their study discussed about the applicability of VIP for exterior retrofitting of an existing wall in subarctic Canadian climate. In the field study they retrofitted the wall using VIP and monitored it over a time period of 3 years to assess the hygrothermal performance of the retrofitted wall. The results for the retrofitted wall were found to be better than

the regular wall and the VIP- foam insulation system was found to be an effective and useful choice to be considered as a retrofit choice.

Parekh et al [24] in their study incorporated VIP as an insulation material covered by foil isocyanurate foam board in a new building construction in Burnaby, Canada. They simulated the numerical simulations using WUFI and after many iterations decided upon using a 15mm thick VIP. WUFI results were found to be satisfying and an overall increase in the hygrothermal performance of the wall construction was observed. The VIP performance was evaluated over time and VIPs were found to working fine over time.

Johansson et al [25] in his study evaluated the performance of a brick wall retrofitted with VIP on the inside. They designed similar wall using WUFI and evaluated its performance in a climate simulator. The moisture content in the building envelop and wooden beams was compared for the wall with VIP and without VIP, but not much difference was observed, although they observed that the higher temperature gradient in the wall led to higher RH in the wooden beams. U value calculations showed a decrease in the overall energy consumption.

Buxbaum et al [26] in his study compared the hygrothermal simulation results for a brick masonry wall. They simulated brick walls interior retrofitted with mineral wool and VIP in Austria and compared the thermal and moisture performance of the walls. The results for the thermal performance of the wall retrofitted with VIP showed significant improvements whereas slight decrease in the moisture performance of the VIP retrofitted wall was observed.

Mukhopadhyaya et al [20] in their study at National Research Council, Canada discussed about the application of hygrothermal modelling tool to assess the performance of a retrofitted and regular wall assembly. The wall performance could be correctly assessed provided the input parameters are well defined. The RHT index thus developed in the study could be used to compare and verify the effect of retrofitting on the moisture and thermal performance of the wall assemblies. The same approach was used in this thesis to evaluate the moisture management risks.

4. Objective

VIP is a relatively new insulation material and thus requires a lot of research and development for its characterization and application in the building practices. VIP provides a great opportunity for reducing the energy consumption of a building by virtue of its high R-Value, i.e. high thermal resistance per unit thickness as compared to conventional insulation materials. VIP could potentially make the building envelope more vapour tight as VIP has a high vapour diffusion resistance, and could increase the risk of interstitial condensation in the wall layers. Increased moisture content with steep temperature gradients in the building envelope could provide an environment for moisture problems in the building using VIP as an insulation material. This thesis aims to evaluate the hygrothermal performance of the wood-frame stucco-cladded VIP retrofitted walls in varying North American climatic conditions and their potential use as a regular insulation material in the retrofitting domain.

5. Methodology

5.1. Proposed Approach

A 2-D model of a wood frame stucco clad wall was constructed using WUFI-2D. The same wall was then retrofitted with VIP on the exterior side using WUFI-2D and then again using VIP on the interior side using WUFI-2D. VIPs have a fragile construction, so in order to preserve their construction use of two XPS insulation boards was suggested to minimize the damage. Eight different North American locations based on their MI (ranging from 0.13 to 1.17) were selected as given in Table 5. Higher moisture risk is associated with the locations having higher MI. The materials used in the wall model were taken from the material database given in the WUFI North American database. The wall was simulated with the changing transient indoor and outdoor weather files and simulated over a time period of three years and a parametric study to evaluate the moisture performance of the buildings retrofitted using the VIP was proposed.

Table 5: Moisture Index for selected North American locations [9]

Location	Moisture Index	Climate Type
Phoenix, AZ	0.13	Hot, Dry
San Diego, CA	0.74	Hot, Dry
Winnipeg, MB	0.86	Cold, Dry
Ottawa, ON	0.93	Cold, Wet
Tampa, FL	0.95	Hot, Wet
Vancouver, BC	1.09	Cold, Wet
Wilmington, NC	1.13	Hot, Wet
St. John's, NL	1.17	Cold, Wet

The wall sections during the parametric study were compared with the varying interior climatic conditions given in WUFI as per ASHRAE 160P and EN 13788 (higher moisture load) guidelines. VIP thicknesses of 8mm, 13mm and 25mm were used in interior retrofitted case to evaluate and compare the effect of varying VIP thicknesses on the overall moisture performance of the wall assembly. The results from the WUFI simulations were then used to evaluate the moisture performance of the interior and exterior retrofitted wall using the 13mm thick VIP. The results thus obtained from the simulation were further verified using the RHT index and freeze-thaw cycles.

5.2. Wall Construction

A wood frame stucco clad wall, which is predominantly used in North America was selected as the base wall for this study. The stucco wall was modelled and used for simulation in WUFI as shown in Figure 10. In order to obtain better result accuracy and reduced simulation time, it was decided to model only the half the length of the wall geometry due to geometrical symmetry. A

19mm thick layer of stucco was installed on the exterior face of the wall with a 1mm thick sheathing membrane (WUFI doesn't support layers less than 1mm [27]) followed by a layer of 11mm thick Oriented Strand Board (OSB). The stud space is fitted with a top and bottom plate of thickness 89mm and height 76mm. The 1124 mm high and 89mm thick wall cavity between the top and bottom plates is called an insulation space and was filled with fibre glass insulation. The insulation was sealed off with a vapour barrier of 1mm thickness followed by 11mm thick gypsum board USA, termed as drywall in the wall assembly drawing as shown in Figure 10.

The same stucco clad wall was then used as the base wall for the exterior and the interior retrofit option. The VIP was introduced in the construction, sandwiched between two layers of XPS insulation. The extra XPS insulation layers are added to prevent damage to the VIP layers during the building construction. The VIP sandwich assembly for the exterior retrofitting is added before the stucco layer in the wall construction, whereas in the interior retrofitting it is added before the drywall layer and after the vapour barrier layer. The construction details for the exterior retrofitted wall are as shown in Figure 11.

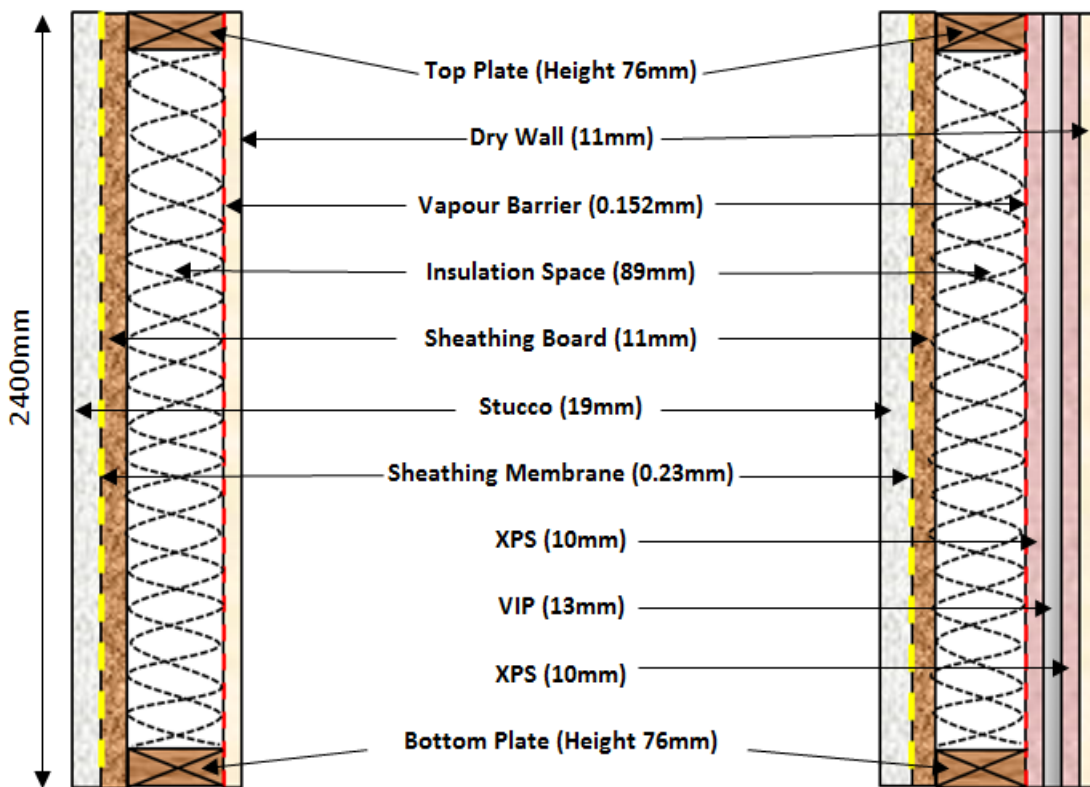


Figure 10: Regular and interior VIP retrofitted wall assembly

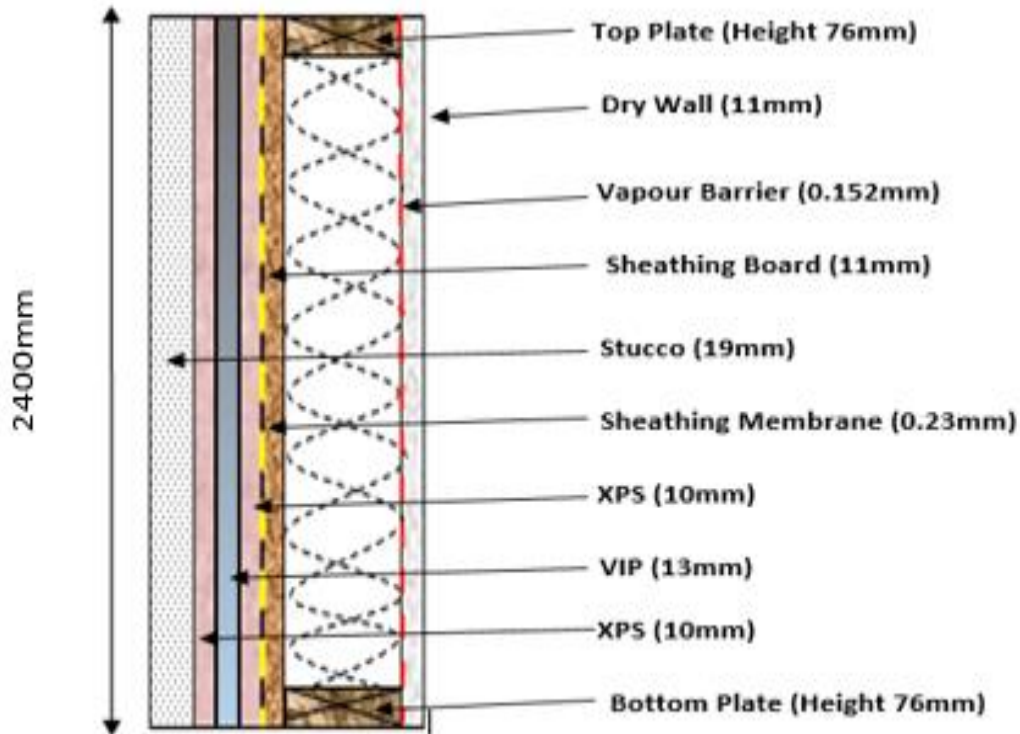


Figure 11: Exterior VIP retrofitted wall assembly

5.3. Material Data

The materials required for the modelled building geometry were taken from the material database supplied with WUFI. The material properties tend to vary a lot by the geographical locations and for this study the North American database provided by the Oak Ridge National Laboratory (ORNL) was used. New materials are constantly being added into the database and the properties for the other materials are constantly being updated in the WUFI database. The assigned materials were selected from the North American database as shown in Table 6. Regular Portland Stucco was used for the stucco layer which was followed by a spun bonded polyolefin membrane layer used as the sheathing membrane and was then followed by a layer of Oriented Strand Board High used as a sheathing board. The frame for the wall assembly was comprised of studs made of Spruce wood, thus making the top and bottom plate in the assembly take on Spruce wood properties. The stud space inside the frame was filled with fiberglass insulation material taken from the database. A vapor retarder 1 perm was used as the vapor barrier from the database and was followed by a layer of Gypsum Board USA used as a drywall layer in the wall assembly. For the retrofitted assemblies, a layer of VIP (0.007) was sandwiched between two extruded polystyrene insulation boards. The VIP of thermal conductivity of 0.007W/mK was selected to evaluate the long time performance of the wall, as VIP tend to lose vacuum over time due to air infiltration.

Table 6: Material properties from the WUFI database

Description	Material	Bulk Density (kg/m³)	Porosity (m³/m³)	Specific Heat Capacity (J/kgK)	Thermal Conductivity (W/mK)	Water Vapour Diffusion Resistance Factor
Stucco	Regular Portland Stucco	1955.5	0.225	840.0	0.399	355.7
Sheathing Membrane	Spun Bonded Polyolefin Membrane	448.0	0.001	1500.0	2.4	328.4
Sheathing Board	Oriented Strand Board High	725.0	0.95	1880.0	0.115	1015.1
Bottom Plate	Spruce	400	0.9	1880.0	0.086	552.0
Top Plate	Spruce	400	0.9	1880.0	0.086	552.0
Insulation	Fibre Glass	30	0.99	840.0	0.035	1.3
Vapour Barrier	Vapor Retarder (1Perm)	130.0	0.001	2300.0	2.3	3280.0
XPS	Extruded Polystyrene Insulation	28.6	0.99	1470.0	0.025	170.56
VIP	Vacuum Insulation Panel	200	0.001	800	0.007	1500000.0
Dry Wall	Gypsum Board (USA)	850.0	0.65	870.0	0.163	6.0

5.4. Initial Conditions

The materials installed in the building construction have some amount of water content already present in them because of their hygroscopic nature. Thus a default value of water content was already specified for the materials based on the temperature and the relative humidity. A default relative humidity of 80% and a temperature of 20°C was used for all the materials and the corresponding moisture content for the building layers was assigned for each of the components as calculated from the moisture storage function given in WUFI. Table 7 gives the overview of the specified RH and temperature for each of the material with the corresponding moisture content for each of the components.

Table 7: Initial Conditions

Material	Temperature (°C)	Water Content (kg/m³)	Relative Humidity (%)
Regular Portland Stucco	20	106.6	0.8
Spun Bonded Polyolefin Membrane	20	0	0.8
Oriented Strand Board High	20	89.9	0.8
Spruce	20	55.8	0.8
Spruce	20	55.8	0.8
Fibre Glass	20	1.9	0.8
Vapor Retarder (1Perm)	20	0	0.8
Extruded Polystyrene Insulation	20	0.3	0.8
Vacuum Insulation Panel	20	0	0.8
Gypsum Board (USA)	20	6.2	0.8

5.5. Surface/Climate

The boundary and climatic conditions for the wall assembly were defined through the Surface/Climate option in WUFI-2D. Both the indoor and outdoor conditions for the wall assembly were defined for the regular and retrofitted walls. Heat transfer coefficients for the exterior surface were defined as $17\text{W/m}^2\text{K}$, with a short wave radiation absorptivity of 0.4 and long wave radiation emissivity of 0.9. Similarly for the indoor surface the heat transfer coefficient of $88\text{W/m}^2\text{K}$ was assigned with an oil paint layer having a short wave radiation absorptivity of 0.3 and a long wave emissivity of 0.94. The climate file defining the temperature fluctuations and the relative humidity fluctuations with rain loads was assigned from the climate database for the respective locations in the consideration. The WUFI climate database provides an overview of the annual temperature and relative humidity profiles for the selected location as shown in Figure 12 in the Temperature/Relative Humidity tab. Similarly it provides a climate overview in the Climate Analysis tab, wherein it computes and updates the average, minimum and maximum values of the temperature and relative humidity and also provides a sun radiation sum and driving rain sum rose diagrams as shown in Figure 13. The indoor climatic conditions can be defined in either of the five given ways; by selecting the weather file for the location from the database, by specifying user defined conditions, by defining the indoor conditions as per the outdoor conditions based on the EN13788 guidelines, or the EN 15026 guidelines or the ASHRAE 160P guidelines. For this study two types of indoor conditions based on the ASHRAE 160P and EN 13788 guidelines were used to simulate the wall assembly. The overview of the relative humidity and temperature for the eight North American locations is as shown in Table 8.

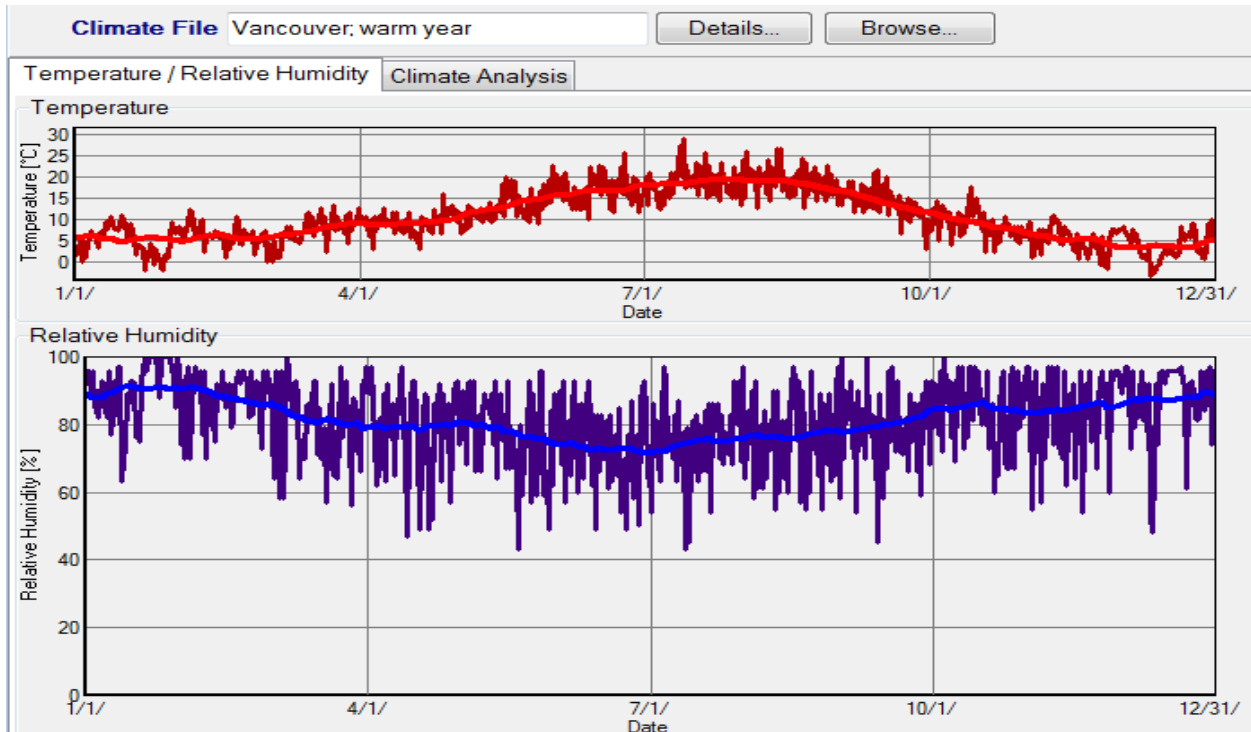


Figure 12: Temperature/ Relative Humidity overview for Vancouver in WUFI

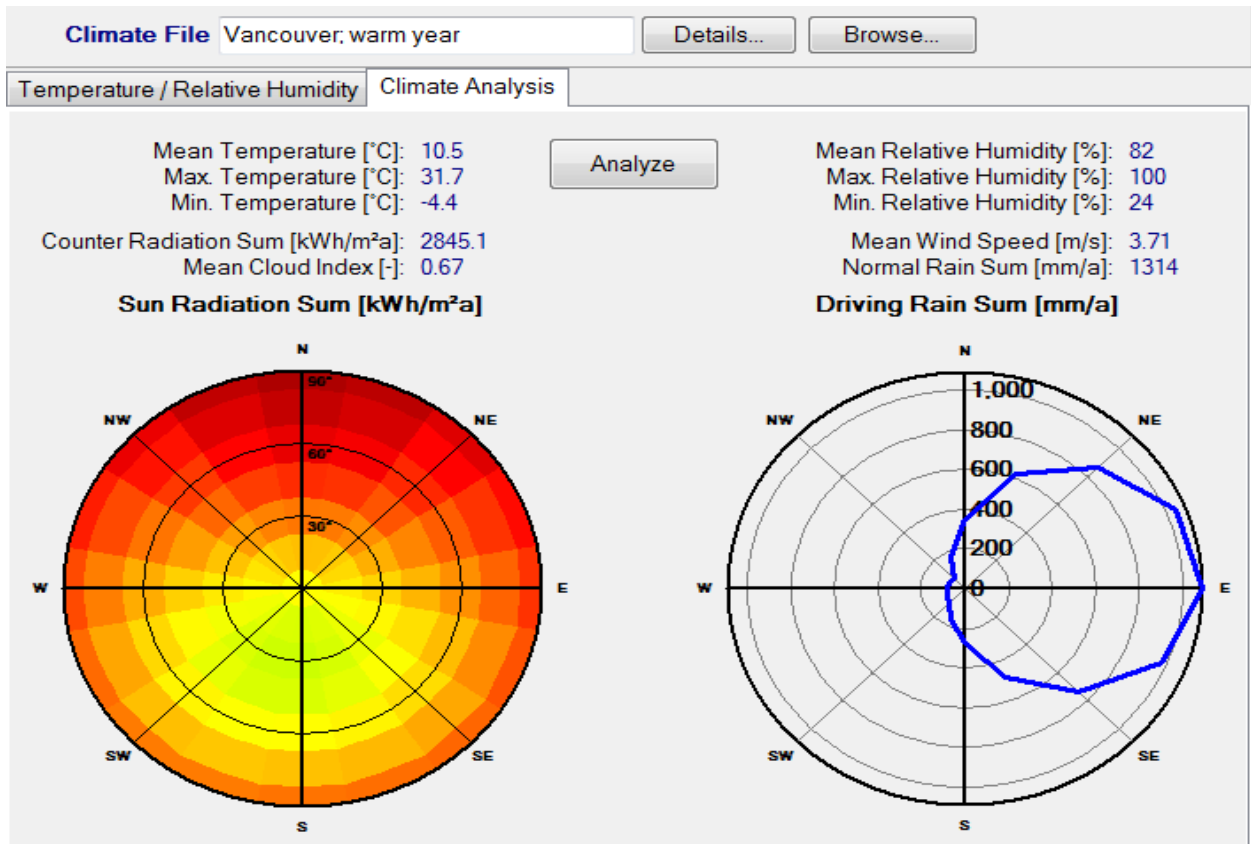


Figure 13: Climate Analysis for Vancouver in WUFI

Table 8: Surface/Climate data for the North American locations

Location	Average Temperature (°C)	Max Temperature (°C)	Min Temperature (°C)	Ave Relative Humidity (%)	Max Relative Humidity (%)	Min Relative Humidity (%)	Normal Rain Sum (mm/a)
Vancouver	10.5	31.7	-4.4	82	100	24	1314
Ottawa	7.1	33.8	-26.8	71	100	14	491
Winnipeg	4.0	37.9	-32.5	66	100	13	283
St. John's	5.5	25.6	-15.0	85	100	21	985
Phoenix	24.3	46.1	-0.6	33	100	4	184
Tampa	22.8	36.7	-5.6	72	100	15	1138
Wilmington	18.4	35.6	-6.1	75	100	16	1457
San Diego	19.2	37.2	6.7	73	100	6	249

The wall sections with the defined indoor and outdoor climatic conditions were simulated for a period of three years starting from January 2013 until January 2016. The results for Relative Humidity, Water Content and Temperature were calculated from the simulations and given as an output.

5.6. Analysis Methods

The simulation results obtained for the Relative Humidity, temperature and Water Content were used as the basis for the evaluation of hygrothermal performance of the regular and the retrofitted walls at those eight selected North American locations.

Walls were simulated using different VIP thicknesses to find an effective VIP thickness for the retrofitting, which has the minimum moisture risk associated and yet provides sufficient thermal resistance. VIP of thicknesses 8mm, 13mm and 25mm were used for the evaluation. The regular wall construction and the interior VIP retrofitted wall assembly with the specified thicknesses were simulated with the same defined weather conditions over the period of three years using ASHRAE 160P guidelines. The thermal performance of the wall assembly retrofitted with VIP thickness of 25mm would be higher than with the VIP thicknesses of 13mm and 8mm. Therefore in order to assess the effect of the VIP thickness on the hygrothermal performance of the building envelope the results for the relative humidity and water content were analyzed for all the eight locations. The results only from the third years were used for the evaluation. The initial conditions given in the input file, result in higher variation for the first year results. It requires some time for the building components to get “conditioned” to the environment and generally the results from the second year onwards are deemed useful for the evaluation.

The VIP thickness thus decided after evaluation was used for the simulations of the interior VIP retrofitted wall assembly and exterior VIP retrofitted wall assembly. Both the regular wall assembly and the retrofitted wall assembly were simulated with the same climatic conditions over

the same time period of three years from January 2013 till January 2016. The wall assemblies were simulated with different interior moisture loading based on ASHRAE 160P (normal moisture load) and EN13788 (higher moisture load) guidelines to assess the hygrothermal performance and the effect of increased interior moisture loading on the wall performance. The results for all the simulations were compared with the regular wall assembly to assess the effect on hygrothermal performance of the VIP retrofitted walls. Table 9 given below outlines the type and number of simulations run over the period of this study.

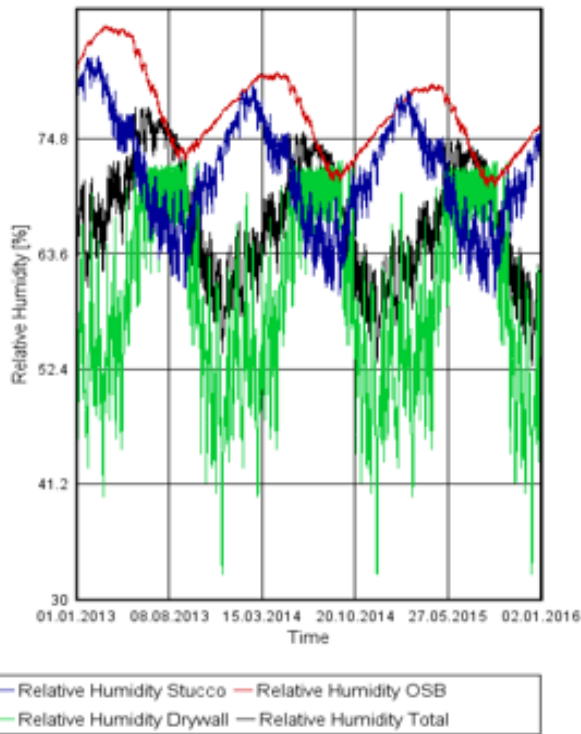
Table 9: Wall configurations and boundary conditions

Regular Wall	Interior Retrofitted Wall	Exterior Retrofitted Wall
ASHRAE 160P	ASHRAE 160P – 8mm	ASHRAE 160P – 13mm
	ASHRAE 160P – 13mm	
	ASHRAE 160P – 25mm	
EN 13788	EN 13788 – 13mm	EN 13788 – 13mm

The simulation results thus obtained from WUFI were further used to evaluate the moisture problems within the wall assembly. RHT indices based on two conditions were calculated for all the eight locations. RHT (80, 0) and RHT (80, 5) were calculated and the results for the normal wall, interior retrofitted wall and exterior retrofitted wall were compared using the RHT index to assess any increase in the performance of the retrofitted wall assembly. The results were also used to calculate the approximate Freeze-Thaw cycles for regular wall, interior retrofitted wall and exterior retrofitted wall.

WUFI provides an overview of the calculations by plotting the results obtained for the hourly simulation in a graphical format. Figure 14, shows the RH plot for Vancouver; similar plots were generated for the WC and temperature profiles. WUFI provides the option to select individual elements, a wall layer or the whole wall assembly from the simulated wall construction, and then individual plots for the selected elements can be obtained. For this study the results for the stucco layer, OSB layer, Drywall layer and Total construction were plotted and compared for the hygrothermal performance of the wall assembly.

Relative Humidity Vancouver



Relative Humidity Vancouver VIP

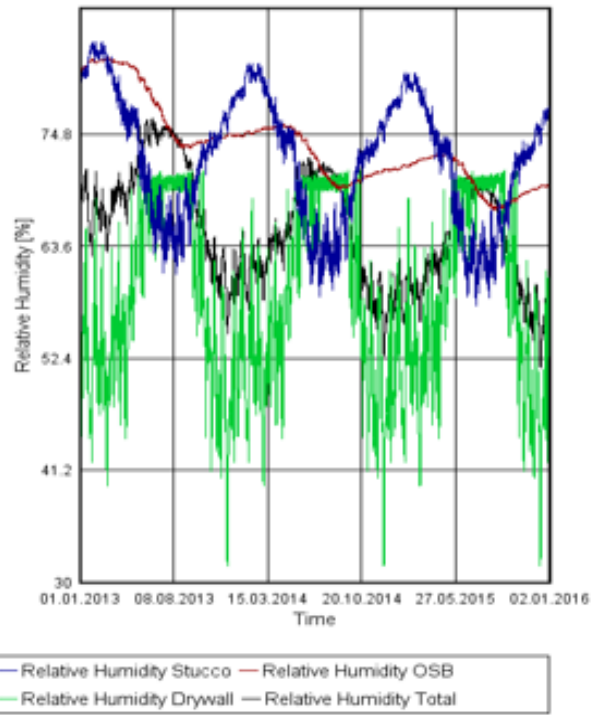


Figure 14: WUFI RH graph at Vancouver for regular wall and interior VIP retrofitted wall

The hourly results from the simulation plots were imported in excel and average, minimum and maximum values from the third year results were calculated as shown in Figure 15. The results from the WC, RH and temperature were used to evaluate and compare the performance of the regular wall and retrofitted walls.

Time	Relative Humidity Stucco	Relative Humidity OSB	Relative Humidity Drywall	Relative Humidity Total							
01.01.2013	80	80	80	80							
01.01.2013	79.66186	80.02525	70.82196	79.20729	MAX	79.48019	80.11887	72.60776	74.82526		
01.01.2013	79.72238	80.06633	65.43671	78.66153	MIN	59.34265	70.05615	32.4492	52.75723		
01.01.2013	79.79749	80.1127	61.72258	78.16211	AVERAGE	70.85255	75.77135	59.4909	65.83236		
01.01.2013	79.8726	80.1598	59.02744	77.66567							
01.01.2013	79.94207	80.20609	56.902	77.14957							
01.01.2013	80.0042	80.25112	54.82612	76.58683							
01.01.2013	80.04208	80.29497	53.10248	76.00767							
01.01.2013	80.0897	80.33757	52.0649	75.45674							
01.01.2013	80.14986	80.37856	51.41628	74.92766							
01.01.2013	80.09505	80.41779	50.95008	74.41654							
01.01.2013	80.10353	80.45458	50.46588	73.94052							
01.01.2013	80.02968	80.4864	50.05009	73.51125							
01.01.2013	79.92517	80.51748	49.68617	73.13374							

Figure 15: RH Calculation example for Vancouver location using MS Excel

An added risk of Freeze-Thaw damages is expected with the addition of insulation either on the exterior or interior side of the wall, due to the changed temperature gradients in the wall. Calculation of the approximate number of Freeze-Thaw cycles can help in determining the performance and durability of the wall assembly. A freeze thaw cycle can be explained as a cycle when the moisture present in the wall assembly layers freezes when the temperature goes below 0°C and changes to liquid when the temperature goes above 0°C. The number of Freeze-Thaw cycles thus calculated can give an approximation of the extent of damage caused by freeze thaw. The results from the third year simulation results were calculated and excel was used to calculate whenever the temperature fell below 0°C and turned back above 0°C. The Freeze-Thaw cycle results were calculated for all the wall systems with both the ASHRAE 160P and EN13788 guidelines.

A relatively new concept of RHT index was used to predict the moisture performance of the regular wall and retrofitted walls. Two RHT index of relative humidity 80% and temperature 0°C and relative humidity 80% and temperature 5°C were used as an evaluation criterion from the results of the third year simulation results. It is observed from the studies that higher RHT index points to higher moisture problems in the wall system.

6. Results and Discussion

The aim of this thesis was to evaluate and assess the application and performance of VIP as a retrofitting option in North American locations. The Temperature, Relative Humidity and Water Content results for the stucco layer, OSB layer, drywall layer and the total wall construction were chosen as the evaluation criterion. VIP by virtue of its vapor tight construction and high vapour diffusion resistance can be used as a vapor barrier, thus making the evaluation of the OSB layer and the Drywall layer critically important during the interior retrofitting and exterior retrofitting options. VIP could hinder the vapour diffusion flow from the inside to outside or vice versa based on the retrofitting application. WUFI-2D simulations for the regular wall, interior retrofitted wall and exterior retrofitted wall for both the interior moisture loading conditions of ASHRAE 160P (normal moisture loading) and EN13788 (higher moisture loading) were used in this study and the results obtained from this study are as described below.

6.1. Moisture Performance with ASHRAE 160P Guidelines

6.1.1. Moisture Performance Evaluation of Wall Retrofitted with 8mm, 13mm and 25mm VIP

VIPs are manufactured in standard sizes and thicknesses and the VIP construction makes it difficult to alter or redesign the VIP based on the building design and construction. In order to obtain appropriate sizing of the VIP, simulations for interior retrofitted wall assemblies under similar conditions with ASHRAE 160P guidelines but with different VIP thicknesses of 8mm, 13mm and 25mm were undertaken and the results for the WC and RH around all the eight different locations were compared. The results for the OSB layer and Drywall layer were critically analyzed. Table 10 gives an overview of the maximum WC in the OSB layer for the wall retrofitted with 8mm, 13mm and 25mm VIP.

Table 10: Maximum WC in OSB layer for interior retrofitted wall with 8mm,13mm and 25mm VIP

WC (kg/m ³) OSB								
VIP Thickness	Phoenix	San Diego	Winnipeg	Ottawa	Tampa	Vancouver	Wilmington	St. John's
8mm	23.7	64.1	53.8	65.9	66.2	76.2	72.4	88.5
13mm	23.5	63.9	53.7	65.9	65.7	76.3	72.0	88.8
25mm	23.4	63.6	53.7	65.9	64.9	76.6	71.4	89.4

The range plot comprising of the maximum and minimum WC for the VIP thicknesses of 8mm, 13mm and 25mm were plotted at each of the eight locations and compared. From the graph shown in Figure 16, it is observed that the WC range for all of the VIP configurations was similar, with a very little deviation between each.

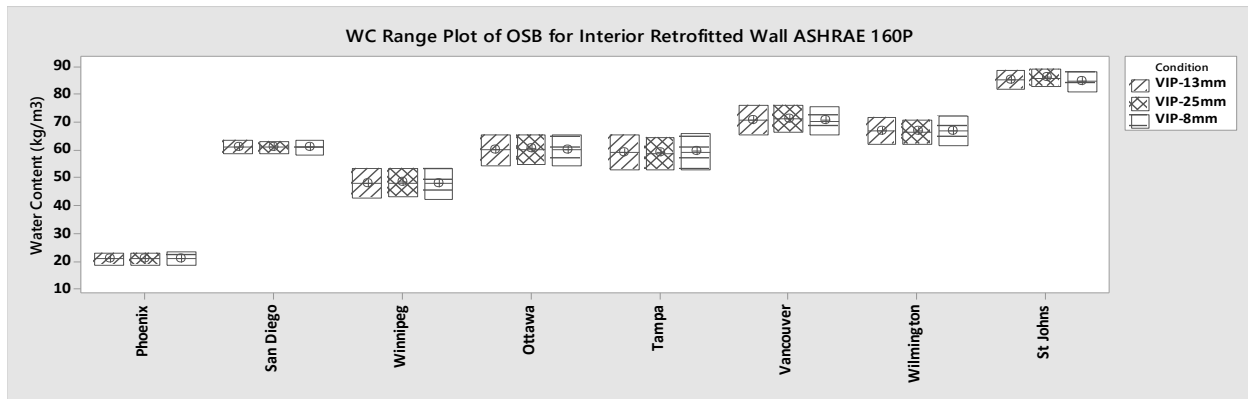


Figure 16: WC range plot of OSB for interior retrofitted wall with 8mm, 13mm and 25mm VIP

The graph shown in Figure 17 gives the % change in the maximum WC of the OSB layer for the wall retrofitted with 13mm VIP and wall retrofitted with 25mm VIP as compared to the maximum WC of the wall retrofitted using the 8mm VIP. The maximum % increase in the WC was observed to be 0.3% at St John's and minimum % decrease was observed to be 0.8% at Tampa. Similarly for the wall retrofitted using the 25mm thick VIP the maximum % change increase was observed to be 1% at St. John's whereas the maximum decrease was observed at Wilmington standing at 1.4%. From the % change results in OSB layer we could conclude that there was not a significant change in the WC performance of the OSB layer with changed VIP thicknesses.

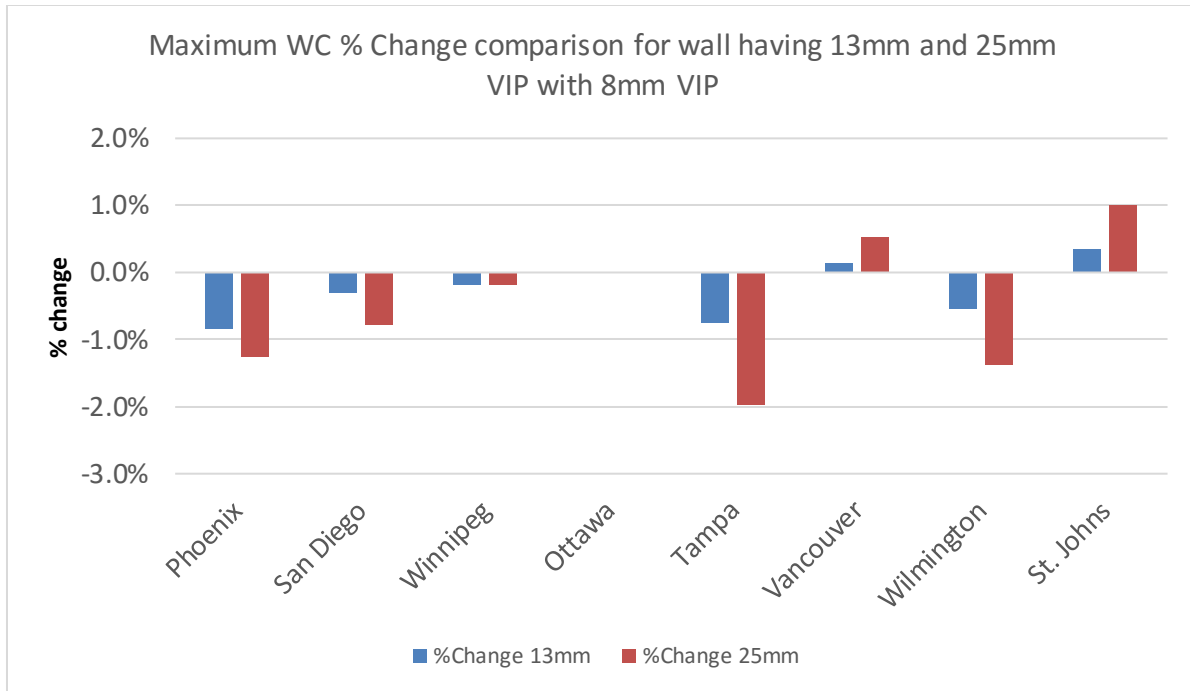


Figure 17: Maximum WC % change in OSB for interior retrofitted walls with 13mm and 25mm VIP compared with the 8mm

Similarly the maximum and the minimum WC for all retrofitted walls was plotted for the drywall layer as shown in Figure 17. Table 11, shown below, gives the maximum WC in the drywall layer for all the eight locations.

Table 11: Maximum WC in drywall for interior retrofitted wall with 8mm, 13mm and 25mm VIP

WC (kg/m ³) Drywall								
VIP Thickness	Phoenix	San Diego	Winnipeg	Ottawa	Tampa	Vancouver	Wilmington	St. Johns
8mm	5.0	5.1	5.1	5.1	5.1	5.1	5.1	5.1
13mm	5.0	5.1	5.1	5.1	5.1	5.1	5.1	5.1
25mm	5.0	5.0	5.0	5.0	5.0	5.0	5.1	5.1

The Figure 18 provides the range plot of the drywall layer for the wall retrofitted on the interior with 8mm, 13mm and 25mm thick VIP respectively. It could be observed from the range plots that the change in the WC levels of the drywall layer with the changed VIP thickness was not significant thus not noticeable.

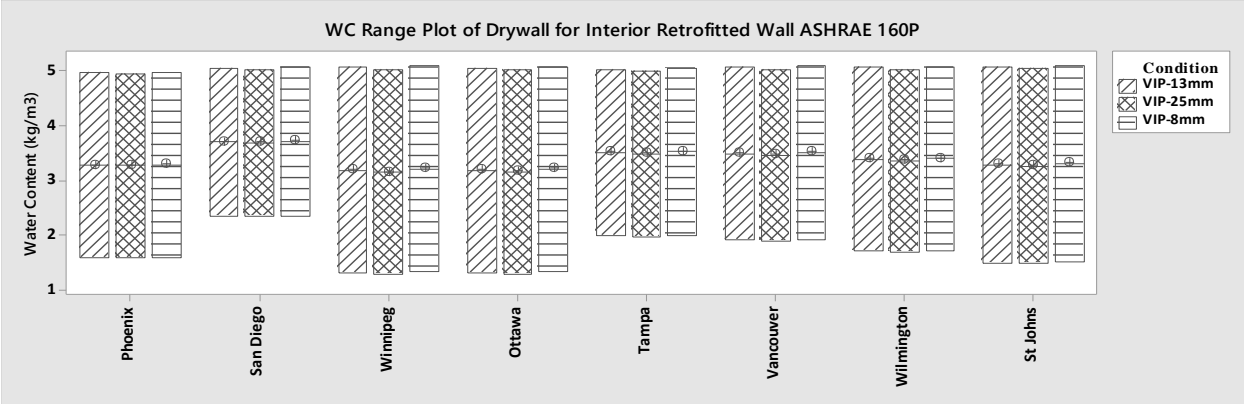


Figure 18: WC range plot comparison in drywall for interior retrofitted wall with 8mm, 13mm and 25mm VIP

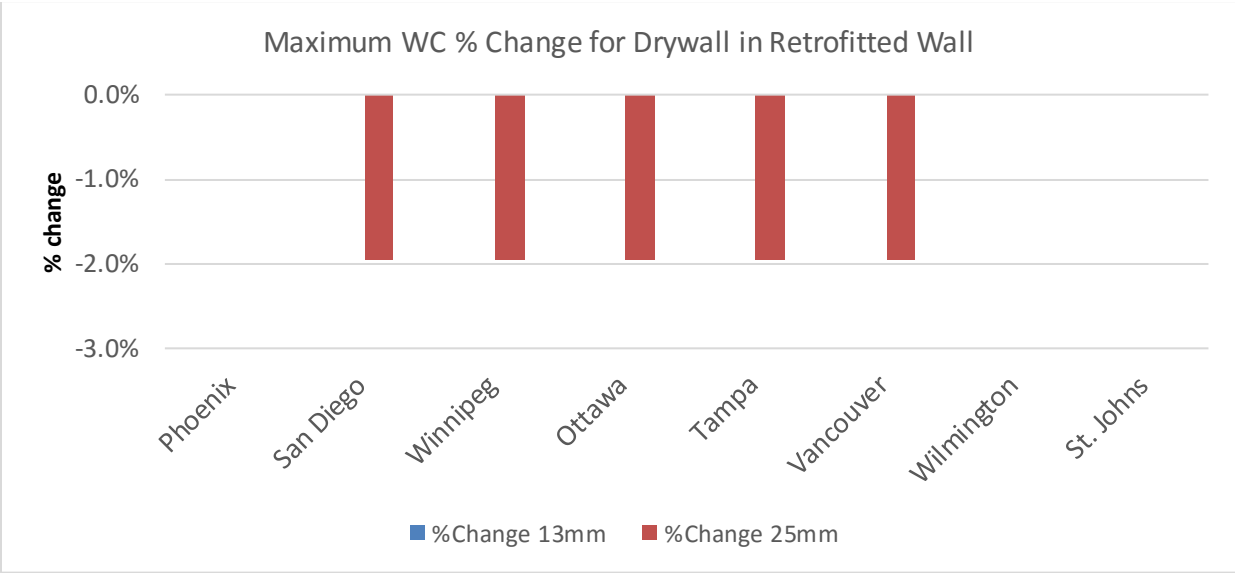


Figure 19: Maximum WC % change in drywall for interior retrofitted walls with 13mm and 25mm VIP compared with 8mm

Figure 19 shown above gives the % change in the maximum WC of drywall layer for the wall retrofitted with 13mm VIP and wall retrofitted with 25mm VIP as compared to the wall retrofitted with 8mm VIP. From the results we can observe that no change was observed in the WC of the wall retrofitted with 13mm VIP, whereas the maximum % decrease of 2% was observed in the WC of the wall retrofitted using 25mm VIP as compared to wall retrofitted using the 8mm VIP and no changes were observed for the Phoenix, Wilmington and St. John’s location.

The results for the RH for the drywall and the OSB layer were also used to evaluate the effect of increasing the VIP thickness on the moisture performance of the retrofitted wall. The Table 12 shows the maximum RH from the third year simulation results for the wall retrofitted on the interior side using 8mm VIP, 13mm VIP and 25mm VIP.

Table 12: Maximum RH in OSB in interior retrofitted walls with 8mm, 13mm and 25mm VIP

RH (%) OSB								
VIP Thickness	Phoenix	San Diego	Winnipeg	Ottawa	Tampa	Vancouver	Wilmington	St. Johns
8mm	31.1	66.0	59.5	67.1	67.3	72.9	71.0	79.3
13mm	30.9	65.8	59.4	67.1	67.0	73.0	70.7	79.5
25mm	30.7	65.7	59.4	67.1	66.5	73.1	70.4	79.8

Figure 20, below gives the RH range plots for the interior retrofitted wall with the VIP thicknesses of 8mm, 13mm and 25mm. It can be observed from the range plot that the variation in the RH in the OSB layer at all the locations was similar.

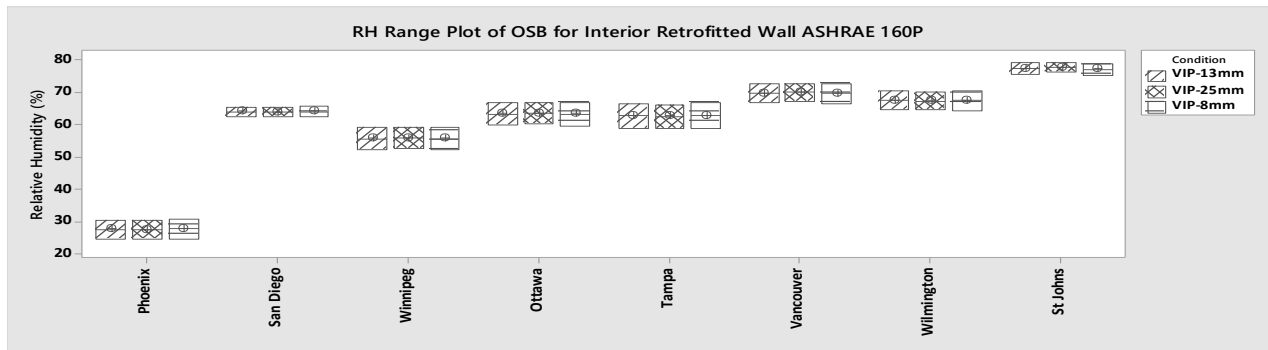


Figure 20: RH range plot comparison for interior retrofitted wall with 8mm, 13mm and 25mm thick VIP

Figure 21 gives the % change comparison of the RH in the walls retrofitted with VIP of thicknesses 13mm and 25mm with the wall retrofitted with VIP of 8mm. From the results it was observed that the maximum increase in the % change was observed to be 0.3% for 13mm VIP and 0.6% for the 25mm VIP; both of them were for St. John's. Similarly the maximum decrease in the % change was calculated at 0.6% for the 13mm VIP and 1.3% for the 25mm VIP for the St. John's location.

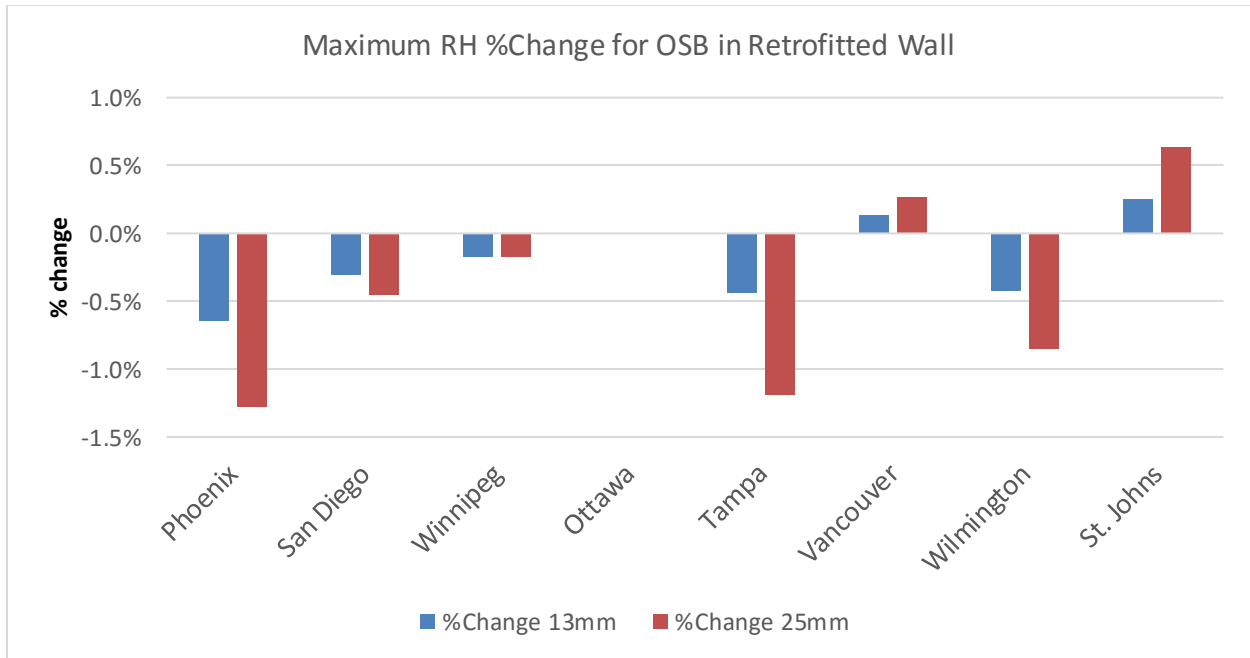


Figure 21: Maximum RH % change in OSB for interior retrofitted walls with 13mm and 25mm VIP compared with the 8mm

Similarly like OSB the RH results for the drywall layer were also calculated and compared for the wall retrofitted using VIP thicknesses of 13mm and 25mm and 8mm. Table 13, given below, compares the maximum RH for all retrofitted wall with the VIP thicknesses of 8mm, 13mm and 25mm at all the eight locations.

Table 13: Maximum RH in drywall for interior retrofitted wall with 8mm, 13mm and 25mm VIP

RH (%) Drywall								
VIP Thickness	Phoenix	San Diego	Winnipeg	Ottawa	Tampa	Vancouver	Wilmington	St. Johns
8mm	70.5	71.3	71.4	71.3	71.0	71.4	71.3	71.5
13mm	70.4	71.1	71.2	71.1	70.9	71.2	71.2	71.3
25mm	70.2	70.8	70.9	70.9	70.7	70.9	70.9	71.0

The RH variation around all the eight locations was also critically observed and range plots were plotted for the eight locations for the VIP configuration used, as shown in Figure 22. It could be noted from the range plots that the ranges for all the configurations were similar and a very small variation between the RH plots for the drywall layer was observed.

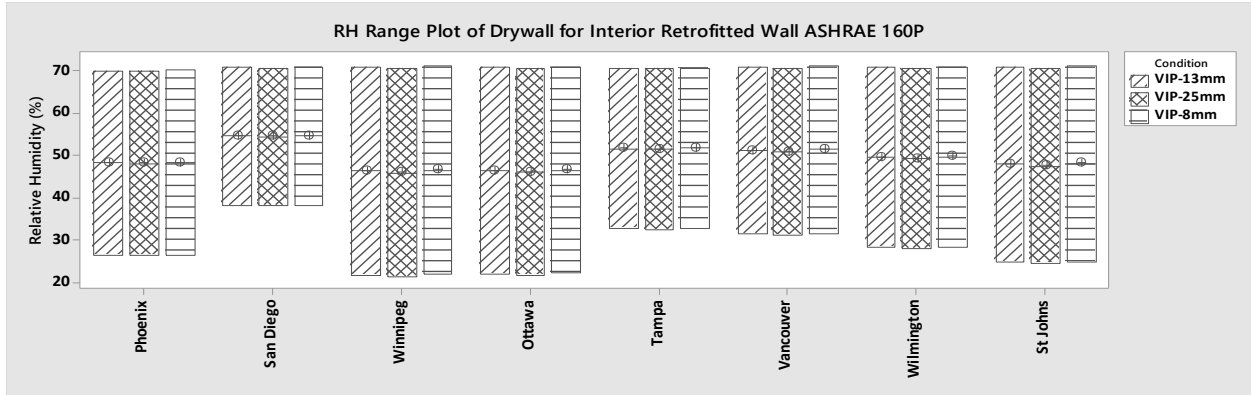


Figure 22: RH range plot comparison in drywall for interior retrofitted walls with 8mm, 13mm and 25mm VIP

Figure 23, shown below gives the maximum % change in RH for the drywall layer for the walls retrofitted using 13mm and 25mm VIP with the wall retrofitted using the 8mm VIP. From the calculations it was observed that the max increase in the difference was 0.3% for the wall retrofitted using the 13mm VIP whereas for the wall retrofitted using 25mm VIP it was 0.7%.

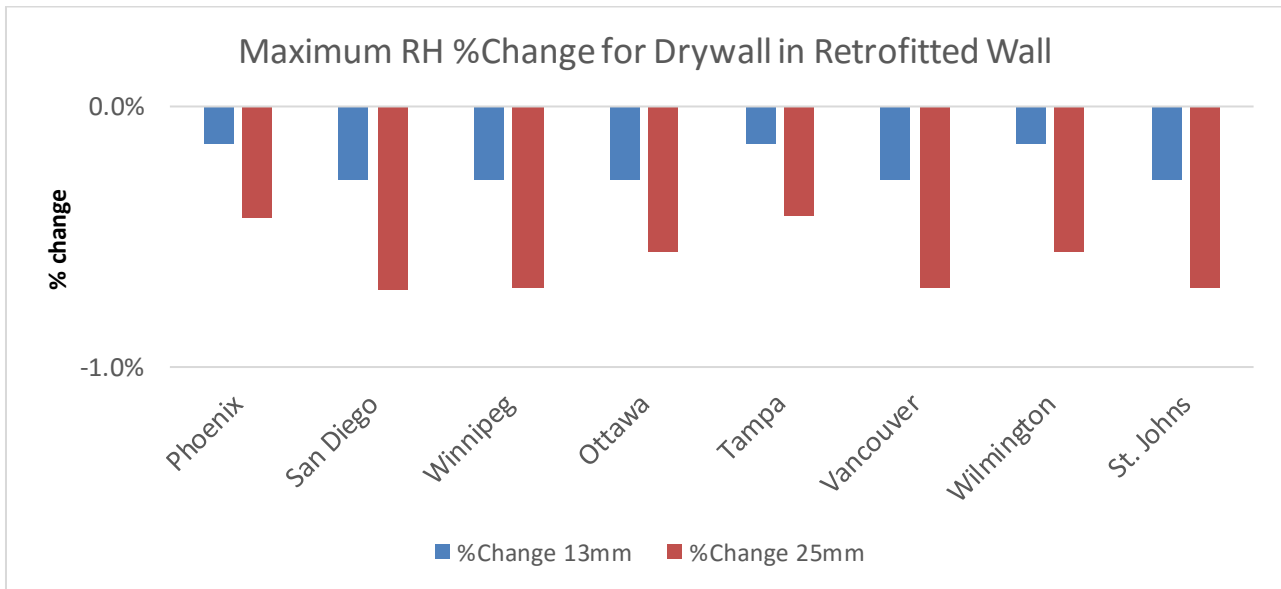


Figure 23: Maximum RH % change in drywall for interior retrofitted walls with 13mm and 25mm VIP compared with the 8mm

From the comparative study it was concluded that the hygrothermal performance of the critical component in the wall construction i.e. drywall and OSB were similar for all the retrofitting option. Increasing the R-Value of the insulation improves the overall thermal efficiency of the house, which means that the overall thermal resistance of the wall assembly would be higher when using VIP of thickness 25mm as compared to the VIP of 8mm and 13mm thicknesses. The cost of VIP construction increases with the increasing VIP thicknesses, thus increasing the overall cost of retrofitting the building envelope. Thus, by taking all the possibilities in consideration, it was decided to calculate the results using 13mm thick VIP.

6.1.2. Moisture Performance Evaluation of Regular Wall, Interior VIP Retrofitted Wall and Exterior VIP Retrofitted Wall

The regular wall assembly, interior VIP retrofitted wall and exterior VIP retrofitted wall were modelled and simulated using WUFI-2D. The walls were simulated in the same locations and same conditions to compare the hygrothermal performance of the wall sections. The hygrothermal results from the third year simulations were used to compare the RH, WC and temperature profiles for the stucco layer, OSB layer, drywall layer and total wall assembly for the simulation cases.

RH for the OSB layer for the three configuration was compared for evaluation as shown in Figure 24. It could be observed from the range plot that the interior retrofitted wall had a smaller range as compared to the exterior retrofitted configuration, except at Tampa and Wilmington location. It could be observed from the range plot that maximum RH for all the locations for OSB layer was lower than 80% for the interior and exterior retrofitted configuration, whereas it rose up to 90% for the regular wall configuration.

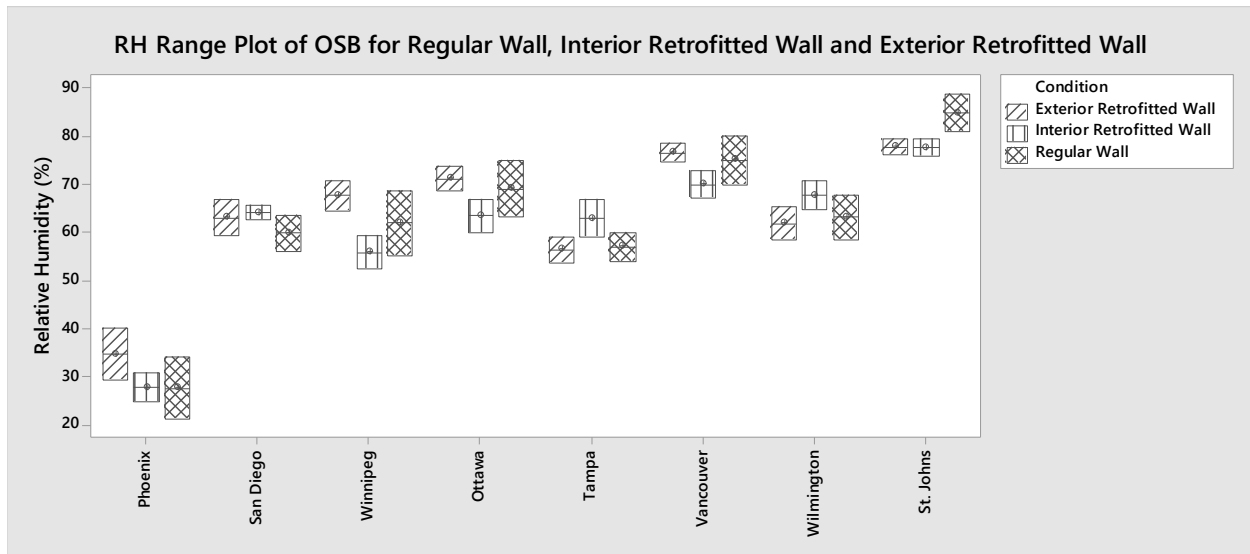


Figure 24 RH range plot comparison in OSB for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall

Similarly the RH range plot for the drywall layer was also plotted for the regular wall, interior retrofitted wall and exterior retrofitted wall as shown in Figure 25. From the range plots it could be concluded that the maximum RH for both the interior retrofitted wall and exterior retrofitted wall was 70% or below, which results in less moisture problems. The range plots were observed to be similar for both the retrofitting configuration, resulting in suitability of using VIP as a retrofitting measure for interior or exterior retrofitting.

Water content range plots for all the three configurations, i.e. regular wall, interior retrofitted wall and exterior retrofitted wall were plotted and compared as shown in Figure 26. From the range plot it could be concluded that maximum WC for the interior retrofitted wall was lower than the exterior retrofitted wall except at Tampa and Wilmington locations. Wide range for the regular wall was observed for the regular wall construction and reached the highest level above 110kg/m³ for the St. John's location.

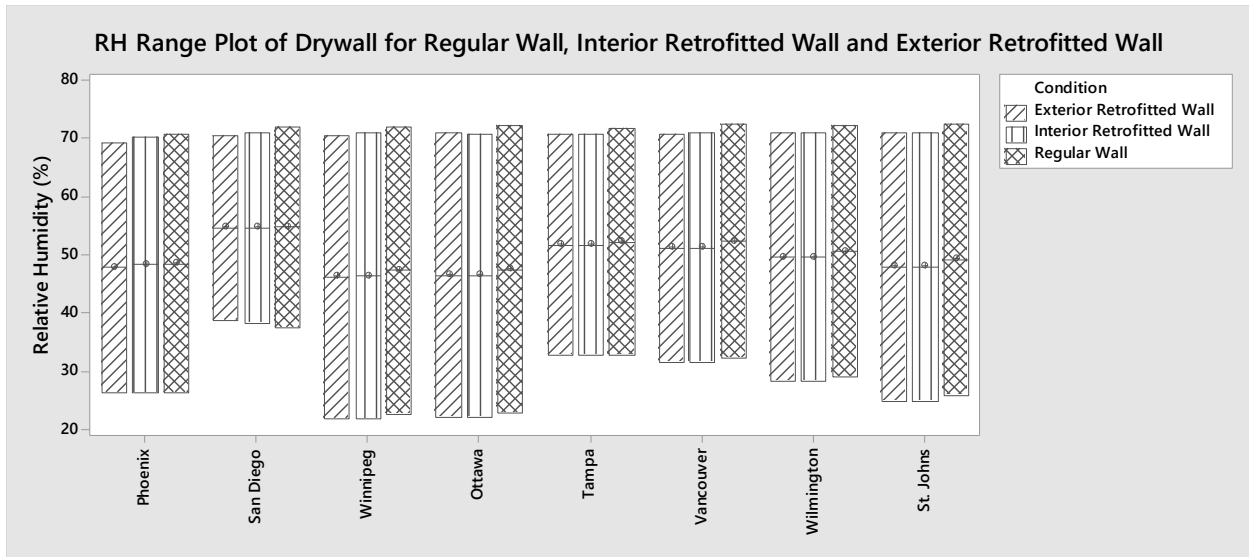


Figure 25 RH range plot comparison in OSB for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall

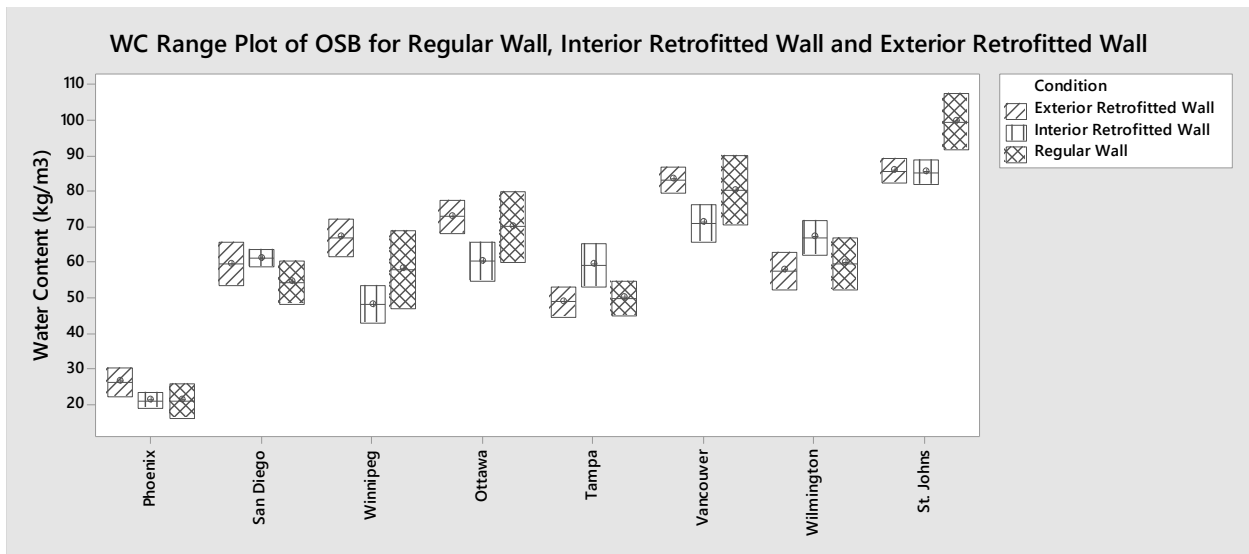


Figure 26 WC range plot comparison in OSB for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall

Similarly WC range plot for the drywall layer was also computed and compared. From the Figure 27 it could be observed that the WC range plots for the interior retrofitted wall and exterior retrofitted wall were similar and wider range was observed for the regular wall configuration.

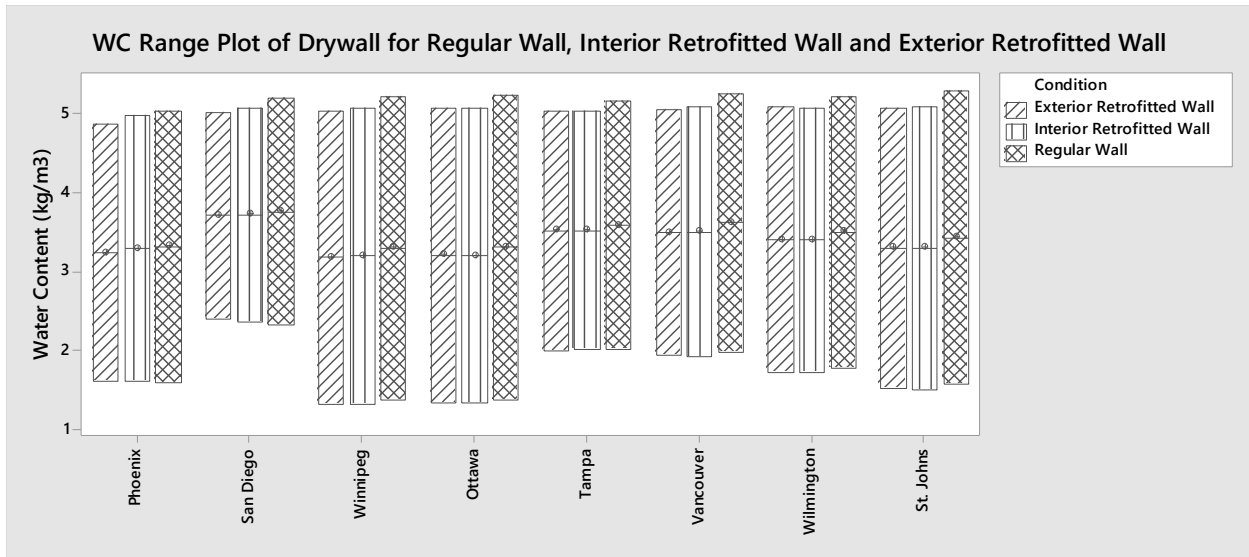


Figure 27 WC range plot comparison in drywall for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall

The temperature range plots of the regular wall, interior retrofitted wall and exterior retrofitted wall were also compared for the drywall layer as shown in Figure 28. It could be observed from the figure that temperature range after retrofitting was lower as compared to the range plots for the regular wall and was hotter and cooler than the interior retrofitted wall and exterior retrofitted wall.

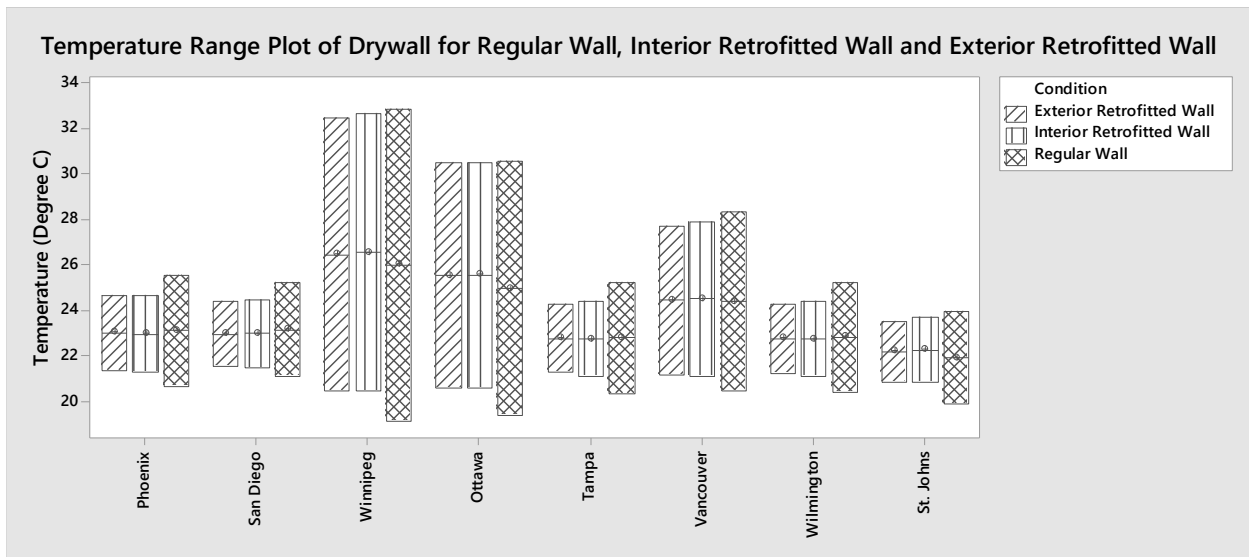


Figure 28 Temperature range plot comparison in drywall for regular wall, interior retrofitted wall and exterior retrofitted wall

Temperature range plot of OSB layer for the regular wall, interior retrofitted wall and exterior retrofitted wall was also compared as shown in Figure 29. From the figure it could be concluded

that the temperature fluctuations were least for the exterior retrofitted wall. Interior retrofitting further lowers the OSB temperature compared to the regular wall which could potentially lead to increased freeze thaw damages and deteriorate the appearance and performance of the wall.

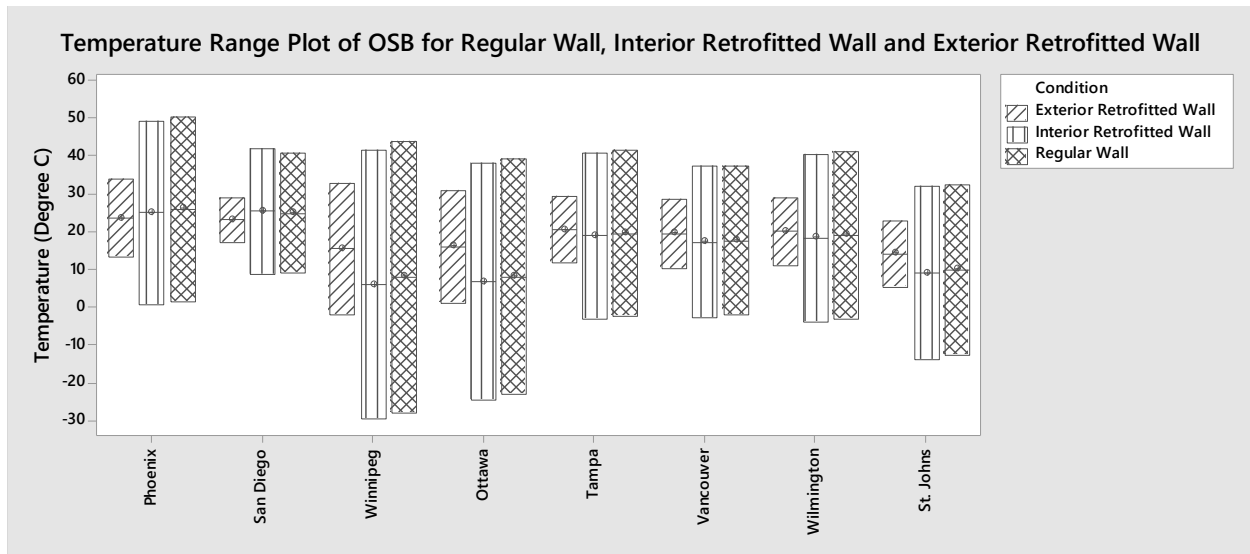


Figure 29 Temperature range plot comparison in OSB for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall

6.2. Moisture performance with EN 13788 Guidelines

To evaluate the wall performance of the wall assembly with higher interior moisture loads the wall was also simulated with EN 13788 guidelines but with higher moisture loading. In order to evaluate the performance of the wall assembly, regular walls and retrofitted walls both with interior VIP and exterior VIP were used and simulated for the same surface and boundary conditions over the time period of three years. The RH, WC and temperatures results were then exported into excel and were compared to evaluate the wall performance with ASHRAE 160P and EN 13788 guidelines.

6.2.1. Moisture Performance Evaluation of Regular Wall in ASHRAE 160P and Regular Wall in EN 13788

The results obtained from the simulation of the regular wall with EN 13788 conditions was compared with the results obtained for the regular wall with ASHRAE 160P conditions. The RH, WC and Temperature profiles were summarised in a range plot for both of the wall sections and were used to compare the moisture performance of the wall under higher moisture loading conditions. Figure 30 gives the WC range plot of the drywall layer for the regular wall for both the moisture loading conditions. From the figure, it could be observed that the maximum WC in the drywall layer for the ASHRAE 160P guidelines was lower for all the locations when compared to the EN 13788 guidelines.

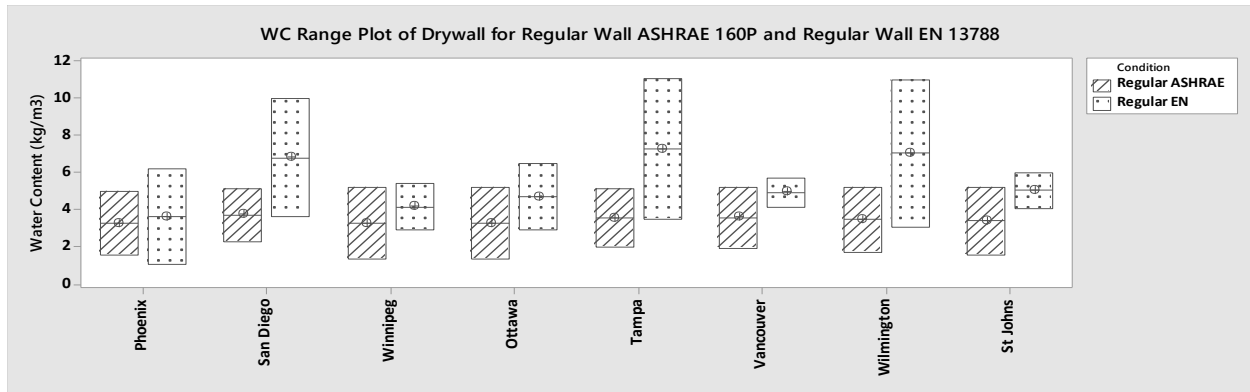


Figure 30: WC range plot comparison in drywall for regular wall ASHRAE 160P and regular wall EN 13788

Similarly the results for the WC in the OSB layer were also analyzed and evaluated for their performance compared with the ASHRAE 160P results as shown in Figure 31. The maximum WC for the EN 13788 conditions was observed to be a lot higher when compared to the maximum WC with ASHRAE 160P conditions. For the St. John's location the WC range was significantly higher than the range at ASHRAE 160P conditions. Increased moisture loading in the inside and the incoming moisture from the outside combined with the lesser time available for drying resulted in the increase in WC in the OSB layer. Increased amount of WC in the building layers can induce the mold generation and can also increase the risk of Freeze-Thaw damages.

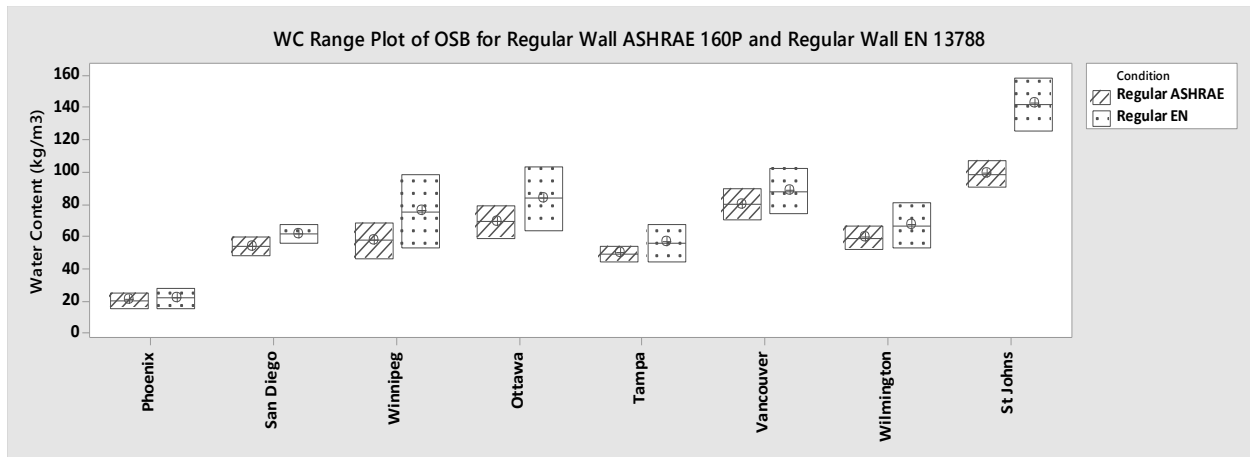


Figure 31: WC range plot comparison in OSB for regular wall ASHRAE 160P and regular wall EN 13788

Similarly the RH range plots for both the OSB layer and drywall layer were plotted for the regular walls with both moisture loading conditions. The RH range plot for the drywall layer is as shown in Figure 32, from the figure we can observe that the maximum RH for all the locations increased in the EN 13788 conditions and the highest was 91% for Tampa and Wilmington, which is right on the edge for the onset of mold formation, but mold formation also requires a threshold temperature for its growth. Higher RH could also potentially affect the freeze-thaw cycles and harm the outer wall layers of the wall assembly. The results for the freeze-thaw cycles are discussed later in the thesis.

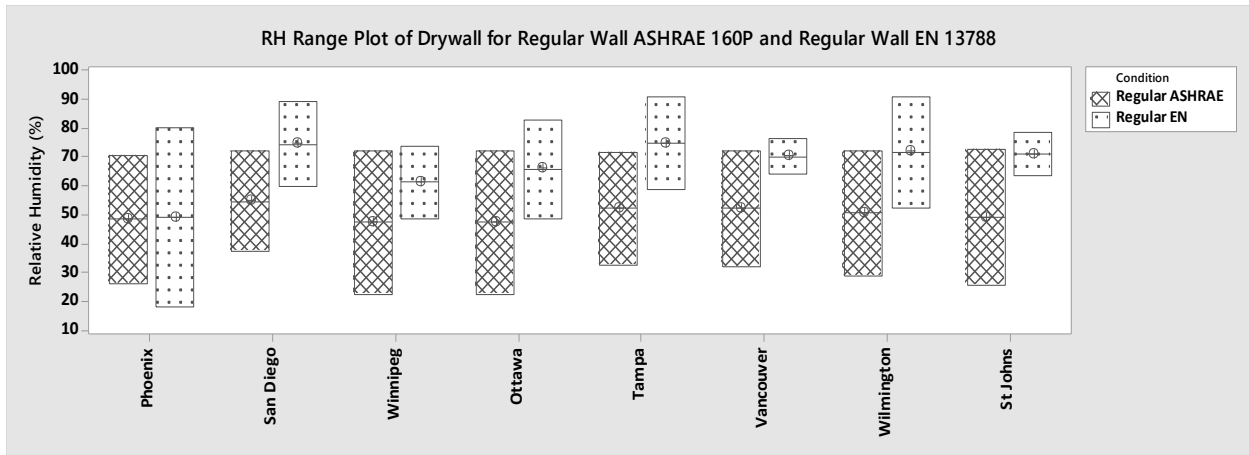


Figure 32: RH range plot comparison in drywall for regular wall ASHRAE 160P and regular wall EN 13788

The results for the RH range plot of the OSB layer are as shown in Figure 33. Similar results for the OSB layer were observed as compared to drywall layer. The maximum RH at the St. John's location was highest at 91% which is interesting as the St. John's has relatively higher MI when compared to the other locations, and higher moisture loading could adversely affect the wall performance. The increased RH could also potentially increase the risk for freeze thaw damages.

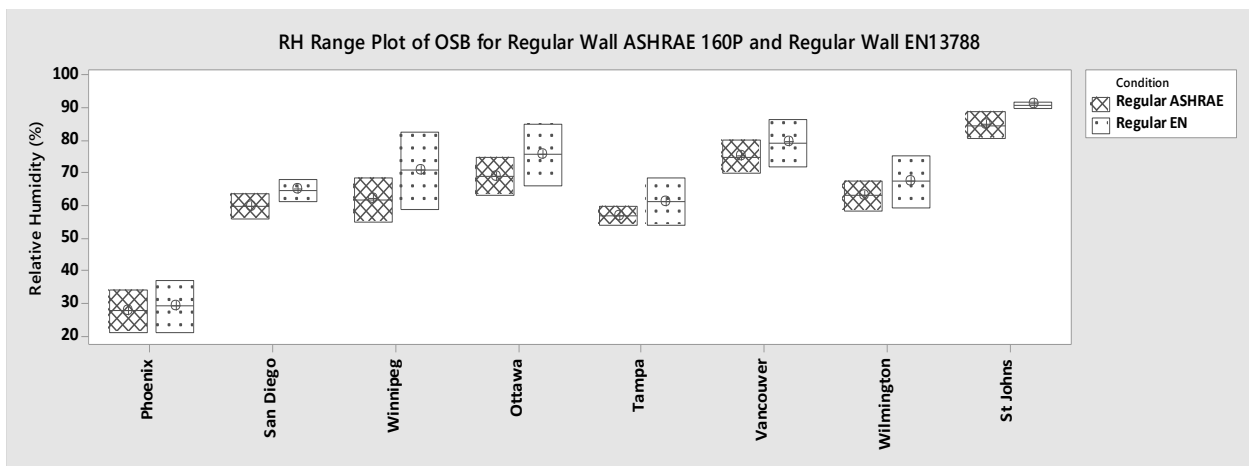


Figure 33: RH range plot comparison in OSB for regular wall ASHRAE 160P and regular wall EN 13788

Temperature range plots were plotted and analyzed to assess the indoor and outdoor conditions of the building envelope. The range plot for the drywall layer is as shown in Figure 34. From the range plot we can observe that the range for the drywall layer for the ASHRAE 160P conditions are relatively wider when compared to the ranges for the EN 13788 conditions, which is because in the ASHRAE 160P we had selected only the heating for the Canadian locations and the floating temperature shift was selected as 2.8°C for the 21.9°C set point temperature, whereas for the EN 13788 conditions the indoor temperature was set at 20°C, which resulted in the wider ranges for the temperature range plots of the locations with ASHRAE 160P conditions.

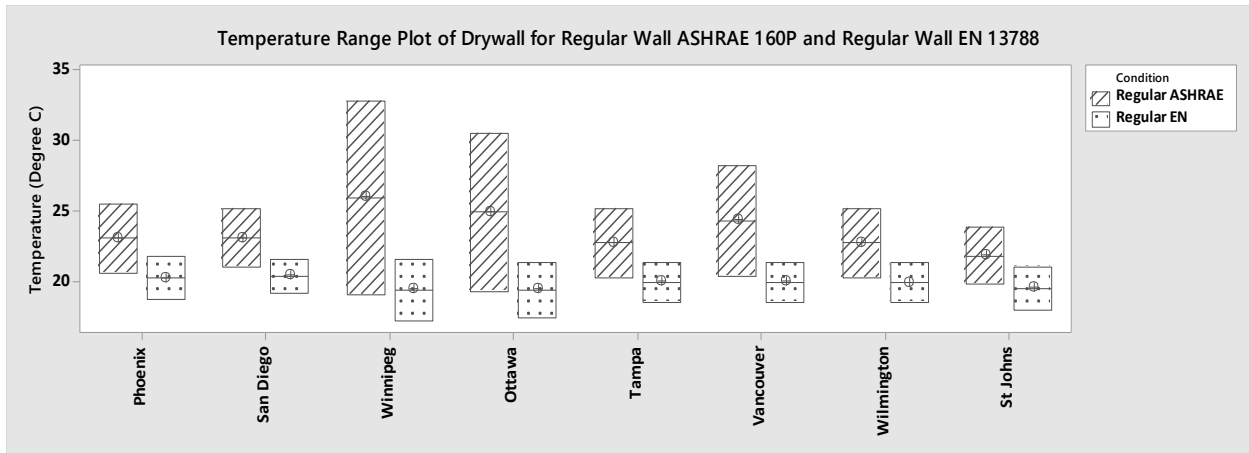


Figure 34: Temperature range plot comparison in drywall for regular wall ASHRAE 160P and regular wall EN 13788

Similarly the temperature range plots for the OSB layer for both the ASHRAE 160P conditions and EN 13788 conditions were selected to compare the temperature profiles of the wall layer. From Figure 35 it can be concluded that the average temperature profile for both the EN 13788 and ASHRAE 160P conditions were more or less similar.

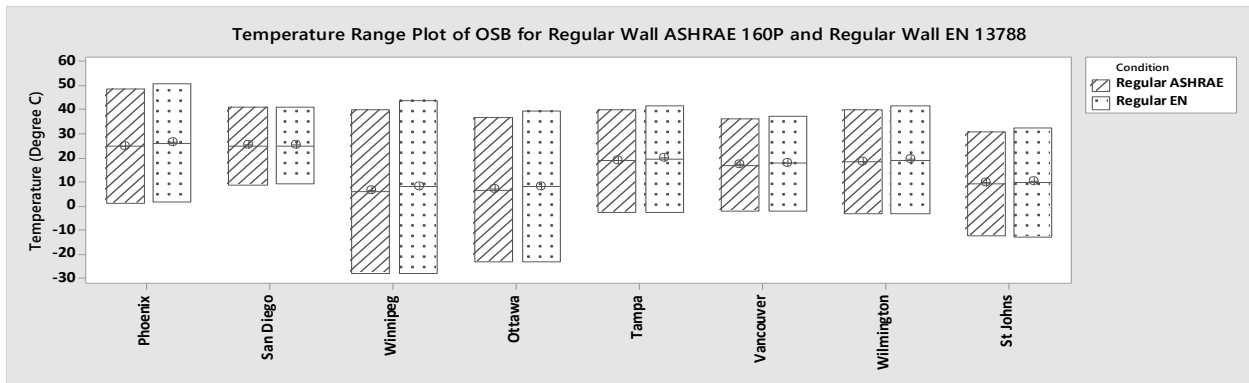


Figure 35: Temperature range plot comparison in OSB for regular wall ASHRAE 160P and regular wall EN 13788

6.2.2. Moisture Performance Evaluation of Interior VIP Retrofitted Wall with ASHRAE 160P and Interior VIP Retrofitted Wall with EN 13788

VIP has a high vapour diffusion resistance factor because it provides higher resistance to the vapour diffusion depending on the position it is placed. For the interior retrofitting with higher interior moisture loading conditions, it could result in higher RH and WC in the drywall layer by lowering the vapor diffusion from the inside to the outside. Thus, in order to evaluate the performance of the wall assembly with higher moisture loading conditions the wall was retrofitted with VIP and a higher moisture loading of EN 13788 was applied and the results were compared with the wall retrofitted on the interior with ASHRAE 160P conditions.

Range plots were used to compare the results for the RH, WC and temperature of the interior VIP retrofitted wall using the ASHRAE 160P and EN 13788 conditions. Figure 36, describes the WC range plot of the drywall layer. From the figure we can observe that the range plots for the EN

13788 conditions are significantly wider than the ASHRAE 160P conditions. The range plots for the US locations, which are hot and humid, have considerably higher range when compared to the cold Canadian locations. Also higher WC in the drywall layer could possibly increase the risk for mold generation in the wall assembly.

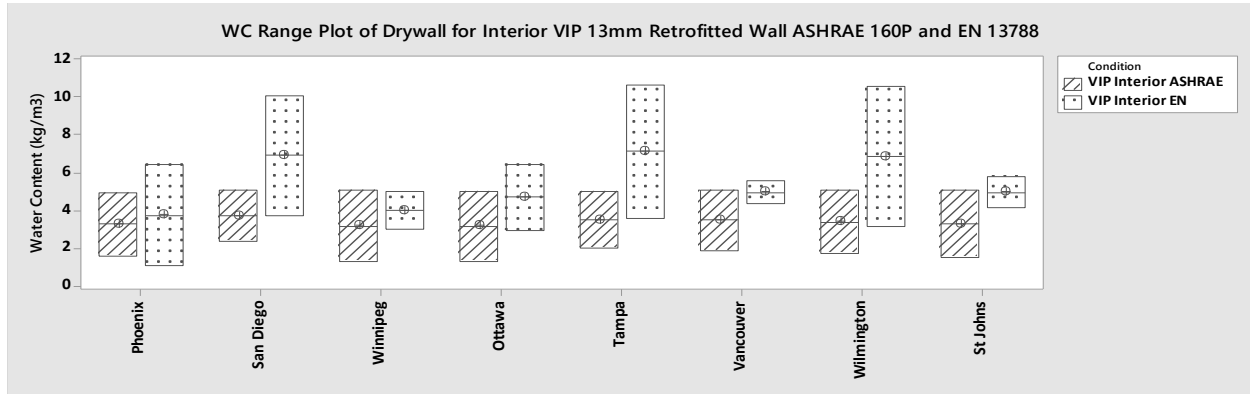


Figure 36: WC range plot comparison in drywall for interior VIP retrofitted wall ASHRAE 160P and EN 13788

The range plots for the WC of OSB layer in the interior retrofitted wall assembly for both the ASHRAE 160P and EN 13788 conditions is as shown in Figure 37. From the figure we can observe that the maximum WC was highest for the St. John’s location at 91kg/m³ for the EN 13788 which was comparable with the maximum WC of 89kg/m³ with the ASHRAE 160P conditions. From the figure we can deduce an inference that the WC for the OSB layer with ASHRAE 160P conditions was similar to the WC for the OSB layer with EN 13788 conditions.

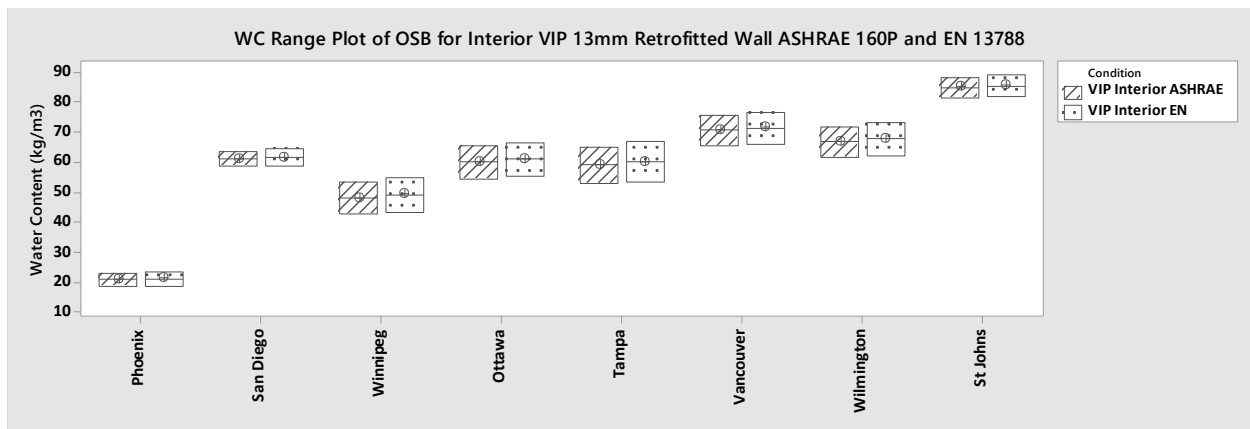


Figure 37: WC range plot comparison in OSB for interior VIP retrofitted wall ASHRAE 160P and EN 13788

Similarly the RH range plots were plotted for the interior VIP retrofitted wall assembly for both the EN 13788 and ASHRAE 160P conditions. The RH range plot for the OSB layer is as shown below in Figure 38. Range plots for both the EN 13788 and ASHRAE 160P conditions were observed to be similar, with the maximum RH of 79.8% for St. John’s, wherein the threshold RH for the mold growth was at 80%.

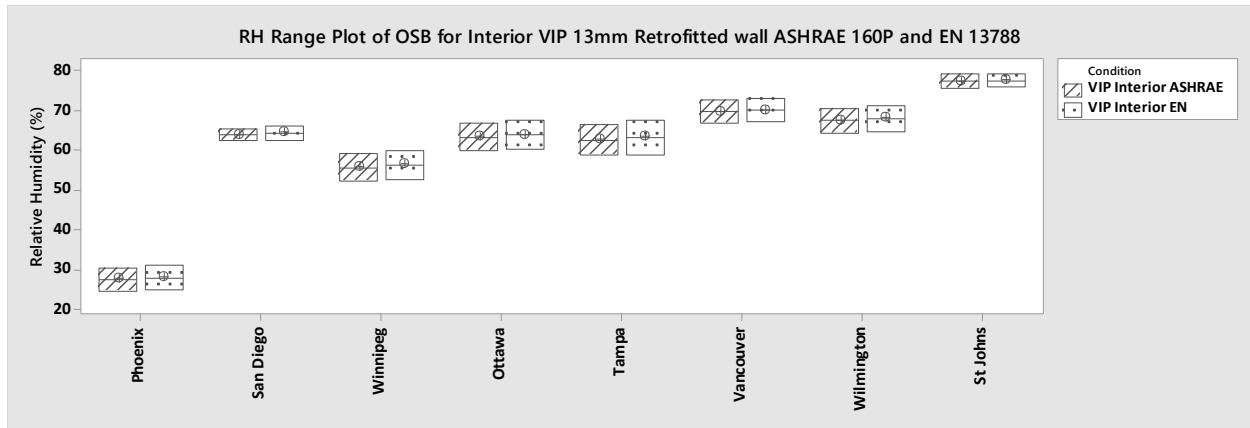


Figure 38: RH range plot comparison in OSB for interior VIP retrofitted wall ASHRAE 160P and EN 13788

Similarly the results for the drywall layer were compared for both the EN 13788 and ASHRAE 160P moisture loading conditions and the results were plotted in the range plots as shown in Figure 39. From the figure it was observed that the RH for the EN 13788 conditions was a lot higher when compared to the ASHRAE 160P results. This was expected as VIP provides a vapour tight construction to the flow of water vapours and reduces the vapour diffusion, resulting in higher RH levels in the EN 13788 conditions. The range for the maximum drywall RH for the ASHRAE 160P condition was between 70% -71.3% for all the eight locations whereas for the EN 13788 conditions the range was between 71% - 90.4%. RH higher than 80% could potentially lead to mold production and could damage the building.

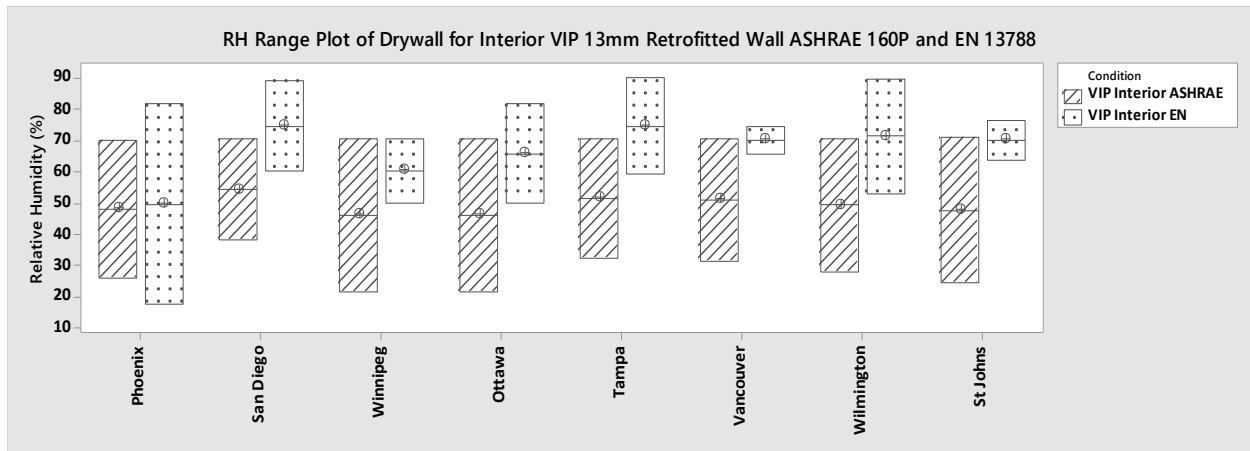


Figure 39: RH range plot comparison in drywall for interior VIP retrofitted wall ASHRAE 160P and EN 13788

Temperature range plots for the ASHRAE 160P and EN13788 conditions were also plotted and compared to assess the effect of increased moisture loading on the performance of the interior VIP retrofitted wall assembly. The temperature range plot for the drywall layer is as shown below in Figure 40. From the figure it can be observed that the temperature range for the EN 13788 conditions was significantly smaller than the temperature range of ASHRAE 160P wall assembly. The large range variation for the locations of Winnipeg, Ottawa and Vancouver is because for the ASHRAE 160P conditions only heating was used for the Canadian locations which resulted in higher inside temperatures of the drywall.

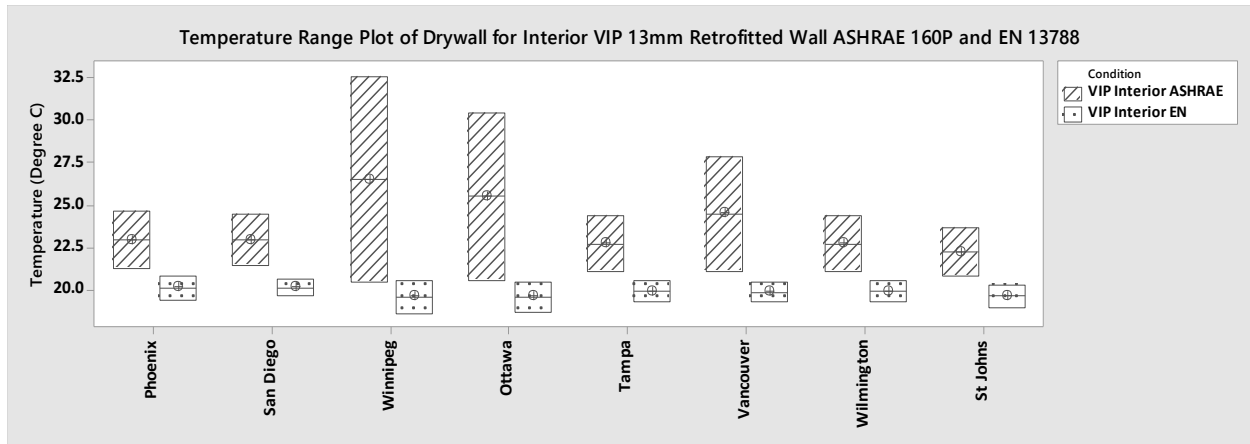


Figure 40: Temperature range plot comparison in drywall for interior VIP retrofitted wall ASHRAE 160P and EN 13788

Similarly the temperature range plots of the OSB layer were also plotted and the results are as shown in Figure 41. From the figure it can be concluded that the results for both the EN13788 and ASHRAE 160P conditions were similar with similar range plots. The lower OSB layer temperatures however could lead to increased freeze-thaw cycles and could potentially affect the performance of the building envelope, if the temperature and humidity are unfavourable to the outer wall layers.

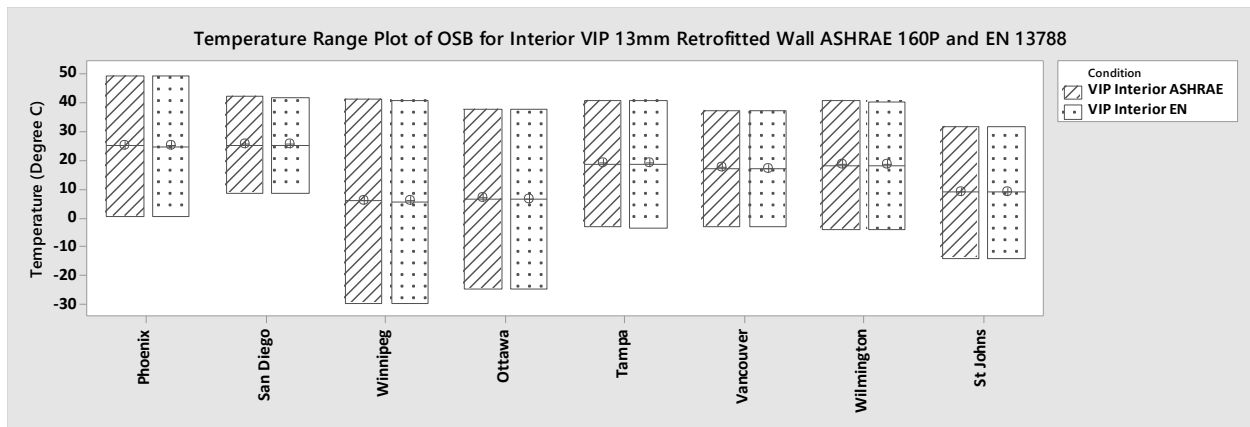


Figure 41: Temperature range plot comparison in OSB for interior VIP retrofitted wall ASHRAE 160P and EN 13788

6.2.3. Moisture Performance Evaluation of Exterior VIP Retrofitted Wall with ASHRAE 160P and Exterior VIP Retrofitted Wall with EN 13788

The wall assembly was also simulated with the ASHRAE 160P and EN 13788 conditions when they were modelled with the VIP retrofitted on the exterior side. The range plots for the WC, RH and temperature were plotted and used to compare and assess the potential for moisture problems in the retrofitted walls. The range plots for the walls are described below.

The WC range plots of the drywall layer for both the ASHRAE 160P and EN 13788 conditions is as shown in Figure 42. From the figure it can be observed that the range for the EN 13788

conditions were wider when compared with the ASHRAE 160P conditions. Higher WC in the drywall could possibly increase the risk for mold growth in the wall layers.

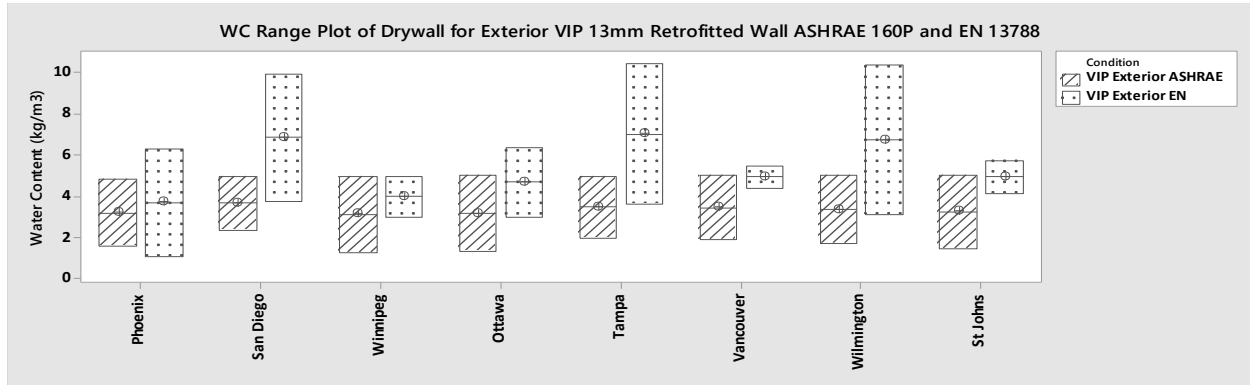


Figure 42: WC range plot comparison in drywall for exterior VIP retrofitted wall ASHRAE 160P and EN 13788

Similarly the WC range plot for the OSB layer for both the EN 13788 and ASHRAE 160P conditions was plotted as shown in Figure 43. From the figure it was concluded that the WC in the OSB layer for the EN 13788 condition was higher for all the locations and being significantly higher for the St. John’s location.

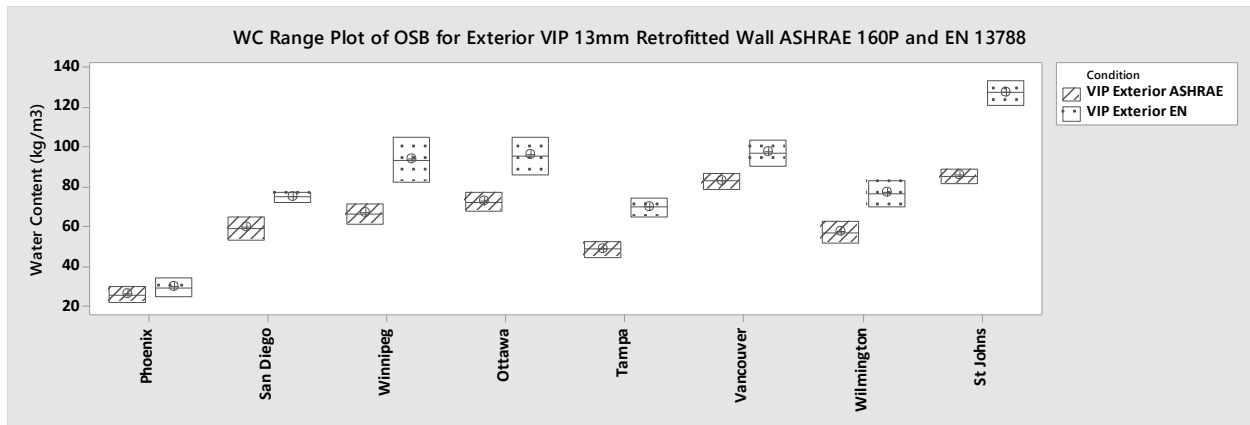


Figure 43: WC range plot comparison in OSB for exterior VIP retrofitted wall ASHRAE 160P and EN 13788

The range plots for the RH comparison for the drywall layer exterior VIP retrofitted wall for both ASHRAE 160P and EN 13788 is as shown below in Figure 44. From the figure we can observe that the maximum RH for the EN 13788 conditions was considerably higher than the ASHRAE 160P conditions. The maximum RH at San Diego, Tampa and Wilmington was close to 90% and could lead to mold growth problem, if the wetting period gets extended.

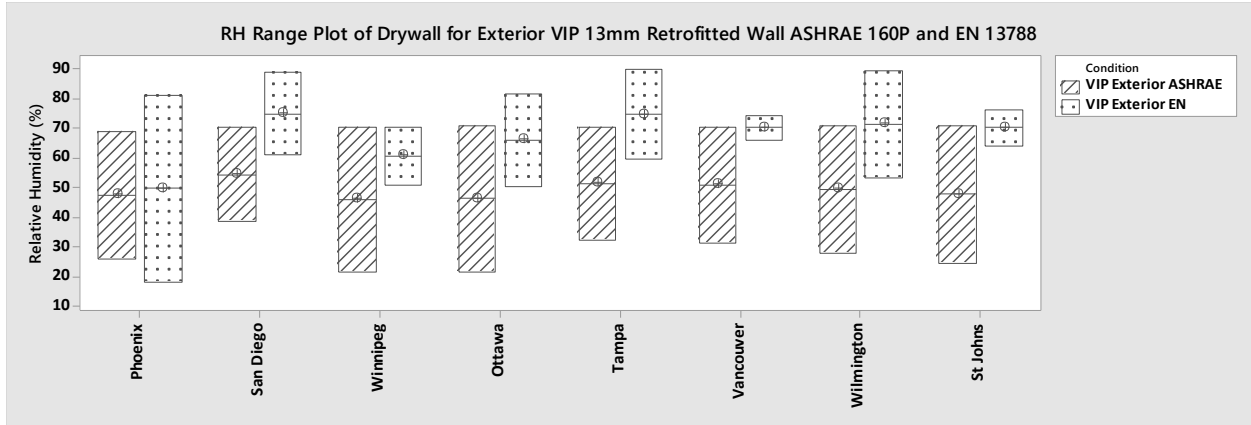


Figure 44: RH range plot comparison in drywall for exterior VIP retrofitted wall ASHRAE 160P and EN 13788

Similarly the RH range plot of the OSB layer for the exterior retrofitted wall was also plotted for ASHRAE 160P and EN 13788 conditions. From the graph we can observe that the RH for the wall with EN 13788 conditions when retrofitted using VIP on the exterior side is higher as compared for the ASHRAE 160P conditions. Higher RH in the OSB layer was expected as the VIP lowers the vapour diffusion from the inside to the outside when retrofitted on the exterior and results into moisture accumulation in the wall layers before it as shown in Figure 45.

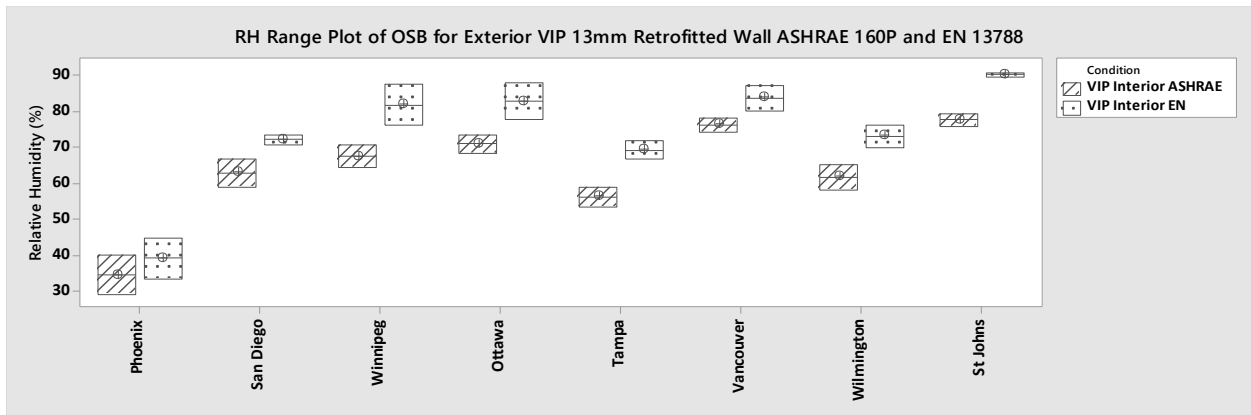


Figure 45: RH range plot comparison in OSB for exterior retrofitted wall ASHRAE 160P and EN 13788

The temperature range plots of the drywall layer for the exterior retrofitted wall for ASHRAE 160P and EN 13788 conditions is as shown in Figure 46. From the figure it can be observed that the temperature range of the wall with ASHRAE 160P was considerably wider when compared with EN 13788 conditions.

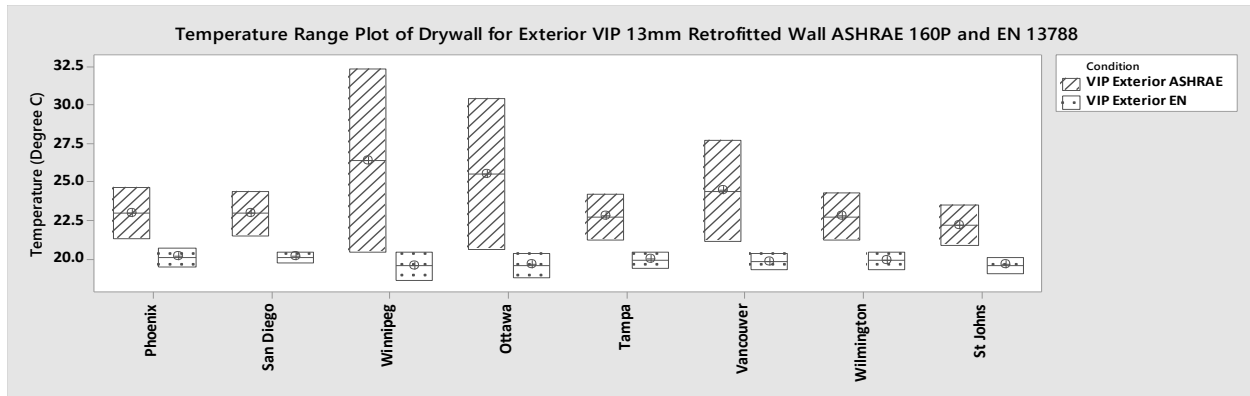


Figure 46: Temperature range plot comparison in drywall for exterior retrofitted wall ASHRAE 160P and EN 13788

Similarly the temperature range plot of the OSB layer for the exterior retrofitted wall for the ASHRAE 160P and EN 13788 conditions was plotted and is as shown in Figure 47. From the figure we can conclude that with the exterior retrofitting the temperature for the OSB layer for both the ASHRAE 160P and EN 13788 conditions was significantly higher than the interior retrofitted wall sections.

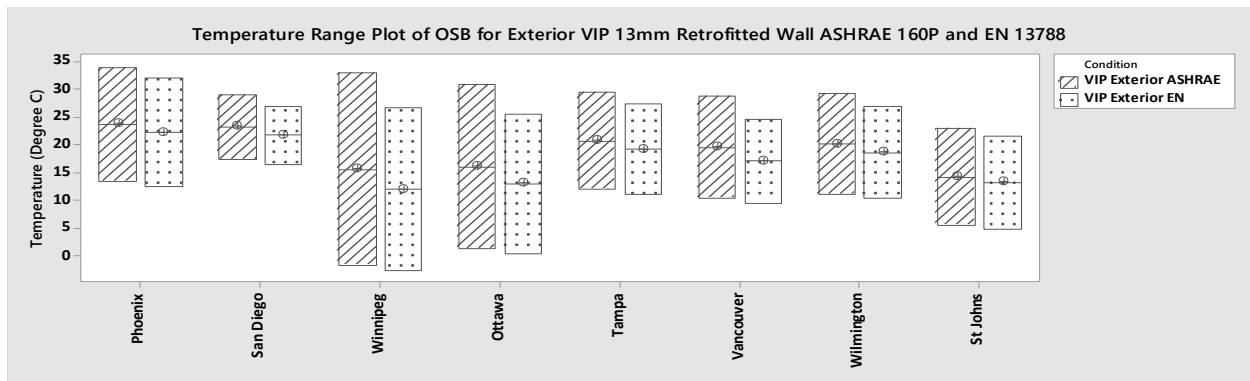


Figure 47: Temperature range plot comparison in drywall for exterior retrofitted wall ASHRAE 160P and EN 13788

6.3. Moisture Performance Evaluation with Increased RH in the Building Components

This study aims to evaluate the moisture performance of the wall when a saturated wall component is installed in the building envelope. For this study OSB with a relative humidity of 95% corresponding to an initial moisture content of 257.2 kg/m³ was selected as an initial condition in the wall design. The base wall and the retrofitted walls were then simulated as per the ASHRAE 160P guidelines and the moisture performance was evaluated.

6.3.1 Moisture Performance Evaluation of the Non-Retrofitted Regular Wall

The non-retrofitted wall using the saturated OSB layer was simulated for the period of three years using the similar parameters as described in the above sections and the range plots were plotted for the RH, WC and Temperature and compared with the regular non-retrofitted wall with regular

OSB conditions. The moisture analysis was done for the OSB and drywall layer as these are most prone to moisture management risks. This section discusses the results obtained from the analysis.

The WC range plot for the drywall layer with both the conditions are as shown in Figure 48. From the figure, it can be observed that the moisture performance of the drywall remained similar for both the conditions irrespective of the increased moisture content in the OSB layer.

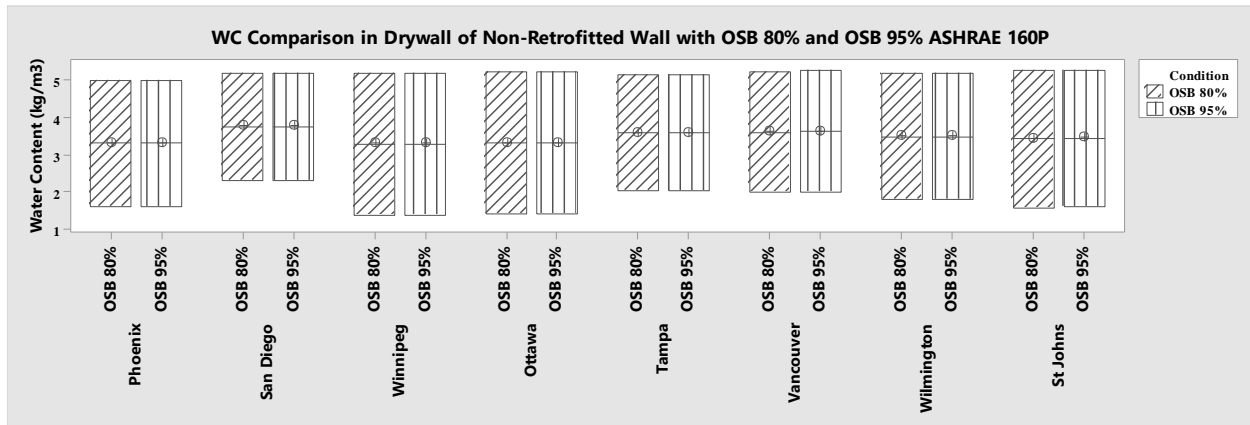


Figure 48: WC comparison in the drywall for regular wall with OSB RH of 80% and 95%

Similarly the WC range plot for the OSB layer was also plotted for both conditions as shown in Figure 49. From the figure, it can be seen that the WC range plots were wider for all the cold climatic conditions irrespective of the MI number. The WC range plot for the St. John’s was significantly wider for the wall with 95% OSB, thus increasing the moisture management risk in the non-retrofitted walls at the locations which are cold and having higher MI.

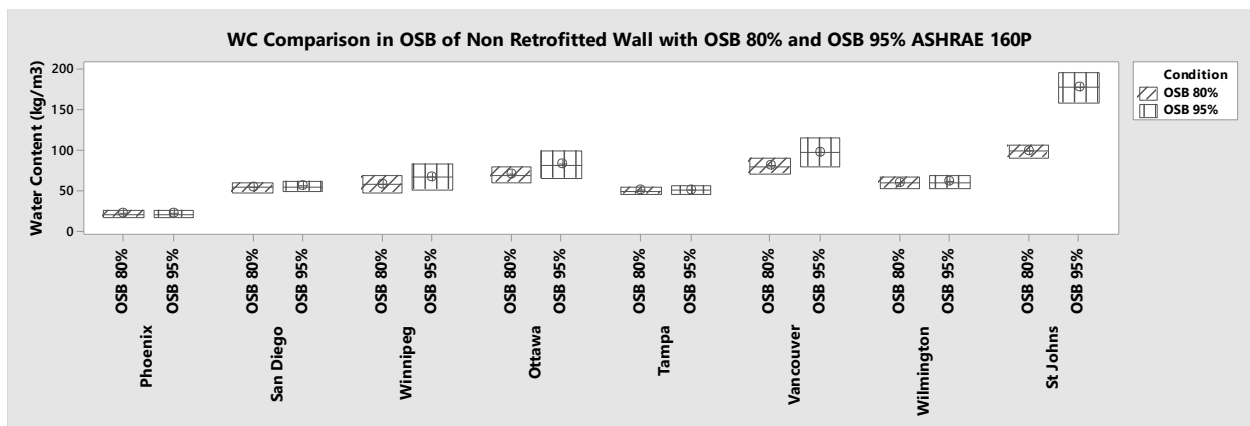


Figure 49: WC comparison in the OSB for regular wall with OSB RH of 80% and 95%

The RH range plots for the drywall layer were also plotted for both the conditions and compared, as shown in Figure 50. From the figure, it could be concluded that the RH performance of the drywall layer in the non-retrofitted wall assembly was similar for both the conditions and increased

moisture content in the OSB layer did not had any impact on the moisture performance of the drywall layer.

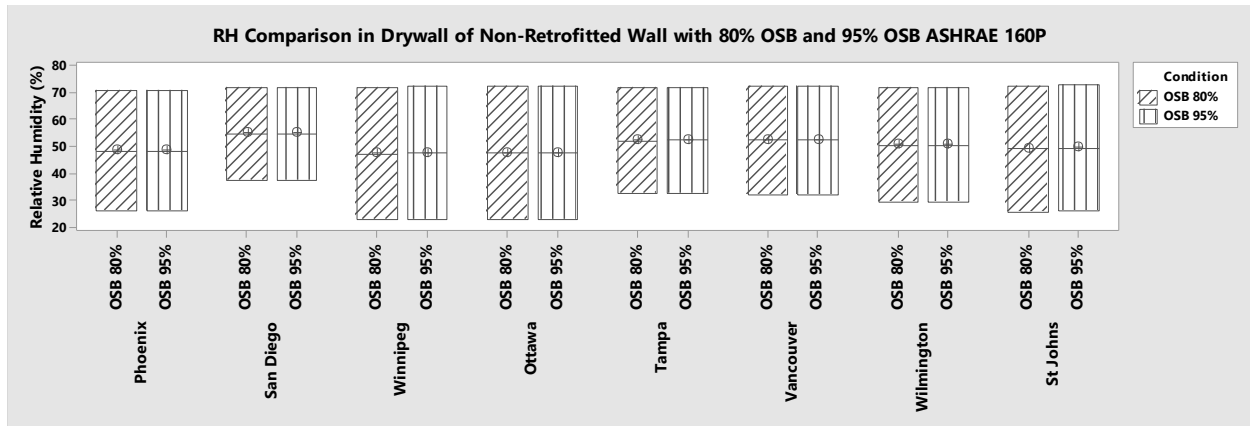


Figure 50: RH comparison in the drywall for regular wall with OSB RH of 80% and 95%

However a change in the moisture performance of the OSB layer was observed when both the conditions were compared with each other as shown in Figure 51. From the figure, it could be observed that the maximum RH and the minimum RH for the cold climates, irrespective of the MI number, increased. Hot climates, even though they have higher MI number and prolonged heating conditions, tended to stabilize the increased moisture contents in the wall assembly.

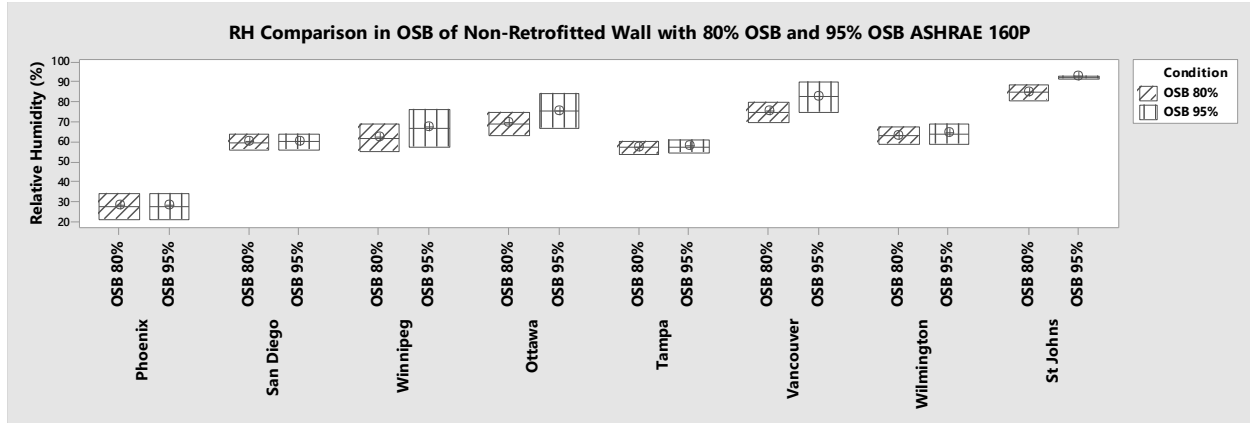


Figure 51: RH comparison in the OSB for regular wall with OSB RH of 80% and 95%

Temperature variations for the OSB layer and drywall layers were also compared for both conditions and the results of the comparison are as shown in Figures 52 and 53. From the figures, it can be seen that the temperature variations for both the conditions were similar to one another. Increased moisture content in the OSB layer had no effect on the temperature variations of the OSB and drywall layers.

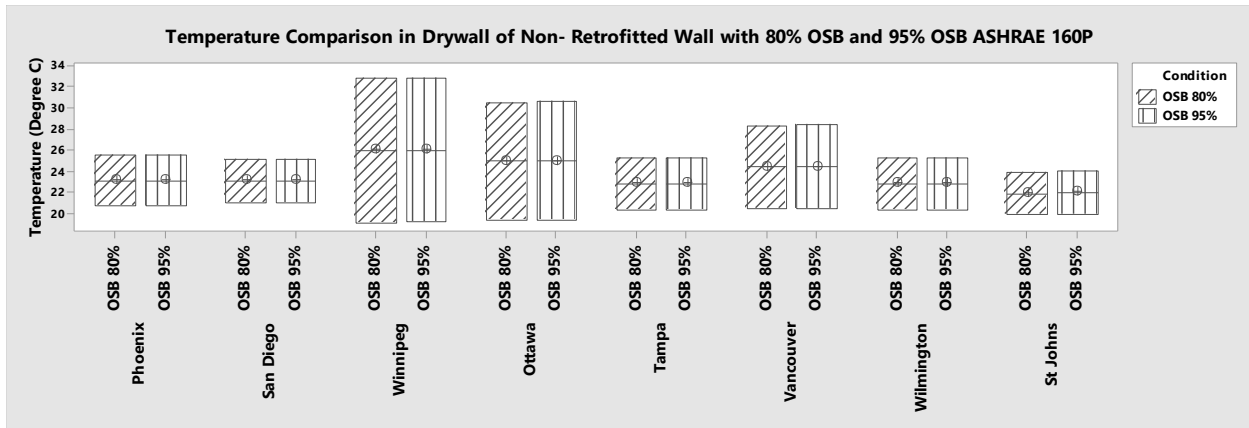


Figure 52: Temperature comparison in the drywall for regular wall with OSB RH of 80% and 95%

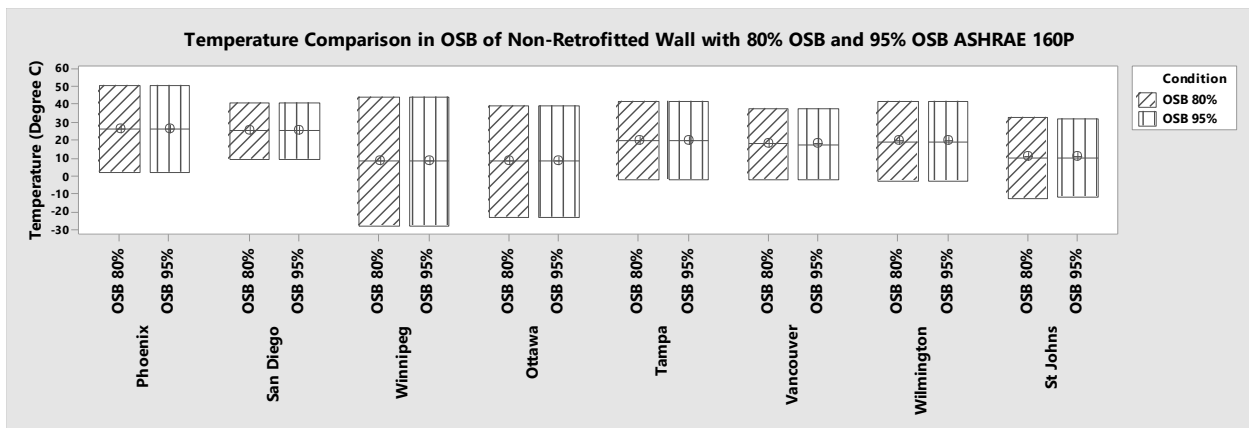


Figure 53: Temperature comparison in the OSB for regular wall with OSB RH of 80% and 95%

6.3.2. Moisture Performance Evaluation of the Interior Retrofitted Wall

The moisture performance of the interior VIP retrofitted wall was also evaluated as per the ASHRAE 160P guidelines for the OSB with 80% RH and 95% RH respectively. The modeled walls were simulated with similar conditions as described in the above sections over a period of three years. The results thus obtained were compared using the range plots.

Figure 54, gives the WC comparison in the OSB layer for the interior VIP retrofitted wall for both the walls with 80% OSB and 95% OSB. From the figure, we could observe that the maximum WC for all the locations increased as compared to the wall with OSB with 80% RH. The increase was observed even for the hotter locations, which could be explained by the fact that the VIP has a very high vapour diffusion resistance factor and could lead to increase in the WC in the OSB layer. The WC in the OSB layer increased for all the locations as the MI increases.

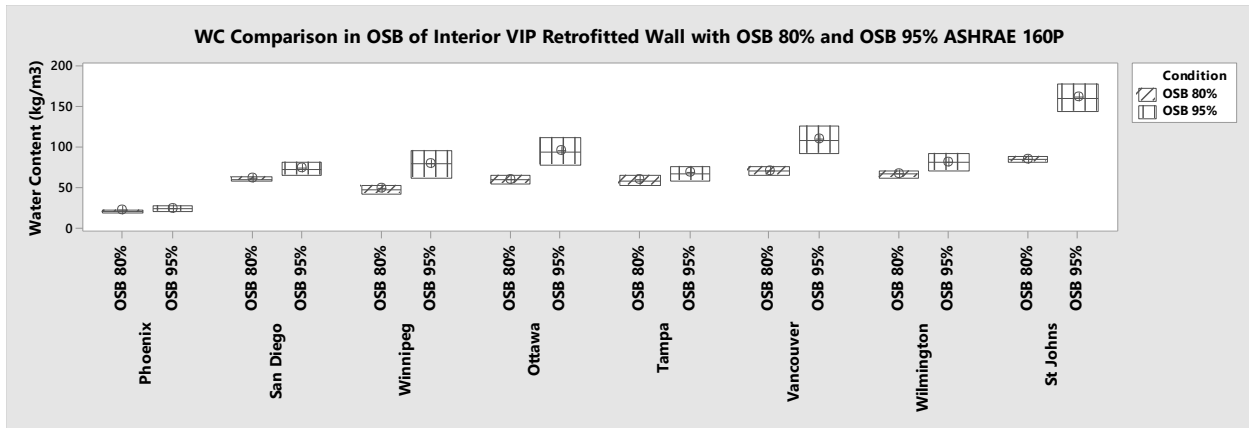


Figure 54: WC comparison in the OSB for Interior VIP retrofitted wall with OSB RH of 80% and 95%

Similarly the WC range plot for the comparison of Interior VIP retrofitted wall with 80% OSB and 95% OSB was also plotted as shown in Figure 55. From the figure it can be concluded that the no change to the moisture performance of the drywall layer was observed. The VIP acts as a vapour barrier and doesn't allow vapour diffusion from the wet OSB layer to the drywall in the inside. Resulting in overall increase in the WC of the OSB layer.

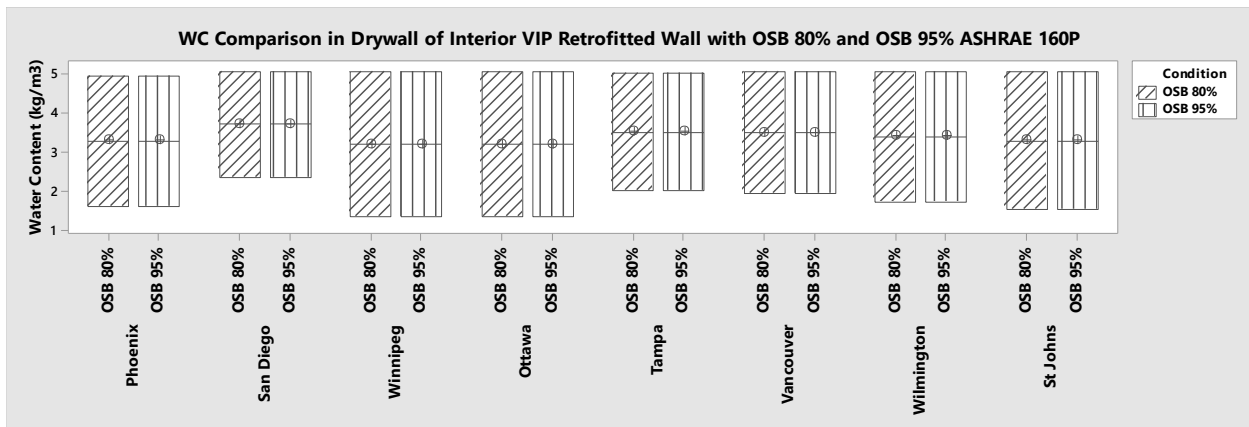


Figure 55: WC comparison in the drywall for Interior VIP retrofitted wall with OSB RH of 80% and 95%

RH range plots for both the OSB and drywall layer were also plotted and the results were compared for both the OSB 80% and 95% configurations. Figure 56 discusses the RH comparison for the OSB layer. From the figure it can be observed that the RH range for all the locations was wider and higher irrespective of the MI. This could be explained by the fact that when VIP is on the interior side of the wall, it decreases the vapour diffusion to the inside as VIP has a high vapour diffusion resistance factor and leads to an overall increase in the RH levels in the OSB layer as compared to the 80% OSB RH levels.

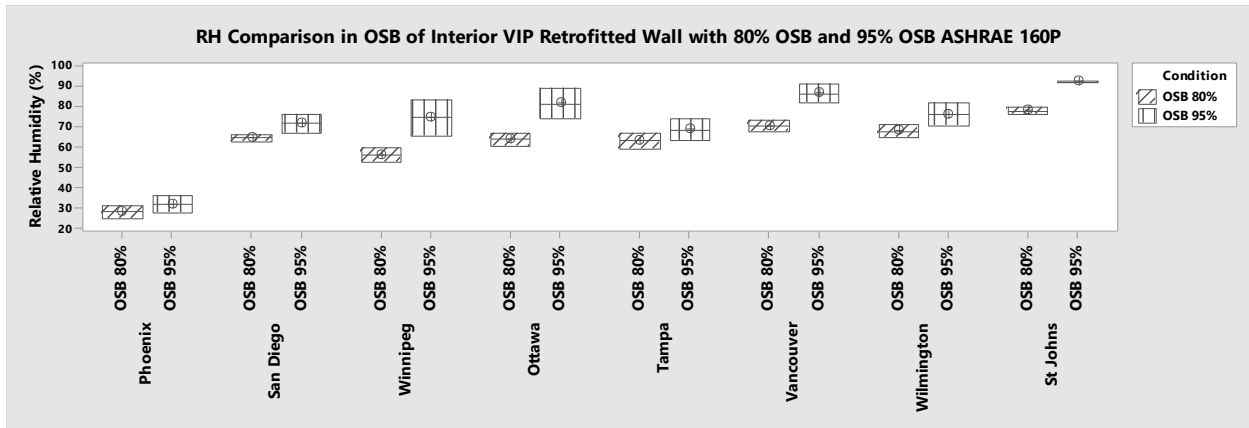


Figure 56: RH comparison in the OSB for Interior VIP retrofitted wall with OSB RH of 80% and 95%

Similarly the RH comparison in the drywall layer for both the configurations was also plotted as shown in Figure 57. From the figure it can be observed that the VIP placement in the wall assembly reduces the vapour diffusion to the inside, thus keeping the RH in the drywall layer similar as obtained with 80% OSB RH.

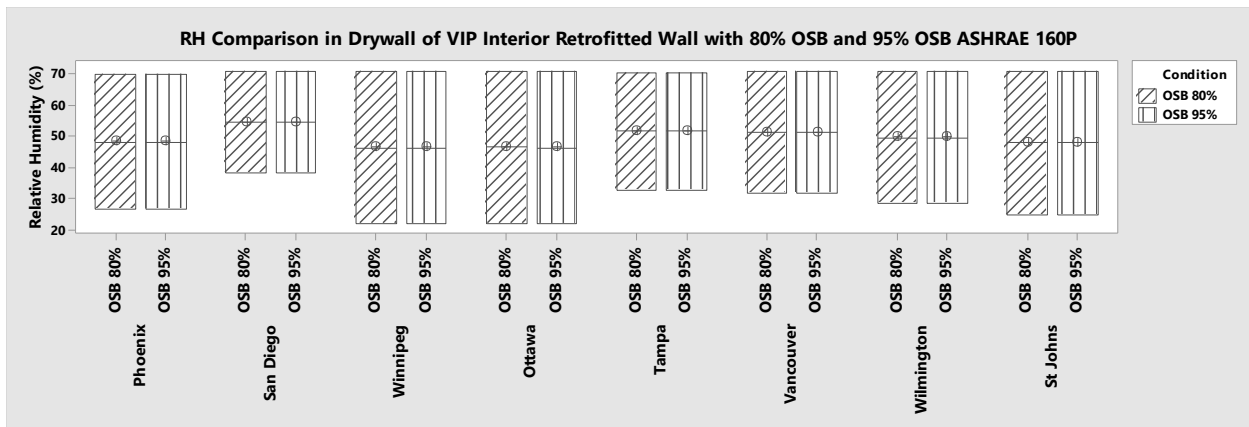


Figure 57: RH comparison in the drywall for Interior VIP retrofitted wall with OSB RH of 80% and 95%

The temperature profiles for both the drywall and the OSB layers were also compared.

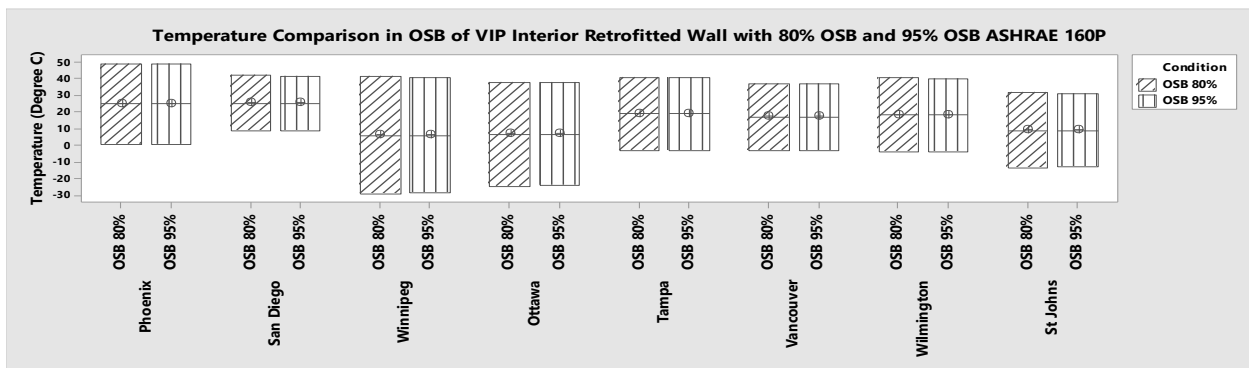


Figure 58: Temperature comparison in the OSB for Interior VIP retrofitted wall with OSB RH of 80% and 95%

The range plots were found to be similar for both the configurations with the increased OSB RH. Figures 58 and 59 outline the range plot of the OSB and the drywall layers respectively.

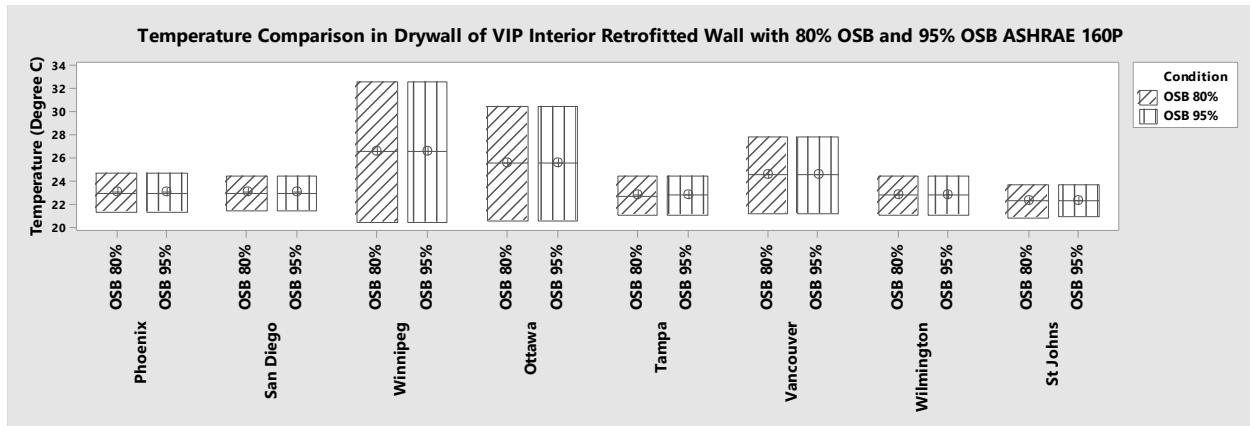


Figure 59: Temperature comparison in the drywall for Interior VIP retrofitted wall with OSB RH of 80% and 95%

6.3.3. Moisture Performance Evaluation of the Exterior Retrofitted Wall

The moisture performance of the wall retrofitted with VIP on the exterior side was also studied and the results were compared for both the OSB 80% and OSB 95% RH conditions. The walls were simulated with the same conditions as discussed in above section. The results obtained from the study are as discussed below.

Figure 60 provides the WC comparison in drywall layer for the exterior VIP retrofitted wall with the OSB RH levels of 80% and 95% respectively. From the figure, it can be observed that the WC levels for the drywall layer for both the conditions was similar, suggesting the increased OSB RH does not have any effect on the overall performance of the drywall layer.

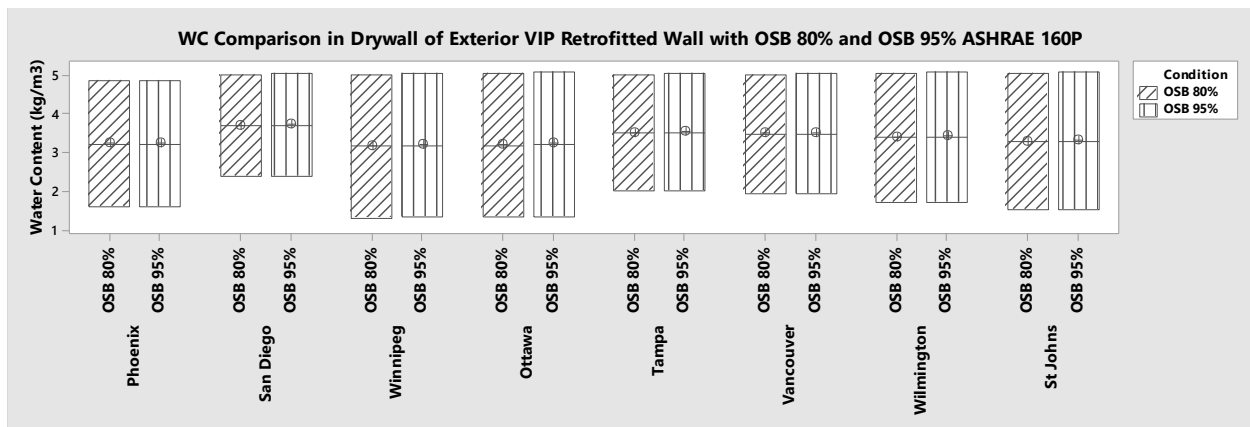


Figure 60: WC comparison in the Drywall for Exterior VIP retrofitted wall with OSB RH of 80% and 95%

However the WC in the OSB layer for the wall having OSB at 95% RH was significantly altered, as could be seen from Figure 61. The range as well as the maximum and minimum WC for the retrofitted wall having the OSB layer at 95% RH was significantly higher for all the locations

irrespective of the MI numbers. The WC levels for the exterior retrofitted wall was higher than the interior retrofitted wall and could be due to the fact that the VIP, by virtue of its higher vapour diffusion resistance factor, results in the reduction of the vapour diffusion from the OSB layer to the inside and could potentially lead to increased moisture management risks.

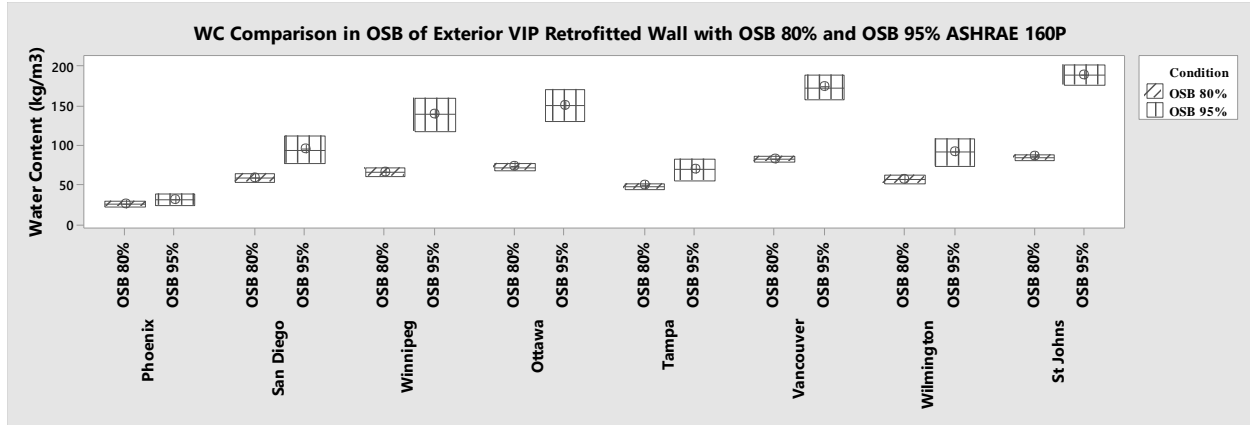


Figure 61: WC comparison in the OSB for Exterior VIP retrofitted wall with OSB RH of 80% and 95%

Similarly the range plots for the drywall and OSB comparing the RH for the exterior VIP retrofitted wall for the OSB of 80% and 95% RH were plotted. Figure 62 compares the RH for the drywall layer for both the conditions. From the figure, it can be observed that the RH performance of the drywall at all the climatic condition was similar and no effect of increased RH of the OSB layer was observed on the drywall layer.

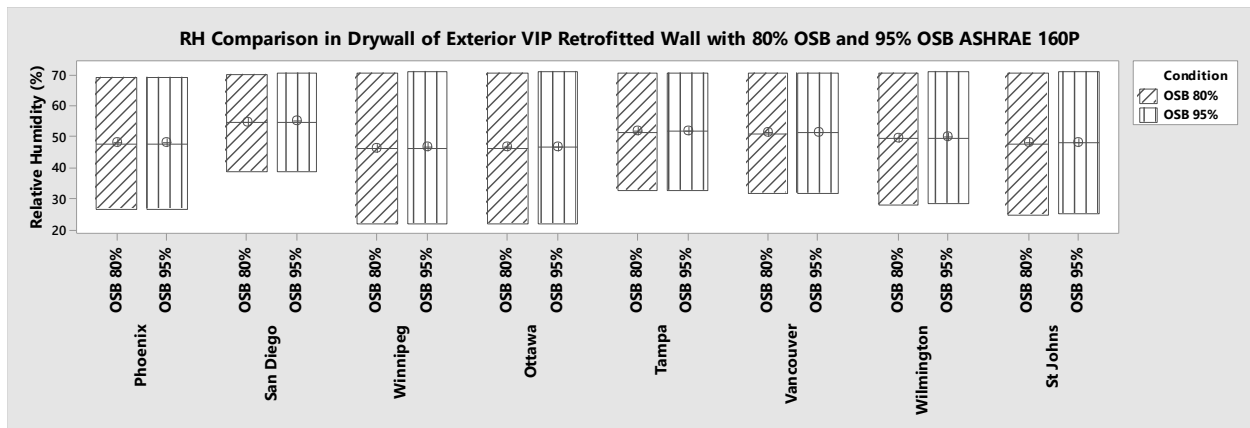


Figure 62: RH comparison in the Drywall for Exterior VIP retrofitted wall with OSB RH of 80% and 95%

Figure 63 given below compares the RH of the OSB layer for both the conditions, and it could be observed that the ranges for the exterior retrofitted walls with increased OSB RH was higher compared to the wall with 80% OSB RH. The increased RH could be explained by the fact that the VIP has a very high vapour diffusion resistance factor and could inhibit the flow of vapour diffusion from the OSB layer to the outside and thus increasing the interior RH around the OSB. The RH was observed to be increased at all the locations, irrespective of the MI number, thus

increasing the risk for moisture management problems for the walls retrofitted with the VIP on the exterior side with increased moisture content in the wall assembly layers.

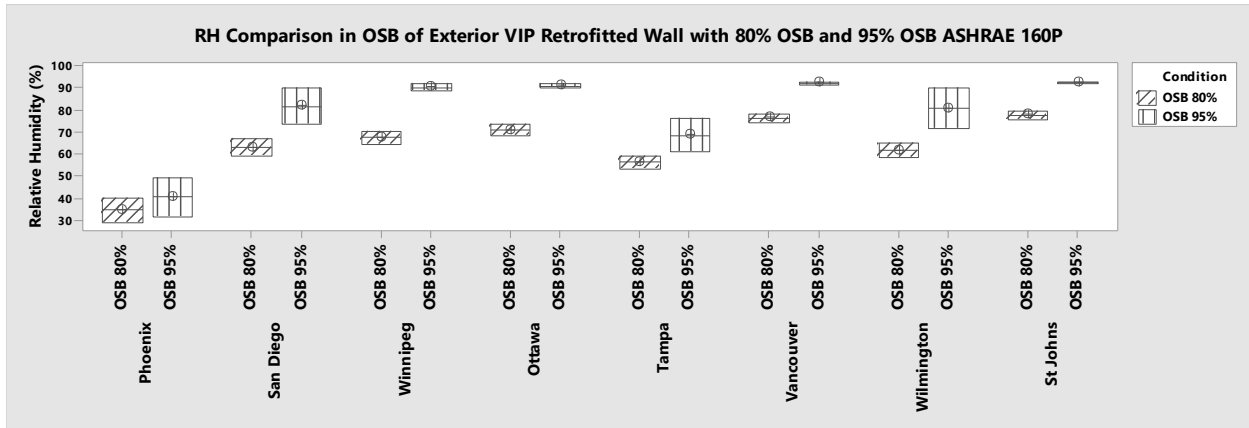


Figure 63: RH comparison in the OSB for Exterior VIP retrofitted wall with OSB RH of 80% and 95%

Similarly temperature range plots for the OSB and drywall layer for the VIP exterior retrofitted wall with the increased OSB RH of 95% and 80% were plotted and compared. Figures 64 and 65 show that the temperature profiles for both conditions in the OSB and drywall layer were similar and the thermal performance remained similar with both the configurations.

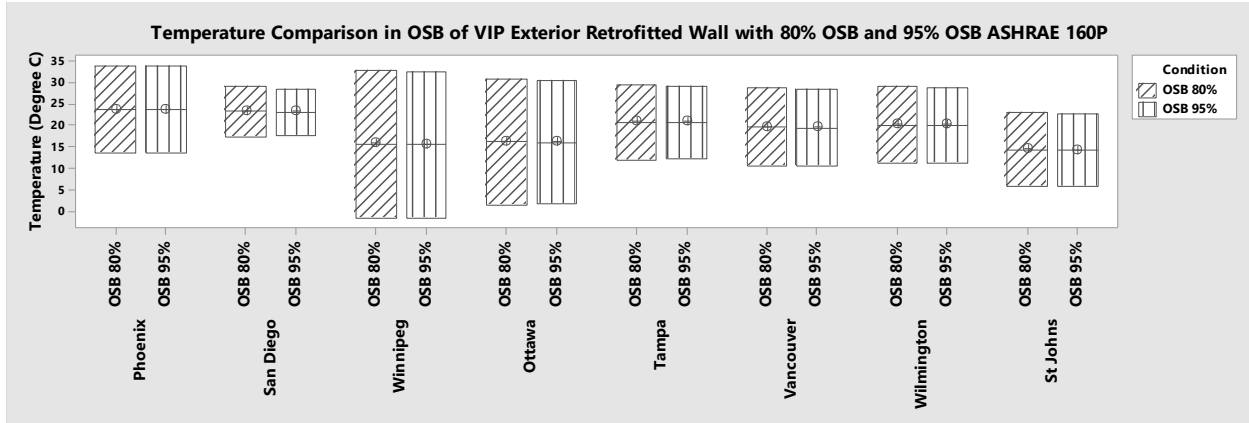


Figure 64: Temperature comparison in the OSB for Exterior VIP retrofitted wall with OSB RH of 80% and 95%

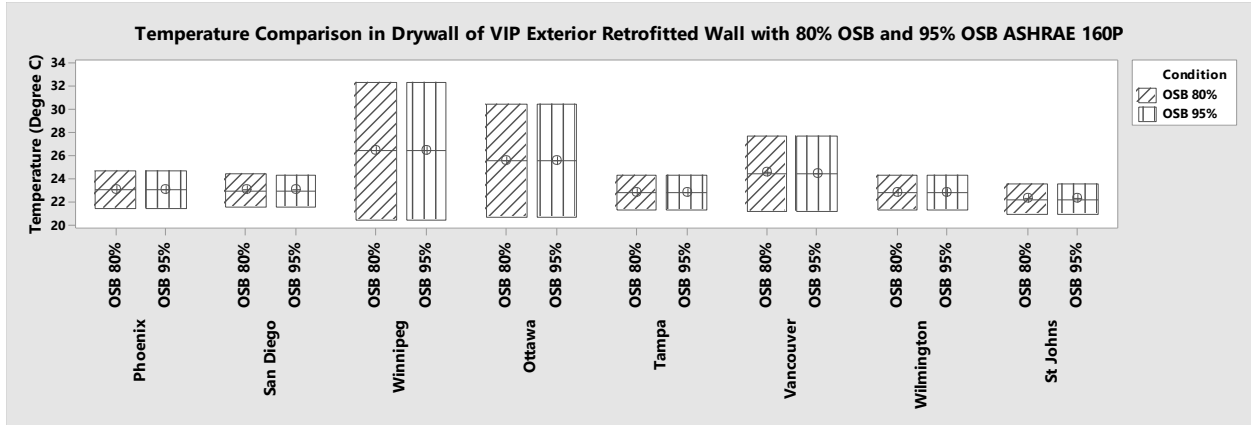


Figure 65: Temperature comparison in the Drywall for Exterior VIP retrofitted wall with OSB RH of 80% and 95%

The results for the RH and WC for OSB layer for the interior retrofitted and exterior retrofitted walls were also compared to evaluate the effect of increased RH inside the building envelope. Figure 66, outlines the maximum WC in the OSB layer for the interior and exterior retrofitted wall. From the figure it can be observed that the WC for the exterior retrofitted wall was higher when compared to the interior retrofitted wall.

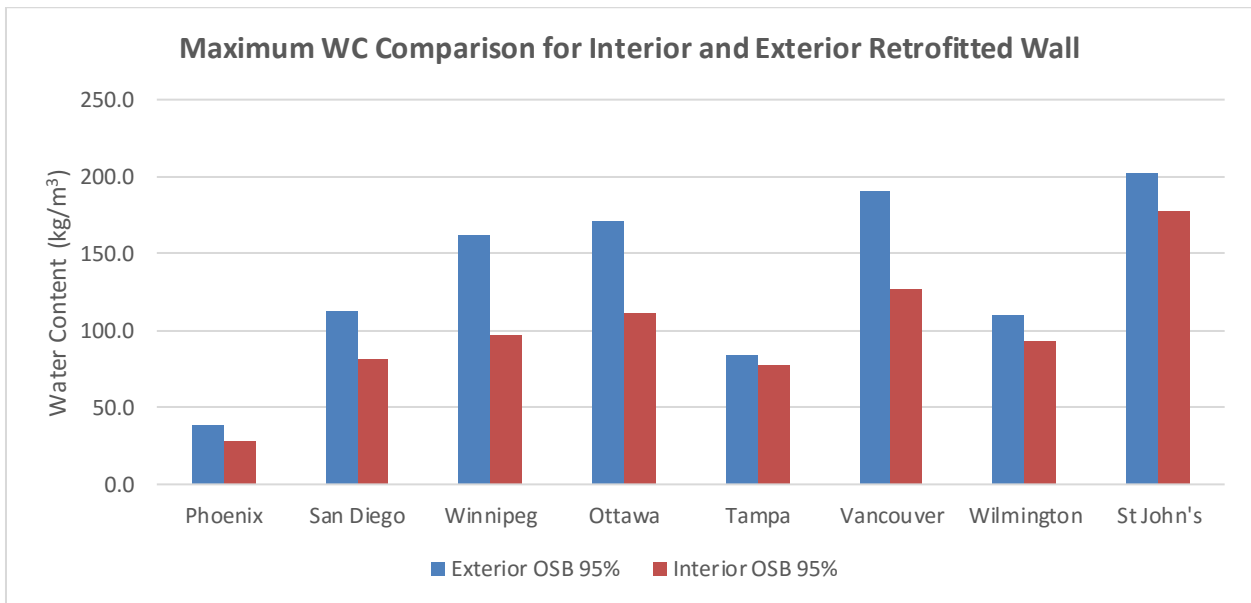


Figure 66: Maximum WC comparison for the interior and exterior retrofitted walls with increased OSB RH

Similarly the results for the maximum RH for both the interior retrofitted and exterior retrofitted walls were compared as shown in Figure 67. It could be observed from the figure that the maximum RH substantially increased for the exterior retrofitted wall when compared to the interior retrofitted wall and could potentially result in increased moisture management risks in the exterior retrofitted wall.

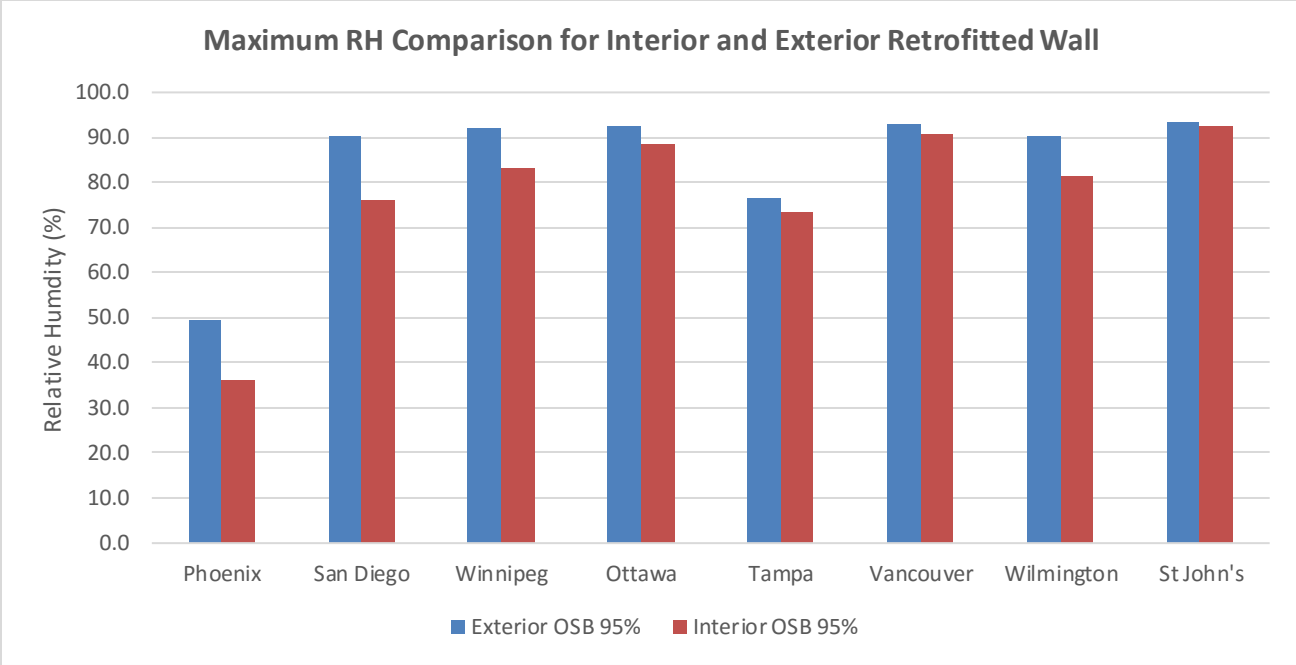


Figure 67: Maximum RH comparison for the interior and exterior retrofitted walls with increased OSB RH

6.4. RHT Evaluation

RHT index was used as a measure to characterize the moisture performance of the wall assembly, as higher RHT index values could lead to increased moisture related problems. RHT index calculation for the regular wall, interior retrofitted wall and exterior retrofitted wall for the OSB layer were performed. The results were evaluated for the conditions of RHT (80,5), RH 80% and T 5°C and RHT (80,0) RH 80% and T 0°C for both the ASHRAE 160P and EN 13788 conditions. Although the approach considered in the MEWS consortium was to use RH of 90% [8], lower value for the RH were considered for this study to avoid any moisture related problem in the retrofitted wall.

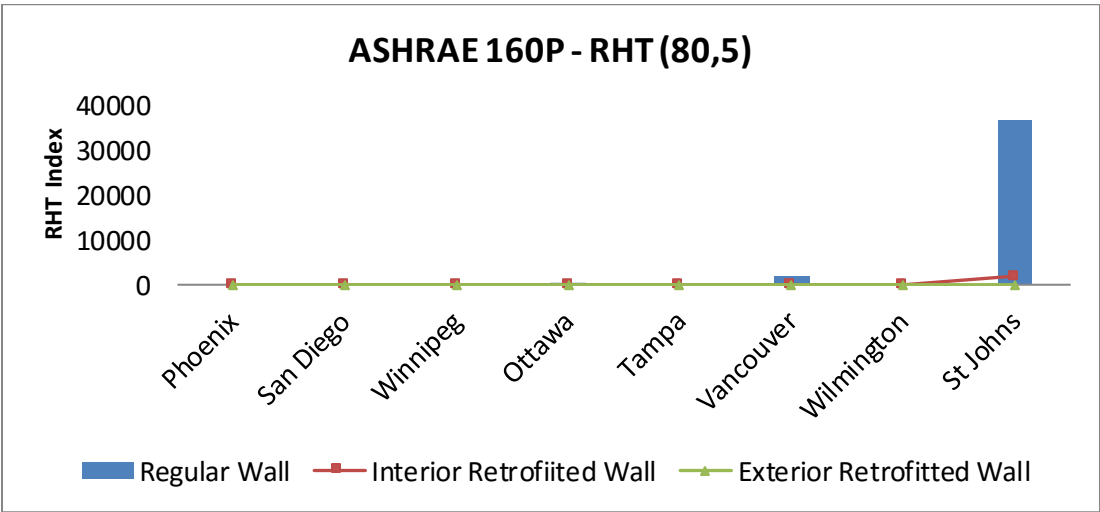


Figure 68: RHT 80-5 index for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall ASHRAE 160P

The calculated RHT was compared for all three wall types and the results for the ASHRAE 160P for RHT (80, 5) are as shown in Figure 68. From the figure we can observe that the wall assemblies in the hotter climates of US locations had RHT index zero for the regular wall, interior retrofitted wall and exterior retrofitted wall, whereas for the colder Canadian locations peaks were observed for the regular walls, with a maximum of 36451 for the St. John's, which had the maximum MI. Vancouver had a peak at a comparatively lower RHT index of 1925 for the regular wall. RHT index was calculated to be zero for the exterior retrofitted wall at all the locations. A small peak at the ST. John's location was observed at the RHT index of 1925 for the interior retrofitted wall with the ASHRAE 160P conditions. From the RHT (80, 5) calculations we could deduce that the risk for moisture damages significantly reduces for the retrofitted walls.

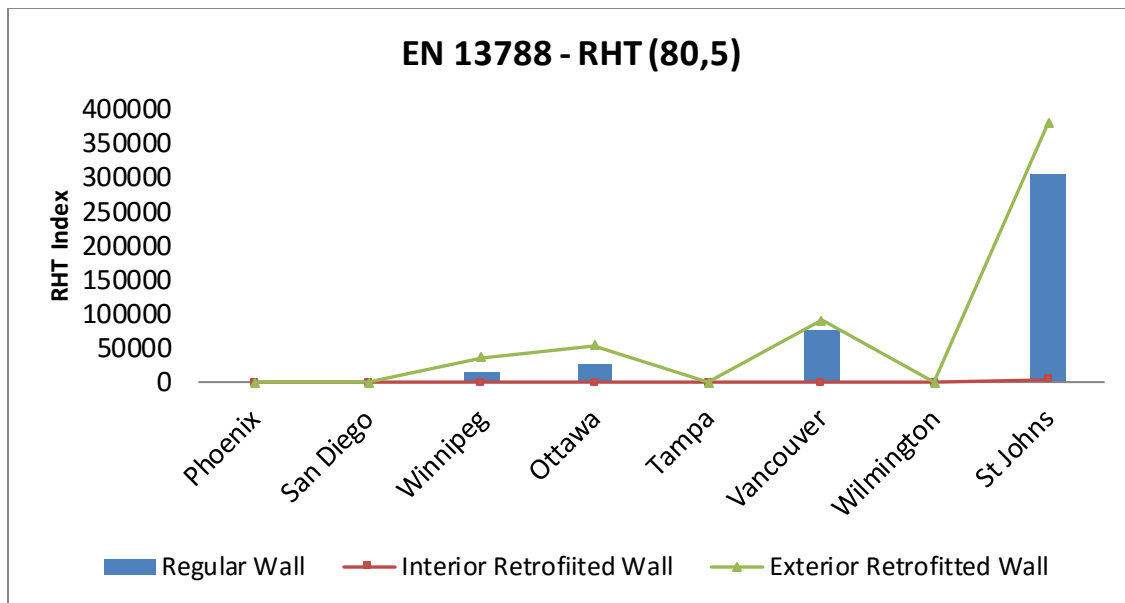


Figure 69: RHT 80-5 index for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall EN 13788

Similarly the results for the RHT (80, 5) with EN 13788 indoor conditions were evaluated and compared for regular wall, interior retrofitted wall and exterior retrofitted wall. The results obtained are as shown in Figure 69. A change in the wall performance was observed with the changed indoor conditions from ASHRAE 160P to EN 13788. For the regular wall significantly higher RHT index values were calculated for the locations of Winnipeg, Ottawa, Vancouver and St. John's. The maximum RHT value of 305351 was calculated for St. John's. RHT values for the exterior retrofitted walls followed a similar pattern as the regular wall, but the RHT values were higher for the exterior retrofitted wall as compared to regular wall. The maximum RHT value of 378816 was observed for St. John's, higher than the RHT value for the regular wall for the same location. The RHT values for the interior retrofitted walls were the least affected for the RHT values, the RHT index values were 0 for all the locations. From the EN 13788 RHT calculations, from the graph it could be concluded that the interior retrofitting resulted in the minimum moisture problems after retrofitting.

RHT index values for the RHT (80, 0) were also calculated for both the indoor moisture conditions of EN 13788 and ASHERAE 160P and plotted on a graph to compare the performance of the wall at different locations with varying retrofitting measures. RHT (80, 0) was chosen to check the wall

performance at lower temperatures, as the materials can start to corrode if the temperature is above that limit although a higher RH of around 90% is required for the initiation. RHT (80, 0) was chosen to observe the changes in the wall performance with the changing RH and temperature conditions. The graph as shown in Figure 70 compares the RHT index of regular wall, interior retrofitted wall and exterior retrofitted wall for the ASHRAE 160P indoor conditions.

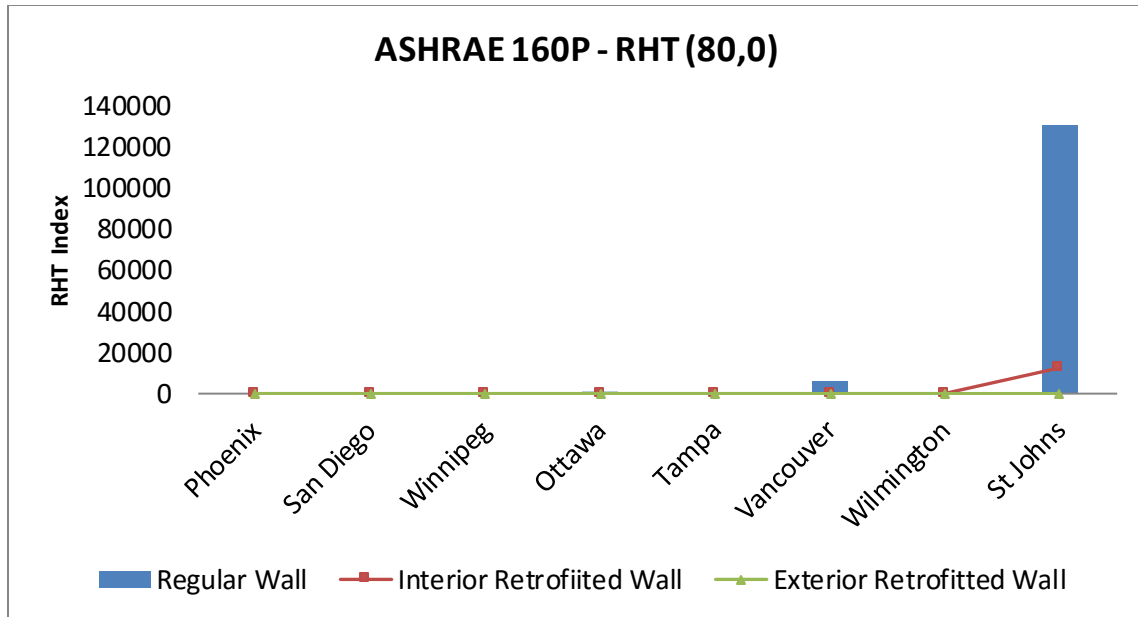


Figure 70: RHT 80-0 index for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall ASHRAE 160P

Regular wall for the ASHRAE 160P conditions had the maximum RHT value of 131078 for St. John's location, which was higher than the RHT value for the RHT (80, 5) and was expected to be higher because of the lower threshold. A small peak at Vancouver was observed at an RHT index of 5852. After interior retrofitting for the same indoor condition, the RHT index decreased to 12541 for St. Johns and was zero for all the other locations. The RHT index for all the exterior retrofitted location was zero for all the locations. From this plot we can conclude that the risk for moisture problem with the interior retrofitting was slightly higher than the exterior retrofitting for the location of St. John's, which is a wet and severely cold location.

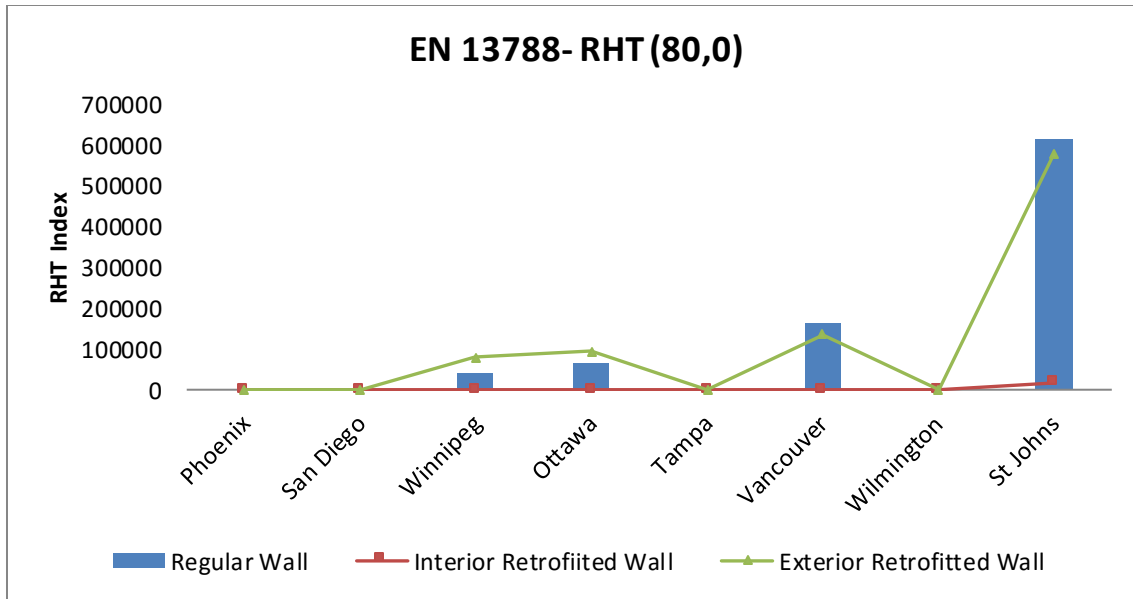


Figure 71: RHT 80-0 index for regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall EN 13788

RHT (80, 0) values for all the locations were also calculated for the EN 13788 indoor conditions and increased RHT values for Winnipeg, Ottawa, Vancouver and St. John’s was observed. The maximum RHT value for regular wall was at St. John’s with 616562. Similar trends were observed for the exterior retrofitted wall with a maximum of 578530 for St. John’s location, with RHT values at the same Winnipeg, Ottawa, Vancouver and St John’s location. No RHT index values were observed for the interior retrofitted wall, even with the increased inside moisture load. Thus, from the RHT results it appears that the interior retrofitted wall would have the least amount of moisture problems as compared to the exterior retrofitted and regular wall. The moisture problem risk for the interior retrofitting was significantly lower for the interior retrofitted wall when compared to the exterior retrofitted wall as shown in Figure 71.

6.5. Freeze-Thaw Performance

Increased moisture loading in the exterior sheathing layers could potentially result in higher freeze-thaw damages in cold climates. It is difficult to calculate the freeze thaw damages to the buildings but calculating freeze thaw cycles could approximately determine the risk for the freeze thaw damages. In this thesis freeze thaw cycles for the regular wall and interior retrofitted wall and exterior retrofitted wall for both the ASHRAE 160P and EN 13788 conditions were calculated and compared. The freeze thaw cycles at moisture content of 30%, 75%, and 90% of the free water saturation of the stucco layer were calculated [9]. Freeze thaw cycles were only obtained for the moisture content of 30%, whereas for the 75% and 90% no freeze thaw cycles were obtained.

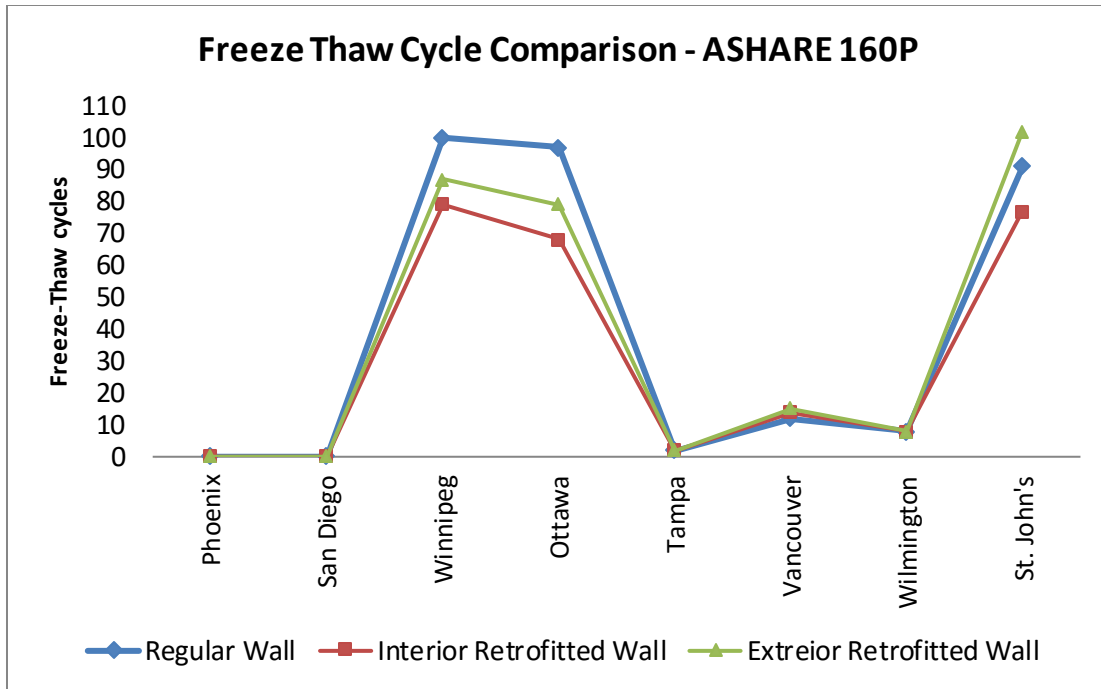


Figure 72: Freeze-Thaw cycles in regular wall, interior VIP retrofitted wall and exterior retrofitted wall ASHRAE 160P

The comparison for the freeze thaw cycles for the ASHRAE 160P conditions is as shown in Figure 72. It was observed from the results that a total of 100 freeze-thaw cycles were calculated for the regular wall which subsequently reduced to 79 for the interior retrofitted wall and was 87 for the exterior retrofitted wall. Freeze thaw cycles were observed to be same or decreasing for the interior retrofitted walls except at Vancouver, wherein it increased from 12 in the regular wall to 14 in the interior retrofitted wall. The freeze thaw cycles for the exterior retrofitted walls were observed to be higher than the interior retrofitted walls. Freeze thaw cycles for the interior retrofitted wall were lower than regular wall for the St. John's location, which had the maximum MI.

Similarly the results for the freeze thaw cycles for the EN 13788 conditions were also calculated for the regular wall, interior retrofitted wall and exterior retrofitted wall and the results obtained are plotted in the graph given below in Figure 73. From the comparison we can observe that there was an increase in the freeze thaw cycles observed at the colder locations, whereas at the other US locations, it was either zero or no change was observed in terms of the freeze thaw cycles. The freeze thaw cycles were observed to be higher for the interior retrofitted wall assemblies as compared to the regular wall assemblies in the colder climates. The freeze thaw cycles were calculated to be highest for the exterior retrofitted wall. The maximum freeze thaw cycles were calculated at 106 cycles, higher by 22 cycles as compared to regular wall.

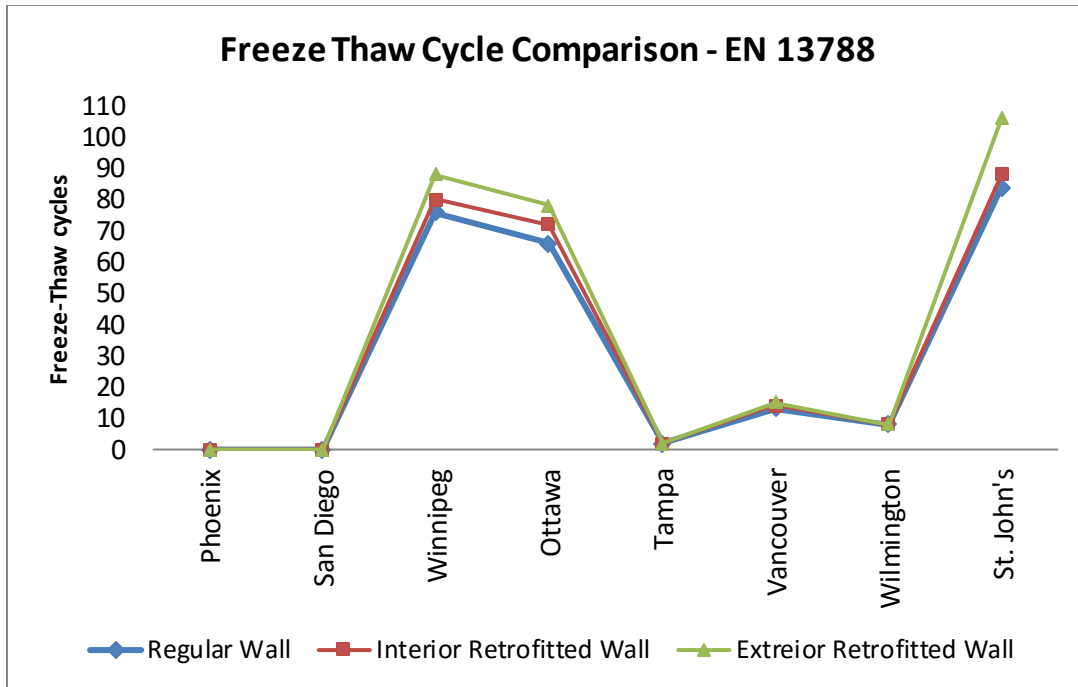


Figure 73: Freeze-Thaw cycles in regular wall, interior VIP retrofitted wall and exterior VIP retrofitted wall EN 13788

6.6. Dew Point Calculations

The results obtained from the WUFI simulations have always been questioned and scrutinized for their accuracy and have always been proved correct time and time again [28] [13]. To validate the results obtained from the WUFI simulations for this study the results were compared with the steady state results obtained using Dew Point method. Dew point method evaluates the performance of a wall section considering only the vapour diffusion as the main criterion for moisture risks and excludes the moisture storage potential of the material. Phoenix, AZ was chosen for the comparison because of its lowest MI number out of all the eight locations, thus limiting the liquid water penetration. WUFI provides RH and Temperature graphs for the locations using the supplied weather data. From the graphs an approximate point in the summer time period was chosen, where the RH was comparatively stable and the corresponding temperature was also recorded. The date range between 10/06 and 15/06 was chosen for the study. From the graph shown in Figure 74 an approximate outside RH of nearly 18% and the corresponding near temperature of 32°C could be assumed. Similarly, for the inside conditions, a temperature of 23.9°C and the corresponding RH of 35% was used, as shown in Figure 75.

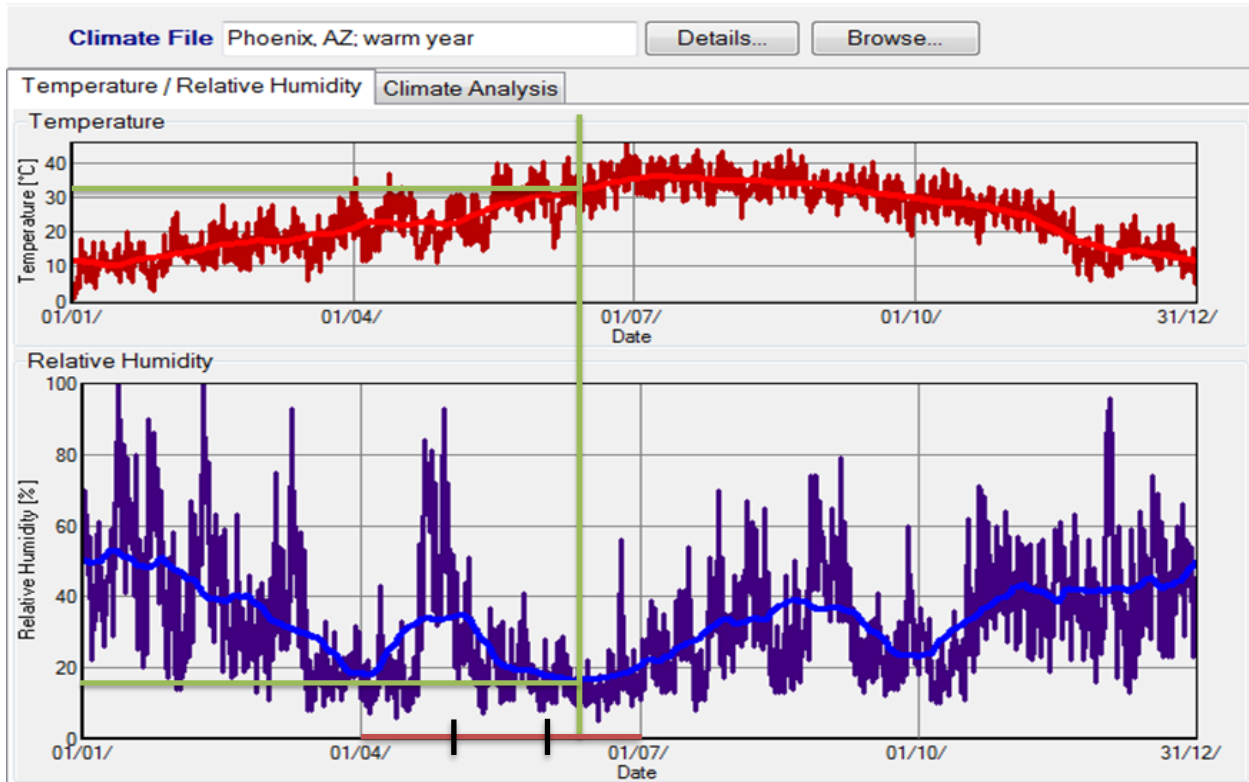


Figure 74: Outdoor temperature overview for Phoenix in WUFI

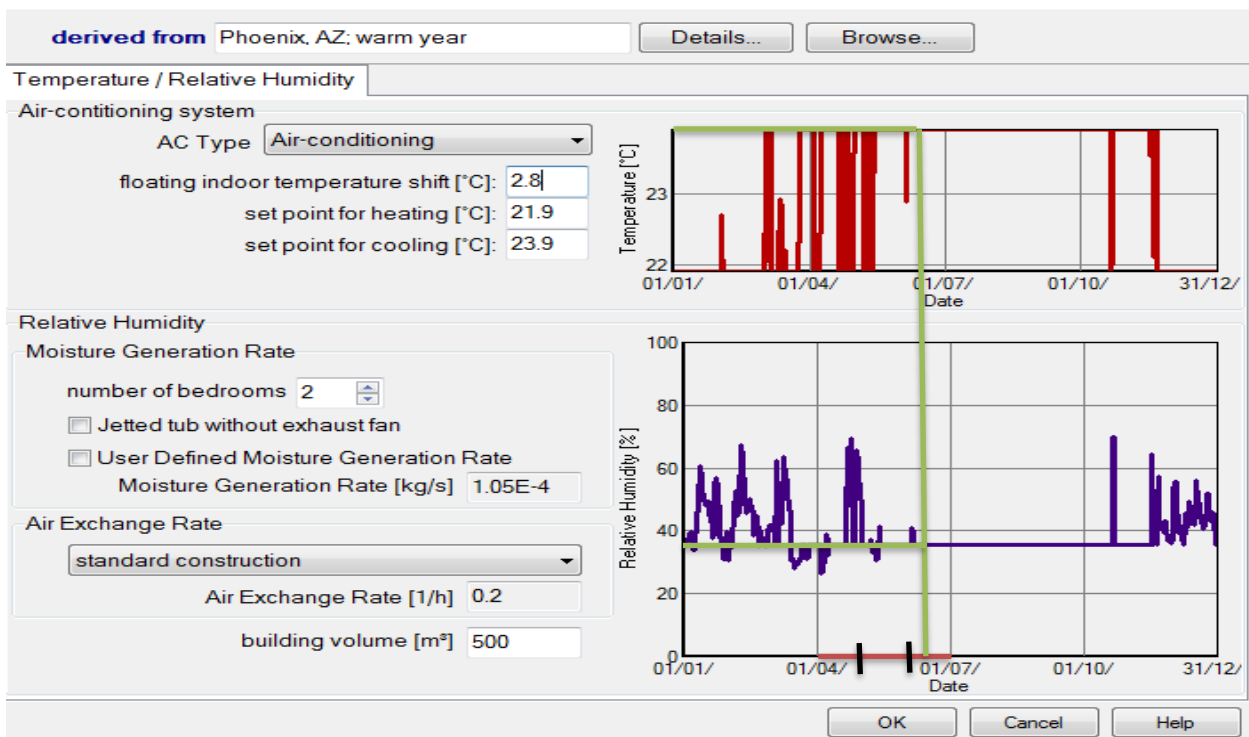


Figure 75: Indoor temperature overview for Phoenix in WUFI

The vapour pressure drop and the surface vapour pressure were computed from the calculations described in the dew point method as given in Appendix E. The resultant vapour pressure for the building components was measured and compared with the saturation vapour pressure. No condensation was observed in the dew point calculations as the resultant vapour pressure was lower than the saturation vapour pressure. For the WUFI result comparison RH was computed from the surface vapour pressure and the resultant RH at the drywall and the stucco layer were 35% and 18% respectively. The RH was compared with the RH calculated using WUFI, as shown in Figure 76. The RH was compared within the date range of 10/06 to 15/06 for the third year.

Relative Humidity Phoenix VIP

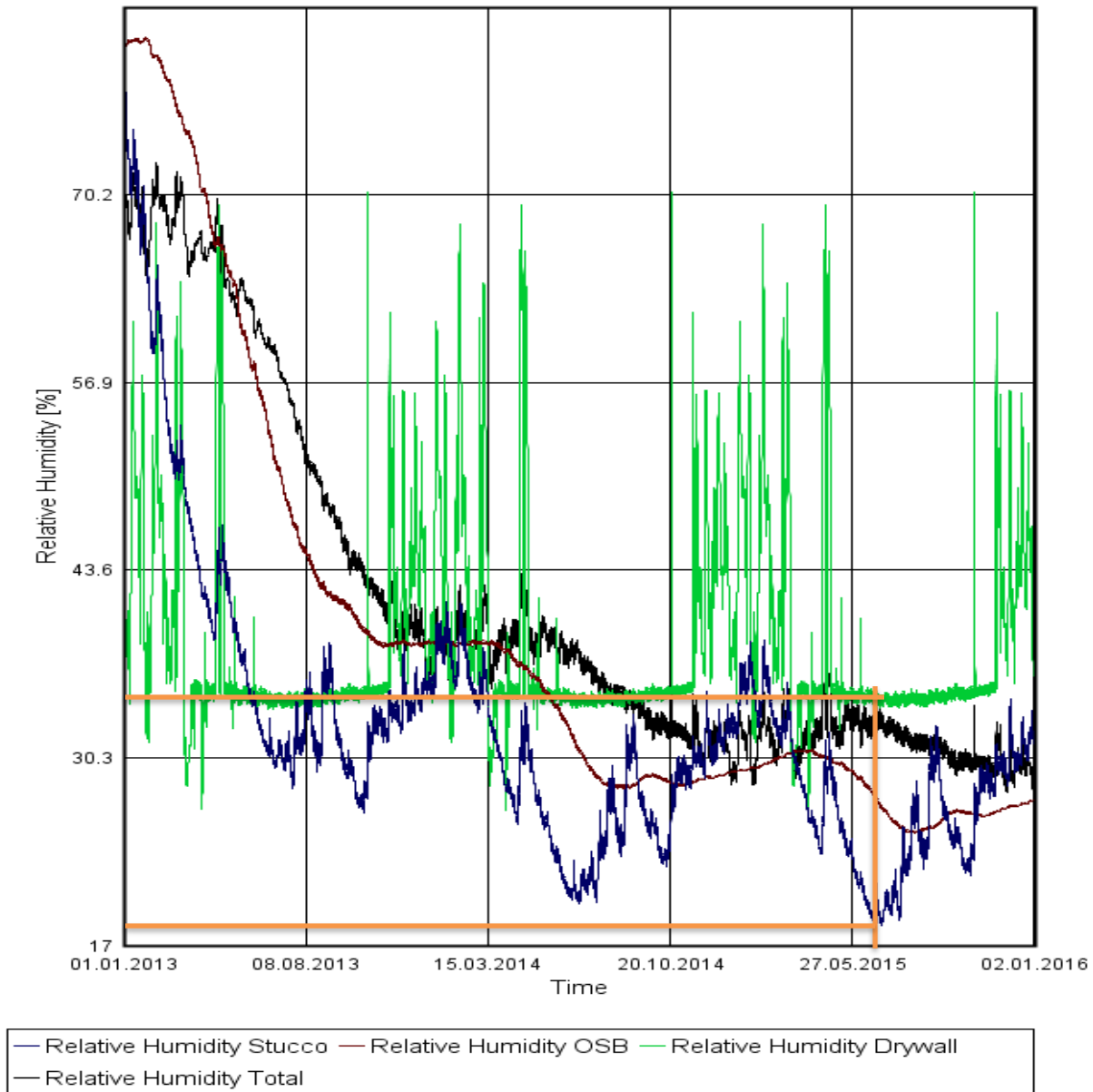


Figure 76: WUFI RH plot at Phoenix for time range 10/06 to 15/06

Table 14: WUFI Maximum, minimum and average relative humidity for Phoenix from 10/06 to 15/06

RH (%)	Stucco	OSB	Drywall	Total
Maximum	20.88	28.55	35.29	33.98
Minimum	19.62	28.14	34.01	31.75
Average	20.09	28.32	34.58	32.98

Temperature Phoenix VIP

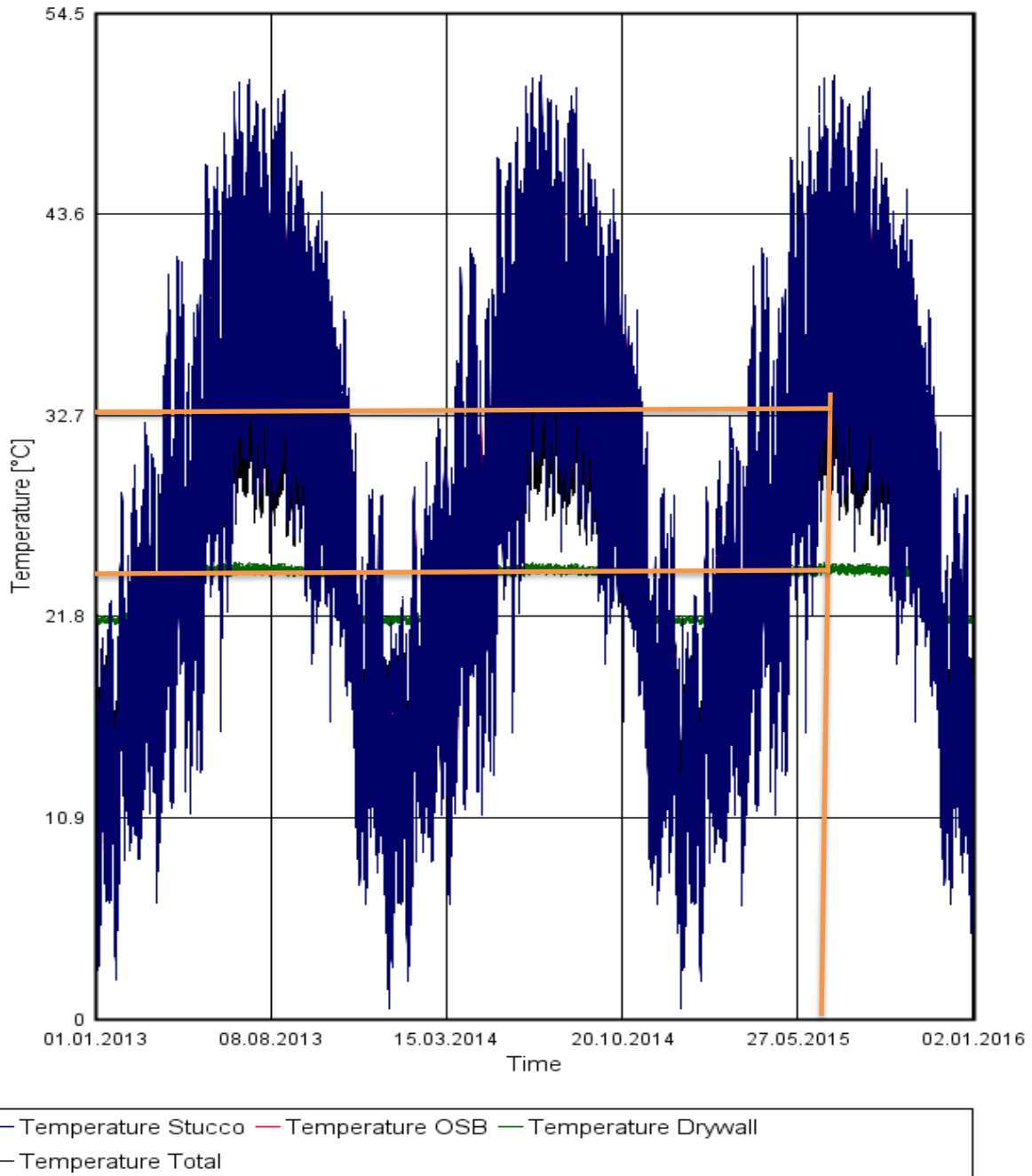


Figure 77: WUFI temperature plot at Phoenix for time range 10/06 to 15/06

Table 15: WUFI Maximum, minimum and average temperature for Phoenix from, 10/06 to 15/06

Temperature (°C)	Stucco	OSB	Drywall	Total
Maximum	48.30	46.70	24.59	38.88
Minimum	21.93	22.44	23.93	23.31
Average	36.15	35.93	24.30	32.15

The results obtained from the WUFI simulations were found to be comparable to the results obtained from the dew point method. Both the RH and temperature were used as the evaluating criterion. The graphs obtained after WUFI simulations were used to approximately find the RH and temperature for the stucco and drywall component. The maximum, minimum and average for the RH and temperature was also computed from the WUFI results for the time range of 10/06 to 15/06 as shown in Table 14 and Table 15 and it was observed that the results were comparable and thus validates the WUFI accuracy.

7. Conclusions

The aim of this thesis was to assess the moisture management performance of the wall retrofitted on the exterior or interior side with Vacuum Insulation Panels (VIPs) as compared to the non-retrofitted wall at eight different North American climatic conditions. The following conclusions could be drawn from the results obtained from the hygrothermal simulations using WUFI-2D.

1. Although increased VIP thickness provides improvement in the thermal performance of the wall, the associated change in moisture management risk with VIP thicknesses up to 25mm is relatively small.
2. The VIP could be used for the interior retrofitting of building envelope, provided the moisture loading inside the building, as indicated by indoor boundary conditions, is within certain limits. The moisture response for the interior retrofitted wall was improved for the cold climate whereas it decreased for the hot climates having a moisture index of 0.74 and above (i.e. San Diego, Tampa and Wilmington) as compared to the regular wall with interior environment conditions following ASHRAE 160P guidelines. However, increased interior moisture loading as per EN 13788 guidelines resulted in increased moisture management risk at all the eight locations, irrespective of the moisture index.
3. The moisture management performance of the interior retrofitted wall was improved as compared to exterior retrofitted wall as indicated by the simulations done with ASHRAE 160P stipulated interior boundary conditions. The moisture performance was better for cold climates and deteriorated for the hot climates above the moisture index of 0.73 (i.e. Tampa and Wilmington).
4. Exterior VIP retrofitting with higher moisture load (i.e. EN 13788) resulted in increased moisture management risks at all the eight locations. The maximum relative humidity (RH) condition in the drywall (gypsum) rose above the 90% mark at certain locations (San Diego, Tampa and Wilmington), whereas the thermal performance was similar for both interior moisture loading conditions.
5. Hygrothermal response, as indicated by RHT index, improved after retrofitting in both the moisture loading conditions. The RHT index for the interior retrofitted wall was found to

be similar for both the interior moisture conditions, whereas it increased for the exterior retrofitted wall with EN 13788 prescribed interior moisture loading.

6. Freeze-Thaw cycle responses for both ASHRAE 160P and EN 13788 interior moisture loading conditions were found to be superior for the interior retrofitted wall as compared with exterior retrofitted wall. No change in freeze-thaw cycles were observed for the hot climates for both the moisture loading conditions.
7. Thus considering all the outputs from hygrothermal simulations, it could be concluded that the interior retrofit with VIPs could potentially perform better, from the moisture management point of view, than exterior retrofit, if and only if moisture loading inside the building envelope is under certain limits and critical hygrothermal analysis is carried out before incorporating any retrofit measures.

8. Future Work

The results from this study suggest that the VIP could be used as a retrofitting measure while considering the associated moisture risks with it. VIP does have a lot of potential and needs further investigation to establish it as a prominent retrofitting option. Some research activities which should be carried out in the coming days are outlined below:

- Field investigations by constructing a wall prototype and comparing the results obtained from the hygrothermal simulations to validate the observations or suggestions made during this study.
- A whole building energy simulation to evaluate the performance of the non-retrofitted walls with the VIP retrofitted walls.

9. References

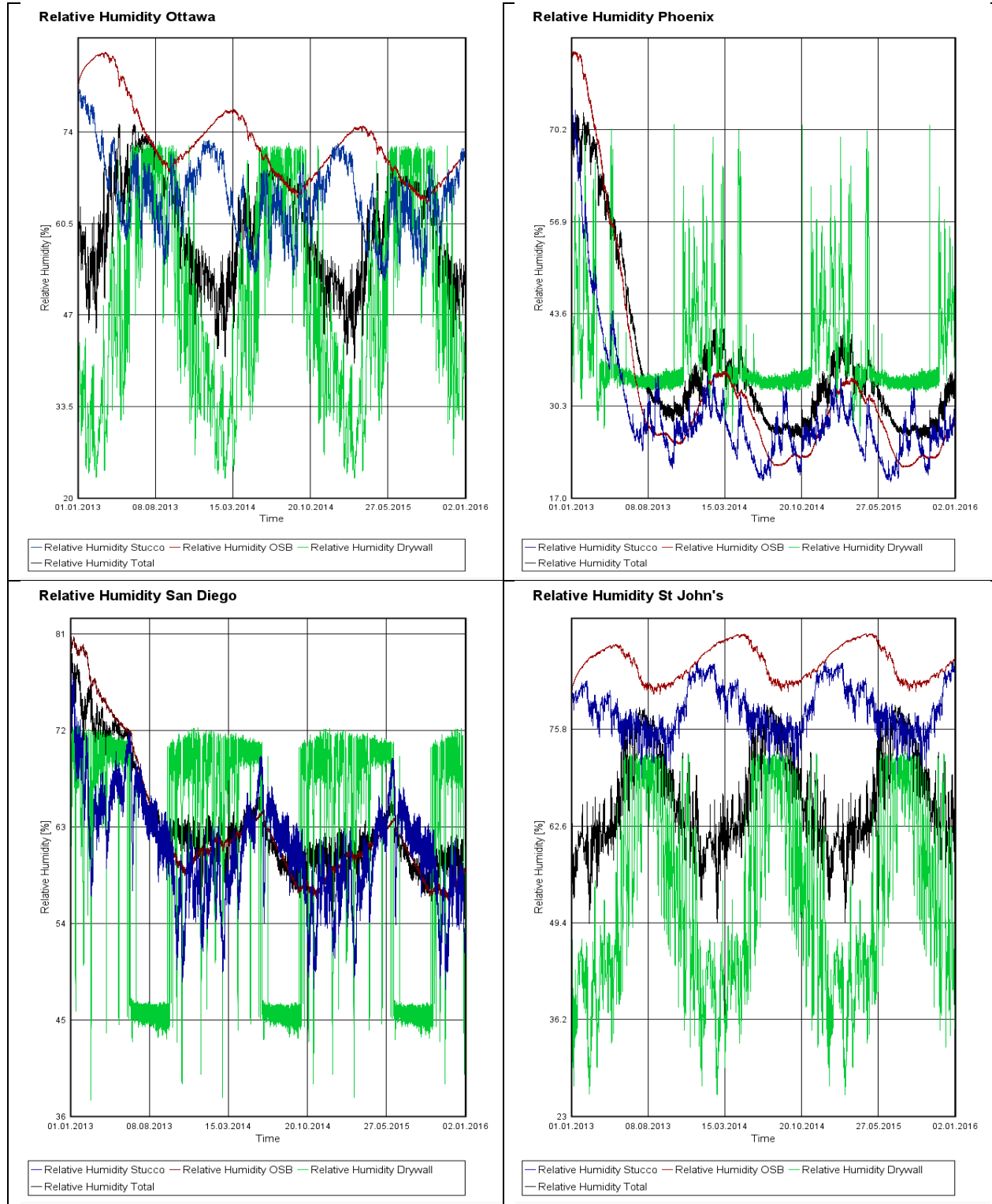
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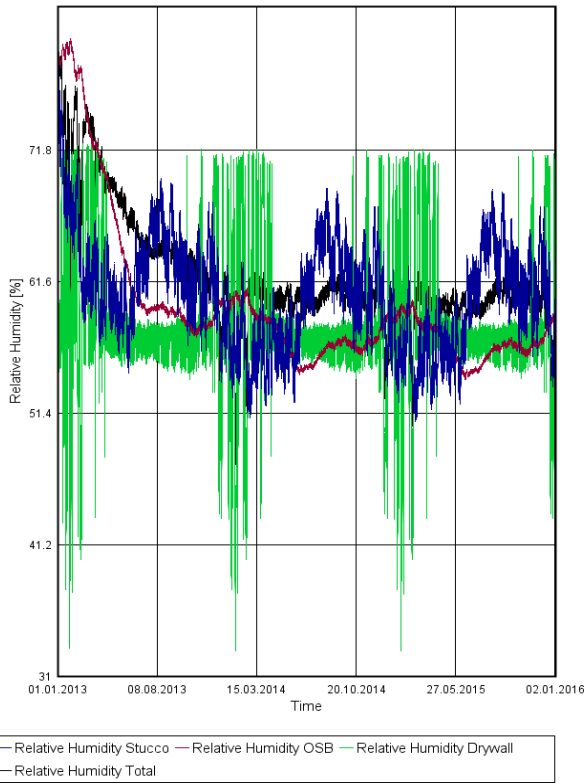
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Appendix A-Regular Wall

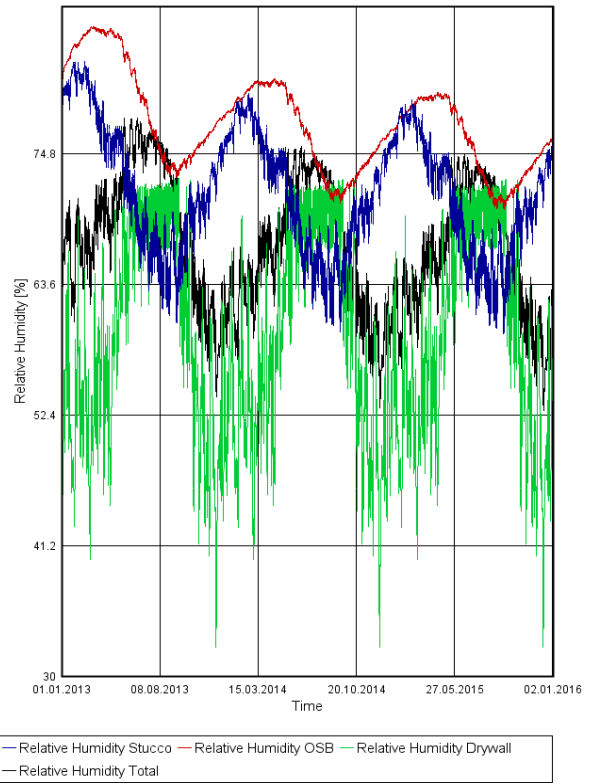
ASHRAE 160P



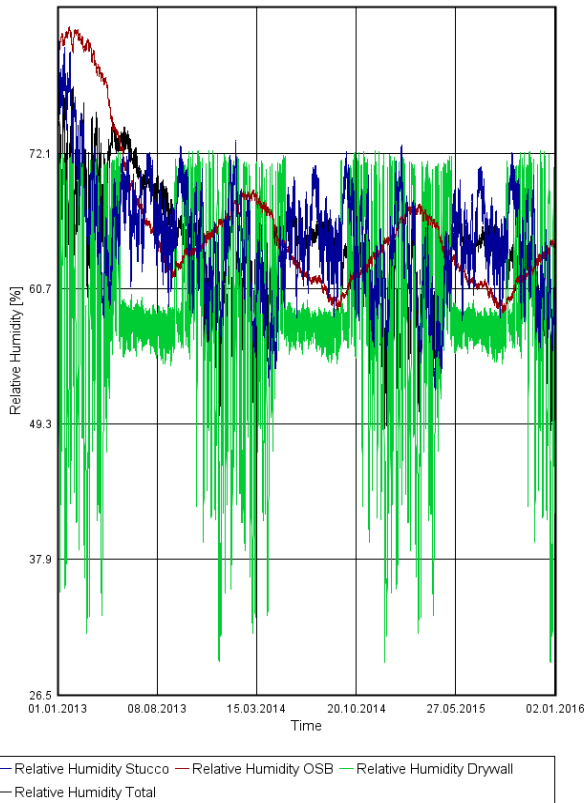
Relative Humidity Tampa



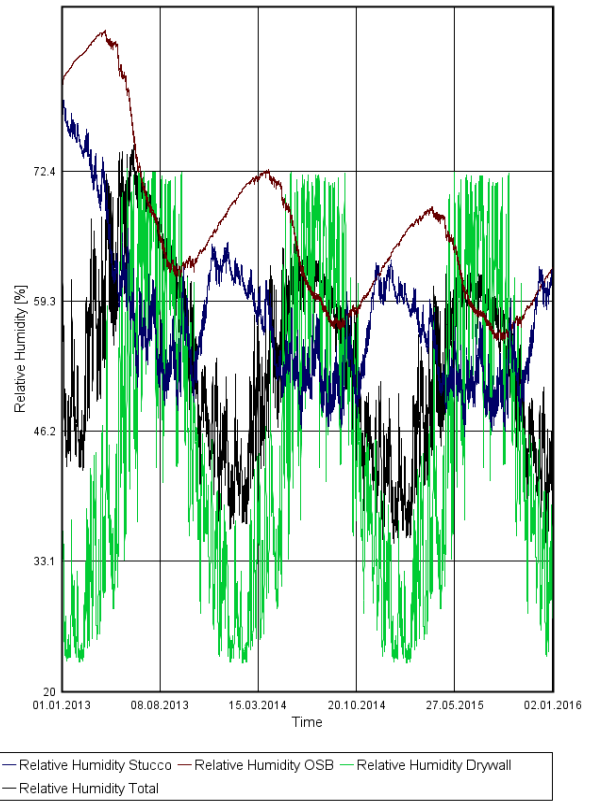
Relative Humidity Vancouver



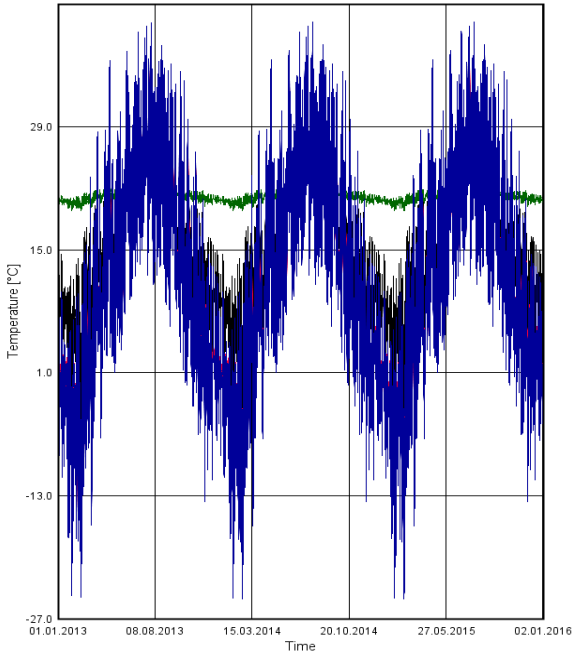
Relative Humidity Wilmington



Relative Humidity Winnipeg

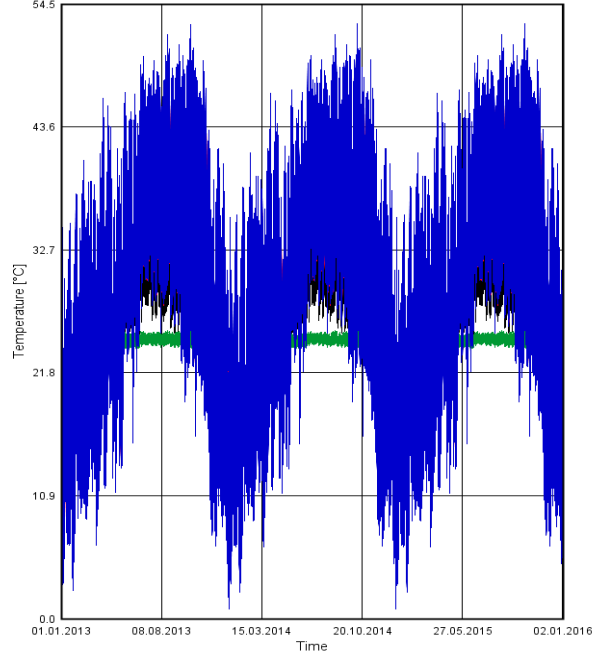


Temperature Ottawa



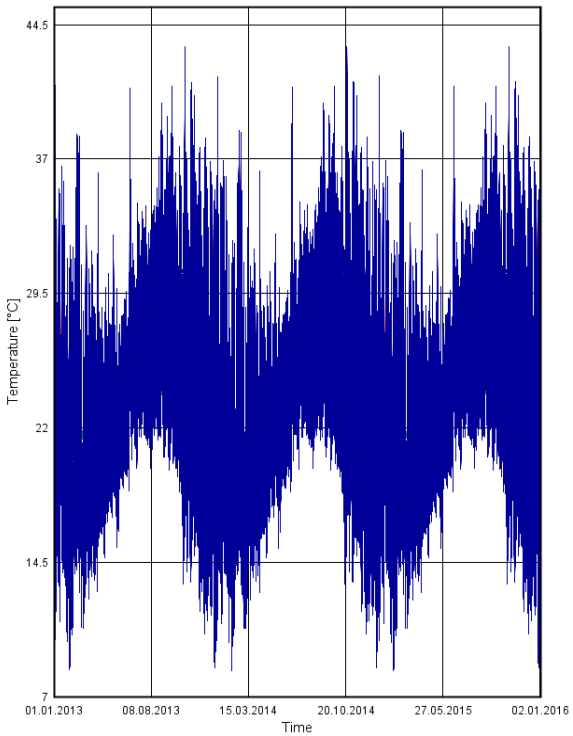
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— Temperature Total

Temperature Phoenix



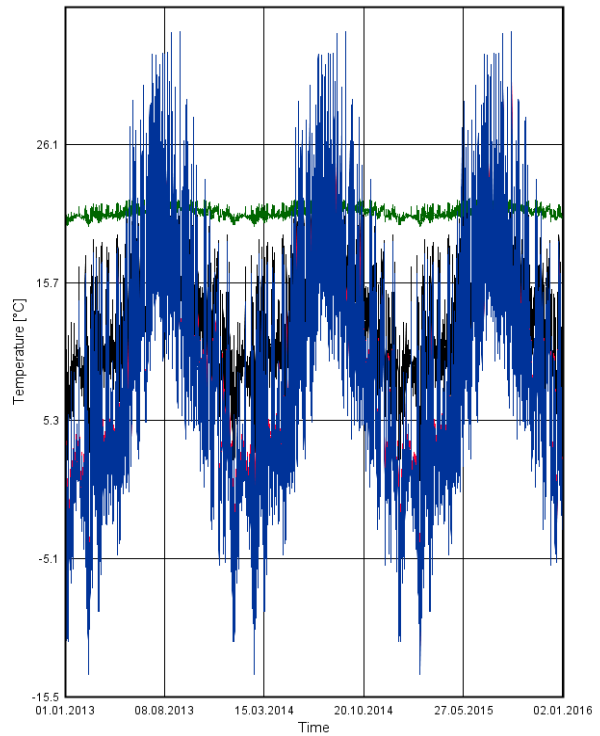
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— Temperature Total

Temperature San Diego



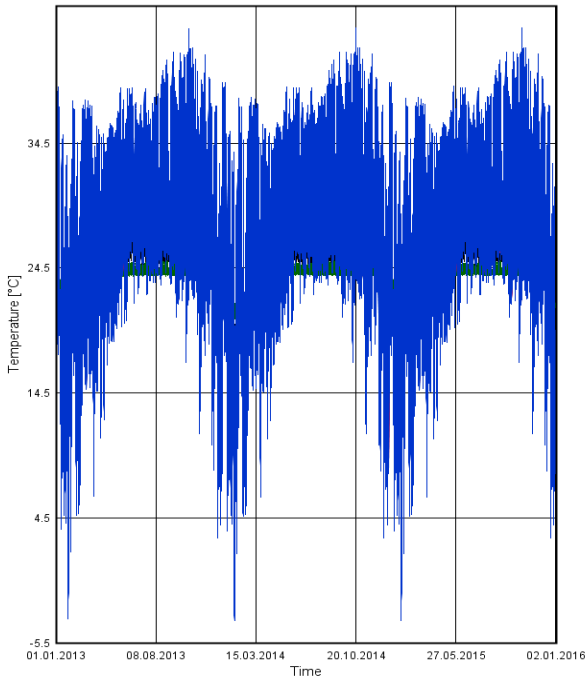
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Temperature St John's



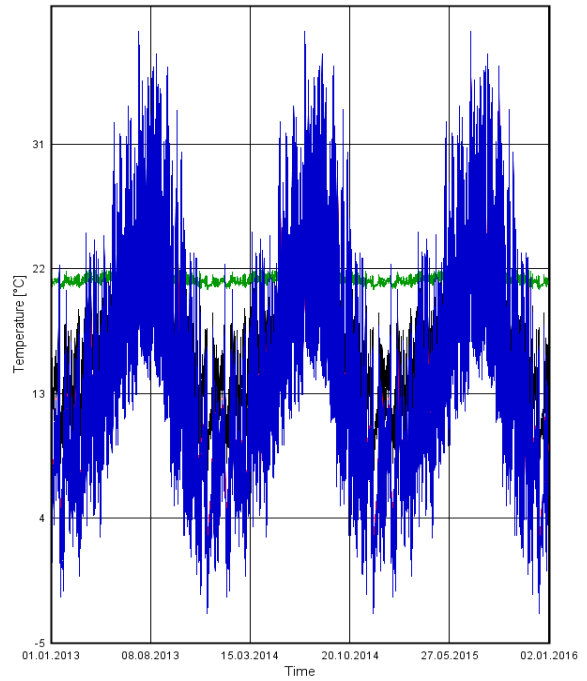
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Temperature Tampa



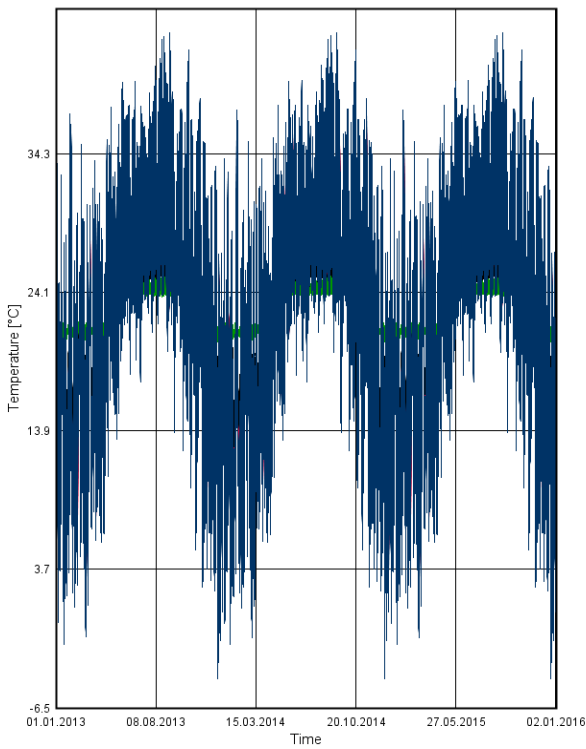
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Temperature Vancouver



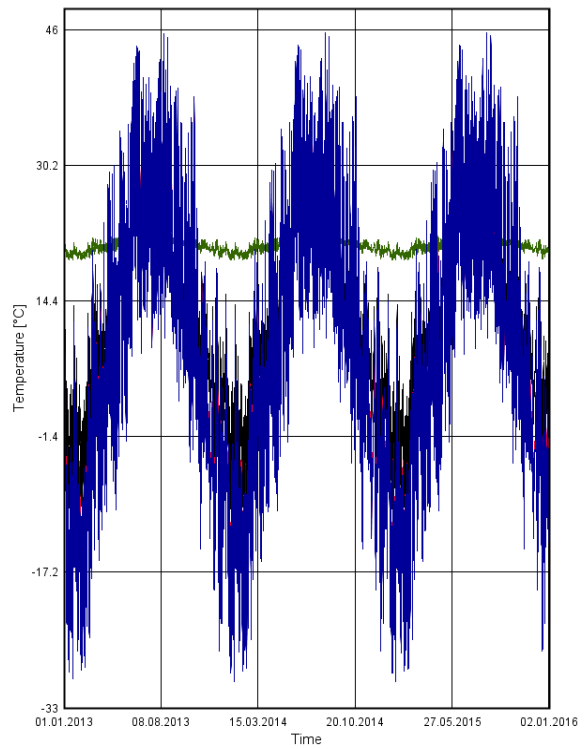
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Temperature Wilmington



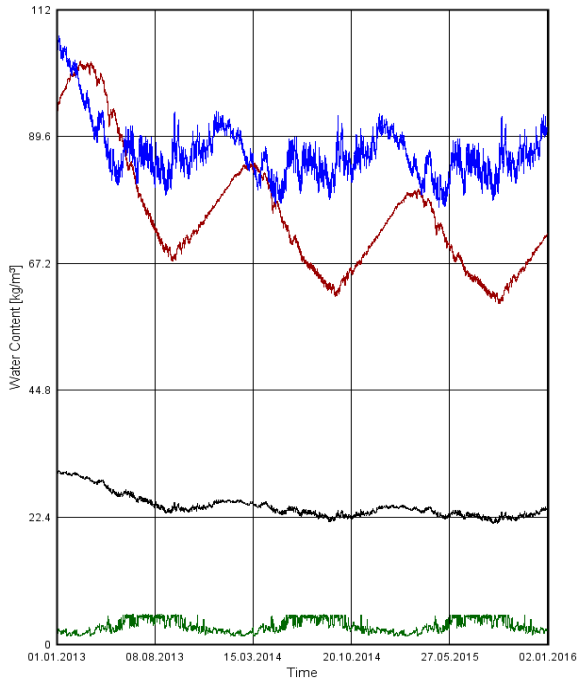
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Temperature Winnipeg



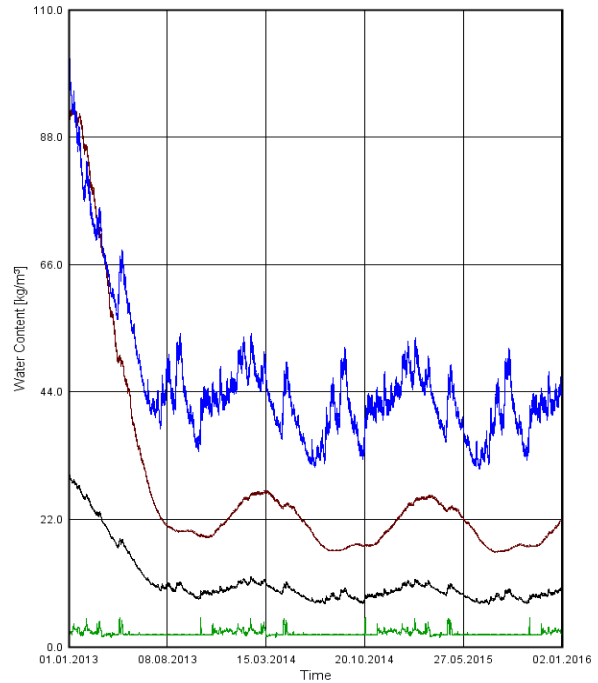
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Water Content Ottawa



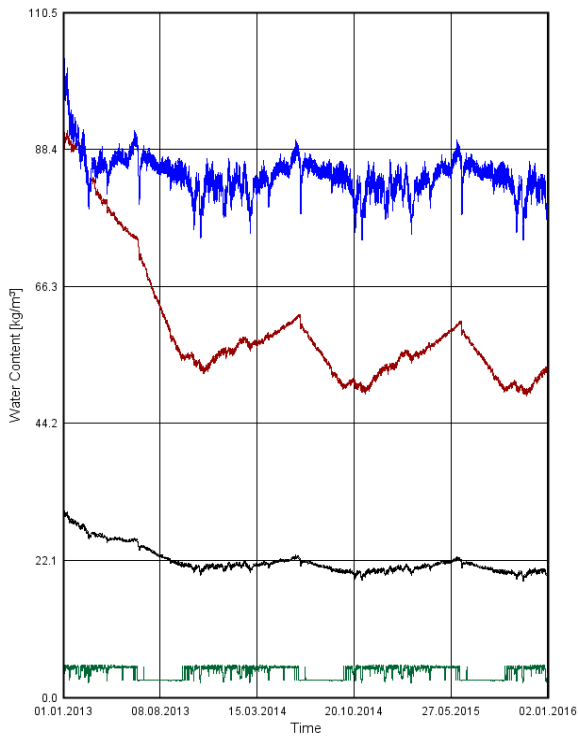
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Water Content Phoenix



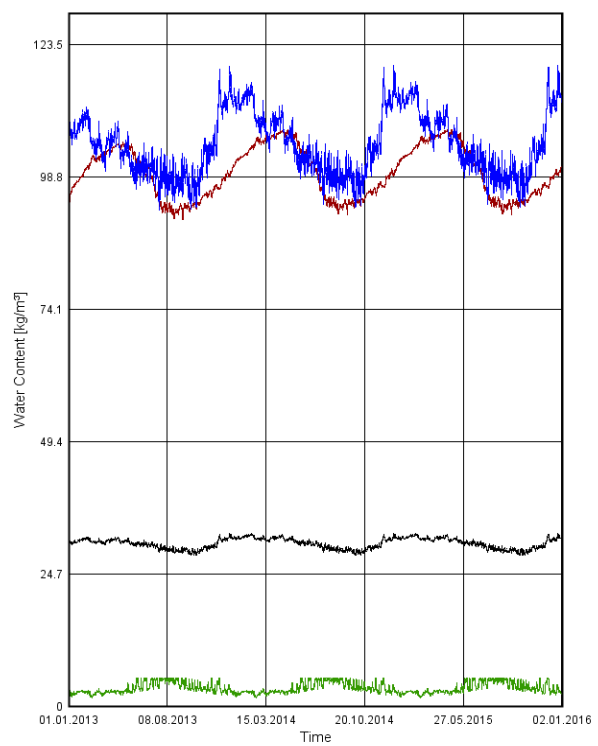
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Water Content San Diego



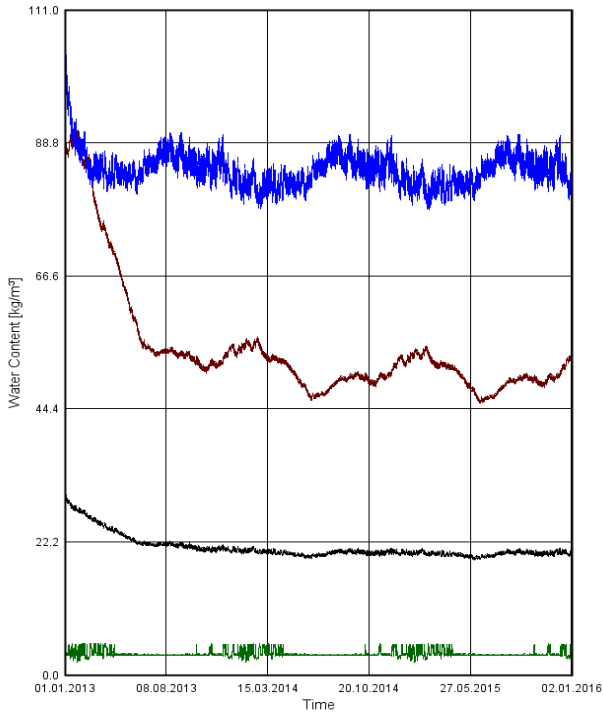
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Water Content St John's



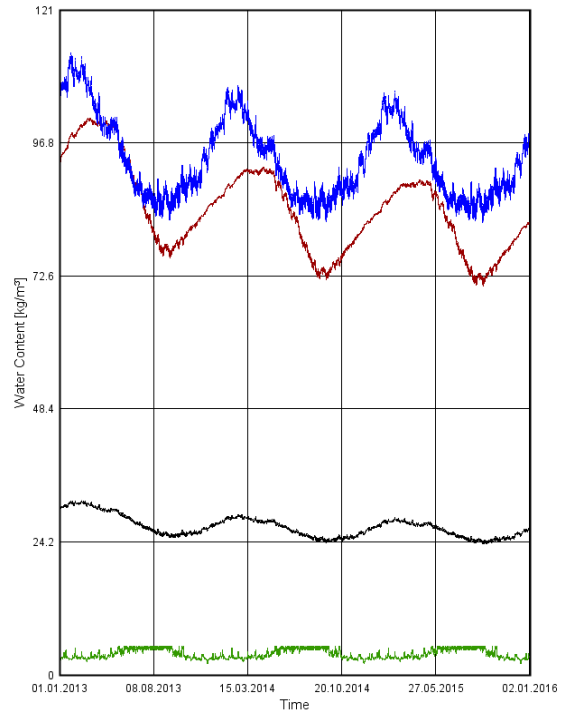
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Water Content Tampa



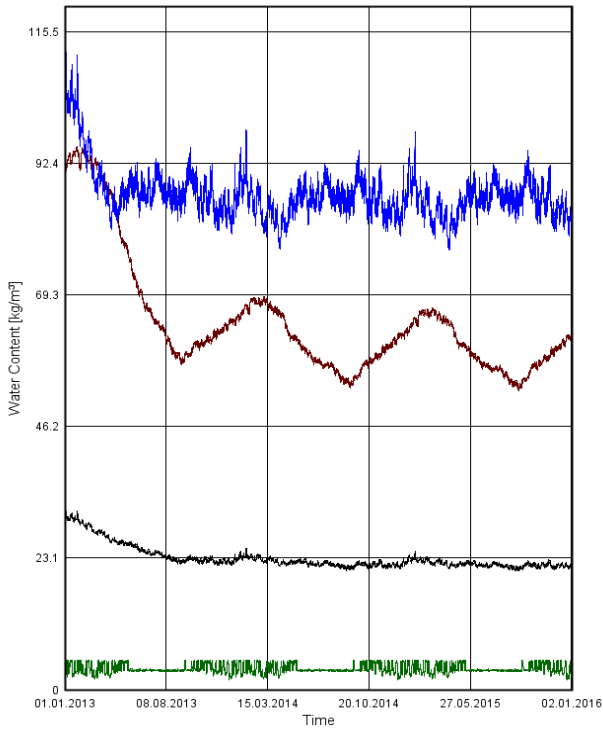
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Water Content Vancouver



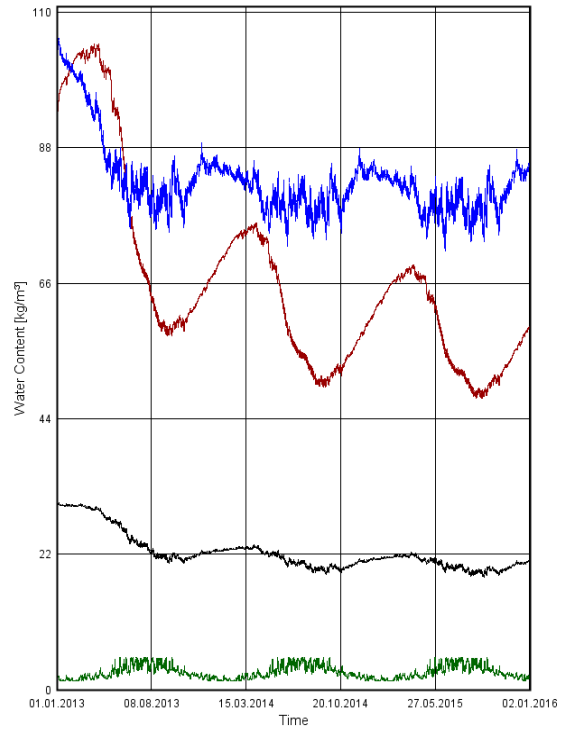
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Water Content Wilmington

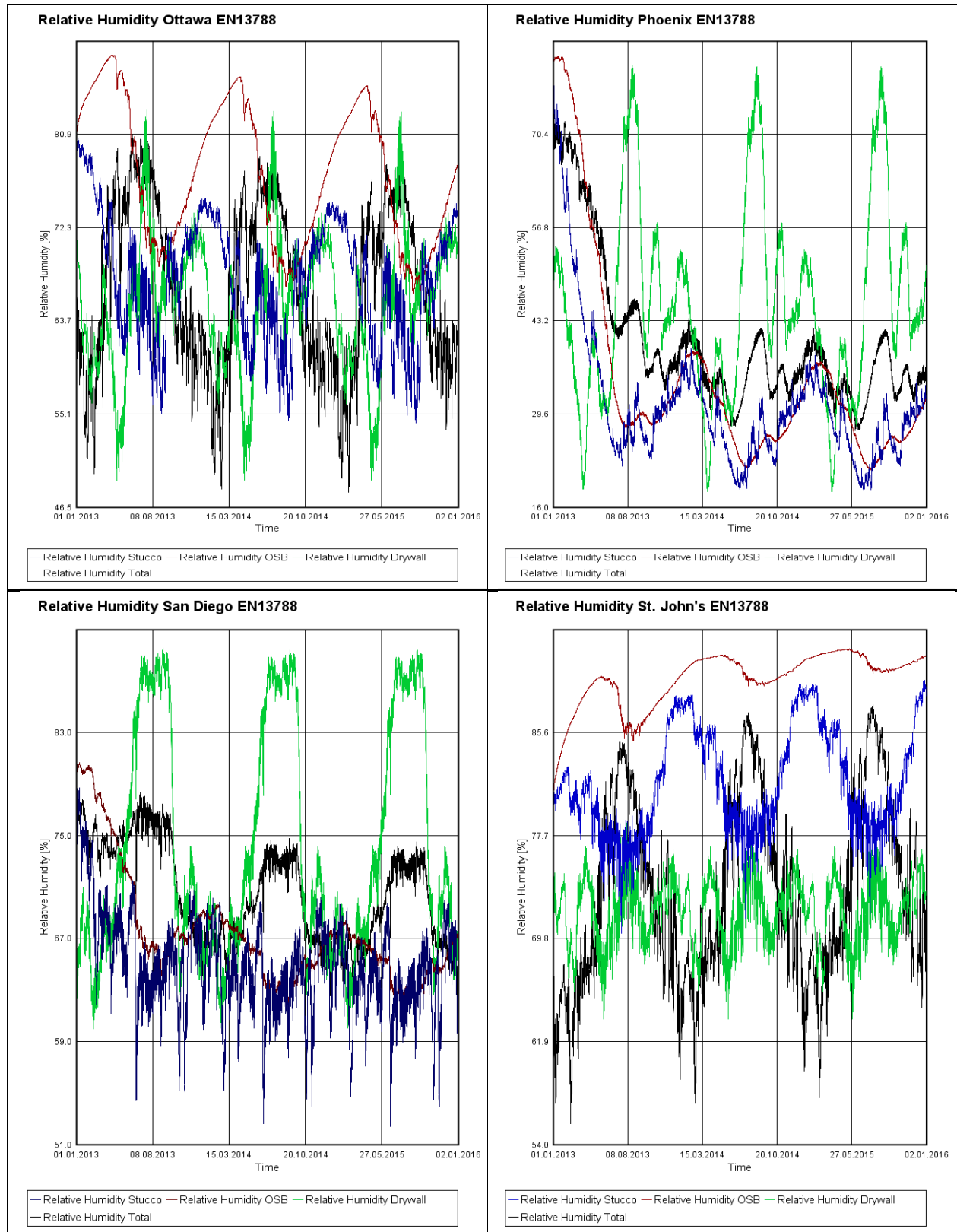


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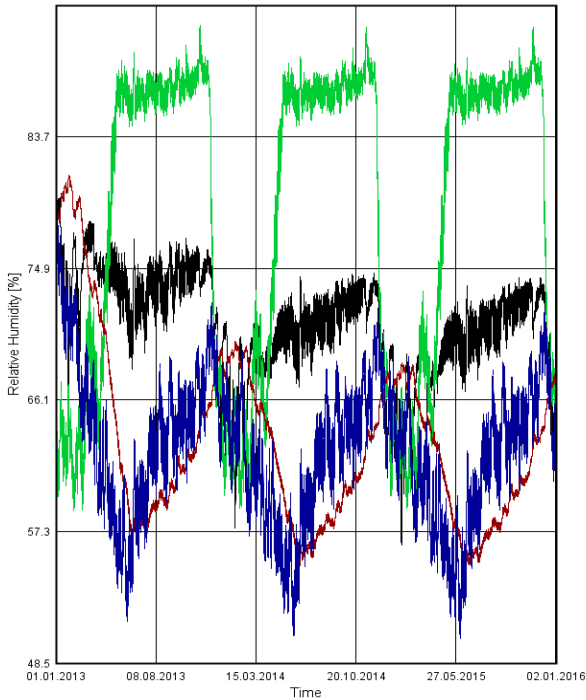
Water Content Winnipeg



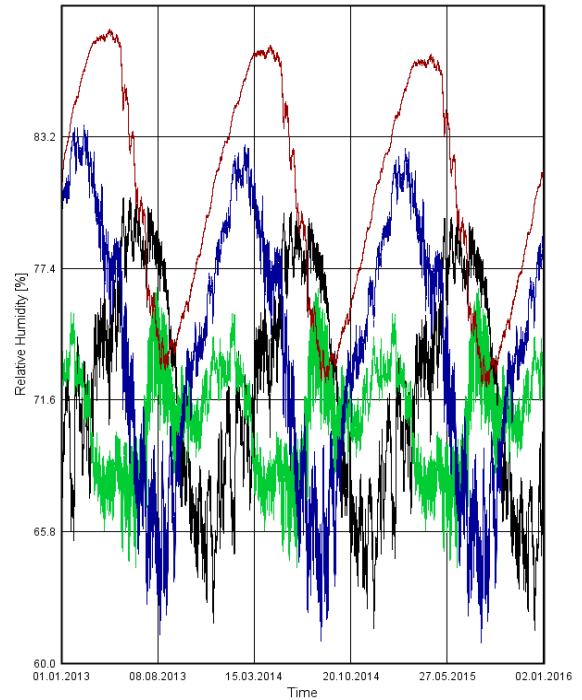
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— Water Content Total



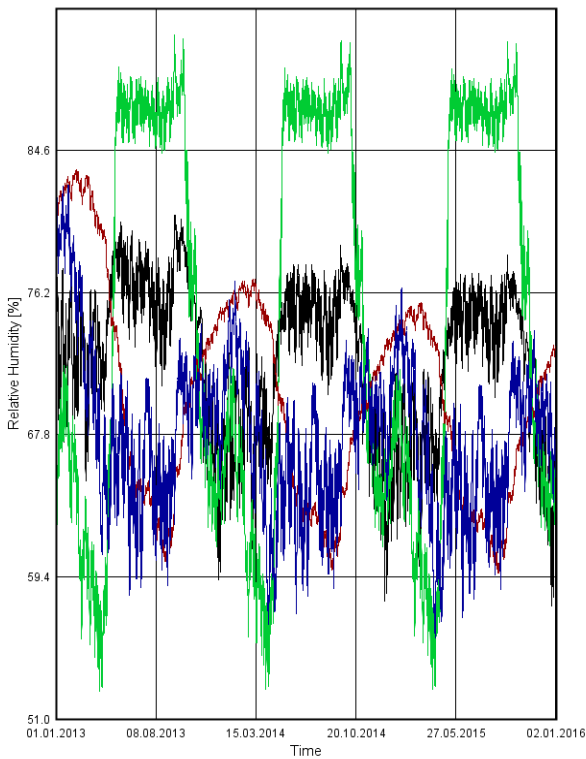
Relative Humidity Tampa EN13788



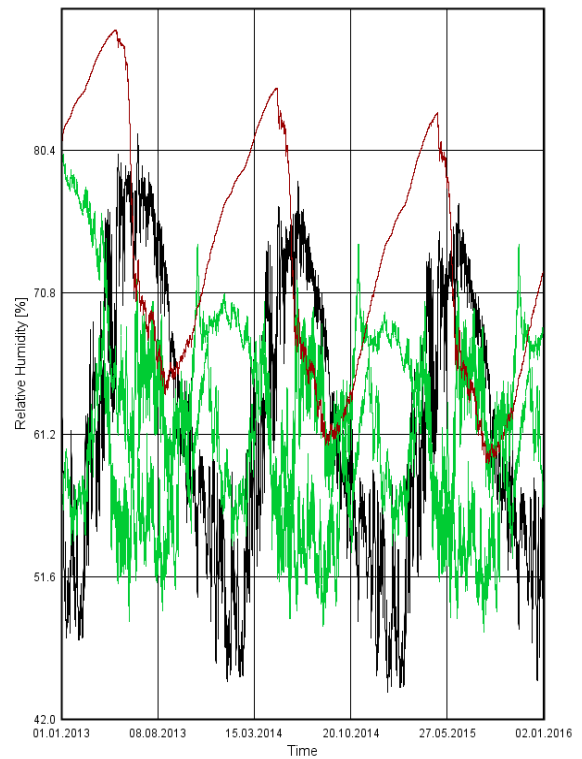
Relative Humidity Vancouver EN13788



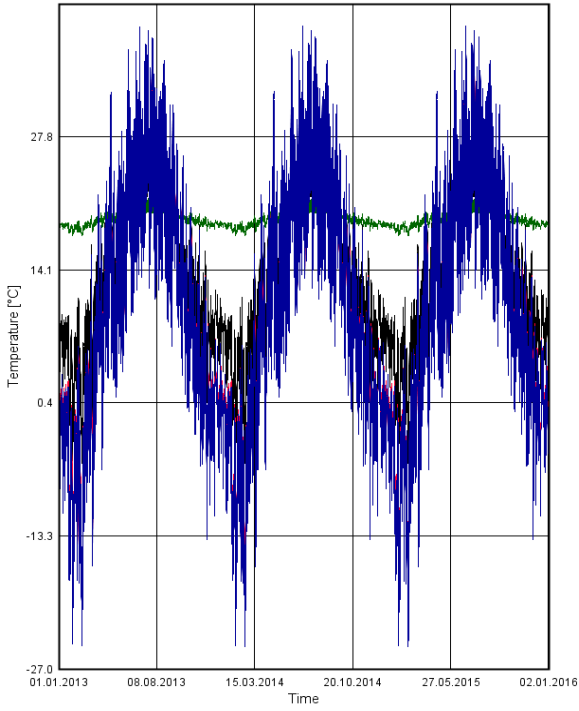
Relative Humidity Wilmington EN13788



Relative Humidity Winnipeg EN13788

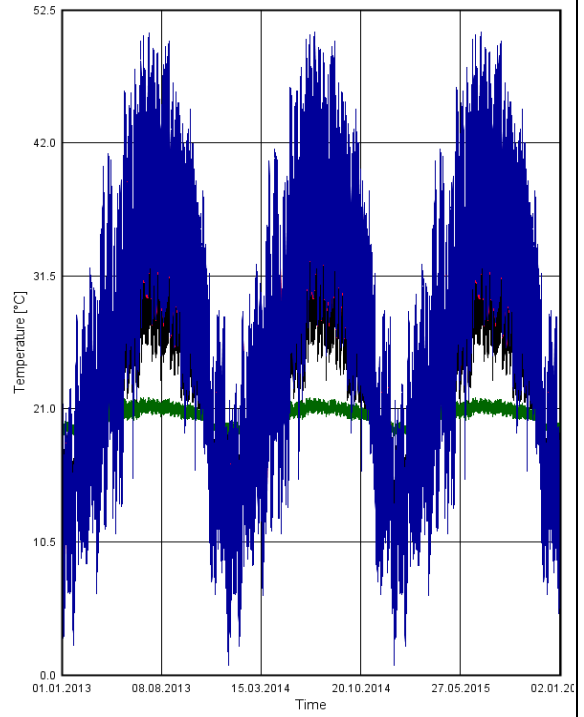


Temperature Ottawa EN13788



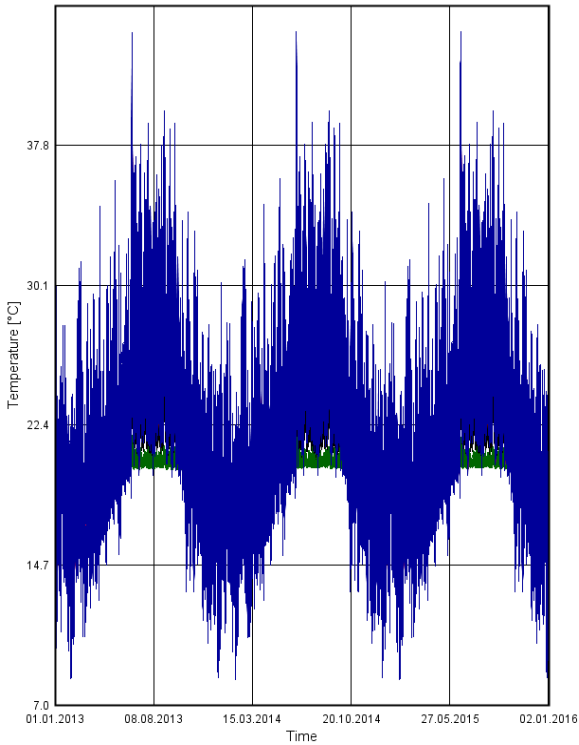
— Temperature Stucco — Temperature OSB — Temperature Drywall
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Temperature Phoenix EN13788



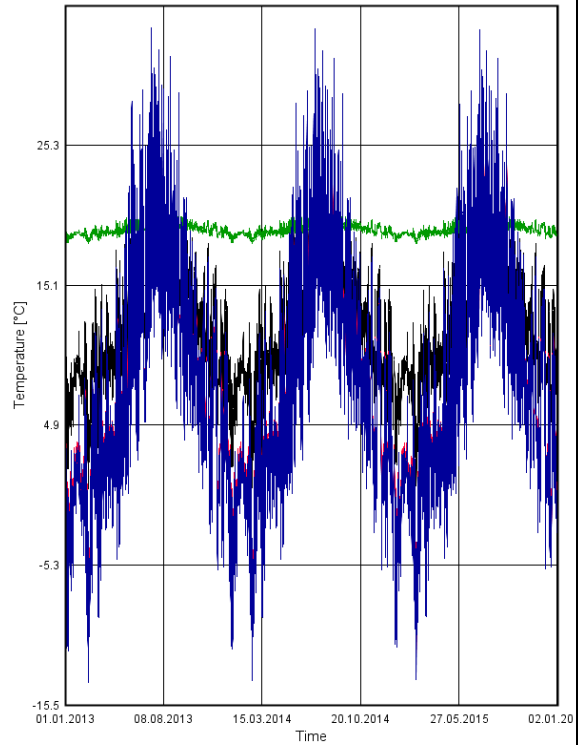
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— Temperature Total

Temperature San Diego EN13788



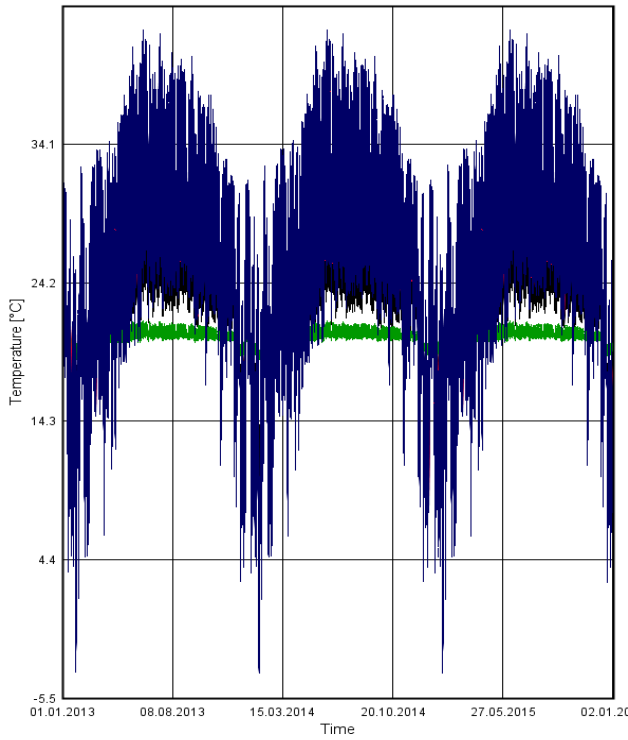
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature St. John's EN13788



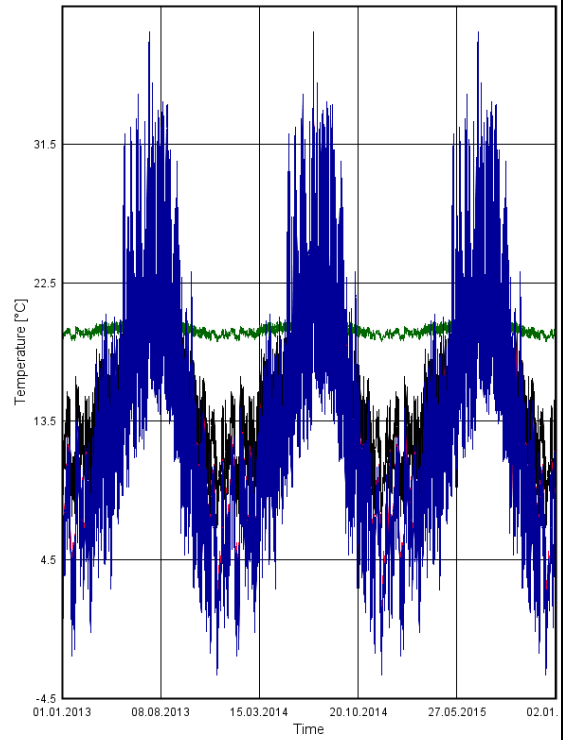
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Tampa EN13788



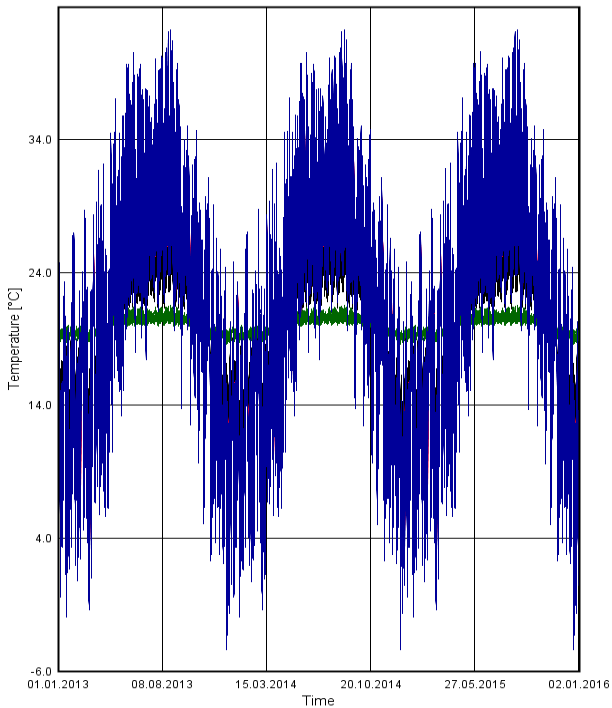
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Vancouver EN13788



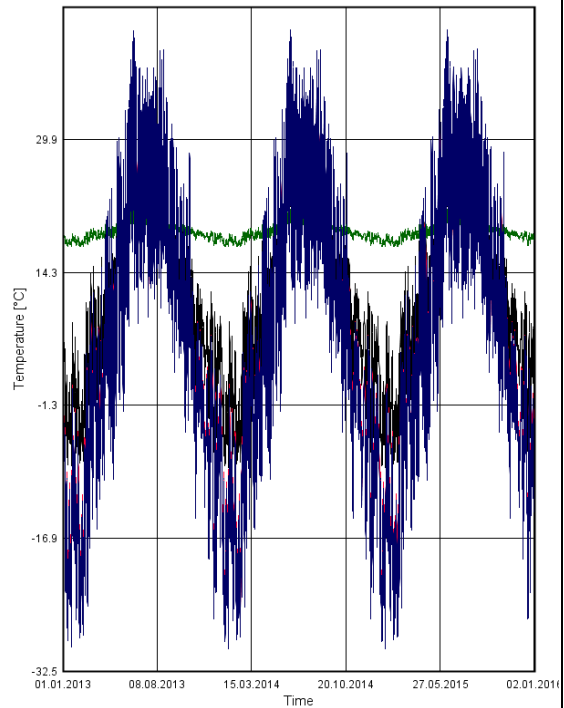
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Wilmington EN 13788



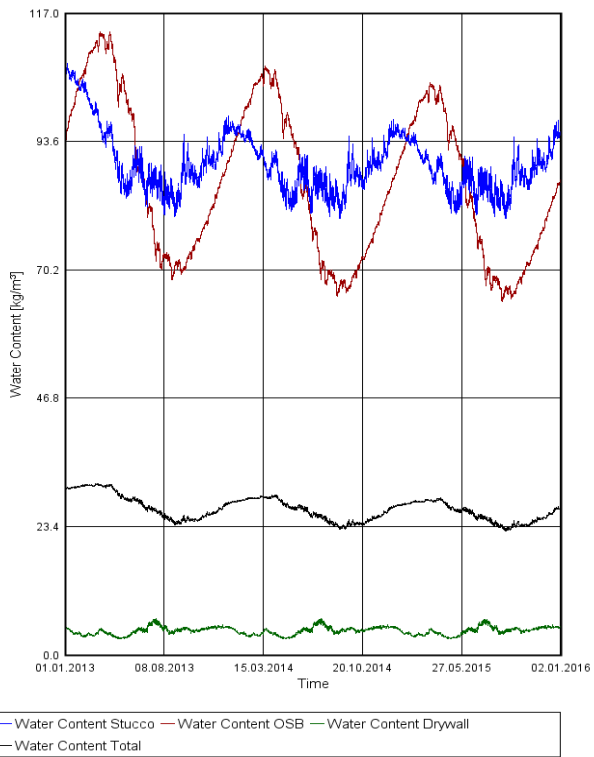
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Winnipeg EN13788

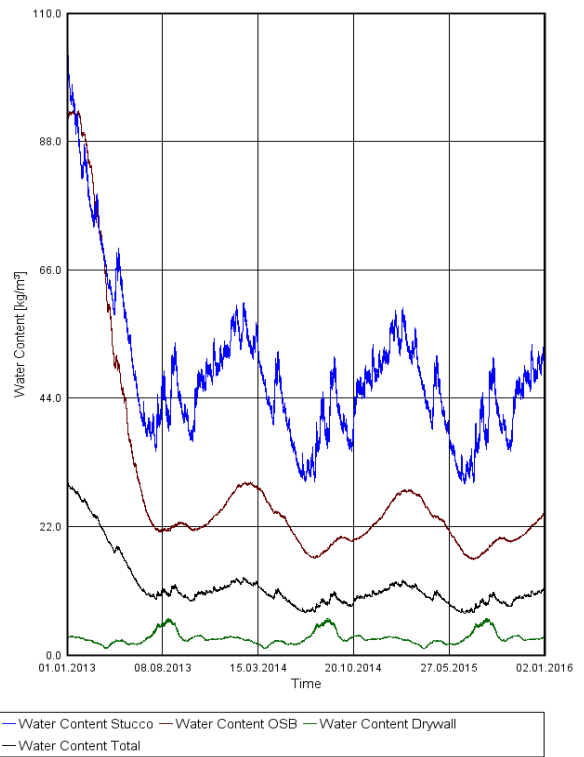


— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

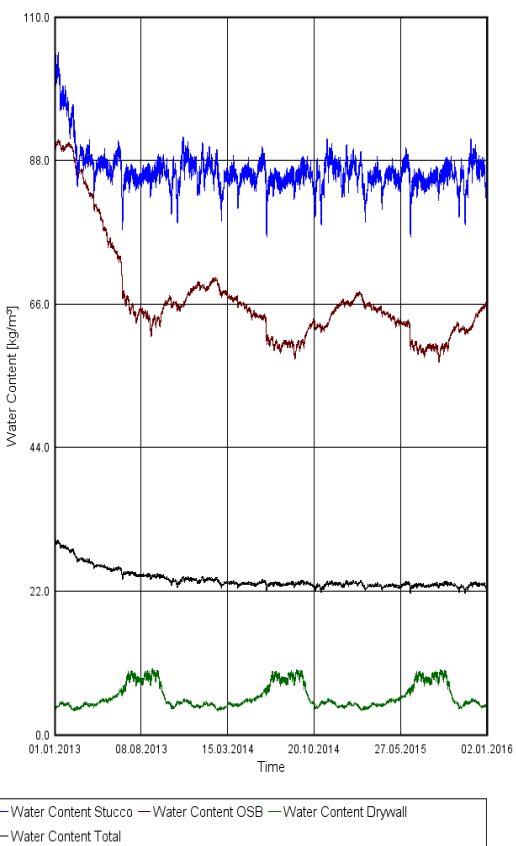
Water Content Ottawa EN13788



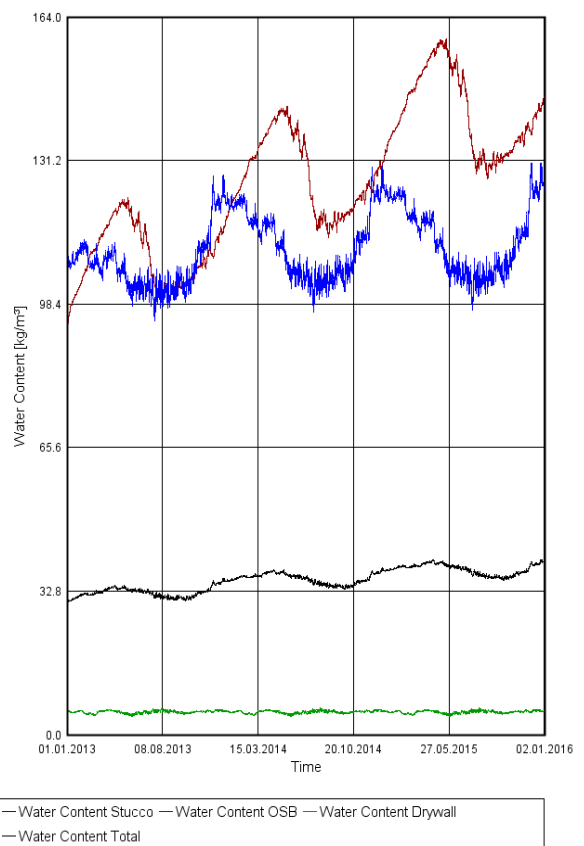
Water Content Phoenix EN13788



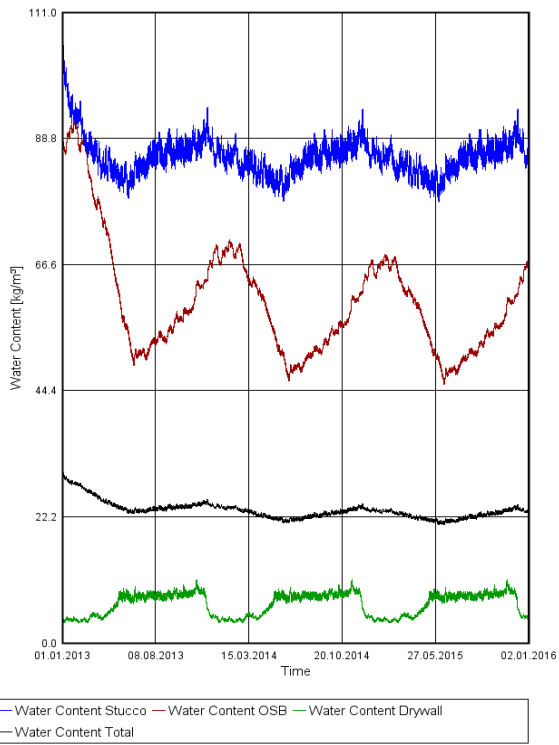
Water Content San Diego EN13788



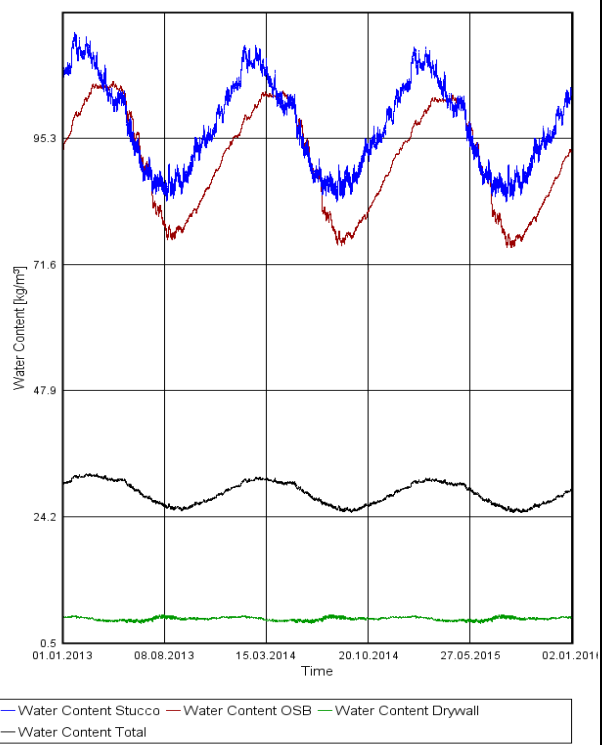
Water Content St. John's EN13788



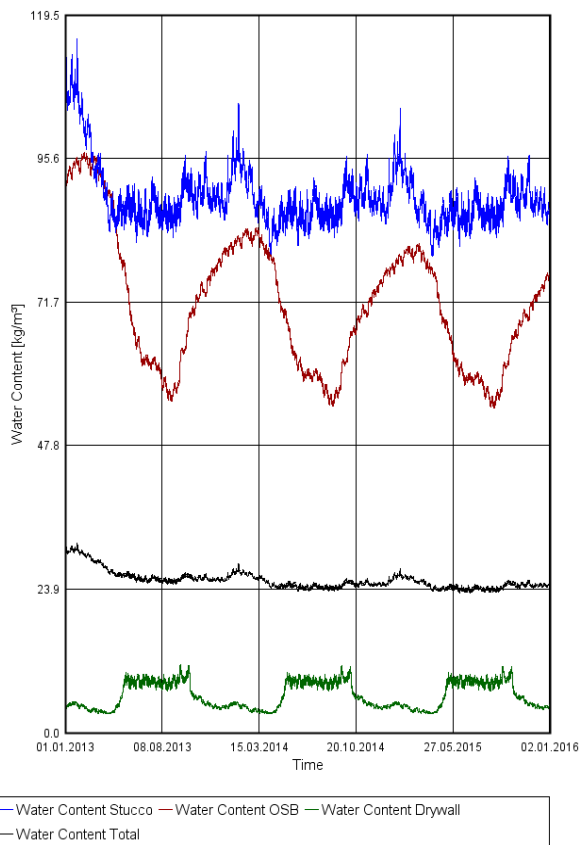
Water Content Tampa EN13788



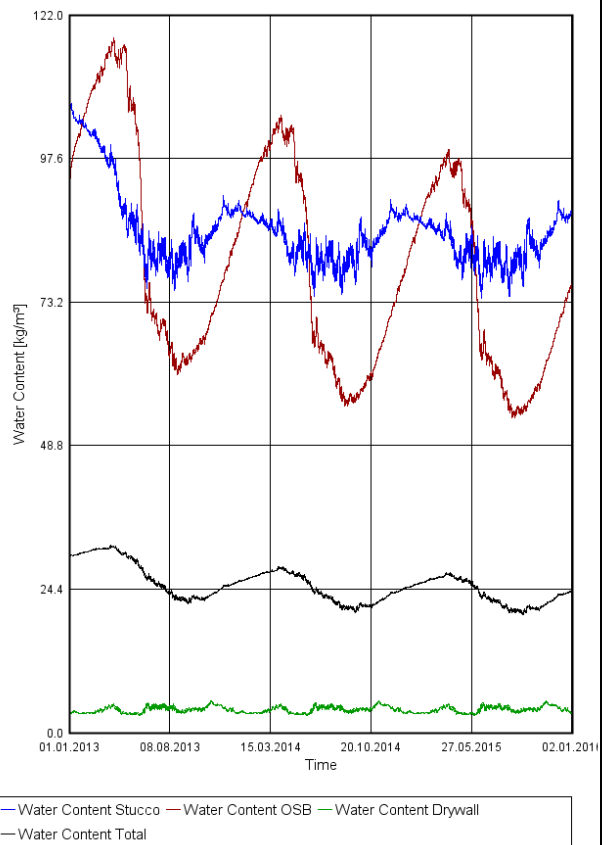
Water Content Vancouver EN13788



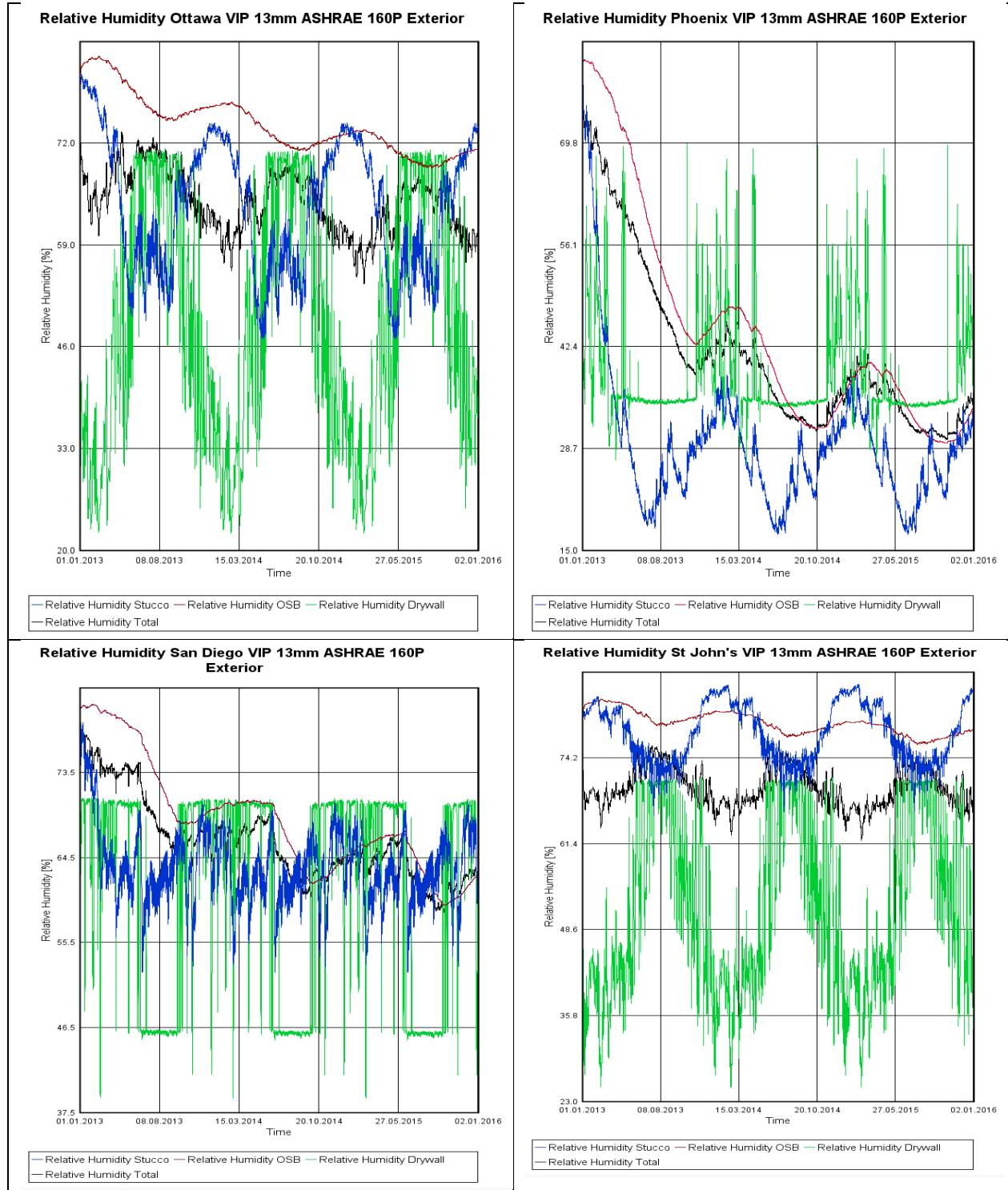
Water Content Wilmington EN13788



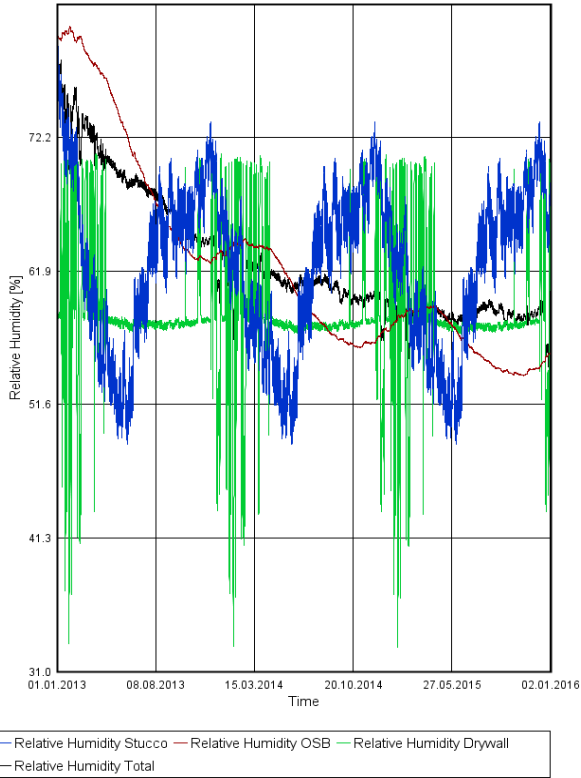
Water Content Winnipeg EN13788



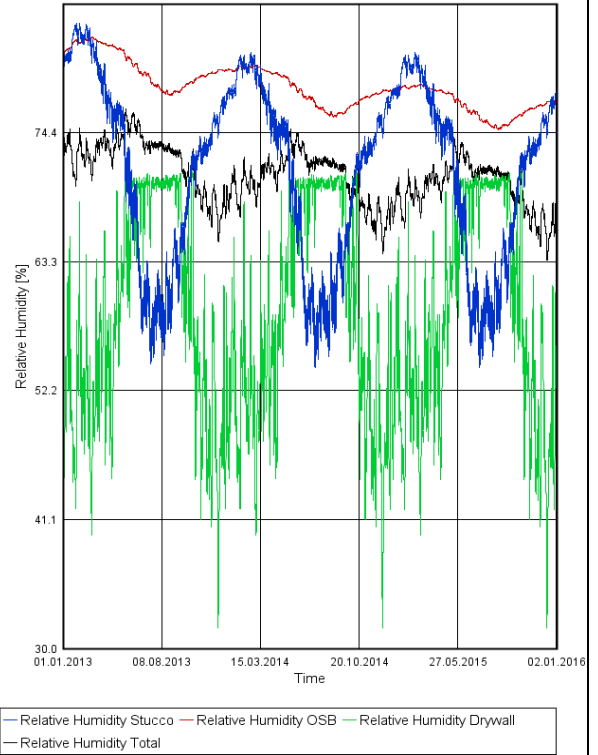
Appendix B – Exterior Retrofitted Wall ASHRAE 160P



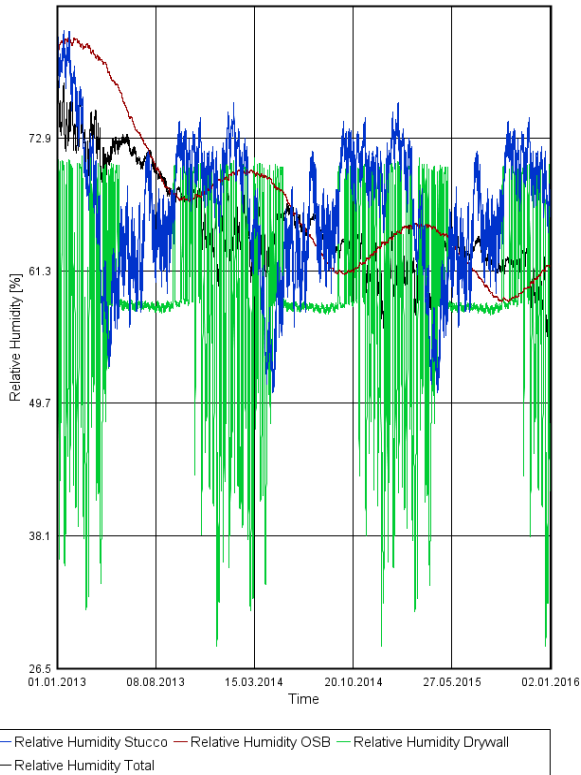
Relative Humidity Tampa VIP 13mm ASHRAE 160P Exterior



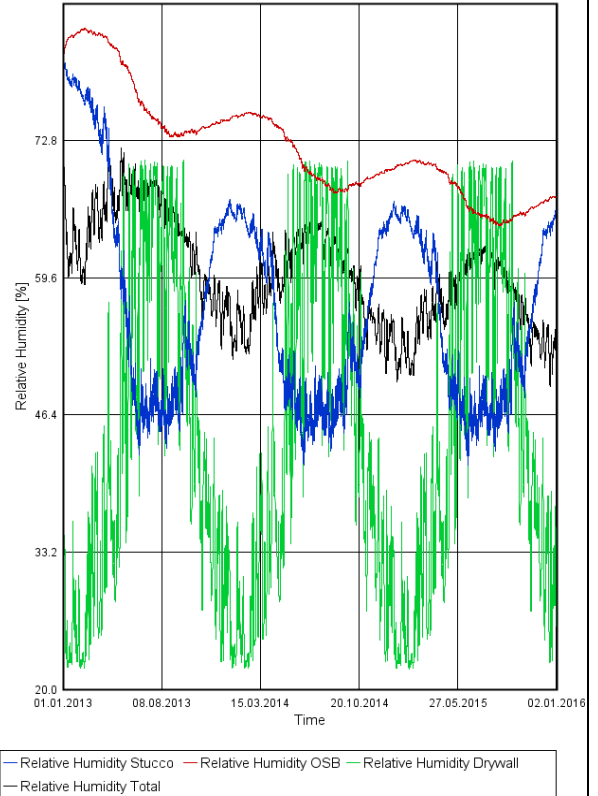
Relative Humidity Vancouver VIP 13mm ASHRAE 160P Exterior



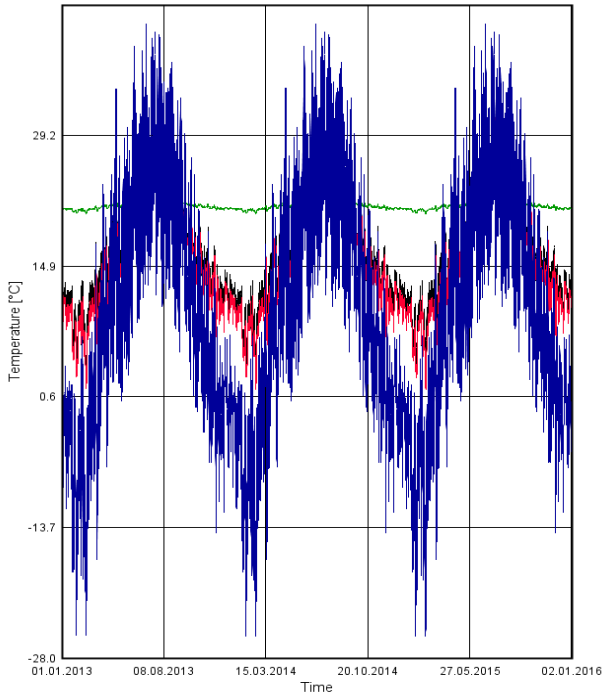
Relative Humidity Wilmington VIP 13mm ASHRAE 160P Exterior



Relative Humidity Winnipeg VIP 13mm ASHRAE 160P Exterior

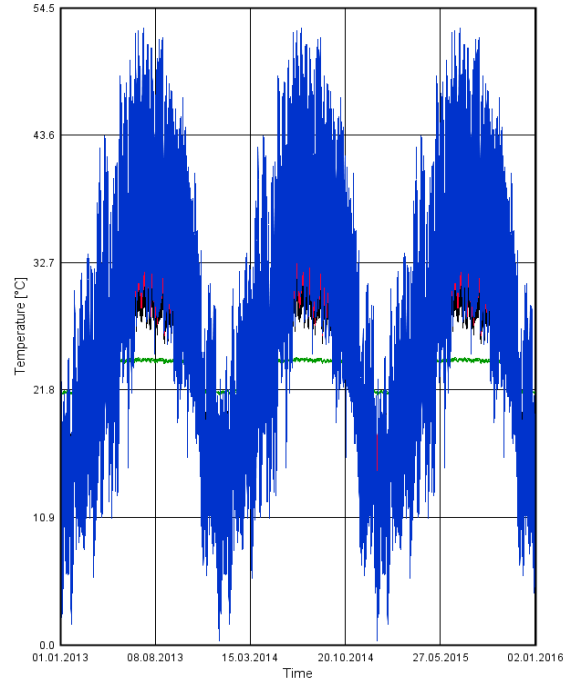


Temperature Ottawa VIP 13mm ASHRAE 160P Exterior



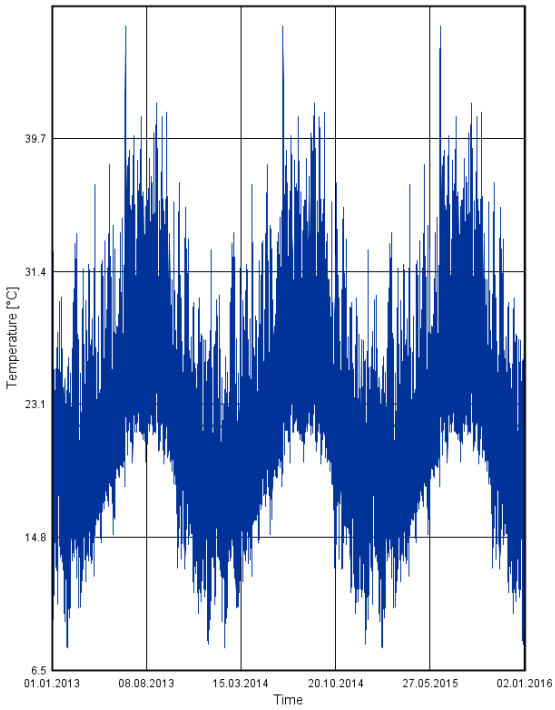
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Phoenix VIP 13mm ASHRAE 160P Exterior



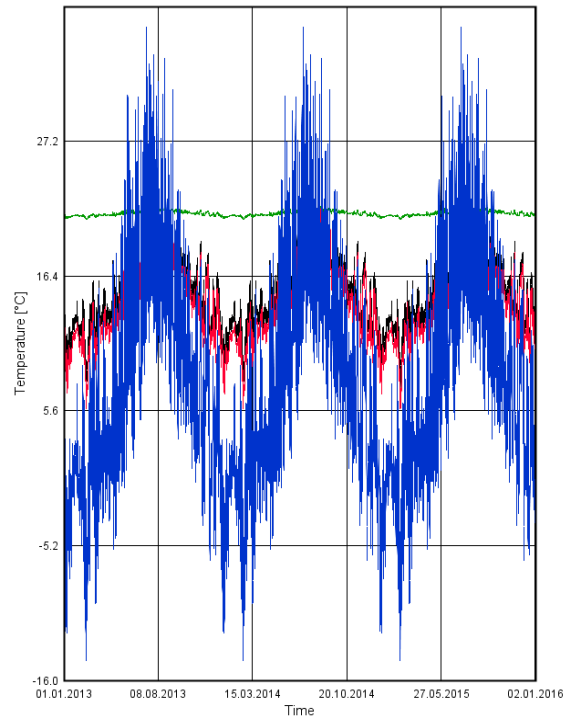
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature San Diego VIP 13mm ASHRAE 160P Exterior



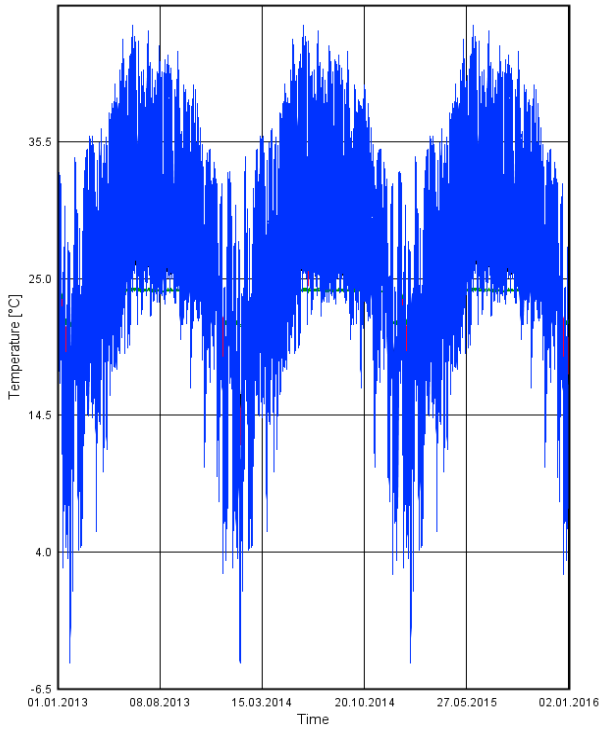
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature St John's VIP 13mm ASHRAE 160P Exterior



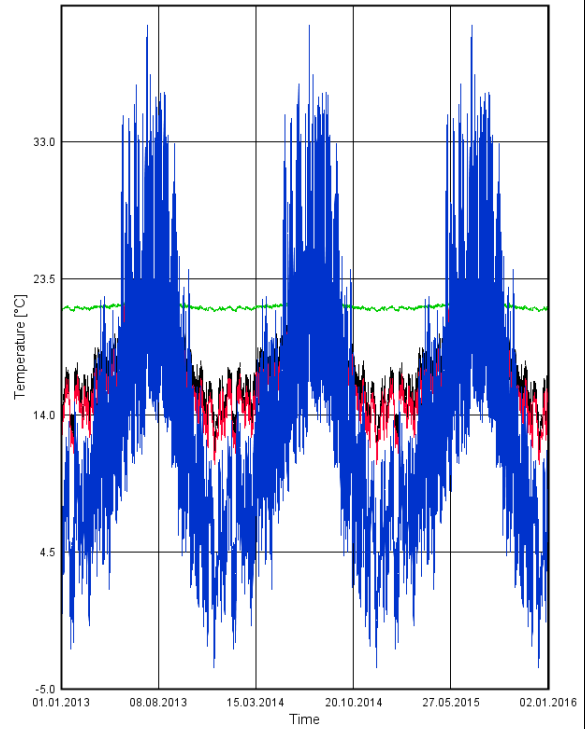
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Tampa VIP 13mm ASHRAE 160P Exterior



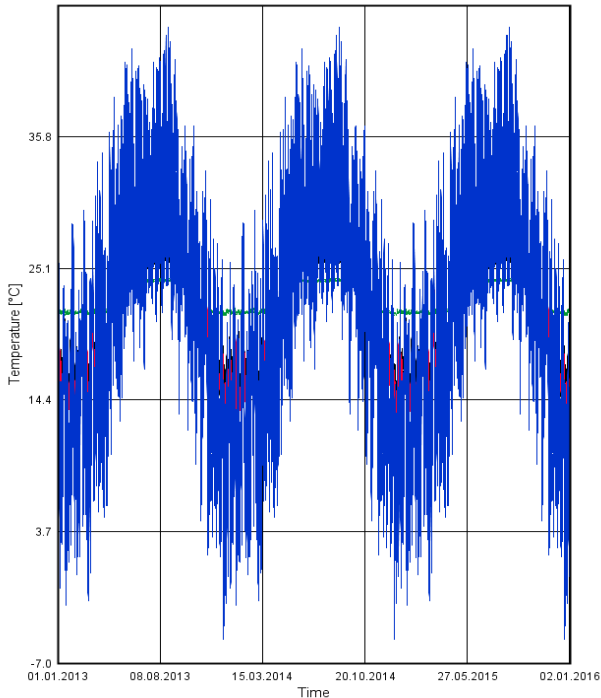
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Vancouver VIP 13mm ASHRAE 160P Exterior



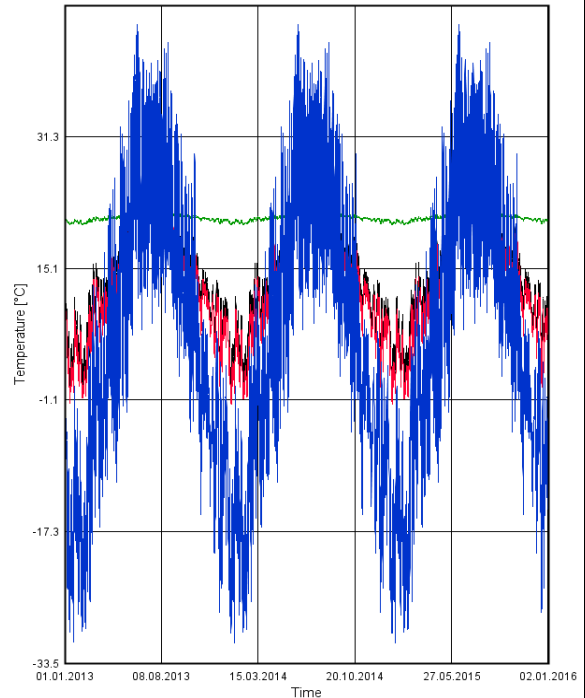
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Wilmington VIP 13mm ASHRAE 160P Exterior



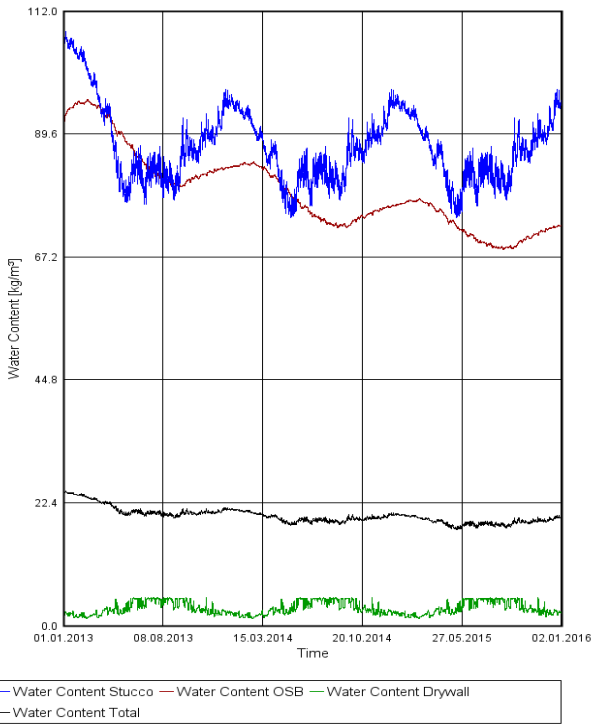
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Winnipeg VIP 13mm ASHRAE 160P Exterior

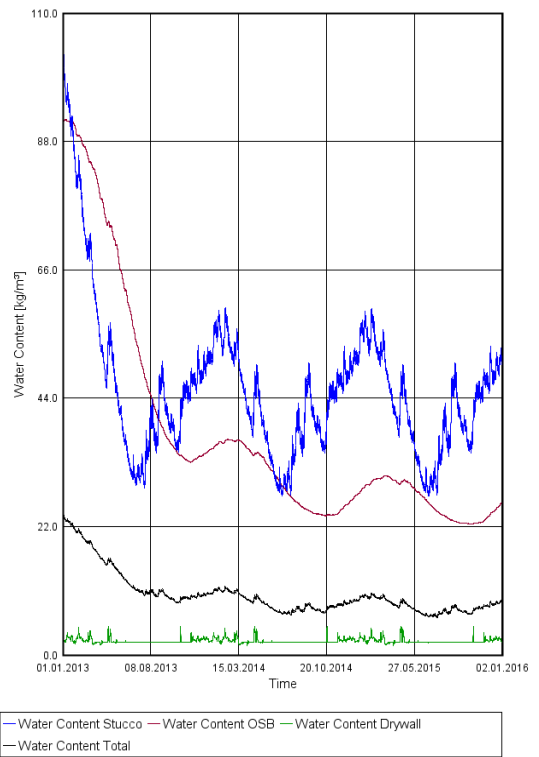


— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

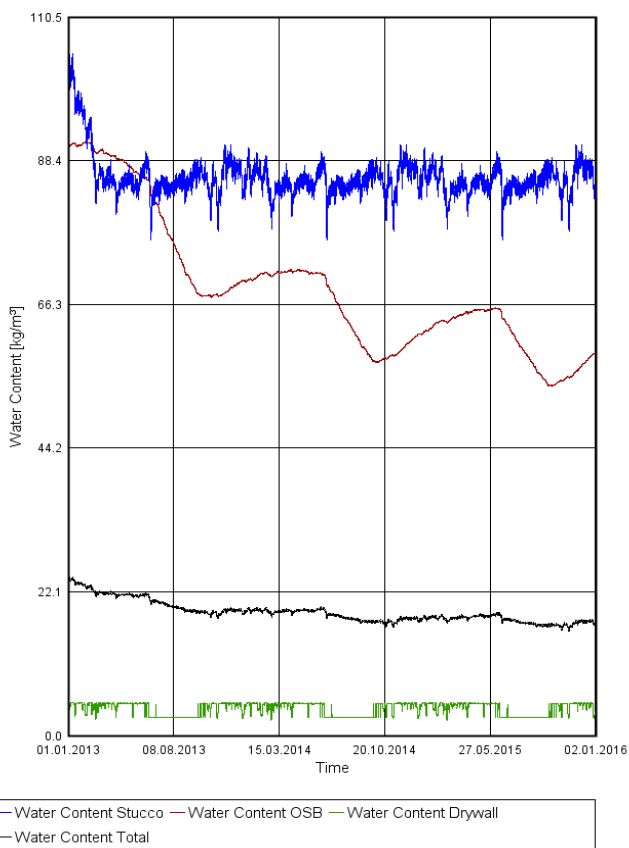
Water Content Ottawa VIP 13mm ASHRAE 160P Exterior



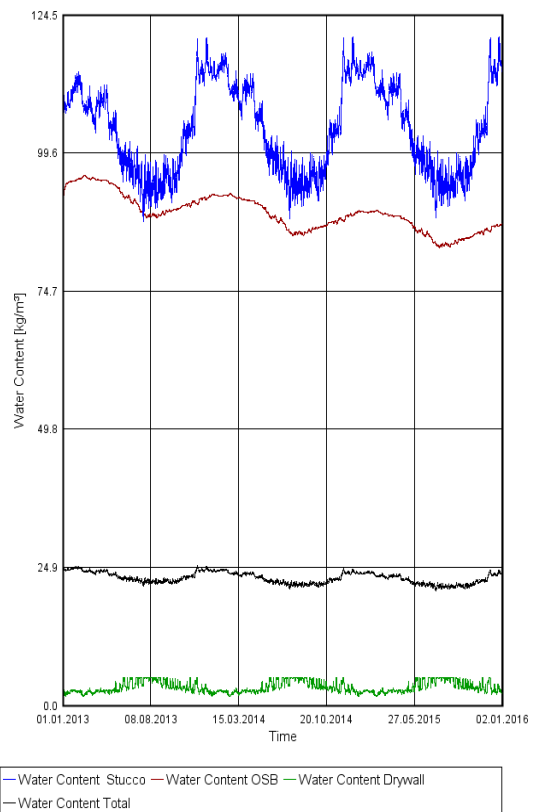
Water Content Phoenix VIP 13mm ASHRAE 160P Exterior



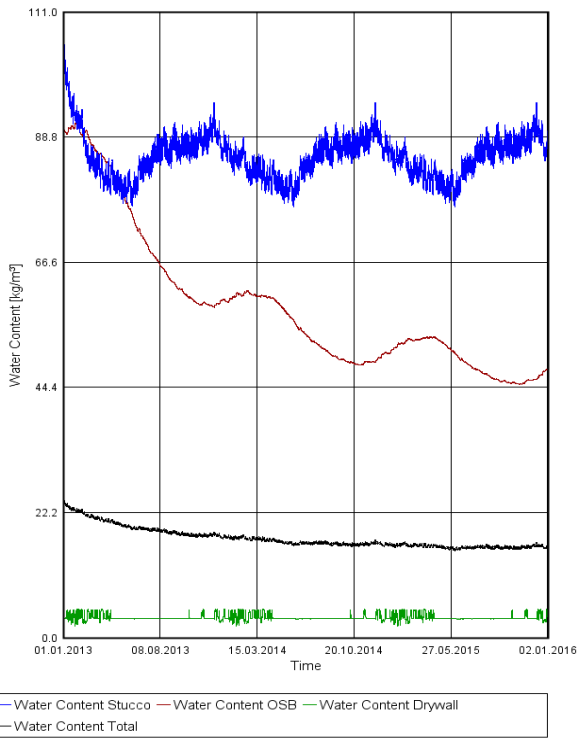
Water Content San Diego VIP 13mm ASHRAE 160P Exterior



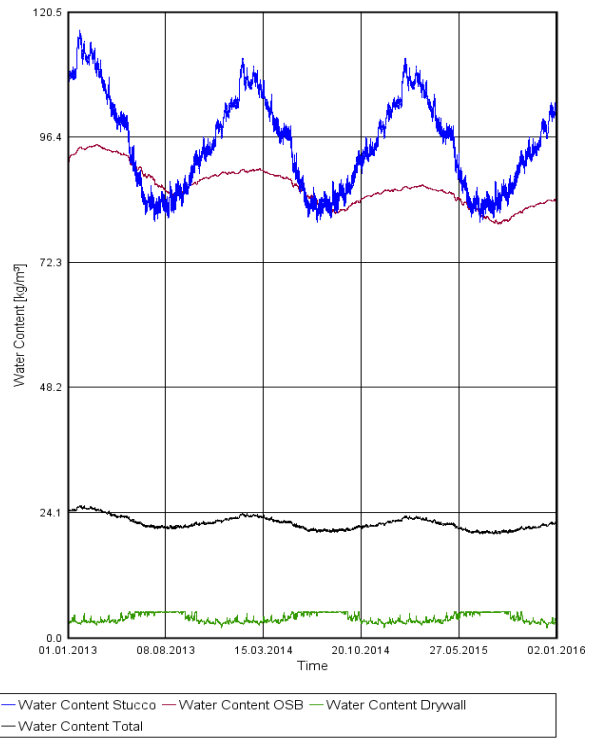
Water Content St John's VIP 13mm ASHRAE 160P Exterior



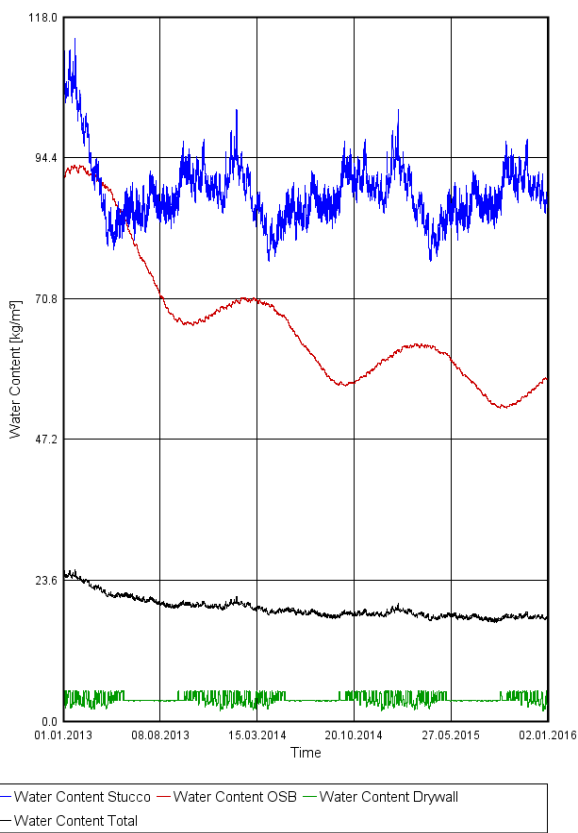
Water Content Tampa VIP 13mm ASHRAE 160P Exterior



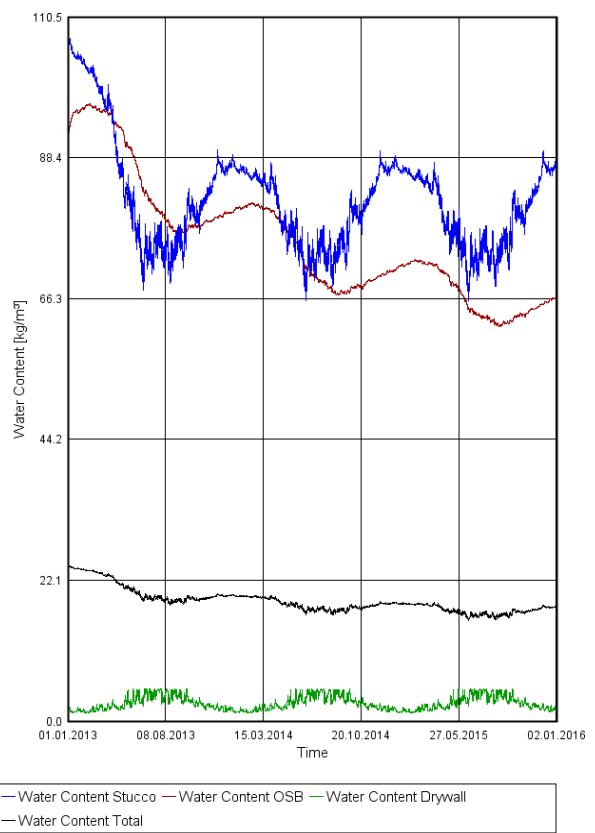
Water Content Vancouver VIP 13mm ASHRAE 160P Exterior

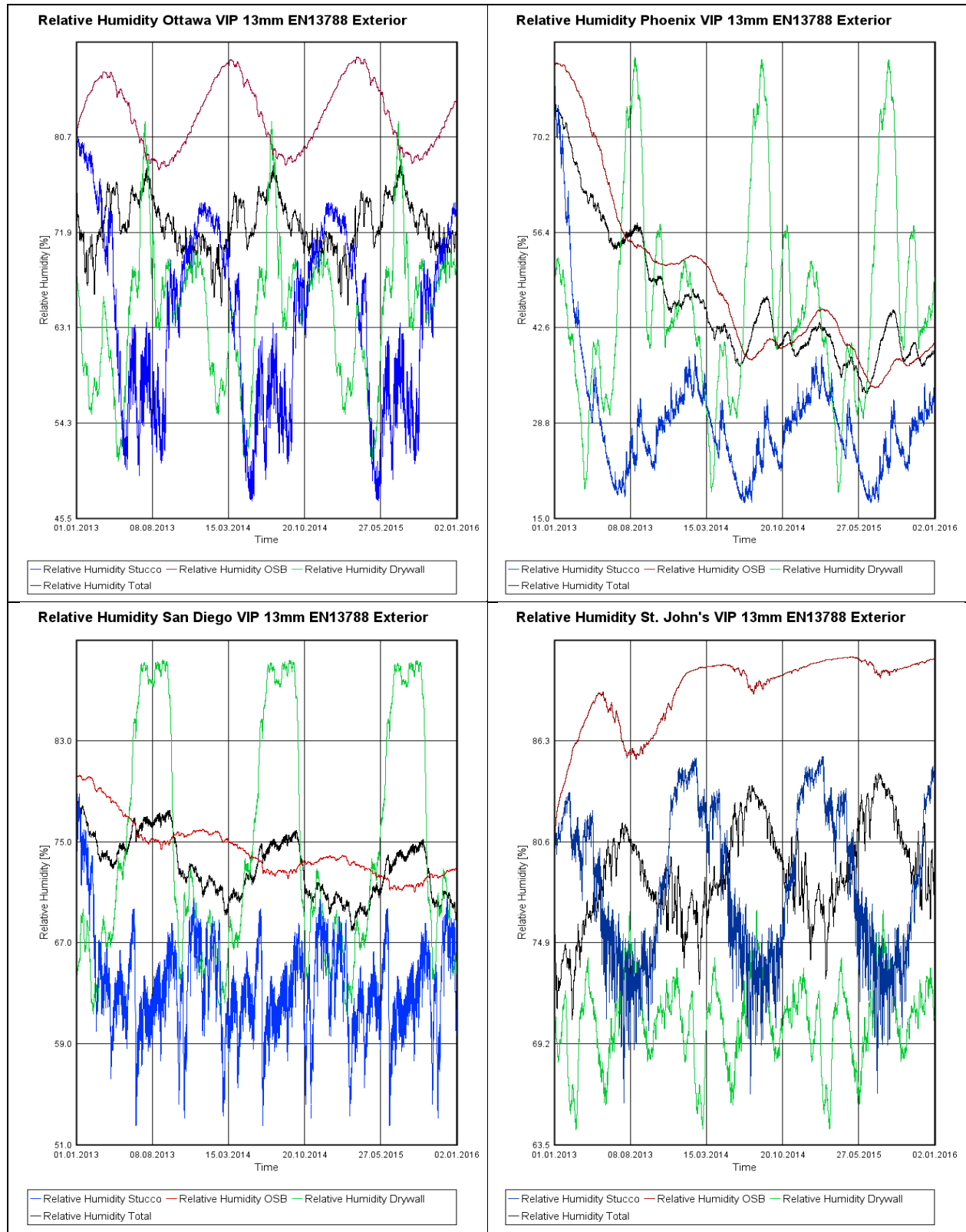


Water Content Wilmington VIP 13mm ASHRAE 160P Exterior

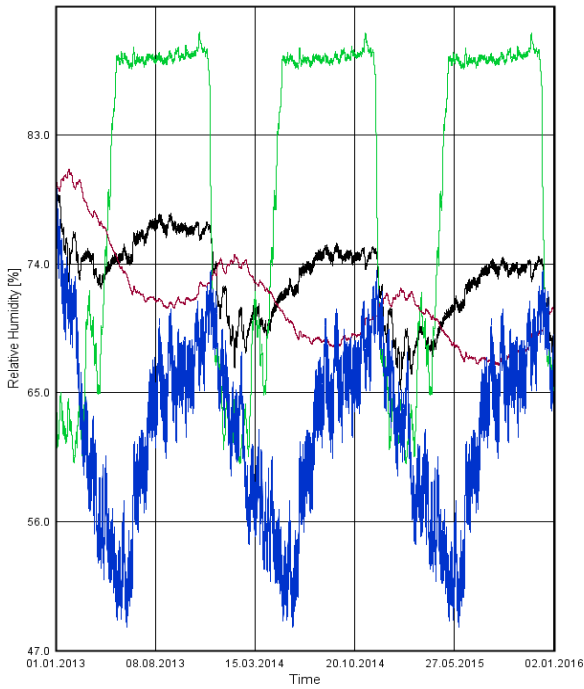


Water Content Winnipeg VIP 13mm ASHRAE 160P Exterior



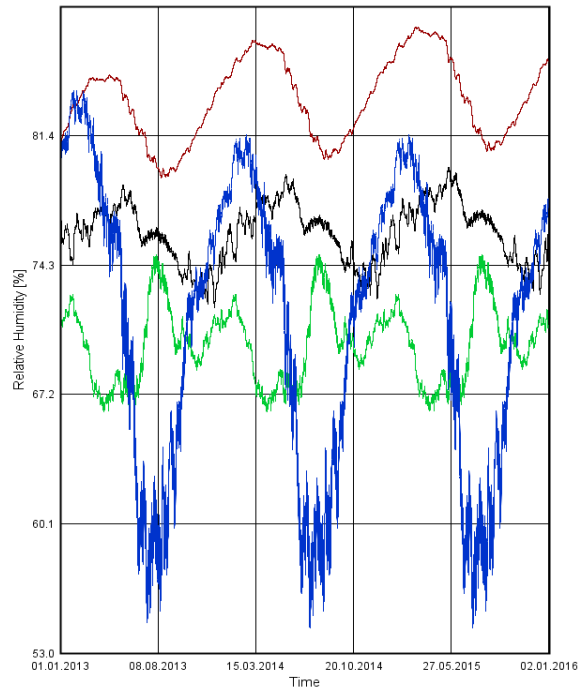


Relative Humidity Tampa VIP 13mm EN13788 Exterior



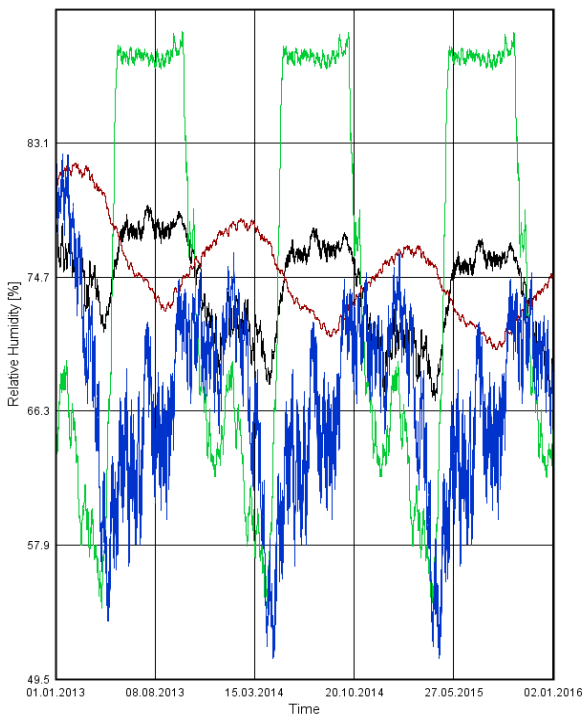
— Relative Humidity Stucco — Relative Humidity OSB — Relative Humidity Drywall
— Relative Humidity Total

Relative Humidity Vancouver VIP 13mm EN13788 Exterior



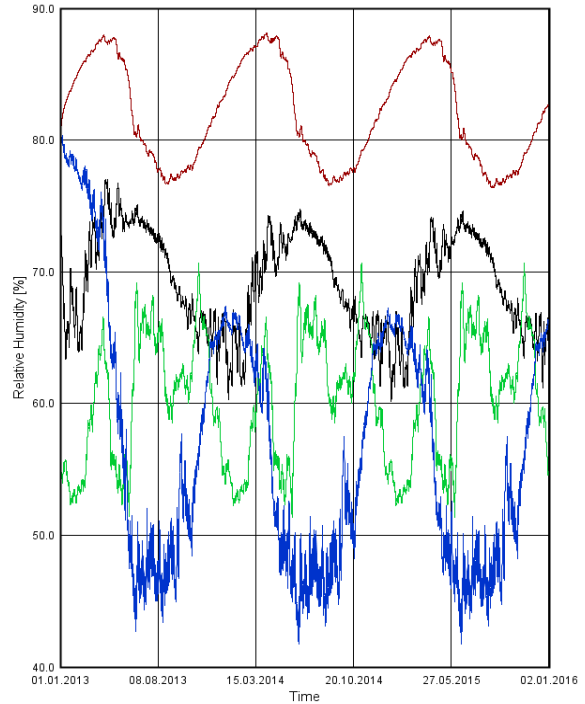
— Relative Humidity Stucco — Relative Humidity OSB — Relative Humidity Drywall
— Relative Humidity Total

Relative Humidity Wilmington VIP 13mm EN13788 Exterior



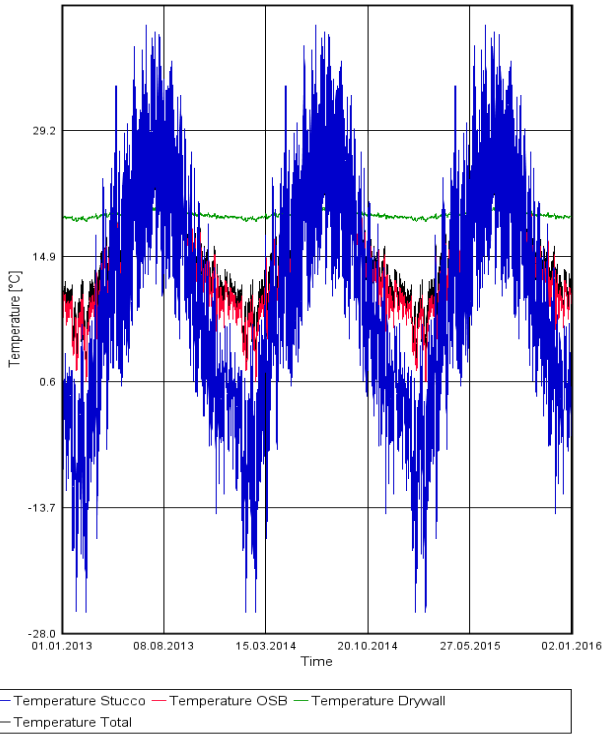
— Relative Humidity Stucco — Relative Humidity OSB — Relative Humidity Drywall
— Relative Humidity Total

Relative Humidity Winnipeg VIP 13mm EN13788 Exterior

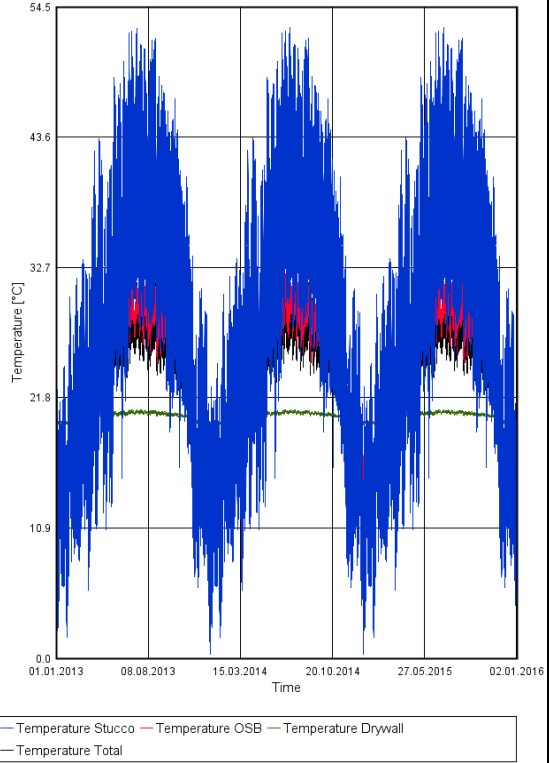


— Relative Humidity Stucco — Relative Humidity OSB — Relative Humidity Drywall
— Relative Humidity Total

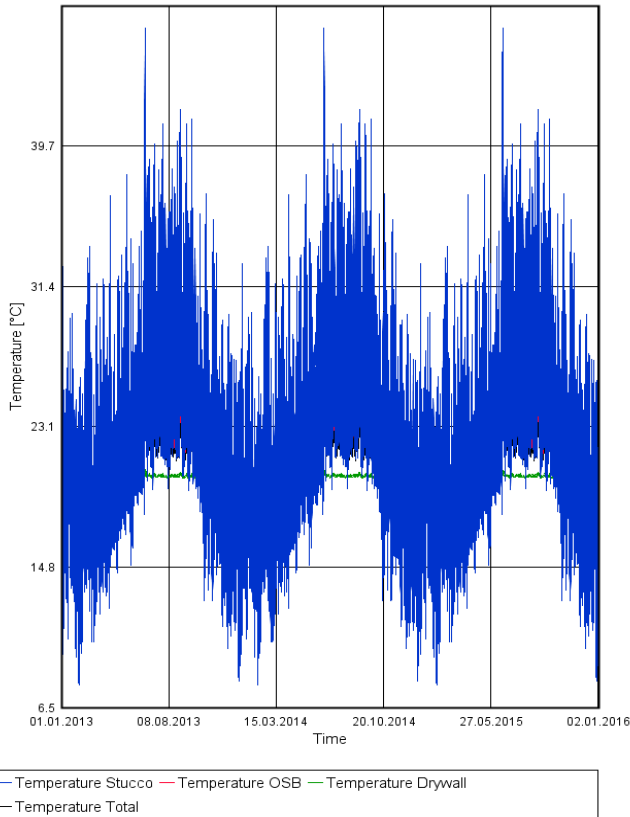
Temperature Ottawa VIP 13mm EN13788 Exterior



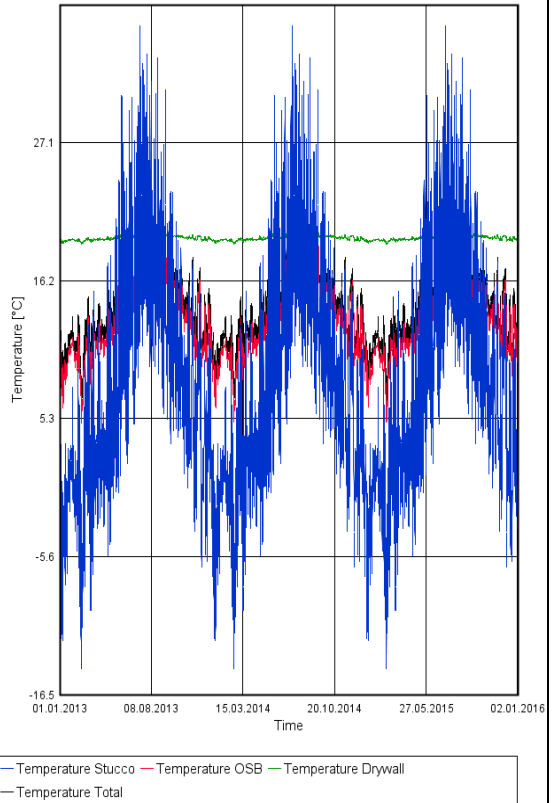
Temperature Phoenix VIP 13mm EN13788 Exterior



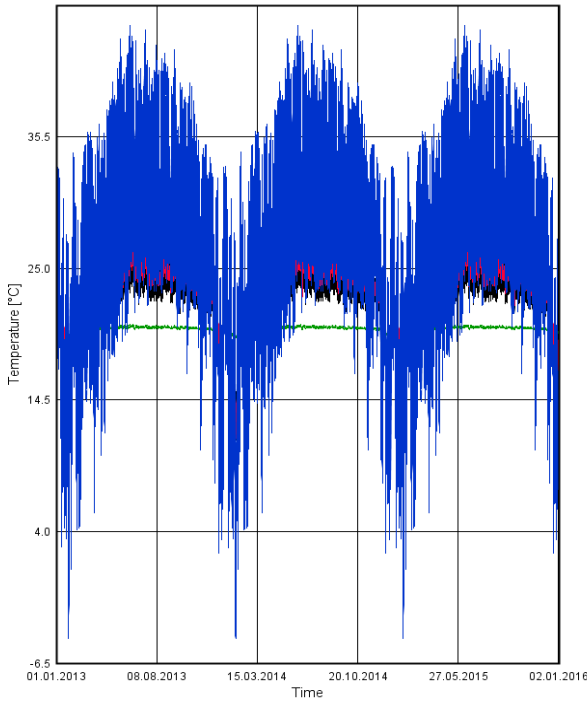
Temperature San Diego VIP 13mm EN13788 Exterior



Temperature St John's VIP 13mm EN13788 Exterior

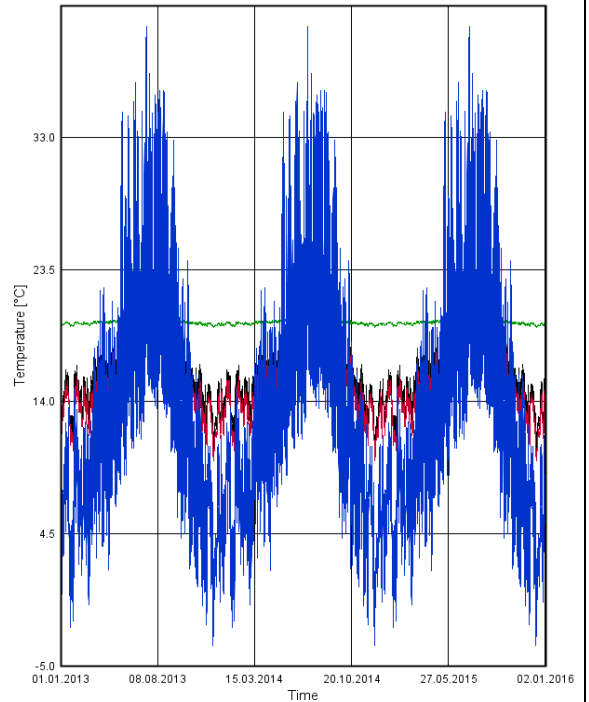


Temperature Tampa VIP 13mm EN13788 Exterior



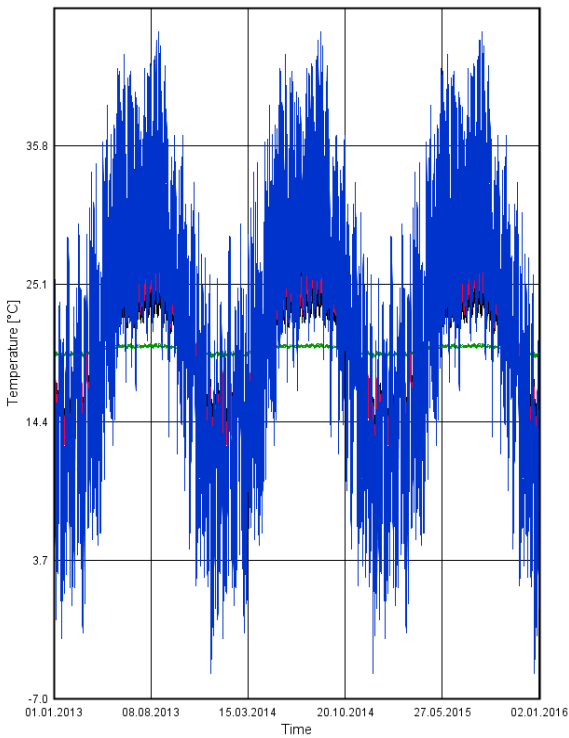
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Vancouver VIP 13mm EN13788 Exterior



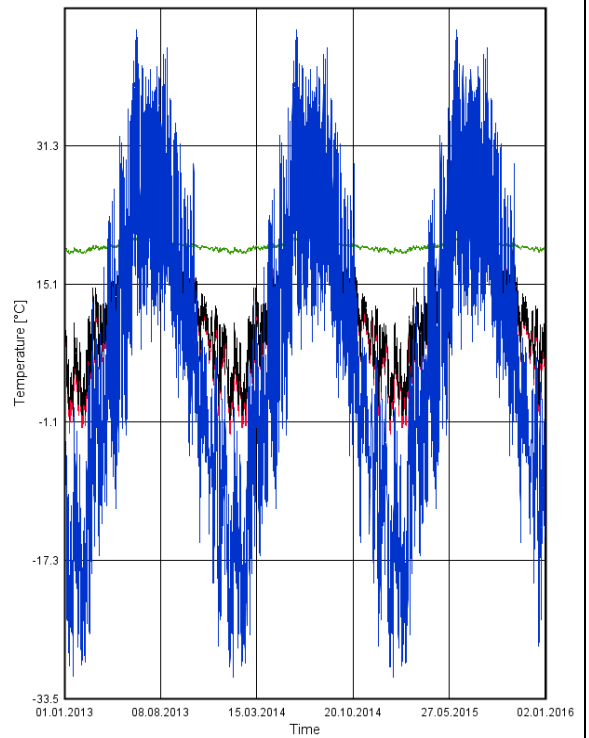
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Wilmington VIP 13mm EN13788 Exterior



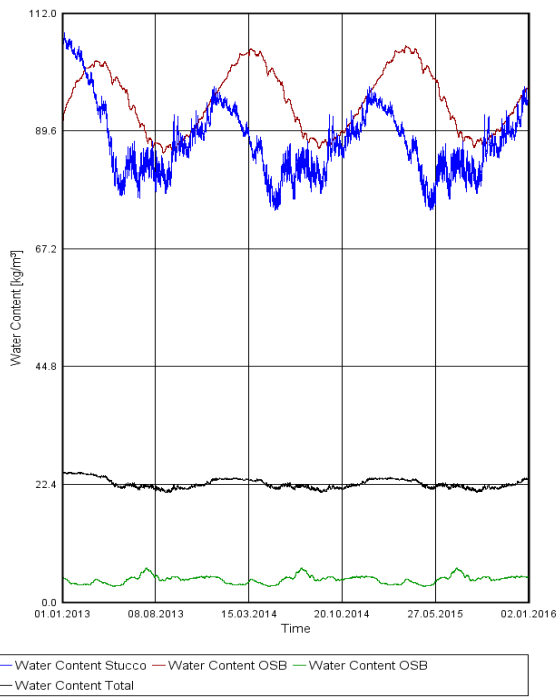
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Winnipeg VIP 13mm EN13788 Exterior

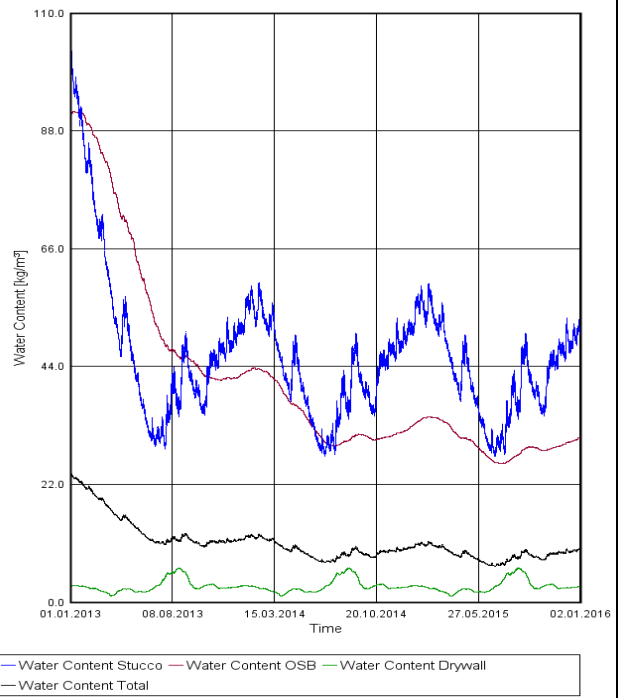


— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

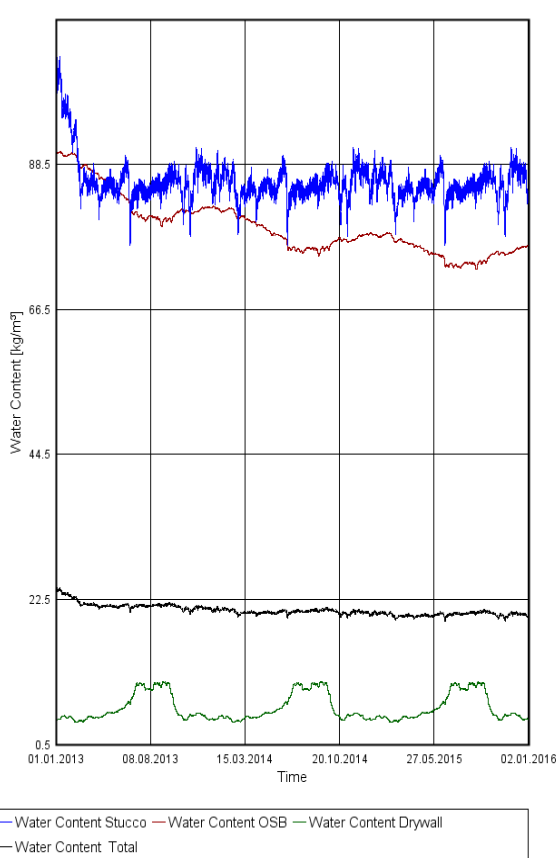
Water Content Ottawa VIP 13mm EN13788 Exterior



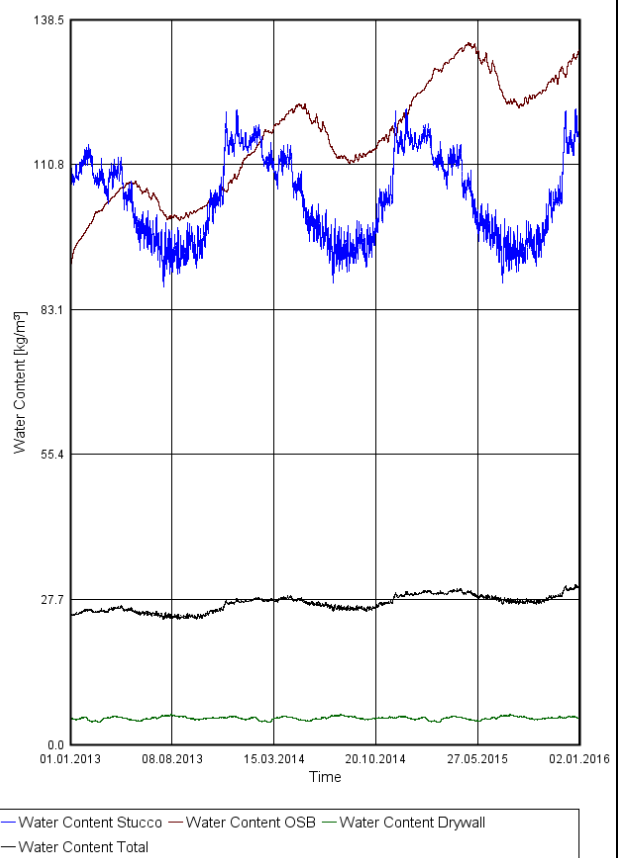
Water Content Phoenix VIP 13mm EN13788 Exterior



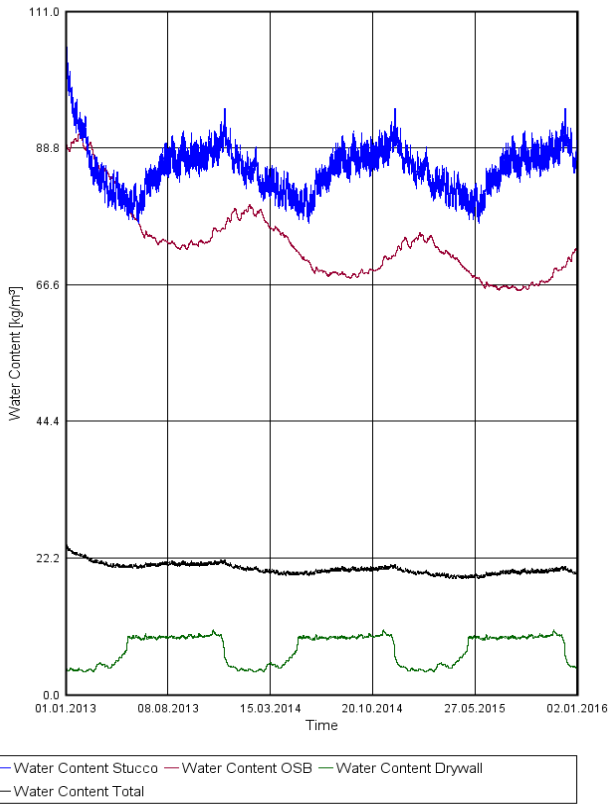
Water Content San Diego VIP 13mm EN13788 Exterior



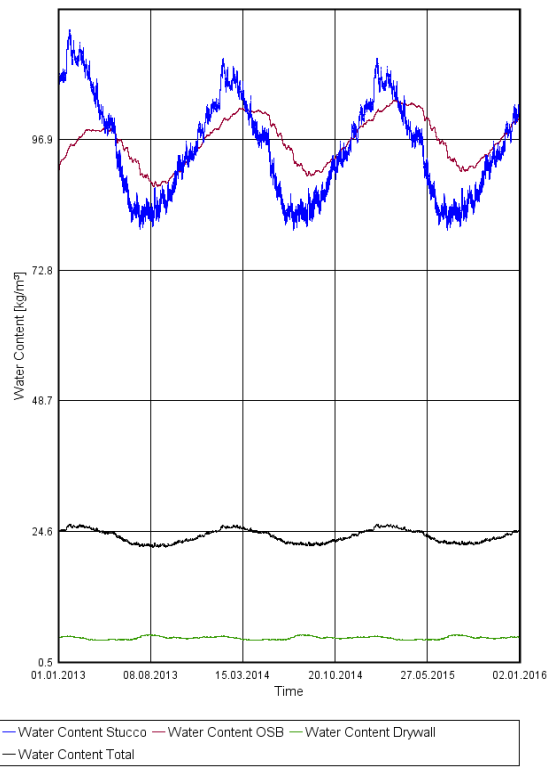
Water Content St John's VIP 13mm EN13788 Exterior



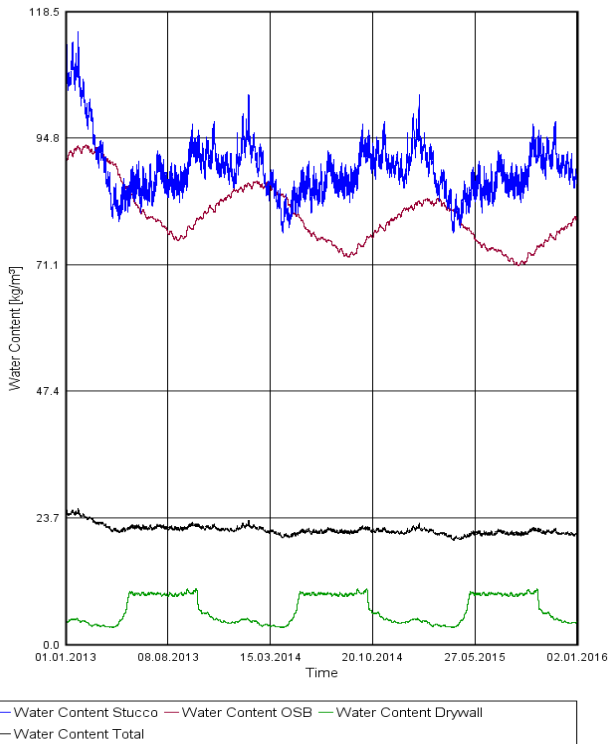
Water Content Tampa VIP 13mm EN13788 Exterior



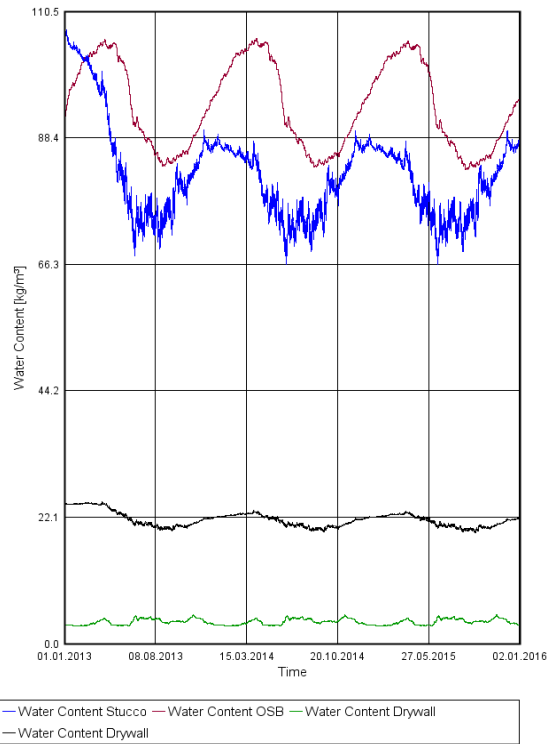
Water Content Vancouver VIP 13mm EN13788 Exterior



Water Content Wilmington VIP 13mm EN13788 Exterior

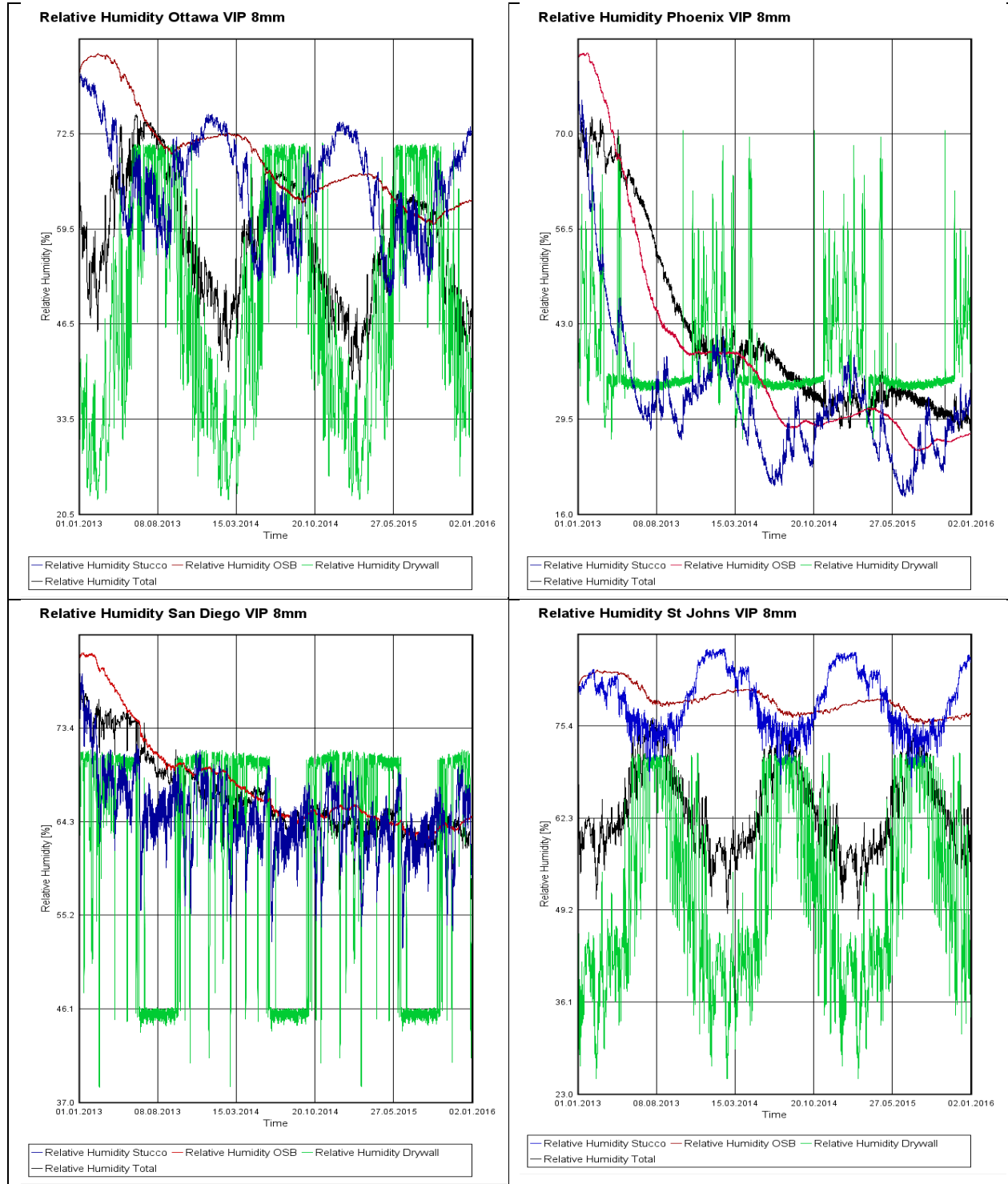


Water Content Winnipeg VIP13mm EN13788 Exterior

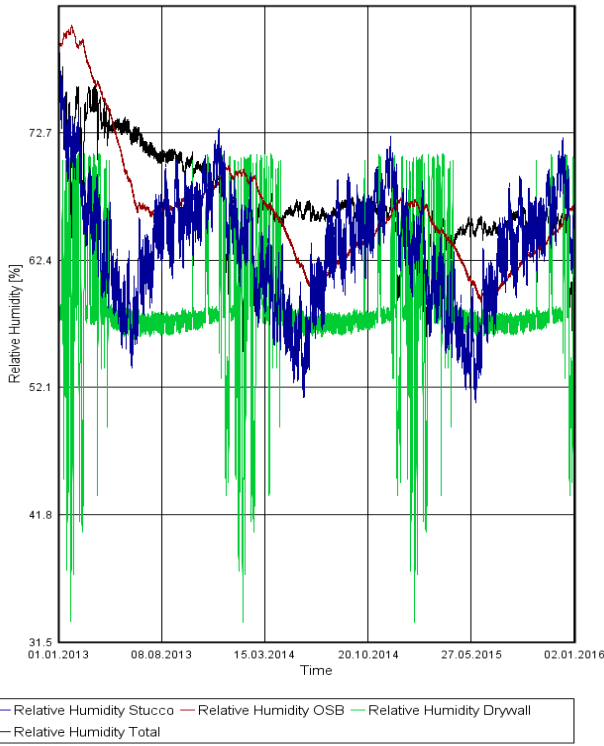


Appendix C - Interior Retrofitted Wall

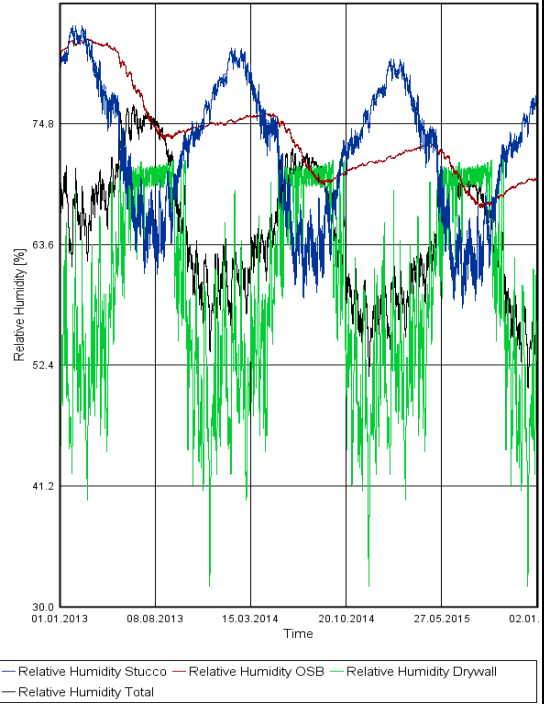
ASHRAE 160P- VIP 8mm



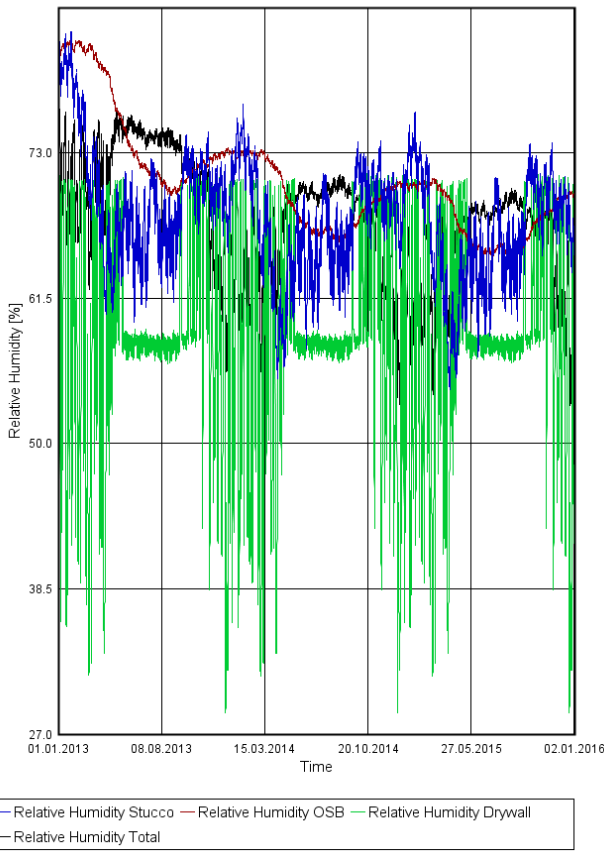
Relative Humidity Tampa VIP 8mm



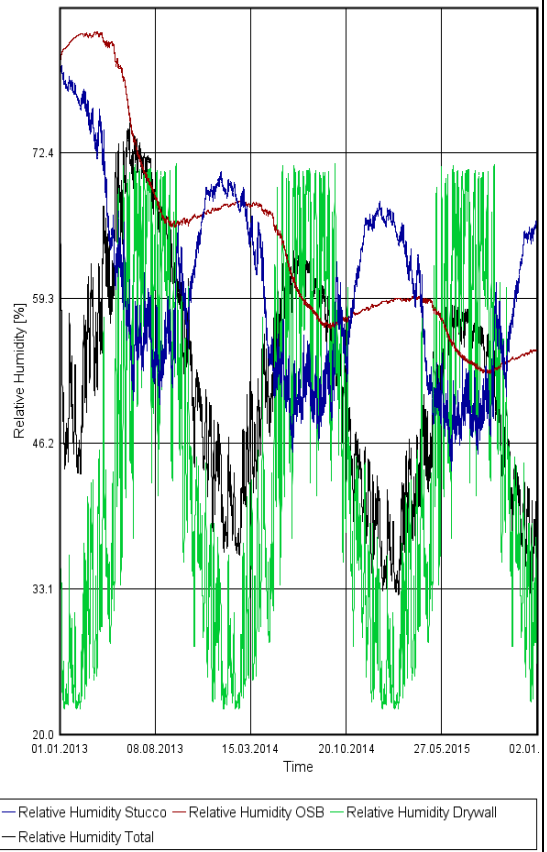
Relative Humidity Vancouver VIP 8mm



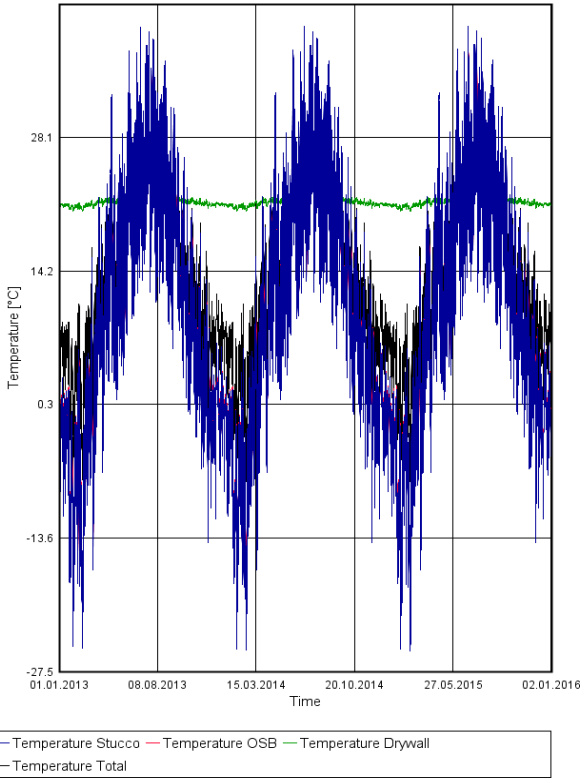
Relative Humidity Wilmington VIP 8mm



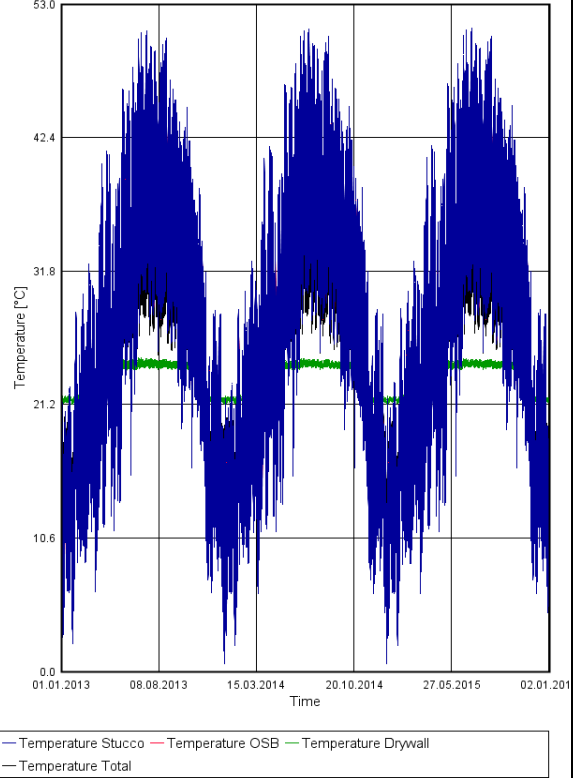
Relative Humidity Winnipeg VIP 8mm



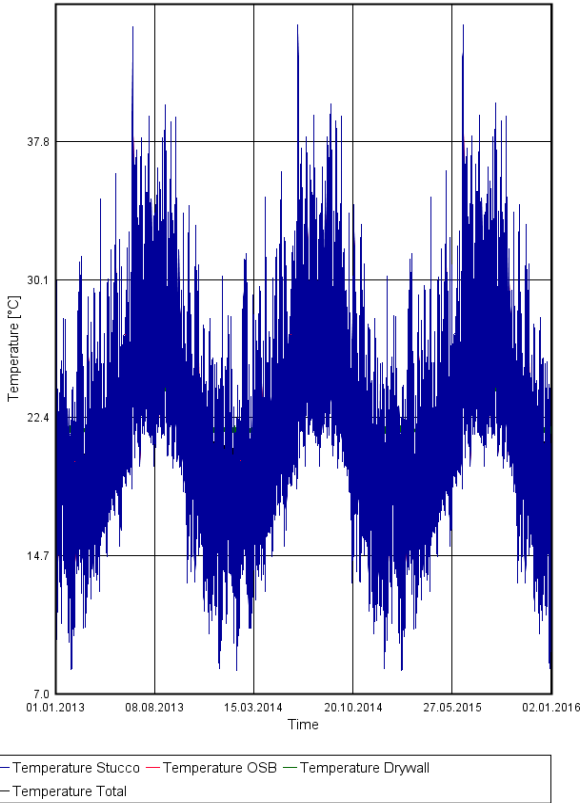
Temperature Ottawa VIP 8mm



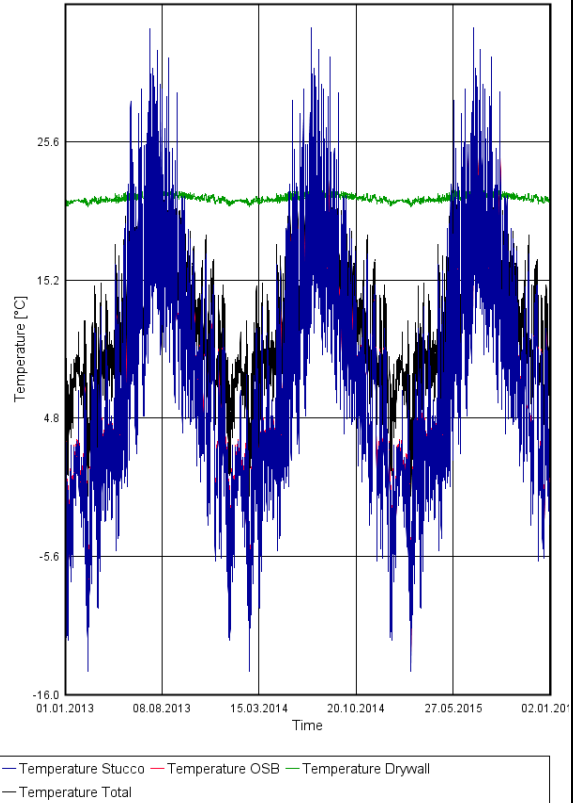
Temperature Phoenix VIP 8mm



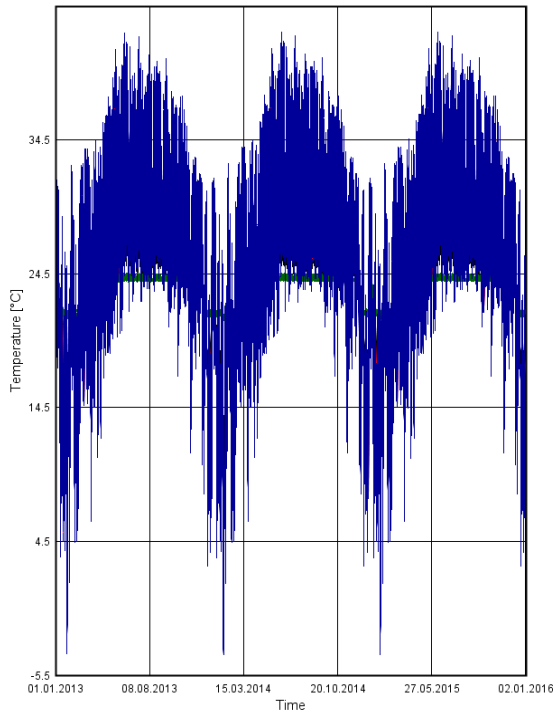
Temperature San Diego VIP 8mm



Temperature St Johns VIP 8mm

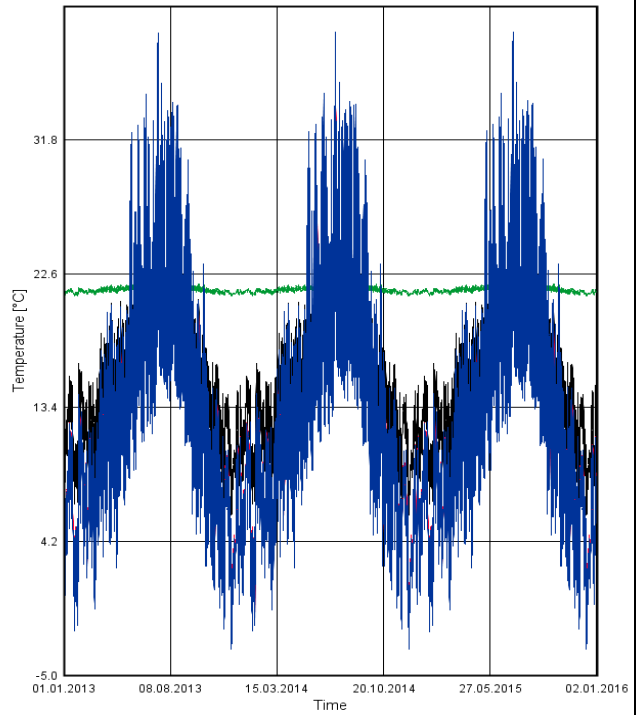


Temperature Tampa VIP 8mm



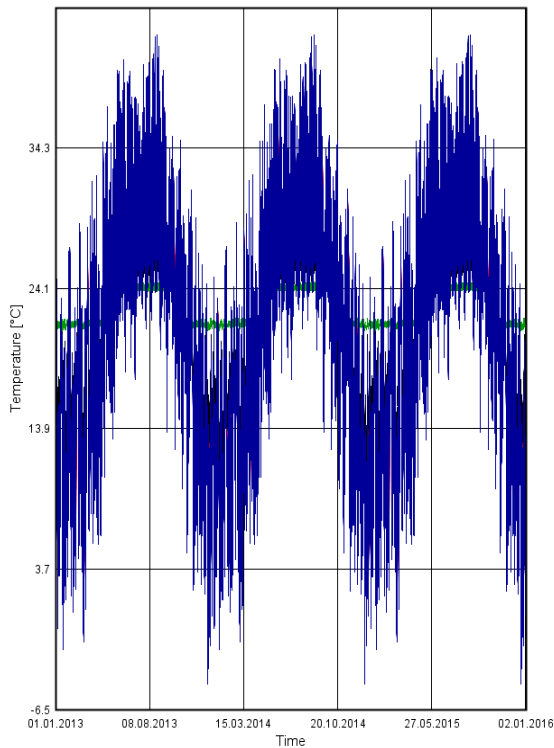
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Vancouver VIP 8mm



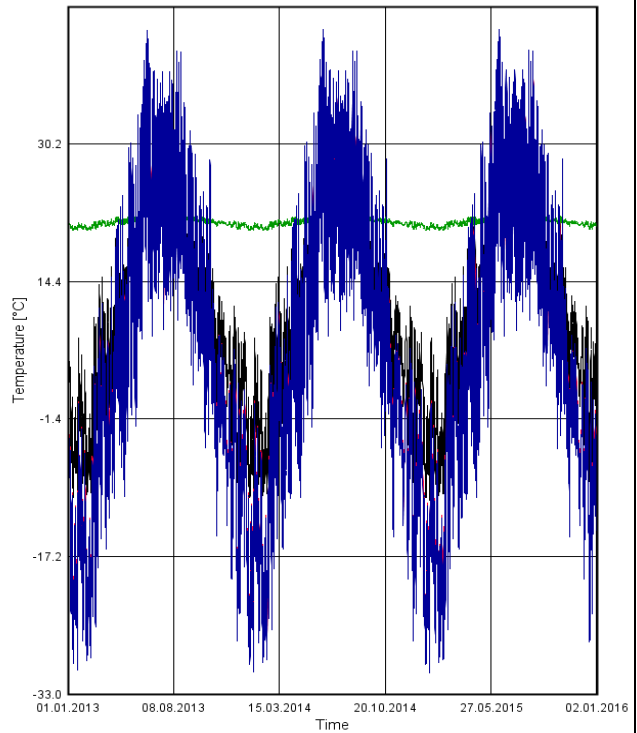
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Wilmington VIP 8mm



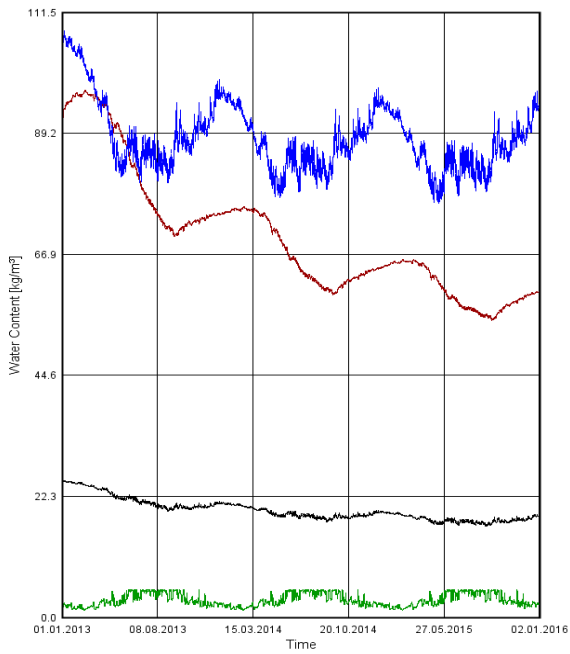
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Winnipeg VIP 8mm



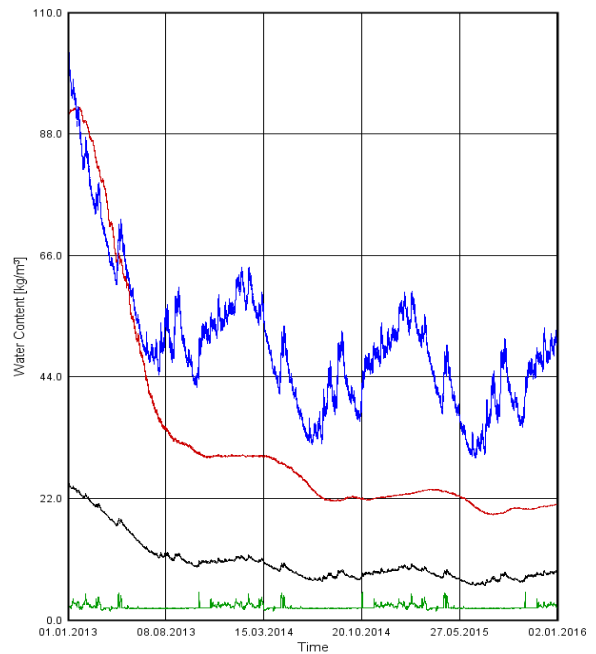
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Water Content Ottawa VIP 8mm



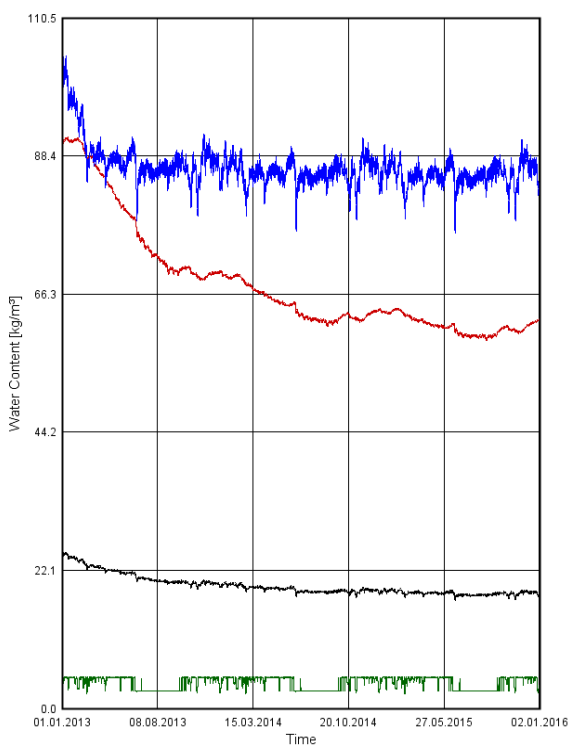
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Phoenix VIP 8mm



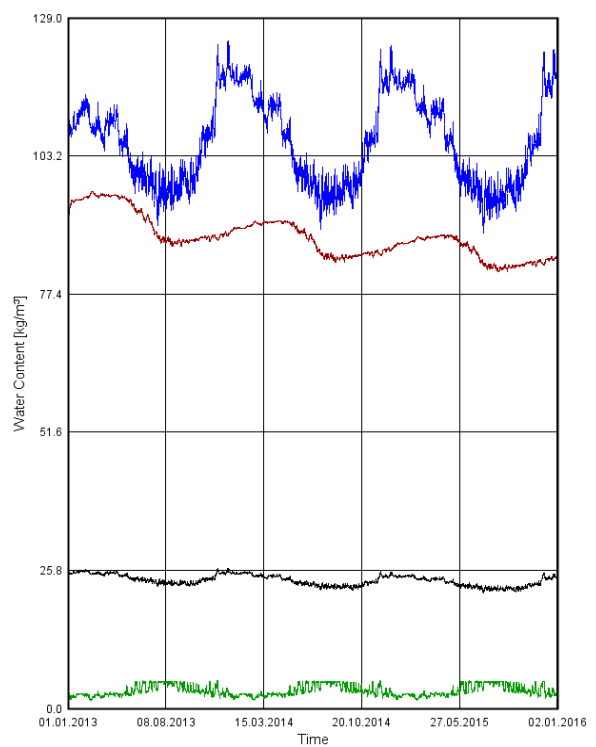
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content San Diego VIP 8mm



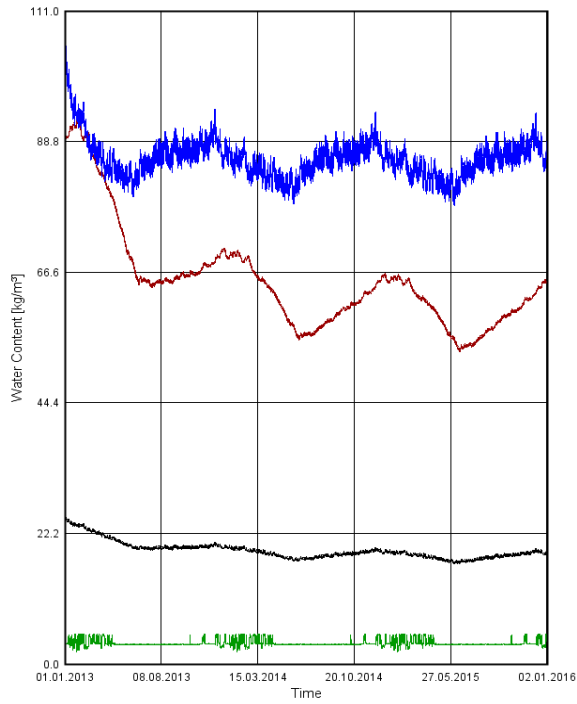
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content St Johns VIP 8mm



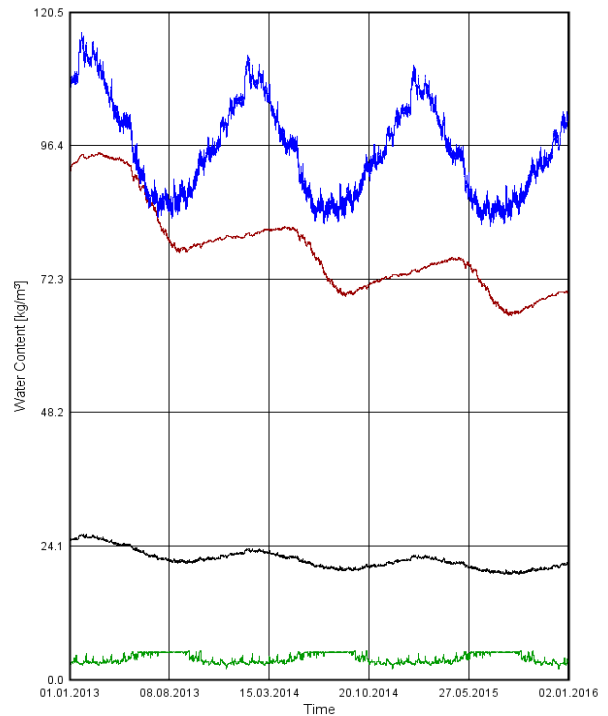
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Tampa VIP 8mm



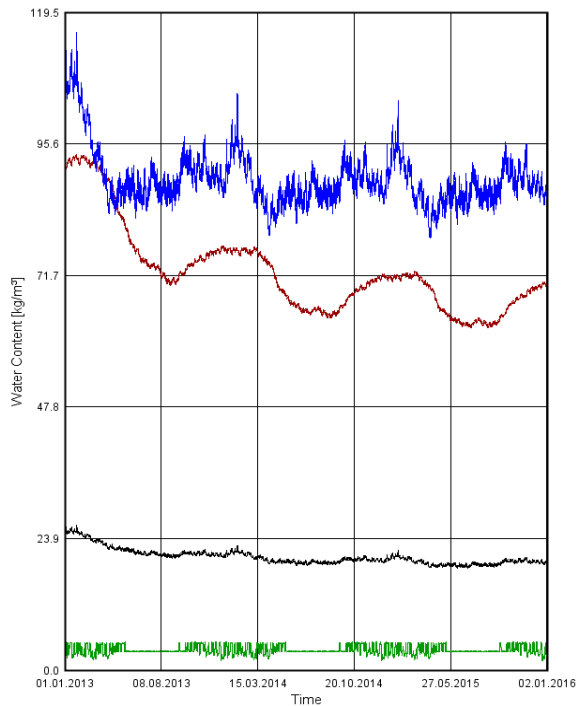
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Vancouver VIP 8mm



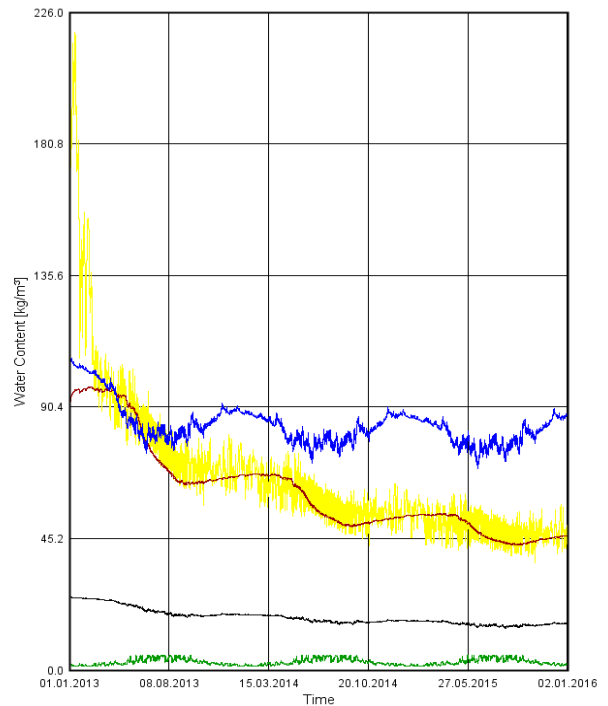
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Wilmington VIP 8mm



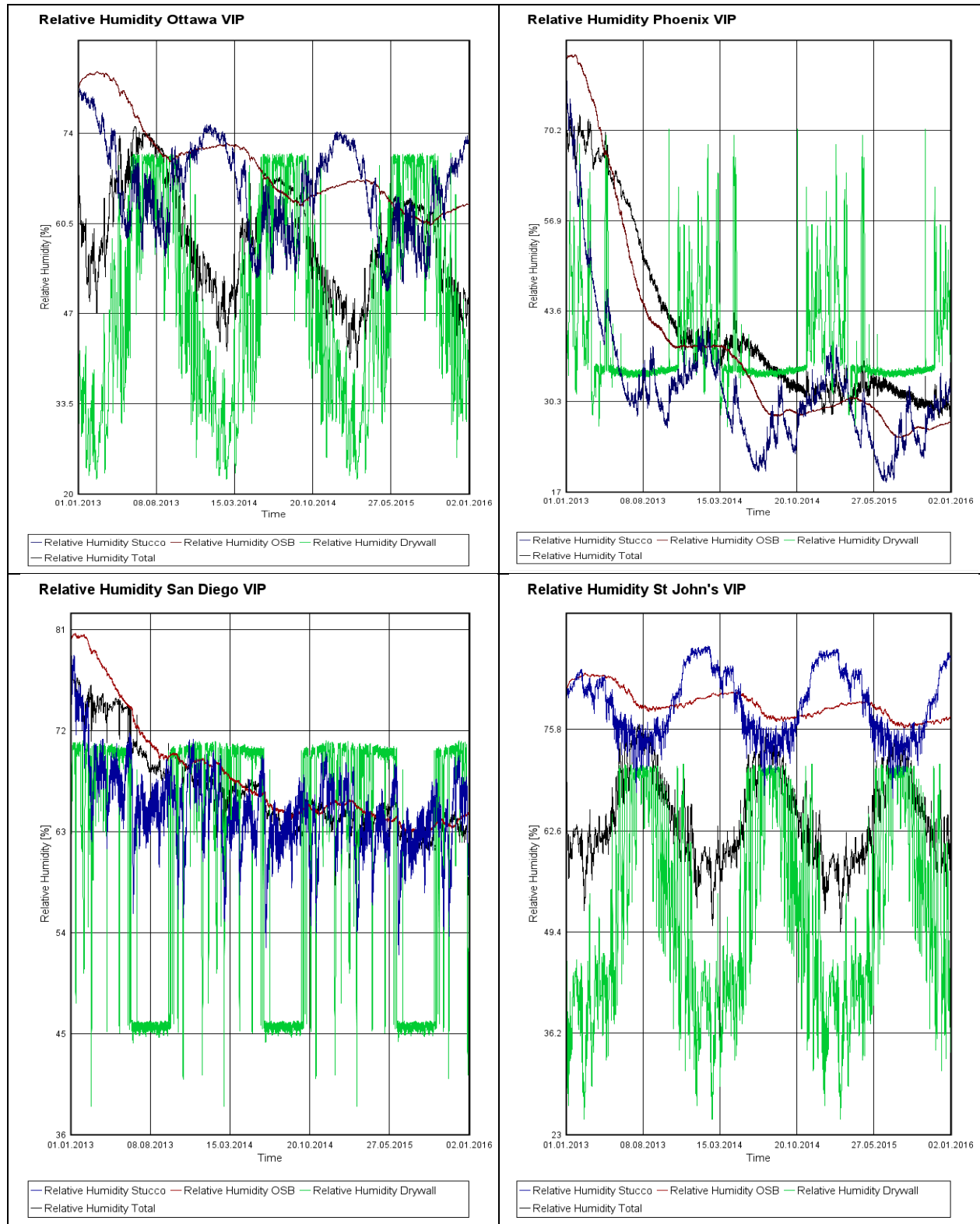
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Winnipeg VIP 8mm

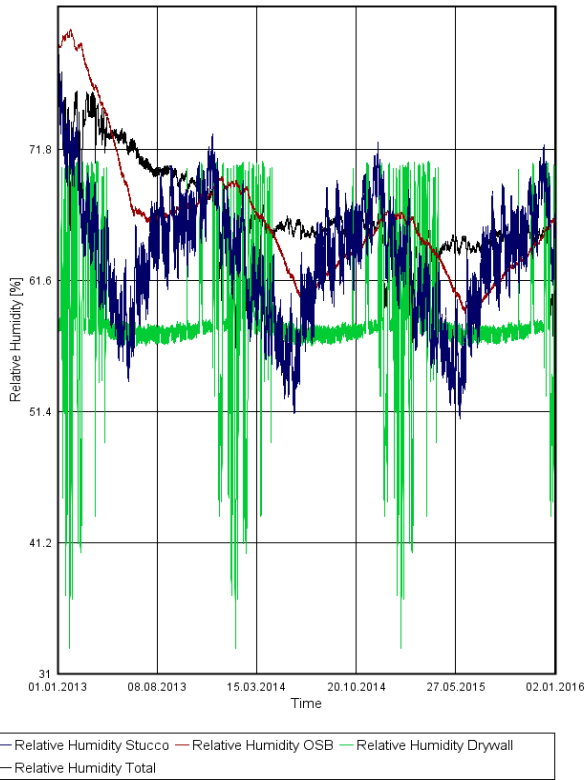


— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total — Water Content OSB interior layer

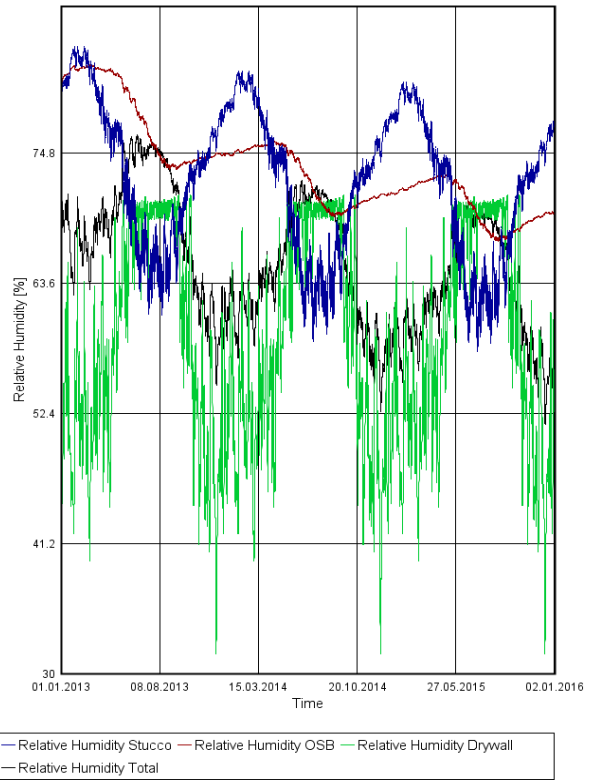
ASHRAE 160P-VIP 13mm



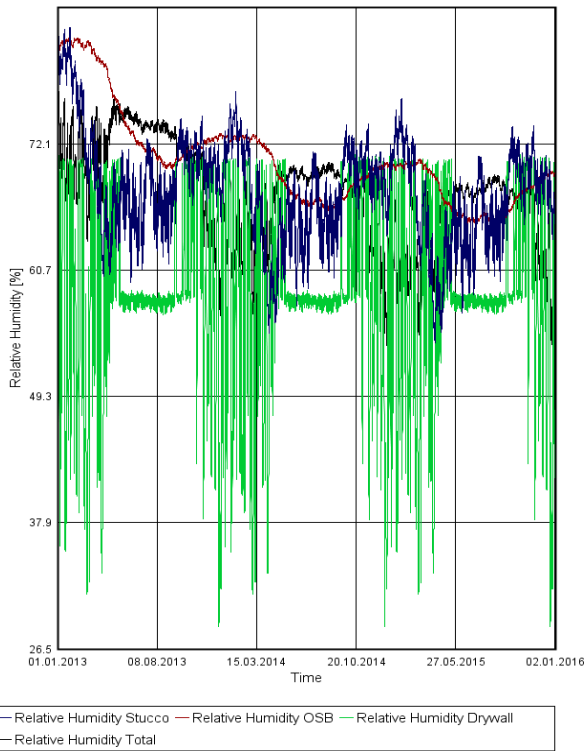
Relative Humidity Tampa VIP



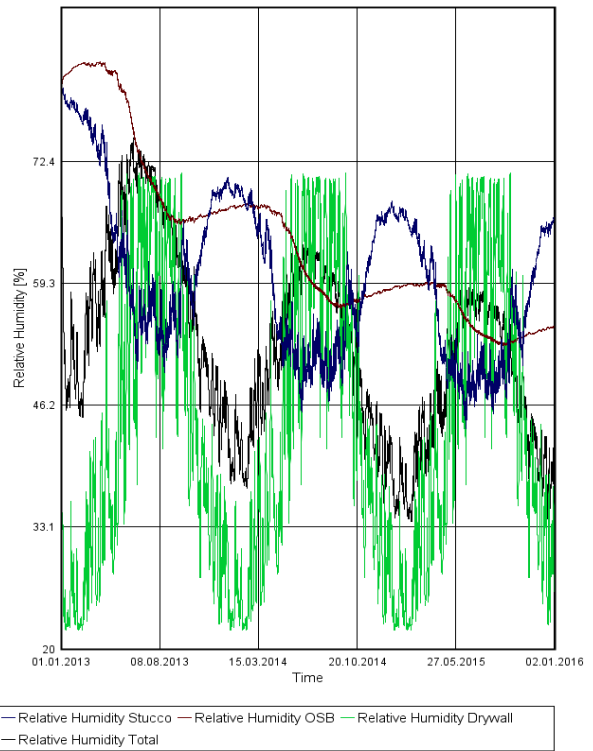
Relative Humidity Vancouver VIP



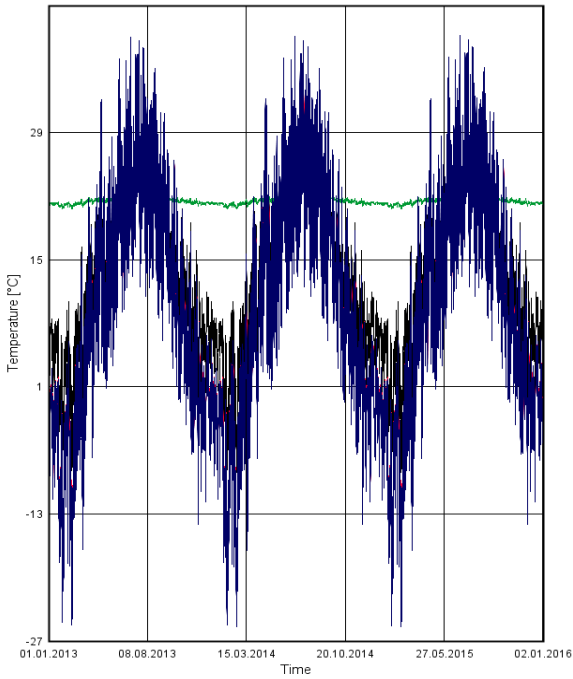
Relative Humidity Wilmington VIP



Relative Humidity Winnipeg VIP

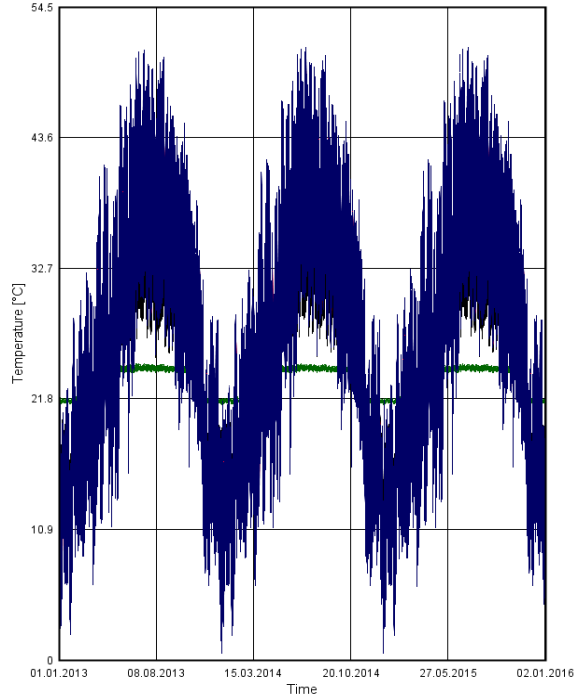


Temperature Ottawa VIP



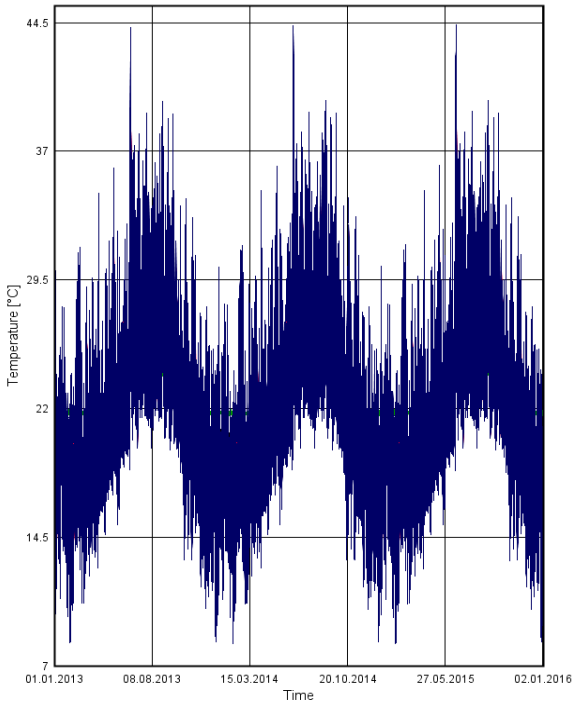
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Phoenix VIP



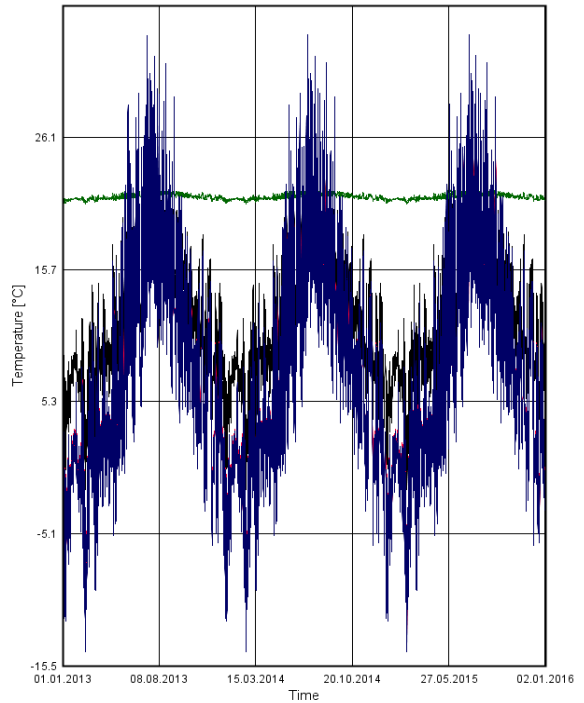
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature San Diego VIP



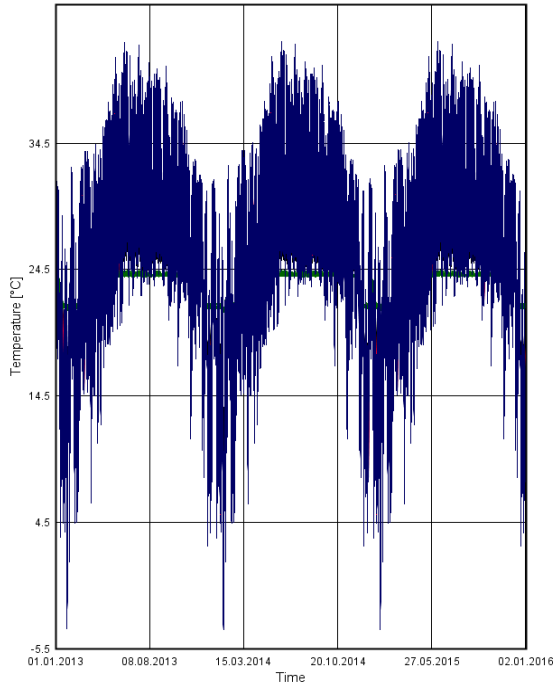
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature St John's VIP



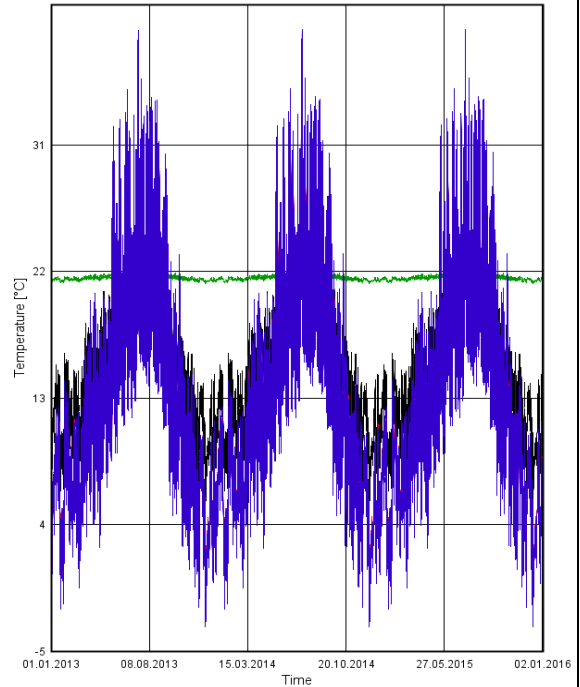
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Tampa VIP



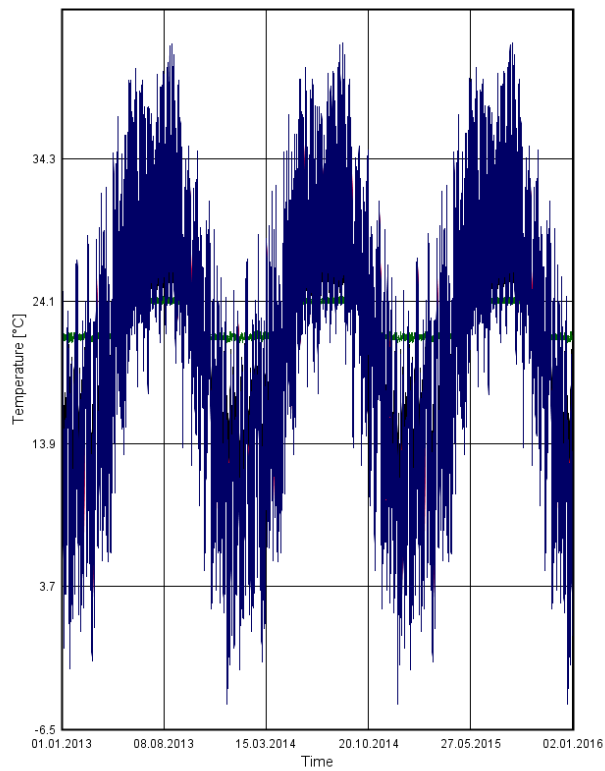
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Vancouver VIP



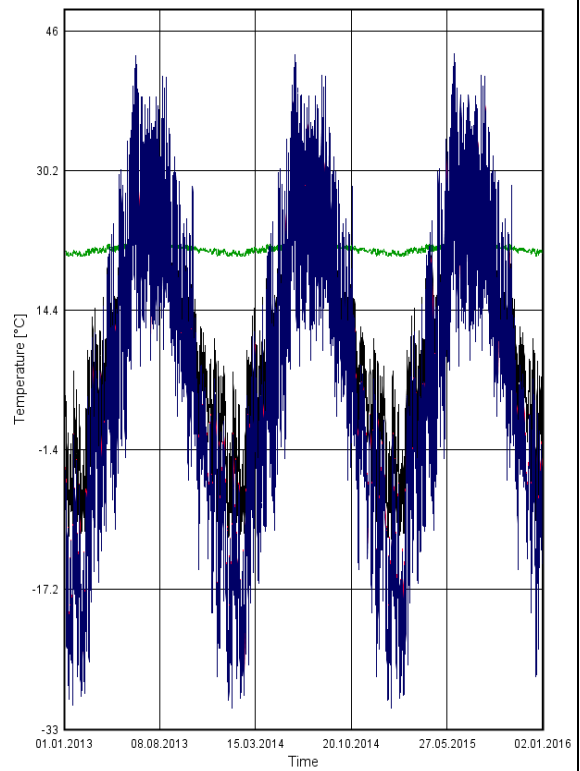
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Wilmington VIP



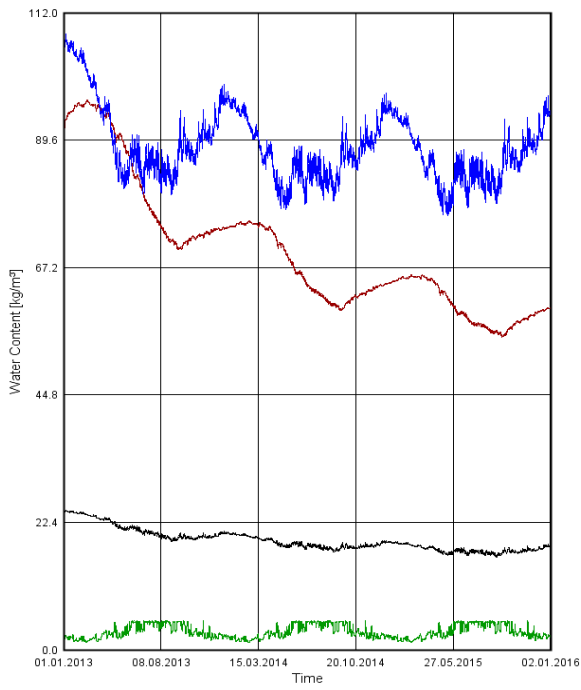
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Winnipeg VIP



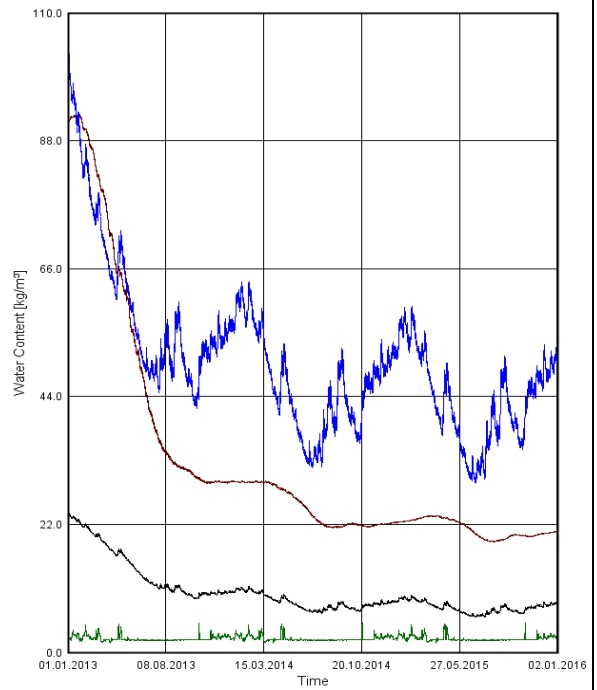
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Water Content Ottawa VIP



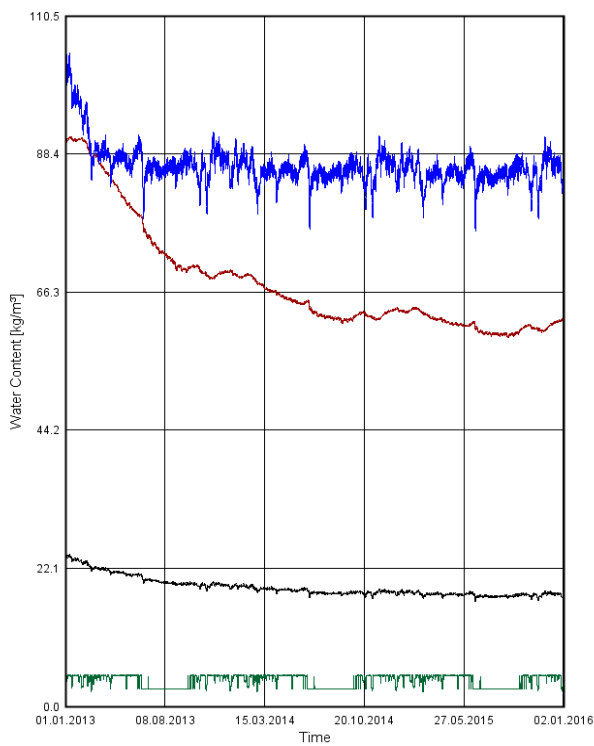
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Phoenix VIP



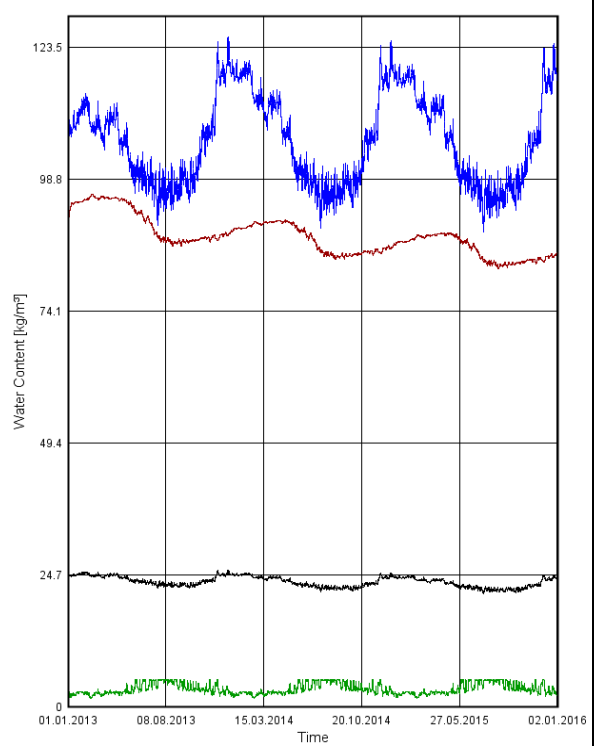
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content San Diego VIP

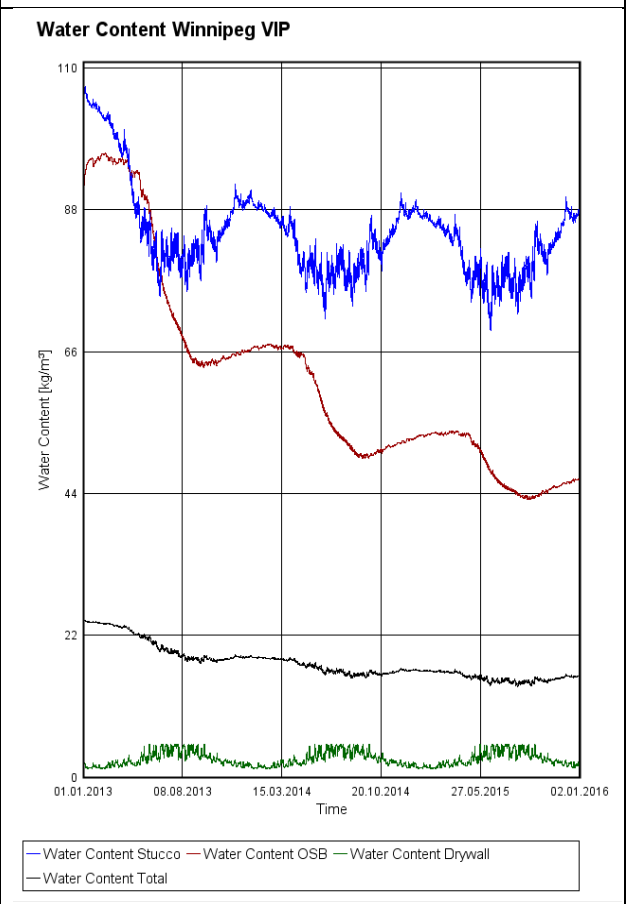
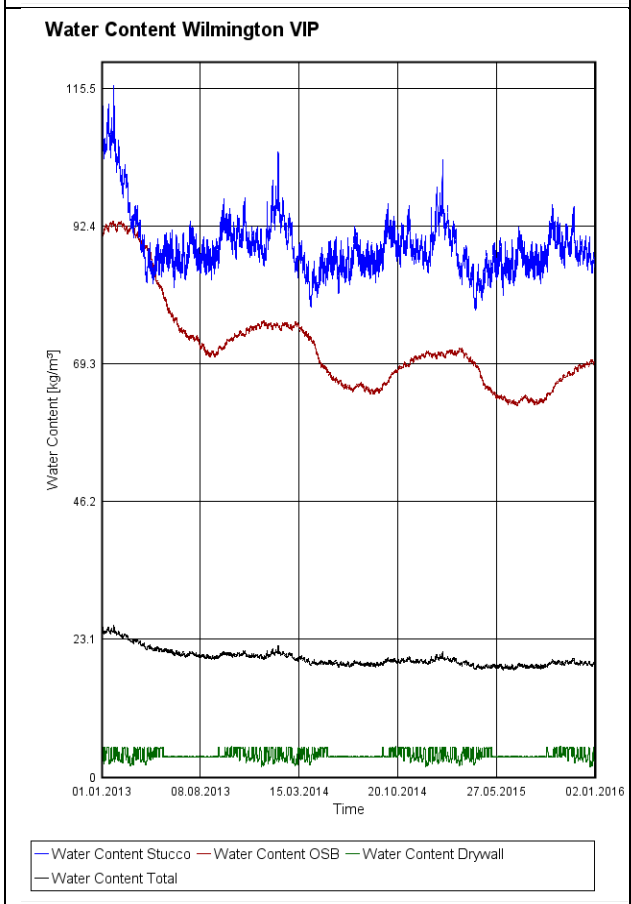
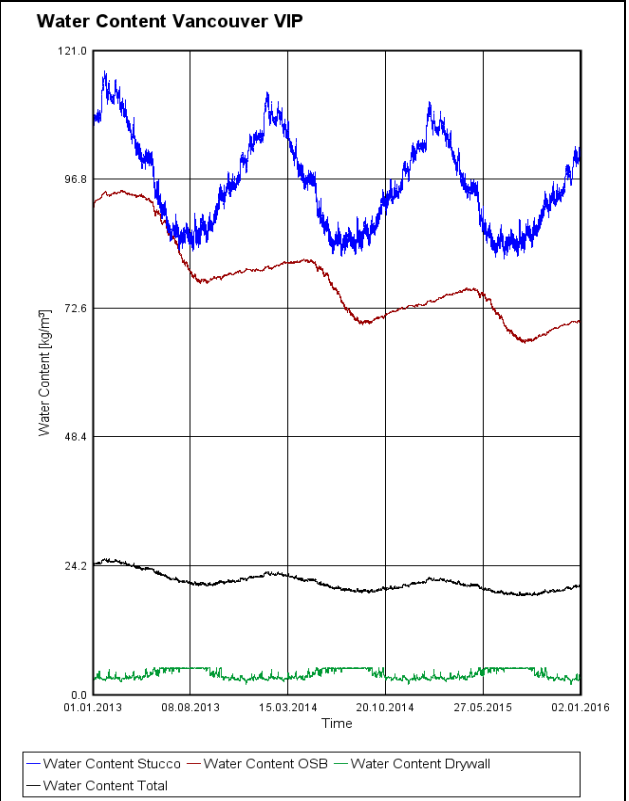
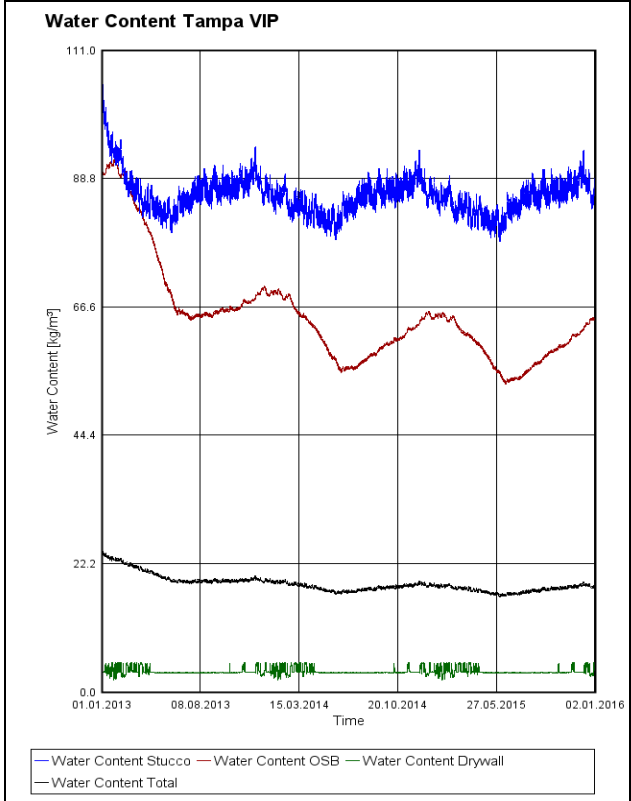


— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

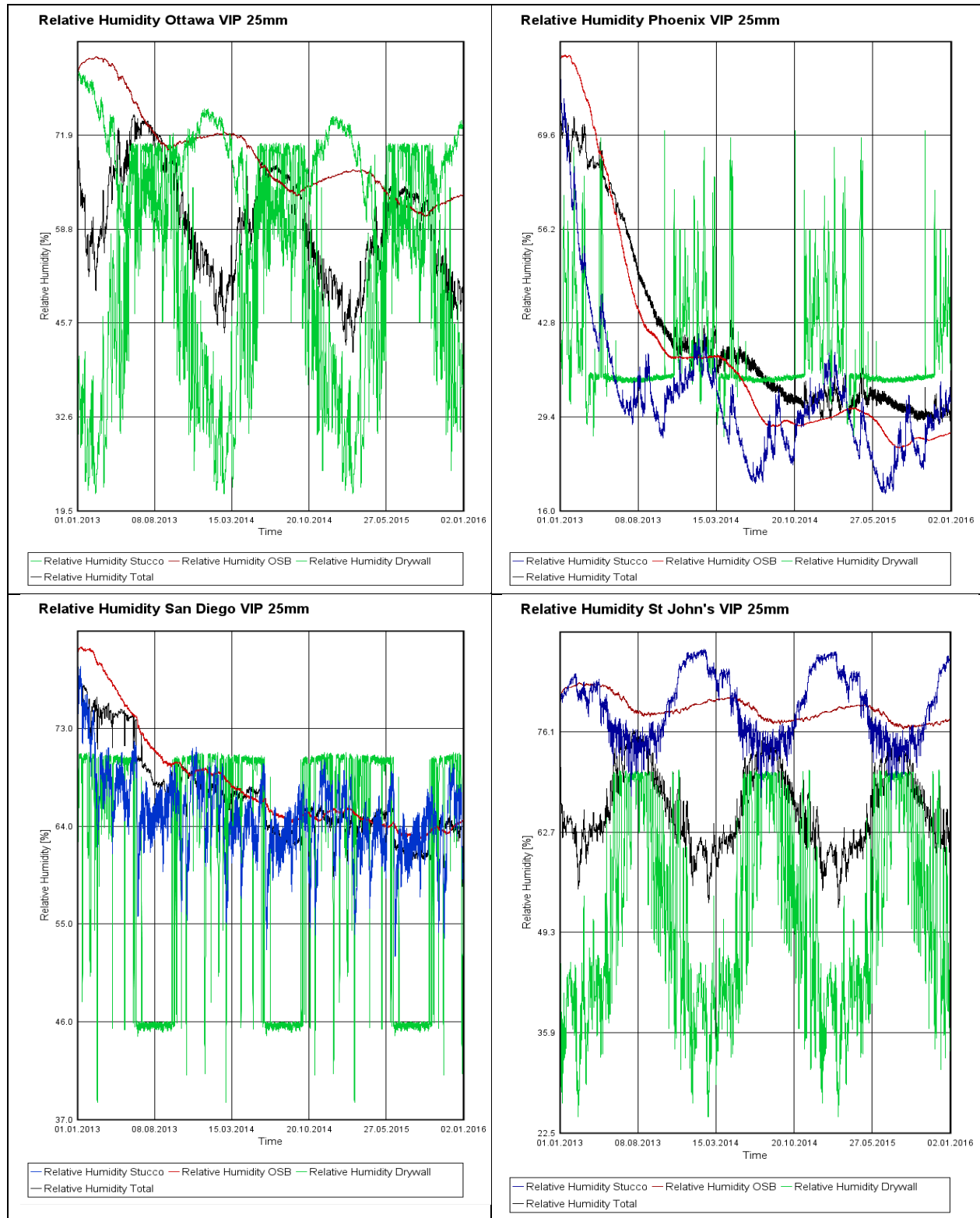
Water Content St John's VIP



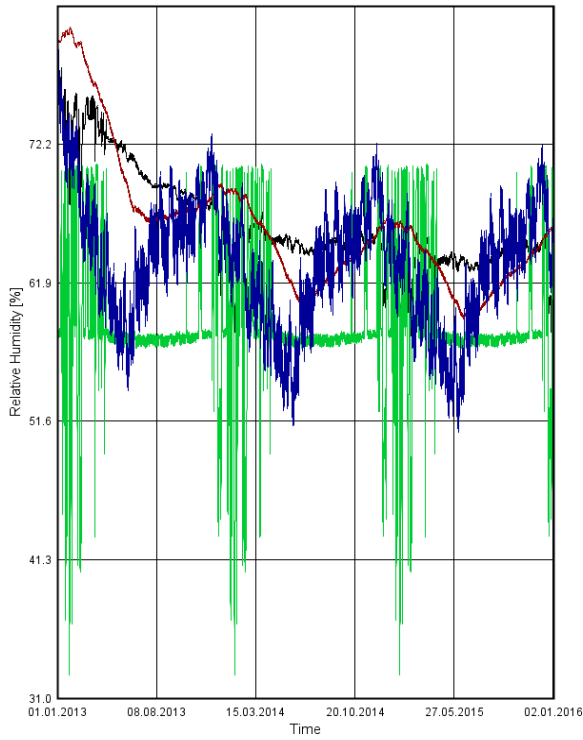
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total



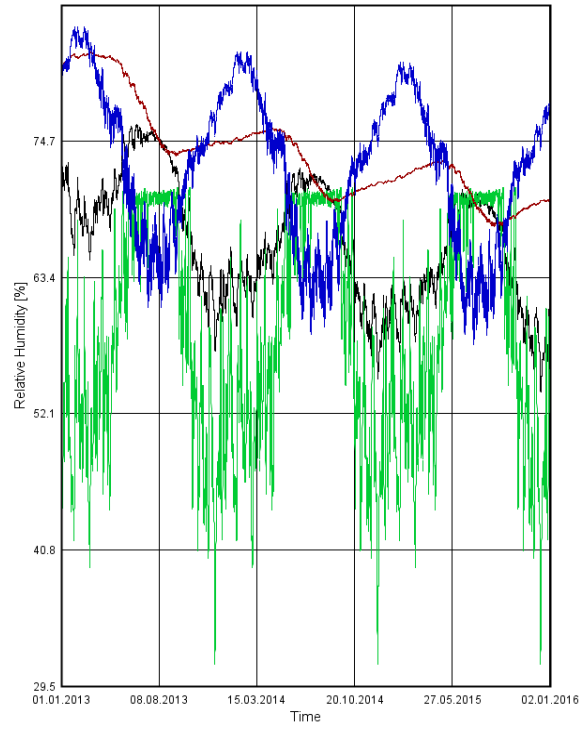
ASHRAE 160P-VIP 25mm



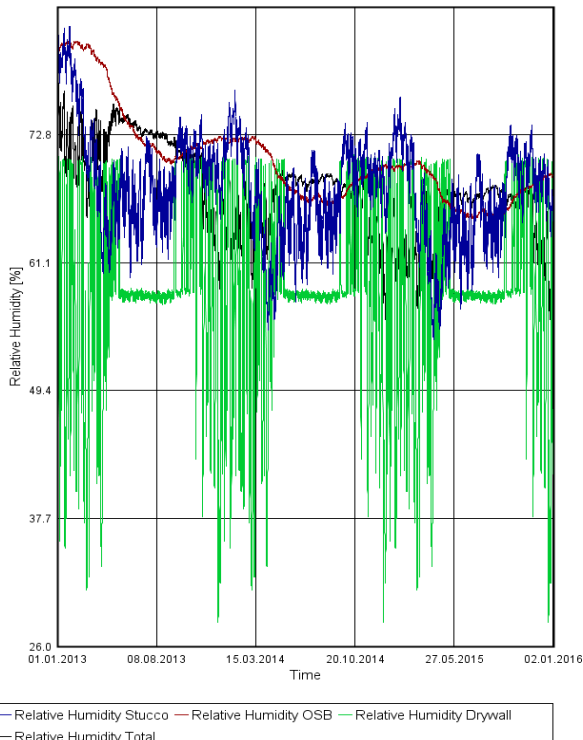
Relative Humidity



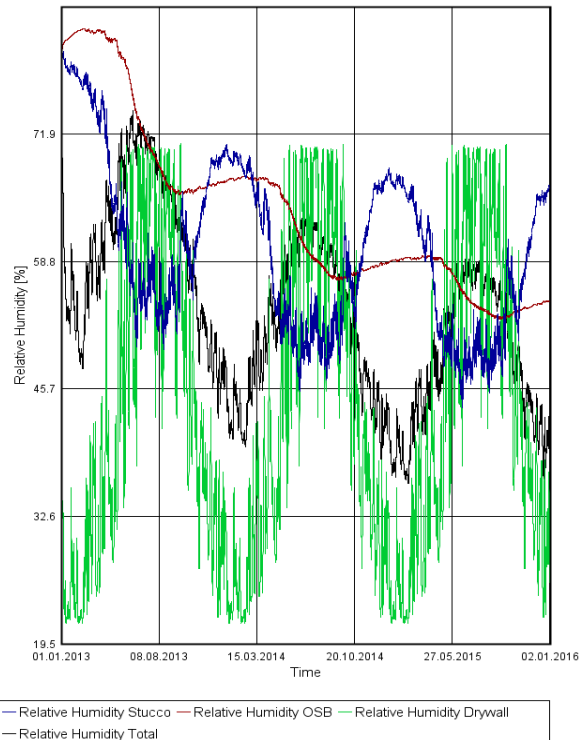
Relative Humidity Vancouver VIP 25mm



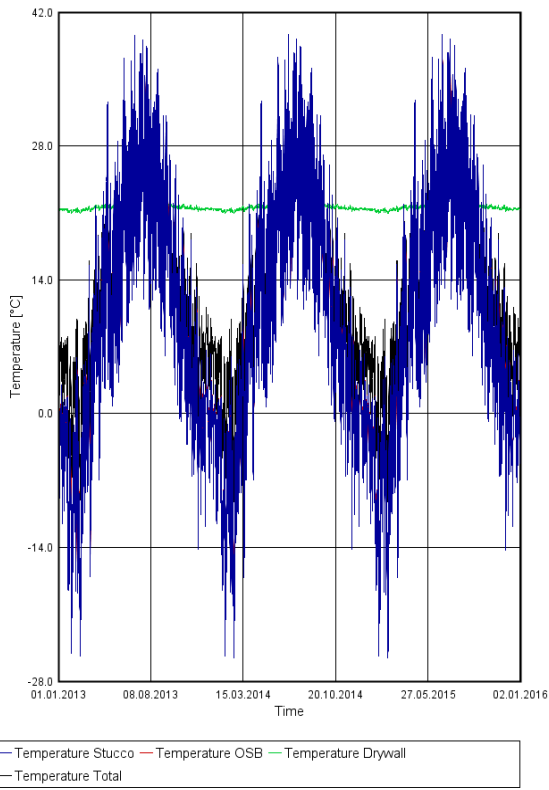
Relative Humidity Wilmington VIP 25mm



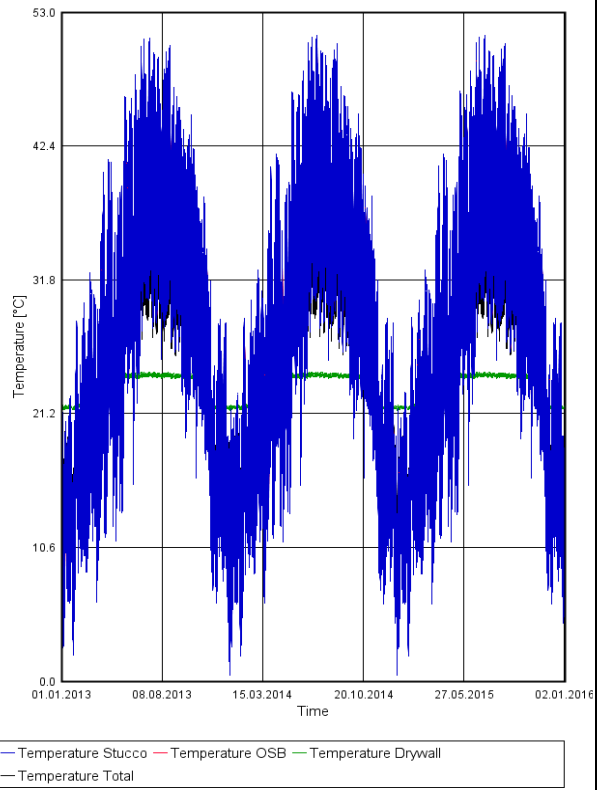
Relative Humidity Winnipeg VIP 25mm



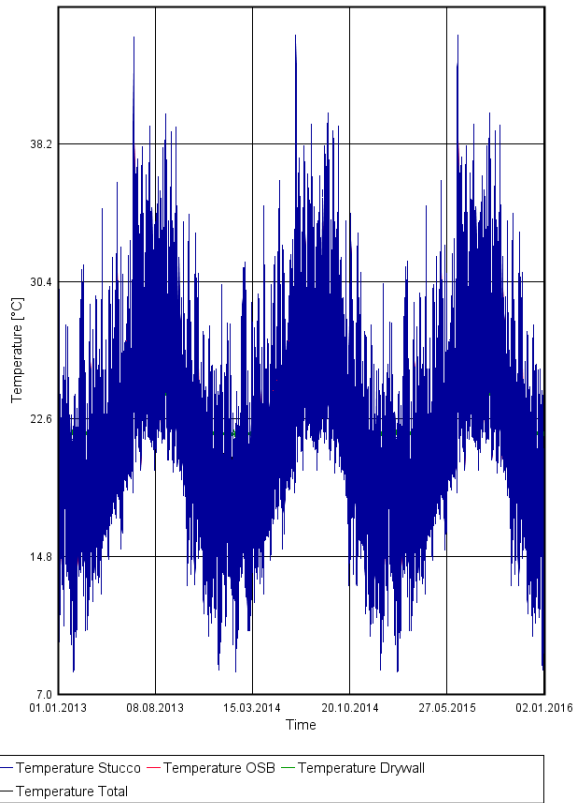
Temperature Ottawa VIP 25mm



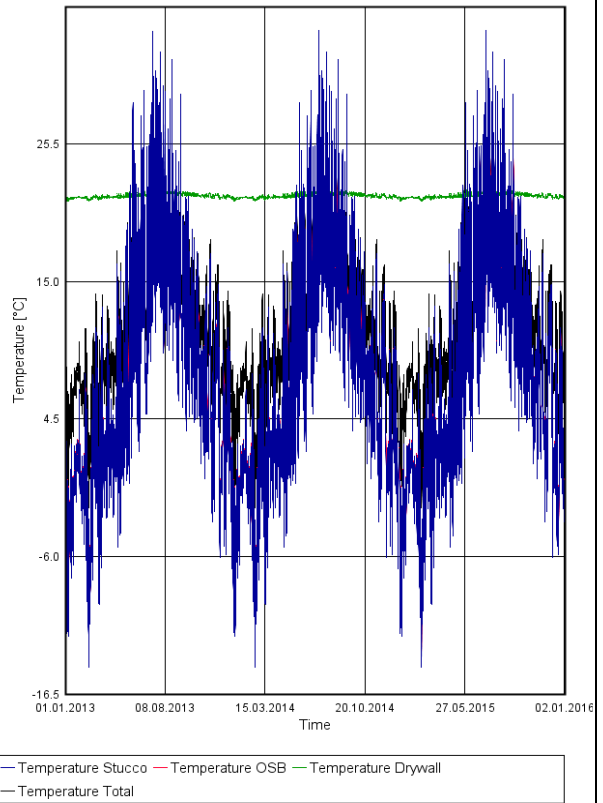
Temperature Phoenix VIP 25mm



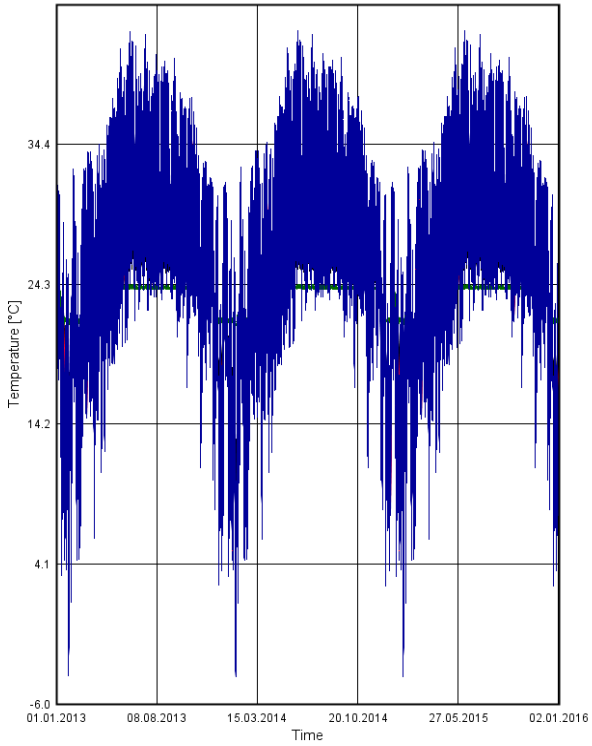
Temperature San Diego VIP 25mm



Temperature St John's VIP 25mm

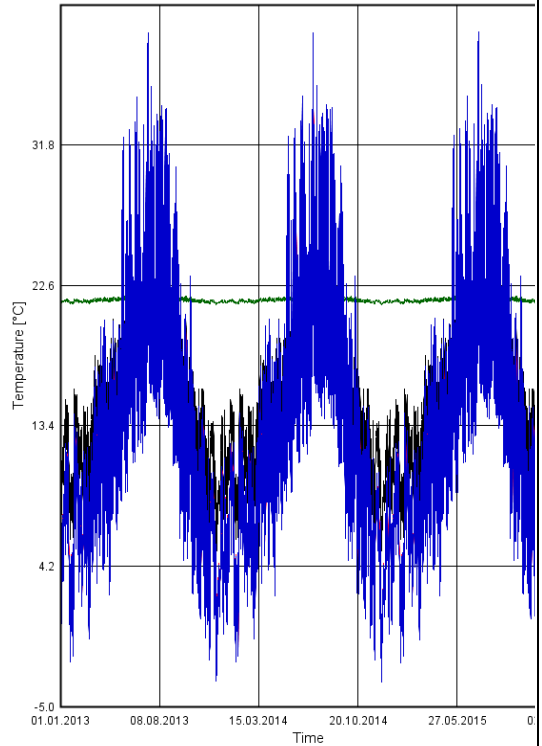


Temperature Tampa VIP 25mm



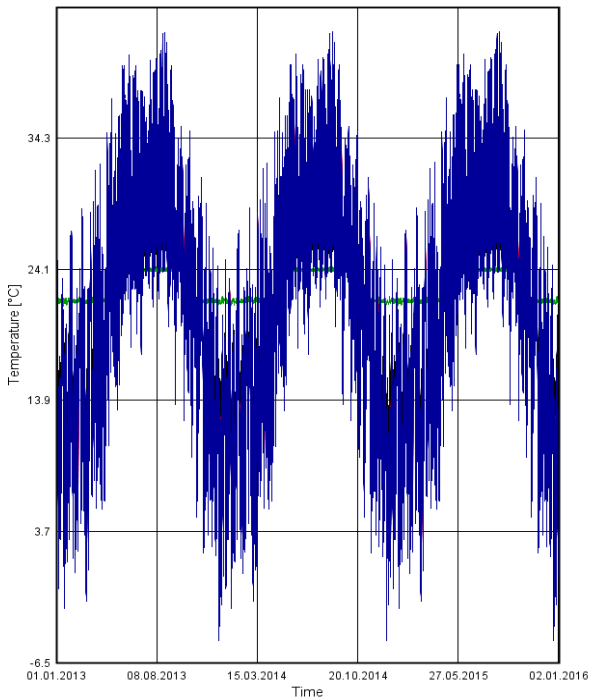
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Vancouver VIP 25mm



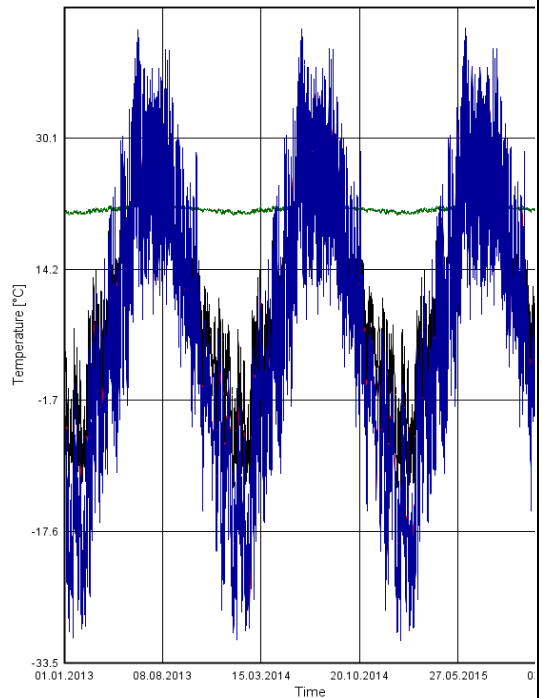
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Wilmington VIP 25mm



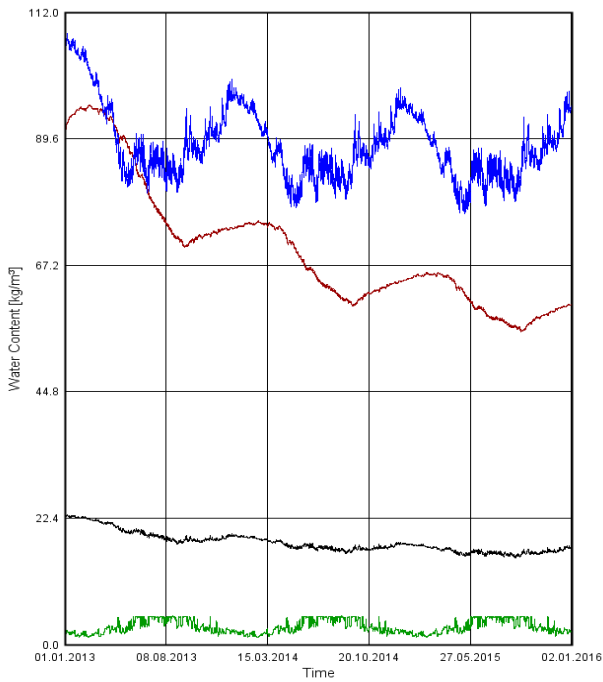
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Winnipeg VIP 25mm



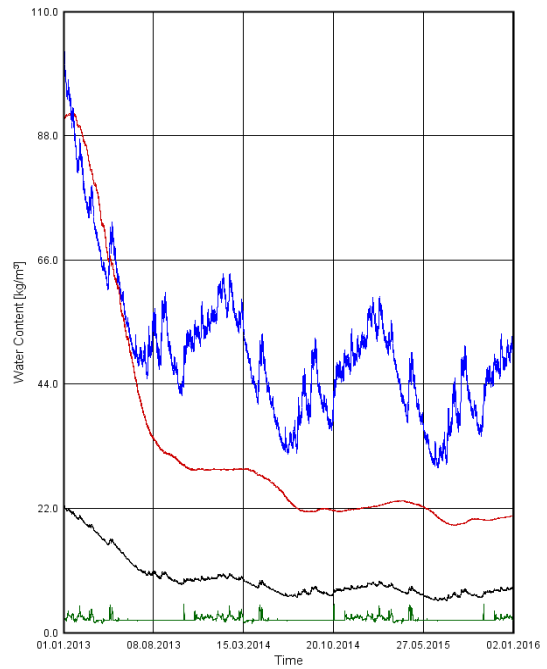
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Water Content Ottawa VIP 25mm



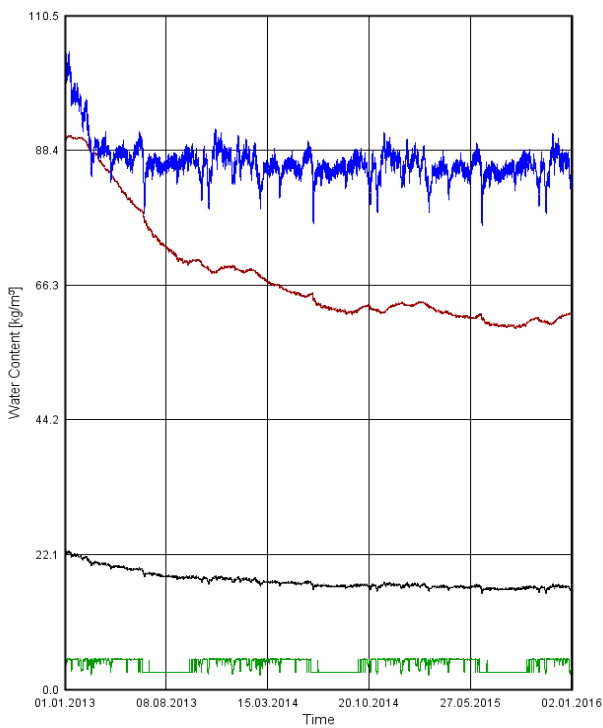
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Phoenix VIP 25mm



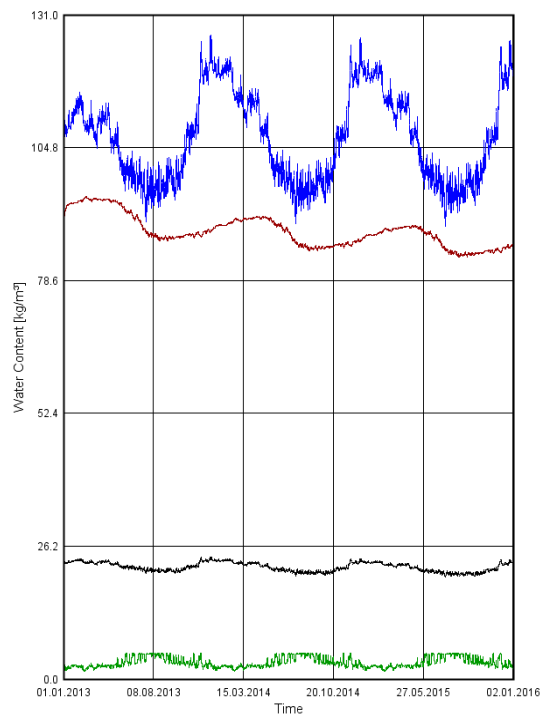
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content San Diego VIP 25mm



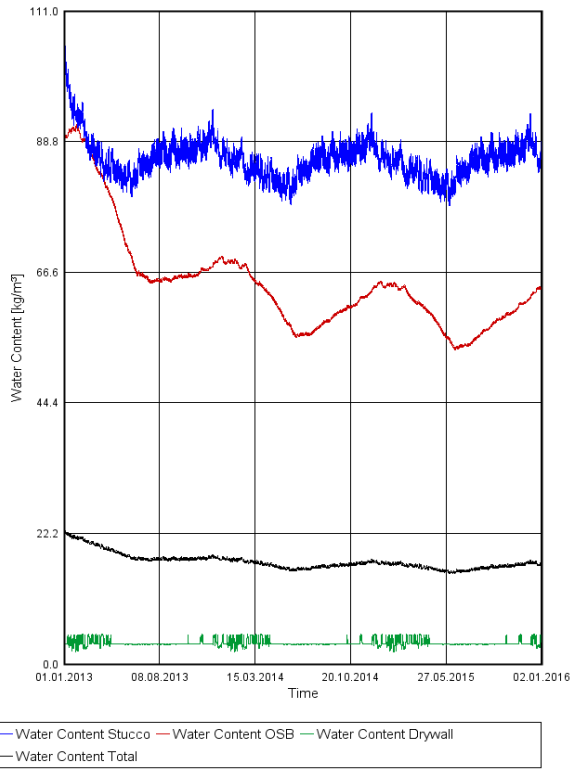
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content St John's VIP 25mm

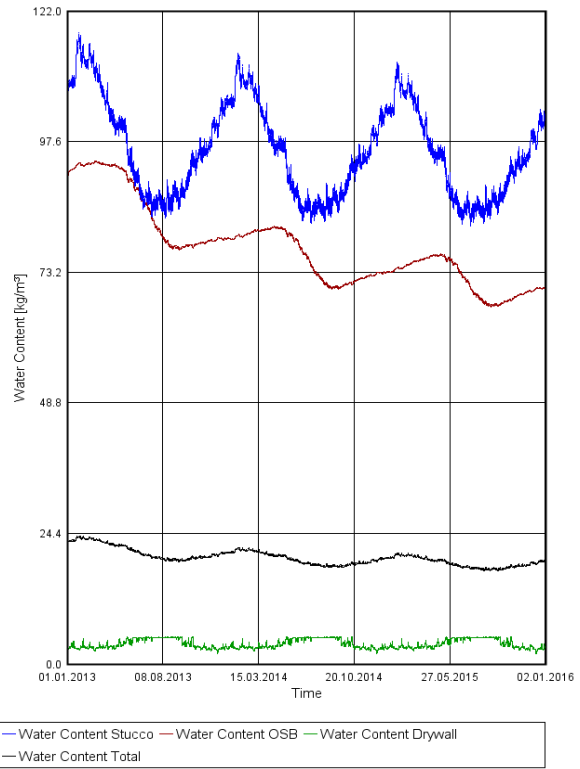


— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

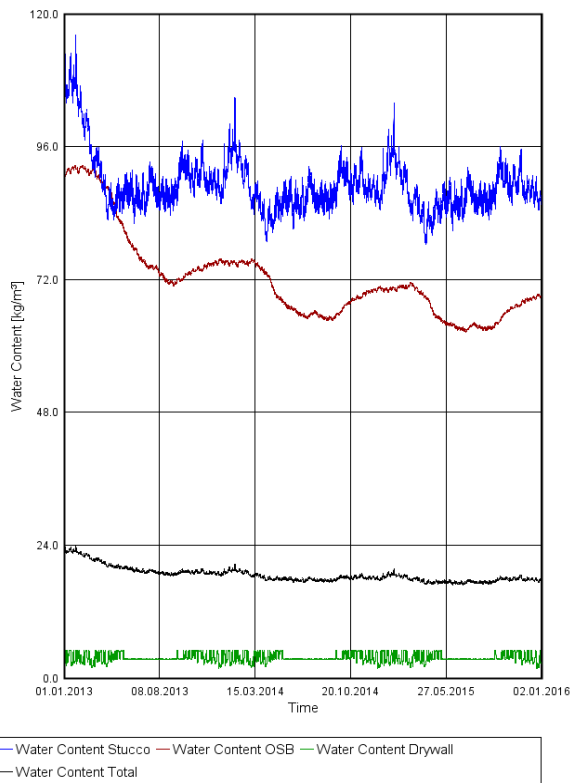
Water Content Tampa VIP 25mm



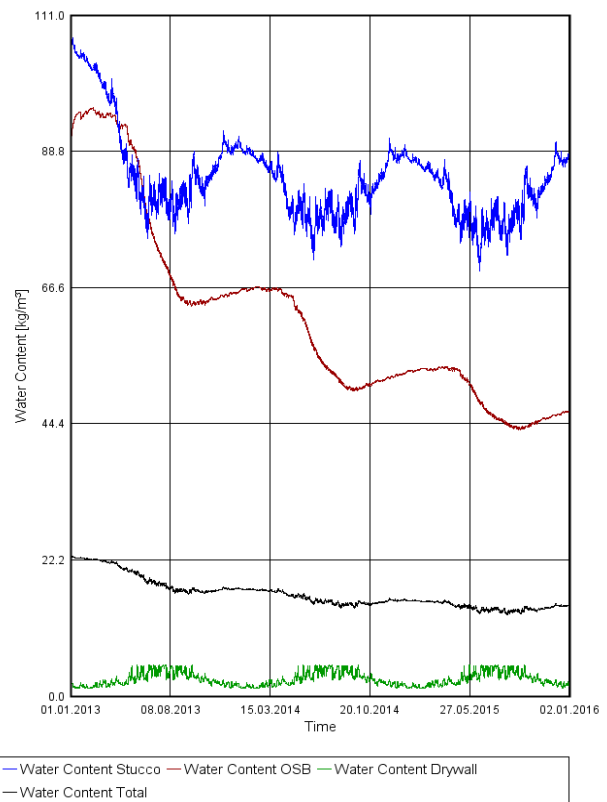
Water Content Vancouver 25mm



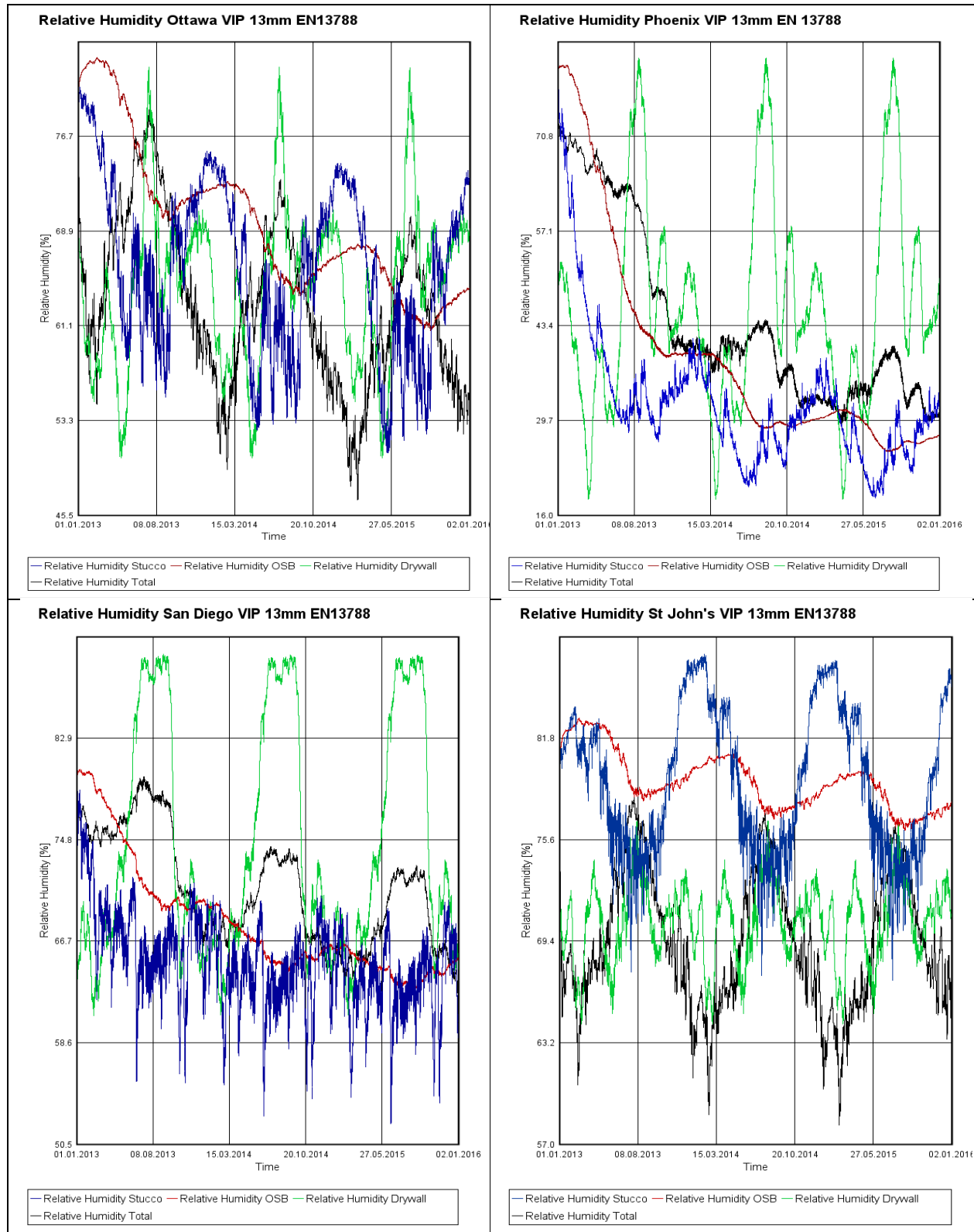
Water Content Wilmington VIP 25mm



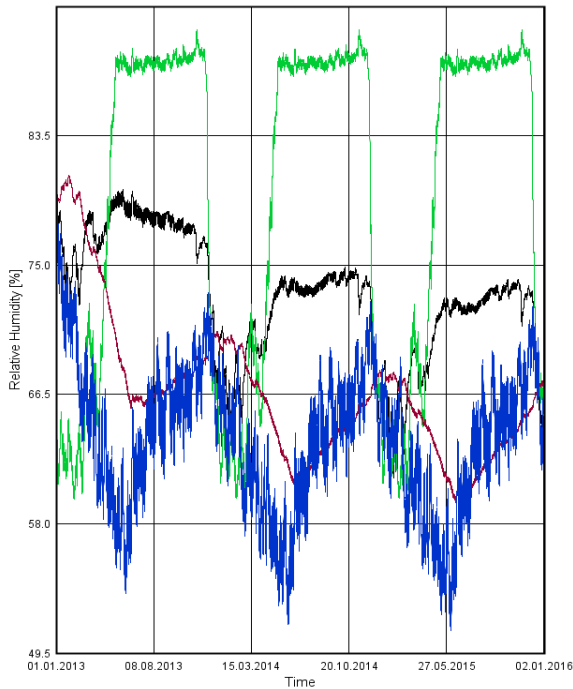
Water Content Winnipeg VIP 25mm



EN 13788-VIP 13mm

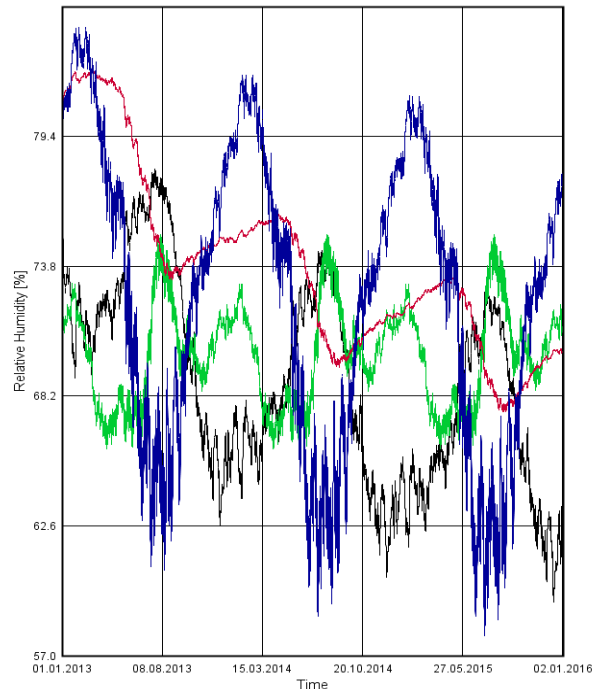


Relative Humidity Tampa VIP 13mm EN13788



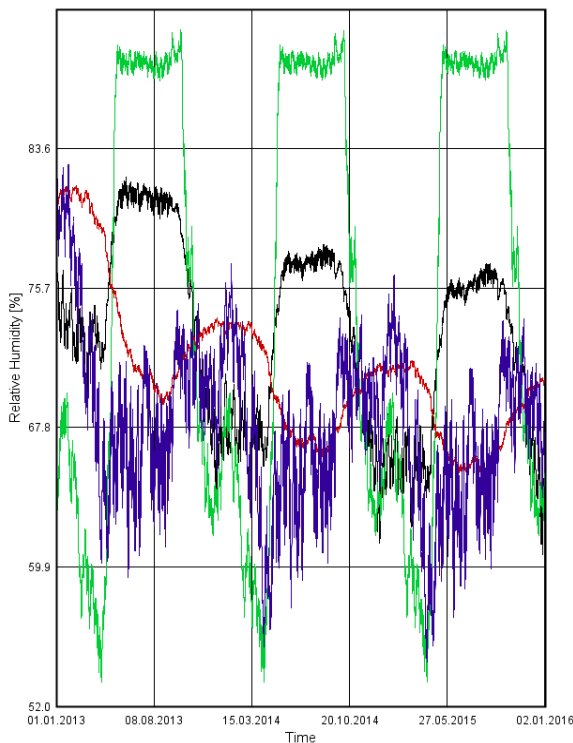
— Relative Humidity Stucco — Relative Humidity OSB — Relative Humidity Drywall
— Relative Humidity Total

Relative Humidity Vancouver VIP 13mm EN13788



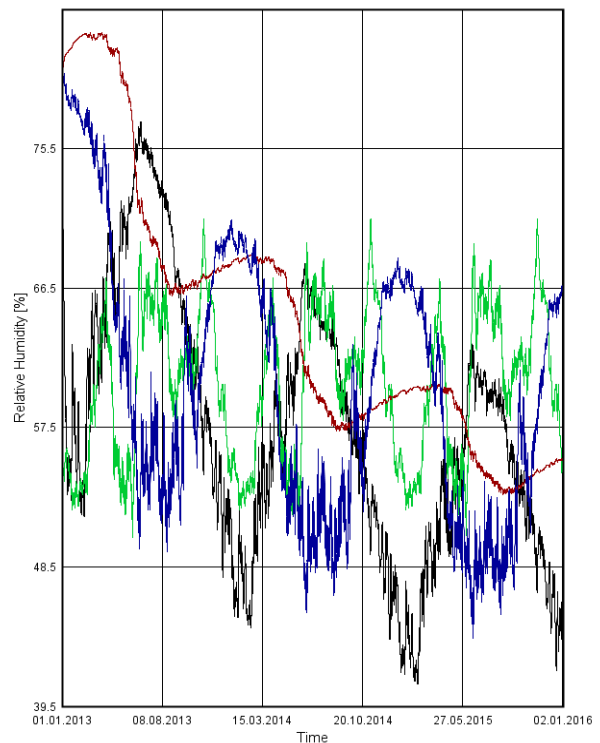
— Relative Humidity Stucco — Relative Humidity OSB — Relative Humidity Drywall
— Relative Humidity Total

Relative Humidity Wilmington VIP 13mm EN13788



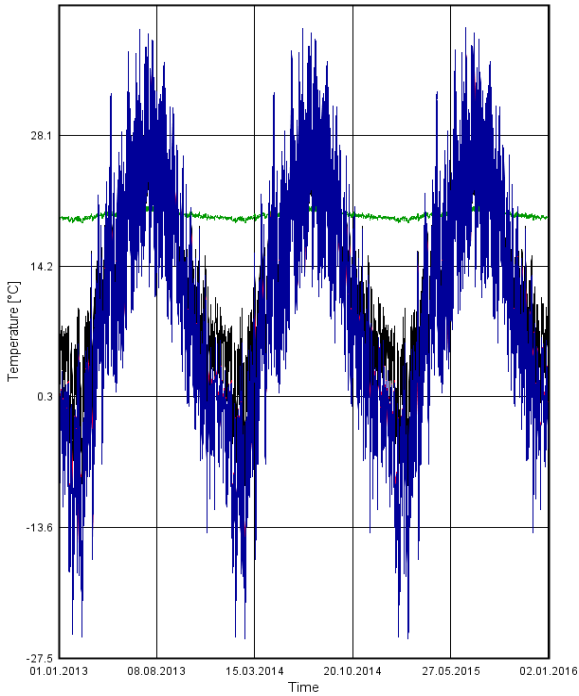
— Relative Humidity Stucco — Relative Humidity OSB — Relative Humidity Drywall
— Relative Humidity Total

Relative Humidity Winnipeg VIP 13mm EN13788



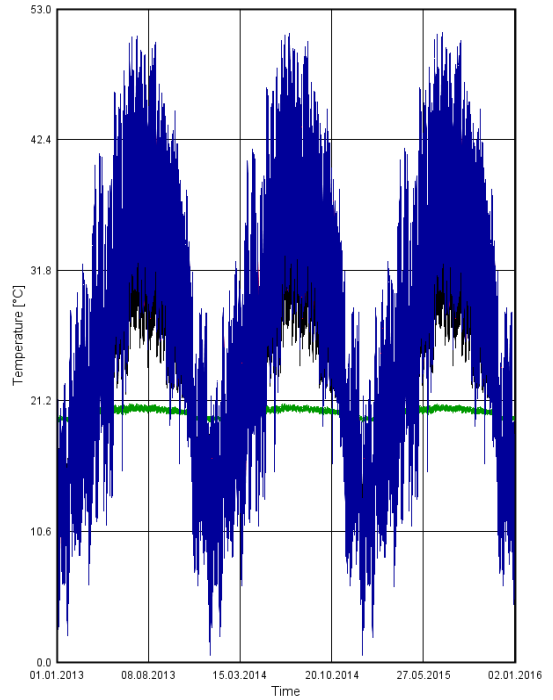
— Relative Humidity Stucco — Relative Humidity OSB — Relative Humidity Drywall
— Relative Humidity Total

Temperature Ottawa VIP 13mm EN13788



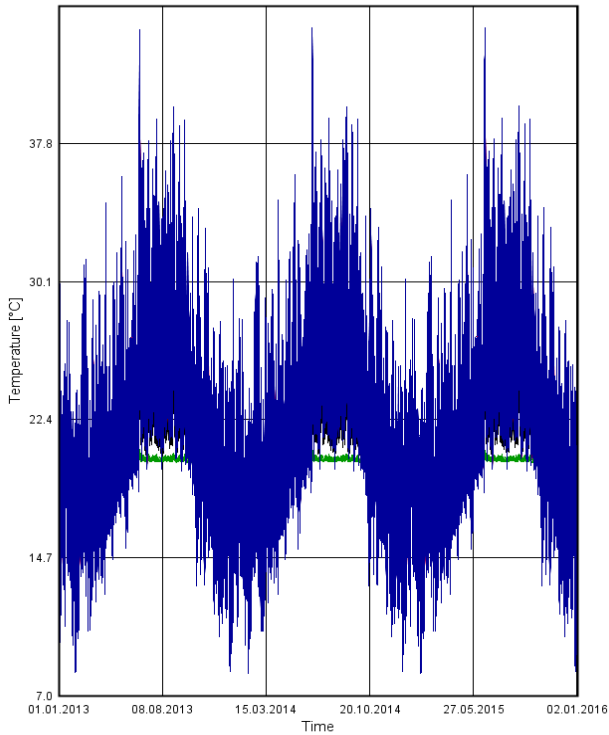
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Phoenix VIP 13mm EN13788



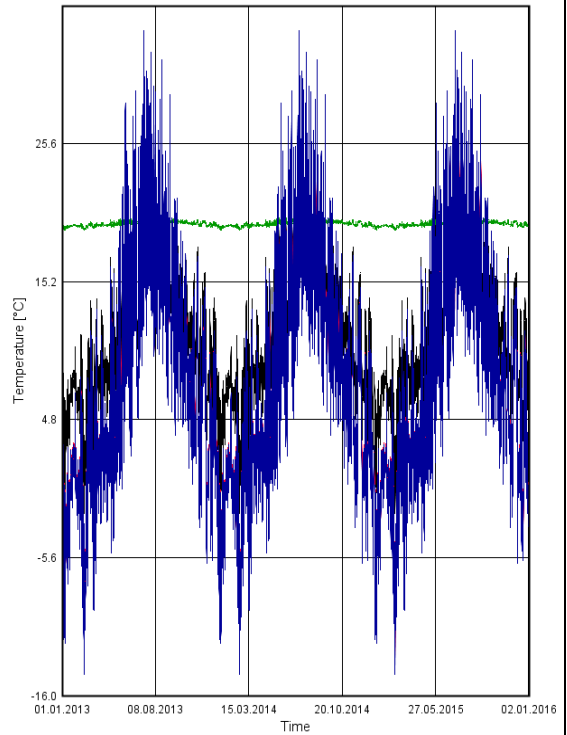
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature San Diego VIP 13mm EN13788



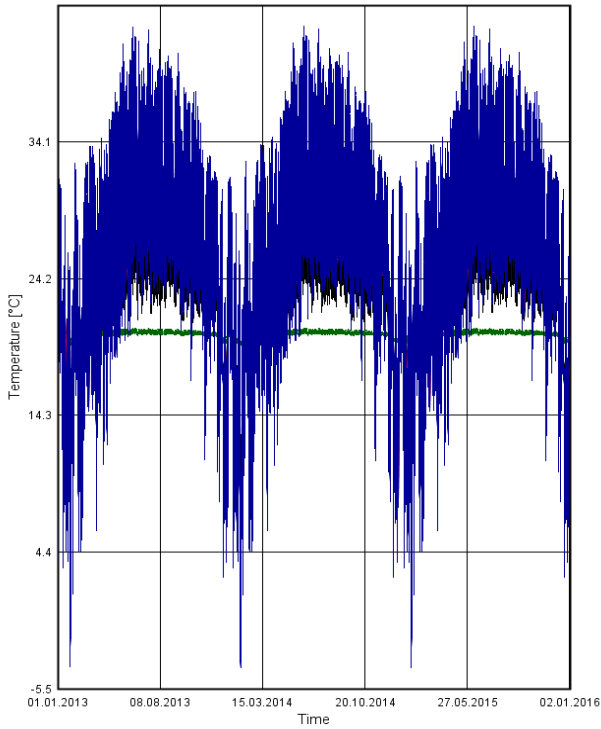
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature St John's VIP 13mm EN13788



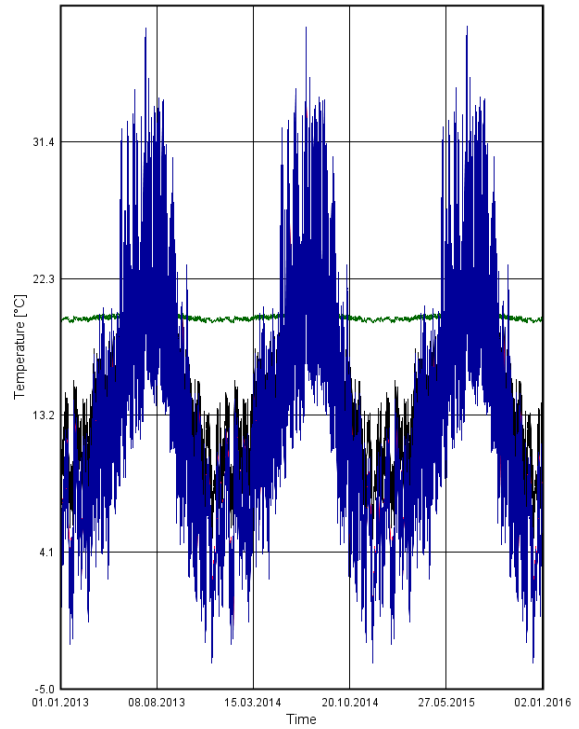
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Tampa VIP 13mm EN13788



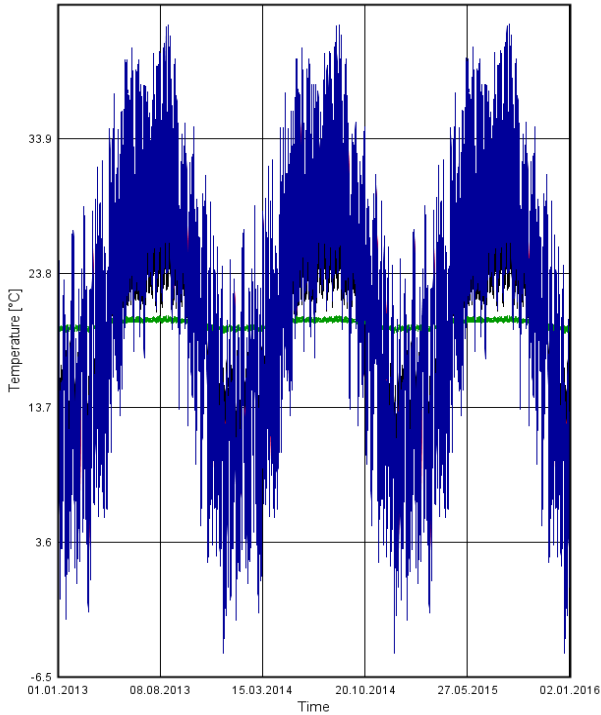
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Vancouver VIP 13mm EN 13788



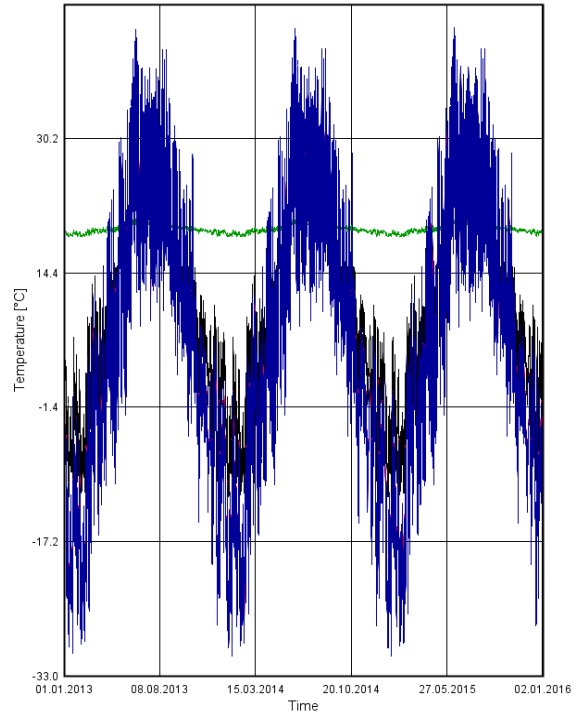
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Wilmington VIP 13mm EN13788



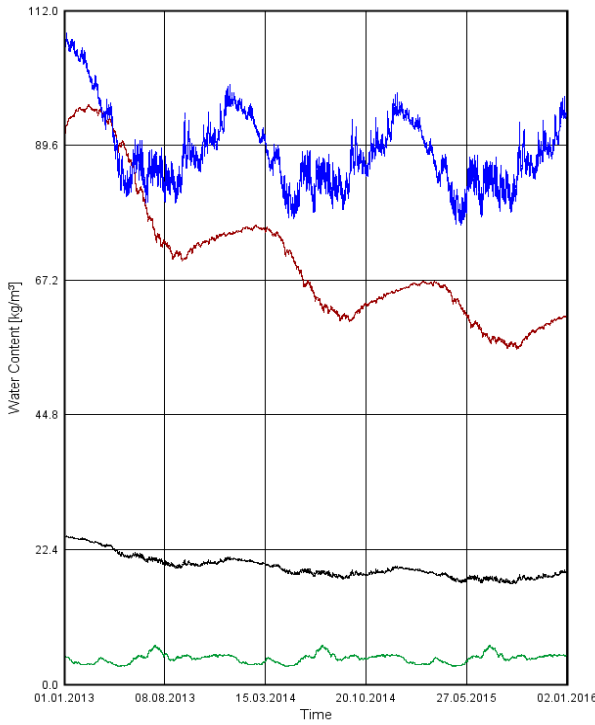
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Temperature Winnipeg VIP 13mm EN13788



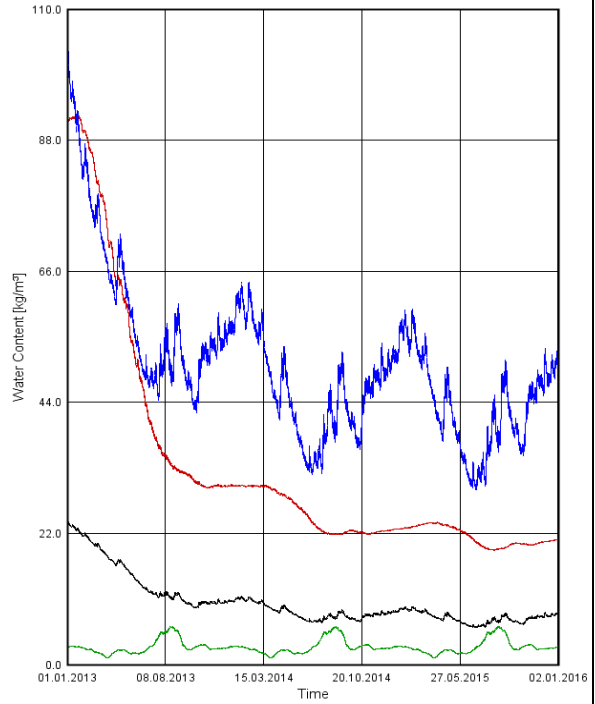
— Temperature Stucco — Temperature OSB — Temperature Drywall
— Temperature Total

Water Content Ottawa VIP 13mm EN13788



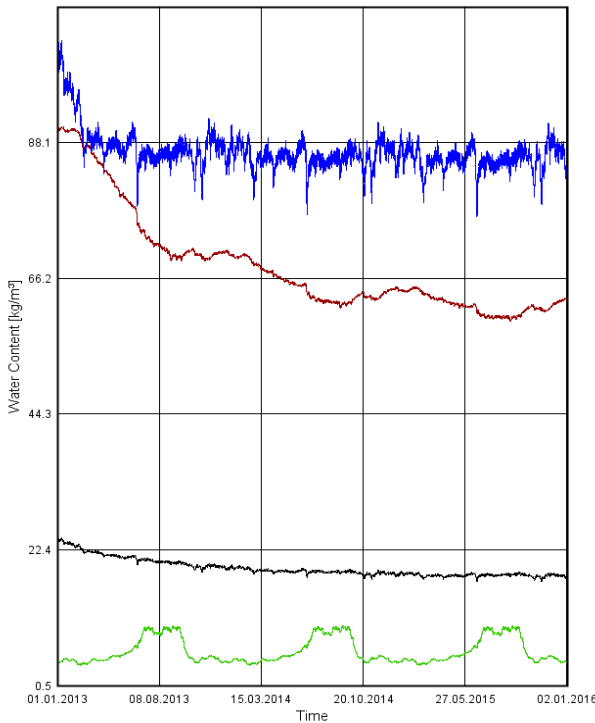
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Phoenix VIP 13mm EN13788



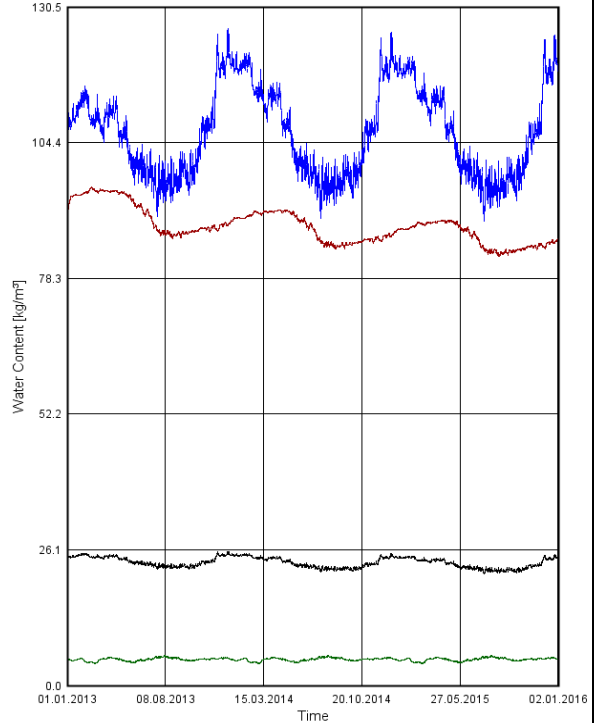
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content San Diego VIP 13mm EN13788



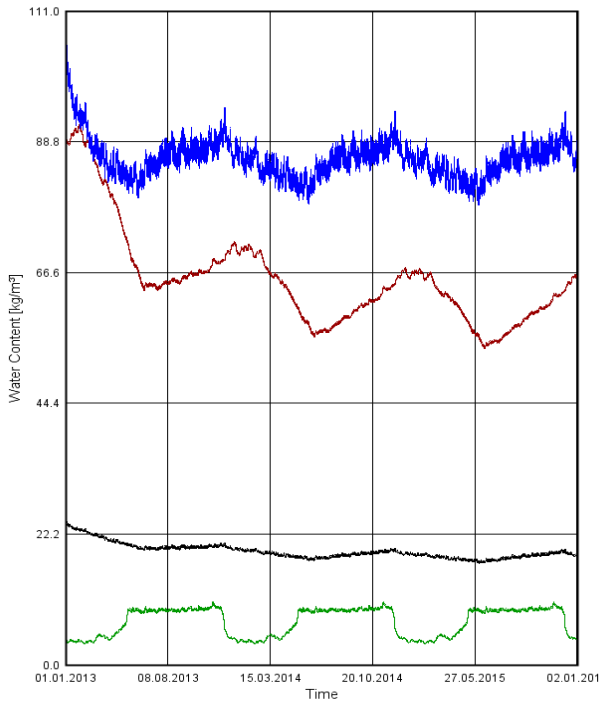
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content St Johns VIP 13mm EN13788



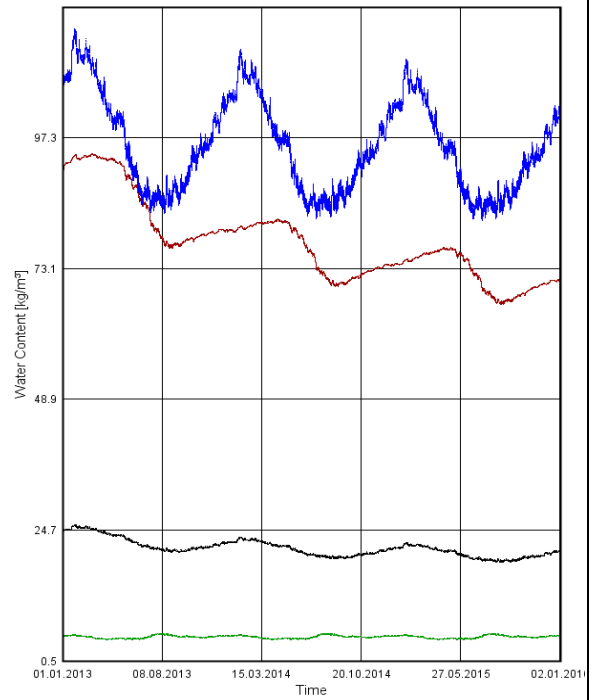
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Tampa VIP 13mm EN13788



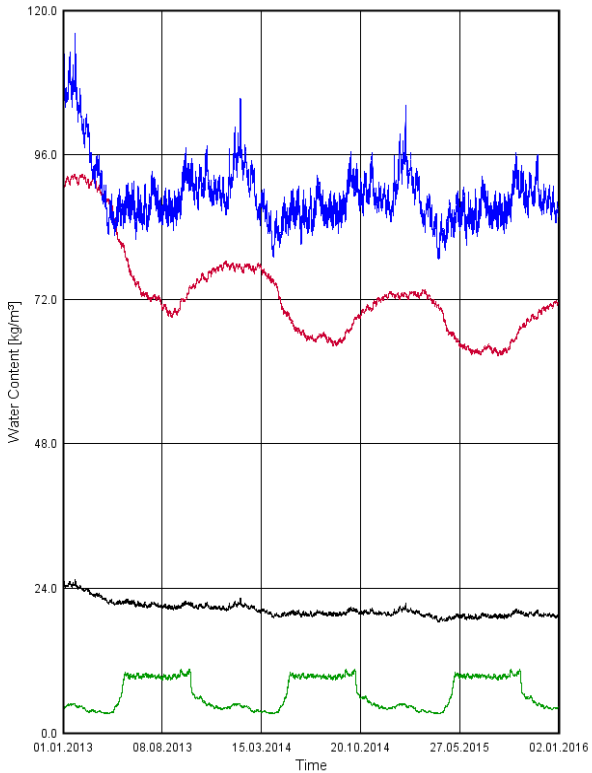
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Vancouver VIP 13mm EN13788



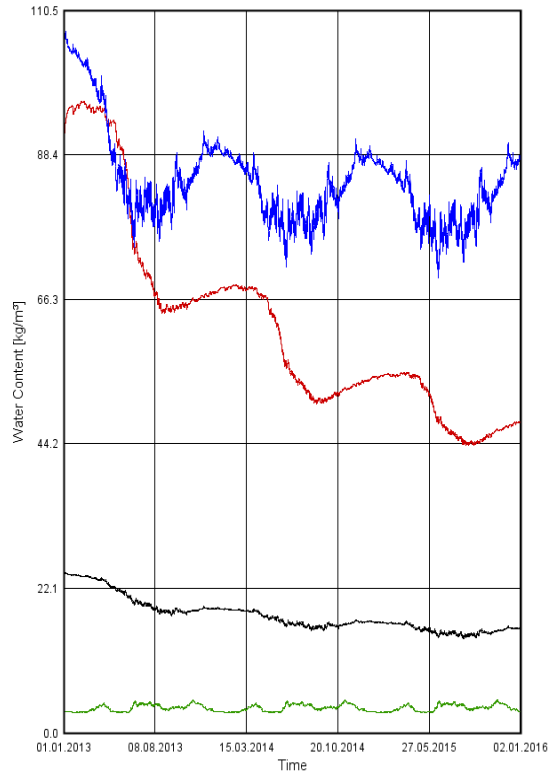
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

Water Content Wilmington VIP 13mm EN13788



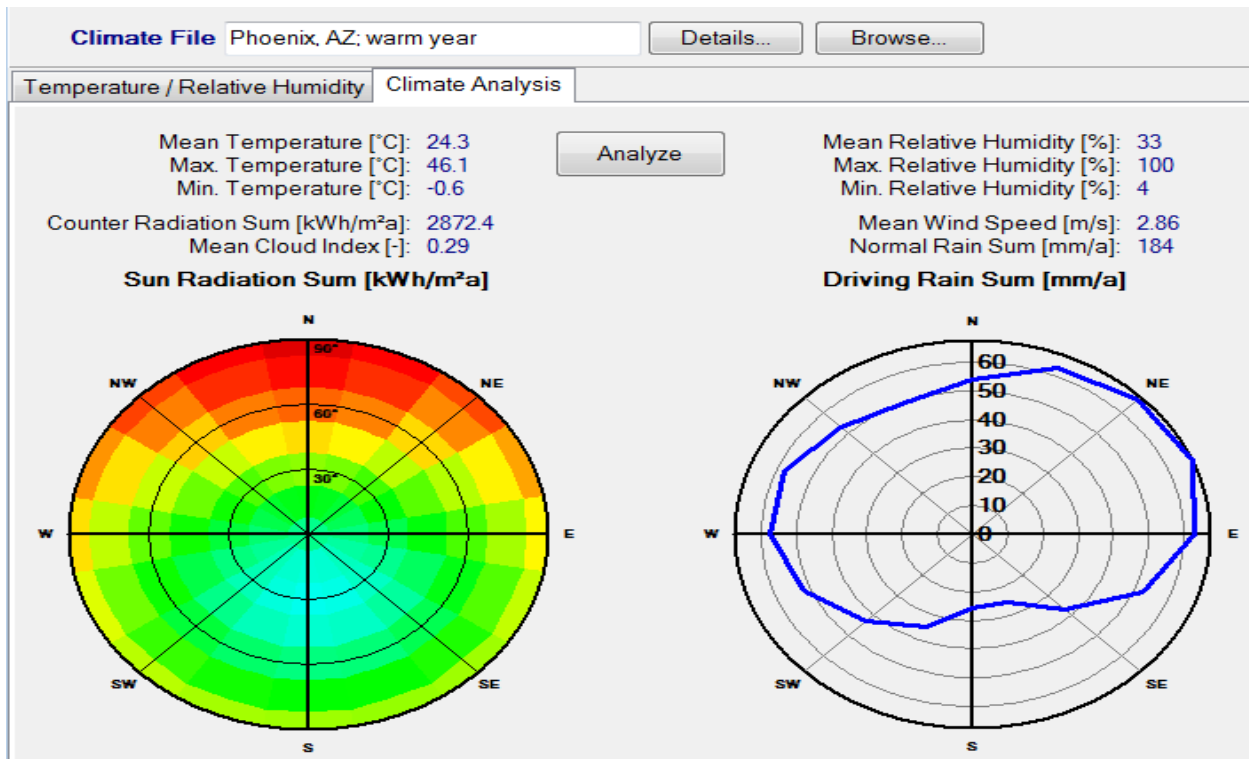
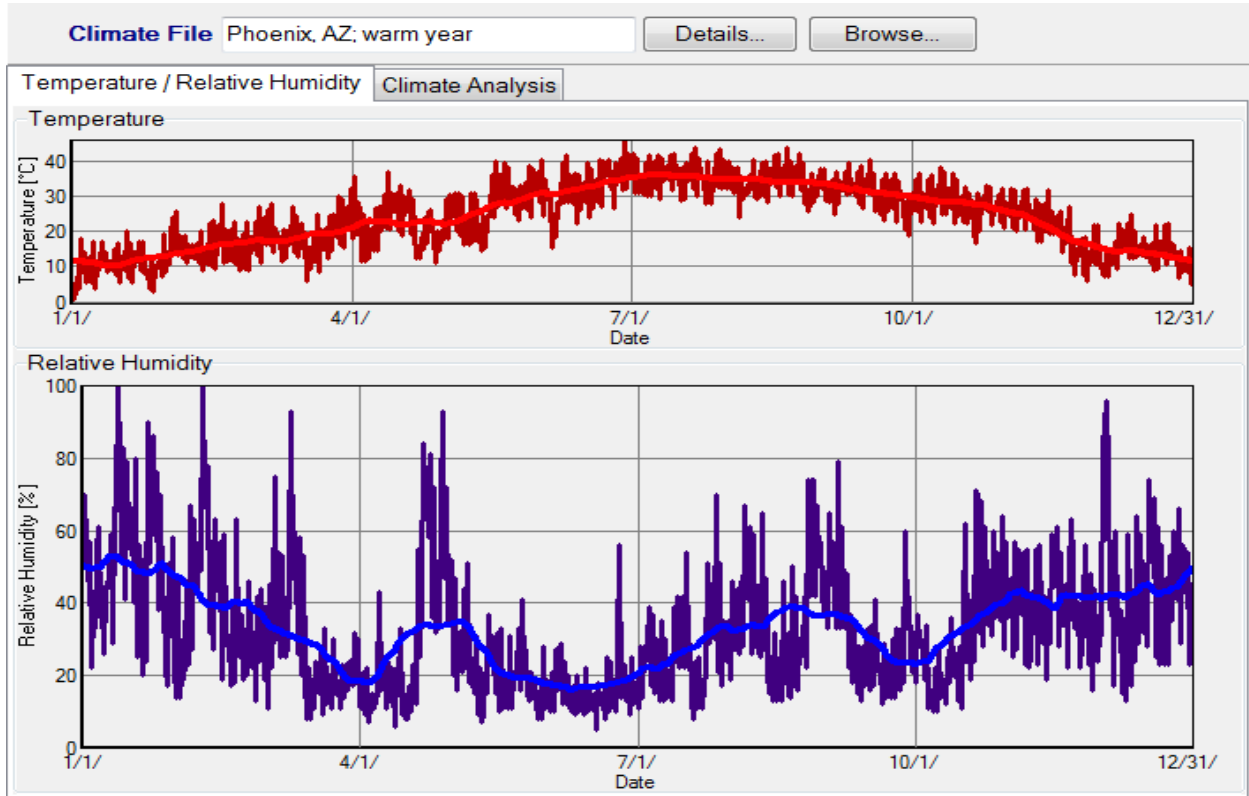
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

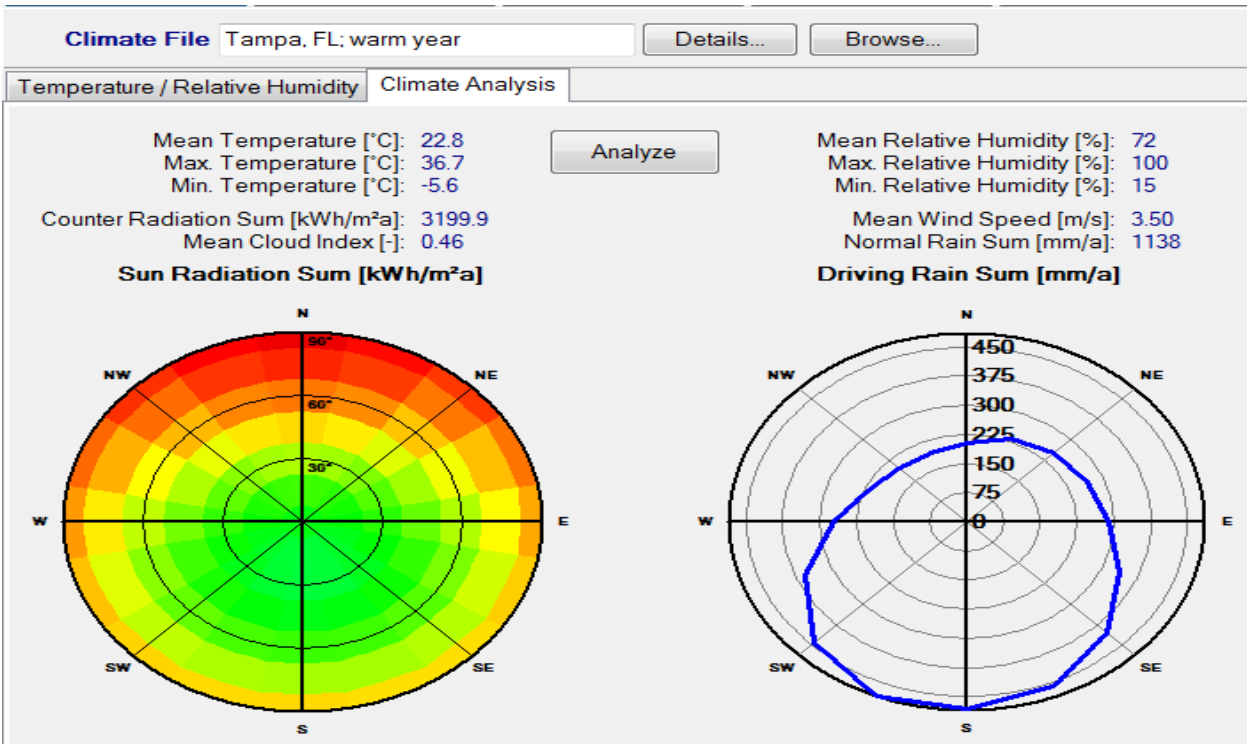
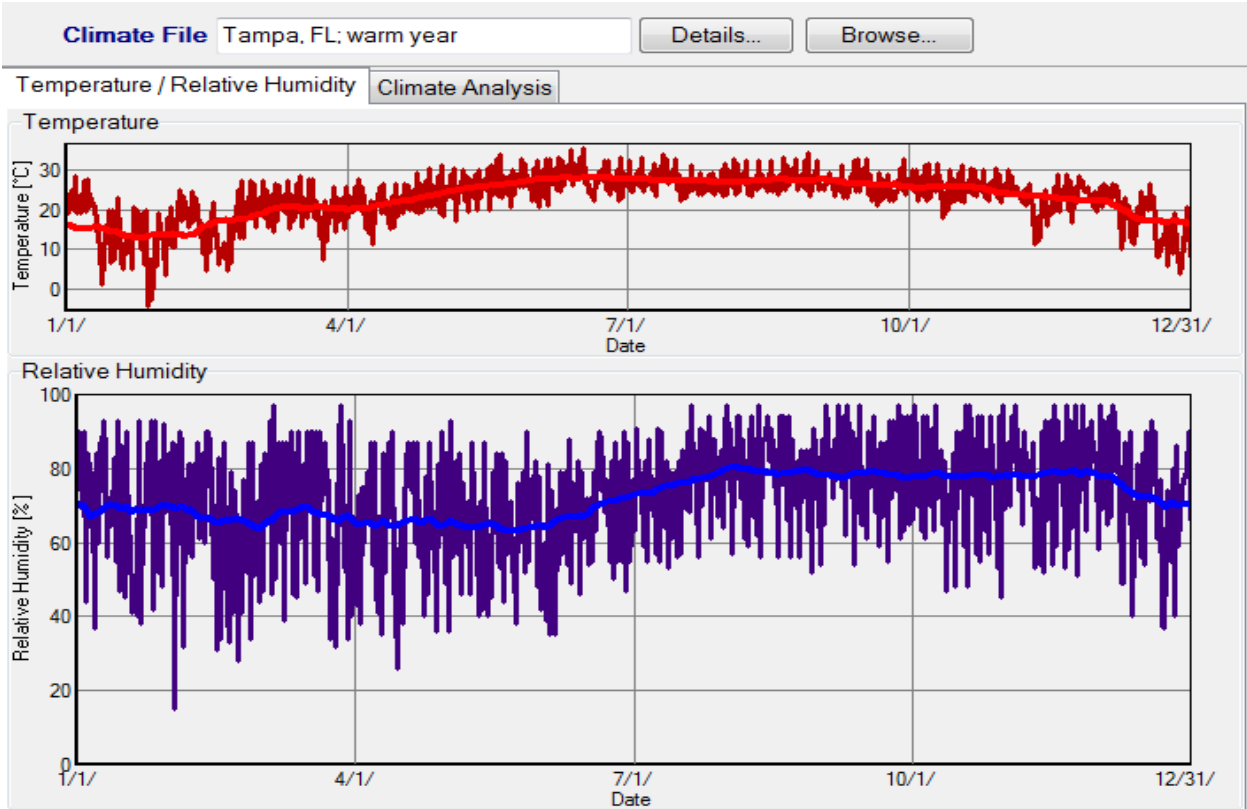
Water Content Winnipeg VIP 13mm EN13788

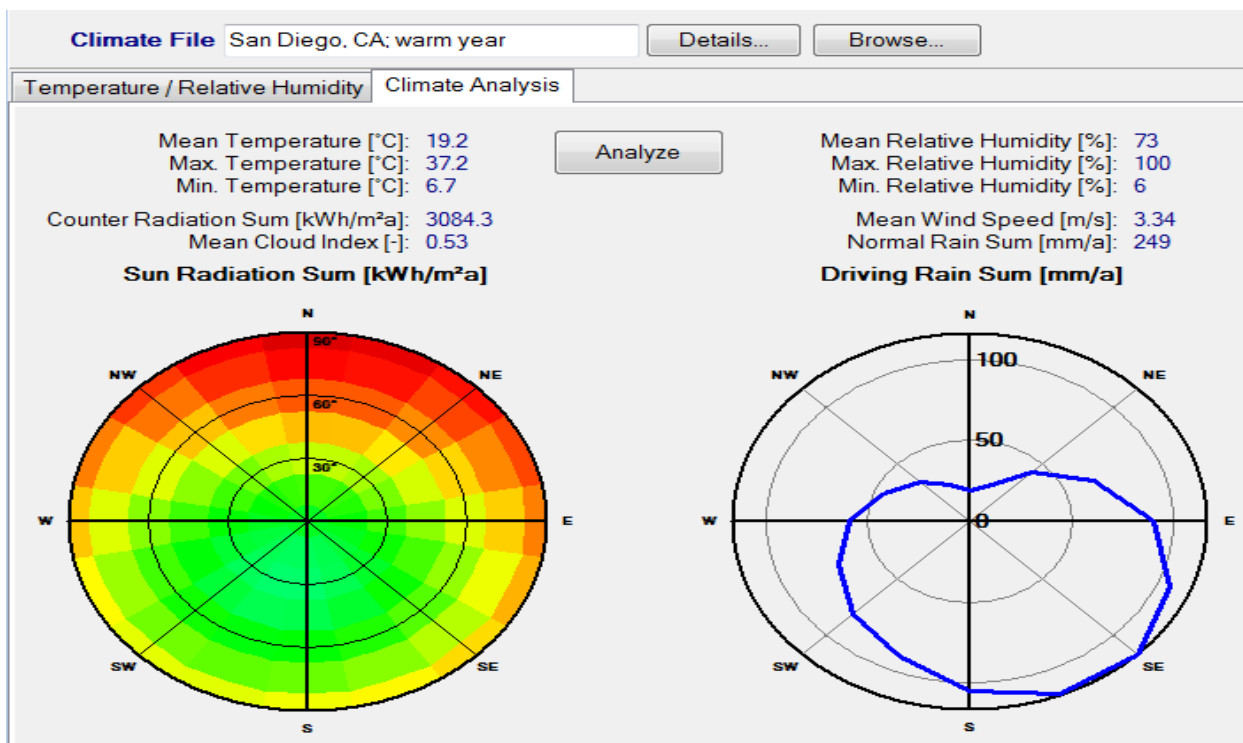
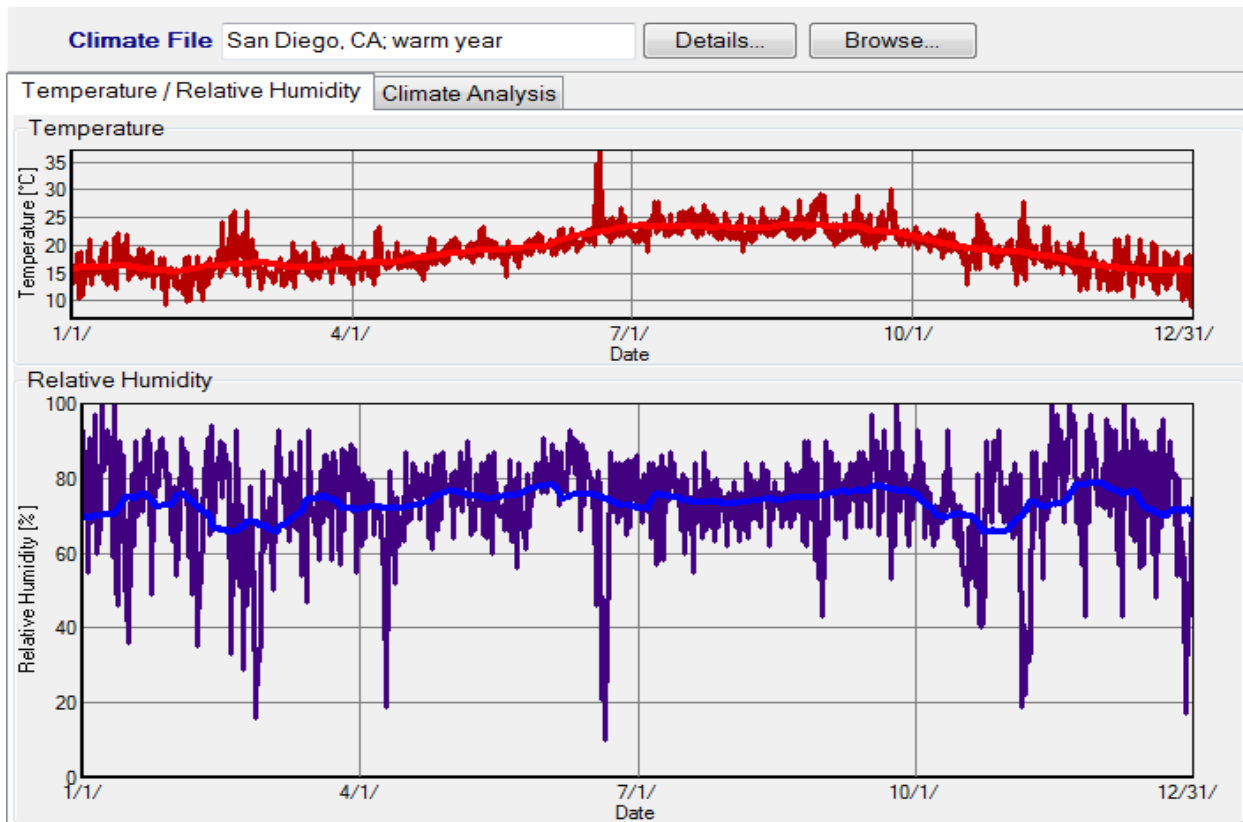


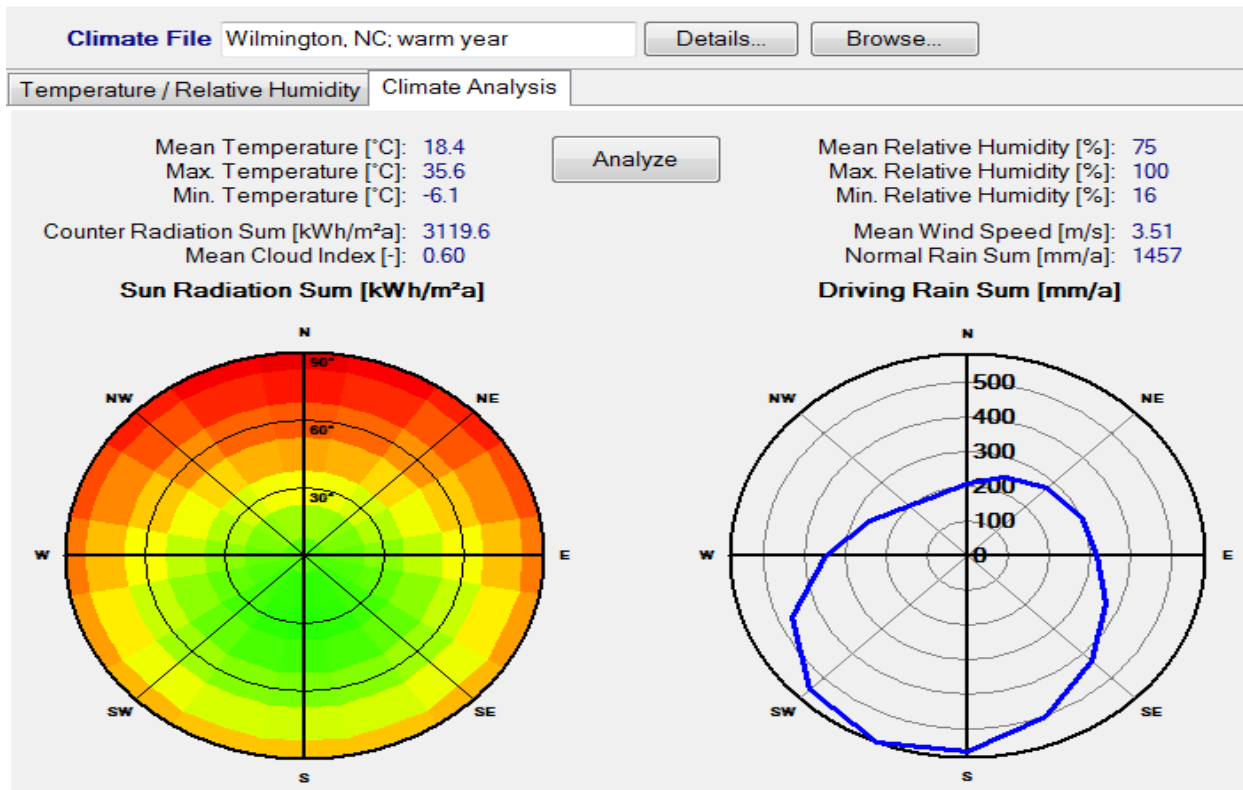
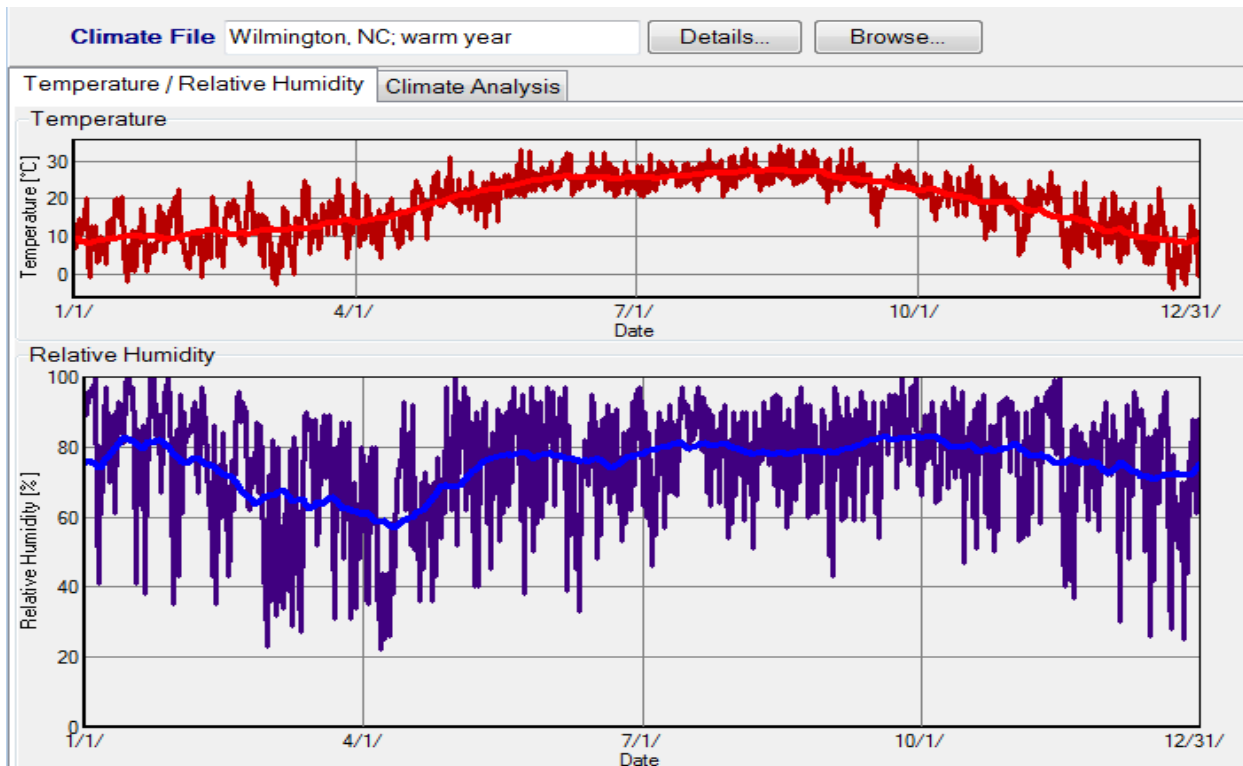
— Water Content Stucco — Water Content OSB — Water Content Drywall
— Water Content Total

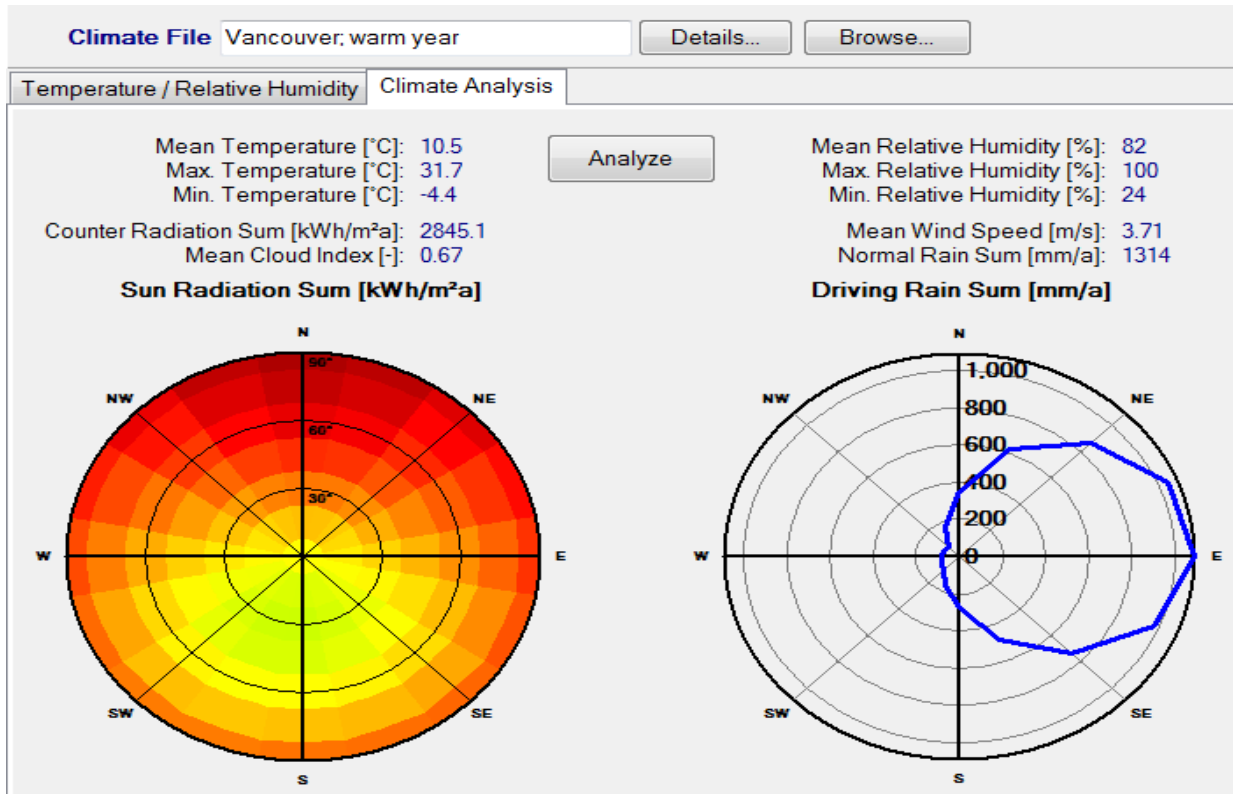
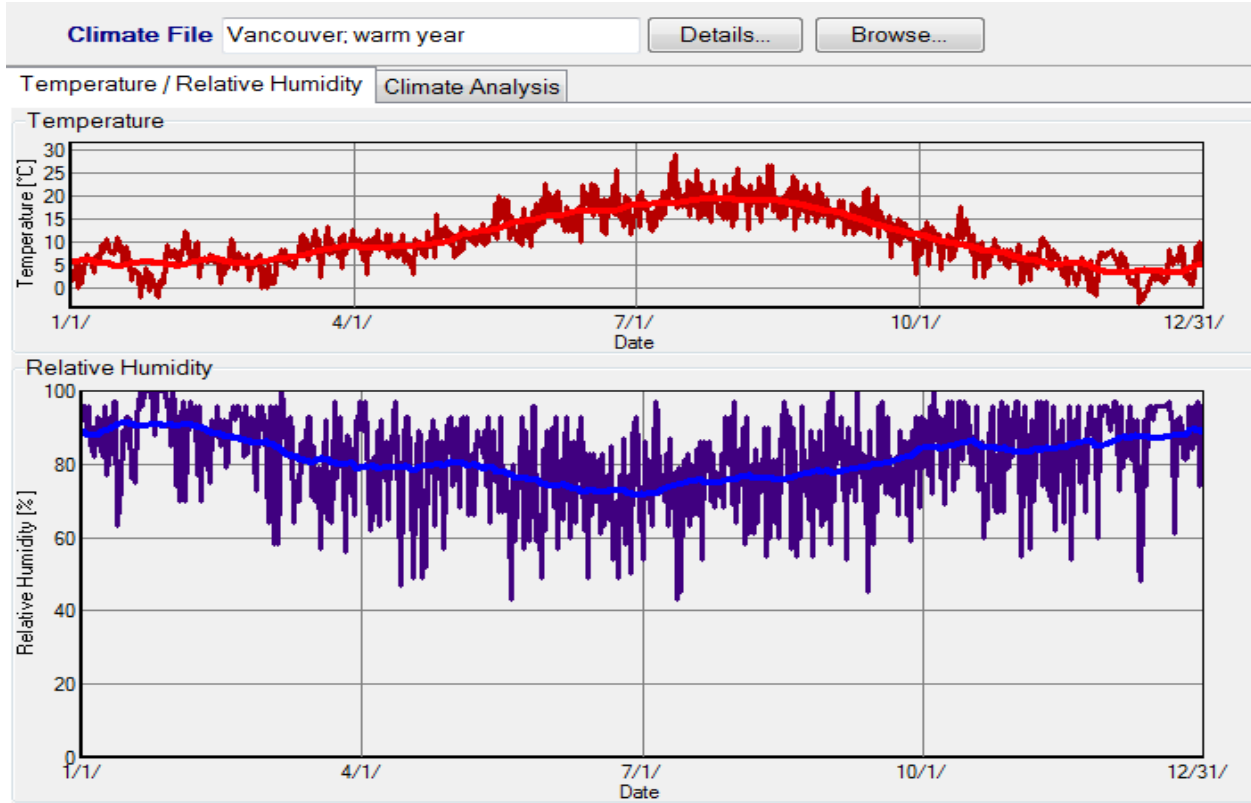
Appendix D - Weather Data

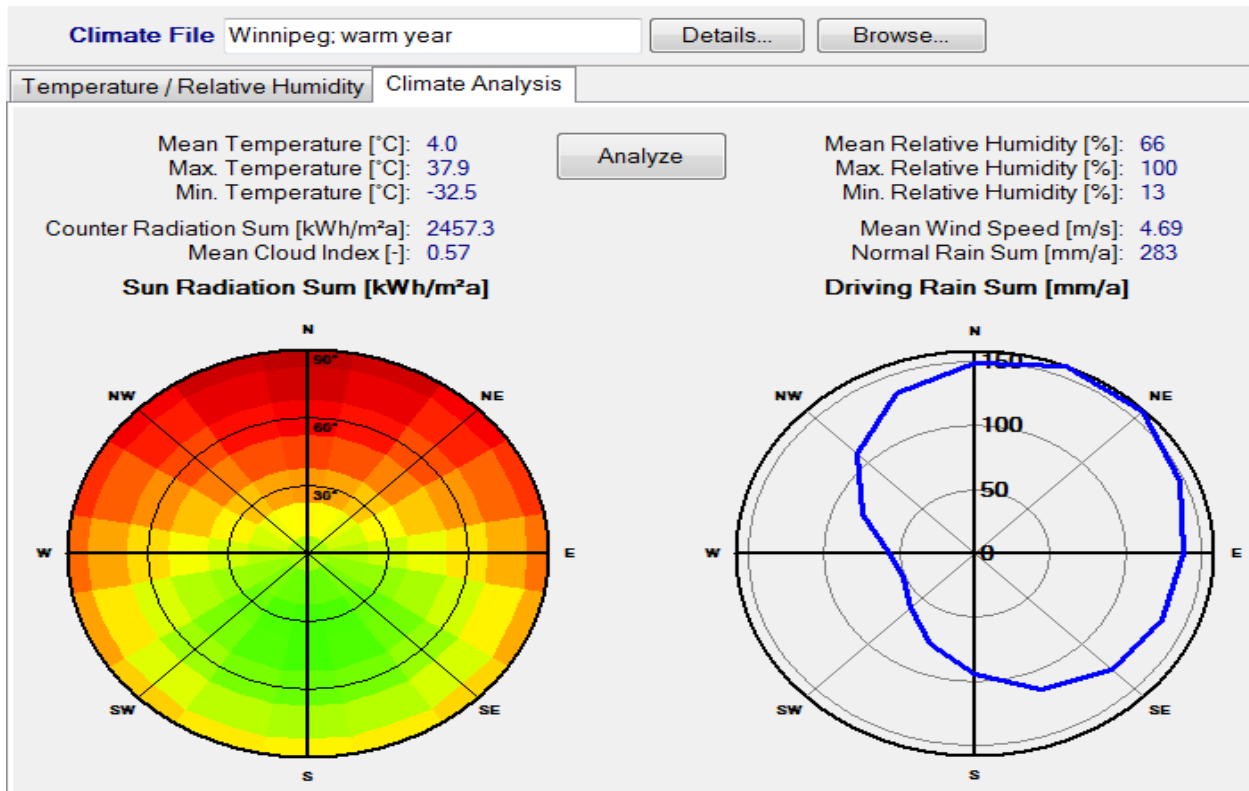
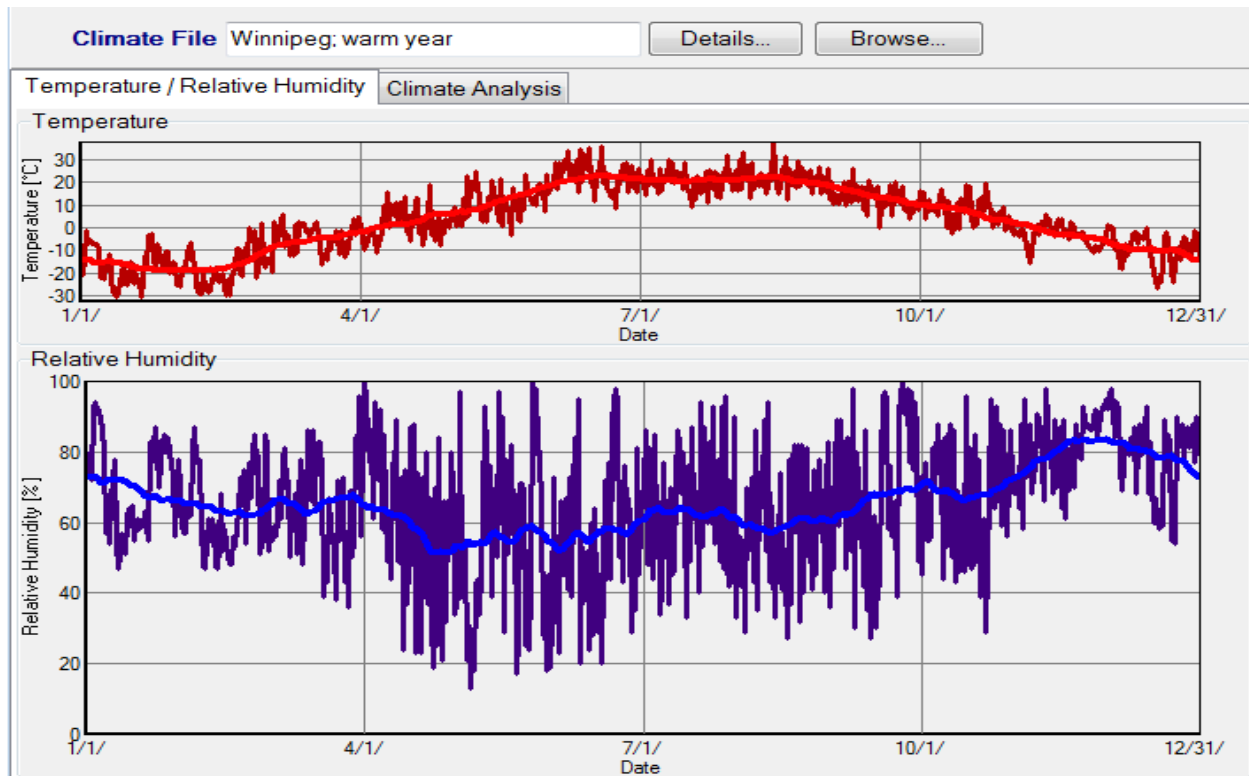


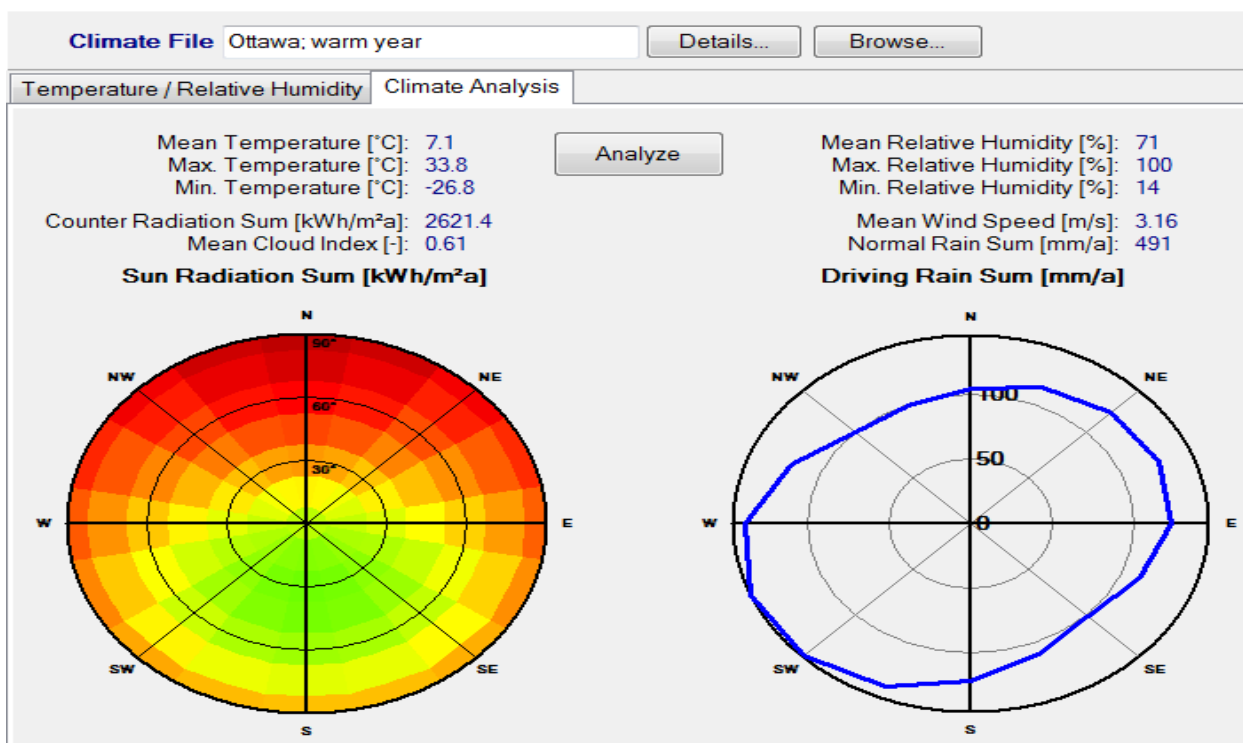
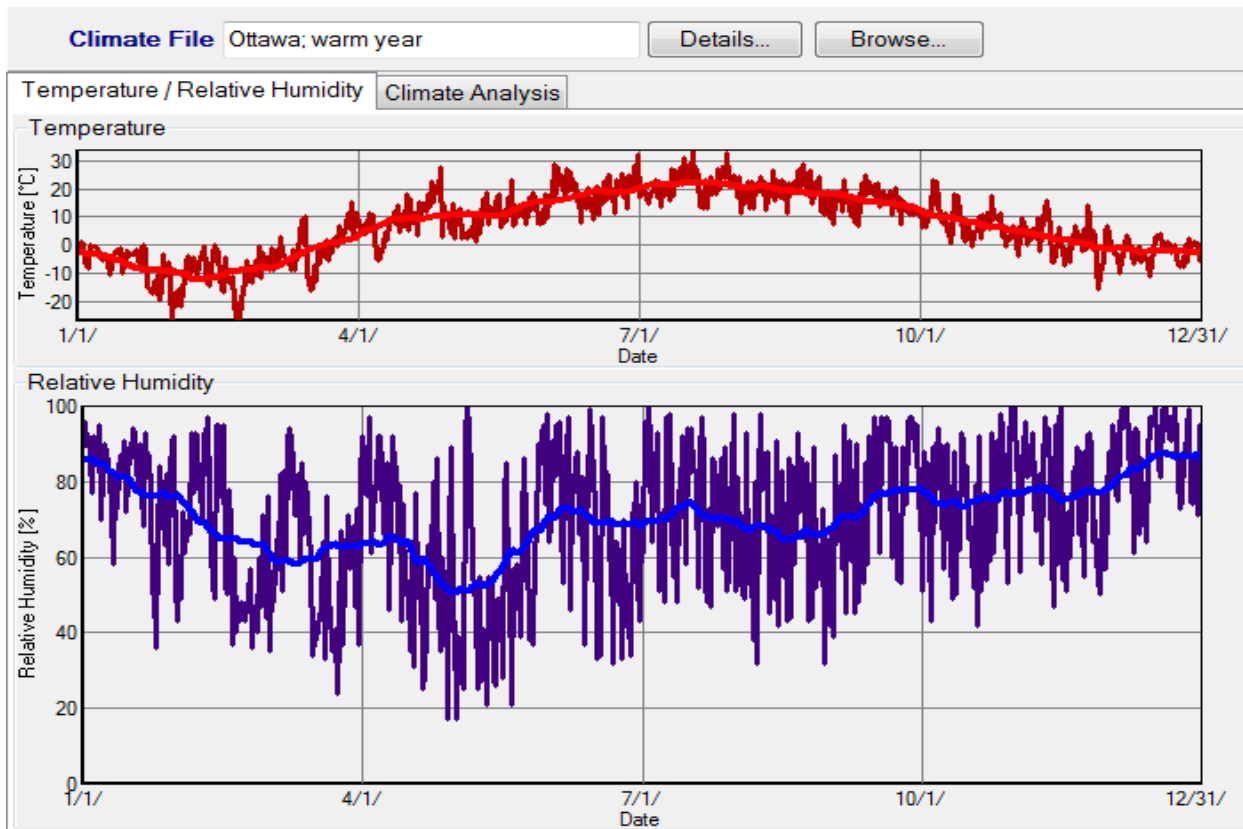


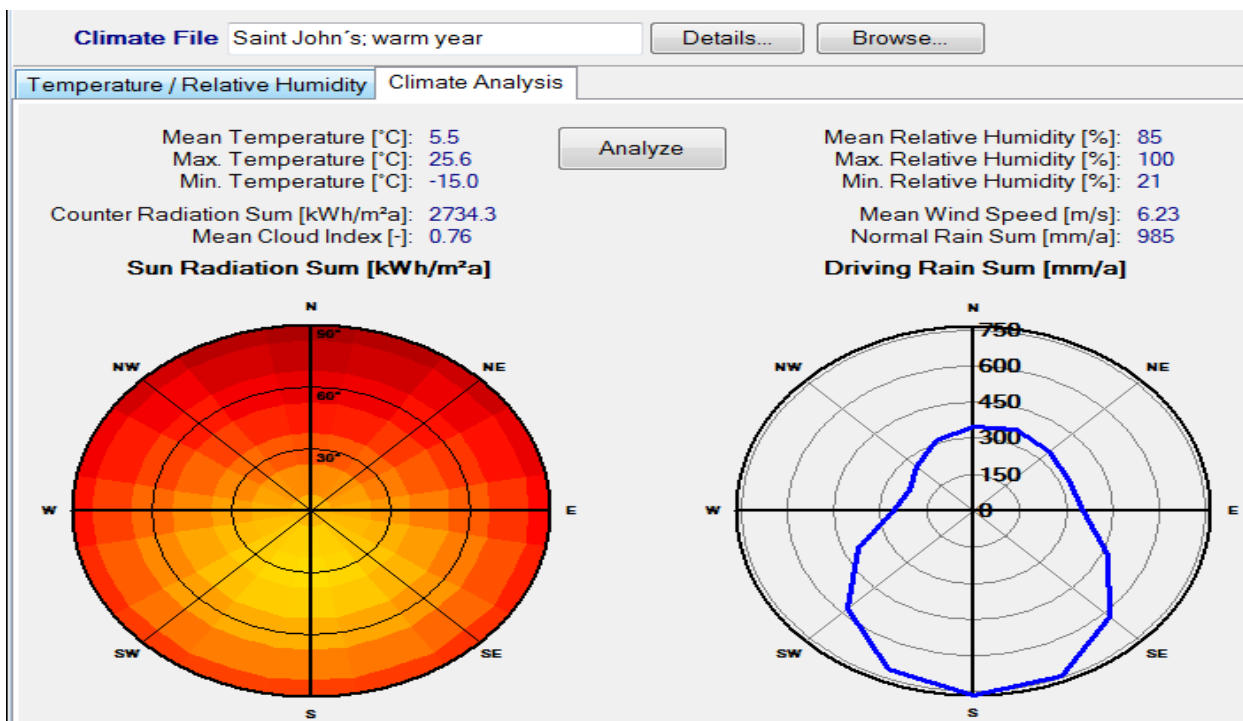
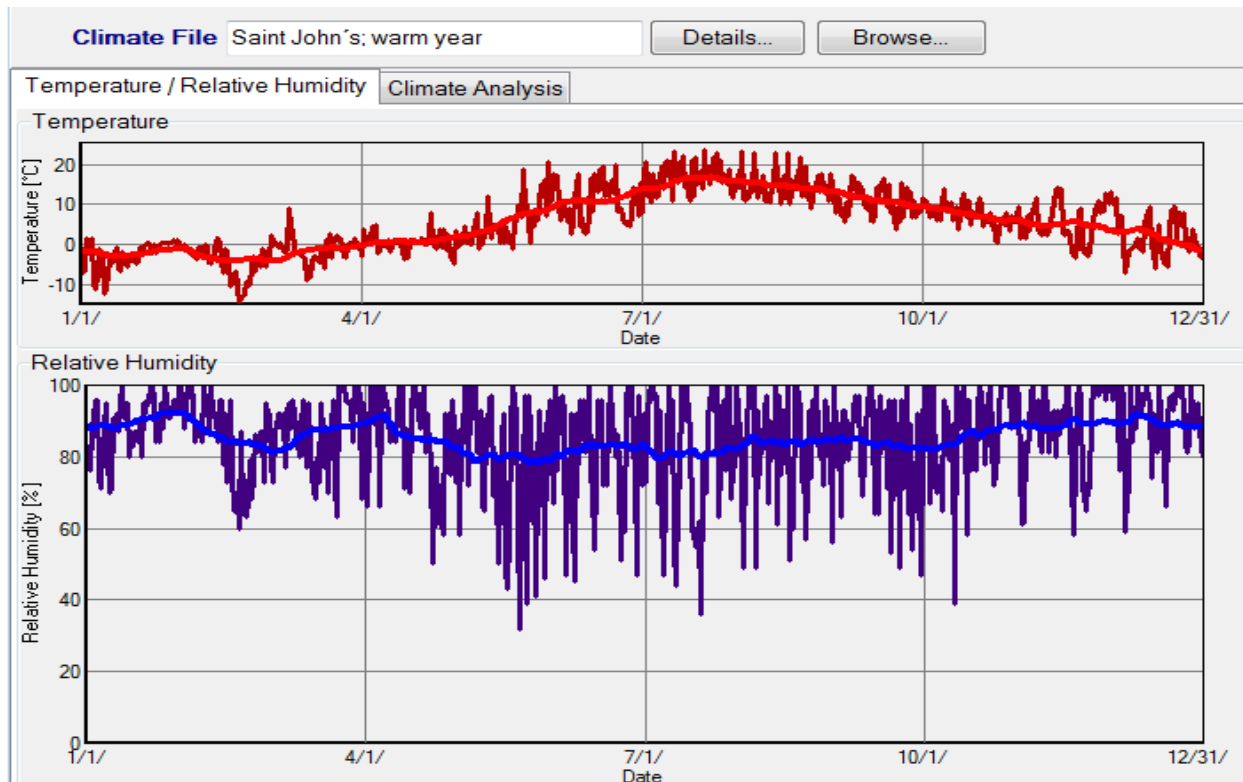












Appendix E - Dew Point

Dew point method requires the properties described in the table given below for the calculation of the effective vapour pressure at the wall interfaces. Table given below describes the material properties and the values need to be known for the dew point calculation.

μ-value	vapor diffusion resistance factor
r-value	thermal conductivity* thickness
Vapor Diffusion resistance =	μ value * thickness
inside temp	23.9
inside RH	0.35
outside temp	32
outside RH	0.18
delta P	34.7
delta T	-8.1

The thickness was used as described in the wall construction figure. The thermal conductivity and μ-value were taken from the WUFI database and the effective R-value and the vapour diffusion resistance were calculated. The formulas used for calculating the μ-value, R-value and vapour diffusion resistance are described in the table given above.

Material	Thickness	Thermal Conductivity	μ-value	R-value	Vapour Diffusion Resistance
Drywall	0.011	0.163	6	0.07	0.1
XPS	0.01	0.025	170.56	0.40	1.7
VIP	0.013	0.007	1500000	1.86	19500.0
XPS	0.01	0.025	170.56	0.40	1.7
Vapor Barrier	0.001	2.3	3280	0.00	3.3
Fiber Glass	0.089	0.035	1.3	2.54	0.1
OSB	0.011	0.115	1015.1	0.10	11.2
SBP Membrane	0.001	2.4	328.4	0.00	0.3
Stucco	0.019	0.399	355.7	0.05	6.8
Total				5.41	19525.1

The outside temperature and RH for the calculation were assumed from the yearly temperature and RH overview provided with the location weather file. The inside RH and temperature were similarly calculated from the inside temperature and RH overview provided with the weather file. The effective temperature drop was calculated using the following formula.

$$\frac{R - \text{Value (material)}}{R - \text{Value (total)}} * \text{Delta } T$$

Similarly the vapour pressure drop is calculated using the following formula

$$\frac{\text{vapour diffusion resistance (material)}}{\text{vapour diffusion resistance (total)}} * \Delta P$$

The results obtained from the temperature drop and pressure drop were used to calculate the effective drops in the material layers and the computed results are as given below in the table. From the results the effective RH was calculated and was compared with the results obtained from the WUFI simulations.

Material	Temperature		saturation pressure
	drop	surface	
Drywall		23.9	3396.6
	-0.10		
XPS		24.00	3417.1
	-0.60		
VIP		24.60	3540.9
	-2.78		
XPS		27.38	4168.5
	-0.60		
Vapor Barrier		27.98	4315.7
	0.00		
Fiber Glass		27.98	4315.8
	-3.81		
OSB		31.78	6321.7
	-0.14		
SBP Membrane		31.93	6381.5
	0.00		
Stucco		31.93	6381.8
	-0.07		
Outside		32.00	6411.7

Material	saturation pressure	vapor pressure		Effective RH
		drop	surface	
Drywall	3396.6		1188.8	35%
		0.00		
XPS	3417.1		1188.8	35%
		0.00		
VIP	3540.9		1188.8	34%
		34.64		
XPS	4168.5		1154.2	28%
		0.00		
Vapor Barrier	4315.7		1154.1	27%
		0.01		
Fiber Glass	4315.8		1154.1	27%
		0.00		
OSB	6321.7		1154.1	18%
		0.02		
SBP Membrane	6381.5		1154.1	18%
		0.00		
Stucco	6381.8		1154.1	18%
		0.01		
Outside	6411.7		1154.1	18%