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Final Report from Task 8 of MEWS Project (T8-03) - Hygrothermal Response of Exterior Wall Systems to Climate Loading: Methodology and Interpretation of Results for Stucco, EIFS, Masonry and Siding Clad Wood-Frame Walls

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Hygrothermal Response of Exterior Wall Systems to Climate Loading: Methodology and Interpretation of Results for Stucco, EIFS, Masonry and Siding-clad Wood-frame Walls

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TASK 8 – Outputs

Hygrothermal Response of Exterior Wall Systems to Climate Loading: Methodology and Interpretation of Results for Stucco, EIFS, Masonry and Siding-Clad Wood-Frame Walls

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Executive Summary

By 1997, several field surveys in North America had indicated that rain penetration in exterior walls and poor construction detailing contributed to the shortening of the service life of recently built exterior walls of low-rise buildings in climates with high exterior moisture loads. There was a movement in industry to rethink the ways that exterior walls had been put together in recent years, as well as a renewed appreciation that exterior climates vary in severity from one location to another.

In 1998, IRC/NRC initiated a research consortium with industry partners to develop guidelines for moisture management for exterior wall systems (MEWS) in low-rise residential buildings of North America. Partners represented the wood industry, manufacturers of cladding systems, insulation materials and water resistive barriers as well as building owners and managers. The project was broken down into several tasks, from a review of literature on current construction practice to experimental work in the laboratory and mathematical modelling. The following four types of cladding systems were included in the project: Portland cement plaster (stucco), Exterior Insulation and Finish Systems (EIFS), masonry and siding, over wood-frame construction.

This TG8 report is a research document. The objectives of the report are three-fold: to describe the research approach in some detail (chapter 1), to summarize its application to the four types of wall assemblies (chapters 2 - 5) and to draw general conclusions (chapter 6), based on the observations in chapters 2 - 5. The reader is strongly advised to consult the research team before the information presented in this report is used for building design considerations.

Hygrothermal Response of the Wall Assembly

2-D computer simulations (using IRC's program "hygIRC") and laboratory experiments were used to predict the hygrothermal response of walls subjected to climate inputs recorded for seven locations covering a wide range of climate severity. Each wall/location combination was re-run several times with different selections of material properties and assemblies to explore their relative effectiveness in dealing with different levels of moisture loads. The parameters studied thus included climate severity, material properties and configurations of wall components. The quantities of main interest from a durability standpoint were the hourly temperatures and relative humidities prevailing in moisture-susceptible regions of the wall assemblies, over a two-year period.

Chapters 2 - 5 illustrate the insights offered by hygIRC simulations and highlight important design considerations. Comparative performances of cladding systems using different moisture management strategies and different materials are the focus of discussion. Comparisons are based on the two-year histories of predicted RH and temperature for a target region in the wall, captured by a single-number indicator called RHT (defined below). The results of the parametric study discussed in Chapters 2 - 5 reveal the sensitivity of the integrated MEWS approach to variations in the characteristics of representative wall assemblies exposed to different climatic conditions found in North America.

Except for one "base case" for each wall/climate combination, all hygIRC simulations included a water leakage path to the stud cavity. The latter simulations demonstrated forensic applications for the MEWS method, as well as the vulnerability of a design to a particular breach in its defenses against water entry. **Although the leakage path was chosen to be plausible and not overly severe (removal of a short length of sealant around a wall penetration), it is not claimed to be the most common deficiency found in practice. Given the necessarily limited scope of the parametric study, it cannot be expected to address the concerns of specific design or analysis situations.**

Relative Humidity and Temperature (RHT) Index

It is widely accepted that building materials are subject to deterioration under the combined effects of temperature and moisture. The most deleterious conditions are those in which moderate or high temperature is coupled with high humidity for extended periods. The RHT index is a new indicator used to quantify and compare the localised hygrothermal response in a critical region of focus of the wall assembly. This index captures the duration of moisture and thermal conditions coexisting above a pair of threshold levels, say X and Y respectively, during an exposure of two years. RHT is defined as the summation of values at 10-day intervals, of (RH, % - X) multiplied by (Temperature, ˚ C – Y), only when both terms are positive. The resulting cumulative RHT value serves as a single-valued index of the hygrothermal response within the region of focus in the given wall over the two-year period of the simulation runs. Two insights from the RHT index are that two different walls with similar cumulative RHT values can still have very different hygrothermal responses over time and that climates or conditions that seem intuitively to be quite different can produce similar cumulative exposure to temperature and RH conditions.

Moisture index (MI), an Indicator of External Moisture Loading Severity

Within the scope of the MEWS project, the main environmental load is, of course, moisture, and for the majority of North American sites, rain plays the leading role, assisted by wind to get it onto the wall surface. The other side of the coin as far as external environment is concerned, is the potential for drying through evaporation. So in addition to rainfall and wind (strength and direction), climate data provides input on temperature and relative humidity as well as solar radiation and cloud cover. The wall system is the environmental separator used to maintain an even and comfortable climate indoors regardless of what happens outside. Two different types of environmental loadings need to be considered, outdoor and indoor, with the wall system in between. Wall performance depends partly on how indoor humidity (RH) and temperature are controlled, and the two loads are analogous to the external and internal wind pressures that determine the net air pressure load on the building envelope.

The basic approach developed in MEWS was to use a Moisture Index to describe the climate. The **MI** permitted a better comparison of moisture loads at various geographic locations than can be gained from the simple distribution of rainfall amounts. The Moisture Index is a function of two terms, the potential for wetting, the Wetting Index (**WI**) and the potential for drying, the Drying Index (**DI**). The higher the value of the **MI**, the more severe is the moisture loading. For this study the **WI** was based on annual rainfall while the **DI** was based on annual potential evaporation. A provisional climatic zoning map of North America based on **MI** was devised, as a byproduct of MEWS research. MI was calculated for 383 North American locations to produce five climate zones varying in moisture load severity.

The Parametric Study

The parametric study investigated the hygrothermal response of different wall assemblies when subjected to exterior moisture loads on the cladding, as well as into the stud cavity when a specific deficiency in the wall assembly provided a water leakage path to the stud cavity. Functions for estimating hourly amounts of water leaking into the stud cavity (referred to as "1Q set of hourly moisture loads") were derived from laboratory experiments on several large-scale wall specimens with and without deficiencies, subjected to simultaneous water spray and air pressure differential simulating wind-driven rain. Specifying a representative deficiency was a challenge, given the many possible variations in the field, as well as a lack of information about them. A length of missing sealant (i.e. 45-50 mm) at the junction between a cover plate for a through-the-wall penetration (duct or electrical receptacle) and the cladding was used for establishing the water driving functions. Most of the parametric study predicting the effect of changes on the wall hygrothermal response was done using a 1Q set of moisture loads in the stud cavity. As trends in RHT(95) wall response started to emerge, it became apparent that a 1Q set of moisture loads tended to oversaturate the wall in climates other than warm and dry. At this level of Qs, several parameters made little difference in the net drying of the wall, and hence in the RHT(95) response of walls exposed to climates with higher MI. To reflect this finding, the last part of the parametric study on vinyl-siding clad wall systems was slightly redesigned to reduce the moisture loads to a quarter of the original 1Q set of moisture loads in the stud cavity. At such reduced moisture loads in the stud cavity, changing the characteristics of some of the parameters started to have a net effect on the drying of the wall assembly and on the RHT(95) hygrothermal response of the wall.

The hundreds of simulations with hygIRC revealed the effects of each input condition and material property, on the predictions of hygrothermal response, giving considerable confidence in the efficacy of the MEWS method. Although the input conditions and properties represented the best attempts of researchers (with input from MEWS partners) to deal with practical situations, the primary objective was to develop the prediction method, not to cover all practical cases, and **not to present definite guidelines for design**. Despite the large number of simulations done, of which Chapters 2 -5 give a summary appreciation, they merely scratched the surface of the situations of interest to the industry and to the owners and occupants of buildings. Chapter 6 provides highlights of the trends observed for the hygrothermal response to moisture loading of the four types of wall systems investigated.

As is often the case with research, the results brought into focus further questions about its application to the original objectives. Certain tasks proved more difficult and time-consuming than anticipated and are still ongoing. Until they are completed, it would be premature to suggest that a comprehensive guide to moisture management of walls has been achieved.

Introduction

Water is the single factor that most affects the durability of building materials and components. Sources of water that can end up in walls include rain, snowmelt, condensation of water vapour in the outside and inside air, and migration of soil moisture (not to mention leaky pipes or roofs). Building materials can also take up water if exposed to the weather during construction. How effectively moisture is managed by exterior walls is therefore of prime importance in assuring their long-term performance. As the severity of the climate increases, so should the margin of safety (or redundancy) in the building envelope system. An integrated research approach to moisture management recognises that the performance of the wall assembly will be affected by:

- the characteristics of outdoor and indoor climates
- the heat and moisture storage and transmission capacities of the materials making up the assembly, as well as the level of redundancy in the moisture management strategy selected for it
- the moisture management strategy applied in other parts of the building envelope (e.g. windows, roof, horizontal projections, soffits). This will affect the moisture loading of the wall.

In 1998, IRC/NRC initiated a research consortium with industry partners to develop guidelines for moisture management for exterior wall systems (MEWS) in low-rise residential buildings of North America. Partners represented the wood industry, manufacturers of cladding systems, insulation materials and water resistive barriers as well as building owners and managers. The project was broken down into several tasks, from a review of literature on current construction practice to experimental work in the laboratory and mathematical modelling. The following four types of cladding systems were included in the project: stucco, Exterior Insulation and Finish Systems (EIFS), masonry and siding, over wood-frame construction.

This TG8[1] report is a research document. The objectives of the report are three-fold: to describe the research approach in some detail (chapter 1), to summarize its application to the four types of wall assemblies (chapters 2 - 5) and to draw general conclusions (chapter 6), based on the observations in chapters 2 - 5. The reader is strongly advised to consult the research team before the information presented in this report is used for building design considerations.

Chapters 2 - 6 illustrate the insights offered by hygIRC simulations and highlight important design considerations. Hygrothermal wall responses for each cladding system using different moisture management strategies and different materials are the focus of discussion. The comparisons were based on two-year histories of predicted RH and temperature for a target region in the wall, summarised by a single-number indicator called RHT. The results of the parametric study discussed in Chapters 2 - 5 reveal the sensitivity of the integrated MEWS approach to variations in the characteristics of representative wall assemblies exposed to different climatic conditions found in North America.

Except for one "base case" for each wall/climate combination, all hygIRC simulations included a water leakage path to the stud cavity. The latter simulations demonstrated forensic applications for the MEWS method, as well as the vulnerability of a design to a particular breach in its defenses against water entry. Although the leakage path was chosen to be plausible and not overly severe (removal of a short length of sealant around a wall penetration), it is not claimed to be the most common deficiency found in practice. Given the necessarily limited scope of the parametric study, it cannot be expected to zero in on the concerns of specific design or analysis situations.

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[1] Throughout this report TG is an abbreviation for Task Group.

Chapter 1. An Integrated Research Approach to Moisture Management

1.1 Summary

A method was developed to predict the relative hygrothermal response of exterior walls to moisture loads in various climates. This method includes the following steps:

- characterize exterior moisture loads through analysis of climate records
- ascertain how materials work together in wall assemblies, through laboratory testing and literature review
- establish hygrothermal properties of common wall materials by laboratory testing
- estimate water leakage rates into wall systems under simulated wind-driven rain conditions using IRC's Dynamic Wall Testing Facility
- based on reliable input from the first four steps, undertake a parametric study of the moisture and temperature balances in walls, using IRC's 2D computer model, hygIRC. This includes i) selecting years of climate records for three years of simulation runs ii) developing an indicator of the hygrothermal response of the wall iii) estimating moisture loads on a vertical wall of a certain height iv) selecting wall materials and combinations of interest to the industry.

Exterior Climate Loads

A climate index called Moisture Index (MI) has been developed based on the wetting and drying potentials offered by local climates. The MI comprises a Wetting Index based on annual rainfall and a Drying Index based on the vapour pressure of the outside air. The MI values vary from 0 to 1.4. A provisional contour map based on MI values for about 400 North American locations proposes five zones of varying severity (from the standpoint of moisture management).

Wall Assemblies

Wood frame walls with four commonly used cladding systems and different moisture management strategies were selected for lab testing and parametric study. These cladding systems were: Portland cement plaster (stucco), Exterior Insulation and Finish System (EIFS), masonry and siding (vinyl and hardboard). A literature review highlighted the significance of water leakage paths that can show up in service, circumventing the intended moisture management strategy. A water leakage path (called a deficiency, since this is a deviation from the design intent) was introduced in each wall assembly. Imperfections in the wall assembly allowing water to enter the stud cavity is an important feature of the application of the method in the MEWS project.

Hygrothermal properties (e.g. liquid diffusivity and water vapour permeability) unavailable for certain materials making up the wall assemblies were measured using established experimental and analytical procedures and were added to a database for the MEWS project. It is intended that this database be made public.

Wetting of Cladding

A procedure was developed to estimate on an hourly basis the exterior moisture loads deposited on a vertical flat wall of a given height and orientation, based on three different years of historical climate records (called "climate years") for a given location. The selection of climate years used in this parametric study was based on a variant of the MI calculation procedure mentioned above, which takes into account the predominant direction of wind-driven rain for each of seven locations representing the range of climate severities across North America.

Water Leakage into the Stud Cavity

Rain entry through deficiencies providing a path to the stud cavity imposed increased moisture loads on sensitive internal elements of wall cladding systems. Large-scale wall specimens with and without a deficiency providing such path were subjected to air pressure loadings (simulating wind) and spray rates (simulating rain) to measure the quantity and destination of water flowing in. The deficiency consisted of a missing portion of a filet bead of sealant at the joints between the cover plate of a through-the-wall penetration such as an electrical outlet or a vent duct and the face of the cladding.

Hygrothermal Response of the Wall Assembly

2-D computer simulations served as the basis for the prediction of the hygrothermal response of a particular wall subjected to two years of climate inputs recorded for seven locations covering a large range of climate severities. Each wall/location combination was re-run several times with different selections of material properties and assemblies to explore their relative effectiveness in dealing with different levels of moisture loads. The parameters studied thus included climate severity, material properties and configurations of wall components. The quantities of main interest from a durability standpoint were the hourly temperatures and relative humidities prevailing in moisture-susceptible regions of the wall assemblies, over the two-year period.

Attention was focussed on temperature and moisture conditions in a small region of a moisture-sensitive material, deemed to have the greatest chance of showing damage first. Although research has not yet been completed to determine precisely what levels and duration of moisture and temperature are necessary for the onset of damage, two levels were used for the simulations documented in chapters 2 - 5. A one-number indicator for summarizing the moisture/temperature/duration state of the region of focus (ROF) for each two-year simulation was developed: the RHT index.

The RHT Index was computed from the following equation, in which the temperatures, T (ºC), and relative humidities, RH (%) predicted within the grid area making up the ROF, were sampled at 10-day intervals and averaged. Two years of a simulation run provided 73 sets of such computations that were summed up to become the single-digit RHT index:

$$RHT(X) = \Sigma\,(RH - X)\cdot(T - 5) \qquad (1)$$

An essential feature of equation 1 was that each of the bracketed terms was taken as 0 when it was not positive. Unless RH exceeded the value X, and T exceeded 5 º C, at the end of a 10-day period, this period did not contribute to the summation. Values of X for the two levels used in MEWS were 80% for corrosion (e.g. of metal fasteners), and 95% for the growth of wood decay fungi. A temperature threshold of 5 ºC was considered appropriate for both damage processes.

Tables of RHT(80) and RHT(95) results for more than 100 simulations per wall type appear in appendices in chapters 2 - 5, and subsets of RHT(95) relating to particular parameter variations formed the basis of observations in the main body of each chapter. Wood decay seemed the better target for these discussions because of the relevance to materials being modeled, but some MEWS partners also showed keen interest in a detailed discussion of RHT(80) as well.

RHT(80) and RHT(95) are just two of many possible indicators of the relative hygrothermal response of different wall assemblies in various climates. Varying the RH threshold restricts attention to moisture conditions appropriate for different damage processes, but at the same time, alters the scale of the RHT indicator. RHT(80) values were generally about 6 times larger than the corresponding RHT(95) values. This suggested that relative differences may be more useful for comparisons among simulation results than the values themselves.

1.2 The Overall Approach

At the time the MEWS project was developed in 1997, several field surveys in North America indicated that rain penetration in exterior walls and poor construction detailing contributed to the shortening of the service life of recently built exterior walls of low-rise buildings in climates with high exterior moisture loads. There was a movement in industry to rethink the ways that exterior walls had been put together in recent years, as well as a renewed appreciation that exterior climates vary in severity from one location to another.

Effective moisture control in the building envelope is essential if acceptable service life is to be achieved for the built environment. Effective moisture control implies both minimizing moisture entry into the system, and maximizing the exit of moisture that does enter, so that no component in the system stays "too wet" for "too long". But what is "too wet" and "too long"? The MEWS research project provided an integrated approach for the prediction of the hygrothermal performance of four types of cladding over wood-frame walls of residential buildings. This approach was used to gain insight into the comparative benefits of changes to the material properties and to the design of the wall assembly on the hygrothermal response of the wall, for a variety of levels of severity in climates as well as in the deficiencies allowing water to bypass the cladding system. This approach is depicted schematically in Figure 1.1 and will be explained in this chapter.

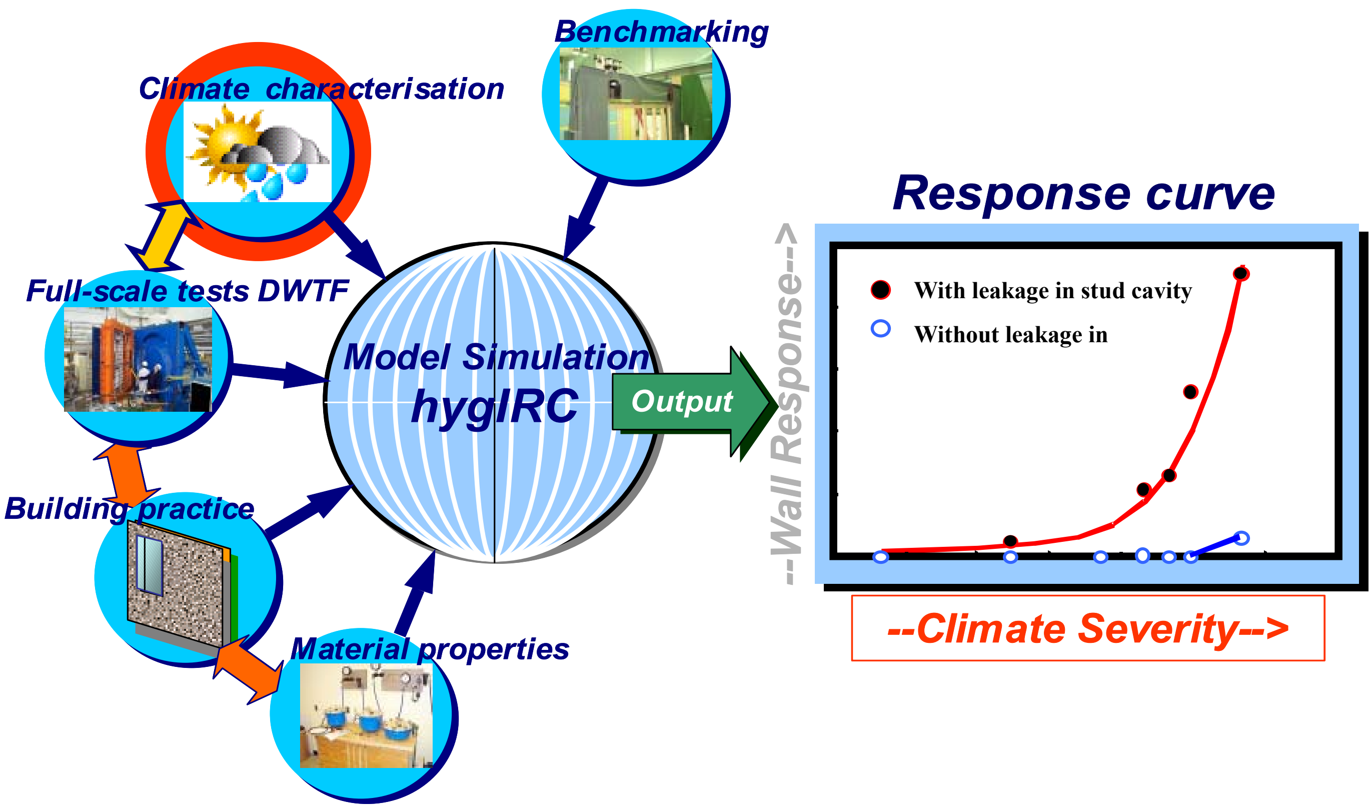


Figure 1.1. Schematic of MEWS integrated research approach carried through the project

Prediction of the hygrothermal response of a wall required an understanding and characterization of the three major components involved: the outdoor climate, the indoor climate and the wall assembly that acts as an environmental separator between them (Figure 1.2).

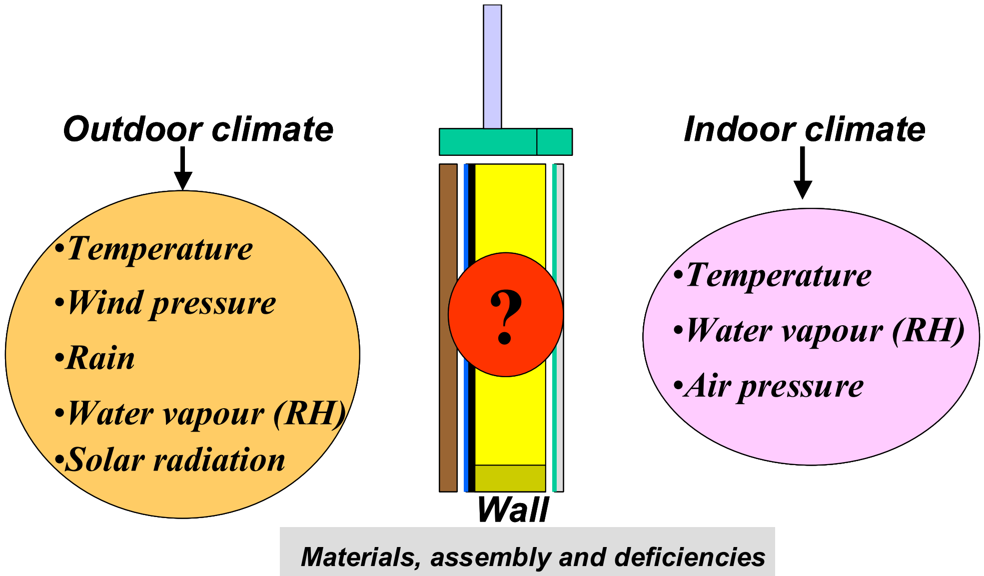


Figure 1.2 An exterior wall as an environmental separator between outdoor and indoor climates

The development of an integrated research method for moisture management for exterior wall systems included these tasks:

- definition of wall types,
- determination of material properties,
- assessment of exterior (and interior) climate loads,
- assessment of the moisture loads leaking into a wall assembly,
- description of moisture and temperature conditions heralding the onset of damage,
- parametric study of simulations to predict hygrothermal response of the four walls.

Each of the following sections describes briefly how each task was tackled and how it fed into the MEWS approach. Research reports describing in detail the methodology and the results for each of these tasks were published under separate covers.

1.3 Assessment of the Outdoor Climate

1.3.1 Characteristics of Outdoor Climates

The consideration of moisture sources and strategies for managing these really amount to designing the wall for durability, so that it remains serviceable for its desired service life. Designing for durability has some things in common with designing for strength to resist wind loads. Like wind, rain is an environmental load defined by the climate of a particular region. In fact, the real concern is rain in the presence of wind, without which very little rain would reach the wall surface. Raindrop trajectories depend on wind flow around the building, and to some extent on flow over structures and topographical features upwind. And like wind pressure, intensity of rain capture varies with position on the windward wall.

Because of their random variations over time and space, both wind and rain loads require statistical treatment of many years of climate records to derive design loads. Structural design is based on a single extreme wind load, with a suitably low risk of being exceeded during the life of the structure. This is achieved in the National Building Code Canada for cladding as follows: the minimum allowable basic design pressure is listed in Appendix C, Climate Information for over 650 municipalities as the hourly wind pressure with 1 chance in 10 of being equaled or exceeded in any year.

Durable design, on the other hand, requires estimation of the whole history of rain loading over the service life of the wall in question, and not just a single wind pressure. The required statistical treatment still must be based on many years of climate records, and in addition, must take account of the coincidence of wind and rain, and possibly wind direction as well. Clearly, the need for statistical assessment of rain loading is even greater than in the case for wind alone, and the questions to be answered are more complex. The implication for design is that statistical variations of outdoor climate parameters, including wind driven rain, are a major part of the unavoidable variability, or uncertainty, in the predicted performance of a wall system, no matter what guidelines or methods are used in making the prediction.

1.3.2 MI, an Indicator of External Moisture Loading Severity

Within the scope of the MEWS project, the main environmental load is, of course, moisture, and for the majority of North American sites, rain plays the leading role, assisted by wind to get it onto the wall surface. The other side of the coin as far as external environment is concerned, is the potential for drying through evaporation. So in addition to rainfall and wind (strength and direction), climate data provides input on temperature and relative humidity as well as solar radiation and cloud cover. The wall system is the environmental separator used to maintain an even and comfortable climate indoors regardless of what happens outside. Two different types of environmental loadings need to be considered, outdoor and indoor, with the wall system in between. Wall performance depends partly on how indoor humidity (RH) and temperature are controlled, and the two loads are analogous to the external and internal wind pressures that determine the net air pressure load on the building envelope.

Climate loads vary from hour to hour, season to season and year to year. Climates also vary within North America from region to region. Russo[i] partitioned the U.S. into 6 different climate types for the construction industry according to temperature (hot, >-1.1°C, mild, and cold, <-9.4°C) and precipitation (wet, >508-mm/yr, or dry). Russo's classification gives an interesting historical perspective on MEWS TG 4 work to select representative climates for TG 7 predictions of the wall hygrothermal response. TG 4 looked for additional climate characteristics relating to wall performance, but the decision was taken to do this independently of the characteristics of the wall (see below).

The basic approach developed in MEWS was to use a Moisture Index (MI) to describe the climate. The **MI** permitted a better comparison of potential moisture loads than the simple distribution of rainfall amounts[ii]. The Moisture Index is a function of two terms, the potential for wetting, the Wetting Index (**WI**) and the potential for drying, the Drying Index (**DI**). The higher the value of the **MI**, the more severe is the moisture loading. For this study the **WI** was based on annual rainfall while the **DI** was based on annual potential evaporation. Ideally, **MI** should take into account all the climate factors that affect the variation in performance of any wall system when exposed to different climates. For wide applicability, **MI** was deliberately made independent of wall characteristics and design strategies that might be used to manage moisture loading. At the outset, only wetting and drying were considered. If other damage mechanisms, such as freeze-thaw damage, are to be considered, additional statistical treatment of the climate data will be needed for wall components. The combined Moisture Index was used to classify North America into zones, and also to choose specific locations in these zones. To assign rankings on the basis of climate analysis for several locations in North America, the following definition was used (details available in Task 4 final report):

$$MI = \sqrt{WI_{normalized}^2 + (1 - DI_{normalized})^2} \qquad (1)$$

Table 1.1 lists the MI for 41 North American locations, calculated with hourly historical weather records, using equation (1).

Table 1.1 : Moisture Index calculated with hourly weather records for 41 North American locations

Location	MI	Location	MI
Mobile AB	1.22	Tampa FL	0.95
New Orleans LA	1.21	Madison WI	0.95
St Johns NF	1.17	Windsor ON	0.94
Shearwater NS	1.15	Montreal QC	0.94
Wilmington NC	1.13	Ottawa ON	0.93
Vancouver BC	1.09	Kansas City MO	0.93
Miami FL	1.08	St. Louis MO	0.92
Atlanta GA	1.06	Toronto ON	0.92
Orlando FL	1.03	Minneapolis MN	0.90
Boston MA	1.01	Edmonton AB	0.89
Houston TX	1.01	Winnipeg MB	0.86
Victoria BC	1.00	San Francisco CA	0.86
Fredericton NB	0.99	Fargo ND	0.85
Seattle WA	0.99	Calgary AB	0.81
Wilmington DE	0.98	Fort Worth TX	0.79
Raleigh NC	0.97	San Diego CA	0.74
Iqaluit NU	0.97	Colorado Springs CO	0.70
Charlotte NC	0.96	Fresno CA	0.49
Baltimore MD	0.96	Phoenix AZ	0.13
Chicago IL	0.95	Las Vegas NV	0.11
Pittsburgh PA	0.95		

Out of these forty-one locations, seven were selected for the parametric study. Two cities from the top third of the ranked list, two from the middle third and three from the bottom third of the list were selected for more in-depth analysis (see shaded locations in Table 1.1). Table 1.2 provides the range of climate types covered by this selection of locations.

Table 1.2 : Location and Climate Characteristics for seven selected locations

Location	Main Driving-Rain Direction	Climate Type (Russo)	Rank, MI_{hourly}
Wilmington NC	North	Warm, Wet	1.13
Seattle WA	South	Mild, Wet	0.99
Ottawa ON	East	Cold, Wet	0.93
Winnipeg MB	North	Cold, Dry	0.86
San Diego	South	Hot, Dry	0.74
Fresno	East	Hot, Dry	0.49
Phoenix AZ	East	Hot, Dry	0.13

1.3.3 Provisional Climate Zoning for North America

The provisional climatic zoning of North America based on **MI** was a byproduct of MEWS research. MI was calculated for 383 North American locations (using annual climate normals instead of hourly records) to produce the five climate zones shown in Figure 1.3. Annual records were used because of the large number of locations to process, but this does result in minor differences in **MI** from those based on hourly data (Tables 1.1, 1.2). The red zones see the most severe moisture load, followed by the orange zones, the yellow zones and then the green zone. The blue zone exhibits the lowest external moisture load (Table 1.3). The current zone boundaries are arbitrary; further research relating the performance of various wall systems within and between climate zones should provide useful insights for improvements.

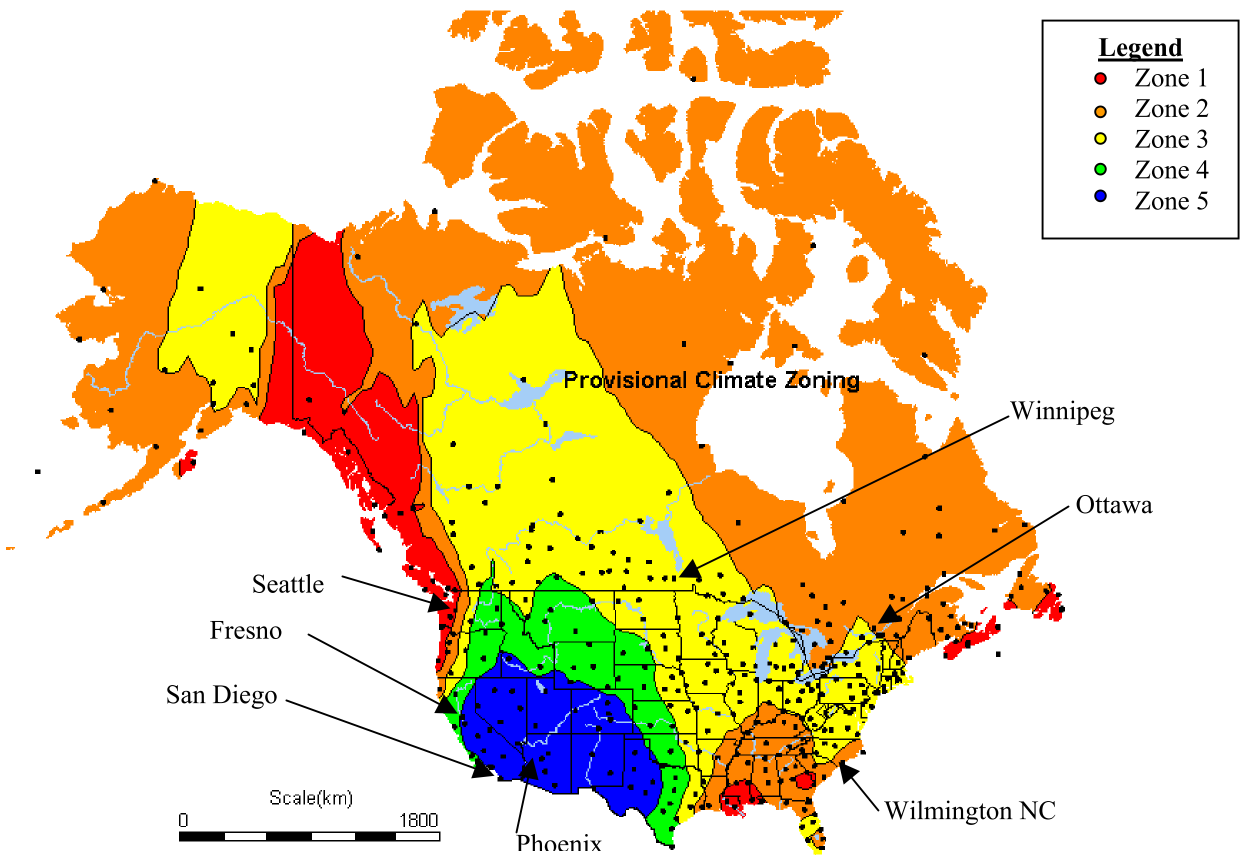


Figure 1.3. Provisional climate zoning map of North America based on the Moisture Index using normal climate records

Table 1.3: Moisture Loading Limits Corresponding to Figure 1.3

Division	Classification based on Moisture Loading	Colour
MI greater or equal to 1.0	Zone 1	Red
MI greater or equal to 0.9 but less than 1.0	Zone 2	Orange
MI greater or equal to 0.8 but less than 0.9	Zone 3	Yellow
MI greater or equal to 0.7 but less than .0.8	Zone 4	Green
MI less than 0.70	Zone 5	Blue

To calculate the MI of hundreds of locations required for mapping North America, it was more practical and less time-consuming to use climate normals (averaged annual data based on three or more decades of data) as opposed to using hourly climate records, as previously done for a smaller number of locations. Please note that a different normalization scheme was used to generate the map (Task 4 Final report). Consequently there are differences between the $MI_{normals}$ used to build the map and the MI_{hourly} used in the parametric study. For example Wilmington NC has a MI of 1.13 calculated using hourly climate records and an MI of 0.96 based in climate normals. This difference does not affect the results or interpretation of the parametric study presented in Chapters 2-5.

1.3.4 Selecting Annual Sets of Climate Records for the Parametric Study

Once the seven representative locations were selected from the original 41 candidate locations, representative annual sets of historical climate records (called "reference years") were chosen for each location. The MEWS parametric study spanned three years of predicted wall hygrothermal response, and it was decided that three different reference years would be used: a Wet, a Dry and an Average year. The hourly data from each chosen reference year would then be used as input to hygIRC. Because the mathematical model can take into account wind direction, the Wetting Index (**WI**) was redefined to rank the years according to how much rain would be deposited on a vertical one-storey high wall (not just rainfall on a horizontal surface, as before). The Wetting Index was defined as the total amount of wind-driven rain impinging on a wall in the predominant direction of wind-driven rain for a year. Note that climate records distinguish between rain and snow (all forms of moisture are reported as precipitation, not rainfall), and WI was based on records of rain only. The year with the highest ranking was defined as the *wet* year (e.g. Wilmington NC 1984), the year with lowest ranking was defined as the *dry* year (e.g. Wilmington NC 1990), and the year with the ranking closest to the mean was defined as the *average* year (e.g. Wilmington NC 1988). The predominant direction of rainfall was determined by calculating the total amount of rain over 30 years or more impinging on a wall rotated through the four cardinal orientations. The orientation with the highest total amount of rain was selected as the predominant direction. Table 1.4 shows how the predominate direction was determined in the case of Wilmington NC. Six different methods were tried and were all in general agreement. Straube's method was selected as the final definition of the Wetting Index for selecting moisture reference years. The definition of the Drying Index remained unchanged.

Table 1.4: Determination of the Predominate Direction of Wind-Driven Rain

Location: Wilmington NC	**Years = 22**	**Orientation**			
Method		**North**	**East**	**South**	**West**
Total Straube mm/m^2		9369	8472	9251	2784
Total Lacy mm/m^2		9871	8987	9862	2821
Total LIF mm/m^2		6846	6260	6911	1913
Total UK method mm/m^2		5422	5000	5568	1438
Total AHM mm/m^2		3525	3220	3547	988
Total dDRI m^2/sec		54.33	50	55.68	14.37

Hourly climate records with seven weather characteristics for each of the seven locations for three selected years (*Wet*, *Average* or *Dry*) were inputs for MEWS parametric study using hygIRC computer model (see example in Table 1.5).

Table 1.5 : Typical Exterior Climate Data Format

Time (hr)	Temp-erature (°C)	Relative humidity (%)	Wind velocity (km/hr)	Wind direction (°)	Radiation (W/m^2)			Rain (mm/hr)	Cloud Index
					Direct	Diffused	Reflective		
104	5.6	83	11.16	280	9	0	9	0.254	10
105	5	89	9.36	270	37	24	32	0.762	10
…..	……..	……….	…….	……..					

1.3.5 The Indoor Climate

The interior room climate was represented by two parameters: temperature (T) and relative humidity (RH). Interior room T and RH were switched from winter values of 22ºC, 25% (when mean monthly outdoor temperature was less than 11ºC) to summer values of 25ºC, 55% for the warmer months, following the ASHRAE criterion [iii iv]. A few more cases with increased RH values during winter and summer (up to 40 and 75% respectively) were also investigated.

1.4 Wall Assemblies for Investigation

The MEWS project focused on wood-frame wall systems for low-rise residential buildings (up to four storeys high). The selection of the generic types of walls (defined by their cladding systems) was made early on in the project and was based on the common interest of all parties participating in the consortium. Walls with the following cladding systems were included: stucco, masonry, Exterior Insulation and Finish Systems (EIFS) and siding (hardboard and vinyl).

1.4.1 Full-Scale Wall Specimens Built for Laboratory Investigation of Water Penetration

A review of the literature and discussion with industry specialists of the consortium contributed to the definition of several moisture management strategies used in exterior wall assemblies of interest (TG2). The review of current practice was used to determine the composition and detailing of full-scale wall specimens for laboratory investigation of water penetration under simulated wind-driven rain conditions in the IRC Dynamic Wall Testing facility (TG6). Also the materials making up these wall assemblies of interest were subjected to a battery of tests that determined their hygrothermal properties (TG3), as these constituted another input file for the parametric study (see section 1.4.2).

Seventeen (17) full-scale wall specimens were included in the water entry evaluation testing: 5 stucco-clad, 5 EIFS, 4 masonry and three siding (2 hardboard and one vinyl) specimens. The specimens within a generic cladding group were different in either their design, the selection of materials or detailing at interfaces. Examples of the composition and detailing of the specimens are given in Figures 1.4 and 1.5. The description of the as-built test specimens (with deficiencies) was presented in the T2-02 MEWS report entitled: "*Description of the 17 Large-scale Wall Specimens Built for Water Entry Investigation in IRC Dynamic Wall Testing Facility",* August 2002.

A recent field survey of failures stressed the importance of the design and construction of the interfaces between walls and other components (i.e. windows, ducts and decks) for the control of rain ingress [v]. Imperfections in the wall assembly providing a water leakage path to the stud cavity became an important feature of the application of the research method applied in the MEWS project.

A water leakage path (called a deficiency, since this is a deviation from the design intent) was introduced in each wall specimen at the interfacing joint between the wall and a window frame, a vent duct or an electrical outlet inserted in the specimen (See examples in Figures 1.6 and 1.7). The TG2 review had highlighted the significance of water leakage paths that can show up in service, circumventing the intended moisture management strategy, exposing the moisture-sensitive materials located further into the wall to moisture loads these materials are not designed to sustain for long periods. Deficiencies[2] within a wall assembly can develop at the design stage (material selection, detailing of assemblies), during construction (material abuse, substitution, detailing & sequence of construction) and during service life (maintenance, exposure). Certain deficiencies present in wall materials and assemblies can have a significant effect on the amount of water that enters the assembly, the amount of water that drains out and the amount of water that remains within the assembly, as well as the locations of accumulation.

1.4.2 Material Properties

The following material properties were measured or derived in the laboratory: water vapour permeability, air permeability, liquid diffusivity, sorption characteristics and suction pressure, dry density, heat capacity and thermal conductivity. Manufacturers supplied the materials; as for site-applied materials (such as stucco and EIFS), they were either fabricated along with the large-scale specimens, or pieces were cut out from these specimens months after rain entry testing was completed. All materials included in the mathematical simulations work (TG7) were analysed for the characterisation of their properties (see MEWS report T3-23 entitled: *Hygrothermal Properties of Several Building materials*", March 2002.

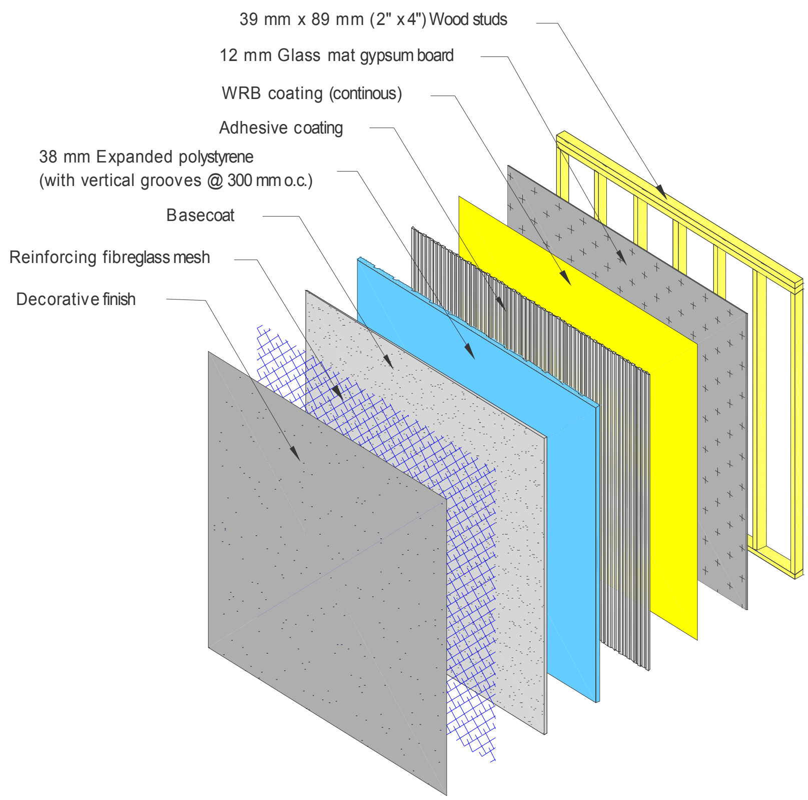


Figure 1.4 Composition of an EIFS-clad wall specimen used for DWTF investigation

[2] For the purpose of the MEWS project, a *deficiency* in a wall assembly was defined as a characteristic of a material or of an assembly of materials that prevents the material or the assembly from fulfilling its function in the context of a given moisture management strategy for the walls. Most likely, a deficiency will provide a water entry path towards the inside of the wall. This in itself may or may not lead to the deterioration of building materials; the outcome will depend on the drying potential of the wall (that in turn is a function of the climate and the construction of the entire wall assembly.

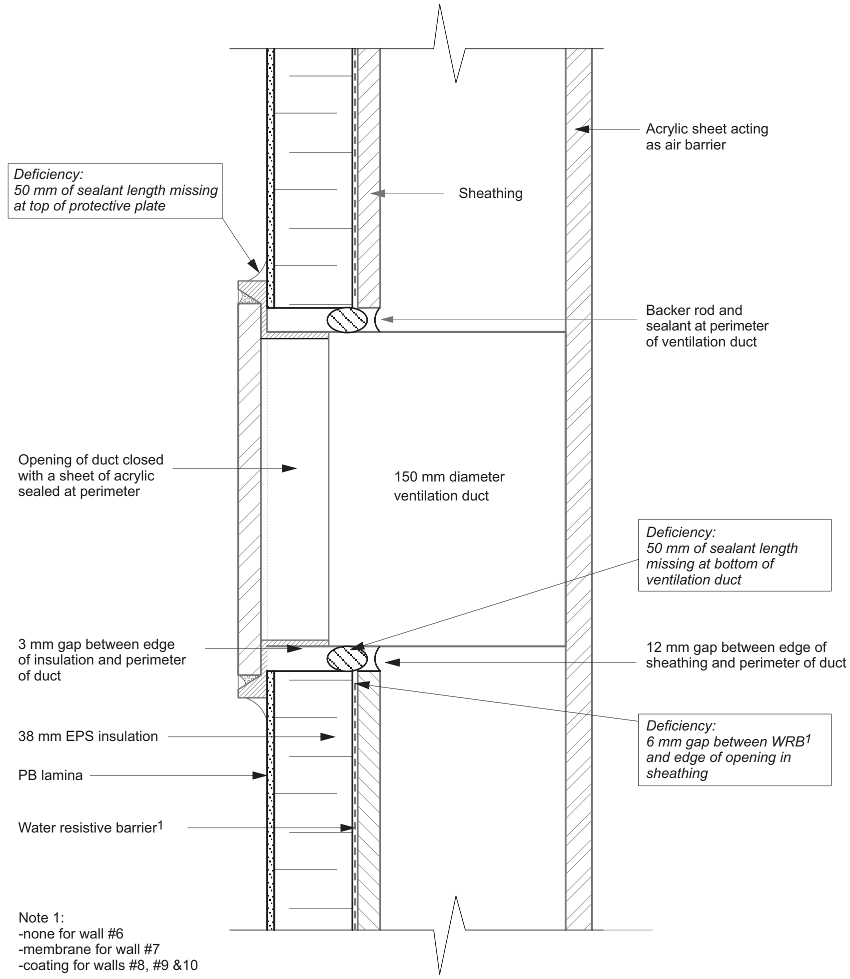


Figure 1.5 Example of the detailing at the duct/wall interface for an EIFS-clad specimen – Vertical section

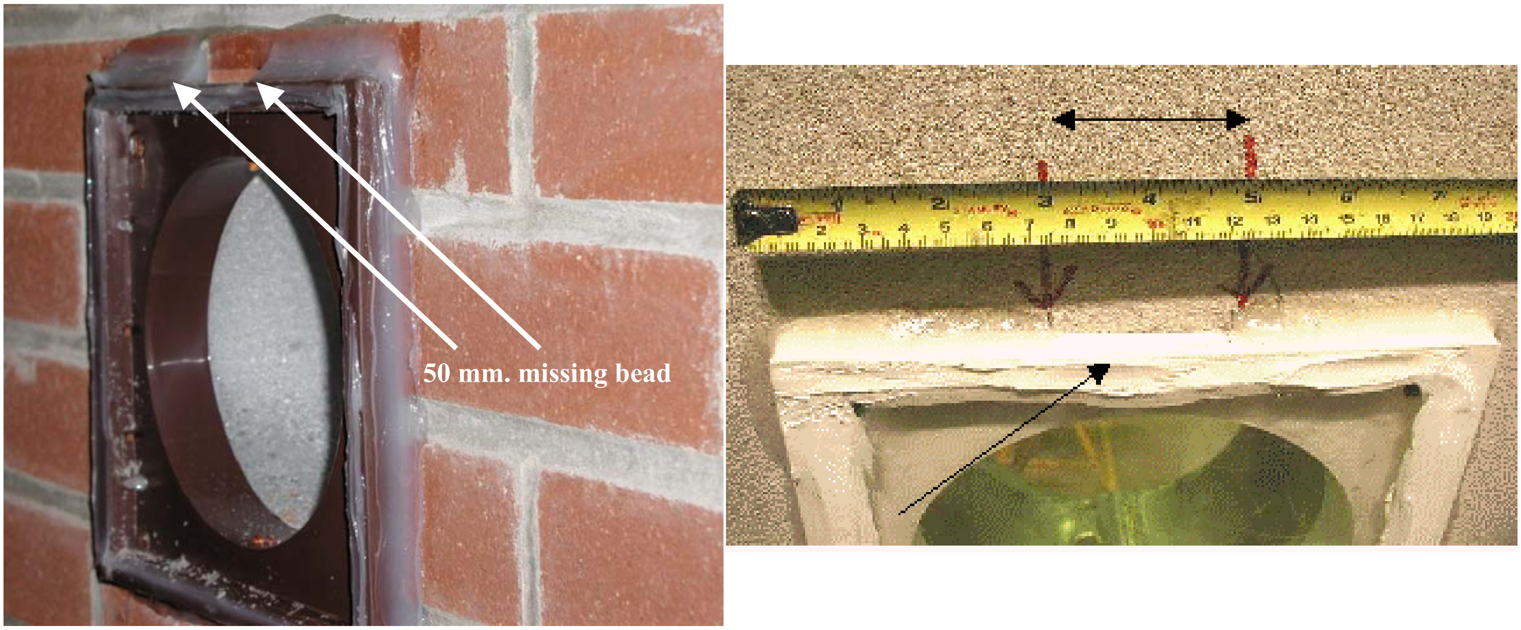
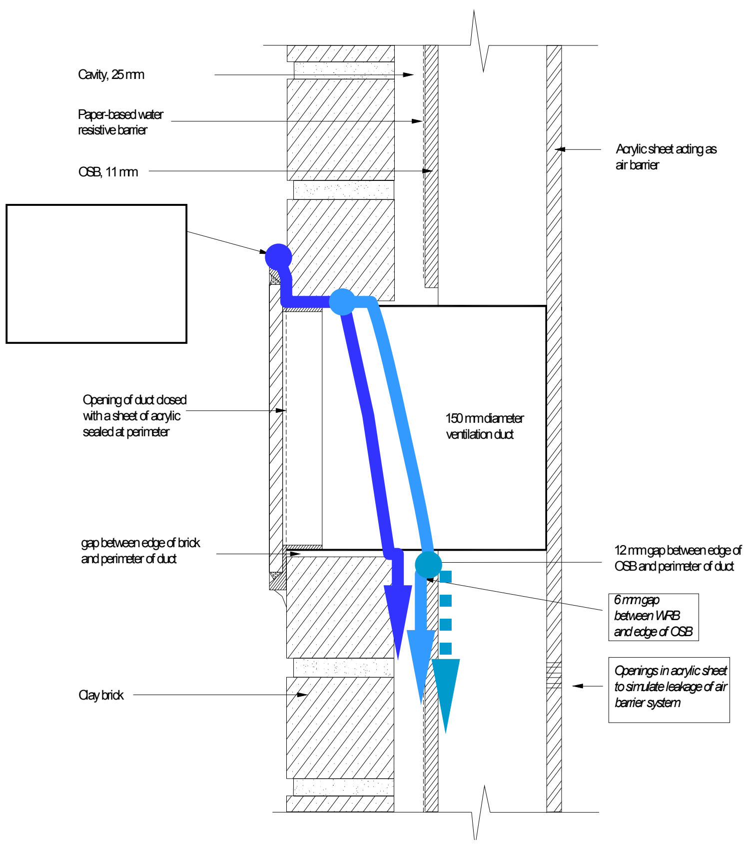


Figure 1.6 Examples of a missing length of a bead of sealant (deficiency) at the cladding/duct cover plate joint in a masonry wall specimen



Vertical section

Figure 1.7 Example of a water leakage path from the external deficiency at the face of the cladding to the various cavities of the wall assembly

1.5 Estimation of Moisture Loads

Since the MEWS interest was in the hygrothermal response of wall cladding systems to moisture loading, the first task was to define the moisture loads as a function of climatic conditions at various North American locations. This was a three-step process:

1) determine the moisture load imposed by a given climate,
2) determine the proportion of that load that can reach the face of the wall and
3) for each cladding system, characterise the additional water loading directly into the stud cavity due to a given water leakage path at any through-the-wall penetration, including the known deficiency.

1.5.1 Climate Moisture Load

The moisture load was determined from the climate data provided by Task Group 4: *Environmental Conditions*. The important parameters were: 1) horizontal rainfall and 2) wind speed and direction. Section 1.3 covers the characterization of the outdoor climate and the selection of climate reference years.

1.5.2 Rain Loads on a Wall

The next step in assessing the moisture load was to relate the horizontal rainfall intensity to the wetting of the wall. External walls receive very little rain in the absence of wind (unless water from the roof is directed onto the wall because of faulty flashings or downspouts, or splashing on horizontal projections). Wind-driven rain, however, is another matter. The basic way of assessing the rain falling through a vertical plane is to calculate the driving-rain index (DRI). The DRI is simply the product of horizontal rain intensity and wind speed. Lacy[vi] proposed a method for evaluating the intensity of wind-driven rain on vertical walls based on many years of observation. His method is a simple modification of the Driving-Rain Index and is given below.

$$WDR = 0.222 * V(h) * r_h^{0.88} \quad (2)$$

where: WDR is the wind driven rain passing through a vertical plane (l/m^2-h)
0.222 is a proportionality and units conversion constant.
r_h is the horizontal rainfall intensity (mm/m^2-h)
V(h) is the wind speed at the height of interest (m/sec)
0.88 is a raindrop size factor.

The rain passing through a vertical plane is not the same thing as rain falling onto the wall of a solid building. As the wind approaches the building, the streamlines are diverted upwards to pass over the roof, and to either side. Depending on the building shape, the size of rain droplets, the strength of the wind and the angle of incidence, rain intensity can vary over the windward wall from light near the bottom and middle to heavy along the top and sides.

One method of deriving wind-driven rain, knowing wind speed and direction as well as horizontal rainfall, was that proposed by Straube[vii]. His method is an elaboration of Lacy's equation[vi]. For walls partitioned into a grid of zones, intensity factors for each zone have been obtained from rain gauges on real buildings[vi], and from computer studies of wind-driven rain on isolated building models[viii]. The UK standard uses a series of factors to account for terrain roughness and topographical effects, and nearby obstructions, in addition to a zone factor for the effect of the building [ix]. As these extra factors would unduly complicate the simulation process, Straube's simpler approach was adopted, using a "Rain Admittance Factor" of 0.4. This is consistent both with Straube's field measurements, and with the BRI zone factor, for the central zone at mid-height of a one-storey building, i.e. 1.8-m. It should be noted that the various methods for computing the rain load on walls are all in general agreement. This is shown in Table 1.4 that shows a sample calculation for Wilmington NC.

Straube's method as used in the MEWS project is summarised below.

Rainload on a wall, R_w (L/m^2) = RAF * DRF(R_h) * cos (Θ) * V(h) * R_h, (3)

RAF is the rain admittance factor

DRF(R_h) is the driving rain factor (akin to Lacey's 0.222, depending on rain drop size and its terminal velocity)

R_h is the horizontal rainfall intensity (mm/h = L/m^2-h)

V(h) is the wind speed at the height of interest, i.e. 1.8 m (m/s)

Θ is the angle of the wind to the wall normal

1.5.3 Moisture Ingress into the Wall Assembly

The final step in assessing the moisture loading was to characterise the ingress of water into each of the wall systems through nominal deficiencies. Full-scale and small-scale laboratory tests were conducted to determine the path of water from an external deficiency to the stud cavity. Contrary to the expectations of MEWS consortium partners who had examined failures in the field, these experiments suggested a rather direct route to the bottom of the stud cavity. For the purposes of the parameter study, in most of the simulations, water was placed at the bottom of the stud cavity. In a few supplementary simulations the leaked water was placed midway up the wall, representing leakage under a window. The indications from the supplementary simulations will be discussed in Section 1.7 Evaluation of Wall Response to Moisture loads.

The dynamic wall test facility (DWTF) was used to subject the specific wall systems, stucco, EIFS, siding, and masonry, without and with the specified deficiencies, to the simultaneous effects of water spray and pressure differential. For each cladding system several representative wall specimens were constructed in accordance with information from Task Group 2, including deliberately introduced deficiencies (see 1.4.1). The deficiencies included a missing length of sealant at the interface between the wall and an electrical outlet receptacle and a ventilation duct. Figure 1.8 shows the elevation of the wall specimens tested in the DWTF indicating the general location of the window, the ventilation duct, the electrical outlet and the studs.

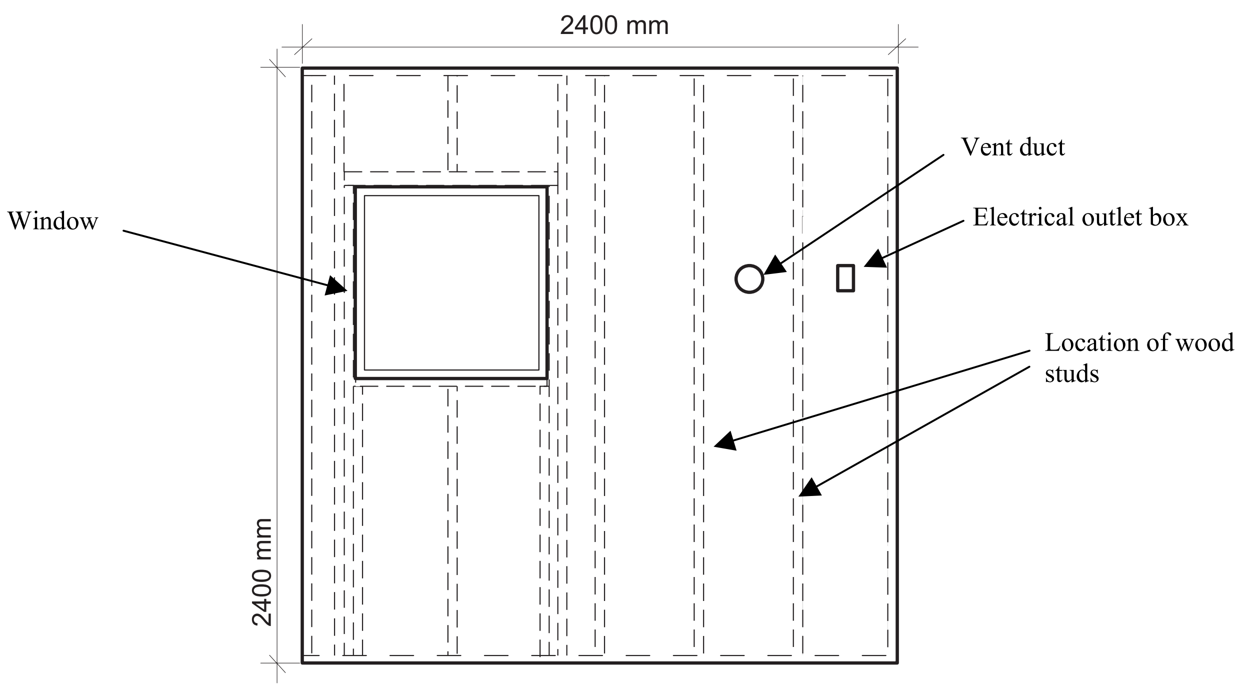


Figure 1.8 Schematic of a typical wall test specimen for the DWTF. The elevation shows the basic wall construction minus the wall cladding as well as the positions of the penetrations.

The DWTF test results for each wall system were used to calculate the rate of water entry (L/h) through a deficiency into the stud space, as a function of spray rate and pressure difference across the entire assembly. The spray rate represented the rain intensity on the wall, as computed from the hourly horizontal rainfall of the climate records (see 1.5.2). The pressure difference across the whole wall was more readily calculated for simulations, using hourly wind speed and direction from the climate records. However the actual pressure differential driving water into the stud space was likely lower than the total pressure differential acting across the wall assembly unless the cladding, sheathing membrane, and sheathing board were much tighter than the interior wall layers, as would be the case for a face-sealed wall system. Full-scale experimental results for each wall system were fitted to equations for computing water entry from the pressure difference across the walls and the water spray rates. These equations were used to determine the hourly quantity of water to inject into the stud cavity of the hygIRC model. The general form is shown by equation (4).

Hourly water entry rate in the stud cavity (Q) = Hourly rainload on the wall (Rw) (from Eq. (3)) * f (ΔP_{wall}) (4)

Rw did not vary from wall to wall, but rather varied with the weather records selected for the location of interest (e.g. Ottawa, wet year, hour No. 104 of the year, rainfall of 0.25 mm with an average wind speed of 11 km/hr). The pressure differential factor (called proportionality factor or dQ/dR_w) in the following equations captured the specific features of each wall system, as the empirical function varied for each wall system investigated. The four functions developed are presented below.

Stucco-clad walls: $dQ/dR_w = 0.0314 + 7.74 \times 10^{-5} \bullet \Delta P_{wall} - 8.14 \times 10^{-8} \bullet (\Delta P_{wall})^2$ (5a)

EIFS-clad walls: $dQ/dR_w = 0.0418 + 0.0243 \bullet \Delta P_{wall} / (110.3359 + \Delta P_{wall})$ (5b)

Masonry-clad walls: $dQ/dR_w = 0.0115 + 1.722 \times 10^{-4} \bullet \Delta P_{wall} - 1.47\ 1x\ 10^{-7} \bullet (\Delta P_{wall})^2$ (5c)

Hardboard and vinyl siding-clad walls:

$dQ/dR_w = 0.0422 + 1.618E^{-5} \bullet \Delta P_{wall} - 3.88E^{-8}(\Delta P_{wall})^2 + 1.115E^{-10}(\Delta P_{wall})^3$ (5d)

These equations are represented graphically in Figure 1.9. This figure shows that the proportionality factor between the spray rate (L/m^2-hr) and the rate of water entry into the stud space (L/hr) increased with the pressure difference for all four wall systems. At a zero pressure difference water entry through a deficiency was due to gravity and surface tension effects, accounting for more than half of the maximum water entry -or about 3 to 4 percent of the water deposited on the cladding- for all but masonry cladding (about 1 percent of the water deposited on the cladding).

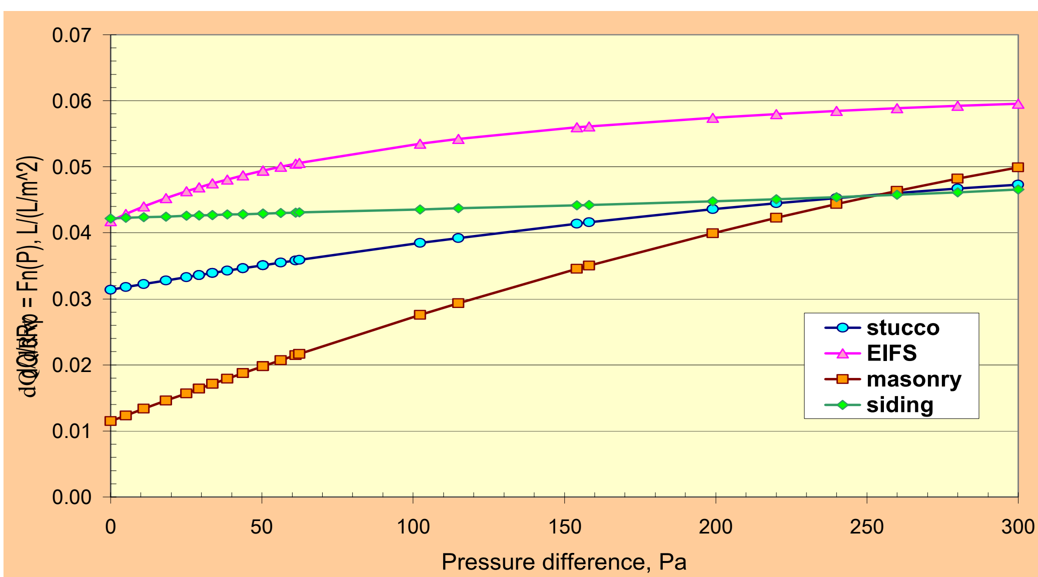


Figure 1.9. Proportionality factor dQ/dRw between pressure difference and hourly water entry Q.

For every hour of simulation, the moisture load that was injected into the reference wall of the parametric study was calculated in the following manner:

- The rate of water deposited on the cladding, Rw, was estimated as described in section 1.5.2.
- The proportionality factor was calculated as follows:
  1- Convert wind speed into static pressure.
  Wind speed from hourly weather records for the location and year of interest was obtained and converted to a corresponding static pressure difference. The following equation was used for the conversion:
  $\Delta P = 1/2\ \rho\ v^2$ where ρ is the density of air and v is the velocity of the wind at the point of interest. For example a wind speed of 52 km/hr translated into a static pressure of about 47 Pa.
  2- Calculate $dQ/dR_{w,}$ using the appropriate equation (5) derived from DWTF experiments.
- The hourly moisture load, in L per hour, to be injected into the stud cavity was obtained by multiplying the rate of water deposition on the cladding, Rw, by the proportionality factor, which was a function of the average wind speed for that hour.

These calculations were carried out every hour of the simulation period, as the moisture loads injected into the stud cavity varied for every hour. The whole set is referred to in Chapter 2-5 as a 1Q set of hourly moisture loads in the stud cavity. A ½ Q set of moisture loads is simply half the 1Q set of loads. Figure 1.10 provides an example of the hourly moisture loads injected in the stud cavity of a masonry-clad walls in Wilmington NC over two years of simulation.

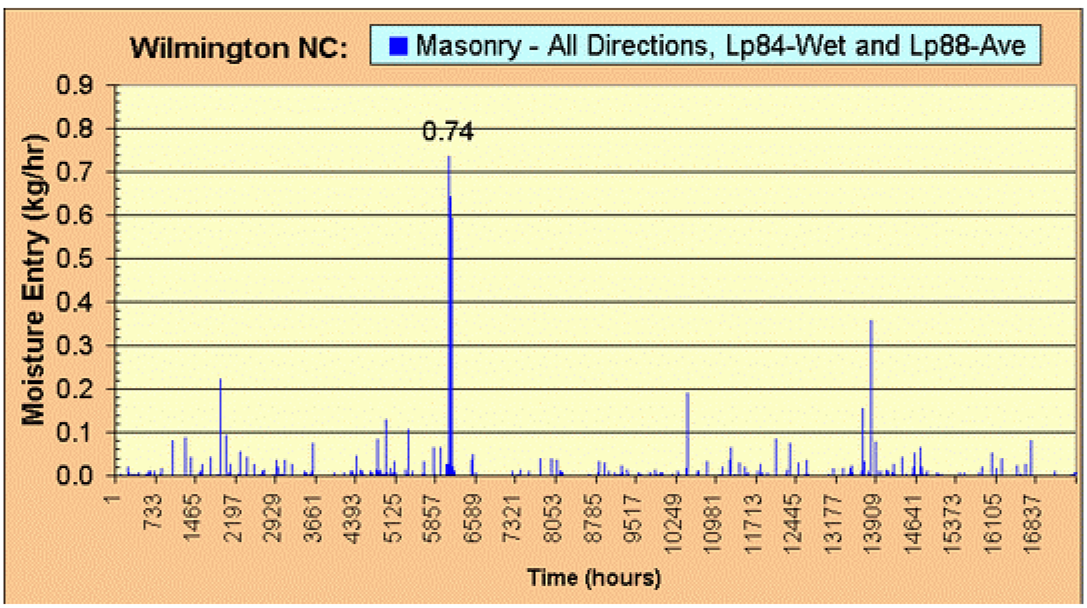


Figure 1.10 Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of masonry-clad reference wall for Wilmington NC for two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days

1.6 Prediction of Wall Hygrothermal Response to Moisture Loading

The next step in the MEWS method was to predict the hygrothermal response of a wall subjected to moisture loading. This was done using IRC's hygIRC mathematical model.

1.6.1 Using IRC hygIRC Mathematical Model

The ideal method for evaluating the long-term response of walls to moisture loading would be to build test specimens and monitor their long-term performance in-situ. For a project with the scope of MEWS this was not a practical approach. The approach chosen was to design a parametric study with reliable input data and an experimentally validated mathematical modelling to simulate the moisture response of the selected wall systems.

There are a number of mathematical models that numerically solve the combined heat, air and moisture transport equations. The model used in the MEWS project is hygIRC. Several publications are now available[x,xi,xii] that document, in detail, the formulation of the combined heat, air and moisture transport equations used in hygIRC and the techniques used to solve those equations. The model was validated through a series of mid-scale, and large scale drying experiments which formed part of Task Group 6[xiii]. The model accommodates many advanced features, to name a few:

- transient heat, air and moisture (liquid and vapour) transport through building assemblies,
- 2 -dimensional spatial formulation,
- material properties that vary with moisture content and temperature,
- air flow through building materials and openings,
- effect of solar radiation,
- presence of moisture source inside the material,
- freeze-thaw effect.

The effective use of advanced numerical tools demands the proper physical understanding of the problem, reliable input data and the ability to judiciously interpret the results. Some features of the wall system lie outside the current capabilities of hygIRC:

- flow of "free water" on materials surfaces and between components is not simulated, e.g. water draining down the face of a material
- water flow path through a deficiency will vary among constructions, and as already explained, they are not modelled, i.e. water needs to be "injected" at a selected location
- variations in vertical cross-section, e.g. through studs, are not modelled (hygIRC is a 2-dimensional model).

Other features could have been modelled, but were not, in general to keep the complexity of the simulations within practical limits for both execution and analysis. The scope of the project did not allow the investigation of everything of interest, or to pursue specific investigations. **The main objective was to determine the effects on temperature and moisture distributions with time and position within the wall, in response to systematic variations in the parameters selected for study:**

- Air leakage was not one of the parameters chosen for systematic study. Air leakage through accidental openings (in joints between materials such as in the air barrier as well as at deficiencies leading from the exterior into the stud space) was not, in general, modelled. Only two simulation runs ("reference" walls for Ottawa and Seattle) were done for certain wall systems, to get some sense of the magnitude of the effect.
- The vertical cross-section considered did not have any external fixtures (e.g. window opening, duct passage etc.) associated with it.

1.6.2 A Parametric Study

Wall cladding systems and materials, and the moisture loadings they experience, can be described by a set of variables, or parameters. The hygIRC parametric study required these variables as inputs for the set of simulations for the prediction of the wall hygrothermal response to environmental loading. As mentioned in the previous paragraphs, the point of the study was to gain insight into the effects of varying the parameters on the wall response. Then, as part of the MEWS method, simulations by hygIRC permitted users to get the **relative responses** of specific wall systems to the moisture loads characteristic of different locations in North America. The ultimate goal was to assist in the development of guidelines that will help designers and builders to improve wall performance and durability.

Unless otherwise indicated, the basic assumptions for the MEWS parametric study are given below. The chapters on the specific wall cladding systems document any changes to or additional assumptions.

- The duration of the simulation was two years, after a year of “conditioning” to a wet year. The first year of the simulation was a “wet” year, and the second year of the simulation was an “average” year as defined by Task Group 4.
- The initial moisture contents in all porous materials were determined by assuming 50% RH in the adjacent air layers.
- Water entry through deficiencies occurred in the first and second years for all the simulations but the "base-case" simulations, which had no deficiency in the walls.
- The interior climate conditions used are described in section 1.2.6.
- The hygrothermal response of the wall assembly was sampled every ten days at a selected region of the wall.

The general approach used in the MEWS parametric study was to vary four basic parameters: the climate, the wall cladding systems, the materials used in the assembly and the amount of accidental water entry into the wall assembly.

<u>Climate</u>

Exterior climate was one of the more influential parameters in the study. The seven locations (Wilmington NC, Seattle, Ottawa, Winnipeg, Phoenix, Fresno and San Diego) represented a sampling of the full range of climate variation throughout North America, and they were selected from a candidate list of more than 40 locations ranked according to a Moisture Index, MI. Recall from Section 1.3.4 that, unlike the version of MI used to prepare the provisional map, the MI used to select locations for parametric study took into account that each location usually had a predominant direction for wind-driven rain.

Reference years were selected for each of the seven locations on the basis of predominant wind-driven rain direction and wall orientation was set accordingly. Amounts of wind-driven rain from directions not at right angles to the wall were reduced in proportion to the cosine of the angle between the wind and the wall, eliminating wetting completely for angles from 90 to 270 degrees.

For the calculation of water entry through deficiencies into the stud cavity (Q), however, the wall was assumed to be always normal to the wind direction. This tended to result in higher moisture loads into the stud cavity than in the case where only moisture loads from certain wind directions were injected into the stud cavity. Q was then used as a variable parameter and was varied from 1Q to ¼ Q and ½ Q for locations of moderate and high external moisture loads and to 2Q and 4Q for locations with low moisture loads. Supplementary simulations (not reported on in detail) were done with the lower directional driving rain amounts and these closely agreed with the extended simulations at Q/2 and Q/4 (see section 1.7.4 for further details).

<u>Wall Cladding Systems and Materials</u>

Four wall systems were simulated: stucco-clad, EIFS-clad, siding-clad and brick veneer-clad. For each of the wall types the materials used in construction were varied. Details for each of the specific wall systems are given in the chapter dealing with the respective wall type.

Before running the first year of the simulations, the simulated walls were "conditioned" during one year of simulation, as described below. Since the initial moisture contents of the wall components were not known at the outset, it was necessary to estimate the starting moisture content. A wall assembly and properties of the materials assumed to be typical were selected; it became the “base-case” or “reference” wall for a particular cladding system. All materials were assumed to have a moisture content that would correspond to a relative humidity of 50%. Then, that wall was subjected, through mathematical modelling, to a *wet* reference year for each of the seven locations of interest, as specified by Task Group 4: *Environmental Conditions*. No accidental water entry into the stud cavity occurred during that conditioning year. The moisture contents of the materials at the end of this year were used as starting point for the two years of simulation runs for the parametric study about a particular wall cladding.

Amount of Accidental Water Entry Into The Stud Cavity (Q)

The fourth basic parameter investigated was the amount of accidental water injected into the stud cavity, where moisture sensitive materials were present. The previous section described how the water entry rate, Q, was determined. Q was directly determined from the weather data and the characteristics of the wall cladding system and was considered a parameter. Fractions or multiples of Q varied the amount of accidental water entry. Two basic variations of water entry were used: Zero Q; i.e. no water entry, and One Q, water entry rates determined from the DWTF laboratory investigation. Other variations such as, 1/4, 1/2, 2 and 4 Q are also investigated for certain wall systems in certain climates.

The water entry rates in the stud cavity were derived from experimental results obtained for a certain water leakage path leading into one 400 mm stud space. However hygIRC is a 2D model and as such, did not represent variations in the third dimension: simulation results were expressed "per metre" of breadth (the dimension in which all properties and quantities were treated as unchanging). It was decided that the parametric study would use the Q driving functions as is and would distribute the calculated Q values uniformly over the grids of the 1 metre breadth of the modeled wall. That meant that each modeled wall grid was subjected to 2.5 times less water loading than otherwise indicated by the DWTF experiment results. The decision for the parameter study, not to multiply by 2.5, will be discussed further in Section 1.7.4.

One might ask next, where in the stud cavity did the water end up? Tests were carried out in the insulation–filled stud cavity of a stucco-clad wall. Water was sprayed onto the wall at 3.4 L/min-m^2 and entered a deficiency (nominal 1-mm x 45-mm) over a ventilation duct. The wall was also subjected to a pressure differential of 75 Pa and the air barrier had air leakage of 0.5 L/min-m^2. Most of the water quickly moved to the bottom of the stud cavity, with a small fraction of the total accumulating in the insulation (ca. 4%). The OSB sheathing adsorbed little or no water over the course of the test. In general, experiments at IRC indicated that the bulk of the water entering the stud cavity fell to the bottom of the space. However, some materials and very low water entry rates may allow some water to be absorbed on its way down. There is also the possibility of lateral spreading into other stud spaces, particularly once it reaches the bottom. For MEWS parametric study, the injection of moisture was placed in the insulation next to the bottom plate in the stud cavity.

Limited Investigations of Other Parameters

Other parameters were investigated for only a few of the wall/climate location combinations. Examples of other types of parameters include but are not limited to:

- First and second years of climate varied (from *wet*, *average* to *wet*, *dry*)
- Variation of interior temperature (T) and relative humidity (RH)
- Air leakage representing an imperfect air barrier
- Removal of vapour barrier

1.7 Evaluation of Wall Response to Moisture Loads

1.7.1 Region of Focus

To predict the hygrothermal response of wall assemblies to moisture loads with hygIRC, one had to select a region on the wall that presents a particular interest. It could have been the whole wall, and in such case the response would represent an average for the whole wall. Instead, a smaller region of the wall was selected as a "worst case" scenario, where moisture-sensitive materials were located and concentrated wetting was expected to accumulate, e.g., in a stud cavity or under a window sill. This smaller region was called the *region of focus*.

Relative humidity and temperature were the hygrothermal conditions for the region of focus that were provided by the hygIRC simulations. Every ten days at midnight several predicted values of relative humidity and temperature were sampled and averaged for the grid points in the region of focus, to constitute a pair of data points for quantifying indicators of wall response. The 10-day interval was selected after several trials to optimize the balance between reducing the bulk of the data and retaining useful information.

1.7.2 A Single Indicator of Performance: Relative Humidity and Temperature Index (RHT)

A Novel Concept

It is widely accepted that building materials are subject to deterioration under the combined effects of temperature and moisture. The most deleterious conditions are those in which moderate or high temperature is coupled with high humidity for extended periods. The RHT index is a new indicator used to quantify and compare the localised hygrothermal response in a critical region of focus of the wall assembly. This index captures the duration of the coexistence of moisture and thermal conditions above a pair of minimum levels, say X and Y respectively, during an exposure of two years. RHT was defined as the summation of values at 10-day intervals, of (RH, % - X) multiplied by (Temperature, ˚C – Y), only when both terms were positive.

The resulting cumulative RHT became a single-valued index of the hygrothermal response within the region of focus in the given wall over the two-year period of the simulation runs. One of the notable insights that arose from the consideration of the RHT index was that two different walls could have similar cumulative RHT values but still have very different hygrothermal responses over time. Hence, climates or conditions that seem intuitively to be very different can, in fact, produce similar cumulative exposure to temperature and RH conditions, which may affect the wall performance. Figure 1.11 illustrates this point in which two examples are provided of wall responses cumulating similar RHT values at the end of a two-year period of simulation. However, within this period, different patterns of hygrothermal fluctuations evidently occurred. The schematic on the left shows rapid and large changes in %RH that led to relatively high RH levels sustained over short periods whereas the schematic on the right shows the RH level somewhat lower than the previous case but sustained that level for comparatively longer periods. The wall with the hygrothermal response represented on the right also had a significantly reduced drying period.

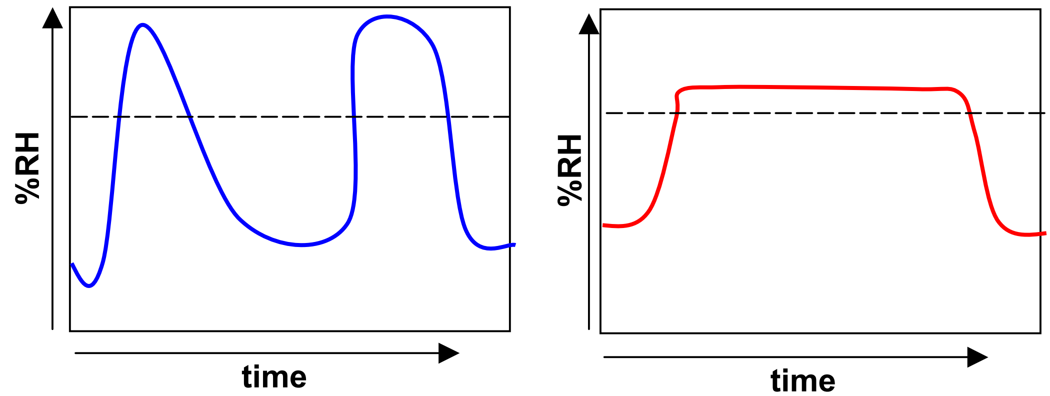


Figure 1.11 Schematic to illustrate differences of RH fluctuations leading to the same cumulative RHT value.

Effects of Temperature and Relative Humidity on the RHT Values

As just mentioned, the RHT index is a reflection of the RH and temperature prevailing in the region of focus of a given wall assembly. The relationship between RH and T in this region can in some cases, affect the RHT results in climates dominated by very different temperature regimes, i.e. cold and warm climates. Winnipeg and San Diego (Figures 1.12 and 1.13) will be used as an example of two locations which both have nearly the same RHT(95) values, about 1300, but with different temperature and relative humidity fluctuations.

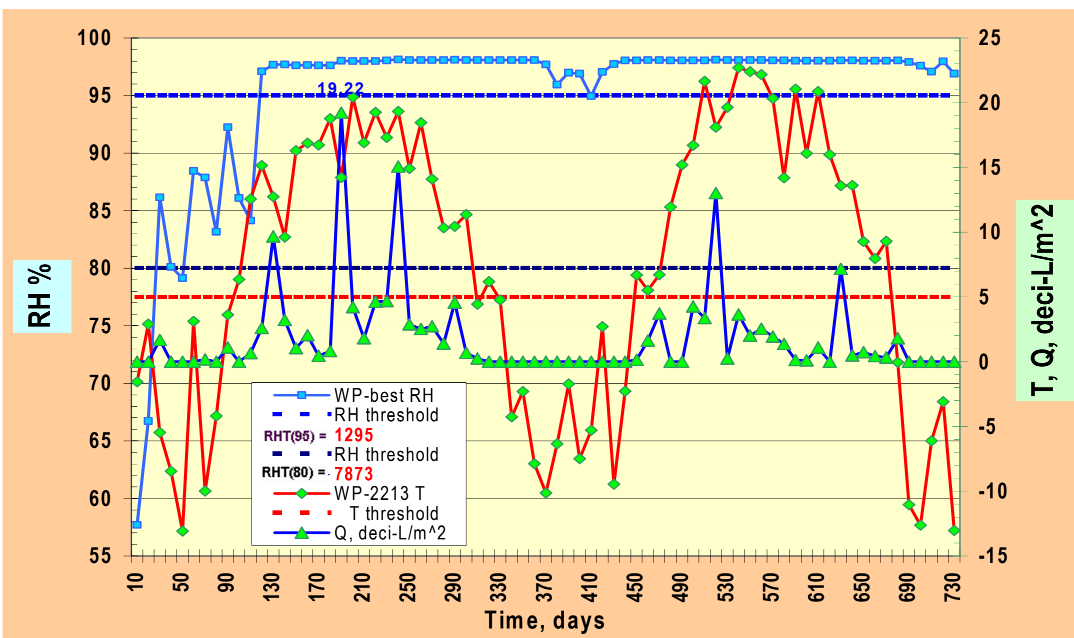


Figure 1.12. Temperature and RH for stucco-clad wall No. 2213 exposed to Winnipeg climate. RHT(95) = 1295, RHT(80) = 7873. MI for Winnipeg is 0.86.

When the temperature of the region is below 5°C or the RH is below 95%*, the value for the RHT is zero. In a cold climate, the temperature in the region of focus will likely be below 5°C for a prolonged period in winter. The duration of that period will depend on the severity of the outdoor climate, the presence of a layer of insulation on the outside of the region of focus and the occurrence of air leakage. During this cold period, the RHT value is zero regardless of the RH level. The presence of long cold spells (about 5-6 months for Winnipeg) "freezes" the RHT value during that period. Thus over the two-year period RHT is controlled by the temperature at the region of focus. Figure 1.12 illustrates a case of stucco-clad wall assembly in Winnipeg. For the first three months and the last two months of the year, the temperature (curve with the squares) was below the threshold of 5°C, and the corresponding RHT contributions were zero for all but 44 of the 73 10-day samples.

Interestingly the same wall exposed to the climate of San Diego, considered hot and dry, also had an RHT(95) of about 1300. In the case of San Diego, the outdoor temperature was well above 10ºC. The same was true for the temperature condition prevailing inside the wall in the region of focus (see Figure 1.13). The possible "active" period for RHT accumulation was twice as long as in Winnipeg. RHT will be positive as long as the RH is above 95%, and this in turn will depend on the pattern of rainfall and wind. Given those conditions, even though the level of annual rainfall was lower in San Diego than Winnipeg (262 mm versus 404 mm, see Figure 1.14), the cumulative RHT of San Diego turned out to be essentially the same as Winnipeg. Of the 73 10-day samples, 35 were non-zero (9 less than the wetter Winnipeg), but this difference was partly compensated by higher temperatures.

This discussion highlights two points: first, the graph of fluctuating individual RH and T provides insights into the behaviour of the region of focus for a given wall in a given climate. Second, when the region of focus is warm (i.e. above 5°C) for most of the year, either because of the characteristics of the outdoor climate or of the wall construction, despite dry spells with RH below 95%, the region of focus can still have nearly the same "active" period for accumulating RHT as a colder, wetter climate and hence may have about the same cumulative RHT.

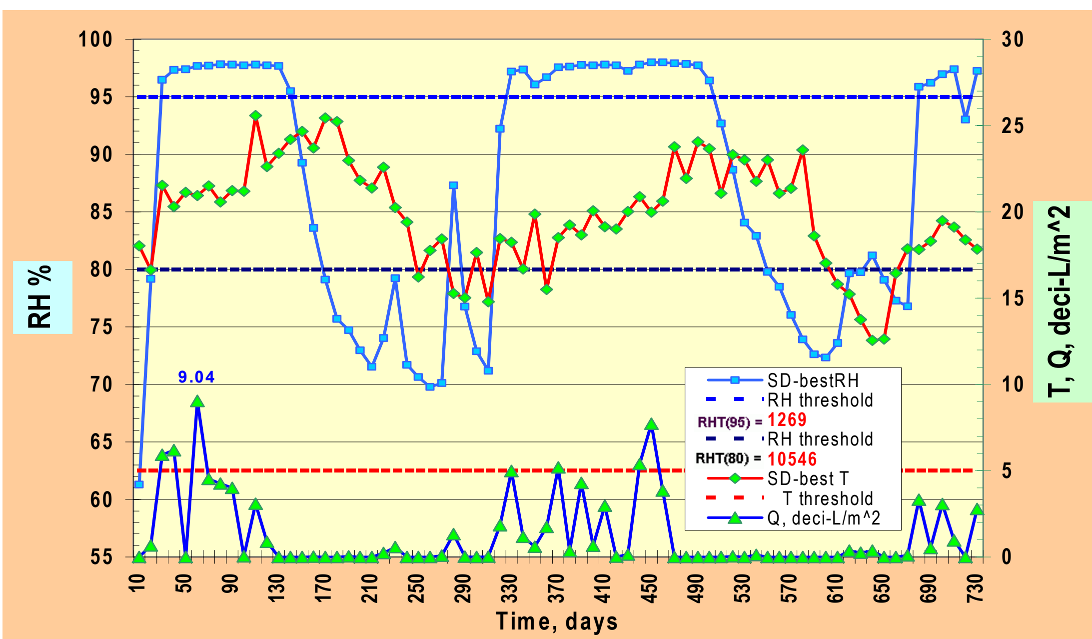


Figure 1.13. Temperature and RH for stucco-clad wall No. 2213 exposed to San Diego climate. RHT(95) = 1269, RHT(80) = 10546. MI for San Diego is 0.74.

* In this example, threshold values for RH and T were 5°C and 95%RH. See the next section for a discussion on the selection of the minimum levels of RH and T for RHT calculations.

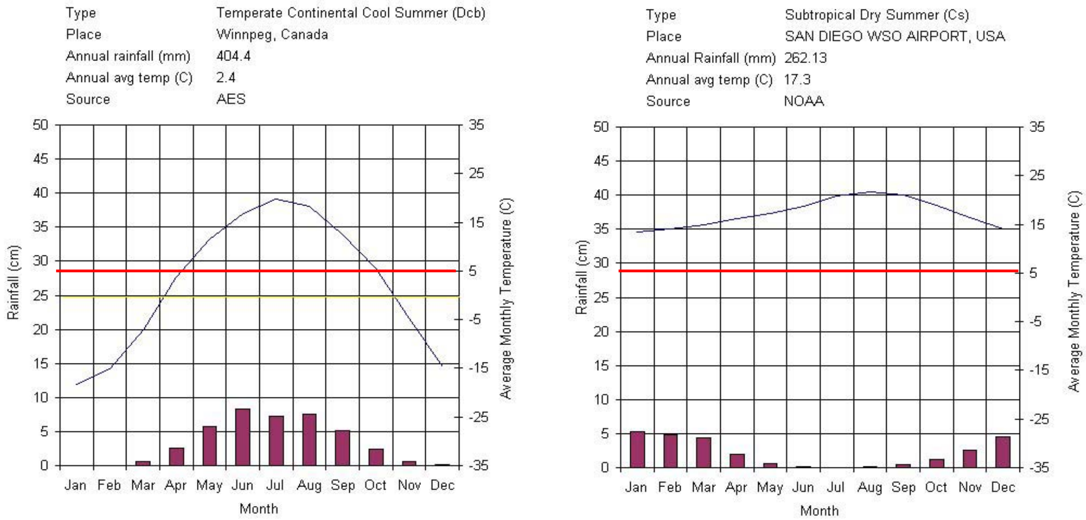


Figure 1.14 Plots of climate normal data for Winnipeg and San Diego, showing monthly average temperature and rainfall

<u>Defining Threshold RH and T Levels for RHT Calculations in the Region of Focus</u>

The wall hygrothermal response predicted by hygIRC is unaffected by the RH and T threshold selected for the analysis. The MEWS method is flexible in allowing users to select the RH and T thresholds for the type of damage and safety margins of interest. The analysis and interpretation of the simulation results will vary according to the nature of the damage mechanisms and the damage functions developed to predict such damage.

The minimum relative humidity and temperature of concern for the region of focus depends on the mechanisms of degradation and the physical processes of interest relevant to the durability of any selected material in that region. The primary focus of MEWS was the durability of wood-frame walls. Hence, the decay of wood and wood-based products used in walls was of particular interest. Two sets of minimum levels of relative humidity have been considered in MEWS. Initially the project used a combination of 80% RH and 5°C temperature averaged over the region of focus of a given material of the assembly for indicating the hygrothermal response of the wall to some wetting. This became known as RHT(80). This level of relative humidity was selected based on literature review that helped identify this value as the lower limit for the onset of potentially deleterious effects on moisture-sensitive wall materials. A large number of hygIRC simulation results were then expressed using RHT(80) index.

In May 2001 it was suggested that a higher level of relative humidity than originally selected be used as a limiting condition for the onset of wood decay. Even though current world research on the limiting conditions required for the decay of wood and wood-based products was not yet conclusive, MEWS partners agreed to use a higher threshold of 95 %, and to present RHT index results in terms of RH(95). This was based on results of work done in Finland (Viitanen 1997) using sapwood of European softwood species and fungi prevalent in Europe. Further work is required to check this for wood materials used and fungi prevalent in North America.

In this context, the main body of the report presents the hygrothermal response of walls using the RHT(95) index. However MEWS partners were also keen to keep available the RHT(80) results and analysis already documented because of their interest in other deterioration processes such as corrosion.

Simulation results based on the RHT(80) index are presented in an appendix at the end of each chapter devoted to a cladding system.

Wall Hygrothermal Response Assessed by RHT(95) Index

Since RHT(95) is based on the limiting conditions for the onset of wood decay, any positive value for the cumulative RHT index should be considered as an indicator of potential risk of decay. Moisture management strategies should seek to minimize the value of RHT(95), or ideally bring it down to zero.

The following nomenclature will be used in chapters 2-5 to describe the impact of effects of changing various parameters on the RHT(95) wall response.

Decisive: RHT(95) was reduced to near zero by a single effect
Substantial: RHT(95) difference of at least 1000 of the larger value compared.
Small: RHT(95) difference less than 1000 and higher than 100 of the larger value compared. It could still have meaning and interest if demonstrating a trend.
Near zero: RHT(95) difference less than 100 of the larger value compared

RHT(80) versus RHT(95) Indices

RHT can be a useful single-valued indicator of particular limiting conditions, but it should be noted that RHT for two different RH thresholds always have different numerical scales, and sometimes produce different rankings across climate locations. Figures 1.12 and 1.13 illustrate these two points. First, RHT(80) values were about 6 times those of RHT(95) for Winnipeg, and 8 times for San Diego, because the area between the 80%RH threshold and the RH curve was so much larger than that portion of the area above the 95%RH threshold. Second, for the examples given in Figures 1.12 and 1.13, RHT(80) was substantially lower for Winnipeg (7873) than for San Diego (10546), while their RHT(95) values were virtually the same (1295 and 1269 respectively). This, in spite of the fact that Winnipeg received a total of 13 L of water through the deficiency, compared to only 8.7 L for San Diego. A detailed examination of the RH and T plots shows why. Temperature governed for Winnipeg, while RH governed for San Diego. In dropping from a threshold of 95% RH to 80% RH, San Diego gained 9 more qualifying events (10-day periods), but Winnipeg gained only 1, which also had lower temperatures, and thus smaller multipliers for each event.

Thresholds must be varied to report on the limiting condition of interest, but it is also advisable to supplement RHT by examination of the RH and T plots, which are invariant for all RH and T thresholds.

1.7.3 Hygrothermal Response of Walls as a Function of Climate Severity

The most important features relating to the hygrothermal response of the walls (expressed with the RHT index) when subjected to various moisture loads attributable to North American climatic conditions (expresses with MI) are captured in a characteristic curve (Figure 1.15).

The blue line shows the characteristic response of a deficiency-free wall (a stucco-clad wall in this case) to driving rain deposited onto the exterior wall surface. In this case there were no deficiencies allowing water entry into the stud cavity, i.e. the wall cladding is perfectly sealed against water entry through accidental openings. Hence moisture was transported only through liquid and vapour diffusion across the individual material layers in the assembly. As well, air movement was restricted by the air permeance of each material layer. These transport processes responded only to the local weather and interior conditions. The slope of this blue line varied depending largely on the wetting and drying characteristics of the specific cladding system and the severity of the climate.

The red curve shows the characteristic response of the same wall when an opening (i.e. deficiency) introduced through design or construction practice, or by deterioration with time, allowed water leakage into the stud cavity for a corresponding moisture load. For MEWS analyses this opening measured 50-mm long and approximately 1-mm wide in one stud space. Depending on the prevailing wind and rain, variable quantities of water enter the insulated stud space through this opening. This moisture load was additional to that of the scenario associated with the blue line. The shape of this line will vary depending on the severity of the climate exposure and the drying ability of the wall once it is wet.

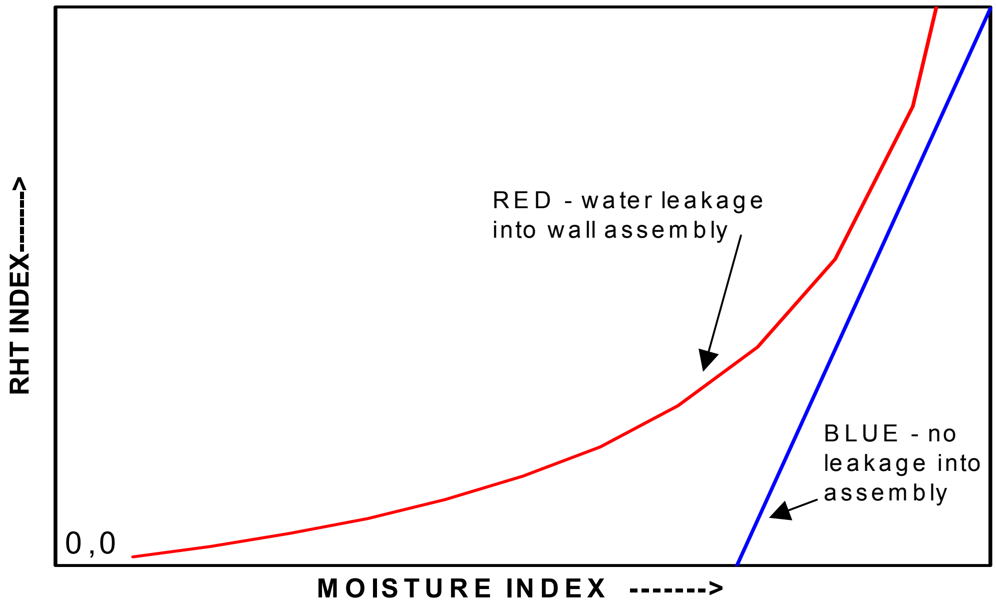


Figure 1.15. An example of characteristic curves for a wall assembly. Similar curves can be constructed for different cladding systems, using different minimum values for the RH and T of the RHT index (e.g. RHT(80), RHT(95)).

1.7.4 Recommendations for Further Research

The development of an integrated research approach to moisture management for exterior wall systems began with the establishment of several research tasks:

- definition of wall types and construction details,
- determination of material properties,
- assessment of exterior (and interior) climate,
- assesment of moisture loads on a wall cladding, and estimation of moisture loads into the stud cavity through a deficiency
- description of moisture and temperature conditions heralding the onset of damage,
- simulations to predict hygrothermal response -parametric study.

These tasks have been largely accomplished, but as is often the case with research, the results brought into focus further questions about its application to the original objectives. *Certain tasks proved more difficult and time-consuming than anticipated and are still ongoing. Until they are completed, it would be premature to suggest that a comprehensive guide to moisture management of walls has been achieved. Detailed information on the effect of temperature as well as the amount and duration of unintentional moisture accumulation on mechanical, chemical and biological deterioration is only forthcoming. This information is essential to address the moisture management in exterior walls in the context of long-term behaviour of building envelope components. Furthermore, the effect of the biological activities within the envelope on the indoor air quality of the built environment should also be considered.*

The parametric study included hundreds of trial applications of the MEWS method, so that the sensitivities of the predictions of wall response to input conditions and properties could be understood and evaluated**. Although the input conditions and properties represented the best attempts of researchers (with input from MEWS partners) to deal with practical situations, the primary objective was to develop the prediction method, not to cover all practical cases, and not to present definite guidelines for design**. Despite the large number of simulations done, of which Chapters 2 -5 give a summary appreciation, they merely scratched the surface of the situations of interest to the industry and to the owners and occupants of buildings.

Further work is required to delineate the damage functions of concern to practitioners (and not just for wood decay, which is still under development). The map showing variations in the Moisture Index for North America is provisional, and MI is expected to be refined to give better correlation with observed trends of wall system performance.

Each of the steps of the MEWS method contributed its own share of uncertainty to predictions of hygrothermal response of walls. The parametric study, as planned, has shown the sensitivity of the results to variations in material parameters, but questions remain about the characterisation of potential deficiencies in wall assemblies. The variabilities of external climates, and to a lesser extent, interior climates, have yet to be formally described, but they are likely to be of equal or greater importance than variability of materials. Finally, the conditions for defining unacceptable performance, e.g. the onset of wood decay, may well contribute greater uncertainty than the other steps.

Computer model assessments of long-term performance gain in usefulness and credibility when supplied with estimates of their variability, and equally important evidence comes from comparisons between simulated performance and the measured performance of full-scale buildings.

Applications of the MEWS Methodology

Three examples of "decision branches" that affect the applicability of parametric study results to specific situation are worth stating. First, the decision to expose deficiencies to all rainfall as if the wall faced directly into the wind produced more conservative results, i.e. higher RHT values, than taking the alternate decision to treat the wall as fixed, facing into the direction of the predominant wind-driven rain. In comparison to the predominant direction branch, this had the effect of *increasing* the accidental water entry by factors of 1.4 to 2.9 (depending on geographic location) for stucco-clad walls. Second, the decision to apply the accidental water entry for a 406 mm-wide stud space over 1000 mm had the opposite effect, *decreasing* the amounts Q by a factor of nearly 2.5. Third, a multi-decision branch occurs when selecting where to inject the accidental water entry. A rule was developed during the parametric study, to select the location in the wall that showed the most severe wetting conditions with the least variation throughout the simulation period. This obviously depends on which of several possible injection locations is chosen, and by choosing a thin layer of insulation just over the bottom plate, the region of focus for the parameter study became a thin layer of the spruce plate, rather than the bottom corner of the OSB sheathing. Supplementary simulations with injections next to the OSB around mid-height gave RHT results roughly similar to those for the spruce plate. The same is true for early simulations (before the adoption of the above-mentioned rule) in which the region of focus was a thin slice of the bottom quarter of the OSB facing the stud space.

These three examples illustrate the difference between "exercising and understanding" the prediction procedure on one hand, and selecting input conditions for predictions of specific design situations, or classes of design situations on the other. The decisions taken for the parametric study are not necessarily appropriate for an investigation of a particular situation. The important point is to be clear about what was done at each step in the parametric study, so that informed and appropriate choices can be made in applying the MEWS methodology to each practical situation involving the design or analysis of any combination of climate and wall system. With this objective in mind, the MEWS team highlighted and interpreted some of the simulation results for each of the four types of cladded wall systems in Chapter 2-5. Chapter 6 brings in perspective the results for all wall systems and draws some general trends observed for all wall systems.

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Chapter 2. Application to Stucco-clad Walls

2.1 Summary

Wood frame walls with traditional stucco cladding have been widely used for decades in North America and until recently, durability had not been a major concern. Perceptions changed when a rash of premature failures occurred in the Vancouver area in the 1990's. In 1996, CMHC's "Survey of Building Envelope Failures in the Coastal Climate of British Columbia" report suggested that face sealed wall assemblies might not be capable of acceptable performance in that area. Exterior water, entering the wall in most cases at penetrations or interfaces with windows, decks, balconies etc., led to rotting and decay of wood components, water damage to the cladding itself and water penetration to living spaces. The MEWS parametric study also indicated that water bypassing the cladding system and the second line of defence because of deficiencies was a major contributor to elevated RH conditions in the walls.

Highlights of the results are as follows:

- The stucco claddings investigated exhibited significant resistance to water penetration through the field of the wall. The wall response in terms of RHT(95) was zero for all climates but Wilmington NC, which was near-zero.

- When the same stucco-clad reference wall included a small deficiency (nominally 1 mm X 50 mm) that allowed direct water entry beyond the water resistive barrier, i.e. into the stud cavity, the RHT(95) response of the wall was quite different. RHT(95) varied from about 655 in a hot and dry climate of Phoenix to about 3213 for the warm and wet climate of Wilmington NC. This indicated that, given the temperature prevailing in the stud cavity, the amount of water entering (the "1Q" set of hourly moisture loads) was more than could be accommodated by the evaporative drying potential of the materials and makeup of the wall assembly.

- The outdoor climate played an important role in the RHT(95) hygrothermal response of the reference wall, in two ways: it defined the wetting potential of the cladding and the stud cavity, as well as the evaporative drying drive. Walls exposed to climates with severe moisture loads (high MI) reached a stud cavity RH level above 95% after a few months of climate exposure and this RH remained stable until the end of the two years simulation period. Early in the simulation period, the stucco-clad reference wall appeared overwhelmed by moisture loads larger than could be removed by drying during the rest of the run. In mild climates, however, the moisture loads were low and the drying potential high. In that case hygIRC predicted large swings of wetting and drying, resulting in much lower cumulative RHT(95) wall response than in climates like Wilmington NC and Seattle.

- When the moisture load into the stud cavity was reduced to ¼ of the original loads, only a small drop in the RHT(95) wall response was predicted for cold and warm climates with high moisture loads. This suggested that evaporative drying through the materials would not be sufficient for even a quarter of the moisture loads in the reference wall (with deficiency).

- The parametric study was carried out using a 1Q set of hourly moisture loads into the stud cavity. Under this condition, hygIRC predicted that the following variations made only a small difference in the RHT(95) response of the reference wall assembly:
  - Changing the properties of the sheathing board
  - Changing the properties of the water resistive barrier
  - Changing indoor RH level
  - Changing the properties of the vapour barrier membrane
  - Adding a vented cavity behind the stucco cladding

- Introducing airflow in the wall assembly was predicted to result in a small improvement of the RHT(95) hygrothermal response of the reference wall. One specified air leakage path at selected geographic locations appeared to assist in the drying of the wet stud cavity. Further investigation in

the benefits and drawbacks of uncontrolled airflow through a wall assembly is required prior to making general statements.

- A large increase in the vapour transmission characteristics of the interior layer of the wall assembly (i.e. vapour diffusion control by a coating on interior gypsum board, with no other vapour barrier) substantially reduced the predicted RHT(95) at some geographic locations for certain levels of indoor humidity conditions. Further investigation into the effect of the indoor environmental conditions (RH,T and P) on the potential improvement in RHT response needs to be carried out prior to making general statements.

The following sections describe the application of the MEWS method (Chapter 1) to stucco-clad wall assemblies, and provide the RHT (95) predictions obtained in the parametric study.

2.2 Selection of Materials and Design of the Assemblies

Through Task Group 2, MEWS industry members and IRC personnel gathered technical information on current practices in the construction of stucco-clad wall assemblies. This information was used in the design of full-scale wall specimens for the evaluation of water entry under simulated wind-driven rain pressure (TG6), the design of walls to be simulated through modelling in TG 7, and for the characterization of material properties (TG3).

In terms of typical composition of stucco-clad walls, the traditional stucco applied directly on the back-up wall appeared to have been the most frequent design approach used. A water-resistant membrane (or water resistive barrier, WRB) placed behind the stucco plaster provides some redundancy to the cladding system as it introduces a second line of defence against water ingress (Figure 2.1). In British Columbia, in the aftermath of the major building envelope failures of the early 90s, a different approach has been promoted, that is, the introduction of a drained cavity behind the stucco cladding (Figure 2.2). In that case the stucco plaster is applied against a layer of building paper, and separated from the backup wall by vertical furring strips.

2.2.1 Types of Wall Assemblies Selected

Two generic types of stucco-clad assemblies were examined, as defined by the moisture management strategies used:

- Wall without a clear cavity behind the stucco cladding
- Wall with a clear cavity behind the stucco cladding

Both types included a water resistive barrier (WRB) acting as a second line of defense against water ingress into the assembly. Both polymeric and paper-based WRB were used. All specimens incorporated an OSB sheathing board in the wall assembly. Several compositions of stucco plaster were used, from the lime-cement mix or Portland cement plaster (19 mm) to a fibre-reinforced plaster mix with acrylic finish (12 mm).

Five large-scale specimens were built for laboratory investigation of water entry into the assembly under simultaneous water spray on the cladding and air pressure difference across the assembly, to simulate wind-driven rain. The composition of these specimens is briefly presented in Figures 2.1 to 2.2, complemented by Table 2.1. A detailed description of the specimens is given in T2-02 report entitled: *Description of the 17 Large-scale Specimens Built for Water Entry Investigation in IRC Dynamic Wall Testing Facility",* May 2002.

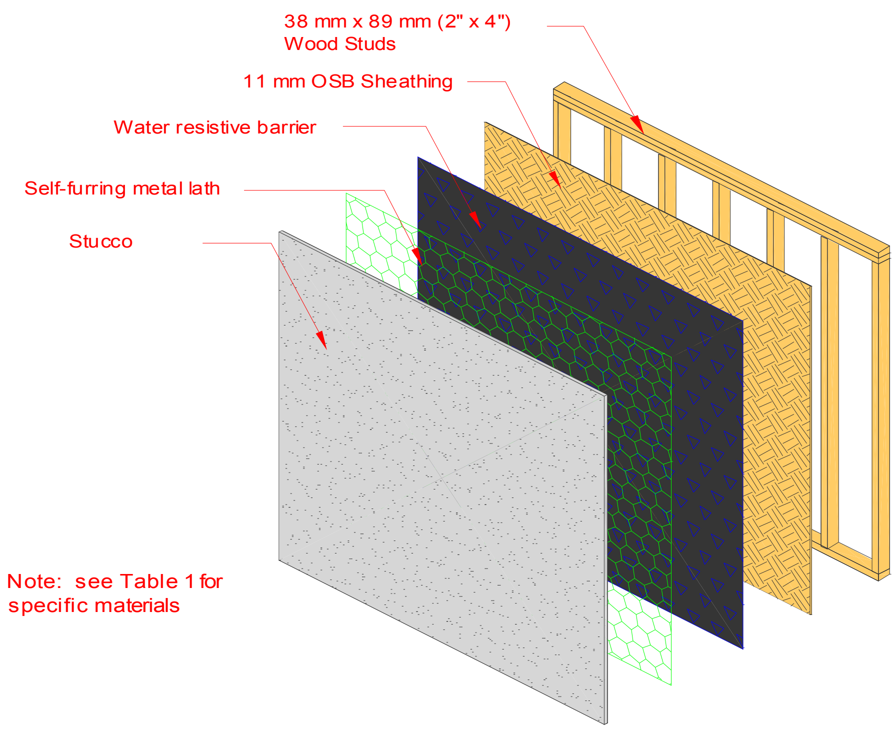


Figure 2.1 Generic composition of specimen No.1 to No. 4 (See Table 2.1 for detailed description of materials making up each wall layer)

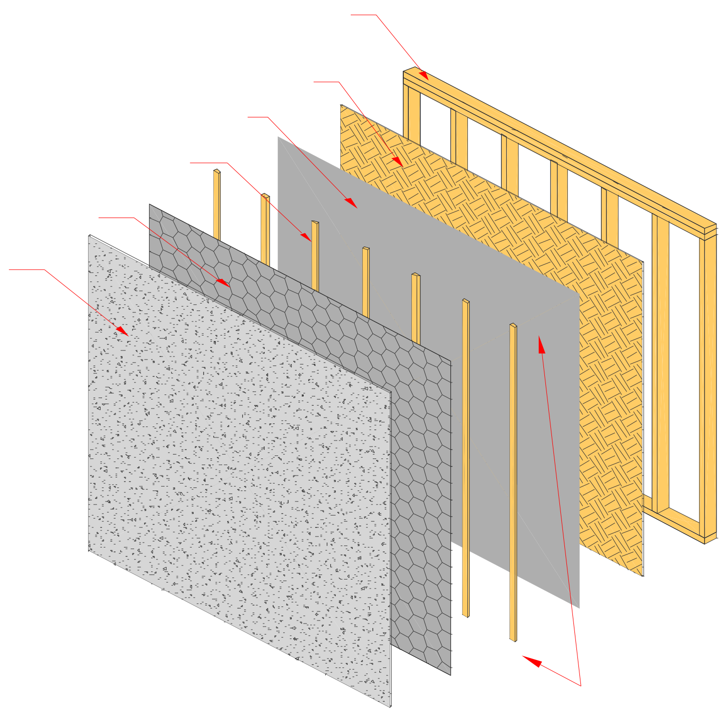


Figure 2.2 Composition of specimen No. 5

Table 2.1. Stucco-clad wall specimens composition

	WALL COMPOSITION
No. 1	19 mm, lime-cement plaster / self-furring expanded metal lath / cross-woven perforated polyethylene membrane / 11 mm OSB sheathing / 38 mm X 89 mm (2X4) wood framing @ 400 mm o.c.
No. 2	19 mm, lime-cement plaster / self-furring woven metal lath / 60-minute rated building paper / 11 mm OSB sheathing / 38 mm X 89 mm (2X4) wood framing @ 400 mm o.c.
No. 3	19 mm, lime-cement plaster / self-furring welded wire metal lath / spun-bonded polyolefin membrane (American type) / 11 mm OSB sheathing / 38 mm X 89 mm (2X4) wood framing @ 400 mm o.c.
No. 4	12 mm, fibre-reinforced plaster pre-mix with acrylic finish / self-furring expanded metal lath / two 30-minutes building paper membranes / 11 mm OSB sheathing / 38 mm X 89 mm (2X4) wood framing @ 400 mm o.c.
No. 5	19 mm, 3 coats Portland cement plaster as specified by BC Building Envelope Research Council / "Tilath" 1/8 in. flat rib with offset paper 2.75 lb / 10 mm cavity, PT wood strapping / two 30-minutes building paper membranes / 11 mm OSB / 38 mm X 89 mm (2X4) wood framing @ 400 mm o.c. This is a drained stucco-clad system with vents at top and bottom of the cavity.

2.2.1 Properties of Materials

Hygrothermal properties of several products of the following basic materials were characterized: Portland cement plaster (stucco), water resistive barrier (WRB), oriented-strand board (OSB), glass fibre insulation, spruce lumber, vapour barrier and gypsum board. Several properties of these materials used as input for running the hygIRC simulations are given in Table 2.2. Other hygrothermal material properties can be found in the MEWS report T3-23 entitled: "*Hygrothermal Properties of Several Building Materials"* March 2002.

Table 2.2. Selected Properties of Materials

Material	Water vapour permeability ng/(m s Pa)		Air permeability x dynamic viscosity (m^2) x 10^{-16}	Liquid diffusivity (10^{-12} m^2/s)
	@ 0%RH	@ 100%RH		
Stucco Plaster				
1	0.00	6.80	0.7	9110
2	0.20	3.30	1.7	39940
3	2.20	4.10	4.2	2330
Water Resistive Barrier				
1	0.06	0.82	222	4.9
2	0.02	1.22	118	3.6
3	0.03	0.03	169	0.0001
Oriented Strand Board (OSB)				
1	0.06	6.0	79	22 in X; 507 in Y
2	0.04	9.3	16	30 in X; 437 in Y
3	0.05	4.5	43	24 in X; 95 in Y
Plywood				
1	0.39	26	85	170 in X; 940 in Y
Uncoated Fibreboard				
1	36	42	46700	999
Vapour Barrier				
1	0.002	0.002	0.001	0.0001
2	0.012	0.012	0.001	0.0001
3	0.006	0.064	0.001	0.0001

2.3 Estimation of Moisture Loads

The methodology presented in Section 1.5 for the estimation of moisture loads in the stud cavity was applied to the stucco-clad wall specimens. Moisture loads impinging on the face of the cladding were based on local climate to which the wall assembly was subjected in simulations. The moisture loading into the stud cavity was based on the results obtained from experiments using IRC Dynamic Wall Testing facility (DWTF) (see report T6-02-R9 Experimental Assessment of Rain Penetration and Entry into Wood-frame Wall Specimens – Final Report, 2002). These experiments provided rates of accidental water entry through deficiencies located in five different wall specimens for several specific combinations of water spray intensity and static air pressure differential across the wall.

2.3.1 Wall with a Drained Cavity Behind the Stucco Cladding

Results from the water entry tests on the stucco-clad wall assemblies using the DWTF revealed that the specimen with a drained cavity did not exhibit any accumulation of water on the inside face of the sheathing board in spite of the presence of deficiencies on the exterior wall surface. In contrast, the other specimens without such a drainage cavity accumulated various quantities of water at those same locations. These results confirmed previous observations that a drained cavity behind the cladding can significantly reduce the likelihood of the exterior moisture load penetrating portions of the wall assembly that contain moisture-sensitive materials. Walls without such a drainage capability likely experience larger moisture loads into the wall, and hence must rely on the evaporative (drying) potential of the wall to ensure removal of accidentally entered moisture. However the drainage ability of a cavity behind the cladding was not fully taken into account in the MEWS hygIRC parametric study; mainly its influence on the drying potential was investigated. For each climate investigated, one single set of hourly moisture loads was injected in the stud cavity of the modelled stucco-clad assemblies, whether or not a drained cavity was present behind the stucco cladding.

2.3.2 Walls With Negligible Drainage Behind the Cladding

<u>Moisture entry into the wall assembly through a given crack</u>

Full-scale and small-scale laboratory tests were conducted to approximate how much of the water sprayed on the exterior face of the wall would penetrate inside the wall stud cavity through a deficiency. The deficiency was represented by an opening approximately 1-mm wide by 50-mm long at the interface between the cover plate of an electrical outlet receptacle and the stucco cladding. An example of a typical deficiency is shown in Figure 2.3. Three of the specimens experienced some water entry in the stud cavity, which was collected at the inside face of the sheathing board, just beneath the electrical receptacle. From these amounts of collected water and the climate loads the specimens were subjected to, an equation was derived to estimate the water entry rate (Q) in one stud cavity as a function of (1) the pressure difference across the wall assembly, ΔP, and (2) the rate of water striking the wall, R_w. The equation is given below:

$$Q \text{ (L/h)} = R_w \times f(\Delta P) = R_w \times \{0.0314 + 7.74 \times 10^{-5}\, \Delta P - 8.14 \times 10^{-8}\, \Delta P^2\} \qquad (1.1)$$

This equation was used to calculate the hourly rates of water entry into the stud cavity of the stucco-clad walls that were modeled in the various hygIRC simulations. Rw and ΔP were based on the hourly climate loads available for the two historical years of weather data selected for each of the seven locations investigated.

Figure 2.4 shows the hourly rates of water entry into the stud cavity of the stucco-clad reference wall represented in hygIRC, for three locations of quite different climate loads, Wilmington NC, Winnipeg and Phoenix.

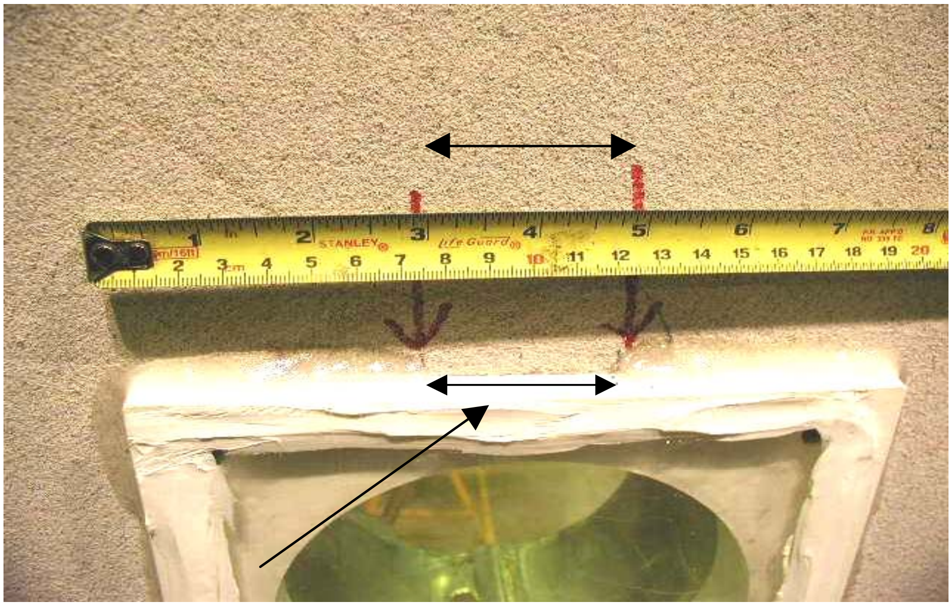


Figure 2.3 Example of a 1 mm by 50 mm deficiency (missing bead of filet caulking) introduced at the joint between the cover plate of a ventilation duct and the stucco cladding

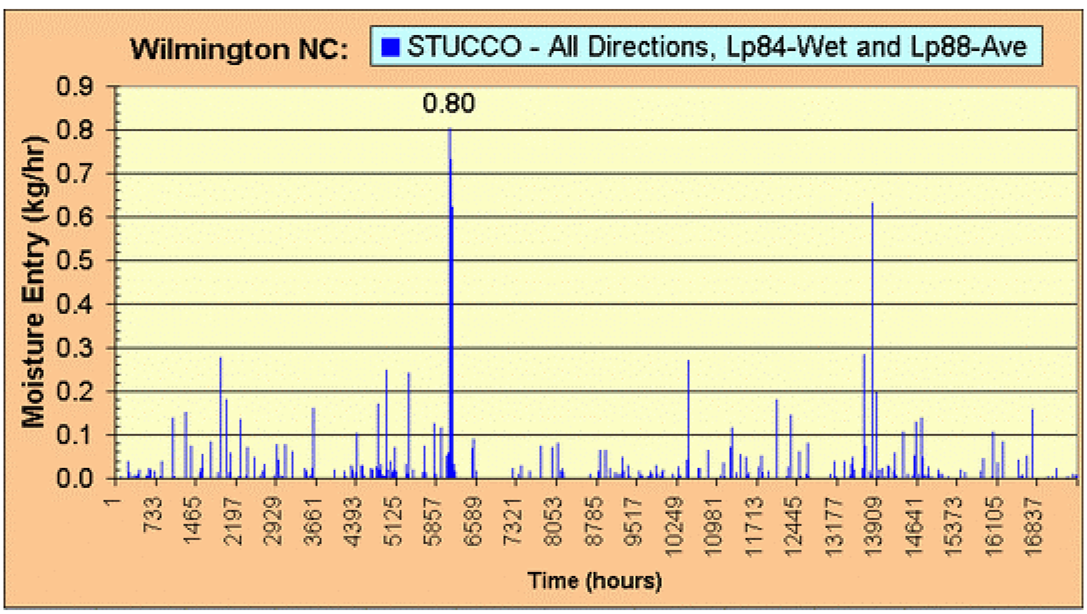


Figure 2.4 a) Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of stucco-clad reference wall for Wilmington NC for the two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

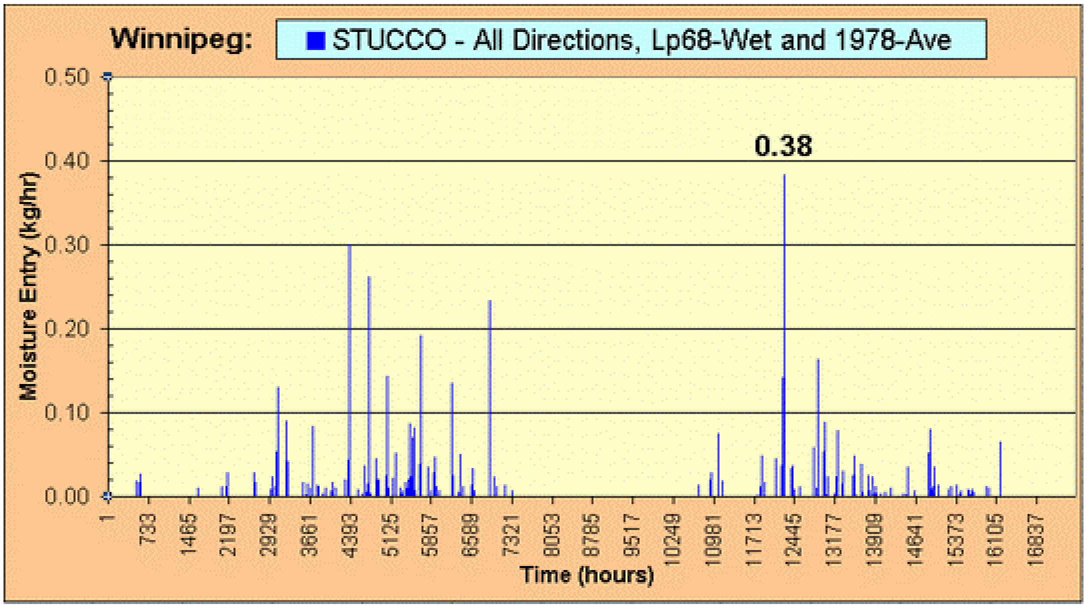


Figure 2.4b) Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of stucco-clad reference wall for Winnipeg for the two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

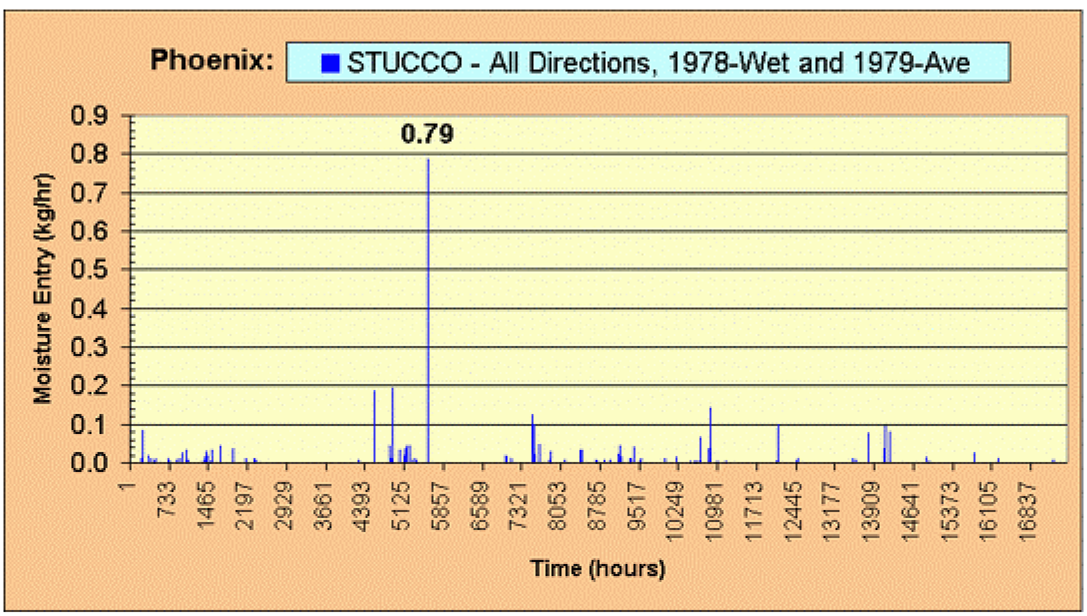


Figure 2.4c) Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of stucco-clad reference wall for Phoenix for the two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

Moisture distribution within the stud cavity

Having established how much water could get into the stud cavity, the next step was to decide where and how to distribute it. As described in Chapter 1, through some computer routines, the modeller deposited the moisture load at the bottom of the stud cavity. The hourly amounts, varying from 0 to a maximum of about 0.8 L (Wilmington NC) were uniformly distributed among several grid points representing a thin layer of stud cavity insulation just above the bottom plate in the wall stud cavity. The injection of moisture to represent the deficiency was placed in the insulation next to the bottom plate.

Selection of the region of focus in the stud cavity

The region of focus was selected for its potential to represent a worst-case scenario (see Chapter 1 section 1.7.1 for more details). In preliminary simulations a region was identified as being the wettest portion of the wall assembly most of the time (see Figure 2.5). For all stucco-clad simulations presented in this chapter, the region of focus was a thin slice (5 mm) of the top surface of the bottom plate, extending 53 mm from the sheathing board.

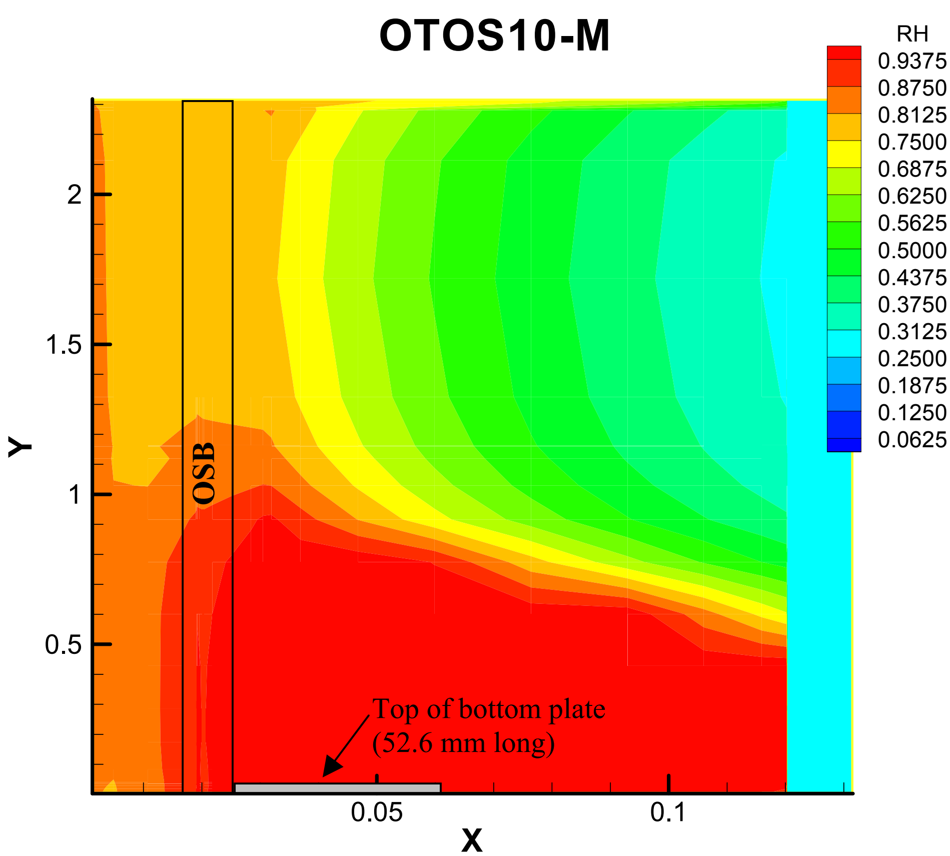


Figure 2.5 A typical RH contour plot generated by hygIRC for the reference wall No. 2211, in Ottawa taken as a snapshot during the two-year simulation. The dark (red) areas were regions for which hygIRC predicted an RH above 87%. The bottom of the stud cavity was predicted to be the wettest portion of the wall assembly most of the time.

2.4 Prediction of Hygrothermal Response of Wall Assemblies

2.4.1 Parameters Investigated

The following parameters were varied to determine their influence on the long-term durability of a reference stucco-clad wall assembly (Figure 2.6):

- Materials: 3 types of exterior stucco plaster, sheathing membrane and board, and vapour barrier
- Location: 5 sites in first series, Wilmington NC, Seattle, Ottawa, Winnipeg, Phoenix (Fresno and San Diego added in second series).
- First and second years of climate varied (from *wet*, *average* to *wet*, *dry*)
- Accidental moisture entry inside the wall varied by factors of 2 and 4
- Ventilation cavity added between stucco and sheathing membrane.

In a second series of simulations, for selected locations only:

- Air leakage through the assembly, representing an imperfect air barrier (Ottawa and Seattle)
- Variation of interior (room) temperature (T) and relative humidity (RH) (Wilmington)
- Removal of vapour barrier membrane (Wilmington)
- Two other sheathing board materials: plywood and uncoated fibreboard (Wilmington NC and Ottawa)
- Optimization of stucco properties (Wilmington NC)
- Combination of materials that individually gave best results in first series (all locations)

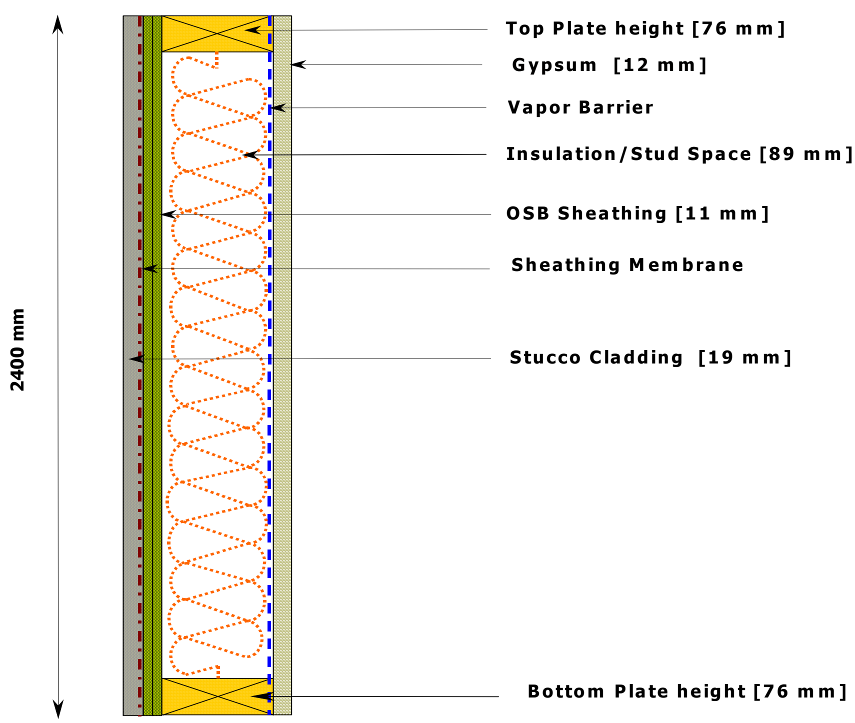


Figure 2.6. A vertical section showing the composition of the reference wall used for most of the parametric study.

NB. For the simulation runs, it was assumed that double top and bottom plates in the stud cavity were in place. In practice it is more common to use only a single plate. It is believed that this discrepancy did not affect the interpretation of the results significantly.

2.4.2 Comparative Results

If all possible combinations of material types were simulated for each of the seven locations with and without moisture entry through a deficiency, over a thousand simulations would have been completed. This is indeed far more than could have been accommodated given the time and resources available for the MEWS project. Hence, after careful consideration and consultation with MEWS partners, it was decided to conduct a sufficient number of simulation runs to reveal the major influences of parameters mentioned above (wall construction details and parameters). The simulations mentioned in this summary represent only a portion of the total number of simulations carried out in this program. Of these, only a handful were singled out for discussion here, but two complete sets of the single indicators of performance (i.e. RHT(95) and RHT(80)) are provided for each simulation in Appendix 2.1. Reported in this section are the comparative effects of the following parameters on the moisture response of the wall expressed by the RHT(95) index.

1. Climate severity
2. Material properties in a given climate
3. Variations in indoor climates
4. Removal of vapour barrier membrane
5. Water leakage rate into the stud cavity
6. A ventilated cavity behind the cladding
7. Air leakage

The following nomenclature is used in the subsequent sections to describe the effects of changing various parameters on the wall response:

Decisive: cumulative RHT(95) value was reduced to near zero by a single change of parameter.
Substantial: cumulative RHT(95) difference of at least 1000 of the larger value compared.
Small: cumulative RHT(95) difference less than a 1000 and higher than 100 of the larger value compared.
Near-zero: cumulative RHT(95) difference less than 100 of the larger value compared

1. Effect of Climate Severity on a Wall Assembly RHT(95) Response

Observation: hygIRC model predicted that the RHT(95) hygrothermal response of a wall assembly increased with the severity of the climate (i.e. MI). Although the stucco-clad reference wall *with no deficiency* showed a zero or near-zero RHT(95) hygrothermal response for all climates, all configurations with the "nominal" deficiency allowing water leakage into the stud cavity registered positive RHT(95) values increasing as a function of climate severity, as defined by the MI. (Effect: *near-zero to substantial*)

Discussion: Figure 2.7 illustrates this effect. When the reference wall assembly included no deficiency that would allow water entry in the stud cavity, it was predicted that the cumulative RHT(95) values for that wall remained at zero for all climates but the most severe investigated, that is Wilmington NC. In that location, the wall response was near-zero at an RHT(95) of 9. Even though the liquid diffusivity of the stucco plaster (Stucco No. 2 in Table 2.2) was not particularly low, it appeared low enough to provide the required water resistance for these climates. When a deficiency that allowed water ingress into the stud cavity was introduced in the assembly, the wall response tended to increase with the climate severity, as indicated by the green and red curves, reaching a RHT(95) high of 3213 in Wilmington NC for the reference wall No. 2211 and a RHT(95) low of 230 in Phoenix for the wall with better drying, No. 2213. That was a general trend, with the exception of wall No. 2211 exposed to San Diego, Winnipeg and Ottawa on the red curve.

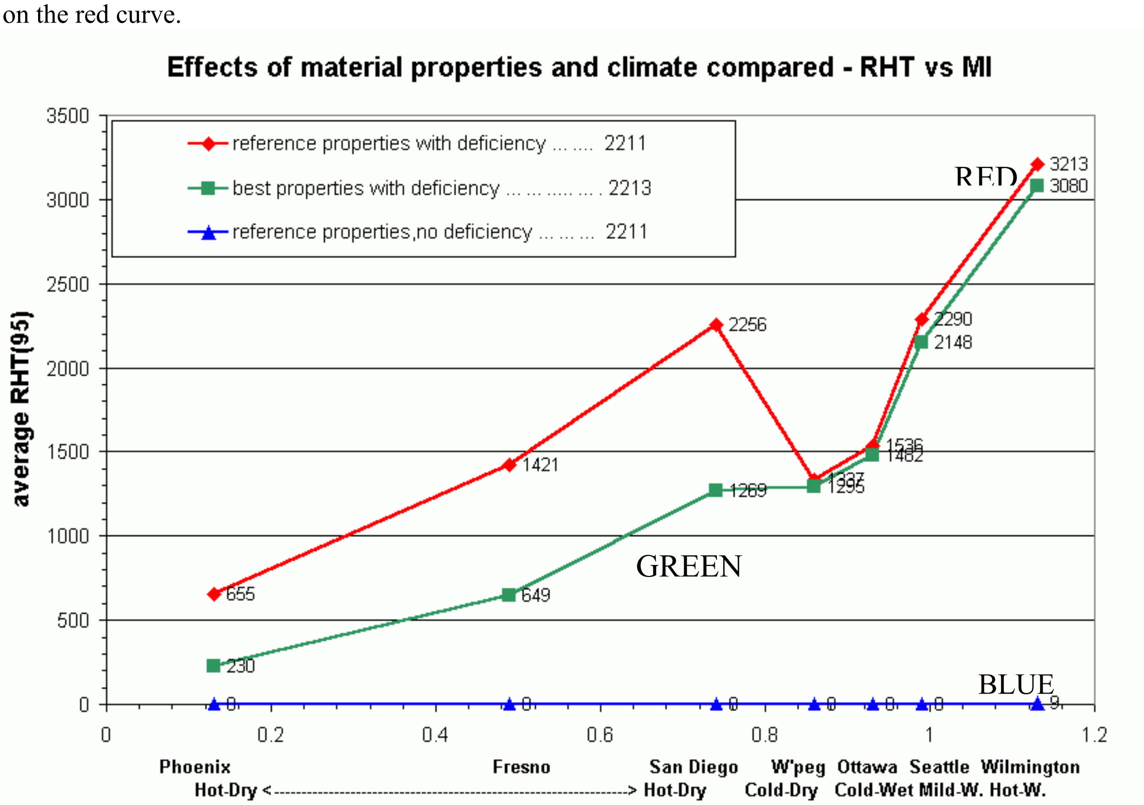


Figure 2.7 Relationship between climate severity and stucco-clad wall response for three scenarios. The blue curve (lower flat line) was the response for a reference wall No. 2211 having no water leakage into the stud cavity (no deficiency). The red curve (upper curve) was the response of the same wall with a deficiency allowing water leakage into the stud cavity. The green curve (middle curve) represented the response of wall No. 2213 having a combination of materials more conducive to drying, and with the same deficiency as was incorporated in wall No. 2211.

Let us examine more closely the shape of the upper line (i.e. for the reference wall with a 1Q set of hourly moisture loads in the stud cavity), and how it fluctuated with the climate. Even though San Diego is drier and warmer than Seattle, leading to different MI indices, the RHT(95) response of the reference wall was essentially the same in these two climates. To explain this behaviour, one needs to examine the predicted RH and T curves that form the basis for the computation of the RHT values at the region of focus. For the San Diego simulations (Figure 2.8a), the wall was predicted to experience two drying spells (when RH at the region of focus dropped below 95%); however the temperature at the region of focus was always higher than that for the wall in Seattle. For the Seattle simulations, the RH reached about 98% after the first month of simulation and stayed at that level for the remaining of the simulation. In Seattle however, the outside temperature was cooler, and as a result, the temperature at the region of focus in the stud cavity was also lower than what was predicted to occur in the reference wall in San Diego. This cooler temperature for Seattle "slowed down" the accumulation of RHT values. Even though the climates of San Diego and Seattle are quite different, the wall RHT (95) responses were about the same because of this combination of effects of the relative humidity and the temperature: Seattle was wetter but cooler than San Diego, which was drier but warmer. In Seattle the temperature drove the accumulation of RHT(95) value, as the RH was almost always above the threshold value of 95%, while in San Diego, the RH drove the computation of the cumulative RHT(95) value, as the temperature was always above the threshold of 5^{o}C and the RH fluctuated.

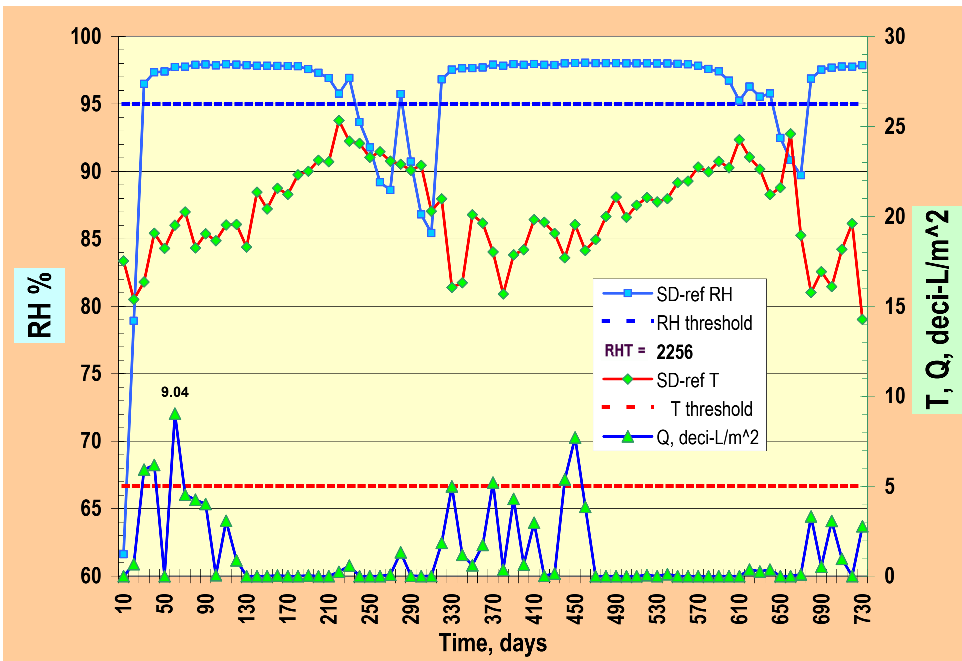


Figure 2.8a RH and T profiles predicted for the reference wall in San Diego. Cumulative RHT(95) = 2256.

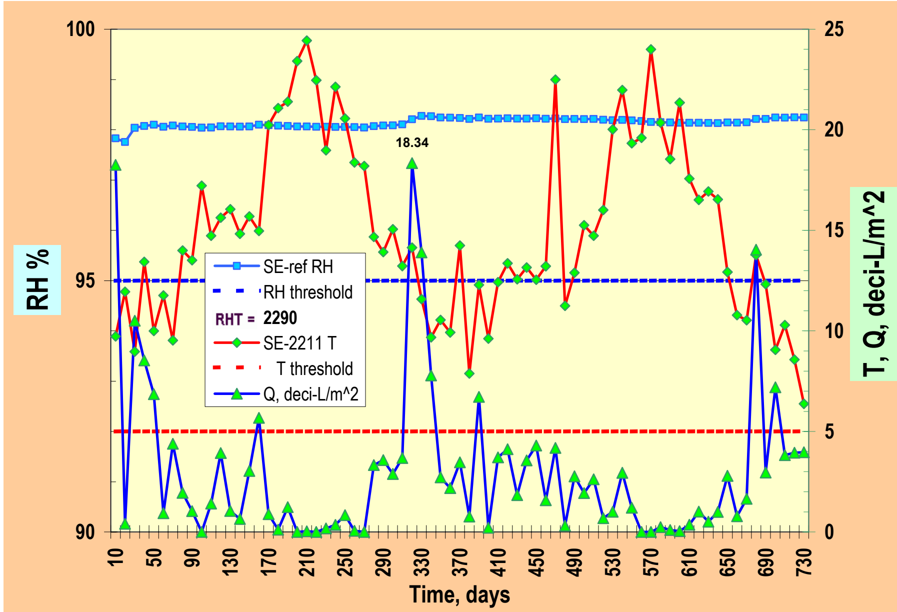


Figure 2.8b. RH and T profiles predicted for the reference wall in Seattle. Cumulative RHT(95) = 2290

The wall response in the two cold climates, Winnipeg and Ottawa, is also worth examining (red upper curve of Figure 2.7). Winnipeg and Ottawa had higher MI indices than San Diego but the reference wall had a lower RHT(95) response in these two cold climates than in San Diego. The temperature at the region of focus fell below 5°C for long periods during the winter months, resulting in no accumulation of RHT(95) during that time. Figure 2.9 shows that in Winnipeg, after about three months of simulation, the RH rose to about 98% and stayed there until the end of the simulation period. However the temperature at the region of focus fluctuated on a seasonal basis and dropped below 5°C during about 4 months a year. That explains why the two-year cumulative RHT(95) value for the reference wall exposed in Winnipeg was lower than the same wall exposed to the San Diego climate, even though the indicator of climate severity, MI, for Winnipeg (MI=0.86) was higher than that of San Diego (MI= 0.74). The same circumstances have been observed for the Ottawa simulation (Figure 2.10).

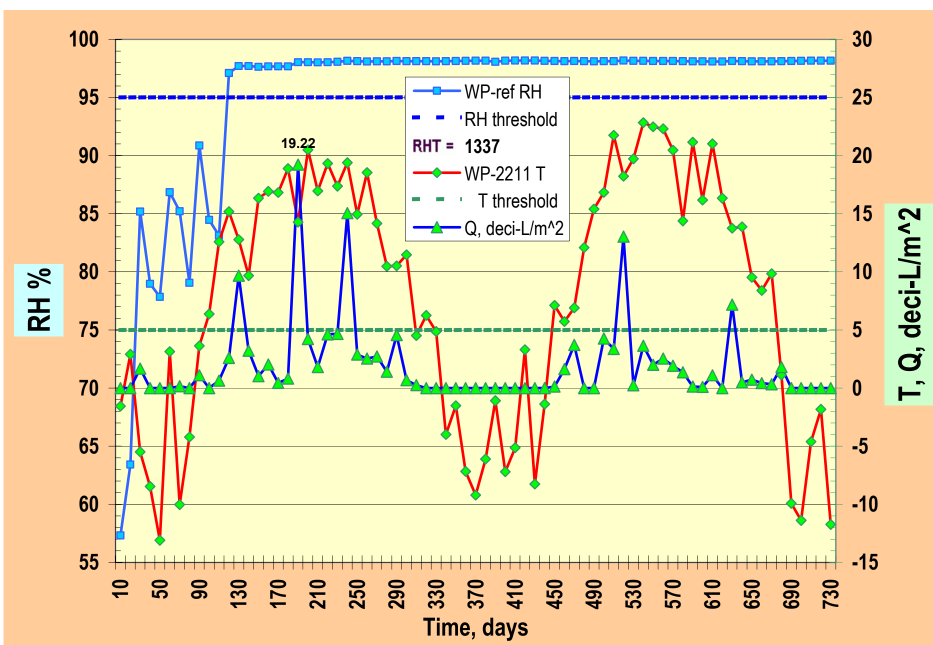


Figure 2.9. RH and T profiles predicted for the reference wall in Winnipeg. Cumulative RHT(95) = 2290

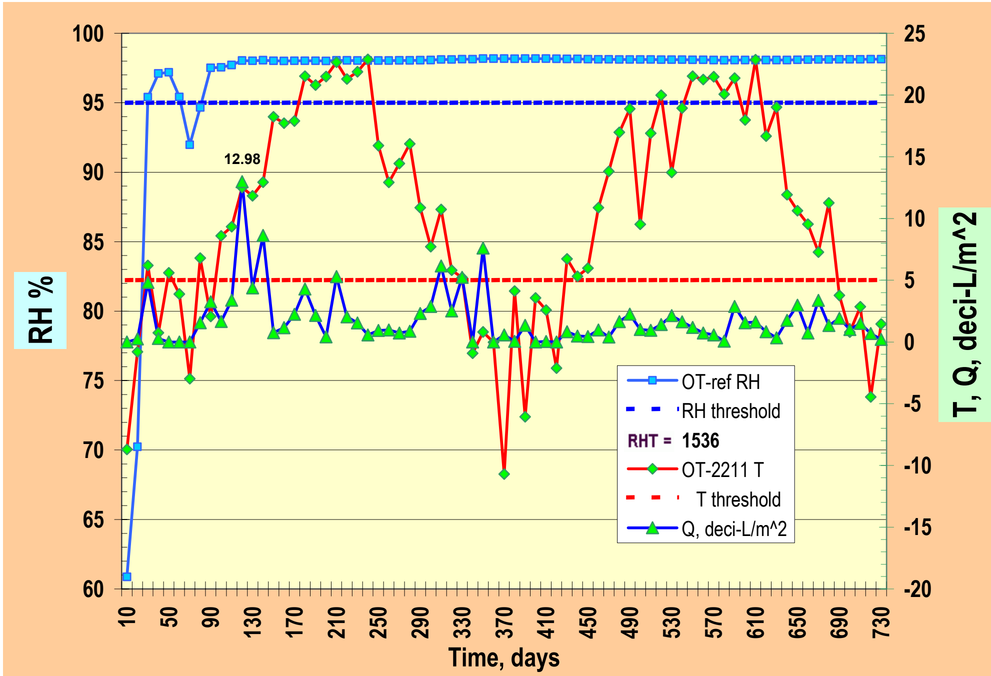


Figure 2.10 Predicted RH and T profile for the reference wall with a 1Q set of hourly moisture loads, exposed to two years of Ottawa climate years. Cumulative RHT(95)=1536

2.0 Effect of the Variation of the Moisture Loads (Q) into the Stud Cavity

Observation No. 1:* *Effect of Q=0. hygIRC simulations predicted that the stucco cladding provided a degree of water resistance sufficient to maintain the RHT(95) wall response at zero in most climates. Even in the most severe location investigated, Wilmington NC, the wall response is near-zero, at a value of 9. (Effect: *decisive*)

Discussion: hygIRC results are presented in Figure 2.7 as well as in Table 2.3. When no water bypassed the cladding system, the properties of the cladding material became the dominant factor for the control of moisture ingress. Even though the liquid diffusivity of the stucco cladding was not amongst the lowest investigated in this project, it was low enough to serve its purpose of first line of defence against water penetration.

Table 2.3 Cumulative RHT(95) values for seven locations for several sets of moisture loads in the stud cavity (Q) for wall No. 2211

Q	Phoenix	Fresno	San Diego	Winnipeg	Ottawa	Seattle	Wilmington NC
0	0	0	0	0	0	0	9
¼	*	*	*	697	864	1979	2841
½	*	*	*	1190	1434	2177	3008
1	655	1421	2256	1337	1536	2290	3213

An asterisk, *, indicates no simulation run for the specific parameter

Observation No. 2: ***Effect of Q≠0.*** For the locations and hourly moisture loads in the stud cavity (Q) investigated, water leakage into the stud cavity increased the RHT(95) hygrothermal response of the stucco-clad wall. The magnitude of that increase was a function of the climate loads, the details of the water leakage path and the properties of the materials making up the assembly.

Discussion: All simulation results for several levels of water leakage into the stud cavity (1/4, ½ and 1Q) for several locations predicted that the wall RHT(95) response was above zero (Table 2.3 and Figure 2.7). The basic deficiency used to estimate the rate of water entry into the stud cavity of the wall specimens consisted of a 1-mm wide by 50-mm long missing bead of sealant at the interface between an electrical receptacle cover plate and a stucco cladding. As deficiencies are accidentally introduced in the detailing of the wall assembly, Qs found in practice may be either lower or higher than the range selected for this parametric study.

Observation No. 3: ***Effect of Q=1***. Most of this parametric study used a 1Q set of hourly moisture loads in the stud cavity (see examples of hourly rates in Figure 2.4). For the wet and cold climates investigated, a 1Q set of wetting rates of the stud cavity seemed "to flood" the reference wall, i.e. no noticeable drying occurred during the two years of simulation runs. (Effect: *decisive*)

Discussion: With a 1Q set of hourly moisture loads in the stud cavity, the wall RHT(95) value reached a low of about 655 in Phoenix and a high of 3213 in Wilmington NC. For the wet and cold climates investigated, the evaporative drying rate offered by the materials in the vicinity of the region of focus and by the outdoor and indoor climates was insufficient to offset the 1Q set of wetting rates of the stud cavity. An examination of the 10-day interval predictions of RH and T in Wilmington NC (Figure 2.11) showed that the region of focus reached an RH of about 98% early on in the simulation run (after about 2 months) and stabilized at that level for the remaining of the two-year simulation. In other words little drying occurred during the simulation period. A 1Q set of wetting rates of the stud cavity was predicted to exceed what the given wall materials can manage by evaporative drying in those climates. In that case the temperature prevailing at the region of focus drove the RHT value.

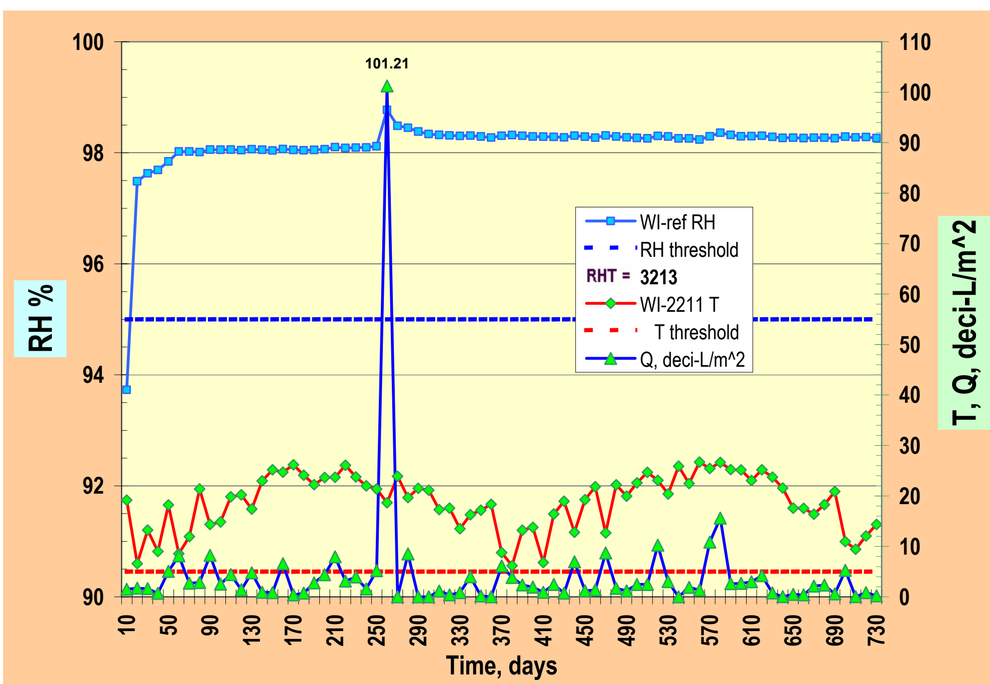


Figure 2.11 RH and T profiles for wall No. 2211 with 1Q set of moisture loads in the stud cavity, for Wilmington NC. RHT(95)= 3213

Observation No.4: ***Effect of Q between 0 and 1***. hygIRC predicted that the RHT(95) hygrothermal response of the wall improved in all locations when the moisture loads in the stud cavity was reduced to ¼ of the original loading (i.e. 1Q). (Effect: *small*)

Discussion: As mentioned before, allowing water entry into the stud cavity had a major effect on the hygrothermal performance of the wall. How much did Q have to drop to obtain a decisive reduction in RHT(95)? These hygIRC simulations suggested that Q would have to drop to less than ¼ of the original loads.

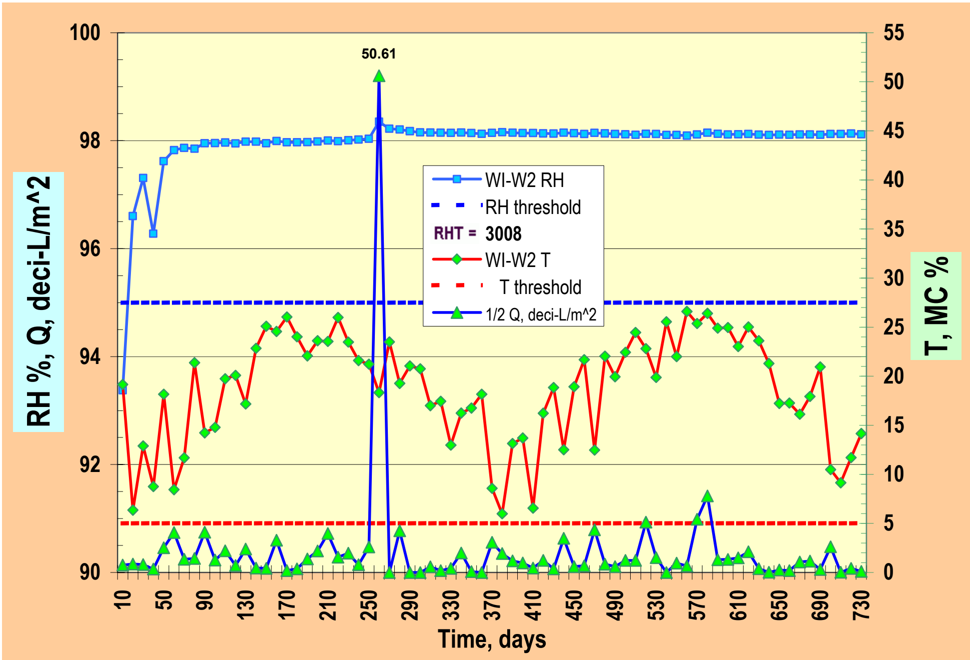


Figure 2.12 Predicted RH and T fluctuations for the reference wall in Wilmington NC when 1/2Q moisture loads in the stud cavity

It is interesting to note that the ½ Q simulation results for locations of higher moisture loads and lower drying potential had little effect on the RHT(95) wall response (Table 2.3). This suggested that even at ½ Q, the stud cavity was still "flooded", i.e. the wetting rate of stud cavity was about the same as the rate at which the indoor and outdoor climates (the forces) and the material properties (the path of resistance) promoted the drying of the materials. An examination of the RH fluctuations at the region of focus of the wall in Wilmington NC (Figure 2.12) and Winnipeg (Figure 2.13) suggested that little net drying effect occurred (the RH is rather stable around 98%).

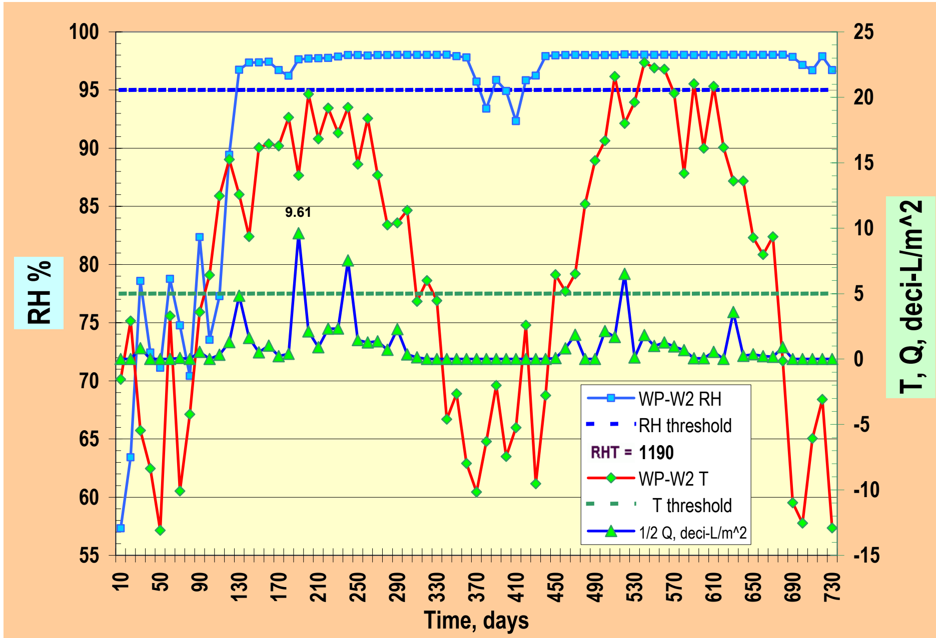


Figure 2.13 Predicted RH and T fluctuations for the reference wall in Winnipeg when 1/2Q moisture loads in the stud cavity

The relationship between cumulative RHT(95) and multiple of Q was not linear in climates with moderate to high moisture loads (Figure 2.14). The slope of the curve decreased as the moisture loads into the stud cavity got past a certain value (1/2 Q in Winnipeg and Ottawa; ¼ Q in Wilmington NC and Seattle).

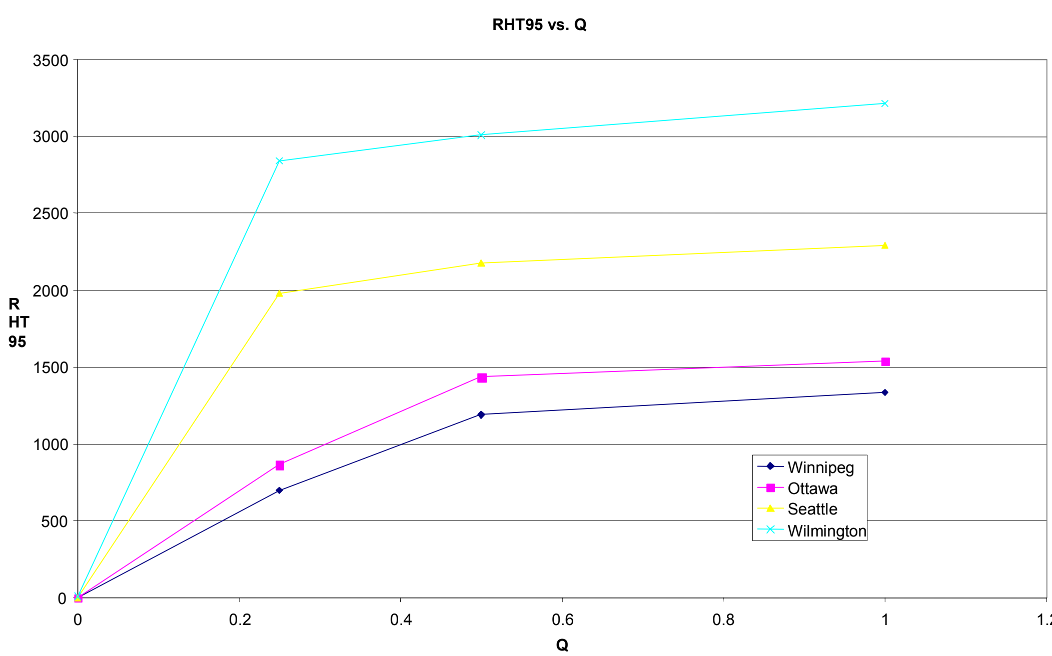


Figure 2.14. Predicted relationship between the RHT(95) hygrothermal response of the wall and the magnitude of the set of moisture loads into the stud cavity (Q) between 0 and 1

Effect of Material Properties in a Given Climate

Effect of the Properties of the Stucco Cladding

Observation: hygIRC simulations predicted that the properties of the three stucco plasters investigated in the parametric study would have essentially no effect on the hygrothermal response of the reference stucco-clad wall assembly, once water has entered the stud cavity at 1Q set of hourly moisture loads. Only in Phoenix did the reference wall showed a small improvement in RHT(95) with changing stucco plaster properties. (Effect: *near-zero to small*)

Discussion: Three stucco claddings were investigated (see Table 2.2 for some of properties). The simulation results are given in Table 2.4. One can see that when no water bypassed the stucco cladding and the water resistive barrier (at 0Q), the predicted RHT(95) wall response was at or near zero. That implied that the stucco cladding had a sufficient water resistance level to control water entry into the wall. When water bypassed the stucco cladding (at 1Q), the properties of these three stucco claddings did not make a difference in the wall RHT(95) response for the climates of Winnipeg, Ottawa, Seattle and Wilmington NC. In other words, for the wetting due to a 1Q moisture loads in the stud cavity and the external climate loads on the cladding, the drying ability of the wall was not much affected by the variation in properties of these three stucco claddings. Only when the moisture loads were low (i.e. in Phoenix), was there a slight reduction in RHT(95), particularly for Stucco No. 3. Stucco No. 3 had the lowest liquid diffusivity and the highest air permeability of the three stucco plasters investigated in this study.

Table 2.4: RHT (95) index comparison for three stucco claddings

Location/stucco cladding	RHT(95) response at a 1Q set of hourly moisture loads in the stud cavity				
	Phoenix	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
Stucco 2 (reference case) Wall No. 2211, at 0Q moisture loads in the stud cavity	0	0	0	0	9
Stucco 2 Wall No. 2211, at 1Q moisture loads in the stud cavity	655	1337	1536	2290	3213
Stucco 1 Wall No. 1211, at 1Q moisture loads in the stud cavity	427	1334	1528	2289	3186
Stucco 3 Wall No. 3211, at 1Q moisture loads in the stud cavity	326	1335	1530	2281	3168

Effect of the Properties of the Water Resistive Barrier

Observation: For all climates investigated, hygIRC simulations predicted that the properties of the three water resistive barriers included in the parametric study had essentially no effect on the hygrothermal response of the reference stucco-clad wall assembly, as the RHT(95) results were almost identical. (Effect: *near-zero*)

Discussion: Three water resistive barriers were investigated: a polymeric and two paper-based membranes (see Table 2.2 for their properties). The simulation results are given in Table 2.5. The properties of these three water resistive barriers were predicted to have essentially no effect on the hygrothermal response of the wall assembly, once a 1Q set of moisture loads has entered in the stud cavity over the two years of simulation runs. The main purpose of the water resistive barrier is to protect the back up wall from further water intrusion once water has penetrated the cladding assembly. In the simulations, water was allowed to bypass the water resistive barrier and the sheathing board and reach the stud cavity (simulating a poor detailing around a through-the-wall penetration). The simulations mainly investigated how the hygrothermal properties of the water resistive barrier could affect the evaporative drying of the stud cavity, rather than its effect on water ingress into the back up wall.

Table 2.5: RHT (95) index comparison for three water resistive barriers

Location/water resistive barrier	RHT(95) response at a 1Q set of hourly moisture loads in the stud cavity				
	Phoenix	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
WRB1 Wall No. 2211	655	1337	1506	2290	3213
WRB2 Wall No. 2111	666	1338	1537	2292	3212
WRB3 Wall No. 2311	713	1338	1538	2294	3217

Effect of the Properties of the Sheathing Board

Observation #3: hygIRC simulations suggested that the properties of the three sheathing boards included in the parametric study only made a very small difference in the wall RHT(95) hygrothermal response, once a 1Q set of hourly moisture loads entered the stud cavity. (Effect*: near-zero to small*)

Discussion: hygIRC prediction results are presented in Table 2.6. In simulation runs for Ottawa and Wilmington NC, the use of uncoated fibreboard in lieu of OSB or plywood resulted in a very small improvement in RHT(95) wall response. Changing OSB for plywood made essentially no difference in the RHT(95) wall response. Even uncoated fibreboard, with its higher vapour and air permeabilities, was unable to lower RHT(95) significantly, considering the magnitude of the moisture loads wetting the stud cavity.

Table 2.6: RHT(95) index comparison for three sheathing boards

	RHT(95) wall response at 1Q set of moisture loads in the stud cavity			
	For Ottawa		For Wilmington NC	
Sheathing board	Wall No. 2211[1]	Wall No. 2213[2]	Wall No. 2211[1]	Wall No. 2213[2]
OSB	1536	1482	3213	3080
Plywood	1468	1395	*	3003
Uncoated fibreboard	1329	1122	*	2927

1. Wall No. 2211 was the reference wall used for most of the parametric evaluation
2. Wall No. 2213 had the combination of material properties that appeared most beneficial on RHT reduction

An asterisk, *, indicates no simulation for the specific parameter

Effect of the Properties of Vapour Barrier Membrane

Observation No. 1: For climates with lower MI, hygIRC predicted that using a vapour barrier membrane with a higher vapour permeance (VB3 membrane) improved the RHT(95) hygrothermal response of the wall assembly at the region of focus. For other climates investigated, the improvement varied from marginal to very small. (Effect: *near-zero to small*)

Discussion: Three vapour barrier membranes were investigated for several locations (See Table 2.2 and Figure 2.15 for some of their properties). Simulation results are presented in Table 2.7, as well as in Figure 2.7 (green curve). VB3 was more water vapour permeable than the other two membranes. No RHT(95) reduction could be measured in locations of higher moisture loads because the wetting rate of the stud cavity was larger than the drying capability contributed by even the more permeable of the three membranes investigated. It would take a material of much higher permeability to overcome the wetting rate of the stud cavity associated with these more severe climate loads (see observation No.2).

It should be noted that the apparent improvement in moisture response of the walls with a loosening of the vapour barrier should not be taken outside the context of the MEWS parametric simulations. The interior conditions assumed played a role in the results. The interior RH conditions of 55% in the summer and 25% in the winter provided a strong driving force for drying to the interior. The effect might be much less or even reversed if different interior conditions prevail.

Table 2.7: RHT (95) index comparison for vapour barriers of different properties

	RHT(95) wall response at a 1Q set of moisture loads in the stud cavity						
Vapour barrier membrane	**Phoenix**	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
VB1 membrane (Wall No.2211)	655	1421	2256	1337	1536	2290	3213
VB2 membrane (Wall No. 2212)	389	*	*	1321	1517	2245	3161
VB3 membrane (Wall No. 2213)	230	649	1269	1295	1482	2148	3080

An asterisk, *, indicates no simulation for the specific parameter

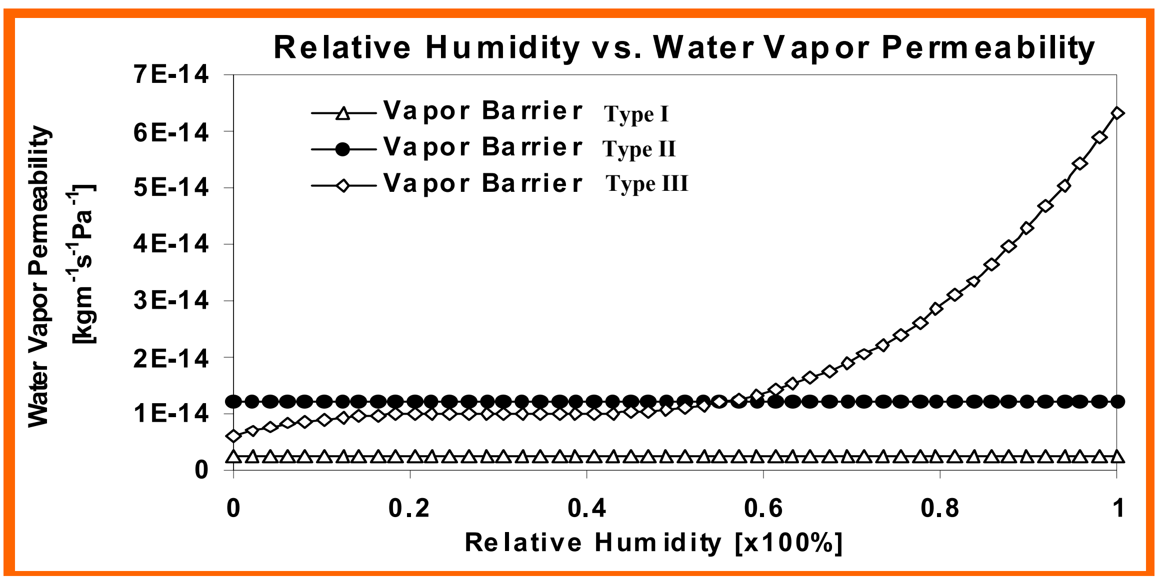


Figure 2.15 Relationship between vapour permeability and relative humidity of 3 VB membranes

Observation No. 2: hygIRC simulations predicted that a large increase in the vapour transmission characteristics on the interior side of a wet stud cavity improved the RHT(95) wall response when the indoor RH conditions were well controlled (as per ASHRAE guidelines). (Effect: *substantial*)

Discussion: Table 2.8 provides sets of the simulation results leading to that observation. Looking at the two middle rows of results, one can compare the RHT(95) response of the wall with a VB3 membrane with the RHT(95) response of the wall with no vapour control strategy, as well as with the response of the wall with three coatings on the interior gypsum board but no VB membrane.

The vapour transmission rate of the interior layer of materials was higher when no vapour barrier membrane was in place; this allowed moisture from the wet stud cavity (due to exterior water leakage allowed by a deficiency) to migrate indoors as the indoor vapour pressure was lower than the vapour prssure in the wet stud cavity. As a result of this moisture transfer indoor, the magnitude of the RHT(95) response at the region of focus dropped. The drop in RHT(95) was predicted to be substantial even when the indoor RH was higher (see at 50-75% RH) for the wall with no vapour control strategy in place. Even though this set of simulation results presented an indication of a trend, in practice, interior gypsum board in residential buildings gets a finishing treatment of some sort, and this treatment would affect the vapour transmission characteristics of the drywall, most likely reducing its vapour permeability. The single result in the right-hand side column for a coated gypsum board with no vapour barrier membrane indicated a substantial improvement in the RHT(95) wall response but of smaller magnitude than the improvement predicted when no coating was in place.

Further investigation into the hygrothermal response of wall assemblies when changing the vapour transmission characteristics of the interior layers of the wall assembly, the indoor climate severity and the other typical characteristics of wall assemblies found in practice, such as air leakage, is necessary prior to make general statements.

Table 2.8 RHT(95) wall response for wall No. 2213 exposed to varying indoor RH levels, with and without a VB membrane in Wilmington NC

Winter RH (%)	Summer RH (%)	RHT (95) for wall with VB3 membrane	RHT (95) for wall without VB membrane, and with an unpainted gypsum board	RHT (95) for wall without VB membrane, and with a painted gypsum board (see Note 1)
25	55	3080	*	1128
25	65	3094	926	*
25	75	3117	*	*
40	65	3099	1085	*
40	75	3123	*	*
50	75	3126	1610	*

An asterisk, *, indicates no simulation for the specific parameter

Note 1. The interior gypsum board was coated with a coat of primer and two coats of latex paint (vapour permeability varying between 2 ng/Pa·s·m at 0%RH to 31 ng/Pa·s·m at 100%RH (in the X axis))

Effect of Variations in Indoor RH

Observation No. 1: One set of hygIRC simulation runs for a wall exposed to severe exterior moisture loading (i.e. Wilmington NC) showed that increasing the indoor RH had no effect on the RHT(95) wall response when a tight vapour barrier was in place and no air leakage paths were present. (Effect: *near-zero*)

Discussion: Most of the simulations made use of ASHRAE guidelines on indoor RH and T for summer and winter conditions (i.e. 25%RH in winter and 55%RH in summer). It was pointed out by MEWS consortium members that actual indoor conditions in the warm and wet climate of Wilmington NC are generally much more humid. To investigate this situation, additional simulations were done in which indoor RH was varied from 25% to 50% in winter, and from 55% to 75% in summer for the wall with the "best" combination of properties. Table 2.8 presents the results of the simulations (in the grey column). The absence of an effect due to increased indoor RH levels can be explained by the very low water vapour transmission characteristics of the vapour barrier membrane as well as the absence of air leakage path between indoors and the stud cavity. In other words, the way the simulation run was set up, there was essentially no mechanism for moisture transfer between indoors and the stud cavity. The following set of simulations explored what might happen when the water vapour transmission resistance between indoors and the stud cavity is reduced.

Observation No. 2: One set of hygIRC simulation runs for a wall assembly exposed to severe exterior moisture loading (i.e. Wilmington NC) predicted that increasing the indoor RH had a negative effect on the RHT(95) wall response when no vapour barrier strategy (e.g. no membrane or coating interior finish gypsum board) was in place and no air leakage paths were present. (Effect: *small*)

Discussion: Table 2.8 (middle column of results) suggests that an increase in indoor RH resulted in a small increase in the RHT(95) hygrothermal response of the wall No. 2213. As the resistance to moisture transfer between indoors and the stud cavity was reduced when no vapour transmission control strategy was in place, it is likely that some moisture diffusion from the wet stud cavity to indoors occurred. However the rate of such moisture transfer slowed down as the indoor RH increased because the vapour pressure difference across was lower. Again in this simulation set, no air leakage path was in place to allow additional mass transfer from a location of higher pressure to a location of lower pressure. It is generally accepted that air leakage is a more powerful mechanism of mass transfer than diffusion.

Effect of Adding a Vented Cavity Behind the Stucco Cladding

Observation: hygIRC simulations suggested that the addition of an unobstructed cavity behind the stucco cladding did not affect the RHT(95) response of the reference wall when a 1Q set of moisture loads was placed in the stud cavity. Whether vents were in place at the bottom only or at both top and bottom of the cavity appeared to make little difference. (Effect: *near-zero*)

Discussion: To investigate the drying potential of a cavity behind the stucco cladding, different wall configurations were exposed to three different sets of climatic conditions (i.e. Winnipeg, Ottawa and Seattle). One configuration was for a given assembly *without* a clear cavity behind the cladding. The same assembly but *with* a cavity were also simulated: one with continuous openings at the bottom only and another with continuous openings at both top and bottom. These walls contained a deficiency that allowed a 1Q set of moisture loads into the stud space. Please note that the simulation set-up was such that the drying ability offered by a cavity was the prime object of the simulation run, as opposed to the ability of the cavity to drain off, and thus reduce, the moisture loads placed in the stud cavity. Indeed, in this run, Q, the set of moisture loads injected in the stud cavity was the same for the wall without a cavity and with the cavity. Results of simulations are presented in Table 2.9. For all three climates investigated, the results clearly indicated that the RHT(95) wall response was not sensitive to the addition of a cavity, whether fully or partially vented. The RHT(95) responses suggested that the rates of moisture loading into the stud cavity was much larger than the rates of moisture withdrawal (evaporation) contributed by the introduction of a clear open cavity.

Table 2.9 RHT(95) response with and without a vented cavity behind the cladding

Location & simulated wall configurations	RHT(95) response at 1Q set of moisture loads in the stud cavity
Winnipeg (MI= 0.86)	
Wall No. 2231 with 1 slot of vent at top and bottom of 19 mm cavity	1426
Same wall with 1 slot of vent at bottom of 19 mm cavity	1437
Same wall with no cavity (reference)	1320
Ottawa (MI = 0.93)	
Wall No. 2231with a slot of vents at top and bottom of 19 mm cavity	1603
Same wall with 1 slot of vent at bottom of 19 mm cavity	1634
Same wall with no cavity	1515
Seattle (MI= 0.99)	
Wall No. 2231with a slot of vents at top and bottom of 19 mm cavity	2376
Same wall with no cavity	2260

Effect of Air Flow

Observation: hygIRC predicted that some air flow introduced into the stucco-clad reference wall in Ottawa and Seattle would improve the RHT(95) wall response when a 1Q set of moisture loads was injected into in the stud cavity. (Effect: *small*)

Discussion: The reference wall used for the parametric study did not include any opening (or path) to allow airflow through the wall assemblies. The only airflow occurring in the reference wall was based on the air permeance of each material. However in practice, walls are not completely free of unintentional cracks and openings that allow some through-flow of air in the presence of forces like wind and temperature difference. This airflow could have an effect on the wetting and possibly the drying of a wet assembly. As a result, one additional set of simulations was included to investigate this effect. Ottawa and Seattle were selected to represent cold and warm climates with high moisture loads. Openings at the top on the exterior and at the bottom on the interior of the reference wall were introduced to allow an indirect air leakage path. The opening size represented a leakage area of 2cm^2 per m^2 of wall, about the average measured in residential buildings. Results from the simulations are presented in Table 2.10.

Table 2.10 RHT(95) response for a wall with and without uncontrolled airflow, at 1Q set of moisture loads in the stud cavity

	RHT(95) for Ottawa	RHT(95) for Seattle
Reference wall (No. 2211) *without* uncontrolled airflow	1536	2290
Same wall *with* uncontrolled airflow	1198	1735

Small reductions in RHT(95) wall response were predicted for both locations when some uncontrolled airflow was introduced into the assembly. In the simulation runs, the direction of the flow was dictated by the natural occurrence of wind and stack effects. Mostly exfiltration of indoor air was observed in the simulation runs. In these runs, indoor air was quite a bit dryer (25%RH in winter and 55%RH in summer) than the stud cavity (around 98%). Exfiltration of small amounts of warm and relatively dry indoor air through such an indirect path was predicted to contribute to the drying of a stud cavity wetted by rain penetration.

Air leakage is an uncontrolled phenomenon that may have negative effects on the hygrothermal performance of wall assemblies in certain climates and circumstances. Most research on air leakage has focused on the wetting potential related to the exfiltration of large amounts of humid indoor air, which is not the case in these simulation runs. The rate of air leakage can be of critical importance in regard to the potential for transporting moisture in or out of the wall cavity. The drying potential associated with a *small* flow of mostly warm and relatively dry air across a wet wall assembly compared to the same wall with *zero* air leakage has not yet been examined thoroughly. Further investigation into the positive and negative effects of various rates of air leakage on the moisture deposition and moisture removal capacity of air flow through a wall assembly in different climates are required prior to making general statements.

Appendix 2.1 All hygIRC Simulation Results
(See the codes for the simulation ID on page 2-26)

RHT (95) Indices (Bottom Plate)

Simulation ID	RHT (95) Index
OTTAWA	
OTS2M2O1V1BC	0
OTS2M2O1V1	1536
OTS2M2O2V1	1506
OTS2M2O3V1	1515
OTS1M2O1V1	1528
OTS3M2O1V1	1530
OTS2M1O1V1	1537
OTS2M3O1V1	1538
OTS2M2O1V2	1517
OTS2M2O1V3	1482
OTS2M2O1V1W2	1434
OTS2M2O1V1W4	864
OTS2M2O1V1WD	
OTS2M2O3V1CB	1603
OTS2M2O3V1CL	1634
OTS2M2F*V3	1122
OTS2M3F*V1	1633
OTS2M2F*V1BC	
OTS2M2F*V1	1329
OTS3M1O1V3BP	
OTS1M1O3V3BR	
OTS2M3O1V1WR	
OTS2M2P*V3	1395
OTS2M3P*V1	1483
OTS2M2P*V1BC	
OTS2M2P*V1	1468
OTS2M2O1V0NV	170
OYS2M3O1V0NV	170
OTS2M2O1V1AL	1198
OTS2M2O1V1NAG	
OTS2M2O1V1LT	

Simulation ID	RHT (95) Index
PHOENIX	
PHS2M2O1V1BC	0
PHS2M2O1V1	655
PHS2M2O2V1	562
PHS2M2O3V1	585
PHS1M2O1V1	427
PHS3M2O1V1	326
PHS2M1O1V1	666
PHS2M3O1V1	713
PHS2M2O1V2	389
PHS2M2O1V3	230
PHS2M2O1V1W2	
PHS2M2O1V1W4	
SEATTLE	
SES2M2O1V1BC	0
SES2M2O1V1	2290
SES2M2O2V1	2244
SES2M2O3V1	2260
SES1M2O1V1	2289
SES3M2O1V1	2281
SES2M1O1V1	2292
SES2M3O1V1	2294
SES2M2O1V2	2245
SES2M2O1V3	2148
SES2M2O1V1W2	2177
SES2M2O1V1W4	1979
SES2M2O3V1CB	2376
SES2M2O3V1CBBC	
SES2M2O1V1AL	1735
Grey = Second series	

Simulation ID	RHT (95) Index
WILMINGTON	
WIS2M2O1V1BC	9
WIS2M2O1V1	3213
WIS2M2O2V1	3168
WIS2M2O3V1	3180
WIS1M2O1V1	3186
WIS3M2O1V1	3168
WIS2M1O1V1	3212
WIS2M3O1V1	3217
WIS2M2O1V2	3161
WIS2M2O1V3	3080
WIS2M2O1V1W2	3008
WIS2M2O1V1W4	2841
WIS2M2O1V1WD	
WIS2M2F*V3	2927
WIS2M3F*V1	
WIS2M2F*VIBC	
WIS2M2F*V1	
WIS3M1O1V3BP	
WIS3M1O3V3BR	
WIS2M3O1V1WR	
WIS2M2P*V3	3003
WIS2M3P*V1	
WIS2M2P*VIBC	
WIS2M2P*VI	
WIS2M2O1V0NV	
WIS2M3O1V0NV	
WIS2M2O1V32575	3117
WIS2M2O1V35075	3126
WIS2M2O1V32565	3094
WIS2M2O1V34075	3123
WIS2M2O1V34065	3099

Simulation ID	RHT (95) Index
WIS2M2O1VN2575	
WIS2M2O1VN5075	1610
WIS2M2O1VN2565	926
WIS2M2O1VN4065	1085
WIS2M2O1V1BC_VD	
WIS2M2O1V1NRBC	
WIS2M2O1V0CG	1128
WINNIPEG	
WPS2M2O1V1BC	0
WPS2M2O1V1	1337
WPS2M2O2V1	1310
WPS2M2O3V1	1320
WPS1M2O1V1	1334
WPS3M2O1V1	1335
WPS2M1O1V1	1338
WPS2M3O1V1	1338
WPS2M2O1V2	1321
WPS2M2O1V3	1295
WPS2M2O1V1W2	1190
WPS2M2O1V1W4	697
WPS2M2O3V1CB	1426
WPS2M2O3V1CL	1437
(F) FRESNO	
FRS2M3O1VI	
FRS2M2O1V3	649
FRS2M2O1V1BC	0
FRS2M2O1V1	1421
(G) SAN DIEGO	
SDS2M3O1V1	
SDS2M2O1V3	1269
SDS2M2O1V1BC	0
SDS2M2O1V1	2256

RHT (80) Indices

Simulation ID	RHT (80) Index
OTTAWA	
OTS2M2O1V1BC	74
OTS2M2O1V1	9118
OTS2M2O2V1	8981
OTS2M2O3V1	9016
OTS1M2O1V1	9178
OTS3M2O1V1	9162
OTS2M1O1V1	9120
OTS2M3O1V1	9103
OTS2M2O1V2	9058
OTS2M2O1V3	8941
OTS2M2O1V1W2	8826
OTS2M2O1V1W4	7912
OTS2M2O1V1WD	
OTS2M2O3V1CB	9960
OTS2M2O3V1CL	10032
OTS2M2F*V3	8723
OTS2M3F*V1	9665
OTS2M2F*V1BC	
OTS2M2F*V1	9049
OTS3M1O1V3BP	
OTS1M1O3V3BR	
OTS2M3O1V1WR	
OTS2M2P*V3	8610
OTS2M3P*V1	8827
OTS2M2P*V1BC	
OTS2M2P*V1	8828
OTS2M2O1V0NV	4173
OYS2M3O1V0NV	4188
OTS2M2O1V1AL	7948
OTS2M2O1V1NAG	
OTS2M2O1V1LT	

Simulation ID	RHT (80) Index
PHOENIX	
PHS2M2O1V1BC	0
PHS2M2O1V1	7826
PHS2M2O2V1	8034
PHS2M2O3V1	8034
PHS1M2O1V1	5932
PHS3M2O1V1	5164
PHS2M1O1V1	7884
PHS2M3O1V1	8344
PHS2M2O1V2	5547
PHS2M2O1V3	4170
PHS2M2O1V1W2	
PHS2M2O1V1W4	
SEATTLE	
SES2M2O1V1BC	3495
SES2M2O1V1	13273
SES2M2O2V1	13050
SES2M2O3V1	13099
SES1M2O1V1	13336
SES3M2O1V1	13322
SES2M1O1V1	13284
SES2M3O1V1	13260
SES2M2O1V2	13138
SES2M2O1V3	12905
SES2M2O1V1W2	12976
SES2M2O1V1W4	12504
SES2M2O3V1CB	14309
SES2M2O3V1CBBC	
SES2M2O1V1AL	11157
Grey = Second series	

Simulation ID	RHT (80) Index
WILMINGTON	
WIS2M2O1V1BC	10796
WIS2M2O1V1	18386
WIS2M2O2V1	18179
WIS2M2O3V1	18227
WIS1M2O1V1	18413
WIS3M2O1V1	18366
WIS2M1O1V1	18385
WIS2M3O1V1	18378
WIS2M2O1V2	18253
WIS2M2O1V3	18065
WIS2M2O1V1W2	17943
WIS2M2O1V1W4	17597
WIS2M2O1V1WD	
WIS2M2F*V3	18116
WIS2M3F*V1	
WIS2M2F*VIBC	
WIS2M2F*V1	
WIS3M1O1V3BP	
WIS3M1O3V3BR	
WIS2M3O1V1WR	
WIS2M2P*V3	17739
WIS2M3P*V1	
WIS2M2P*VIBC	
WIS2M2P*VI	
WIS2M2O1V0NV	
WIS2M3O1V0NV	
WIS2M2O1V32575	18144
WIS2M2O1V35075	18176
WIS2M2O1V32565	18092
WIS2M2O1V34075	18167
WIS2M2O1V34065	18106

Simulation ID	RHT (80) Index
WIS2M2O1VN2575	
WIS2M2O1VN5075	14550
WIS2M2O1VN2565	11447
WIS2M2O1VN4065	11978
WIS2M2O1V1BC_VD	
WIS2M2O1V1NRBC	
WIS2M2O1V0CG	12431
WINNIPEG	
WPS2M2O1V1BC	0
WPS2M2O1V1	7999
WPS2M2O2V1	7886
WPS2M2O3V1	7922
WPS1M2O1V1	8037
WPS3M2O1V1	8026
WPS2M1O1V1	8003
WPS2M3O1V1	7982
WPS2M2O1V2	7962
WPS2M2O1V3	7873
WPS2M2O1V1W2	7616
WPS2M2O1V1W4	6372
WPS2M2O3V1CB	8718
WPS2M2O3V1CL	8746
FRESNO	
FRS2M3O1VI	
FRS2M2O1V3	6287
FRS2M2O1V1BC	828
FRS2M2O1V1	12119
SAN DIEGO	
SDS2M3O1V1	
SDS2M2O1V3	10546
SDS2M2O1V1BC	0
SDS2M2O1V1	17753

Explanations for the coding used in the simulation ID in the tables

Simulation id. are similar in formatting to this example: OTS2M2F*V1BC

- The first two letters define the location. Example, OT for Ottawa, etc
- The next letter and number define the stucco cladding. Ex: S2 is stucco No.2
- The next letter and number define the type of water resistive membrane. Ex. M2 is membrane No.2
- The next letter and symbol define the sheathing board. O means OSB, P for plywood and F for natural fibreboard. The star is replaced by a number when more than one product had been characterised in laboratory.
- The next letter and number define the vapour barrier. V1 is vapour barrier No.1. V0 means no vapour barrier

There may be additional letters at the end of the code to give more information on the simulation case. Ex. BC means base case i.e. the wall has no deficiency for water leakage into the stud cavity.

When a simulation ID has following letters, it means:

BC : No water entry into the stud cavity
CB : Cavity behind the stucco has opening both at top and bottom
CL : Cavity behind the stucco has opening at the bottom only
WD : Simulation done with Wet-Dry weather years instead of Wet-Average
F* : Presence of natural fiberboard in place of OSB
P* : Presence of plywood in place of OSB
BP : Simulation done with the best material combination derived from parametric analysis
BR : Simulation done with the best material combination derived from RHT indices
WR : Simulation done with the worst material combination derived from RHT indices
NV : No vapour barrier
AL : Air leakage included
NAG : No air-gap between sheathing membrane and sheathing board
LT : Alternate Wet-Avg years
_VD : Vapor permeability and liquid Diffusivity of the stucco have been altered

Chapter 3. Application to EIFS-clad walls

3.1 Summary

Several field surveys and studies have indicated that EIFS lamina has exhibited a high resistance to water penetration in the field of the wall. Observed moisture problems have had to do with water that bypassed the EIFS lamina and water resistive barrier (e.g. through some interface deficiencies) and entered further into the wall assembly. The results of hygIRC parametric study of EIFS-clad walls pointed in the same direction. The design of the EIFS wall was sensitive to water entering the stud cavity. The combined effect of higher stud cavity temperature because of the outboard thermal insulation and lower drying potential due to the low vapour permeability of the wall materials had a detrimental effect on the RHT(95) hygrothermal response of the wall when water accidentally entered the stud cavity.

Highlights of the results are as follows:

- The EIFS laminas investigated exhibited a level of water resistance that reduced significantly the amount of water getting through the field of the wall. The characterization of the material properties (TG3) indicated that the liquid diffusivity of the EIFS lamina –the measure of the capacity of liquid water to pass through a material- was relatively low. hygIRC simulations indicated that when no water was allowed to enter into the wall assembly (i.e. no deficiency), the RHT(95) hygrothermal response of the reference EIFS-clad wall was predicted to be zero, even in a climate of severe moisture loads like Wilmington NC.

- When the same EIFS-clad reference wall included a small deficiency (nominally 1 mm X 50 mm) that allowed direct water entry beyond the water resistive barrier, i.e. into the stud cavity, the RHT(95) response of the wall was quite different. The RHT(95) hygrothermal responses varied from a value of about 1200 in a hot and dry climate of Phoenix to about 4000 for the warm and wet climate of Wilmington NC. This indicated that this amount of water entering the stud cavity (the "1Q" set of hourly moisture loads) was excessive in relation to the evaporative drying potential offered by the properties of the materials in the wall assembly and the temperature prevailing in the stud cavity. Both the thermal characteristics and the vapour permeance of the wall materials affected the wall response. The presence of the exterior insulating sheathing (EPS insulation) dampened outdoor temperature swings in the stud cavity: in the heating season the temperature in the stud cavity was higher compared to that in a wall with no exterior insulating sheathing, and in the cooling season, it was lower. Higher temperature in the region of focus resulted in higher RHT(95) values, when the RH condition of 95% was met. Secondly, the outer and inner layers of the walls offered only a limited drying capability for the assembly, as the vapour permeance of the materials on both sides of the wetted stud cavity was quite low.

- The outdoor climate played an important role in the RHT(95) hygrothermal response of the reference wall, in two ways: it defined the wetting potential of the cladding and the stud cavity, as well as the evaporative drying drive. Walls exposed to climates with severe moisture loads (high MI) reached a stud cavity RH level above 95% after a few months of climate exposure and this RH remained stable until the end of the two-year simulation period. Early on, the EIFS-clad reference wall appeared overwhelmed by the moisture loads, which were not adequately reduced by drying during the course of the simulation run. In mild climates, the moisture loads were low and the drying potential high. In that case hygIRC predicted large swings of wetting and drying of the region of focus (i.e. low MI) of the reference wall resulting in much lower cumulative RHT(95) wall response than in climates like Wilmington NC and Seattle.

- When the moisture load in the stud cavity was reduced, a small to substantial drop in the RHT(95) wall response was predicted to occur. A substantial drop in RHT(95) response was predicted in all climates investigated when ¼ of the original moisture loads (referred to as 1/4Q) was injected into the stud cavity. This moisture load reduction brought the reference wall RHT(95) to a near-zero value in Fresno while the same wall in Wilmington NC reached an RHT value approaching 3000. When the load in the stud cavity was reduced by half, a small reduction in RHT(95) was predicted for cold, or for warm and humid climates (i.e. Winnipeg, Ottawa, Seattle and Wilmington NC) while the RHT(95) drop was substantial in Fresno and San Diego.

- The parametric study was carried out using a 1Q set of hourly moisture loads into the stud cavity. Under this condition, hygIRC predicted that the following variations made a near-zero to small difference in the RHT(95) response of the reference wall assembly:
  - Changing the thickness of the EIFS lamina
  - Changing the properties of the sheathing board
  - Changing the properties of the water resistive barrier
  - Changing indoor RH level
  - Changing the severity of the second climate year

- Interchanging vapour barrier *membranes* was predicted to have a small to near-zero effect on the RHT(95) wall response for all climates investigated. The drying potential offered by their vapour permeance was not sufficient to offset the wetting due to a 1Q set of moisture loads in the stud cavity. A single additional simulation for Wilmington NC predicted that a large increase in the vapour permeance of the materials placed on the inside of the stud cavity (i.e. the vapour barrier membrane is traded for three coats of paint on the interior finish gypsum board) brought a noticeable drop in the RHT(95) wall response. However the interior conditions set for the simulation favoured drying to the inside, and the simulation result should not be generalized without further analyses for other sets of indoor conditions.

- In all climates investigated, hygIRC predicted that the reference wall ***with*** insulation in the stud cavity obtained a substantially ***lower*** RHT(95) value than did the same wall without insulation. The effect was less pronounced in locations of mild moisture loads. Examination of RH contour plots over a full height cross-section of the wall assembly indicated that this reduced RH response can be related to a "wicking" effect of the cavity insulation in contact with the bottom plate (i.e. the region of focus), and the associated redistribution of moisture away from the region of focus. The thermal insulation in the stud cavity had little effect on the temperature regime *at the region of focus*, i.e. the top of the bottom plate, as heat conduction through the wood was the predominant mechanism of heat transfer.

- For Ottawa and Seattle climates, the introduction of uncontrolled climate-driven air flow through the wall assembly was predicted to result in a near-zero to small reduction in the RHT(95) response of the EIFS-clad reference wall, for both "1Q" and 1/4Q sets of moisture loads in the stud cavity. Further investigation into the effects of various rates of airflow through a wetted assembly on moisture deposition and removal is required prior to making general statements.

- Based on a single simulation run for Ottawa, changing the location of the water deposition from the bottom of the stud cavity to mid-height of the wall between the WRB and sheathing board, was predicted to have a very small effect on the cumulative RHT(95) value for the respective region of focus in question. However the pattern of moisture distribution was somewhat different.

The following sections describe how the MEWS method (Chapter 1) is used to predict the RHT(95) response of EIFS-clad wall assemblies, and provide a discussion of the RHT (95) response obtained in the parametric study.

3.2 Selection of Materials and Design of the Wall Assemblies

MEWS industry members and IRC personnel (TG2) gathered technical information on current practices in the construction of EIFS-clad wall assemblies. This information was used for the design of 5 full-scale wall specimens for the investigation of water entry into stud cavities under simulated wind-driven rain pressure (TG6), the design of wall assemblies for the hygIRC parametric study (TG 7) and for the characterization of material properties (TG3).

Published literature of field survey and laboratory testing indicated that several water penetration problems in EIFS-clad walls have been related to poor detailing allowing water entry behind the EIFS lamina. Traditionally, EIFS systems have not included a drained cavity between the water resistive barrier (also known as sheathing membrane) and the EIFS foam board. New EIFS systems that include some means of facilitating the drainage at that interface are now available on the market. These features include but are not limited to vertical grooves in the foam insulation, notches in an adhesive coating and drainage mats. Several features of these systems are included in the 5 large-scale wall specimens used for the investigation of water entry in IRC Dynamic Wall Testing facility (DWTF).

3.2.1 Types of Wall Assemblies Selected

Two generic types of EIFS-clad assemblies were examined, as defined by the moisture management strategies used:

- One wall assembly without a drained cavity behind the EIFS lamina and foam board (Figure 3.1). This one included no WRB in the field of the wall but included some redundancy at interfaces with penetrations.
- Four wall assemblies with different features intended to facilitate water drainage behind the EIFS lamina and foam board (Figures 3.2, 3.3, 3.4 and 3.5)

The construction of the 5 EIFS wall specimens investigated in the DWTF is described in T2-02 report entitled: *Description of the 17 Large-scale Specimens Built for Water Entry Investigation in IRC Dynamic Wall Testing Facility,* May 2002.

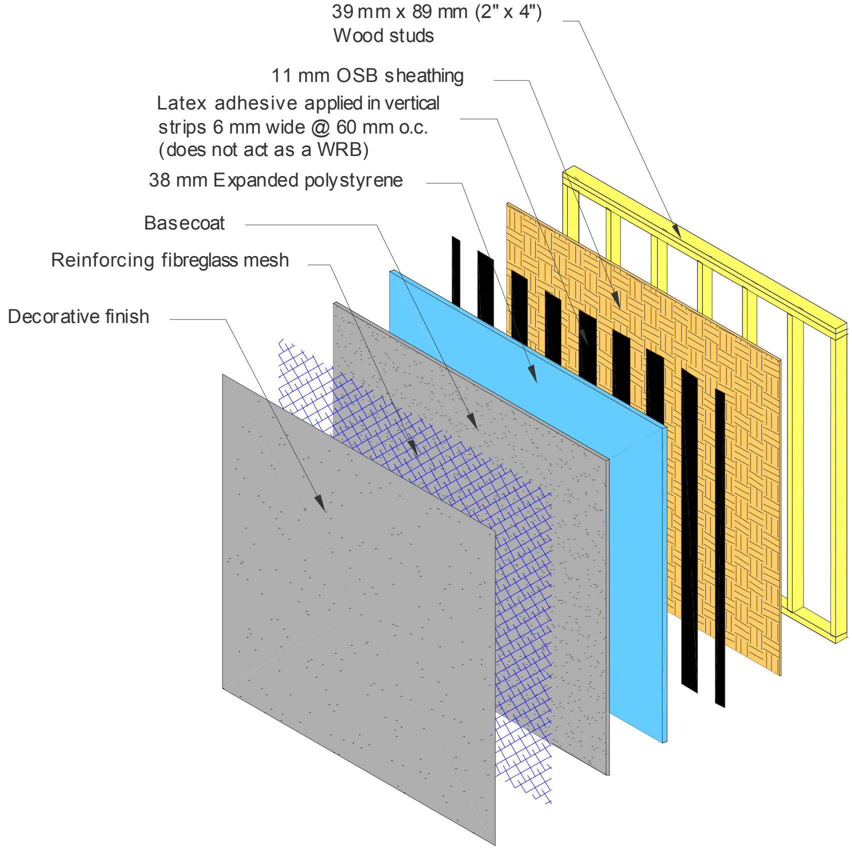


Figure 3.1. EIFS-clad wall assembly (specimen No. 6) with no WRB in the field of the wall.

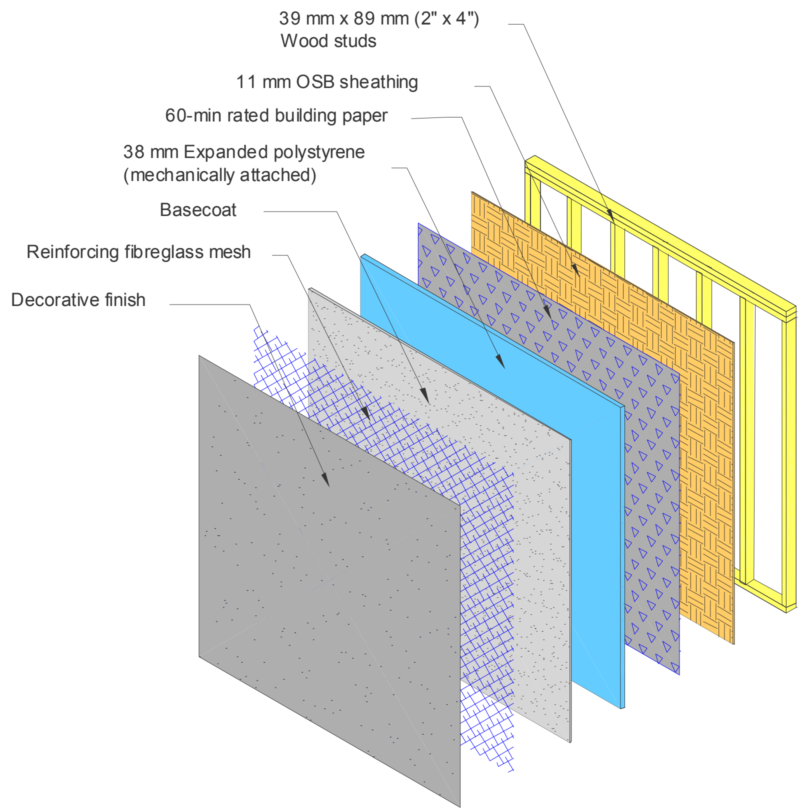


Figure 3.2. EIFS-clad wall (specimen No. 7) with a WRB and mechanical attachment of the EPS board

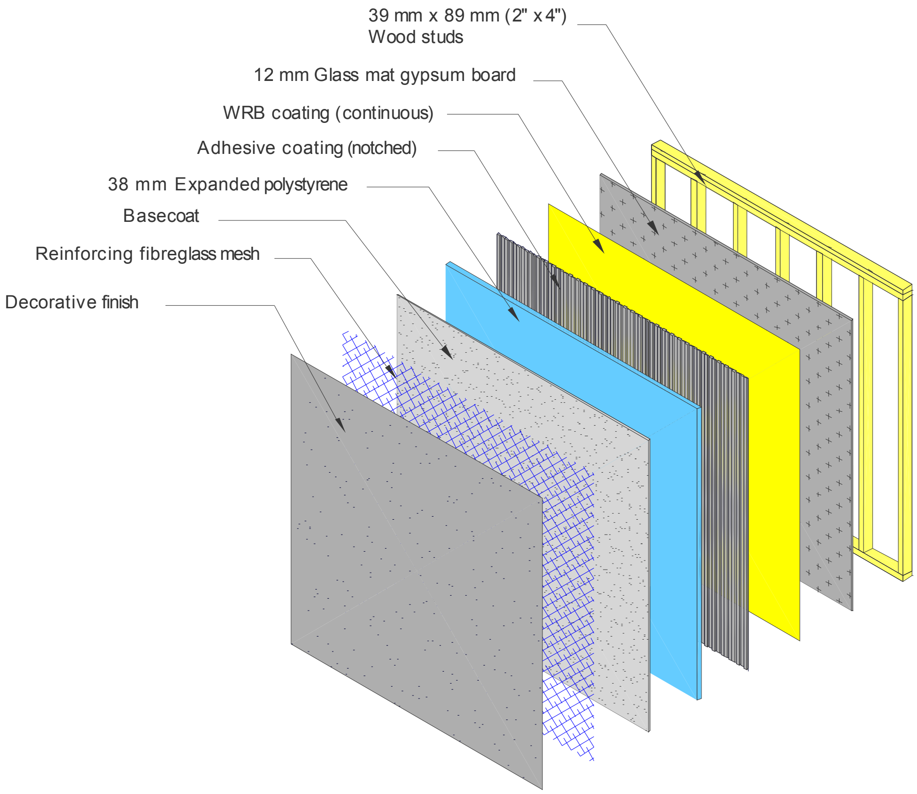


Figure 3.3. EIFS-clad wall (specimen No. 8) with a WRB and an adhesive coating notched for drainage

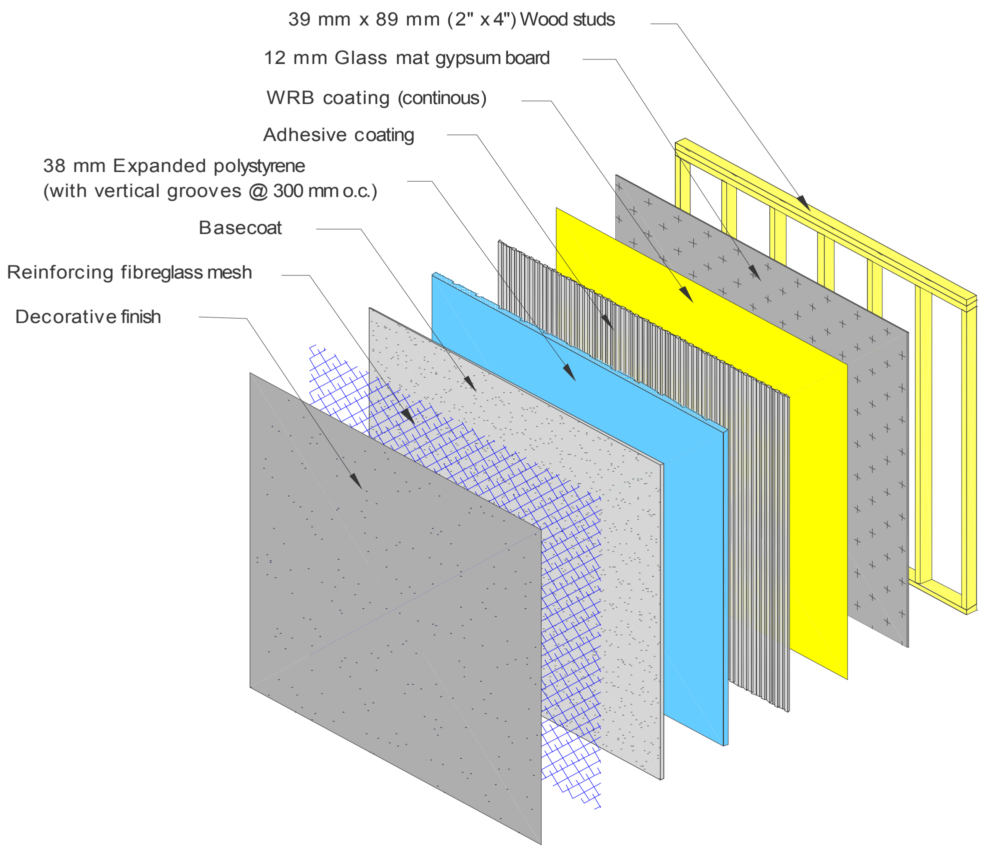


Figure 3.4. EIFS-clad wall (specimen No. 9) with a WRB and EPS foam with vertical grooves for drainage

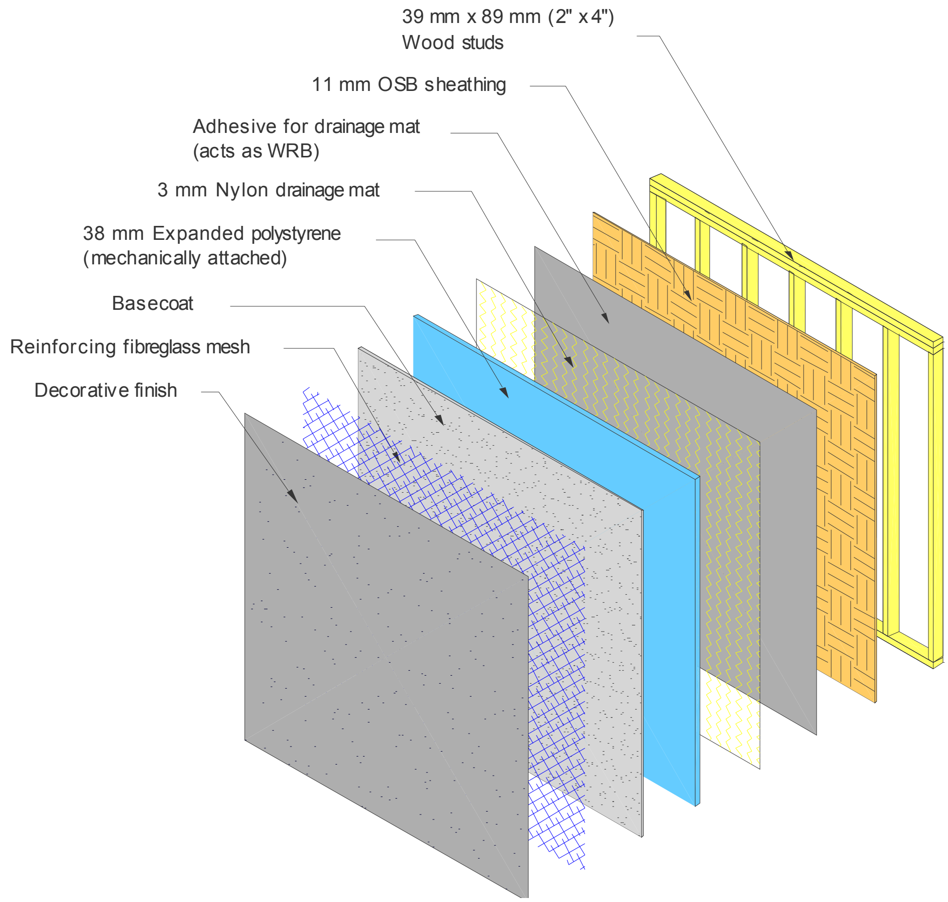


Figure 3.5. EIFS-clad wall (specimen No. 10) with a WRB and drainage mat

3.2.2 Properties of Materials

Hygrothermal properties of several products of the following generic materials were characterised: EIFS lamina (base and finish coats), building paper and polymeric water resistive barrier (WRB) membranes as well as a cementitious coating, oriented strand board (OSB), plywood, glass mat gypsum board sheathing, glass fibre insulation, spruce lumber, paper and plastic vapour barriers and gypsum board interior finish. Several properties of these materials used as input for running hygIRC simulations are given in Table 3.1. Other hygrothermal material properties can be found in the MEWS report T3-23 entitled: "*Hygrothermal Properties of Several Building Materials"* March 2002.

Table 3.1: Selected Properties of Materials

Properties / Materials	Water vapour permeability ng/(m s Pa)		Liquid diffusivity (10^{-12} m^2/s)	Air permeability x dynamic viscosity (m^2) x 10^{-16}
	@ 0%RH	@ 100%RH		
EIFS lamina*	3.5	3.5	24.4	1
Foam board				
EPS insulation*	2.95	4.5	0.0001	370030
Sheathing board				
OSB*	0.06	6	22 (x) 510 (y)	79
Glass mat gypsum board	47.36	180 (facings) 92 (core)	5 (x) 214 (y)	570
Plywood	0.39	26	170 (x) 940 (y)	85
Water resistive barrier				
No. 5	0.06	0.82	4.9	222
No. 27 *	0.51	1.70	4.9	358
No. 7	0.03	0.03	0.0001	169
Cementitious coating**	0.32	0.32	0.21	358
Vapour Barrier				
No. 8*	0.002	0.002	0.0001	0.001
No. 9	0.012	0.012	0.0001	0.001
No. 10	0.006	0.064	0.0001	0.001
Painted gypsum board int. finish	1.9 (x) 31.9 (y)	30.8 (x) 62.0 (y)	370000	678

* properties of materials used for the reference wall
** only simulated in combination with glass mat gypsum board exterior sheathing

3.3 Estimation of Moisture Loads

Moisture Loads Impinging on the Face of the Cladding

Moisture loads impinging on the face of the wall assembly were assessed based on selected weather records for each of the seven locations included in the parametric study. The procedure used to estimate the moisture loads (Rw) impinging on the face of a vertical cladding is described in section 1.5.2 in Chapter 1. In fact for a given location, all reference walls (clad with stucco, EIFS, masonry or siding) in the parametric study were subjected to the same moisture loading impinging on the face of the cladding. The moisture loads injected into the stud cavity however, did vary from one wall system to another (see next page).

Moisture Entry into the Wall Assembly Through a Given Opening

The moisture loading into a stud cavity was based on the results of TG6 laboratory investigation of five EIFS-clad large-scale specimens (Figures 3.1 to 3.5) using IRC Dynamic Wall Testing facility (DWTF) (Draft Report T6-02-R10 entitled: "*Experimental Assessment of Water Entry into Wood-frame Wall Assemblies – Results from EIFS Wall Assemblies"* August 2001). These experiments provided rates of water entry into stud cavities through a given deficiency offering a leakage path to the inside, for several combinations of water spray intensity and static air pressure differential. This deficiency was a missing bead of filet caulking approximately 1mm wide by 50mm long at the interface between the top of the cover plate of an electrical outlet receptacle and the EIFS lamina.

Two of the specimens experienced some water entry into the stud cavity when that deficiency was in place. The water was collected at the inside face of the sheathing board, just beneath the electrical receptacle. From the data obtained on the amounts of collected water in these specimens for given spray rates and air pressure differences, an equation was derived to estimate the water entry rate (Q) in one 400 mm stud cavity as a function of (1) the rate of water impinging on the wall surface (Rw) and (2) the pressure difference across the wall assembly (ΔPwall). The equation is given below:

$$Q\ (L/h)_{\text{for a 0.4 m stud cavity}} = Rw \times f(\Delta Pwall)$$

$$= Rw \times \{0.0418 + 0.0243 \bullet \Delta Pwall / (110.3359 + \Delta Pwall)\} \quad (3.1)$$

Using the hourly weather records of the selected reference climate years, hygIRC calculated each hour's moisture load to inject and spread uniformly into the 1 metre wide stud cavity of the modeled EIFS-clad reference wall at every hour of the simulation run. Rw was the water impinging on the face of the wall (see previous page) and ΔPwall was based on a conversion from wind speed. Figure 3.6 shows the hourly rates of water entry into the stud cavity of the EIFS-clad reference wall used in MEWS hygIRC simulation runs, for three locations with different external climate load (Wilmington NC, Winnipeg MB, and Phoenix AZ).

Note that the equation (3.1) was based on water collected into a 400 mm wide stud cavity, while hygIRC, a 2 D model[1] injected its moisture load in a 1 meter wide cavity. The hourly quantities of water injected in the stud cavity calculated in equation 3.1 for the seven locations were not multiplied by 2.5 to give the same moisture load per metre length of wall as the amount collected in one 0.4 m stud space in the DWTF experiments. This reduction to 40% of the water accumulated in one stud space may not have been a solution to cope with a limitation of hygIRC, i.e. gravity flow and redistribution of free water were not modeled, but it had that effect. Only one stud space contained the deficiency, but the water coming through it may well end up in more than one stud space through gravity-driven liquid flow between the plate and the bottom of the studs. Further discussion of how this affected the results of the parametric study for all cladding systems is given in Chapter 1 section 1.6.2.

[1] hygIRC is a 2D model representing a vertical slice through the middle of a stud space, showing the height and thickness of the wall assembly. By the very nature of the 2D model, variations of the wall construction in the third dimension, such as studs dividing the wall up into 400 mm compartments are not represented. In fact, a 2D model like hygIRC assumes constant properties throughout that one metre width and results are given "per metre" of wall width.

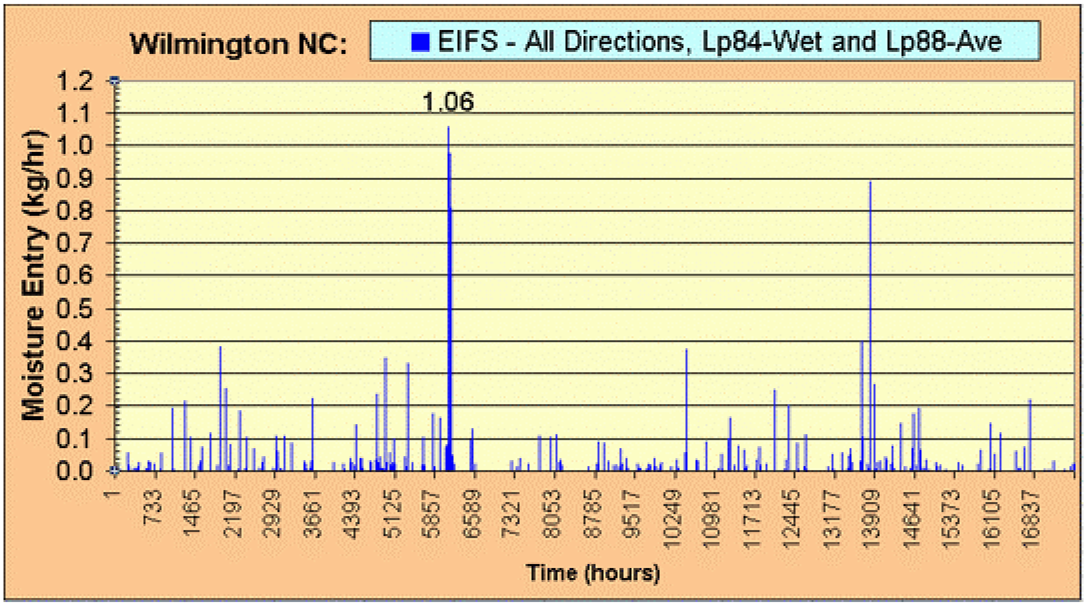


Figure 3.6 A) Hourly rates of water entry “injected” in the stud cavity (referred to as “1Q”) of EIFS-clad reference wall for Wilmington NC for two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

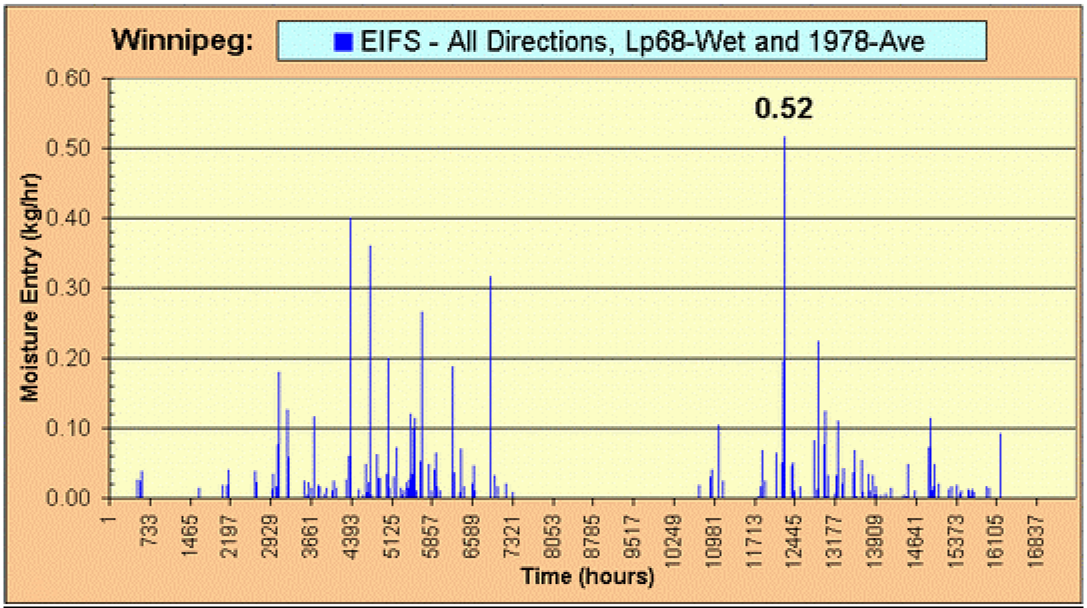


Figure 3.6 B) Hourly rates of water entry “injected” in the stud cavity (referred to as “1Q”) of EIFS-clad reference wall for Winnipeg for two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

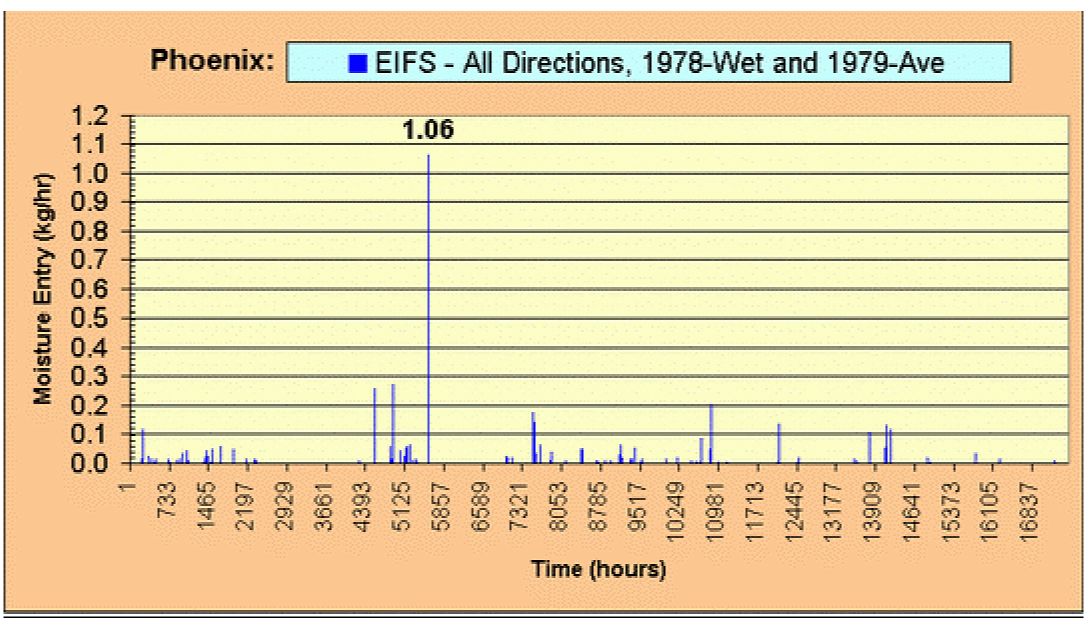


Figure 3.6 C) Hourly rates of water entry “injected” in the stud cavity (referred to as “1Q”) of EIFS-clad reference wall for Phoenix for two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

Moisture Distribution Within the Stud Cavity

Having established how much water could get into the stud cavity, the next step was to decide where and how to distribute it. As described in Chapter 1, through some computer routines, the modeller deposited the moisture load at the bottom of the stud cavity. The hourly amounts, varying from 0 to a maximum of about 1.06 L (Wilmington and Phoenix) were uniformly distributed among several grid points representing a thin layer of stud cavity insulation just above the bottom plate in the wall stud cavity.

Selection of the Region of Focus in the Stud Cavity

In the first exploratory EIFS hygIRC simulations, a microanalysis of the local hygrothermal response in the vicinity of the bottom of the stud cavity was performed for a climate with high moisture loads (i.e. Wilmington NC) (see figure 3.7). These simulation results indicated that the top layer of the bottom plate appeared to remain wet for prolonged periods. As explained in Chapter 1 (section 1.7.1), the region of focus was usually selected for its potential to represent a worst-case scenario. For this reason, the region of the stud cavity selected for EIFS simulations was located in a region that measured 53 mm long (i.e. in the x-direction) and 5 mm high at the top of the bottom plate adjacent to the sheathing board.

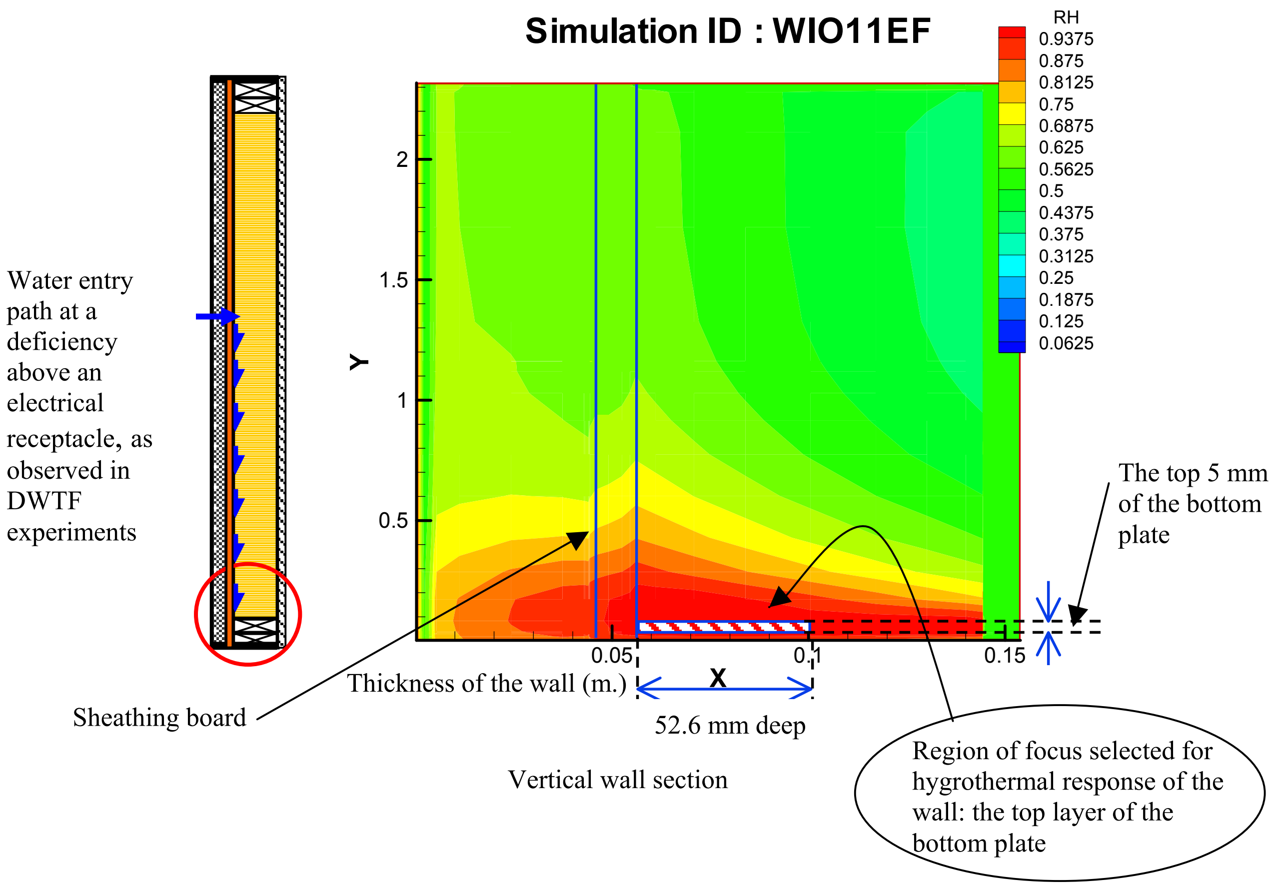


Figure 3.7 A snapshot of hygIRC typical RH contour plot for the reference wall in Wilmington NC. The dark (red) areas indicate the regions at an RH above 87%. The bottom of the wall is the wettest portion of the assembly most of the time. Note that drawing is not to scale: the X-axis has been expanded.

3.4 Prediction of Wall Hygrothermal Response to Moisture Loading

3.4.1 Parameters Investigated

An EIFS-clad wall assembly was selected as a reference for the parametric study (Figure 3.8). The following parameters were varied to determine their influence on the hygrothermal response of a reference EIFS-clad wall assembly:

1. Climate severity
2. Moisture loads in the stud cavity (0Q, Q/4, Q/2, 1Q, 2Q and 4Q)
3. Material properties
   - 3 thicknesses of EIFS lamina
   - 3 water resistive barriers (building paper and polymeric membrane, and one cementitious coating)
   - 3 sheathing boards (OSB, plywood and glass mat gypsum board)
   - 4 vapour barriers (type 1 & type 2 membranes, kraft paper and coating on gypsum board)
4. Indoor relative humidity (RH) levels
5. Removal of insulation in the stud cavity
6. Air leakage across the wall assembly
7. Location of water deposition inside the wall assembly (bottom of stud cavity, mid-height of wall between WRB and sheathing board)
8. Severity of second simulation climate year (average vs. dry)

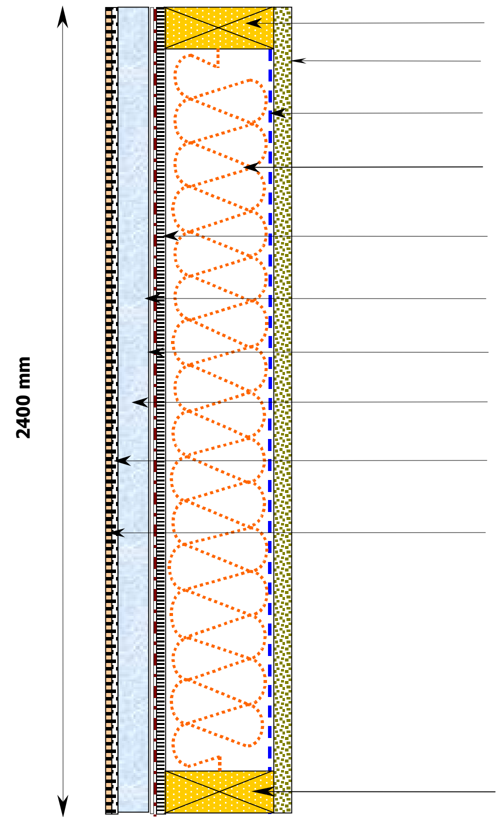


Figure 3.8 A vertical section showing the composition of the wall assembly used as the reference for the parametric study.
It was assumed that double top and bottom plates in the stud cavity are in place. In practice it is more common to use only a single plate. It is believed that this difference did not affect the interpretation of the parametric study results.

3.4.2 Comparative Results

All possible combinations of material types for each of the seven locations with and without moisture entry through a deficiency would yield about a thousand simulations. This is indeed far more than could have been accommodated given the time and resources available for the MEWS project. Hence, after consultation with MEWS partners, it was decided to conduct a sufficient number of simulation runs to reveal the major influences of the parameters mentioned above. The simulations presented in this document constitute only a portion of those carried out in this program. Reported in this section are the comparative effects of the parameters listed in section 3.4.1 on the hygrothermal response of the wall expressed using the RHT(95) indicator. Two complete sets of the single indicators of performance, RHT(95) and RHT(80) are provided in Appendix 3.1.

The following nomenclature is used in the subsequent sections to describe the impact of effects of changing various parameters on the wall response.

Decisive: RHT(95) was reduced to near zero by a single change of parameter
Substantial: cumulative RHT(95) difference of at least 1000 of the larger value compared
Small: cumulative RHT(95) difference less than 1000 and higher than 100 of the larger value compared.
Near zero: cumulative RHT(95) difference less than 100 of the larger value compared

1.0 Effect of Climate Severity on a Wall Assembly Response

Observation: hygIRC predicted that the RHT(95) hygrothermal response of a wall assembly would increase with the severity of the climate (i.e. MI). Although the EIFS-clad reference wall *with no deficiency* showed no adverse hygrothermal response for all climates, all configurations with the "nominal" deficiency allowing water leakage into the stud cavity registered positive RHT index values increasing with MI.

Discussion: Figure 3.9 summarizes this observation. The blue curve shows the predicted RHT(95) response for the reference EIFS-clad wall of given properties with no water leakage in the stud cavity (i.e. no deficiencies). The RHT(95) values for that wall remained at zero even in climates with a high Moisture Index (MI) such as Wilmington NC. The green and red curves show the predicted RHT(95) index value for two EIFS-clad walls with different material properties but with the same nominal deficiency allowing water entry into the stud cavity. Under these circumstances, hygIRC showed that in general the RHT(95) index for the wall increased with the severity of the outside climate as characterized by the MI.

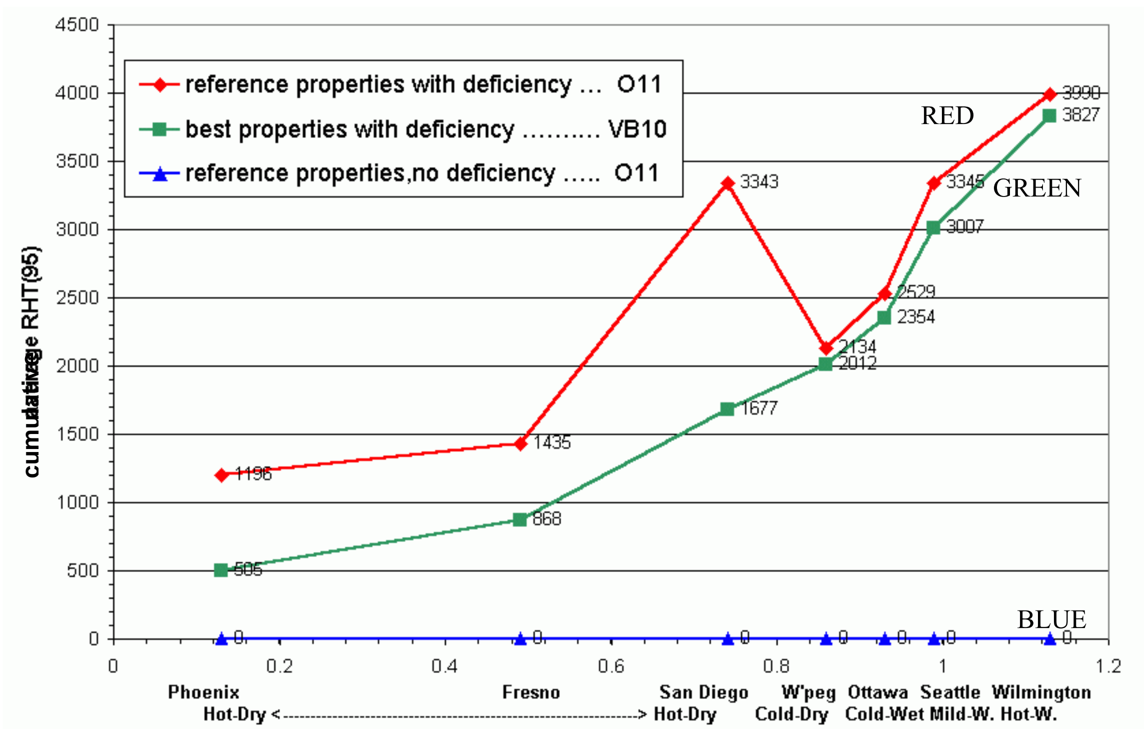


Figure 3.9 Relationship between climate severity and EIFS-clad wall response for three scenarios. The lower flat line (in blue) is the response for a reference wall **O11 having no water leakage into the stud cavity (no deficiency). The upper curve (in red) is the response of the same wall with a deficiency allowing some water leakage into the stud cavity. The middle curve (in green) represents the response of another wall (**VB10) having a combination of materials more conducive to drying, and with the same deficiency as was incorporated in wall **O11.

Let's examine more closely the shape of Figure 3.9 upper line (i.e. reference wall with a 1Q set of hourly rates of water entry in the stud cavity) and how the predicted wall response fluctuated as a function of the severity of the exterior climate. Interestingly, the RHT(95) wall response for San Diego stands out and is in line with the wall response predicted in Seattle and Wilmington NC, instead of nesting between Winnipeg and Fresno. The following paragraphs offer an explanation for this difference.

An examination of the predicted 10-day interval RH and T plots for the region of focus, which form the basis for the computation of the cumulative RHT values, provides an explanation for this observation. In San

Diego, Seattle and Wilmington NC the predicted relative humidity and temperature profiles at the region of focus are very similar, resulting in similar cumulative RHT(95) values (Figure 3.10). This is related to the magnitude of the moisture loads (1Q) injected in the stud cavity (wetting) in relation to the wall materials ability to transfer water out of the system (drying). The moisture loads in the stud cavity appeared to overwhelm the wall early on in the simulation runs (see next point on the effect of the variation of the water entry rate (Q) in the stud cavity): the RH level quickly rose above 95% and stabilized near that point. Under these circumstances, temperature became the factor that controls the computation of positive RHT values. That brought up the importance of the exterior insulating sheathing as a damper to outdoor climate effects on the region of focus in the stud cavity. EIFS cladding always includes an exterior insulating sheathing as the substrate for the EIFS lamina. This insulating sheathing thermally isolated the region of focus in the stud cavity from the fluctuating outdoor climate. Similar temperature responses in the region of focus in the stud cavity were predicted for all warm climates investigated in the study[§].

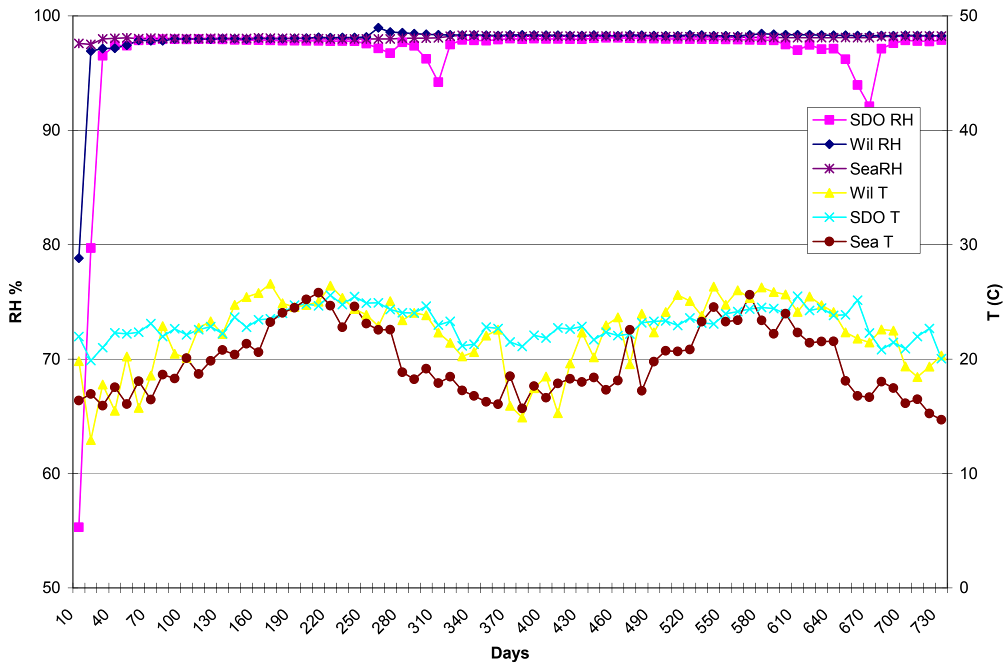


Figure 3.10 Fluctuations of temperature and relative humidity in the region of focus at 10-day intervals for San Diego, Seattle and Wilmington NC for simulation with a 1Q set of moisture loads into the stud cavity. Note the similarity in RH and T profiles for the reference EIFS-clad wall located in these climates. These similar RH and T profiles yield similar cumulative RHT values.

[§] Phoenix and Fresno also showed similar temperature profiles at the region of focus

In cold climates the exterior thermal insulation had the same effect of damping down the fluctuations of outdoor temperature in the stud space; however, seasonal temperature swings at the region of focus remained larger than those predicted for the warmer climates of Seattle, Wilmington NC and San Diego (see ups and downs of temperature in Figure 3.11 for Winnipeg for example). In cold climates, the exterior insulating sheathing did not completely offset the effect of cold outdoor temperature on the stud cavity, and temperatures below 5^{o}C were predicted to occur at the region of focus during the coldest periods. When the temperature dropped below 5^{o}C, the RHT value for that period was zero. This resulted in a cumulative RHT(95) lower than that for San Diego.

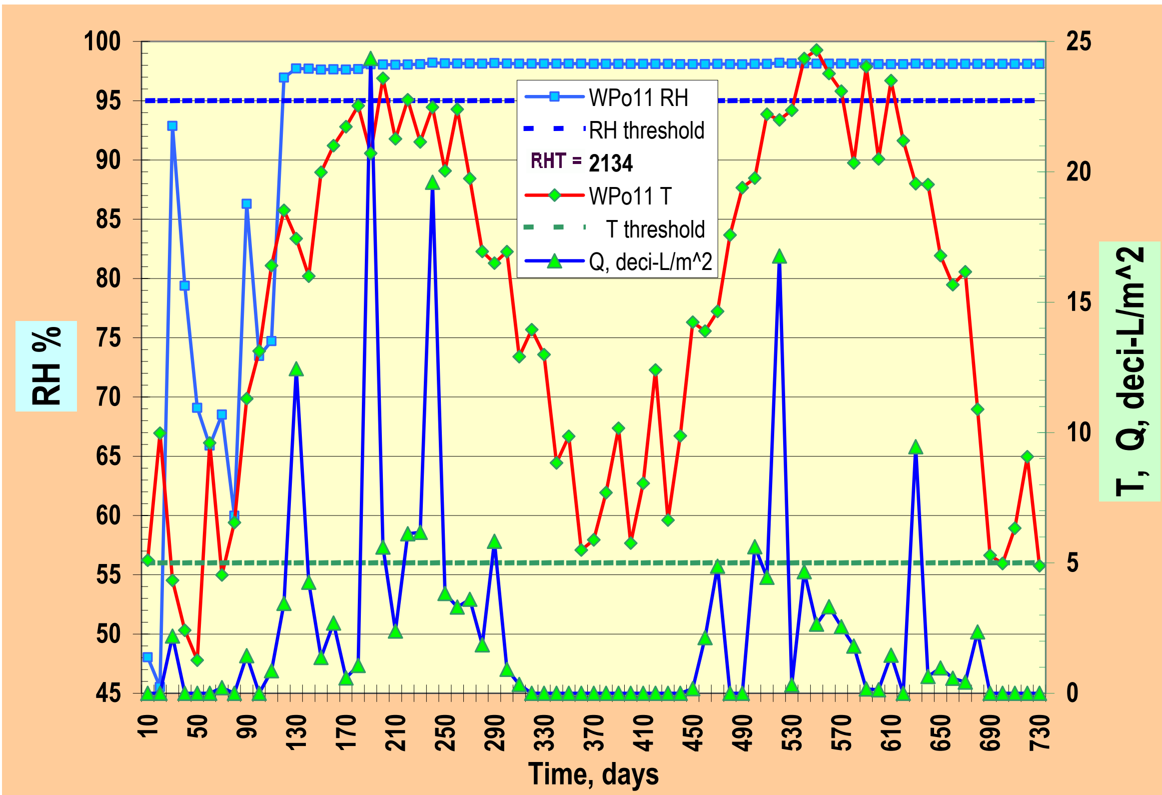


Figure 3.11. RH and T profiles predicted for the reference wall in Winnipeg. Cumulative RHT(95): 2134

As for the RH profile, one can see that for cold climates (Figure 3.11) and warm climates of moderate to severe moisture loads (Figure 3.10), a 1Q set of hourly rates of moisture entry into the stud cavity resulted in rapid increase in RH level at the region of focus. Early on in the two years of simulation, the RH reached levels higher than 95% and basically stabilised at that level. Under these circumstances, temperature became the factor that controlled the computation of positive RHT values. For Fresno and Phoenix, -hot and relatively dry climates-, the 1Q set of moisture loads in the stud cavity was much smaller and consequently some drying occurred (i.e. lower RH), leading to lower RHT values (Figure 3.12).

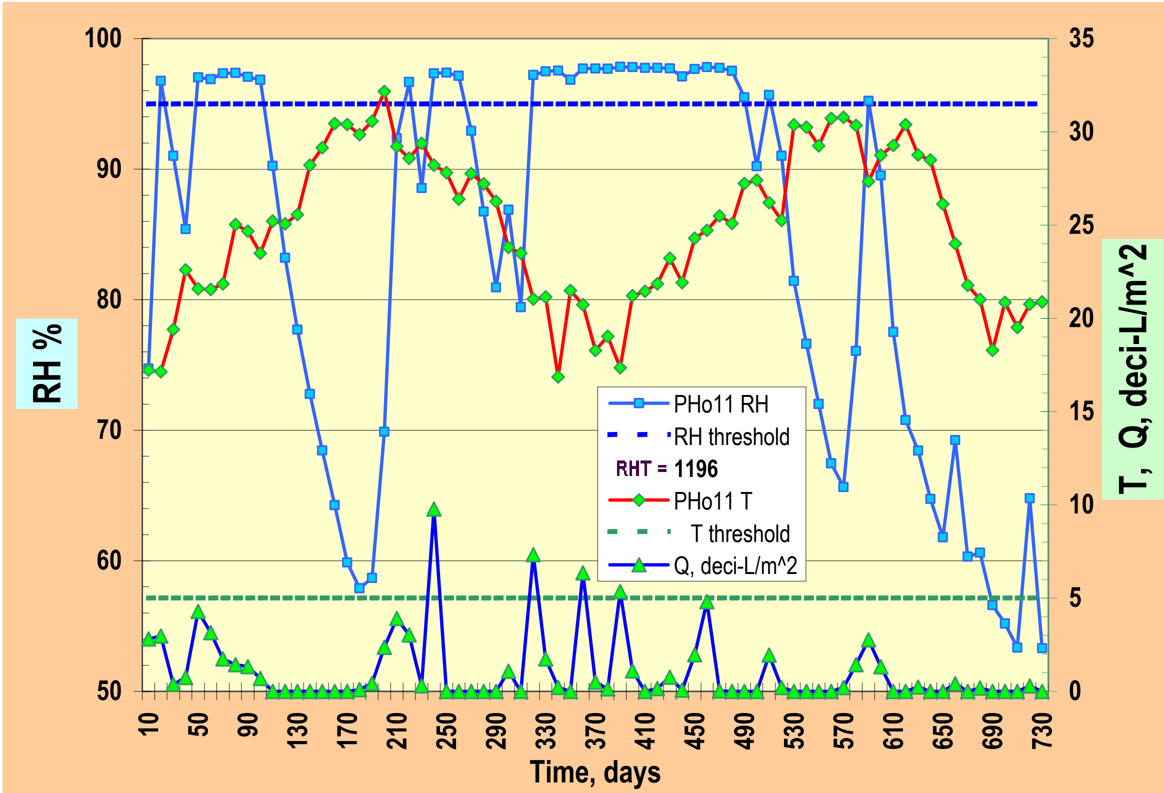


Figure 3.12. RH and T profile for Phoenix for the two years of simulation. Notice the frequent drops in RH below the threshold of 95%. Cumulative RHT(95): 1196.

2.0 Effect of Variation of the Rate of Water Entry into the Stud Cavity (Q)

Observation No. 1: hygIRC predicted that when no water was allowed to enter the stud cavity (i.e. Q=0), the EIFS lamina provided a high degree of water resistance, even under severe outdoor moisture loads like those present in Wilmington NC, and as such these materials reduced significantly external moisture migration towards the region of focus in the stud cavity. (Effect: *decisive*)

Discussion: For all climates investigated, in the absence of deficiencies allowing water entry into the stud cavity (i.e. Q=zero), the RHT(95) response for the reference EIFS-clad wall assembly was zero (Table 3.2 and the corresponding plot in Figure 3.13). The EIFS lamina exhibited a level of water resistance that reduced significantly the amount of water getting through the field of the wall. The characterization of the material properties (TG3) indicated that the liquid diffusivity of the EIFS lamina –the measure of the capacity of liquid water to pass through a material- was relatively low.

Table 3.2 Cumulative RHT(95) values for seven locations for several sets of rates of water entry in the stud cavity (Q)

Moisture loads in stud cavity (Q)	Phoenix	Fresno	San Diego	Ottawa	Winnipeg	Seattle	Wilmington NC
0	0	0	0	0	0	0	0
¼	---	58	195	278	768	1242	2885
½	---	451	1140	2176	1841	2884	3622
1	1196	1435	3343	2529	2134	3345	3990
2	3196	*	*	*	*	*	*
4	4394	*	*	*	*	*	*

* No simulation run was done for that parameter

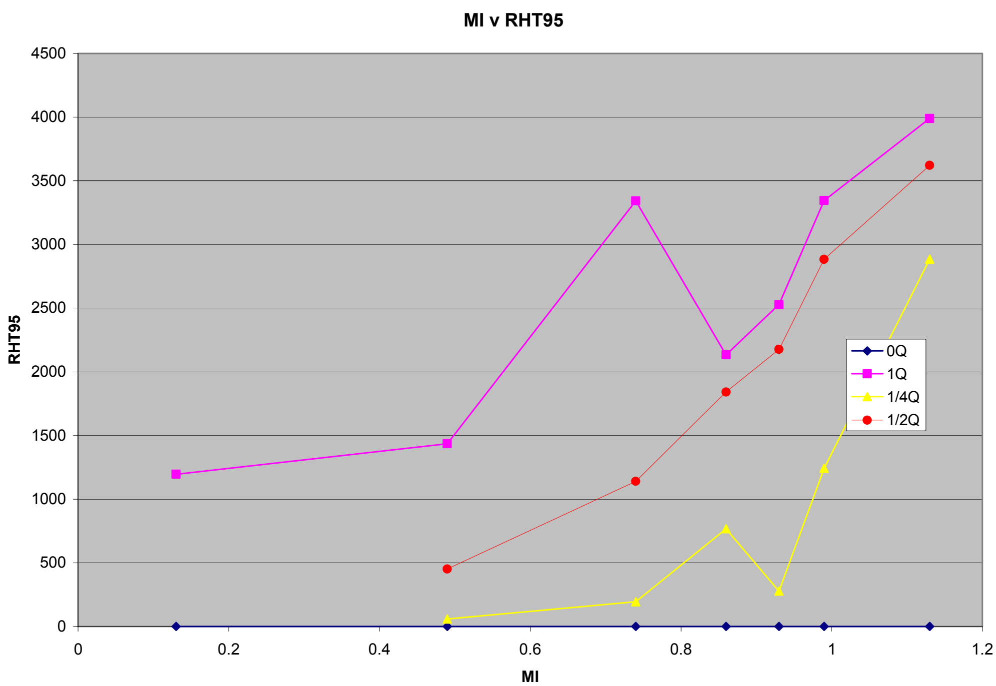


Figure 3.13. RHT (95) variations as a function of the climate index MI and Q, the set of moisture loads into the stud cavity.

Observation No. 2: hygIRC simulations predicted that a 1Q set of moisture loads in the stud cavity had a large effect on the RHT(95) value of the EIFS-clad reference wall. (Effect: *Substantial*). The drying capability of the materials on both sides of the stud cavity was insufficient - even in favourable climates - to maintain the RHT(95) value at the region of focus at zero.

Discussion: Figure 3.13 illustrates the point: the top line (1Q) is situated well above the RHT(95) threshold of zero. When the reference wall was exposed to Phoenix climate years, its cumulative RHT(95) value reached a low of about 1200 while in Wilmington NC, it reached a high of 4000.

The explanation for that large increase in RHT(95) when water entered the stud cavity at a 1Q set of moisture loads has to do with the limited drying rate of the wall materials compared to the wetting rate of the stud cavity. The drying capability offered by the materials on both sides of the region of focus (i.e. EIFS lamina, water resistive barrier, sheathing board, vapour barrier and interior drywall) appeared insufficient to make a difference in the RH conditions predicted for the region of focus (i.e. thin slice of the bottom plate). Figure 3.10 shows the 10-day fluctuations of RH and T in the region of focus in the stud cavity for the EIFS-clad reference wall exposed to 3 distinct climates for the two-year period of the hygIRC simulation run. The simulation showed that the region of focus reached a high RH value of about 97% after the first two months of the first year of simulation and that RH level hardly dropped for the rest of the simulation period (except for San Diego which experienced two short-lived drying spells). In other words, the drying potential offered by materials in the vicinity of the region of focus was insufficient to counterbalance the wetting effect due to a 1Q climate-related moisture loads into the stud space.

Observation No. 3: For all cases investigated, reducing the moisture loads in the stud cavity (to half or to a quarter of the original 1Q values) was predicted to lower the RHT(95) wall response. (Effect*: small to substantial*). However dropping Q to even a quarter of the original loads was not sufficient to result in a decisive effect on the RHT(95) value for the EIFS reference wall. Other measures to reduce the wetting rate and to increase the drying rate would be needed to contribute to lower further the RHT(95) wall response.

Discussion: Figures 3.13 and Table 3.2 show the RHT(95) wall response predicted when the moisture load in the stud cavity of the wall was reduced. Figure 3.14 gives the relationship between RHT(95) and multiples of Q for all seven locations investigated. For climates other than Fresno and San Diego, one can see that the RHT(95) response for a ½ Q moisture loading in the stud cavity was not much less than the RHT(95) response at 1Q. Even half the moisture loads in the stud cavity appeared to be excessive in relation to the drying potential offered by the climate and the properties of the materials. The RH predictions for the reference wall in Seattle and Winnipeg at ½ Q moisture loads showed RH values around 98% (Figure 3.15), suggesting that little net drying effect occurred.

The relationship between EIFS-clad reference wall RHT(95) response and Q was not linear in climates with moderate to high moisture loads. The slope of the curve decreased noticeably as the rate of water entry into the stud cavity dropped below a certain value (1/4 Q in Ottawa, Winnipeg, Seattle and Wilmington NC). In milder climates like San Diego and Fresno, the situation is different as a substantial RHT(95) reduction occurred when the moisture loads in the stud cavity was dropped by half. In that case the drying mechanisms overpowered the wetting mechanisms. The relationship between RHT(95) response and Q was somewhat more linear for those two locations.

When the moisture load in the stud cavity was reduced to a quarter of the original loads, the drying rate of the building materials located on both sides of the region of focus somewhat overcame the wetting of the stud cavity. Figure 3.16 and 3.17 show the 10-day RH and T predictions for the reference wall with a quarter of the original stud cavity moisture load for Fresno, San Diego, Seattle and Wilmington. Looking at the RH fluctuation at the region of focus, one can compare the duration of the drying spells below 95%RH yielding different cumulative RHT value for the reference wall exposed in these three locations. Even at ¼ Q, the reference wall in Wilmington remained above 95%RH for long periods (RHT(95) = 2885) while in milder San Diego, the RH dropped below 95% for long periods (RHT(95)=195).

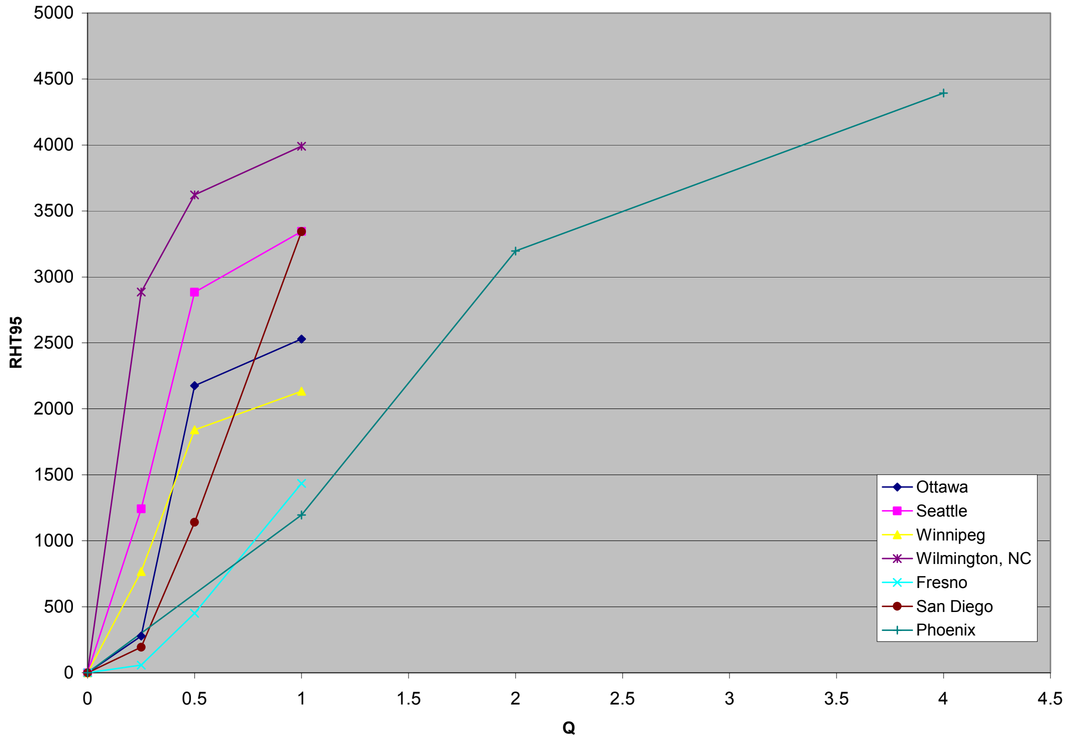


Figure 3.14 Relationship between the moisture loads in the stud cavity (Q) and the severity of the wall response (RHT(95)

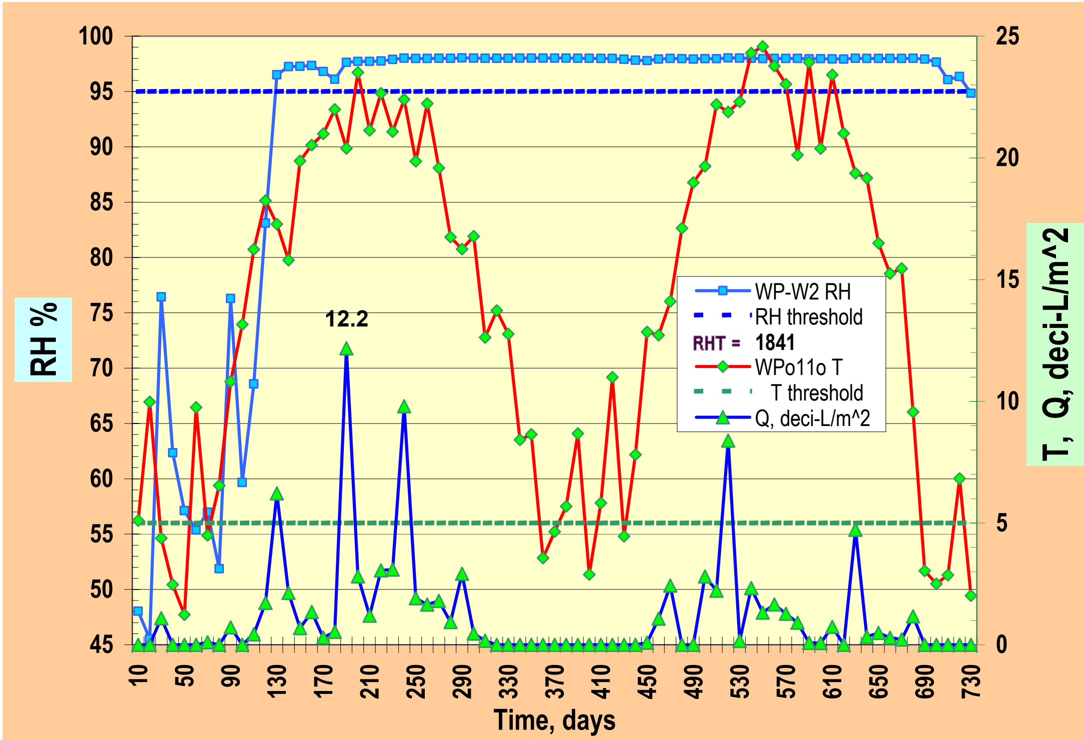


Figure 3.15 RH and T profiles for the region of focus of the reference wall in Winnipeg for ½ Q set of moisture loads in the stud cavity. RHT(95) = 1841. After the first 3 months of simulation, the RH remained at 98% for most of the rest of the two-year period.

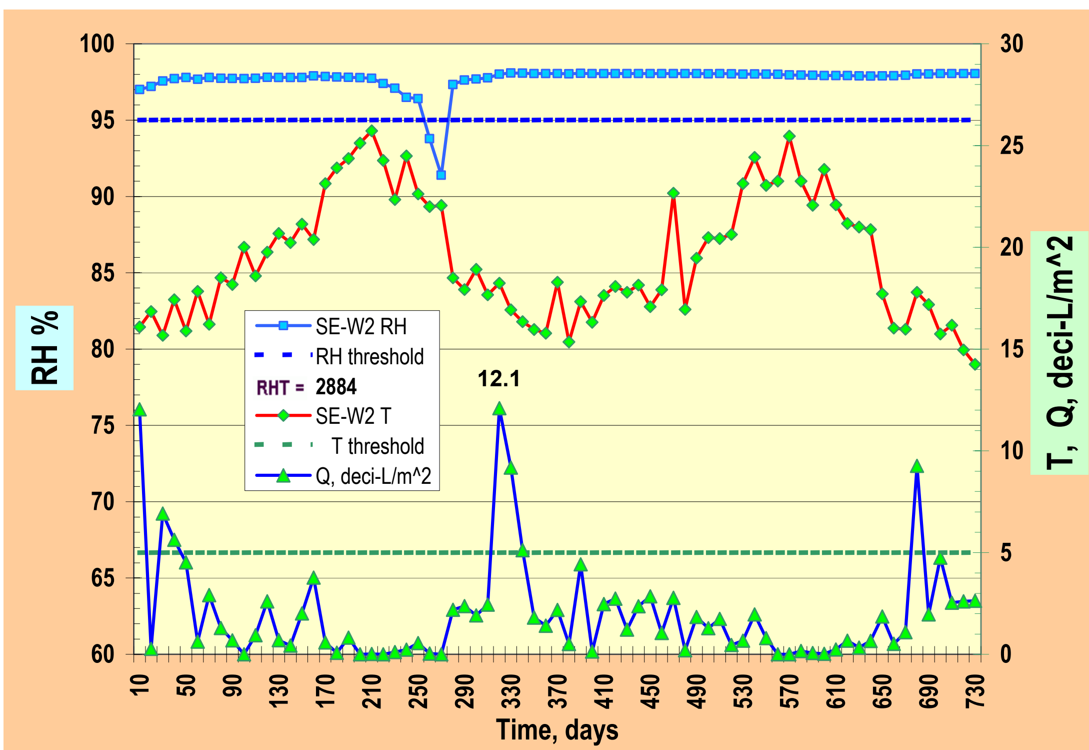


Figure 3.15 B. RH and T profiles for the region of focus of the reference wall in Seattle for ½ Q set of moisture loads in the stud cavity. RHT(95) = 2884. The RH remained at about 98% for all of the simulation run, except for a two-month dip.

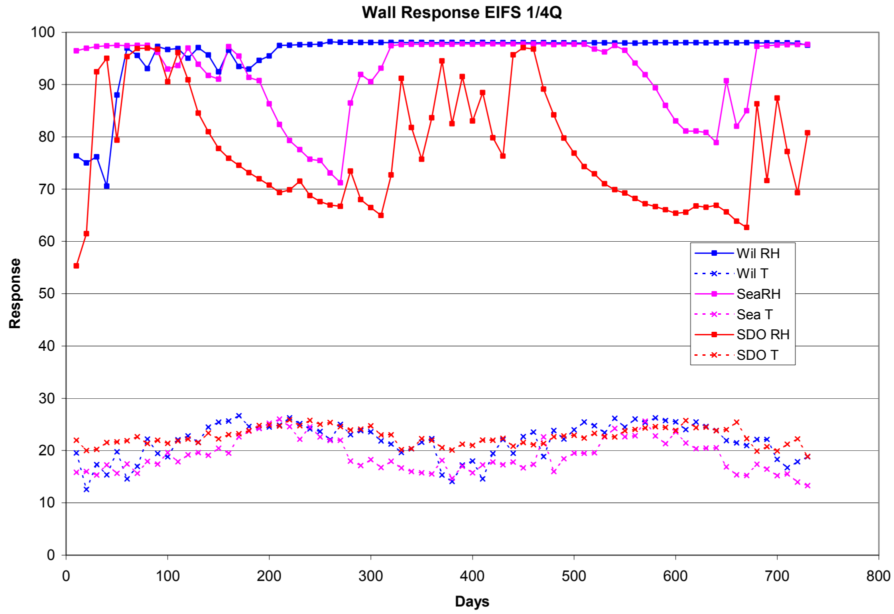


Figure 3.16 RH and T profiles for the region of focus of the reference wall in San Diego, Seattle and Wilmington NC, for ¼ Q. RHT(95) SD=195; RHT(95) Seattle=1242 RHT(95) Wilmington NC=2885

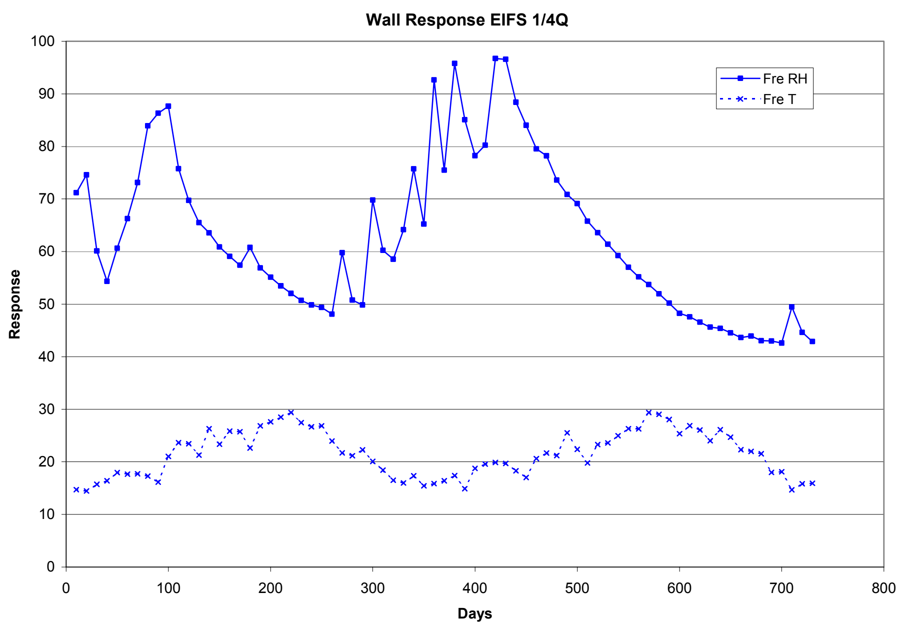


Figure 3.17 RH and T profiles for the region of focus of the reference wall in Fresno for ¼ Q. RHT(95)= 58

3.0 Effect of Material Properties in a Given Climate

Effect of the Properties of the EIFS Lamina

Observation: For all climates investigated, hygIRC simulations showed that the EIFS lamina of the reference wall acted as an effective first line of defence against rain penetration further into the assembly. (Effect: *Decisive*)

Discussion: As can be seen on Figure 3.9, the RHT(95) response of the reference wall with no water leakage into the stud cavity was at zero for all climates investigated. This had to do with the high water resistance of the EIFS lamina.

Effect of the Thickness of EIFS Lamina

Observation: For all climates investigated, changes in the thickness of the EIFS lamina (i.e. the base and finish coats) of the reference wall were predicted to have little effect on the hygrothermal response of the EIFS wall assemblies (Effect: *Near-zero*).

Discussion: The effect of reducing the thickness of the lamina was investigated because field applications could result in some variations. The following three thicknesses of EIFS lamina were investigated: 5 mm, 4 mm and 2.5 mm. TG 3 characterized the hygric properties and thickness of one sample of EIFS lamina cutout from one of the large-scale specimens built for DWTF testing. The finish coat and base coat were characterized as one layer of a given total thickness as opposed to two separate elements. Values for several properties of a 5 mm thick lamina used as input to hygIRC are provided in Table 3.1. Properties for different thicknesses of lamina were then calculated proportionally.

Table 3.3 provides the RHT(95) response of the wall in the region of focus for all locations and thicknesses of EIFS laminas investigated with hygIRC. When water entered the stud cavity at a 1Q set of hourly moisture loads, changing the thicknesses of the EIFS laminas had little effect on the hygrothermal response of the wall assembly. The RHT results for the reference wall remained in the same order of magnitude, well above the threshold of zero for the three thicknesses of the lamina. As the moisture loads in the stud cavity "bypassed" the lamina, the thickness of that lamina had little effect on the wetting of the stud cavity. The thickness of the lamina also had little effect on the drying of the wall elements when a 1Q set of moisture loads was present in the stud cavity: its vapour permeability was quite low and a reduction of 1 to 2.5 mm in thickness was not sufficient to tilt the balance towards a net drying effect.

Table 3.3: RHT (95) index comparison for three thicknesses of EIFS lamina

	RHT(95) index for reference wall at 1Q set of moisture loads in the stud cavity						
EIFS lamina	**Phoenix**	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
5 mm (Reference wall)	1196	1435	3343	2134	2529	3345	3990
4 mm (CO1)	1187	1423	3306	2131	2526	3341	3987
2.5 mm (CO2)	1157	1403	3238	2127	2522	3336	3984

Effect of the Properties of Three Sheathing Boards

Observation: For all climates investigated, hygIRC predicted that the properties of the three sheathing boards included in the study would have little effect on RHT(95) hygrothermal response of the EIFS wall assemblies. (Effect: *Near-zero to small*).

Discussion: Three sheathing boards were investigated: OSB, plywood and glass mat gypsum board. The hygric properties of these three materials were characterized in TG3 (Table 3.1). When a 1Q set of hourly moisture loads entered the stud cavity, changing the sheathing board had little effect on the RHT(95) response of the reference wall (see Table 3.4). Plywood was slightly more vapour permeable than OSB and a small reduction in RHT(95) response was predicted for climates with mild moisture loads and high drying potential (i.e. Phoenix, Fresno and San Diego). In locations of either cold or warm and wet climates, a near-zero reduction was predicted. The larger the moisture loads in the stud cavity, the less noticeable was the net drying effect due to a small increase in vapour permeability of the sheathing board. There appeared to be no particular trend in the RHT(95) response in the reference wall with the glass mat gypsum board covered by a cementitious coating compared to the wall with the OSB sheathing covered by the water resistive barrier No. 27. In any case, RHT(95) changed very little either way.

Table 3.4: RHT (95) index comparison for the reference wall using three sheathing boards

	RHT(95) index for reference wall at 1Q set of hourly rates of moisture entry in the stud cavity						
board	**Phoenix**	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
OSB	1196	1435	3343	2134	2529	3345	3990
Plywood	976	1264	3072	2059	2479	3304	3923
Glass mat gypsum board	902	1578	3497	1982	2272	3215	*

An asterisk, *, indicates that no simulation run was done for that parameter
Note: in hygIRC simulations, the water resistive membrane No. 27 covered plywood and OSB sheathings, while the gypsum sheathing was covered with a cementitious coating.

Effect of the Properties of the Water Resistive Barrier

Observation: For all climates investigated, hygIRC predicted that the properties of the three sheathing membranes included in the study would have little effect on the RHT(95) response of the EIFS-clad reference wall. (Effect: *Near-zero* for all but Phoenix where effect was *small*).

Discussion: Three water resistive barriers were investigated: two polymeric and one paper-based membranes. The hygric properties of these three materials were characterized in TG3 and a summary of the properties used as input for the modelling is presented in Table 3.1. Table 3.5 provides the RHT(95) hygrothermal response of the reference wall with different water resistive barriers for all locations investigated. When a 1Q set of moisture loads entered the stud cavity, changing the water resistive barrier had little effect on the RHT(95) response of the reference wall. In the parametric study, a variable amount of water was introduced into the stud cavity every hour. This implies that some water by-passed the water resistive barrier whose primary function was to act as a second line of defence against rain penetration into the back up wall. So in this particular scenario, the WRB was not that useful at reducing the wetting of the stud cavity. The properties of the water resistive barrier can also affect the potential for evaporative drying of the wet stud cavity to the outside. The magnitude of water vapour permeance of these three membranes was such that their drying potential was predicted to be very similar.

Table 3.5: RHT (95) index comparison for three water resistive barriers

barrier	RHT(95) response for the reference wall at 1Q set of hourly moisture loads in the stud cavity						
	Phoenix	Fresno	San Diego	Winnipeg	Ottawa	Seattle	Wilmington NC
No. 27 (reference case)	1196	1435	3343	2134	2529	3345	3990
No. 5	1227	1448	3364	2134	2529	3345	3991
No. 7	1378	1595	3692	2144	2545	3370	4014

Effect of the Properties of Vapour Barrier Membranes

Observation No. 1: Increasing the vapour permeability of the vapour barrier *membranes* included in the parametric study was predicted to reduce the RHT(95) response of the EIFS-clad reference wall. The effect was more pronounced in climates with lower MI (i.e. Phoenix, Fresno and San Diego). (Effect: *Near-zero to small*)

Discussion: Three vapour barrier membranes were investigated. A summary of hygric properties characterized by TG3 can be found in Table 3.1. Vapour barriers B8, B9 and B10 are ranked in order of increasing vapour permeability at 100%RH. Figure 3.18 shows the relationship between their vapour permeability and relative humidity.

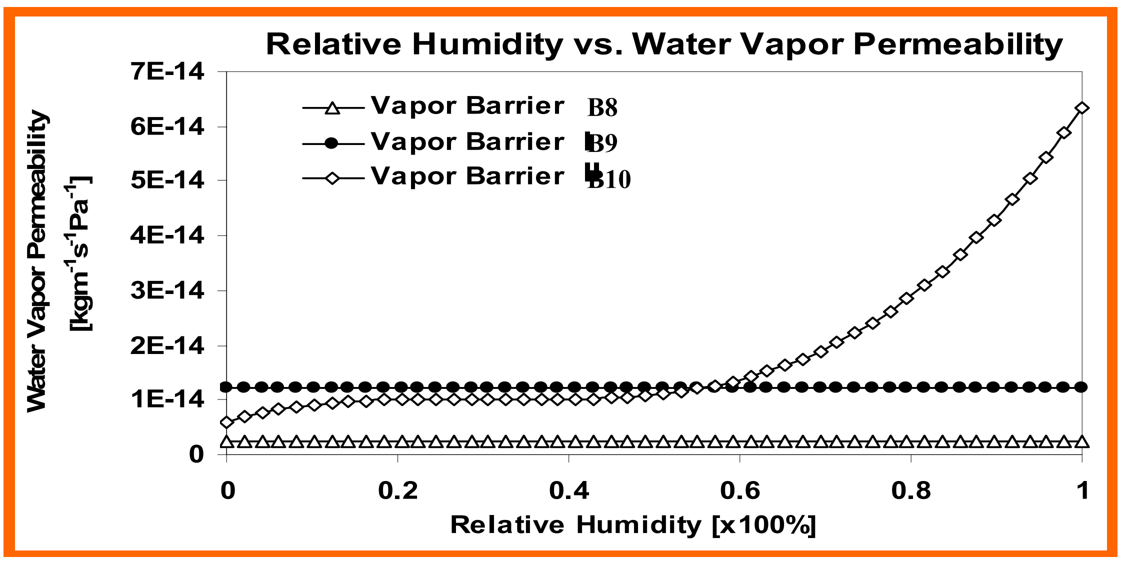


Figure 3.18. Relationship between vapour permeability and relative humidity of three vapour barrier membranes (TG3)

Table 3.6 provides the RHT(95) wall response predicted by hygIRC for the three vapour barrier materials. In the cold climates, or warm and wet climates investigated, changing from a very tight vapour barrier *membrane* (i.e. B8 membrane) to a more vapour permeable *membrane* (i.e. B10 membrane) was predicted to make a small difference in the RHT(95) hygrothermal response of the stud cavity of the wall. In those climates, the rates of moisture loading into the stud cavity were in excess of the rates of evaporative drying offered by any of the three vapour barrier membranes investigated. A small effect of increasing the vapour permeance of the vapour barrier membranes was captured under these circumstances (Effect: near-zero to very small). However when the moisture loads in the stud cavity were much lower, as in the case of climates of lower MI (i.e. Phoenix, Fresno and San Diego), using B10 membrane instead of B8 membrane was predicted to have a stronger effect on the RHT(95) wall response (Effect: *small to substantial*). The evaporative drying offered by the B10 membrane did not change from climate to climate, but its ability to reduce the RHT(95) wall response was somewhat controlled by the magnitude of the moisture loads in the stud cavity.

Table 3.6: RHT (95) index comparison for vapour barriermembranes of different properties

	RHT(95) response for the reference wall at 1Q set of hourly moisture loads in the stud cavity						
membrane	**Phoenix**	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington**
B8	1196	1435	3343	2134	2529	3345	3990
B9	733	1094	2347	2092	2474	3281	3926
B10	505	868	1677	2012	2354	3007	3827
No VB membrane; Painted gypsum board	*	*	*	*	*	*	1363

An asterisk, *, indicates no simulation run for the specific parameter

Observation No. 2: When the vapour permeance of the layer of materials placed on the inside of the stud cavity was increased by a large factor - in this case several thousand-fold -, a large drop in the RHT(95) response for the reference wall in Wilmington NC occurred. (Effect: *substantial*)

Discussion: In a second series of simulation runs, the vapour barrier membrane was removed from the reference wall and one coat of primer with two coats of latex paint were added to the unpainted gypsum board interior finish. The vapour permeance of this assembly was much higher than any of the three vapour barrier membranes investigated previously (see Table 3.1). The simulation was only run for a climate with severe moisture loads, i.e. Wilmington NC. The result indicated that a large increase in the vapour permeance of the vapour barrier would produce a substantial reduction in the RHT(95) response of the reference wall. It should be noted that the apparent improvement in the RHT(95) response of the reference wall with an increase of the vapour permeance on the inside of the stud cavity should not be taken outside the context of the MEWS parametric simulations. The interior conditions assumed as the internal boundary condition played a large role in the drying drive to the interior. The interior RH conditions of 55% in the summer and 25% RH in the winter promoted drying to the inside. The effect might be much less or even reversed when different interior conditions prevail.

4.0 Effect of Variations in Indoor Climates

Observation: hygIRC simulation results suggested that changes in the indoor RH made no difference in the RHT(95) wall response in the region of focus in the stud cavity of the reference wall with a 1Q set of hourly moisture loads in the stud cavity, for a climate of high MI (i.e. Wilmington NC). (Effect*: near-zero*)

Discussion: Table 3.7 shows that the results of the simulation runs were very much the same for all combinations of indoor RH investigated. Even the wall exposed to the lowest indoor RH condition (i.e. 25% in winter and 55% in summer) investigated obtained RH values of about 98% in the region of focus in the stud cavity for most of the duration of the two-year simulations (Figure 3.10). That high RH in the stud cavity had to do with the magnitude of the moisture loads injected in the stud cavity. Increasing the indoor RH level any further can only increase slightly the RHT(95) wall response.

It is likely that the presence of a tight vapour barrier behind the drywall and the absence of airflow through the wall assembly minimized any moisture exchange between the stud cavity and indoors. Without much opportunity for moisture exchange, increasing the indoor RH was unlikely to affect the RHT wall response at the region of focus in the stud cavity.

Table 3.7: Comparison of RHT(95) response of a reference wall exposed to different indoor RH levels, with VB10 membrane in Wilmington NC for a 1Q set of moisture loads in the stud cavity

Winter RH (%)	Summer RH (%)	RHT (95) for wall with VB10 membrane
25	55	**3827**
25	65	**3846**
25	75	**3872**
40	65	**3861**
40	75	**3887**
50	75	**3893**

5.0 Effect of Insulation in the Stud Cavity

Observation No. 1: In all climates investigated, hygIRC predicted that the reference wall ***with*** insulation in the stud cavity would have a ***lower*** RHT(95) response than the same wall without insulation. The effect was less pronounced in locations of moderate moisture loads. (Effect: *small to substantial*)

Discussion: Figure 3.19 illustrates this effect. The upper line is the RHT response of the wall at the region of focus when the stud cavity was not filled with insulation and the lower line is the RHT response when insulation filled the stud cavity. It is clear that the wall with cavity insulation had a lower RHT response than the wall without cavity insulation.

In general the change in RHT (95) response can be traced to changes in temperature or/and changes in RH at the region of focus. Examination of the RH and T fluctuations for the reference wall with and without cavity insulation indicated that reduced RH was the main contributor to reduced RHT(95) values for the wall with cavity insulation (see Figure 3.20 for Wilmington NC, and Figure 3.21 for Winnipeg). For Wilmington NC, one can see after the first 3 months of the simulation period, the RH level for the wall with insulation stabilized at a lower value than the wall with cavity insulation. The temperature profile at the region of focus, i.e. the top layer of the bottom plate in the stud cavity, was very similar for both cases, as the thermal gradient across the wall assembly was not large in such a warm climate.

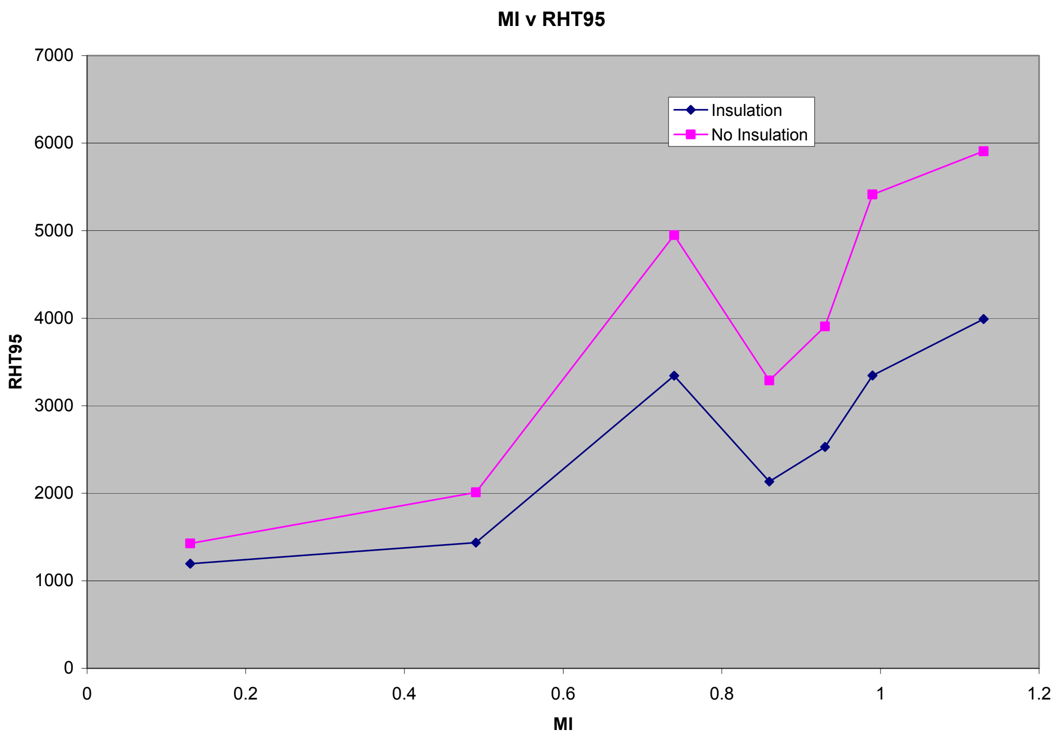


Figure 3.19. RHT(95) fluctuations for the reference EIFS-clad wall with and without insulation in the stud cavity as a function of the severity of the climate defined by the MI (for a 1Q set of hourly moisture loads in the stud cavity)

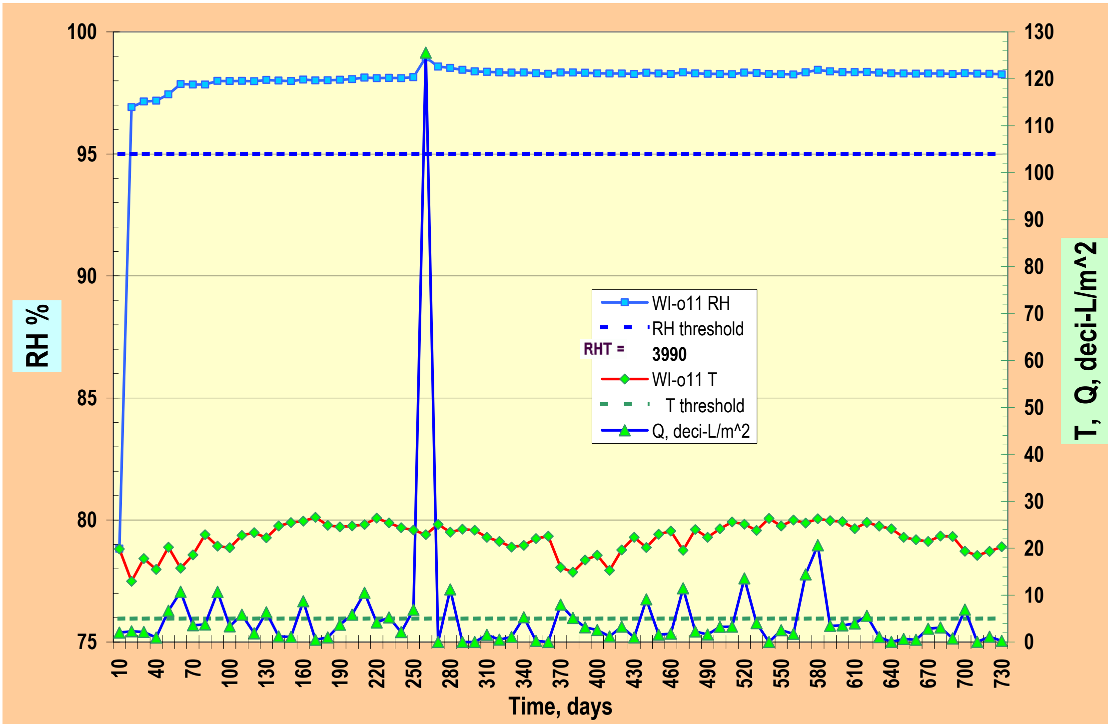


Figure 3.20 A) Reference wall with insulation in the stud cavity- Wilmington NC. RHT(95)= 3990

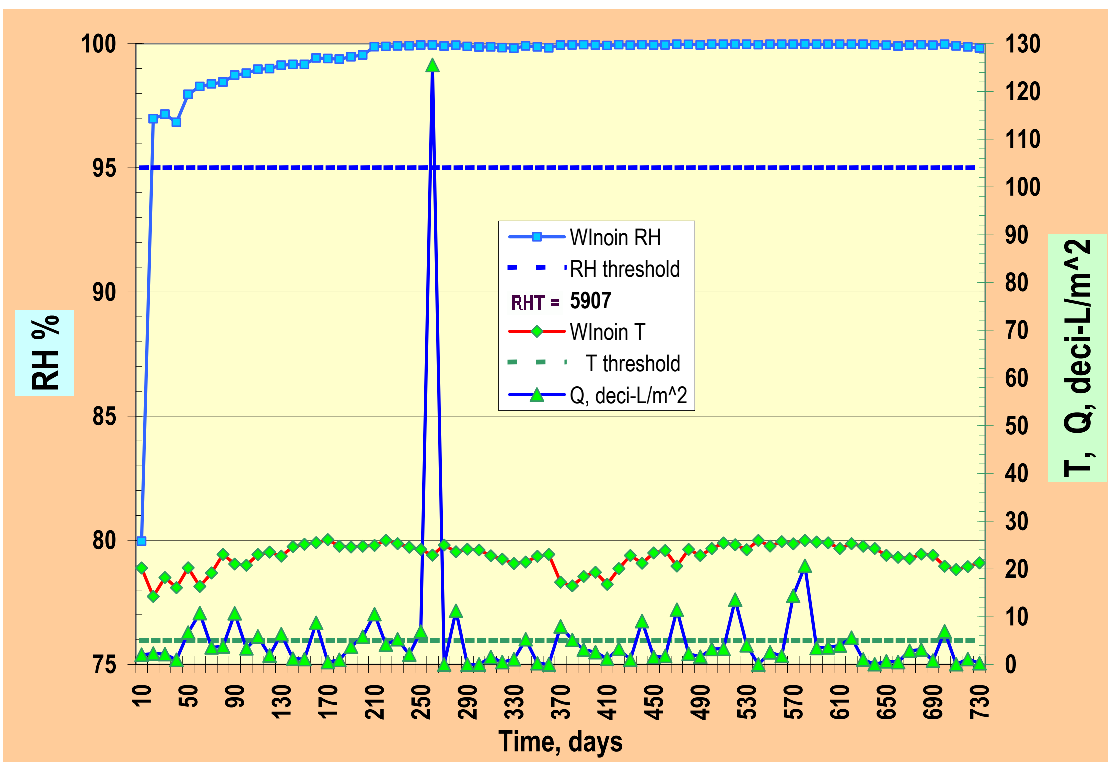


Figure 3.20 B) Reference wall with **no** insulation in the stud cavity- Wilmington NC RHT(95) = 5907

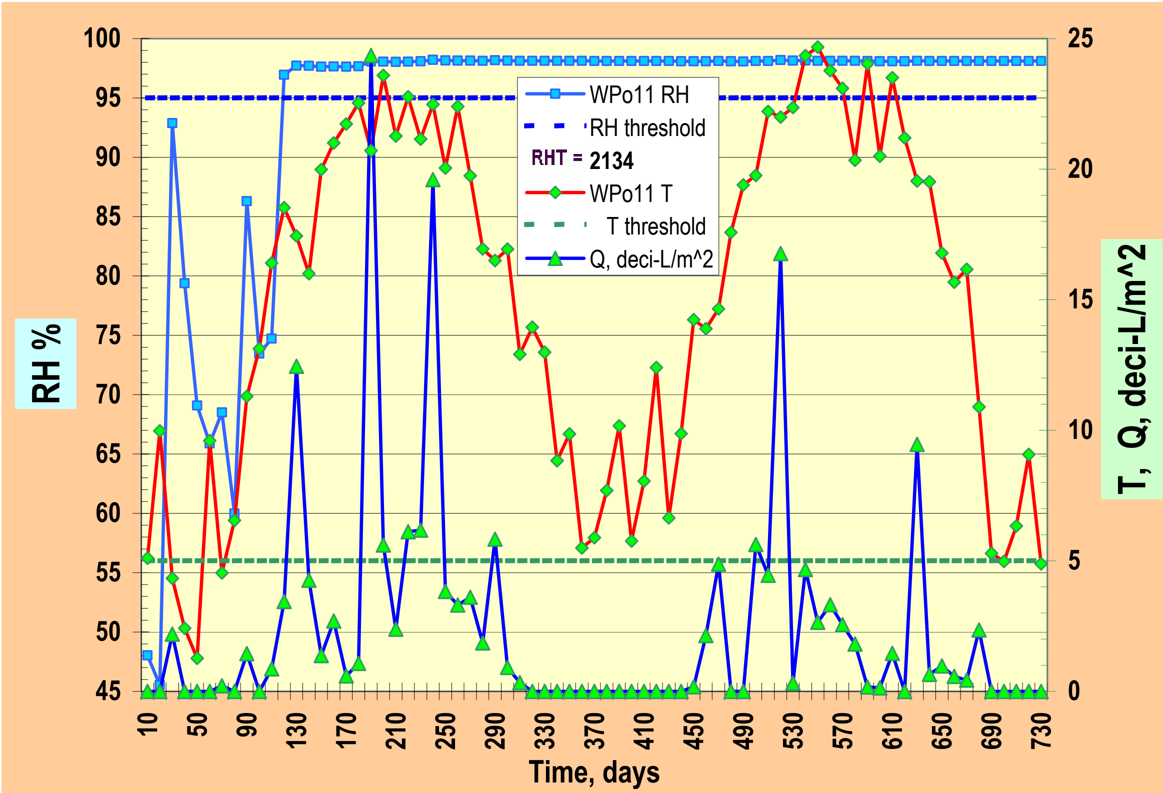


Figure 3.21 A) Reference wall <u>with insulation</u> in the stud cavity- Winnipeg. RHT(95)= 2134

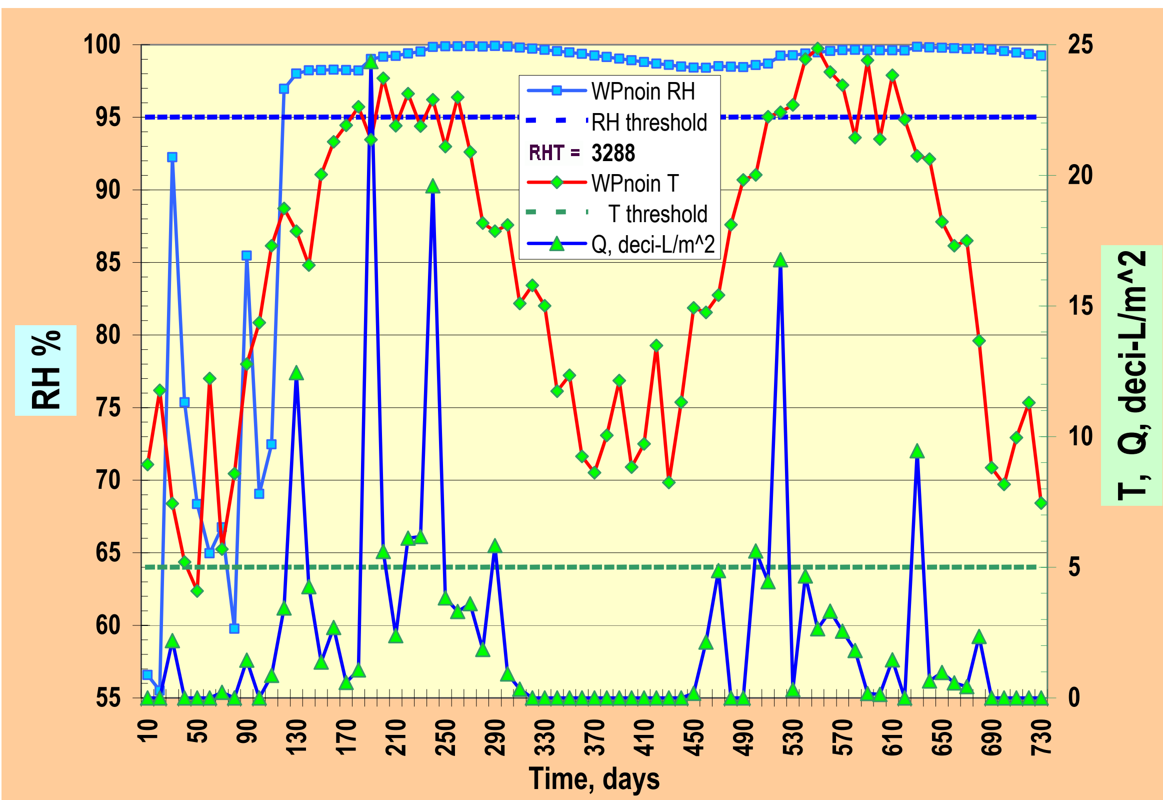
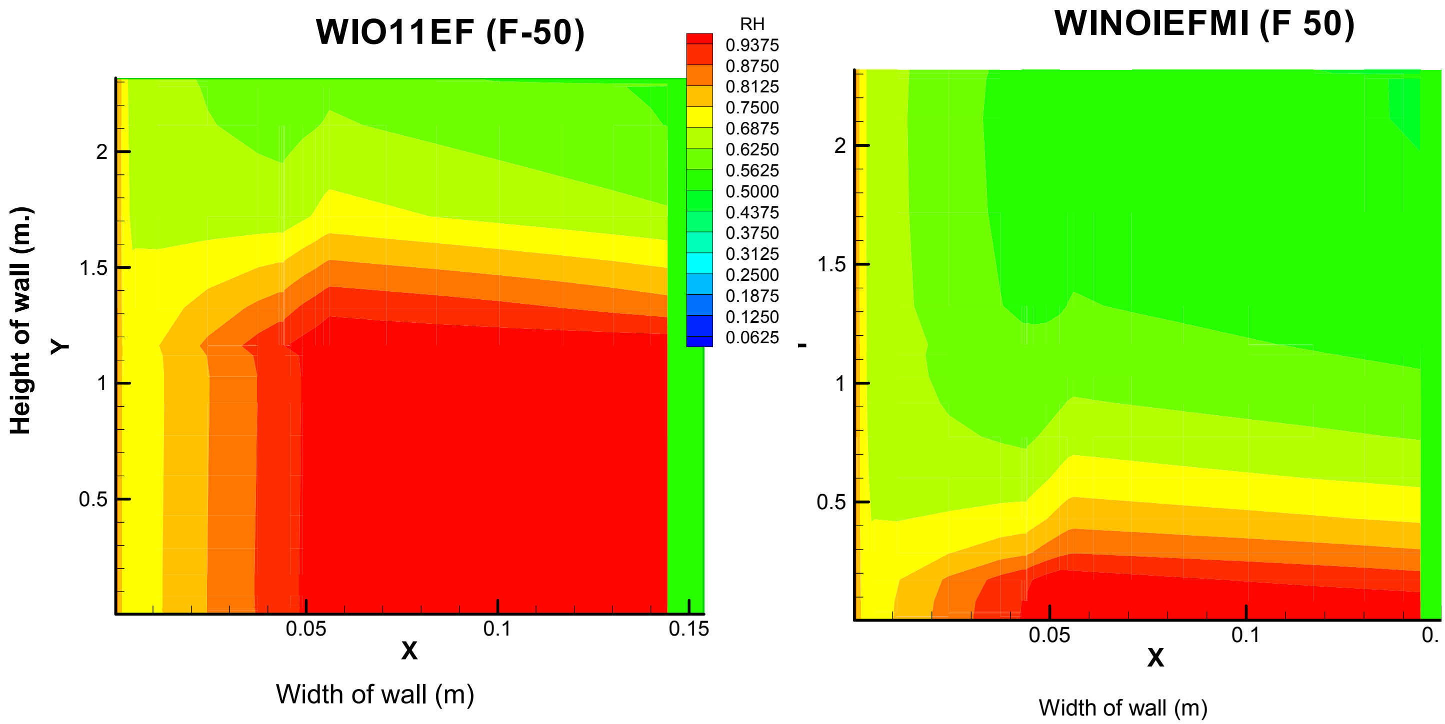


Figure 3.21 B) Reference wall <u>with no insulation</u> in the stud cavity- Winnipeg. RHT(95) 3288

For the climate of Winnipeg the same observation about lower RH for the wall with cavity insulation can be made (Figure 3.21). As for the temperature prevailing at the region of focus during the winter months, it was slightly higher for the reference wall without cavity insulation than it was for the wall with cavity insulation. This accounted for a portion of the increase of RHT for the wall with no cavity insulation. Indeed in cold climates, the absence of insulation in the stud cavity would on average raise the temperature in the stud cavity, as the major temperature drop would then occur across the exterior insulating sheathing.

The reduced RH for the wall with cavity insulation may be due to a redistribution of moisture away from the region of focus. The insulation may have acted as a "wick" that picked up the water sitting on the bottom plate and distributed it to a larger area and volume in the stud cavity. In an empty cavity, convection currents can also redistribute evaporating moisture within the stud cavity, but probably at a lower rate than liquid water in a porous medium. Contour plots of RH levels in the stud cavity (filled and unfilled with insulation) are presented in Figure 3.22. These show that the reference wall with no insulation (on the right) had a smaller and more confined region of very high RH (darkest area) close to the bottom of the cavity while the wall with insulation (on the left) in the stud cavity exhibited a much larger area of high RH.



A) <u>Wall **WITH** insulation in stud cavity.</u>
RHT(95) 3990

B) <u>Wall **WITHOUT** insulation in stud cavity</u>
RHT(95) 5907

Figure 3.22 Snapshot of predicted contour plots of RH levels in the stud cavity for Wilmington NC

For hot and dry climates like Phoenix and Fresno the effect of removing the cavity insulation on the RHT(95) response was small. This may be explained by the smaller moisture loads in the stud cavity in those climates. The more limited availability of free water on the surface of the bottom wood plate used as region of focus may provide less opportunity for a wicking effect in the glass-fibre insulation.

Observation No. 2. The cavity insulation may assist in dispersing water from the region of focus to other locations, hence reducing the RHT(95) response at the region of focus, compared to a wall with no cavity insulation. However when a very high level of moisture is present in a relatively airtight and vapour tight stud cavity, this moisture redistribution to other locations in the stud cavity may not be beneficial, for that redistribution may result in a larger area of the materials facing the stud cavity being exposed to high relative humidity levels.

Discussion: The argument for such behaviour has been presented in the paragraphs above. The point indicates the usefulness of predicted RH contour plots particularly when moisture distribution occurs in a non-homogenous material or assembly, such as a stud cavity interfacing with a bottom plate. Analysis of RH contour plots in this 2-D model assisted in understanding how RH might be distributed over a large area, as opposed to looking at a small area like the selected region of focus.

6.0 Effect of Air Flow

Observation: hygIRC simulations predicted that some airflow introduced into a wall assembly can result in a reduction of the RHT(95) response of the EIFS-clad reference wall when this wall is subjected to two sets of moisture loads in the stud cavity (1Q and ¼ Q) in Seattle and Ottawa. (Effect: *small*)

Discussion: The reference wall used for the parametric study (Figure 3.8) included no openings to allow airflow through the wall assemblies. The only airflow occurring in the reference wall was based on the air permeability of each material; no leakage path was in place. In practice, walls are not completely free of unintentional cracks and openings that would allow some through-flow of air in the presence of a pressure difference and that such airflow across the wall might have a significant effect on the wetting and possibly the drying of the assembly. As a result, a few additional simulations were included to investigate this effect. Ottawa and Seattle were selected to represent cold and warm climates with high moisture loads. Openings at the top on the exterior and at the bottom on the interior of the reference wall were introduced to allow an indirect air leakage path. The opening size represented a leakage area of 2 cm^2 per m^2 of wall, about the average measured in residential buildings.

Table 3.8 presents the simulation results. Small reductions in RHT(95) wall response for both locations when some uncontrolled airflow was introduced into the assembly were predicted. In the simulation runs, the direction of the flow was dictated by the natural occurrence of wind and stack effects. Mostly exfiltration of indoor air was observed in the simulation runs. In these runs, indoor air was dryer (25% RH in winter and 55%RH in summer) than the stud cavity (around 98%). Exfiltration of small amounts of warm and relatively dry indoor air through such an indirect path was predicted to contribute to the drying of a stud cavity (wetted by rain penetration).

Table 3.8 RHT(95) response for the reference wall with and without uncontrolled airflow

	RHT(95) response with a 1Q moisture loads in the stud cavity	
	for Ottawa	for Seattle
Reference wall (No. O11) with 1Q moisture loads in the stud cavity and no air flow	2529	3345
Same wall with some uncontrolled air flow	2322	2984
Wall O11W4 with 1/4Q moisture loads in the stud cavity and no air flow	278	1242
Same wall with some air flow	256	906

One should recognise that air leakage is an uncontrolled phenomenon that may have negative effects on the hygrothermal performance of wall assemblies in certain climates and circumstances. Most research on air leakage has focused on the wetting potential related to the exfiltration of large amounts of humid indoor air, which was not the cases in these simulation runs. The rate of air leakage can be of critical importance in regard to the potential for transporting moisture in or out of the wall cavity. The drying potential associated with a *small* flow of mostly warm and relatively dry air across a wet wall assembly compared to the same wall with *zero* air leakage has not yet been examined thoroughly. Further investigation into the positive and negative effects of various rates of air leakage on the moisture deposition and moisture removal capacity of air flow through a wall assembly in different climates are required prior to making general statements.

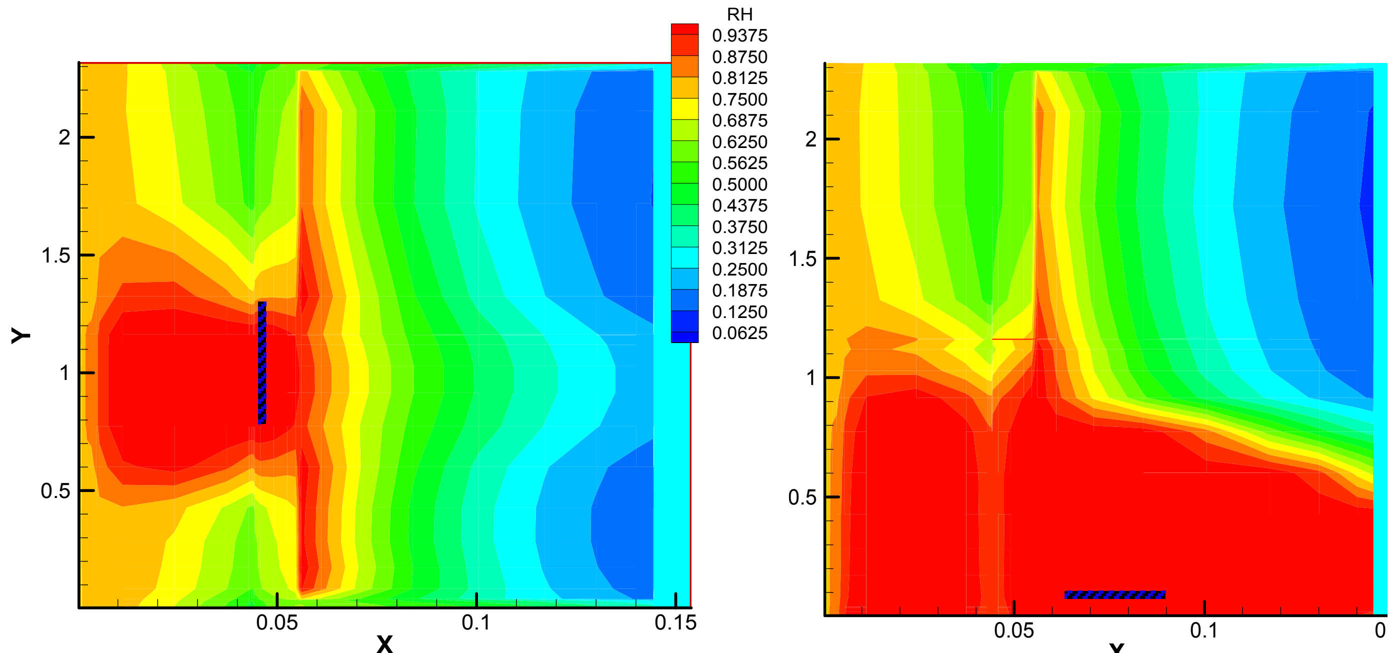
7.0 Effect of the Location of Water Deposition Inside the Wall Assembly

Observation: A single set of hygIRC simulations for Ottawa climate predicted that changing the location of the water deposition into the wall, from the bottom of the stud cavity to the WRB/sheathing board interface at mid-height of the wall would have little effect on the cumulative RHT(95) value for the region of focus in question. However the pattern of moisture distribution was different. (Effect: *small*)

Discussion: Investigative field surveys of EIFS-clad walls indicated water damage on the sheathing board below leaky windows; MEWS partners referred to a "Fu Manchu mustache" pattern of damage on the sheathing board. One hygIRC simulation for Ottawa was run to explore the effect of "depositing" the water leaking into the wall at the interface between the WRB and the sheathing board on the RHT(95) wall response. Remember that hygIRC model did not mimic gravity flow of water. Rather the model was programmed to deposit a moisture load (defined by the climate loads for a given year of actual climatic records in a given locality and by a given size of deficiency) in a given location of the wall assembly at the beginning of every hour of simulation.

In terms of RHT (95) response for the region of focus, hygIRC predicted very similar outcomes in this case (i.e. RHT(95) of 2686 and 2529). Keep in mind that the region of focus selected at mid-height of the wall was much larger (i.e. 500 mm wide by 1.5 mm thick) than the region of focus selected at the bottom of the stud wall (i.e. 53 mm wide by 1.5 mm thick), and that the size of the region of focus selected can affect the averaging of the predicted RHT(95) value.

The profiles of moisture distribution were different. Figure 3.23 provides the pattern of moisture distribution predicted by hygIRC at the end of two years of simulation for Ottawa for both locations of moisture deposition into the wall. For the scenario with water leakage at mid-height of the wall (case A on the left), the most severe wetting was at the point of entry with some water distribution towards the outside. There was also some moisture movement laterally around the point of entry between the WRB and the sheathing board. With the water deposited on the bottom plate in the stud cavity (Case B on the right), there was some opportunity for the water to migrate through the batt insulation and to be redistributed upwards into the stud cavity instead.



<u>Case A</u>. **RHT(95): 2686** <u>Case B</u>. **RHT(95): 2529**

Figure 3.23. Moisture contour profiles for EIFS-clad wall where A) moisture was deposited at mid-height of the wall, at the interface between the WRB and the sheathing board B) moisture was deposited at the bottom of the stud cavity.

8.0 <u>Effect of Change of Severity of Simulation Years</u>

<u>Observation</u>: Changing the severity of the second simulation year (from "average" to "dry" was predicted to result in little difference in the cumulative RHT(95) values for four climates (Winnipeg, Ottawa, Seattle and Wilmington NC). (Effect: *near-zero*)

<u>Discussion</u>: It was presumed that a second simulation year of lesser climate severity would result in lower RHT(95) response of the wall. However hygIRC predicted that the response hardly changed at all (see Table 3.9). The relatively non-porous nature of the EIFS lamina hampered the removal of trapped moisture through drying. It appeared that enough of the 1Q moisture load injected in the stud cavity during the first simulation year was retained in the stud space and maintained elevated values of RH in spite of a lower moisture loads during the second simulation year.

Table 3.9: RHT(95) response for different simulation years

	RHT(95) response, with a 1Q moisture loads in the stud cavity			
	Ottawa	Winnipeg	Seattle	Wilmington NC
Reference wall (No. O11) with Wet – Average Years	2529	2134	3345	3990
Same wall for Wet – Dry Years	2547	2105	3336	3947

Appendix 3.1 Table of all hygIRC simulation results (See the notation at the end)

Table 1 : RHT (95) Indices

Simulation ID	RHT (95)	Simulation ID	RHT (95)	Simulation ID	RHT (95)	Simulation ID	RHT (95)
OTO11EFBC	0	**(C) SEATTLE**		WIVB10EF4075RH	3887	FRO11EFW2	451
OTO11EF	2529	SEO11EFBC	0	WIVB10EF5075RH	3893	FRO11EFW4	58
OTP20EF	2479	SEO11EF	3345			FRNOIEFMI	2010
OTG22EFBC	0	SEP20EF	3304				
OTG22EF	2272	SESM5EF	3345			**(G) SAN DIEGO**	
OTSM5EF	2529	SESM7EF	3370			SDO11EFBC	0
OTSM7EF	2545	SEVB9EF	3281			SDO11EF	3343
OTVB9EF	2474	SEVB10EF	3007			SDP20EF	3072
OTVB10EF	2354	SECO1EF	3341	**(E) WINNIPEG**		SDG22EF	3497
OTCO1EF	2526	SECO2EF	3336	WPO11EFBC	0	SDSM5EF	3364
OTCO2EF	2522	SEO11EFW2	2884	WPO11EF	2134	SDSM7EF	3692
OTO11EFW2	2176	SEO11EFW4	1242	WPP20EF	2059	SDVB9EF	2347
OTO11EFW4	278	SEO11EFAL	2984	WPG22EF	1982	SDVB10EF	1677
OTO11EFAL	2322	SENOIEFMI	5413	WPSM5EF	2134	SDCO1EF	3306
OTNOIEFMI	3907	SEO11EFWD	3336	WPSM7EF	2144	SDCO2EF	3238
OTNOIEFALW4	256	SEG22EF	3215	WPVB9EF	2092	SDO11EFW2	1140
OTO11EFWD	2547	SEO11EFALW4	906	WPVB10EF	2012	SDO11EFW4	195
OTO11EFLV1	2686	**(D) WILMINGTON NC**		WPCO1EF	2131	SDNOIEFMI	4948
		WIO11EFBC	0	WPCO2EF	2127		
(B) PHOENIX		WIO11EF	3990	WPO11EFW2	1841		
PHO11EFBC	0	WIP20EF	3923	WPO11EFW4	768		
PHO11EF	1196	WISM5EF	3991	WPNOIEFMI	3288		
PHP20EF	976	WISM7EF	4014	WPO11EFWD	2105		
PHG22EF	902	WIVB9EF	3926				
PHSM5EF	1227	WIVB10EF	3827	**(F) FRESNO**			
PHSM7EF	1378	WICO1EF	3987	FRO11EFBC	0		
PHVB9EF	733	WICO2EF	3984	FRO11EF	1435		
PHVB10EF	505	WIO11EFW2	3622	FRP20EF	1264		
PHCO1EF	1187	WIO11EFW4	2885	FRG22EF	1578		
PHCO2EF	1157	WIO11EFWD	3947	FRSM5EF	1448		
PHO11EFW2	3196	WINOIEFMI	5907	FRSM7EF	1595		
PHO11EFW4	4394	WIO11EFV0CG	1363	FRVB9EF	1094		
PHNOIEFMI	1426	WIVB10EF2565RH	3846	FRVB10EF	868		
		WIVB10EF2575RH	3872	FRCO1EF	1423		

RHT (80) Results for EIFS-clad Walls

Simulation ID	RHT (80)
(A) OTTAWA	
OTO11EFBC	0
OTO11EF	15300
OTP20EF	14969
OTG22EFBC	0
OTG22EF	14887
OTSM5EF	15296
OTSM7EF	15331
OTVB9EF	15120
OTVB10EF	14763
OTCO1EF	15288
OTCO2EF	15270
OTO11EFW2	14175
OTO11EFW4	6791
OTO11EFAL	14293
OTNOIEFMI	17389
OTO11EFALW4	4066
OTO11EFWD	15337
(B) PHOENIX	
PHO11EFBC	0
PHO11EF	11897
PHP20EF	11317
PHG22EF	13158
PHSM5EF	12065
PHSM7EF	13144
PHVB9EF	8805
PHVB10EF	7505
PHCO1EF	11830
PHCO2EF	11689
PHO11EFW2	22319
PHO11EFW4	26081
PHNOIEFMI	11491

Simulation ID	RHT (80)
(C) SEATTLE	
SEO11EFBC	0
SEO11EF	19511
SEP20EF	19346
SESM5EF	19508
SESM7EF	19562
SEVB9EF	19359
SEVB10EF	18796
SECO1EF	19498
SECO2EF	19481
SEO11EFW2	18682
SEO11EFW4	12254
SEO11EFAL	18110
SENOIEFMI	22453
SEO11EFWD	19492
SEG22EF	19152
SEO11EFALW4	8267
(D) WILMINGTON NC	
WIO11EFBC	0
WIO11EF	22660
WIP20EF	22473
WISM5EF	22653
WISM7EF	22704
WIVB9EF	22535
WIVB10EF	22337
WICO1EF	22651
WICO2EF	22641
WIO11EFW2	21877
WIO11EFW4	20374
WIO11EFWD	22594
WINOIEFMI	24961
WIO11EFV0CG	16485
WIVB10EF2565RH	22376
WIVB10EF2575RH	22430

Simulation ID	RHT (80)
WIVB10EF4065RH	22400
WIVB10EF4075RH	22453
WIVB10EF5075RH	22465
(E) WINNIPEG	
WPO11EFBC	0
WPO11EF	12719
WPP20EF	12487
WPG22EF	12405
WPSM5EF	12717
WPSM7EF	12732
WPVB9EF	12582
WPVB10EF	12239
WPCO1EF	12708
WPCO2EF	12691
WPO11EFW2	11748
WPO11EFW4	8011
WPNOIEFMI	15041
WPO11EFWD	12645
(F) FRESNO	
FRO11EFBC	0
FRO11EF	12143
FRP20EF	11586
FRG22EF	16300
FRSM5EF	12252
FRSM7EF	13564
FRVB9EF	9701
FRVB10EF	8136
FRCO1EF	12058

Simulation ID	RHT (80)
FRCO2EF	11921
FRO11EFW2	5452
FRO11EFW4	1280
FRNOIEFMI	14155
(G) SAN DIEGO	
SDO11EFBC	0
SDO11EF	22567
SDP20EF	22100
SDG22EF	23699
SDSM5EF	22569
SDSM7EF	23045
SDVB9EF	18292
SDVB10EF	14166
SDCO1EF	22482
SDCO2EF	22358
SDO11EFW2	12569
SDO11EFW4	4424
SDNOIEFMI	24518

Notation

**O11EFBC	Base case: 5 mm EIFS lamina, 11 mm OSB sheathing, sheathing membrane No. 27, VB No. 8 (type 1), no accidental water entry into the stud cavity
**O11EF	Same as **O11EFBC but with moisture entry
**P20EF	Same as **O11EF but with plywood board
**G22EFBC	Same as **O11EFBC but with exterior grade gypsum board
**G22EF	Same as **O11EF but with exterior grade gypsum board
**SM5EF	Same as **O11EF but with sheathing membrane No. 5
**SM7EF	Same as **O11EF but with sheathing membrane No. 7
**VB9EF	Same as **O11EF but with vapour barrier No. 9
**VB10EF	Same as **O11EF but with vapour barrier No. 10
**CO1EF	Same as **O11EF but with different base coat and finish coat thicknesses
**CO2EF	Same as **O11EF but with different base coat and finish coat thicknesses
**O11EFW2	Same as **O11EF but with ½ the reference water entry rate (only exception is Phoenix with twice the reference water entry rate)
**O11EFW4	Same as **O11EF but with quarter of the normal moisture entry (only exception is Phoenix with quadruple moisture entry)
**O11EFAL	Same as **O11EF but with air leakage
**NOIEFMI	Same as **O11EF but with no insulation in stud cavity
**O11EFALW4	Same as **O11EFW4 but with air leakage
**O11EFWD	Same as **O11EF but average weather year is replaced dry weather year
**O11EFLV1	Same as **O11EF but with moisture entry location is at the window level between sheathing membrane and sheathing board (note: in all other cases moisture entry location is at the bottom of the stud cavity).
**O11EFV0CG	Same as **O11EF but no vapour barrier and with painted/coated interior gypsum board.
**VB10EF2565RH	Same as **VB10EF but interior room RH variation (Winter 25%; Summer 65%). Std./Reference case: Winter 25%; Summer 55%
**VB10EF2575RH	Same as **VB10EF but interior room RH variation (Winter 25%; Summer 75%). Std./Reference case: Winter 25%; Summer 55%
**VB10EF4065RH	Same as **VB10EF but interior room RH variation (Winter 40%; Summer 65%). Std./Reference case: Winter 25%; Summer 55%
**VB10EF4075RH	Same as **VB10EF but interior room RH variation (Winter 40%; Summer 75%). Std./Reference case: Winter 25%; Summer 55%
**VB10EF5075RH	Same as **VB10EF but interior room RH variation (Winter 50%; Summer 75%). Std./Reference case: Winter 25%; Summer 55%

**: PH - Phoenix; FR - Fresno; SD - San Diego; WP - Winnipeg; OT - Ottawa; SE - Seattle; WI: Wilmington NC

Chapter 4. Application to Masonry-clad walls

4.1 Summary

Masonry wall assemblies in North America traditionally include a drained and flashed cavity behind the veneer to reduce the risk of water bridging to the backup wall. The cavity is, however, bridged by penetrations such as windows, ventilation ducts and electrical receptacles, in common with other wall systems. In recent years, literature reporting on field investigations has pointed towards the detailing at these penetrations as significant water leakage paths into wall assemblies. While masonry walls were not specifically addressed in those field investigations, it was considered reasonable to include representations of deficiencies in the parametric study of all four wall systems.

The results of the MEWS parametric study of masonry-clad walls using the hygIRC model indicated that, in common with the other wall systems studied, they tolerated some accidental water entry in the stud space, but beyond a certain amount, the capacity for drying was overwhelmed. The selection of materials that promote drying can substantially increase the tolerance of masonry-clad walls to accidental water entry in the stud cavity.

Before reporting the results of modeling, a few words regarding the assumptions should be kept in mind when considering the results. First, the moisture loading of the model walls was calculated in two stages: 1) wind-driven rain, which quantified the water impinging on the exterior cladding of the wall, and 2) water introduced into the stud space in varying amounts to simulate accidental water entry. The relation between the wind-driven rain of stage 1) and the varying amounts of water introduced into the stud space (stage 2), was established by tests of the masonry walls in the DWTF. For the masonry walls tested, this relation was based on leakage through the deficiency over the ventilation duct penetration. The water entering the stud cavity was assumed to collect at the base of the stud space along the top of the bottom plate.

Highlights of hygIRC prediction results are as follows:

- The masonry-clad walls investigated exhibited a level of water resistance that reduced significantly the amount of water getting through the field of the wall. The resistance was largely due to the rain-screen provided by the cladding, the cavity behind the cladding, and the ability of the relatively massive cladding to store and release moisture. hygIRC simulations indicated that when no water was allowed to enter into the wall assembly (i.e. no deficiency), while the wall was exposed to two years of climate data, the hygrothermal response of the reference masonry-clad wall as measured by RHT(95) index was not detectable, even in a climate of severe moisture loads like Wilmington NC.

- When the same reference wall included a deficiency that allowed direct water entry beyond the water resistive barrier, i.e. into the stud cavity, the RHT(95) response predicted for the reference wall varied from a value of about 40 in a hot and dry climate of Phoenix to about 2700 for the warm and wet climate of Wilmington NC. Values near zero (less than 100) are not of great concern, considering the variability of climate conditions and other parameters, but RHT(95) response was substantial (over 1000) for three of the four wettest climates (Winnipeg, Seattle and Wilmington NC). In these three cases, RHT(95) indicated water intake clearly exceeding the evaporative drying potential offered by the properties of the materials in the reference wall assembly with deficiency, and the temperature prevailing in the stud cavity.

- An important part of the parametric study addressed the assessment of leakage through a deficiency (stage 2 of the calculation mentioned above). Although the amount "Q" so defined established a starting point, two other water intake rates were also simulated for the reference wall, to better reveal its drying potential under different service conditions. When the hourly rate of water entry into the stud cavity was varied from 1 Q to zero Q, the RHT(95) index of the wall in the region of focus (i.e. top of bottom plate) dropped linearly, reaching zero at rates of ¼ Q or less for all the climates examined.

- Changing the sheathing board could significantly affect the drying potential of masonry-clad wall systems with excess moisture in the stud cavity. Asphalt-coated fibreboard showed a substantial reduction in RHT(95) over OSB sheathing. Asphalt-coated fibreboard exhibited higher vapour and air permeabilities and its position facing a vented cavity likely contributed to increased evaporative drying of the stud cavity. Changing to XPS sheathing from OSB in a wall assembly subjected to 1Q moisture loads in the stud cavity substantially increased the accumulation of RHT(95) because the addition of thermal insulation on the outside of the stud cavity prolonged the period at which the region of focus was above 5^{o}C. This effect was different from a situation where condensation control would be the only concern; in that latter case, the presence of an insulating sheathing would be desirable because the increased cavity temperature would reduce the period where it is below the dew point temperature of indoor air.

- Increasing the water vapour permeance of the vapour barrier membrane showed some decrease in the value of RHT(95), indicating some drying to the inside occurred. However the interior conditions assumed favoured drying to the inside and the result should not be generalized without further analyses for other indoor conditions.

- Varying the water resistive membranes showed little effect on RHT(95) index. This can be explained as follows: the main function of the water resistive barrier as a secondary *line of defence* against liquid water entry was circumvented when water entered the stud cavity through deficiencies. In any case, the vapour permeance of both water resistive membranes were comparable, and low compared to other elements in the wall.

- Varying the properties of the masonry units comprising the cladding had little effect on the hygrothermal response of the wall. The masonry units in the modeled walls were de-coupled from the region of focus by a 25 or 50 mm vented cavity, leaving no strong transfer mechanism between the region of focus and the masonry elements.

- Increasing the width of the vented cavity behind the cladding had little effect on the values of RHT(95). The cavity provided a capillary break isolating the region of focus from wind-driven rain impinging on the masonry veneer. It also allowed for drying to the air in the cavity. Beyond a 25 mm width of the cavity, however no further benefits for the hygrothermal performance of the wall were derived.

The following sections explain how the MEWS methodology outlined in Chapter 1 was applied to masonry-clad walls, and provide support documentation for each scenario investigated with the hygIRC model for the prediction of the hygrothermal response of wall assemblies.

4.2 Selection of Materials and Design of the Assemblies

Through Task Group 2, MEWS industry members and IRC personnel gathered technical information on current practices on the construction of masonry-clad wall assemblies. This information was used in the design of four full-scale wall specimens for the evaluation of water entry under simulated wind-driven rain (TG6), the design of walls to be simulated through modelling in TG 7 and for the characterization of material properties (TG3).

4.2.1 Types of Wall Assemblies Selected

Four generic types of masonry-clad assemblies were examined, as defined by the construction practices outlined by Task Group 2. All four walls featured 90 mm brick units.

- Wall specimen No. 11 was constructed using 25 mm ship-lapped sheets of extruded polystyrene (XPS) as the sheathing board. The cavity behind the masonry was 25 mm (Figure 4.1).
- Wall specimen No. 12 featured 11 mm OSB sheathing board covered with 30-minute building paper. The cavity behind the masonry veneer was 25 mm (Figure 4.2).
- Wall specimen No. 13 consisted of 30-minute building paper covering 11 mm asphalt-impregnated fibreboard sheathing. The cavity behind the masonry was 25 mm (Figure 4.3).
- Wall specimen No. 14 consisted of a cross-woven perforated polyethylene membrane covering a 12 mm glass mat gypsum board. In this wall the cavity behind the masonry was increased to 50 mm (Figure 4.4).

A complete description of the 4 masonry-clad wall specimens investigated in the DWTF can be found in report T2-02 entitled: *Description of the 17 Large-scale Specimens Built for Water Entry Investigation in IRC Dynamic Wall Testing Facility,* May 2002.

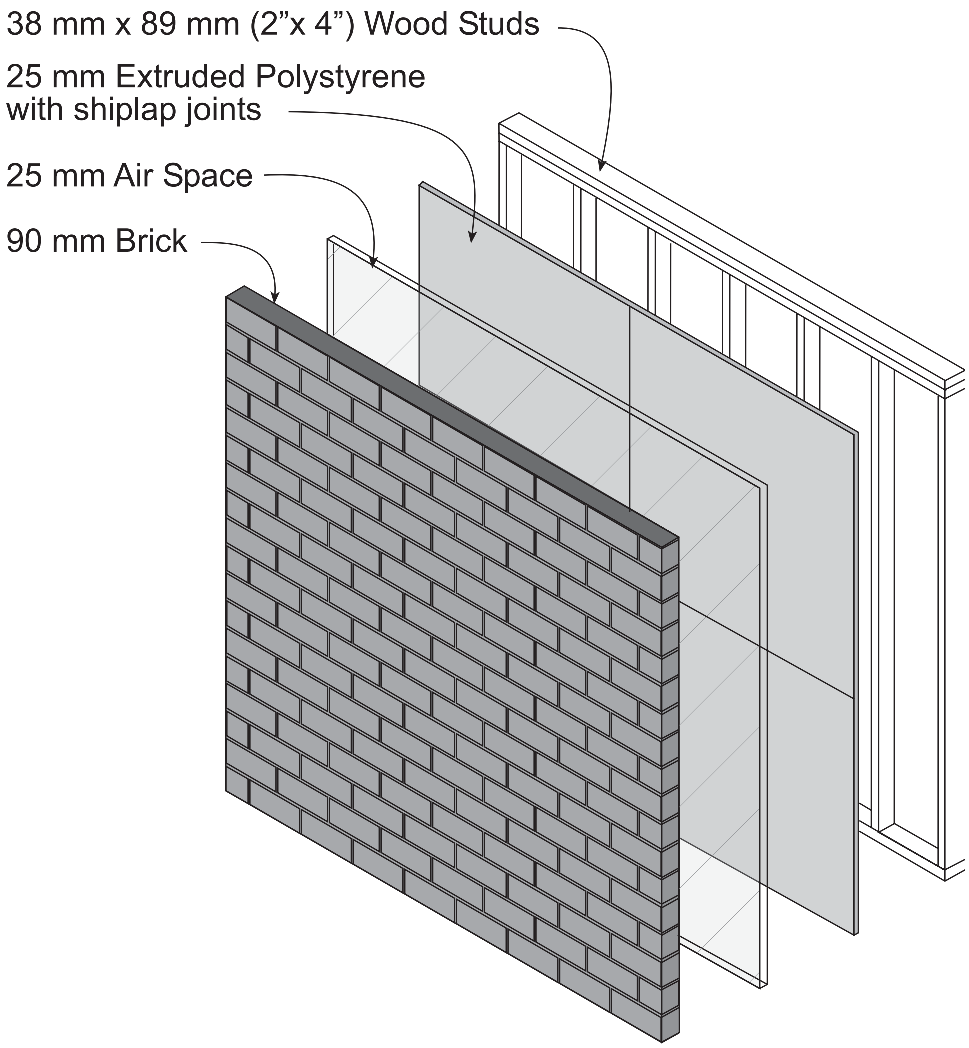


Figure 4.1. Composition of masonry wall specimen No. 11

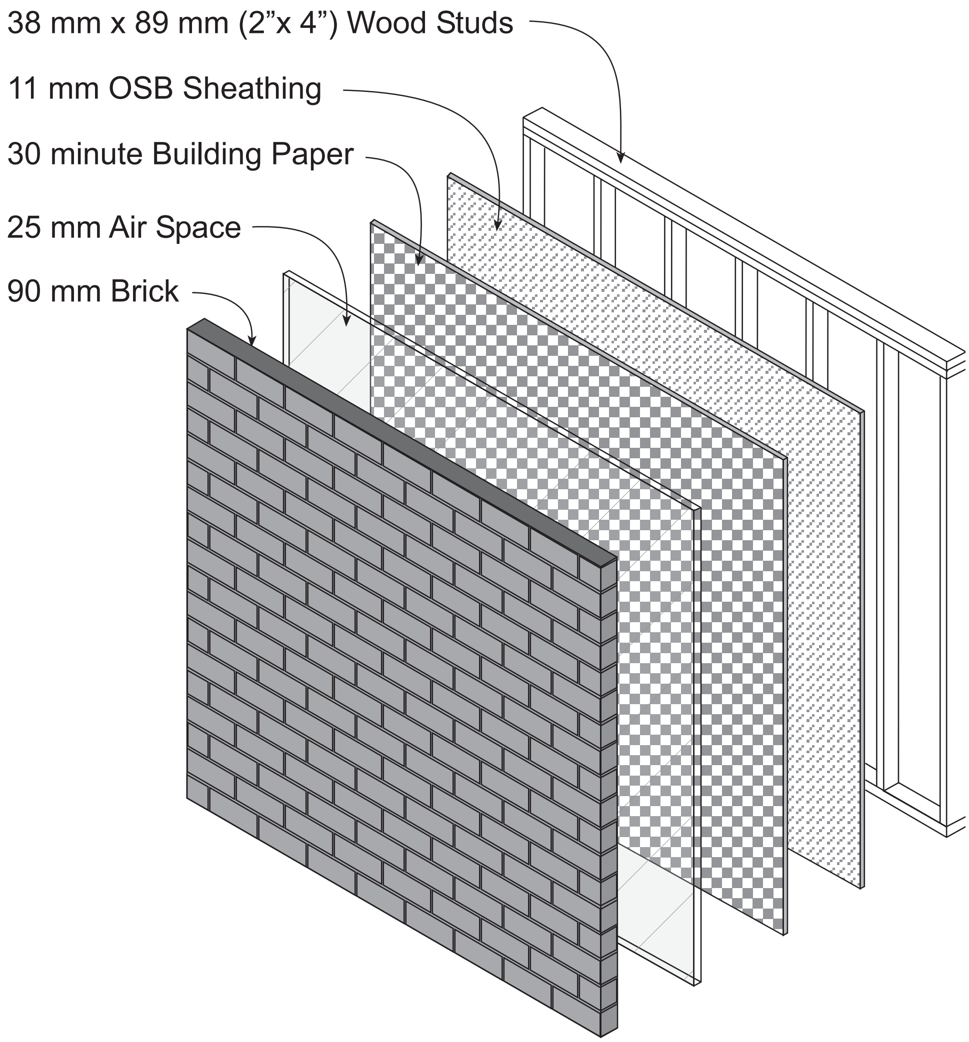


Figure 4.2. Composition of masonry wall specimen No. 12

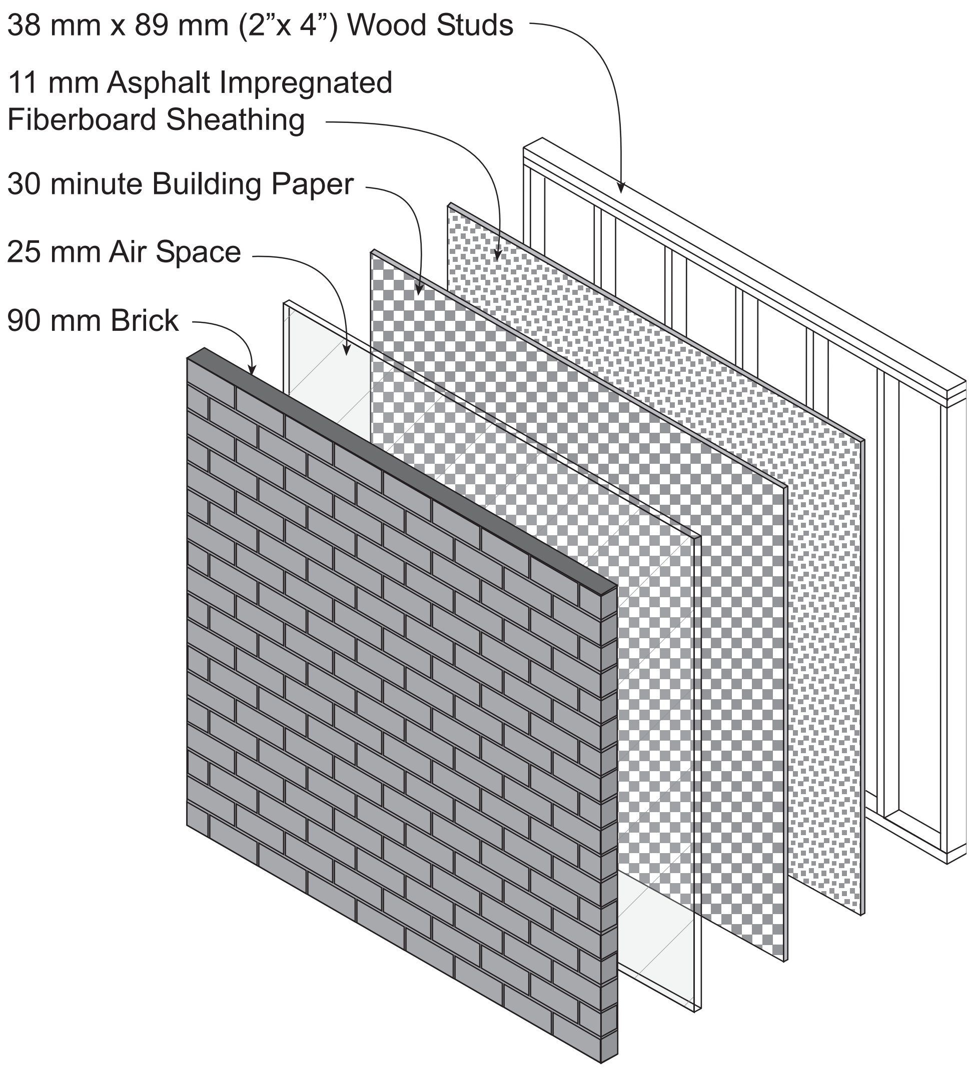


Figure 4.3. Composition of masonry wall specimen No. 13

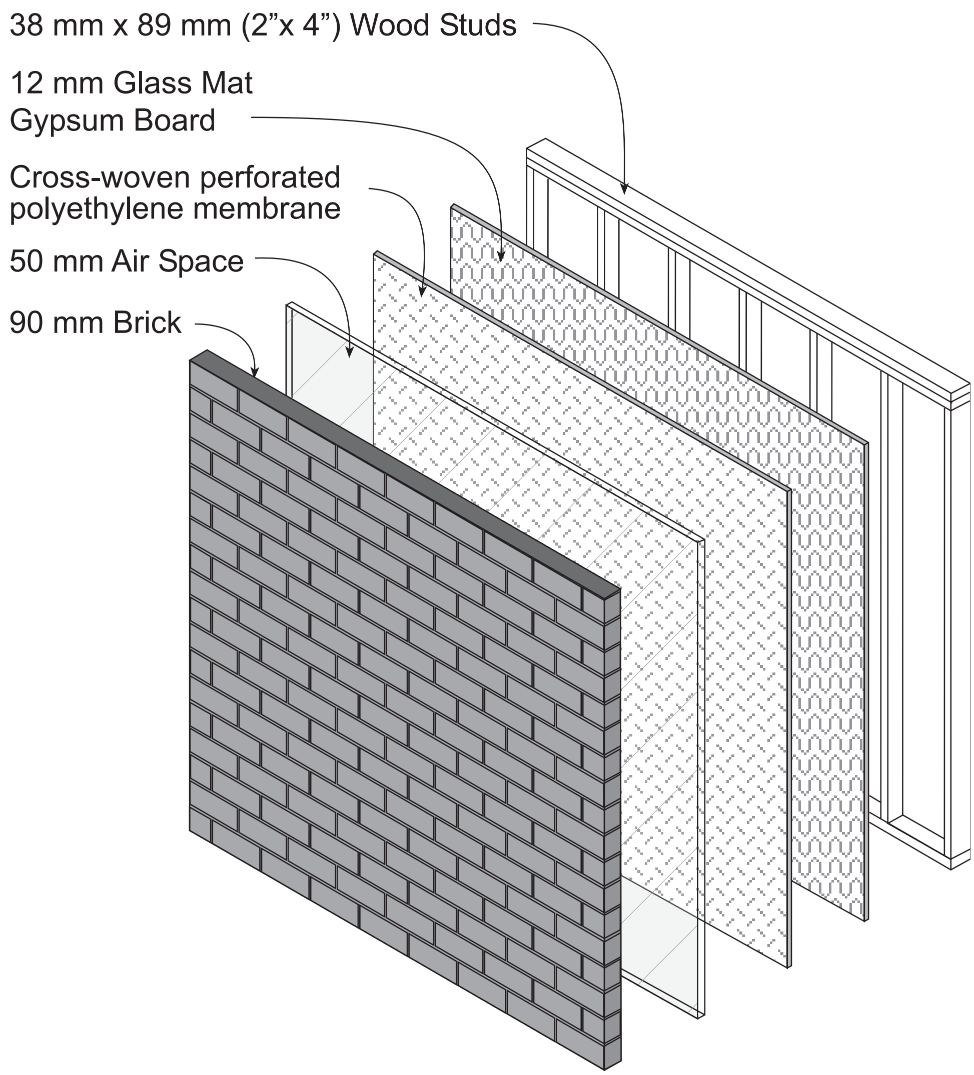
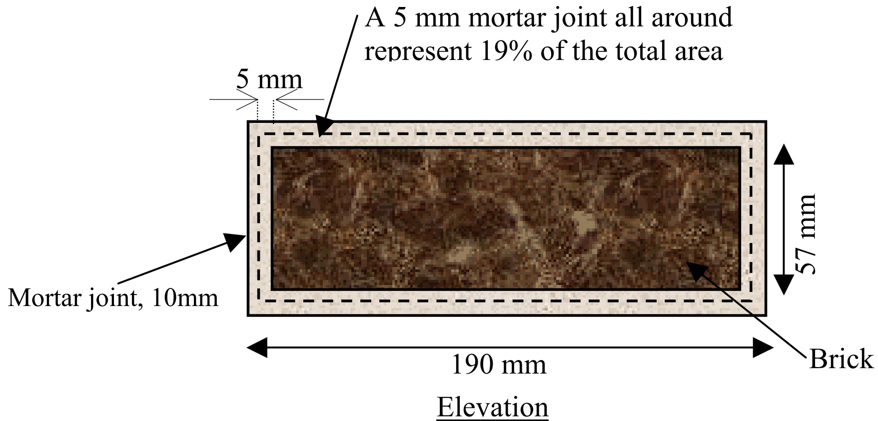


Figure 4.4. Composition of masonry wall specimen No. 14

4.2.2 Properties of Materials

Hygrothermal properties of several products of the following basic materials were characterized: composite masonry units (clay brick, concrete brick, calcium silicate brick, and mortar), polymeric and paper-based WRB membranes, OSB, extruded polystyrene (XPS), and asphalt-coated fibreboard sheathing boards, glass fibre insulation, spruce lumber, paper and plastic vapour barriers and interior grade gypsum board. Several properties of these materials used as input for running hygIRC simulations are given in Table 4.1. Other hygrothermal material properties can be found in the MEWS report T3-23 entitled: "*Hygrothermal Properties of Several Building Materials",* March 2002.

Although it would have been possible to model individual masonry units and the bonding mortar in a masonry-clad wall system, for practical purposes (computation time for example) a bulk material property approach was used; i.e. the cladding was assumed to consist of one material having one set of material properties. The bulk properties of the masonry-clad wall system were calculated as the area-weighted average of the material properties of the masonry unit and the material properties of the bonding mortar. The material properties of these elements are given in Table 4.1. Figure 4.5 gives an example of how the area-weighted average is calculated.



Bulk Property calculation

Brick surface (A_b) = 80.83%

Mortar surface (A_m) = 19.17%

Property (P) $_{bmc}$= (P_b X A_b + P_m X A_m) / (A_b + A_m)

Figure 4.5. Example of how the bulk material properties of a brick-mortar composite were determined for MEWS modelling. The material property in question was calculated as the area-weighted average of the individual elements, masonry units and mortar, of the composite masonry system.

Table 4.1: Selected Properties of Materials

Properties / Materials	Water vapour permeability ng/(m s Pa)		Liquid diffusivity (10^{-12} m^2/s)	Air permeability x dynamic viscosity (m^2) x 10^{-16}
	@ 0%RH	@ 100%RH		
Masonry Elements				
Clay Brick*	1.45	2.1	50600	21
Concrete Brick	1.13	2.7	29200	71
Calcium Silicate	1.77	106	10600	100
Mortar	12.0	35	7850	220
Sheathing board				
OSB*	0.06	6	22 (x) 510 (y)	79
Extruded Polystyrene Foam (XPS) **	0.94	1.4	0.0001	1
Asphalt-Coated Fibreboard	18.82	23	3.2 (x) 1237 (y)	32000
Water resistive barrier				
30 Minute Paper	0.18	1.2	3.6	118
SBPO Polymeric *	0.24	0.2	0.0001	1200
Vapour Barrier				
Type I - 15 ng*	0.002	0.002	0.0001	0.001
Type II - 60 ng	0.012	0.012	0.0001	0.001
Type III - Variable	0.006	0.064	0.0001	0.001

* Materials used for the reference wall
** The values were obtained from laboratory measurements on a product manufactured in 1997 at a thickness of 100 mm. For updated values, the reader should contact the manufacturer.

4.3 Estimation of Moisture Loads

The methodology presented in Section 1.5 for the estimation of moisture loads into the stud cavity was applied to the study of masonry-clad wall assemblies. Moisture loads impinging on the face of the cladding were assessed based on local climate to which the wall assembly was subjected in simulations. The moisture loading into the stud cavity was based on the results obtained from experiments using the Dynamic Wall Testing facility (DWTF). These experiments provided rates of accidental water entry through deficiencies located in four different wall specimens for several specific combinations of water spray intensity and static air pressure differential across the wall. Variations in the composition of the four masonry-clad wall assemblies are described in the TG2 report entitled: *Description of the 17 Large-scale specimens built for water entry investigation in IRC Dynamic Wall Testing Facility*.

Moisture entry into the wall assembly through a given opening

Full-scale laboratory tests were conducted on the four masonry-clad specimens (Figures 4.1 to 4.4) to find out what fraction of the water sprayed on the exterior face of the wall would pass through the given deficiency at an electrical receptacle and end up inside the stud cavity. In the case of the masonry-clad walls the electrical receptacle did not penetrate through the entire wall assembly because of the thickness of the brick veneer. Water that penetrated through the deficiency at the electrical receptacle was collected in the drainage cavity behind the brick veneer and did not penetrate into the stud space. Consequently for masonry-clad walls, a deficiency at the ventilation duct, a through-wall penetration, was used for determining the water entry rates in the stud cavity. This deficiency consisted of a missing bead of sealant, forming a crack of nominally 50 mm long and 1 mm wide at the interface between the top of the cover of a ventilation duct and the masonry cladding. An example of typical deficiency is shown in Figure 4.6. Three of the specimens experienced some water entry in the stud cavity, which was collected at the inside face of the sheathing board, just beneath the ventilation duct. From these amounts of collected water and the climate loads the specimens were subjected to, an equation was derived to estimate the water entry rate (Q) in one stud cavity as a function of (1) the pressure difference across the wall assembly, ΔP, and (2) the rate of water R_w striking the wall. The equation is given below:

$$Q\ (L/h) = R_w \times f(\Delta P) = R_w \times \{0.0115 + 1.722\times10^{-4} \bullet \Delta P - 1.471\times10^{-7} \bullet (\Delta P)^2\} \quad \textit{(equation 4.1)}$$

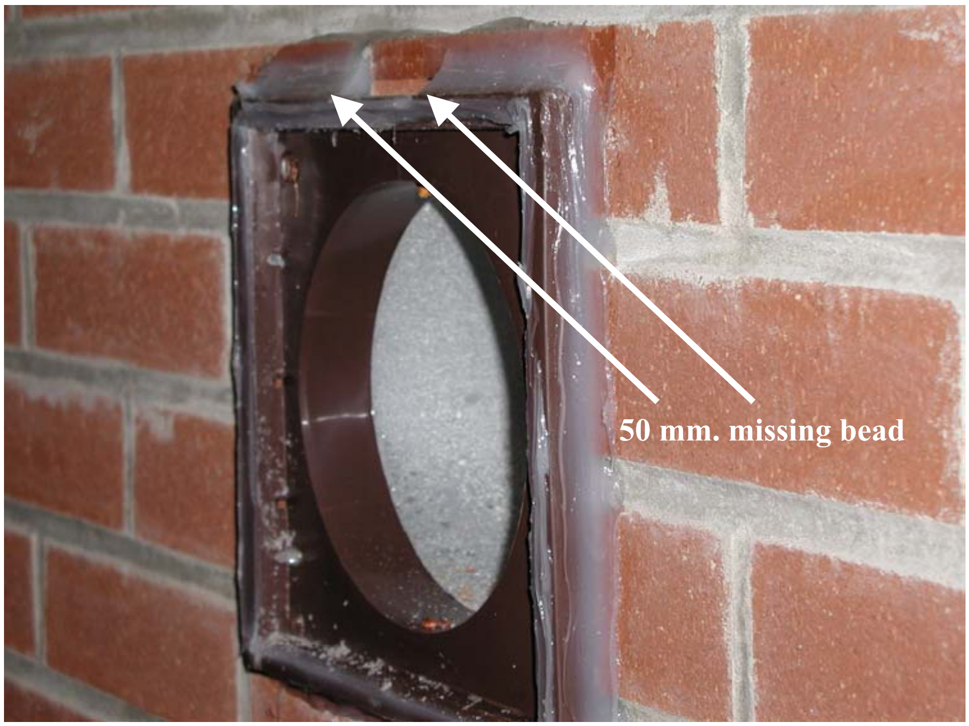


Figure 4.6. Example of a typical deficiency around the ventilation duct in a masonry-clad wall specimen

The hygIRC model used the above equation to calculate each hourly rate of water entry into the stud cavity of the modeled masonry-clad reference wall, based on climate loads in each of the seven locations investigated. hygIRC is a 2D model representing a vertical slice through the middle of a stud space, showing the height and thickness of the wall assembly. However by the very nature of the 2D model, variations of the wall construction in the third dimension, such as studs dividing the wall up into 400 mm compartments were not represented. In fact, the model gave its results "per metre" of wall width, assuming constant properties throughout that one metre width. The hourly quantities (ranging from 0 to about 0.75 L, as a function of the climate inputs of rain fall, wind speed and wind direction) calculated by the above equation for the seven locations were not multiplied by 2.5 to give the same amount per metre length of wall as the amount collected in one 0.4 m stud space. This reduction to 40% of the water calculated for one stud space may not have been a solution to cope with a limitation of hygIRC, i.e. gravity flow and distribution of free water were not modeled, but it does have that effect. Only one stud space contained the deficiency, but the water coming through it may well have ended up in more than one space through gravity-driven liquid flow between the plate and the bottom of the studs. Description of how this factor was taken into account in the modeling study is given in the chapter on the methodology adopted (Chapter 1, section 1.6) for all four types of cladding systems.

Figure 4.7 shows the hourly rates of water entry into the stud cavity of the masonry-clad reference wall represented in hygIRC, for three locations of quite different climate loads, Wilmington NC, Winnipeg MB, and Phoenix AZ.

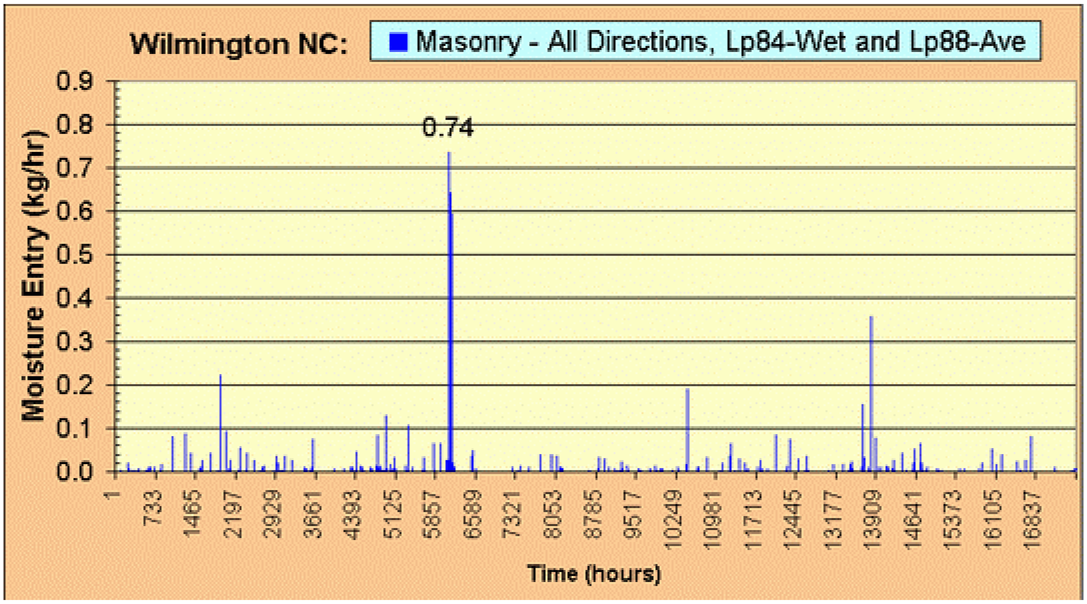


Figure 4.7 A) Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of masonry-clad reference wall for Wilmington NC for two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

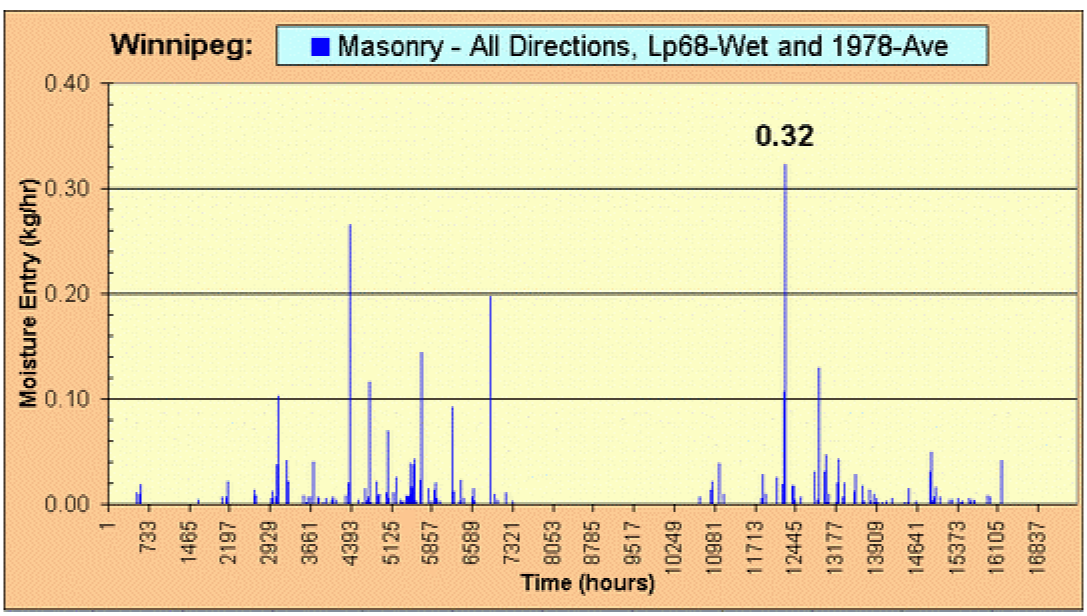


Figure 4.7 B) Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of masonry-clad reference wall for Winnipeg for two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

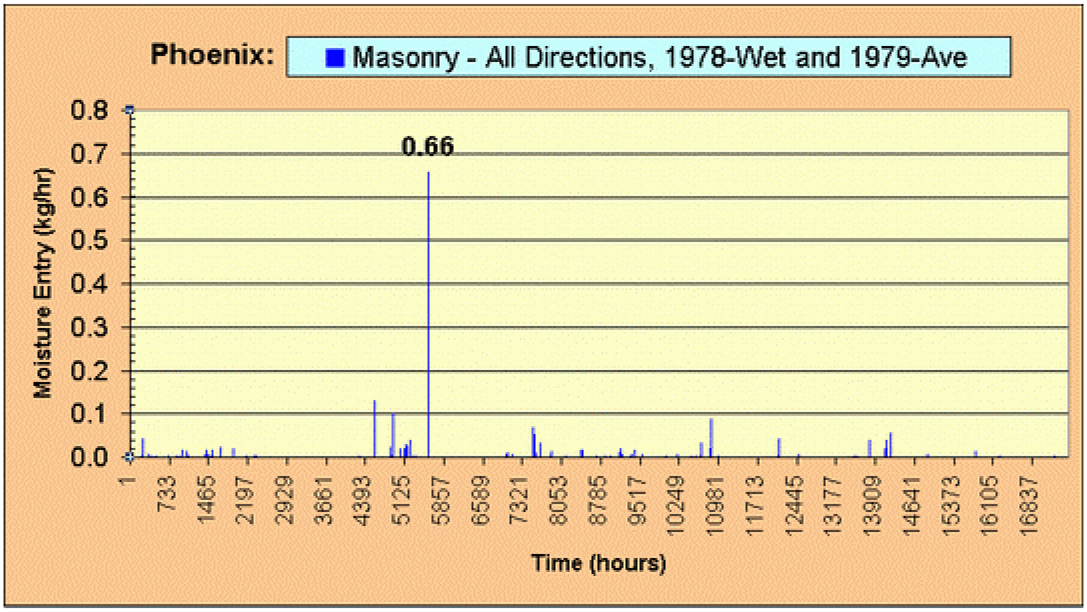


Figure 4.7 C) Hourly rates of water entry “injected” in the stud cavity (referred to as “1Q”) of masonry-clad reference wall for Phoenix for two years of hygIRC simulation. Note that 732 hours is equivalent to 30.5 days.

Moisture Distribution Within the Stud Cavity

Having established how much water could get into the stud cavity, the next step was to determine where that water would go, e.g. into the materials, straight down or a combination of both. Laboratory tests were carried out for the first set of walls investigated, i.e. stucco-clad walls to determine where water goes once it has entered the stud cavity through a deficiency. Gravity flow appeared to be the dominant force and water quickly reached the bottom of the cavity.

Because hygIRC did not model actual openings to represent water entry through deficiencies or gravitational flow, the modeller “injected” liquid water at a certain location in the wall stud cavity, in the hourly amounts calculated from climate data using the equation 4.1. In this case, reflecting what had been observed in the laboratory experiments, moisture was deposited at the bottom of the stud cavity of the modelled wall assemblies.

Selection of the Region of Focus in the Stud Cavity

In the first masonry-clad wall exploratory hygIRC simulations, a microanalysis of the local response in the vicinity of the bottom of the stud cavity for a worst case (i.e. Wilmington NC) was performed. These simulation results indicated that the bottom portion of the OSB sheathing experienced fluctuations of moisture response from drier to wet while the top layer of the bottom plate appeared to remain wet for prolonged periods (Figure 4.8). As explained in Chapter 1 on methodology (section 1.7.1), the region of focus was usually selected for its potential to represent a worst-case scenario. For this reason, the region of the stud cavity selected for all masonry simulations of that series was located in a region that measured 53 mm long (i.e. in the x-direction) and 5 mm high at the top of the bottom plate adjacent to the sheathing board.

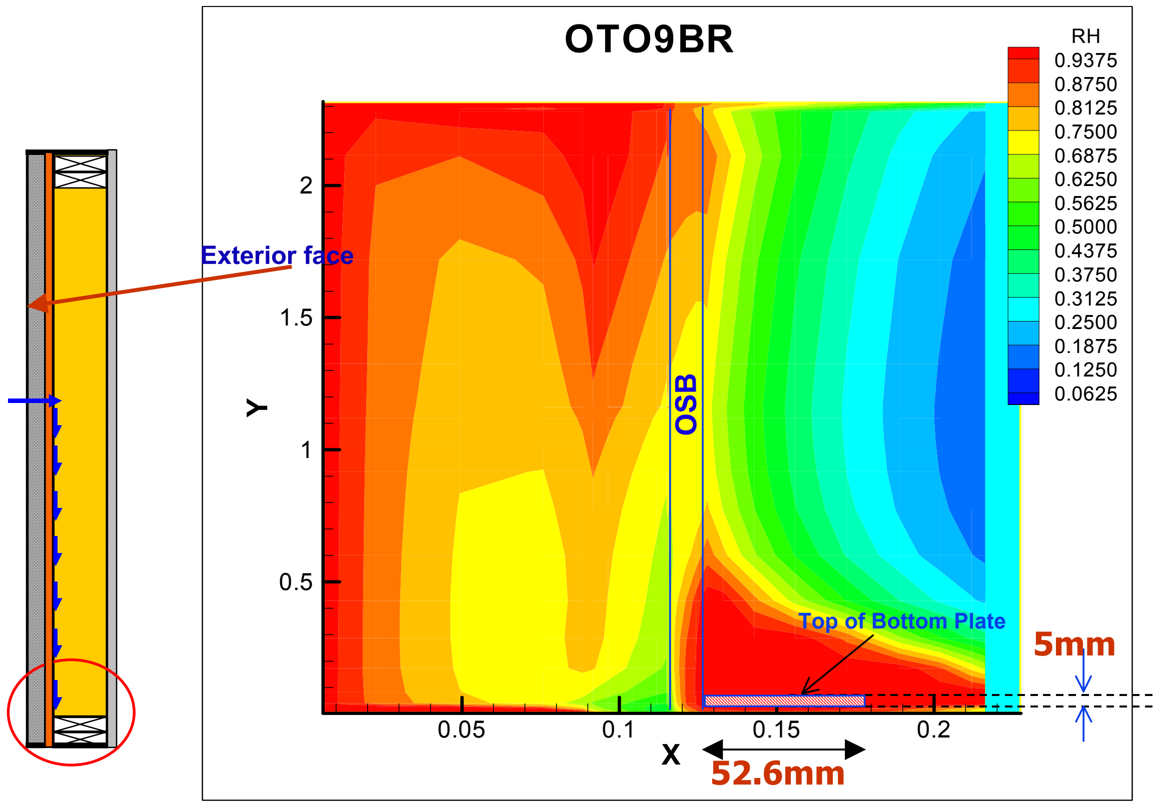


Figure 4.8. A typical RH contour plot generated by hygIRC for the reference wall in Ottawa. The figure is a snapshot from the 730-day simulation run. The dark red areas indicate the regions for which hygIRC model predicted an RH above 87%. The bottom of the wall is the wettest portion of the assembly most of the time. For this reason, it was selected as the primary location for further investigation in the parametric study.

4.4 Prediction of Wall Hygrothermal Response to Moisture Loading

4.4.1 Parameters Investigated

A masonry-clad wall assembly was selected as a reference for the parametric evaluation (Figure 4.9). The following parameters were varied to determine their influence on the hygrothermal response of a reference masonry-clad wall assembly:

1. Climate severity on the moisture response of a given wall assembly
2. Rate of accidental moisture entry inside the stud cavity 0Q, 1Q, Q/2 and Q/4 (2Q and 4Q for Phoenix)
3. Material properties
    - 3 different brick units (clay, concrete and calcium Silicate units)
    - 2 water resistive barriers (30 minute building paper and SBPO polymeric)
    - 3 sheathing boards (OSB, extruded polystyrene (XPS) foam sheathing, and asphalt-coated fibreboard)
    - 3 vapour barrier membranes (Type I, II and III)
4. Change in drainage cavity depth from 25 mm to 50 mm.

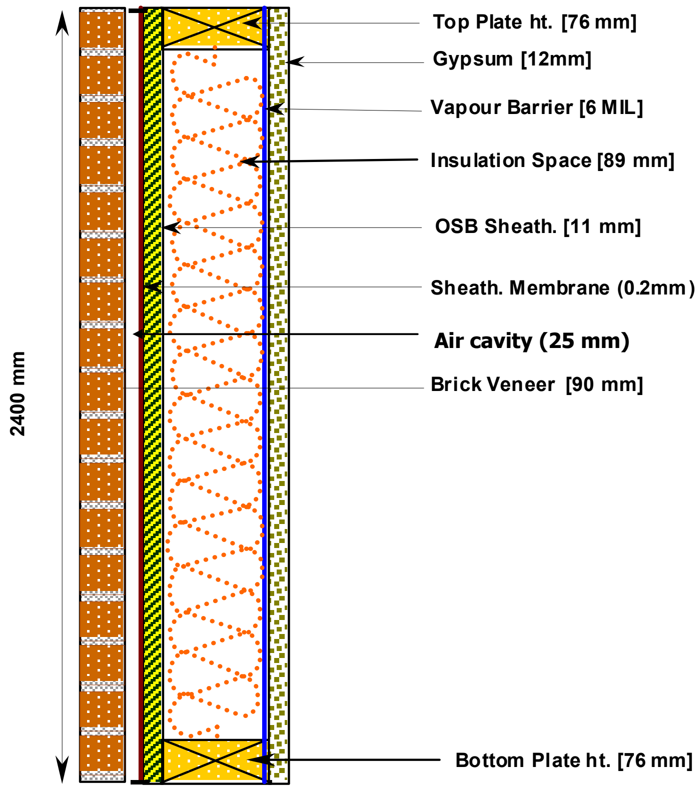


Figure 4.9. A vertical section showing the composition of the wall used as the reference for the parametric study.

It was assumed that double top and bottom plates in the stud cavity were in place at the time of the simulation. In practice it is more common to use only a single plate. It is believed that this discrepancy did not affect the interpretation of the results significantly.

4.4.2 Comparative Results

All possible combinations of material types for each of the seven locations with and without moisture entry through a deficiency would yield about a thousand simulations. This is indeed far more than could have been accommodated given the time and resources available for the MEWS project. Hence, after careful consideration and consultation with MEWS partners, it was decided to conduct a sufficient number of simulation runs to reveal the major influences of parameters mentioned above (wall construction details and parameters). The simulations mentioned in this summary represent only a portion of the total number of simulations carried out in this program. Of these, only a handful is singled out for discussion here, but the complete set of results reported for two single indicators of performance, RHT(95) and RHT(80), for each simulation is provided in Appendix 4.1. Reported in this section are the comparative effects of the parameters listed in section 4.4.1 on the hygrothermal response of the wall expressed using the RHT(95) indicator.

The following nomenclature will be used in the subsequent sections to describe the impact of effects of changing various parameters on the wall response.

Decisive: RHT(95) should be reduced to near zero by a single effect
Substantial: RHT(95) difference of at least 1000 of the larger value compared.
Small: RHT(95) difference less than 1000 and higher than 100 of the larger value compared. It could still have meaning and interest if demonstrating a trend.
Near zero: RHT(95) difference less than 100 of the larger value compared

1.0 Effect of Climate Severity on a Wall Assembly Response

Observation: The hygrothermal response of a wall assembly in terms of RHT increased with the severity of the climate. Although hygIRC predicted that masonry walls with no deficiency exhibited a zero RHT(95) value for all climates, all configurations with the "standard" deficiency registered RHT(95) values increasing with wetness and temperature of the climate.

Discussion: Figure 4.10 illustrates this effect. The results are also tabulated in Table 4.2. The blue curve in Figure 4.10 shows the predicted behaviour of a masonry-clad reference wall without accidental water entry in the stud cavity. For all locations the value of RHT(95) was zero. The red curve shows the response of the same wall, however variable amounts of water, equivalent to a 1Q set of water entry rates, were allowed to enter into the stud space. The value of RHT(95) generally increased with increasing climate severity as measured by the MI index.

The exception to this trend was Winnipeg. The value of RHT(95) for a Winnipeg wall was higher than Ottawa because a greater amount of water was placed in the stud cavity in Winnipeg than was the case for Ottawa. In Winnipeg, although there was less rain striking the ground, higher wind speeds produced more rain impinging on the wall and thus being driven through the deficiency allowing water leakage into the stud cavity. While the climate severity index MI was based on annual rainfall records, the selection of the reference climate years for the modeling, and the calculation of Q were based on wind strength and direction as the interest was about estimating water loads on vertical surfaces. Figures 4.11 and 4.12 show the moisture loads and the detailed hygrothermal response of the reference wall in Winnipeg and Ottawa. Although the responses were similar, Winnipeg's increased moisture load Q can be seen. The sum of water introduced into the stud space after two years for Winnipeg and Ottawa were 8.1 and 6.8 litres respectively. The greater moisture load in Winnipeg led to a significantly greater amount of time during which the RH of the region of focus was above the threshold value of 95%.

Table 4.2 Variation of RHT(95) response with climate severity in terms of Moisture Index

Location	MI_{hourly}	RHT(95) response		
		Reference wall with no moisture loads in the stud cavity	Reference wall with 1Q set of moisture loads in stud cavity	Best materials wall with 1Q set of moisture loads in stud cavity
Wilmington NC	1.13	0	2715	300
Seattle	0.99	0	1560	207
Ottawa	0.93	0	745	39
Winnipeg	0.86	0	1283	121
San Diego	0.74	0	375	0
Fresno	0.49	0	95	0
Phoenix	0.13	0	39	0

The green curve in Figure 4.10 shows the response of a wall made of materials more conducive to drying, specifically the wall with a asphalt-coated fibreboard exterior sheathing (i.e. No. F27BR) with a 1Q set of hourly moisture loads in the stud cavity. The shape of the curve was similar to that of the reference case but its slope was attenuated.

The effect of climate was decisive. Since the amount of water entering in the stud through a nominal deficiency was, in the case of the assumptions made in MEWS, directly related to the climate severity, it stands to reason that the effect of climate was pronounced. A 1Q set of moisture loads in the stud cavity in Phoenix represented very little moisture loading combined with a high drying potential while a 1Q set in Seattle was a significant load in a climate with a low potential; i.e. cool and humid.

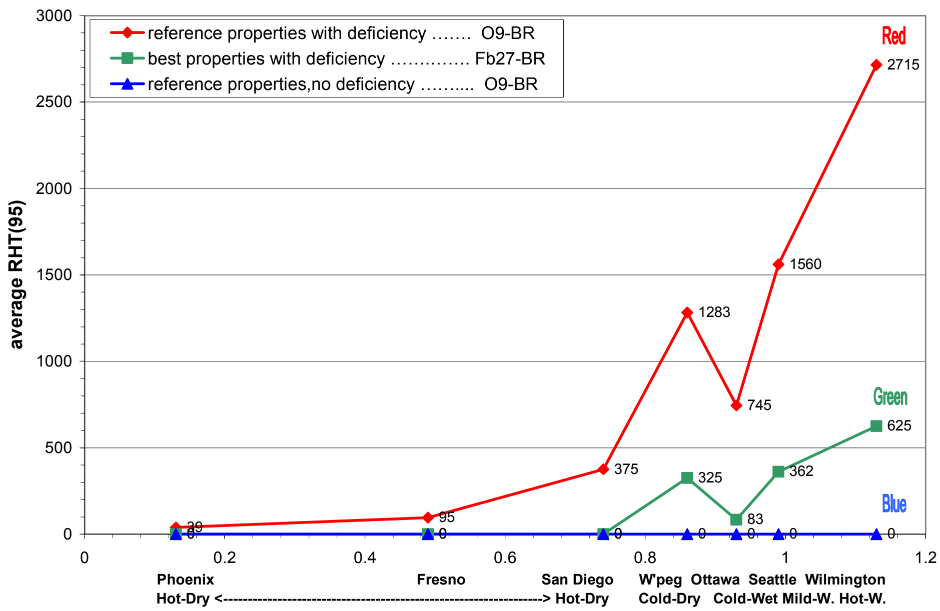


Figure 4.10. Relationship between climate severity and hygrothermal response of masonry-clad wall assemblies for three scenarios. The lower curve (blue) was the response for a reference wall No. 09BRBC having no water leakage into the stud cavity (no deficiency). The upper curve (red) is the response of the same reference wall however, with a deficiency allowing water leakage into the stud cavity (1Q). The middle curve (green) represented the response of wall with asphalt-coated fibreboard instead of OSB (No. F27BR); this assembly has the same deficiency (1Q) as the reference wall No. 09BR (red or upper curve), but has a combination of materials more conducive to drying.

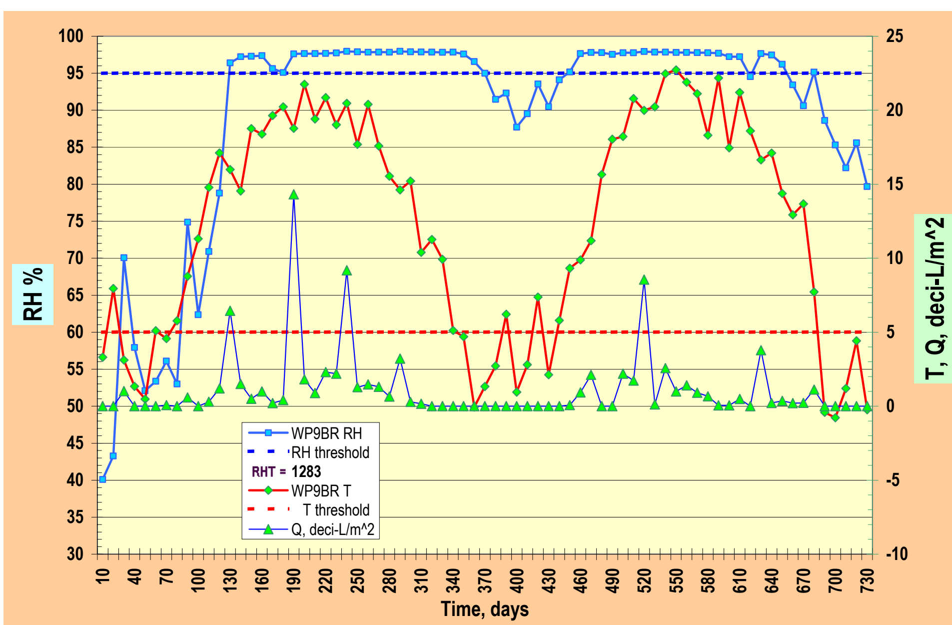


Figure 4.11 Reference wall with "1 Q" set of moisture loads in the stud cavity in Winnipeg MB.
RHT(95) = 1283

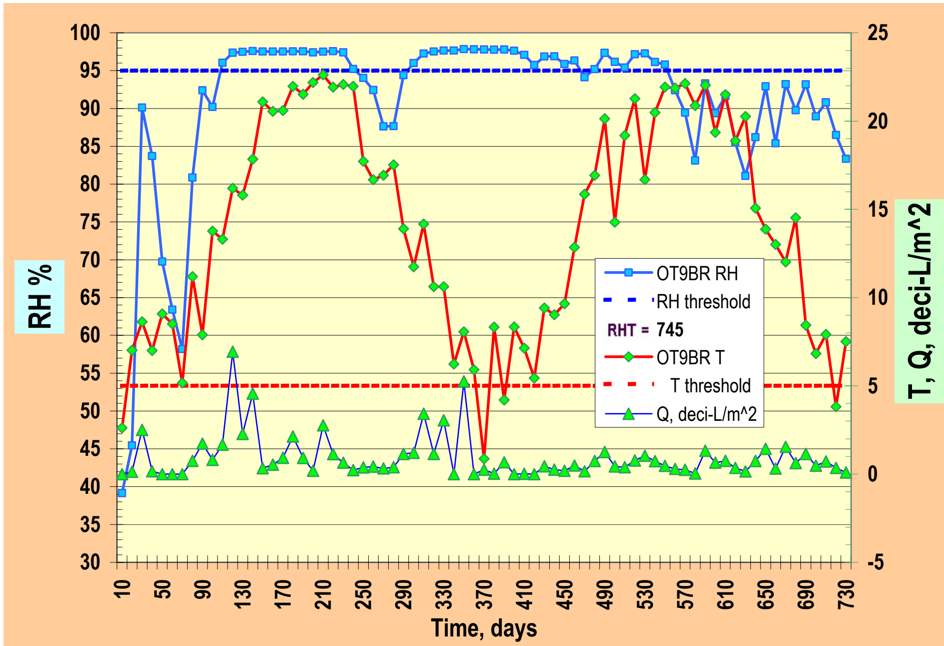


Figure 4.12 Reference wall with "1Q" set of hourly rates of water entry in the stud cavity in Ottawa ON. RHT(95) = 745.

2.0 Effect of Variation of the Water Entry Rate (Q) into the Stud Cavity

Observation: Simulations predicted that when no water was allowed to enter the stud cavity (i.e. Q=0), masonry-clad walls provided a high degree of resistance to water entry into the stud space, even under outdoor moisture loads as severe as in Wilmington NC. When water was allowed to enter the stud cavity, the RHT(95) wall response increased linearly with Q. (Effect: *decisive*)

Discussion: The RHT values for all Qs investigated are tabulated in Table 4.3. In the absence of deficiencies, the reference masonry-clad wall assembly maintained an RHT(95) of zero for all seven climates investigated. This could be partly due to the cavity behind the cladding, which acted as a capillary break isolating the exterior cladding elements from the stud cavity. Additionally, the masonry units can store a certain amount of moisture and subsequently release it during dry periods. When water was allowed to enter the stud cavity, via a leakage path, at a certain level of Q, the rate of water entry exceeded the drying rate of the wall materials, resulting in positive RHT values. This threshold value of Q varied with climate as well as the makeup of the wall. Figure 4.13 provides plots of the 2-year cumulative RHT(95) values versus MI, for varying multiples of the moisture load (Q) for the reference wall assembly. The figure shows that beyond a certain moisture loading, the relationship between the response indicator RHT(95) and the moisture load Q was approximately linear for all seven locations.

Table 4.3 Cumulative RHT(95) values for seven locations and varying sets of hourly moisture loads in the stud cavity (Q) for the reference wall

Q	Phoenix	Fresno	San Diego	Ottawa	Winnipeg	Seattle	Wilmington NC
0	0	0	0	0	0	0	0
¼	*	0	0	0	39	8	240
½	*	0	0	72	428	356	1137
1	39	95	375	745	1283	1560	2715
2	432	*	*	*	*	*	*
4	1987	*	*	*	*	*	*

- An asterisk, *, indicates no simulation run for the specific parameter value.

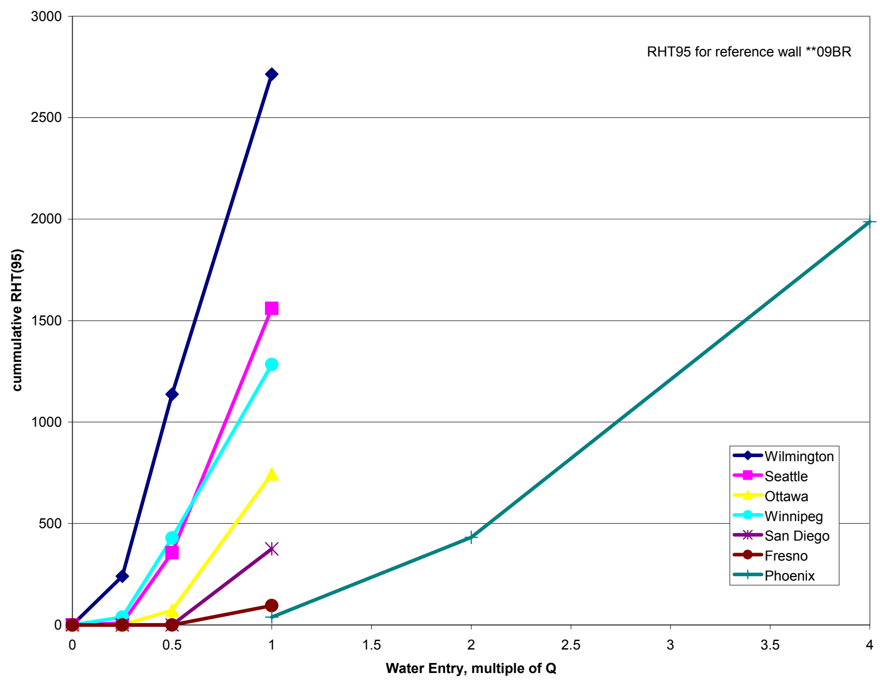


Figure 4.13. Relationship between moisture loads in the stud cavity (Q) and the severity of wall response for a reference masonry-clad wall for varying percentages of Q. Each line shows the response for a particular climate.

3.0 Effect of Material Properties in a Given Climate

Effect of Changing the Sheathing Board

Observation No.1: Substituting XPS foam sheathing board (25 mm) for OSB (12 mm) exacerbated the RHT(95) hygrothermal response of the wall to a 1Q set of hourly moisture loads in the stud cavity. (Effect: *substantial*)

Discussion: hygIRC results are tabulated in Table 4.4 and graphically represented in Figure 4.14 (refer to the blue and red curves). XPS foam sheathing, having a much lower thermal conductivity than OSB, produced higher temperatures in the stud cavity, thus increasing the accumulation of RHT(95) when the RH condition of 95% was satisfied. Figures 4.15 and 4.16 show how the temperature in the region of focus was affected by the thermal characteristics of these two sheathing boards. For example, in Winnipeg at the beginning of the second year, the temperature at the region of focus dropped to about 8°C when XPS foam sheathing was used whereas it dropped to 0°C when OSB sheathing was used. In addition, the hygric properties of XPS foam sheathing seemed to smooth out the RH fluctuations indicated in Figure 4.15 for OSB sheathing. These two factors combined to produce higher values of cumulative RHT(95) when XPS foam sheathing was used in place of OSB. The effect of adding XPS foam sheathing on the outside of a stud cavity that got wet due to outdoor water leakage was different from a situation where condensation of indoor water vapour would be the only concern: in the latter case, the presence of an insulating sheathing would be desirable because the increased cavity temperature would shorten the period below the dew point.

Table 4.4: RHT (95) wall response for three sheathing boards

	RHT(95) response for reference wall at 1Q set of moisture loads in the stud cavity						
Location / **Sheathing Board**	**Phoenix**	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
OSB (Reference wall	39	95	375	1283	745	1560	2715
XPS Foam Sheathing	191	437	*	2145	2179	2497	3557
Asphalt coated fibreboard	0	0	0	325	83	362	625

- An asterisk, *, indicates no simulation run for the specific parameter value.

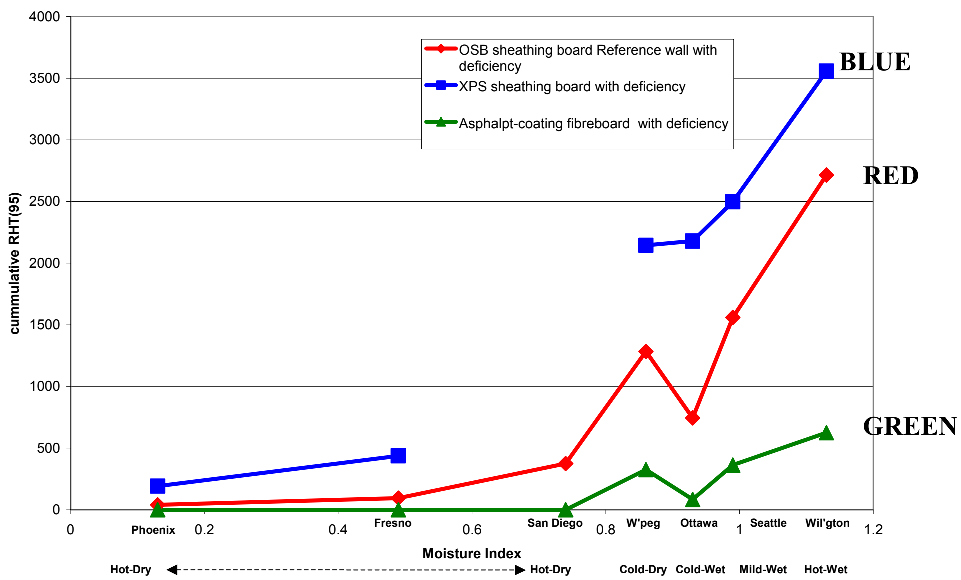


Figure 4.14. The relationship between climate severity and masonry-clad wall response for three different sheathing boards is shown. The middle curve (red) was the response for a reference wall with OSB sheathing board and a deficiency allowing one Q set of moisture loads in the stud cavity. The upper curve (blue) was the response of the wall when XPS foam sheathing replaces the OSB sheathing. The lower curve (green) was the response of reference wall when the OSB sheathing board was replaced with asphalt-coated fibreboard.

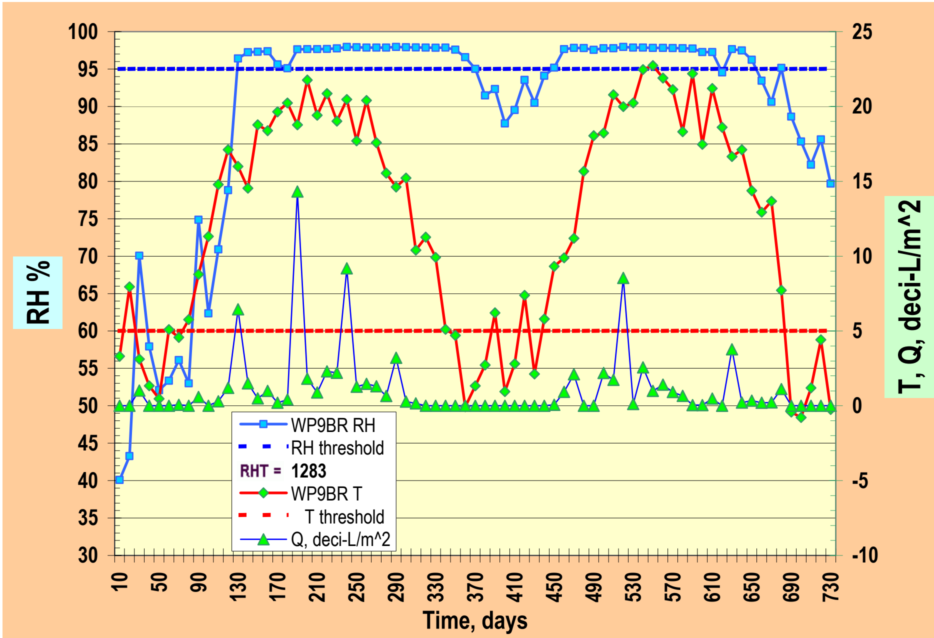


Figure 4.15. Reference masonry-clad wall with OSB sheathing board, with "1Q" set of hourly moisture load in the stud cavity for Winnipeg. RHT(95) = 1283.

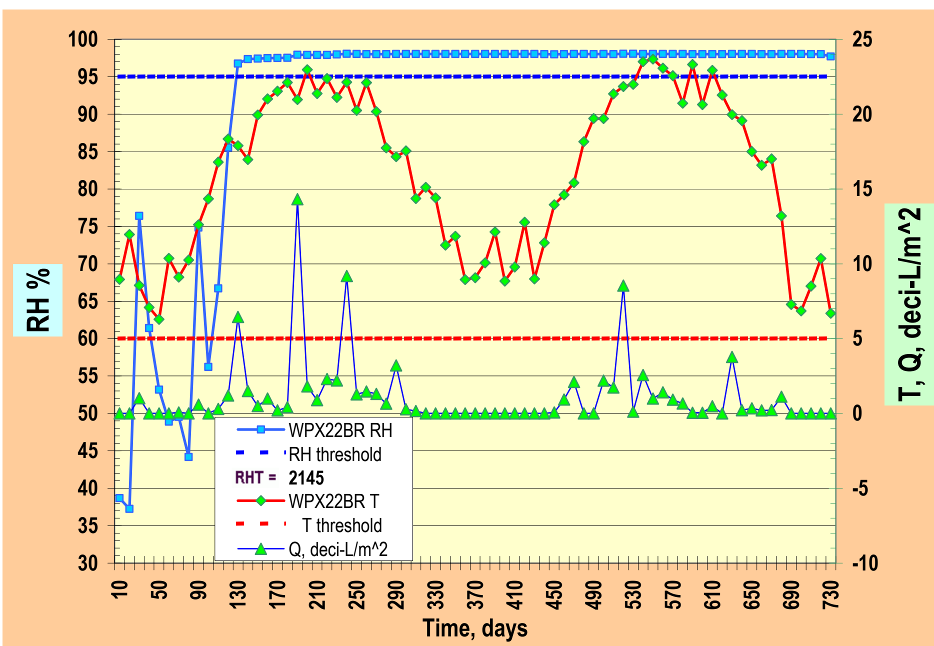


Figure 4.16. Reference masonry-clad wall with XPS foam sheathing board, with "1Q" set of moisture load in the stud cavity for Winnipeg. RHT(95) = 2145.

Observation No. 2: Substituting asphalt-coated fibreboard for OSB improved the RHT(95) hygrothermal response of the reference wall when a 1Q set of hourly moisture loads entered the stud cavity. (Effect: *substantial*)

Discussion: hygIRC results are tabulated in Table 4.4. The properties of asphalt-coated fibreboard appeared to promote faster drying to the outside than OSB sheathing (see Table 4.1 for material properties). The asphalt-coated fiberboard was *more* vapour permeable than OSB thus increasing the capacity for drying to the outside. As well, the air permeance of the asphalt-coated fibreboard was much higher than that for the OSB. Figures 4.15 and 4.17 show the significant reduction in RHT(95) hygrothermal response of asphalt-coated fibreboard over that of the reference wall. The *substantial* effect of replacing OSB with asphalt-coated fibreboard was consistent for all the climates studied (Figure 4.14, refer to the lower green curve).

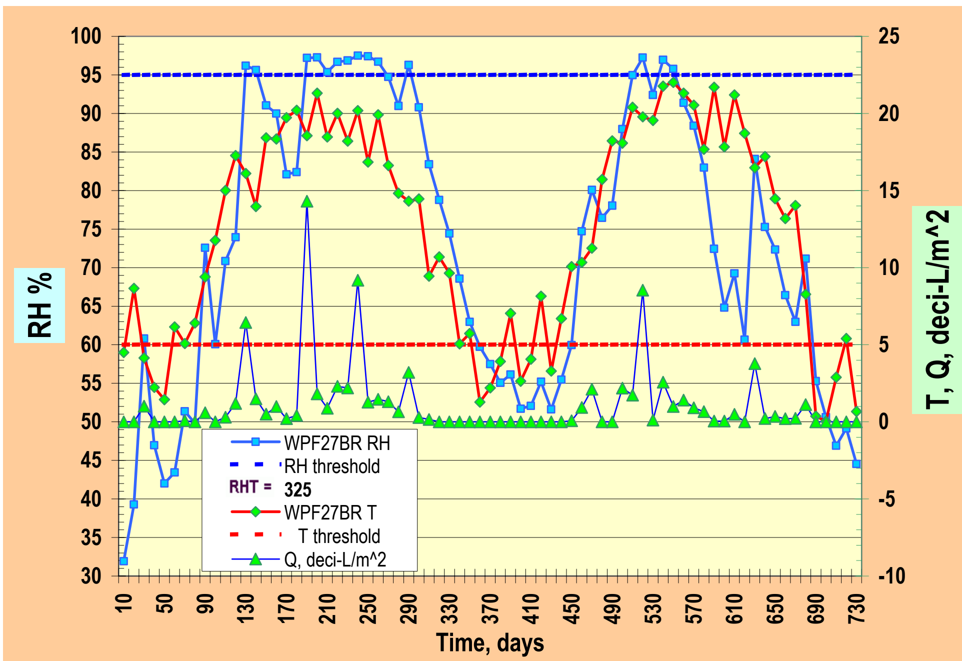


Figure 4.17. Reference masonry-clad wall with "1Q" set of hourly rates of moisture load in the stud cavity in Winnipeg. Asphalt-coated fibreboard is used as a sheathing board RHT = 325.

Effect of Changing the Vapour Barrier Membrane

Observation: For climates other than hot and dry, increasing the vapour permeability of the vapour barrier *membranes* made only a small difference in the hygrothermal response of the wall assembly. For climates such as Phoenix, Fresno and San Diego, no noticeable drop in RHT(95) value was observed for more permeable vapour barrier membranes. (Effect: *to near-zero to small*)

Discussion: Three vapour barrier membranes were investigated for all locations. The hygrothermal properties of these materials have been characterized by TG3 and a summary of properties can be found in Table 4.1. In order of increasing vapour permeability at 0 and 100%RH are vapour barrier Type I, Type II, and Type III. The relationship between vapour permeability and relative humidity as defined by TG 3 laboratory experiments is illustrated in Figure 4.18.

Table 4.5 provides the hygrothermal response in RHT(95) values for all locations and vapour barrier materials. Overall, changing from a tight vapour barrier *membrane* to a more vapour permeable *membrane* was predicted to have a small effect on the hygrothermal response of the region of focus in the stud cavity of the wall for cold climates, or warm and wet climates. The amount and frequency of water introduced into the stud cavity in these climates were sufficiently high that attempts at increasing the drying capacity by increasing the water vapour permeability of the vapour barrier membrane had a small effect on the value of RHT(95). For hot and dry climates, a near-zero change in the hygrothermal response of the reference wall was predicted. In these climates, the rate of water entry (Q) introduced into the stud cavity was much lower because the climate was less severe, and in this case the wall already had an adequate ability to dry out after a rain event. Adding more drying capacity to the interior id not appreciably lower the values of RHT(95). The wall response is shown in Figure 4.19.

It should be noted that the apparent improvement in moisture response of the reference wall with a "*loosening"* of the vapour barrier membrane may not occur outside the context of the MEWS parametric simulations. The interior conditions assumed as the internal boundary condition played a large role. The interior RH conditions of 55% in the summer and 25% RH in the winter promoted drying to the inside. The effect might be much less or even reversed when different interior conditions prevail.

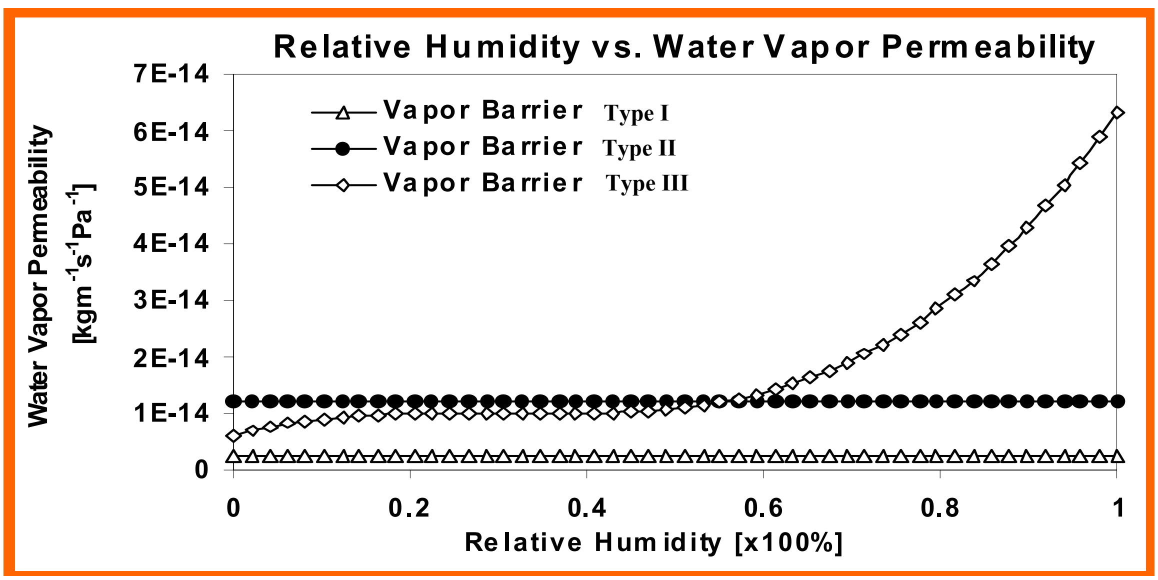


Figure 4.18. Relationship established by TG 3 between vapour permeability and relative humidity of three vapour barrier membranes

Table 4. 5: RHT (95) response for three vapour barrier membranes

membrane	RHT(95) index for reference wall at a 1Q set of moisture loads in the stud cavity						
	Phoenix	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
Type I - 15 ng (Reference wall	39	95	375	1283	745	1560	2715
Type II - 60 ng (**VB7BR)	40	92	350	1053	534	1192	2293
Type III - varies (**VB8BR)	37	90	*	925	434	1043	1937

- An asterisk, *, indicates no simulation run for the specific parameter value.

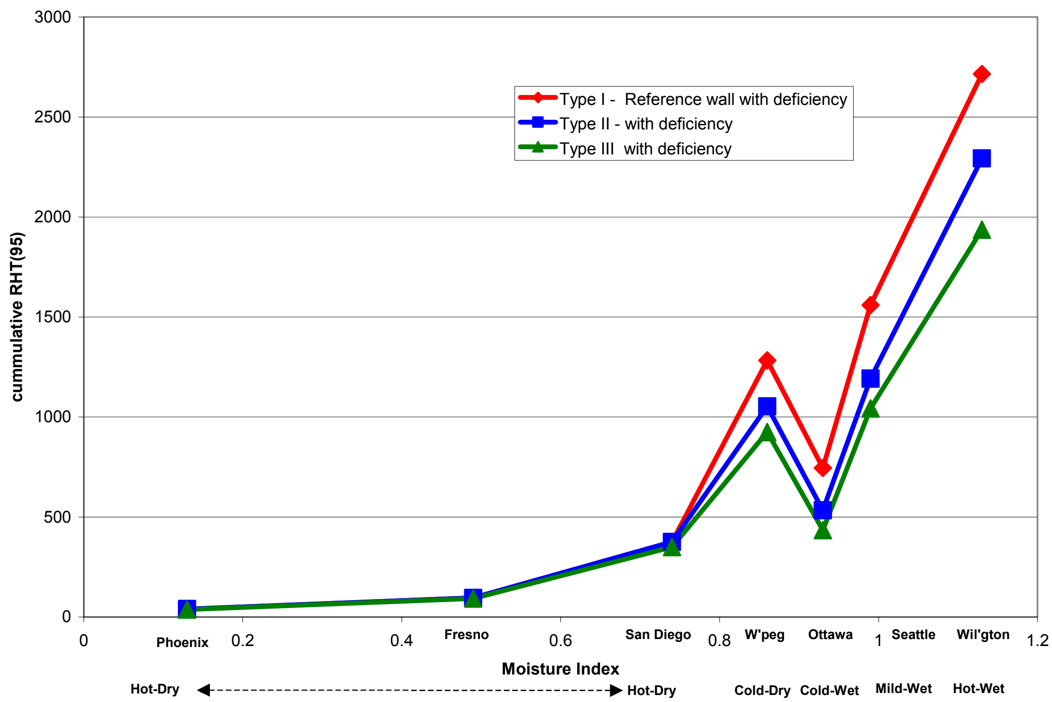


Figure 4.19. The figure shows a plot of RHT(95) versus MI for vapour barrier membranes of different vapour permeabilities. Overall changing the vapour barrier membrane had a small effect. The effect of *loosening* the vapour barrier membrane was larger in wetter climates. These results were strongly tied to the assumed interior conditions and should not be considered outside the scope of the assumptions of the MEWS project.

Effect of Changing the Water Resistive Barrier

Observation: Changing the water resistive barrier from 30-minute building paper to a polymeric membrane had no effect on the cumulative RHT(95) value of the wall, once water entered the stud cavity at a 1Q set of hourly rates. (Effect: *near-zero*)

Discussion: The results are tabulated in Table 4.6 and shown in Figure 4.21. The water resistive barrier was intended to prevent water that has penetrated the exterior cladding from reaching the interior layers. In this wall system, it was likely that the outdoor moisture load on the water resistive membrane was relatively low for the following reason: liquid water did not diffuse from the masonry units through to the water resistive barrier because the wall included a 25 mm drainage cavity and the membrane was not in contact with the masonry units. The only transfer mechanism would be vapour diffusion, which can be a slow process, transferring only small quantities of moisture across the wall[1]. In the parametric study of walls with the deficiency, however, a variable amount of water was introduced into the stud cavity every hour, by-passing the water resistive barrier. Thus through unsatisfactory detailing the water resistive barrier did not perform fully its intended function of controlling liquid water flow. The properties of the water resistive barrier can also play a role in the drying of the stud cavity. While vapour permeabilities of the two membranes differed in the high regions of relative humidity (Figure 4.20), they were both relatively low. Their ability to promote drying was about the same, as indicated by the similar hygrothermal responses.

Table 4.6: RHT (95) index comparison for two water resistive barriers

	RHT(95) index for reference wall at a 1Q set of hourly moisture loads in the stud cavity						
barrier	**Phoenix**	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
30 min. paper (Reference wall)	39	95	375	1283	745	1560	2715
SBPO polymeric (**SM21BR)	39	95	378	1319	784	1625	2744

[1] Note: the situation where water penetrates the masonry cladding and mortar droppings or brick ties provide a direct path for liquid water from the masonry cladding to the water resistive barrier was not simulated.

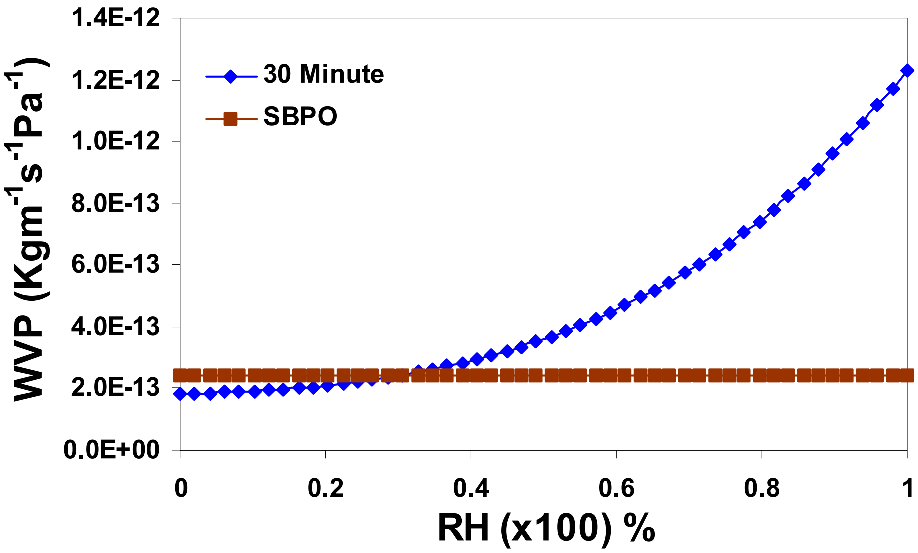


Figure 4.20. The figure shows a comparison of the water vapour permeability of a polymeric membrane and 30-minute building paper at different relative humidities.

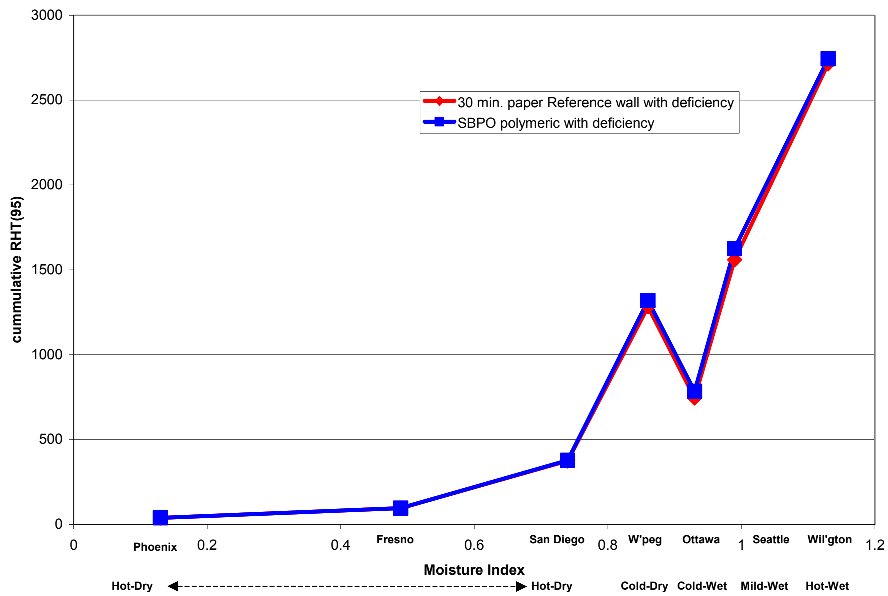


Figure 4.21. The figure shows a plot of RHT(95) versus MI for two different water resistive barriers having different water vapour permeabilities (WVP) characteristics. The WVP characteristics are shown in Figure 4.20. Changing water resistive barriers had little or no effect on the accumulated value of RHT(95).

Effect of Changing the properties of the Masonry Units

Observation: The effect of changing the properties of the masonry units on the RHT(95) of the masonry-clad reference wall was predicted to be negligible. (Effect: *near-zero*)

Discussion: The results are tabulated in Table 4.7 and shown in Figure 4.22. This result can be easily explained by examining the inputs and boundary conditions of the model of the walls simulated. The key element was the cavity between the exterior cladding and the rest of the wall layers. This cavity effectively isolated the masonry units from the rest of the wall. Although changing properties of the masonry units can have a profound impact on their moisture regime, they were isolated from the region of focus inside the stud cavity. The only transfer mechanism was by water vapour permeating through the interior wall elements, across the cavity and into the masonry units (and the reverse path as well).

Table 4.7: RHT (95) index comparison for three masonry units.

	RHT(95) index for reference wall at 1Q set of hourly rates of water entry in the stud cavity						
	Phoenix	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
Clay Brick (Reference wall **09BR)	39	95	375	1283	745	1560	2715
Concrete Brick (**CE24BR)	38	*	*	1137	587	1362	2560
Calcium Silicate (**CS26BR)	38	*	*	1139	589	1349	2589

- An asterisk, *, indicates no simulation run for the specific parameter value.

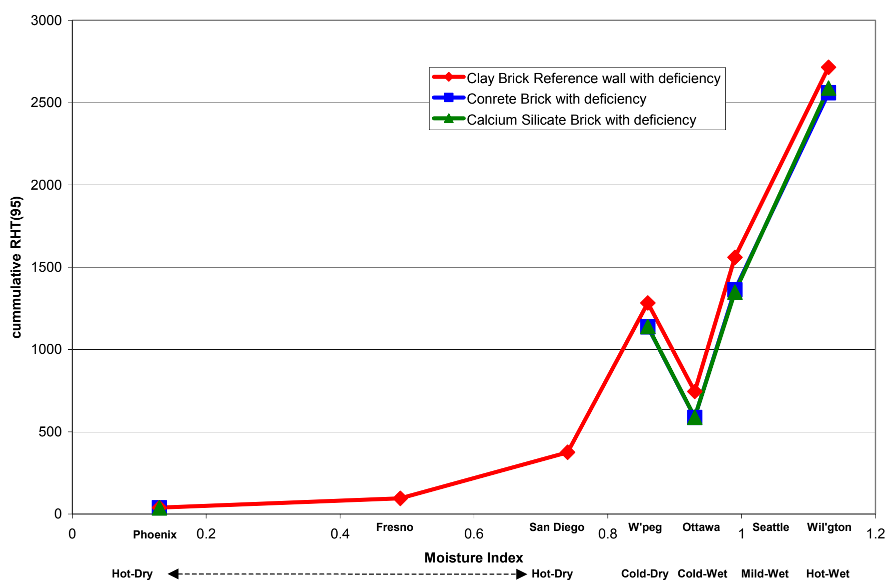


Figure 4.22. The figure shows a plot of RHT(95) versus MI for three different masonry units, clay, concrete and calcium silicate brick.

4.0 Effect of Widening the Drainage Cavity

Observation: The effect of widening the drainage cavity from 25 mm to 50 mm was predicted to have little effect on the RHT(95) response of the reference wall assembly. (Effect: *near-zero*)

Discussion: The RHT(95) results are tabulated in Table 4.8 and shown in Figure 4.23. The drainage cavity isolated the moisture sources at the exterior cladding from the interior wall layers. Increasing the cavity width did not appreciably change the rate of moisture transfer across the wall. The main benefit of increasing the drainage cavity width would be to lessen the likelihood of mortar droppings creating a bridge through which moisture could diffuse or creating a dam in the drainage cavity. These were not considered in the MEWS parametric study.

Table 4.8: RHT (95) index comparison for two drainage cavity widths.

	RHT(95) index for reference wall at 1Q set of hourly rates of water entry in the stud cavity						
	Phoenix	**Fresno**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
25 mm (Reference wall **09BR)	39	95	375	1283	745	1560	2715
50 mm (**50CBR)	38	96	*	1117	591	1451	2600

- An asterisk, *, indicates no simulation run for the specific parameter value.

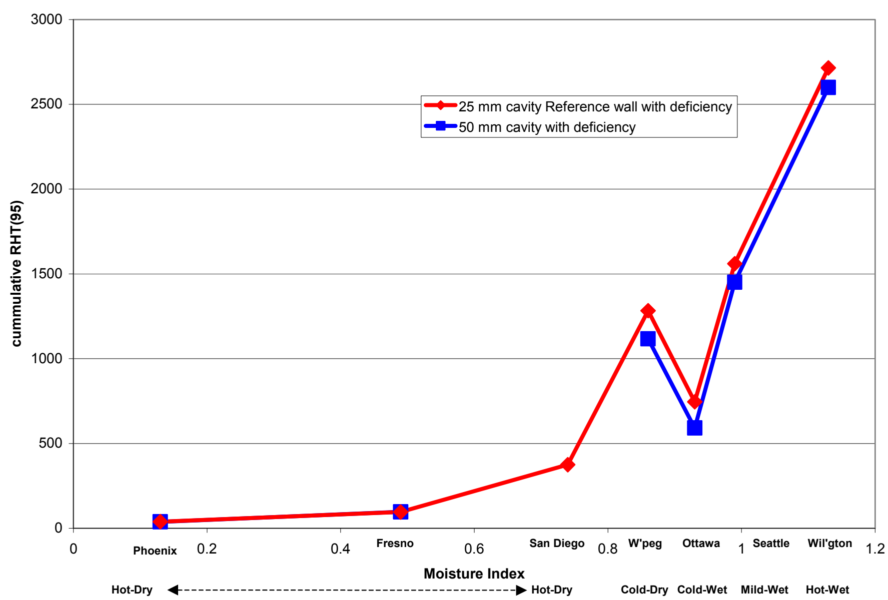


Figure 4.23. The figure shows a plot of RHT(95) versus MI for two drainage cavity widths. Changing drainage cavity widths had little or no effect on the accumulated value of RHT(95).

Appendix 4.1 Table of All hygIRC Simulation Results (See the notation at the end)

RHT (95) Results for Masonry-clad Walls

Simulation ID	RHT (95) Index	Simulation ID	RHT (95) Index	Simulation ID	RHT (95) Index	Simulation ID	RHT (95) Index
(A) OTTAWA							
OTO9BRBC	0	**(C) SEATTLE**					
OT O9BR	745	SEO9BRBC	0				
OTVB7BR	534	SEO9BR	1560				
OTVB8BR	434	SEVB7BR	1192				
OTSM21BR	784	SEVB8BR	1043			**(G) SAN DIEGO**	
OTCE24BR	587	SESM21BR	1625			SDO9BRBC	0
OTCS26BR	589	SECE24BR	1362			SDO9BR	375
OTX22BR	2179	SECS26B4	1349			SDVB7BR	350
OTO9BR50C	591	SEX22BR	2497	**(E) WINNIPEG**		SDVB8BR	313
OTF27BR	83	SEO9BR50C	1451	WPO9BRBC	0	SDSM21BR	378
OTO9BRW2	72	SEF27BR	362	WPO9BR	1283	SDO9BRW2	0
OTO9BRW4	0	SEO9BRW2	356	WPVB7BR	1053	SDO9BRW4	0
		SEO9BRW4	8	WPVB8BR	925		
				WPSM21BR	1319		
				WPCE24BR	1137		
				WPCS26B4	1139		
				WPX22BR	2145		
		(D) WILMINGTON		WPO9BR50C	1117		
		WIO9BRBC	0	WPF27BR	325		
(B) PHOENIX		WIO9BR	2715	WPO9BRW2	428		
PHO9BRBC	0	WIVB7BR	2293	WPO9BRW4	39		
PHO9BR	39	WIVB8BR	1937	**(F) FRESNO**			
PHVB7BR	40	WISM21BR	2744				
PHVB8BR	37	WICE24BR	2560	FRO9BRBC	0		
PHSM21BR	39	WICS26B4	2589	FRO9BR	95		
PHCE24BR	38	WIX22BR	3557	FRVB7BR	92		
PHCS26B4	38	WIO9BR50C	2600	FRVB8BR	90		
PHX22BR	191	WIF27BR	625	FRSM21BR	95		
PHO9BR50C	38	WIO9BRW2	1137	FRX22BR	437		
PHF27BR	0	WIO9BRW4	240	FRO9BR50C	96		
PHO9BRW2	432			FRO9BRW2	0		
PHO9BRW4	1987			FRO9BRW4	0		

RHT (80) Results for Masonry-clad Walls

Simulation ID	RHT (80) Index
(A) OTTAWA	
OTO9BRBC	0
OT O9BR	9031
OTVB7BR	7700
OTVB8BR	7067
OTSM21BR	9214
OTCE24BR	8141
OTCS26B4	8441
OTX22BR	14893
OTO9BR50C	8238
OTF27BR	2047
OTO9BRW2	2352
OTO9BRW4	226
(B) PHOENIX	
PHO9BRBC	0
PHO9BR	1112
PHVB7BR	1068
PHVB8BR	900
PHSM21BR	1111
PHCE24BR	964
PHCS26B4	996
PHX22BR	3060
PHO9BR50C	1142
PHF27BR	0
PHO9BRW2	7286
PHO9BRW4	15271

Simulation ID	RHT (80) Index
(C) SEATTLE	
SEO9BRBC	0
SEO9BR	13077
SEVB7BR	11054
SEVB8BR	10267
SESM21BR	13379
SECE24BR	11865
SECS26B4	11839
SEX22BR	18930
SEO9BR50C	12403
SEF27BR	6228
SEO9BRW2	6110
SEO9BRW4	890
(D) WILMINGTON	
WIO9BRBC	0
WIO9BR	18697
WIVB7BR	17531
WIVB8BR	16049
WISM21BR	18750
WICE24BR	18251
WICS26B4	18331
WIX22BR	21418
WIO9BR50C	18736
WIF27BR	8002
WIO9BRW2	11334
WIO9BRW4	3181

Simulation ID	RHT (80) Index
(E) WINNIPEG	
WPO9BRBC	0
WPO9BR	9495
WPVB7BR	8791
WPVB8BR	8169
WPSM21BR	9565
WPCE24BR	9040
WPCS26B4	9060
WPX22BR	13186
WPO9BR50C	9386
WPF27BR	4861
WPO9BRW2	5368
WPO9BRW4	1488
(F) FRESNO	
FRO9BRBC	0
FRO9BR	1909
FRVB7BR	1669
FRVB8BR	1605
FRSM21BR	1933
FRX22BR	4914
FRO9BR50C	1739
FRO9BRW2	182
FRO9BRW4	0

Simulation ID	RHT (80) Index
(G) SAN DIEGO	
SDO9BRBC	0
SDO9BR	5335
SDVB7BR	5354
SDVB8BR	5001
SDSM21BR	5356
SDO9BRW2	1128
SDO9BRW4	0

Notation

**O9BRBC	Base case; No moisture entry; OSB sheathing Board
**O9BR	Same as **O9BRBC but with moisture entry
**VB7BR	Same as **O9BR but Type I (15ng) vapor barrier is replaced by a Type II (60ng) vapour barrier
**VB8BR	Same as **O9BR but Type I (15ng) vapour barrier is replaced by a vapour barrier that has vapour permeance variable with relative humidity
**SM21BR	Same as **O9BR but 30 minute building paper water resistive barrier is replaced by SBPO polymeric sheathing
**CE24BR	Same as **O9BR but clay brick is replaced by concrete brick
**CS26BR	Same as **O9BR but clay brick is replaced by calcium silicate brick
**X22BR	Same as **O9BR but with OSB sheathing board is replaced by XPS foam sheathing
**O9BR50C	Same as **O9BR but with 25 mm drainage cavity is replaced by 50 mm drainage cavity
**F27BR	Same as **O9BR but with OSB sheathing board is replaced by asphalt-coated fibreboard sheathing
**O9BRW2 :	Same as **O9BR but with half of the normal moisture entry (only exception is Phoenix with double moisture entry)
**O9BRW4 :	Same as **O9BR but with quarter of the normal moisture entry (only exception is Phoenix with quadruple moisture entry)

**: PH - Phoenix; FR - Fresno; SD - San Diego; WP - Winnipeg; OT - Ottawa; SE - Seattle;
WI: Wilmington NC

Chapter 5. Application to Siding-clad Walls

5.1 Summary

The hardboard siding and vinyl-clad wall assemblies investigated exhibited a high degree of water resistance in the field part of the wall. When water was not allowed to "bypass" the siding assembly to get further into the wall assembly, the hygrothermal response of the wall to external moisture loads as measured using the RHT(95) indicator was zero. In this case, the evaporative drying rate of the wall (given the properties of the materials and the indoor and outdoor climates investigated) was larger than the water diffusivity rate through the cladding materials, even in climates with large moisture loads (e.g. Wilmington NC).

When water was allowed to bypass the siding and to enter into the stud cavity (through a deficiency at a through-the-wall penetration), hygIRC simulations suggested that the relatively high resistance to moisture transfer through the cladding and sheathing limited the elimination of moisture from the stud cavity. The hygrothermal response of the wall varied with the severity of the moisture loads, which in turn depended upon the climate (wind, rain, RH and T) and the characteristics of the water leakage path to the stud cavity. Even for the lowest rate of water entry in the stud cavity ("1/4 Q") investigated, hygIRC predicted non-zero values of RHT(95) for all seven climates. In other words the evaporative drying potential offered by the reference materials and climates examined (indoor and outdoor) was not sufficient to keep the region of focus in the wall assembly at an RH below 95% when the temperature was above 5^{o}C during the two-year simulation runs.

Unless otherwise noted the summary of the results applies to both hardboard and vinyl-clad walls investigated. Highlights of hygIRC simulations using MEWS methodology presented in Chapter 1 are as follows:

- Hardboard and vinyl siding-clad wall assemblies exhibited a high level of water resistance through the field of the wall, effective even in climates with high moisture loads. This seemed to be largely because the liquid diffusivity of the siding material – the measure of the capacity of liquid water to pass through a material - was low (TG3).
- When the wall assembly included a deficiency that allowed water leakage into the stud cavity, the predicted hygrothermal responses in terms of the RHT(95) indicator for the region of focus (a 5mm slice of the top layer of the bottom plate) varied as follows:
    - 731 for hardboard siding wall and 1072 for vinyl siding wall, in a hot and dry climate of Phoenix
    - 3297 for hardboard siding wall and 3138 for vinyl siding wall, for the warm and wet climate of Wilmington NC.
- This indicated that hourly moisture loads into the stud cavity (Q) were excessive in relation to the evaporative drying potential offered by the properties of the materials in the wall assembly and the temperature prevailing in the stud cavity.
- When the moisture loads in the stud cavity were dropped to ¼Q for hardboard and 1/8Q for vinyl, RHT(95) dropped as well, but remained above zero.

- For the hardboard siding-clad reference wall the parametric study was carried out using a 1Q set of hourly moisture loads into the stud cavity. Such quantities of water into the stud cavity appeared to be beyond the capacity of the hardboard siding-clad wall to deal with by liquid diffusion and evaporative drying alone. The following variations from the hardboard siding reference wall assembly resulted in little or no improvement of hygrothermal response as defined by the RHT(95) indicator:
  - Changing the properties of the sheathing boards (between OSB and plywood)
  - Changing the properties of the water resistive barrier (between a polymeric membrane and a paper-based membrane)

- The response of vinyl siding-clad reference wall in the 1Q range of water entry was similar to hardboard siding (see point above). For vinyl siding the parametric study was carried out using a ¼Q set of hourly moisture loads into the stud cavity, with the following results:

  - Changing the properties of the water resistive barrier (between a polymeric membrane, a paper-based membrane and no membrane at all) for a wall with an extruded polystyrene sheathing resulted in little or no improvement in RHT(95).

  - Changing to XPS sheathing from OSB substantially increased the accumulation of RHT(95) because the addition of thermal insulation on the outside of the stud cavity prolonged the period at which the region of focus was above 5^{o}C. This effect was different from a situation where condensation control would be the only concern, in which case the presence of an insulating sheathing would be desirable because the increased cavity temperature would reduce the period where it is below the dew point temperature of indoor air.

- For the hardboard siding-clad reference wall, interchanging vapour barrier membranes was predicted to have a near-zero-to-small effect on the RHT(95) response of the wall. However, a major increase in the vapour permeance of the layer of materials placed on the inside of the stud cavity (i.e. removal of vapour barrier membrane, and the addition of three coats of paint on the interior finish gypsum board) produced a small-to-substantial drop in RHT(95) wall response for the five climates investigated (Phoenix, Winnipeg, Ottawa, Seattle and Wilmington NC). The improvement was larger for climates with larger climate moisture loads. The simulation results are based on the assumption that the interior climate was relatively dry, which promoted drying towards the inside. The effect of changes in the vapour permeance of the materials on the interior side of the stud cavity would likely be smaller for more humid interior climates.

- For the vinyl siding-clad wall assembly, replacing the vapour barrier membrane with a membrane having a higher water vapour permeance was predicted to have a small effect (with ¼Q hourly moisture loads in the stud cavity). A noticeable improvement in the RHT(95) wall response was predicted when the vapour diffusion control was provided only by painted interior gypsum board. However even though in this case the capacity for drying to the inside was high and Q was reduced to ¼, the accumulated RHT(95) value still remained above zero. It must be emphasized that in the vapour barrier simulation runs, only one set of interior boundary conditions (temperature and relative humidity) were used and that those conditions promoted drying to the inside.

- For the hardboard siding-clad wall, in the five locations investigated, hygIRC predicted that the introduction of a clear and vented (top and bottom) cavity behind the siding made essentially no difference in the RHT(95) response of the wall in the region of focus, once water entered the stud cavity at a 1Q set of hourly rates. However for both vinyl and hardboard siding, when the rate of water entry into the stud cavity was dropped to a ¼ of the original values used, the addition of a vented cavity behind the siding was predicted to result in a small-to-substantial drop in RHT(95). As the water loading into the stud cavity was reduced considerably, the evaporative drying potential offered by the addition of the vented cavity began to make a noticeable difference in the hygrothermal response of the assembly.

The following sections explain how the MEWS methodology laid out in Chapter 1 was applied to hardboard and vinyl siding-clad walls.

5.2 Selection of Materials and Design of the Wall Assemblies

Through Task Group 2, MEWS industry members and IRC personnel gathered technical information on current practices in the construction of siding-clad wall assemblies. This information was used in the design of 3 full-scale wall specimens for the evaluation of water entry under simulated wind-driven rain pressure (TG6), the design of walls to be simulated through modelling in TG 7 and for the characterization of material properties (TG3).

Review of practice indicated that hardboard siding has been usually applied in two ways in North America. The most common approach was to apply the siding directly on the water resistive membrane of the backup wall. Another approach consisted of applying the siding on furring strips so that a drained continuous air space was formed between the siding and the back up wall. This approach can provide further reductions in the moisture load seen by the second line of defence; it has been promoted in Canadian coastal climates and has been part of traditional installation techniques in Quebec. Vinyl siding tended to be applied directly on the backup wall. Only in retrofit would furring strips be installed on the back up wall, usually for levelling purposes.

5.2.1 Types of Wall Assemblies Selected

Three generic types of siding-clad assemblies were examined, as defined by the moisture management strategies used:

- One wall assembly without a drained cavity behind the siding (Figure 5.1). This assembly included a horizontal lap hardboard siding applied directly against a water resistive membrane.
- One wall assembly with a clear cavity (19 mm deep) behind the siding (Figure 5.2). In this case the hardboard siding was installed on vertical furring strips, which provided a clear air space between the siding and the water resistive membrane.
- One wall assembly with a series of small compartmentalized cavities behind the siding (Figure 5.3). These were formed by the particular profile of the horizontal vinyl siding. The thickness of these cavities varied from near zero to about 15 mm. The siding was applied directly onto an exterior insulating sheathing board.

The construction and detailing of the 3 siding-clad wall specimens investigated for water penetration in the Dynamic Wall Testing facility are described in T2-02 report entitled: *Description of the 17 Large-scale Specimens Built for Water Entry Investigation in IRC Dynamic Wall Testing Facility",* May 2002.

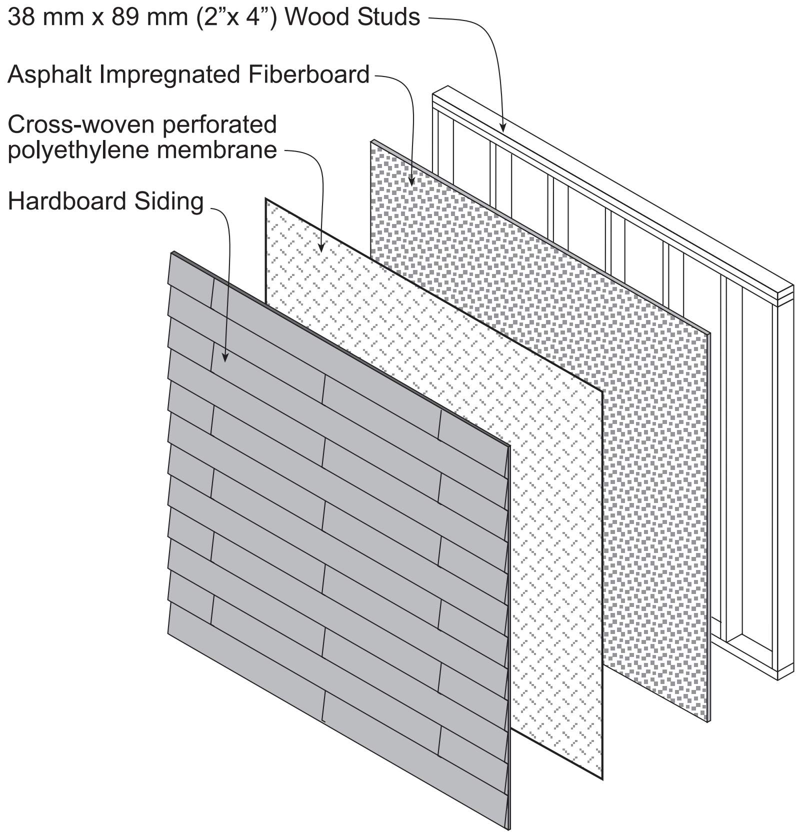


Figure 5.1. Hardboard siding-clad wall assembly (specimen No. 15) with no cavity behind the siding

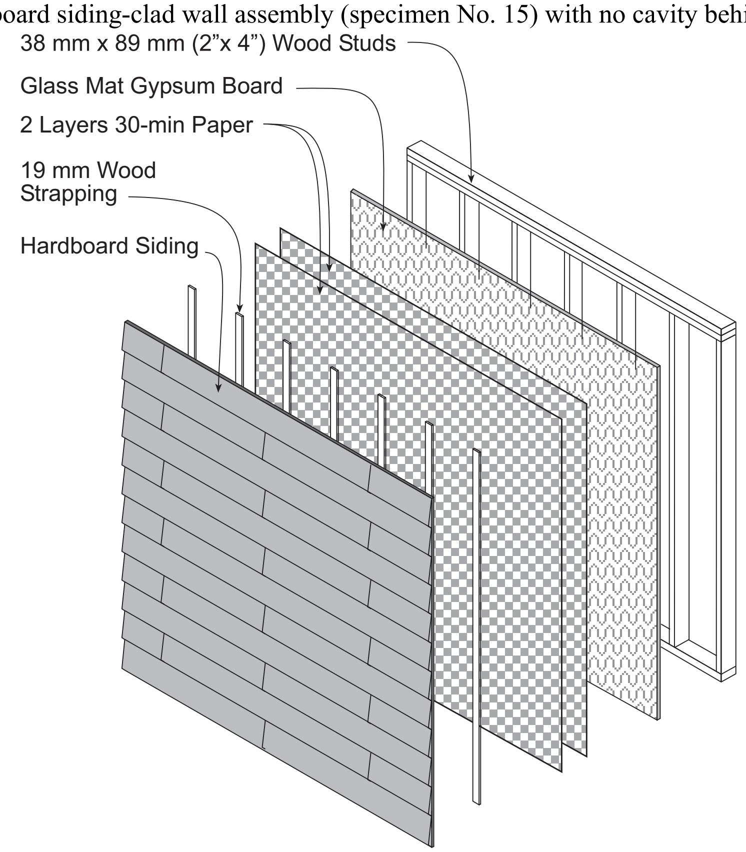


Figure 5.2 Hardboard siding-clad wall assembly (specimen No. 16) with a 19 mm cavity behind the siding

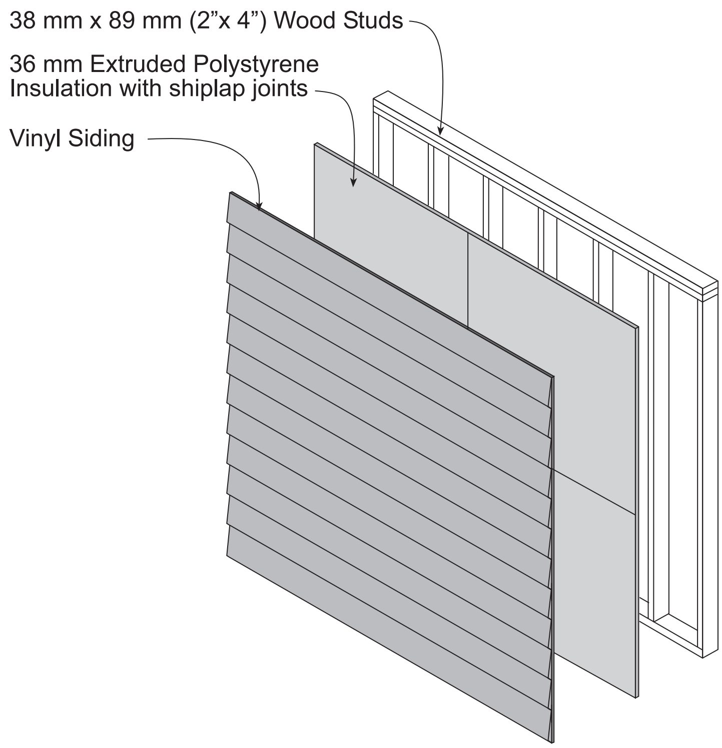


Figure 5.3. Vinyl siding-clad wall (specimen No. 17) with compartmentalized horizontal cavities behind the siding

5.2.2 Properties of Materials

Hygrothermal properties of several products of the following basic materials were characterized: siding materials, building paper and polymeric WRB membranes, OSB, extruded polystyrene foam insulation, glass fibre insulation, spruce lumber, paper and plastic vapour barriers and gypsum board. Several properties of these materials used as input for running hygIRC simulations are given in Table 5.1. Other hygrothermal material properties can be found in the MEWS material property database prepared by TG 3.

Unlike stucco-clad or EIFS-clad walls, the exterior claddings of hardboard and vinyl-clad walls were constructed of individual elements joined together to form an assembly. Horizontal strips of hardboard or vinyl boards overlapped each other and were joined at the ends. Although it was possible to model individual overlapping boards of hardboard and vinyl cladding systems, for practical reasons (computation time for example) a bulk material property approach was used. For the hardboard siding, it was assumed that the lap joints and butt joints were sufficiently tight for the cladding to be modeled as a single panel of material 12 mm thick spanning the height of the wall (See Figure 5.7). A 1mm non-vented air gap was placed between this single panel of hardboard siding and the water resistive barrier, to represent the imperfect contact between the siding and the water resistive barrier. The bulk properties of a single panel of hardboard material were determined in the laboratory and reported by Task Group 3.

Vinyl siding was modeled in the same manner as hardboard siding, i.e. as a flat panel without joints. In practice, vinyl siding assemblies differ somewhat from hardboard siding: drainage holes are provided at the bottom of each board, the vinyl siding profiles are not tightly connected to each other, no sealant is used at joints and an air space of varying thickness is present behind the vinyl profile. In order to model vinyl siding as a flat panel, it was necessary to develop some equivalency using a bulk material property approach. In that approach, two boards with one horizontal joint in between were put together and selected hygrothermal properties (air permeability and water vapor permeability) of the assembly were measured (Figure 5.4). These properties were assumed to be transferable to a modeled flat cladding panel at a thickness of 1.2 mm. The material properties for such a flat panel assembly are given in Table 5.1. As can be seen, the air permeability of the vinyl siding (as modeled based on laboratory measurements) was several orders of magnitude higher than that of the hardboard siding; this can be explained by the presence of drainage holes and loose connections between horizontal strips of siding.

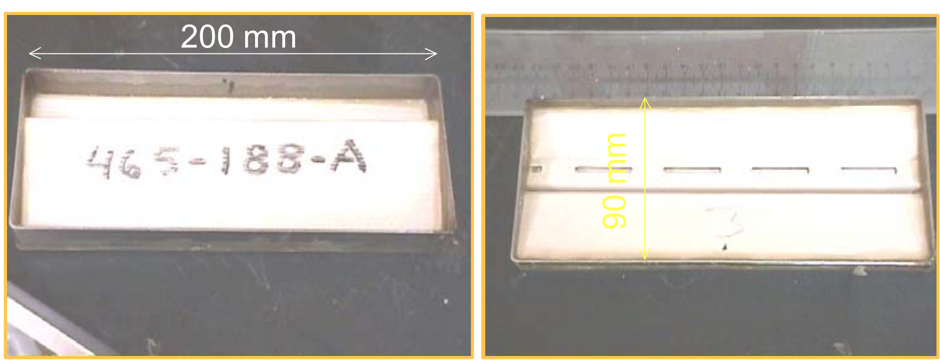


Figure 5.4. Test set up for water vapour permeability and air permeability determination of vinyl siding joint. Note the horizontal joint in the assembly. Although vinyl material had a very low water vapour permeability and liquid diffusivity, the joint greatly increased the air permeability of the assembly.

Table 5. 1: Selected Properties of Materials

Properties / Materials	Water vapour permeability ng/(m s Pa) @ 0%RH	Water vapour permeability ng/(m s Pa) @ 100%RH	Liquid diffusivity (10^{-12} m^2/s)	Air permeability x dynamic viscosity (m^2) x 10^{-16}
Hardboard siding (not backprimed)	0.43	3.5	3.98 (x) 95.58 (y)	3.3
Vinyl siding + 1 joint	0.008	0.008	0.0001	10828
Sheathing board				
XPS insulation (36 mm)*	0.94	1.4	0.0001	1
OSB	0.06	6	22 (x) 510 (y)	79
Asphalt-coated fibreboard	18.82	23	3.2 (x) 1237 (y)	32000
Plywood	0.39	26	170 (x) 940 (y)	85
Water resistive barrier				
Spun bonded polyolefin (0.23mm)	0.24	0.2	0.0001	1200
30 minute building paper (0.22mm)	0.18	1.2	3.6	118
60 minute building paper (0.31mm)	0.51	1.7	4.9	358
Vapour Barrier				
VB1 membrane 15 ng	0.002	0.002	0.0001	0.0001
VBII membrane 60 ng	0.012	0.012	0.0001	0.001
VBIII membrane variable	0.006	0.063	0.0001	1
Painted gypsum board int. finish, 12 mm	1.9 (x) 31.9 (y)	30.8 (x) 62.0 (y)	370000	678

* The values were obtained from laboratory measurements on a product manufactured in 1997 at a thickness of 100 mm. For updated values, the reader should contact the manufacturer.

5.3 Estimation of Moisture Loads

The methodology presented in Section 1.5 (Chapter 1) for the estimation of moisture loads entering the stud cavity through a deficiency was applied to the study of siding-clad wall assemblies. Moisture loads impinging on the face of the cladding were based on climate data for each of the seven locations in the parameter study. The moisture loads injected into the stud cavity were based on the results obtained from experiments in the Dynamic Wall Testing facility (DWTF). These experiments provided hourly rates of water entry in the stud cavity, through deficiencies located in three different wall specimens for several specific combinations of water spray intensity and static air pressure differential across the wall assembly.

Moisture Entry into the Wall Assembly through a Given Opening

Full-scale laboratory tests were conducted on the three siding-clad specimens (see Figures 5.1 to 5.3) to find out the fraction of the water sprayed on the exterior face of the wall that passed through the given deficiency and got into the stud cavity. This deficiency was an opening approximately 1-mm wide by 50-mm long at the interface between the top of the cover of an electrical receptacle and the siding. One of the three specimens experienced some water entry in the stud cavity. That water was collected at the inside face of the sheathing board, just beneath the electrical receptacle. From the amounts of water collected and the climate loads the specimens were subjected to, an equation was derived to estimate the water entry rate (Q) in one stud cavity as a function of the pressure difference across the wall assembly and the rate of water (Rw) striking the wall. The equation used for both hardboard siding and vinyl siding-clad assemblies is given below:

$$Q\ (L/h) = Rw \times f(\Delta P) = Rw \times \{0.0422 + 1.618E^{-5} \bullet \Delta P_{wall} - 3.88E^{-8}(\Delta P_{wall})^2 + 1.115E^{-10}(\Delta P_{wall})^3\} \qquad (1)$$

This equation was used to calculate the hourly rates of water entry into the stud cavity of the siding-clad walls that were modeled in the various hygIRC simulations. Rw and ΔP were based on the hourly climate loads of the two years of weather data selected for each of the seven locations investigated.

Figure 5.5 shows the hourly rates of water entry into the stud cavity of the siding-clad reference wall represented in hygIRC, for three locations with quite different climate loads, Wilmington NC, Winnipeg and Phoenix.

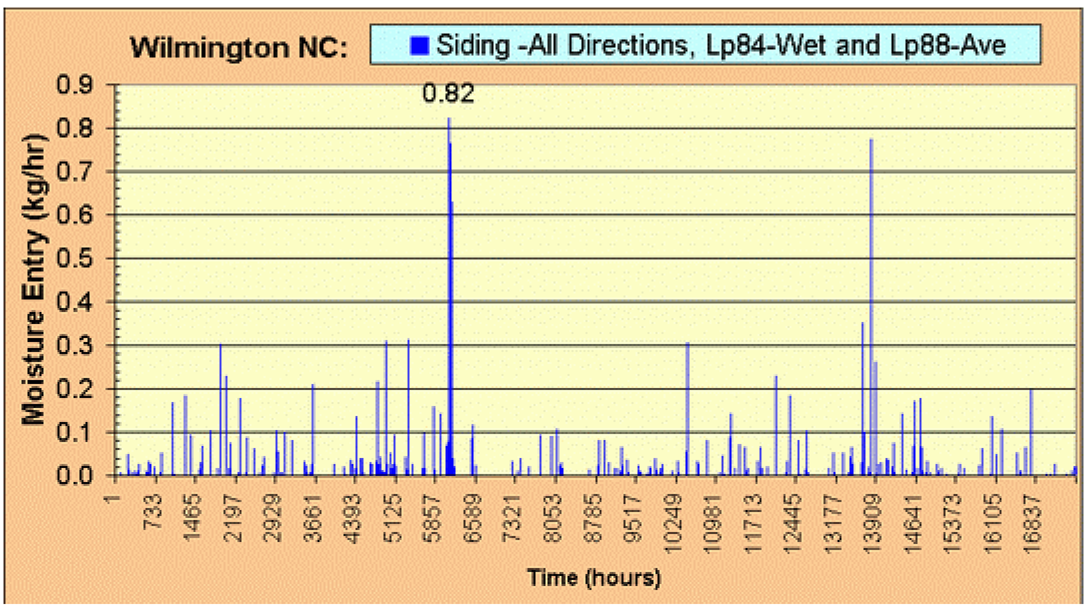


Figure 5.5a) Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of siding-clad reference wall for Wilmington NC for two years of hygIRC simulation.

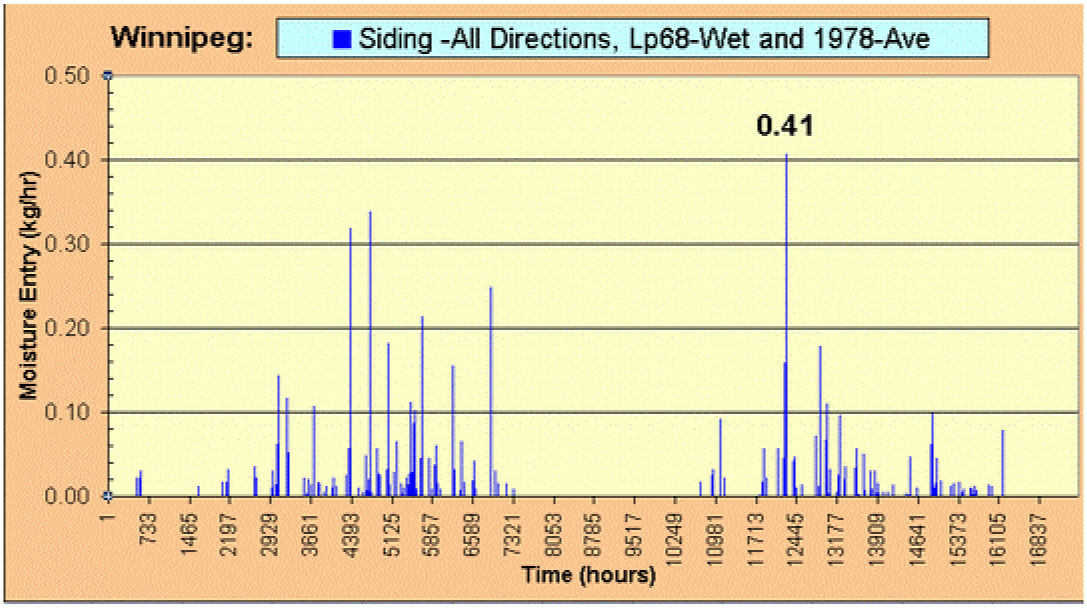


Figure 5.5b) Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of siding-clad reference wall for Winnipeg for two years of hygIRC simulation.

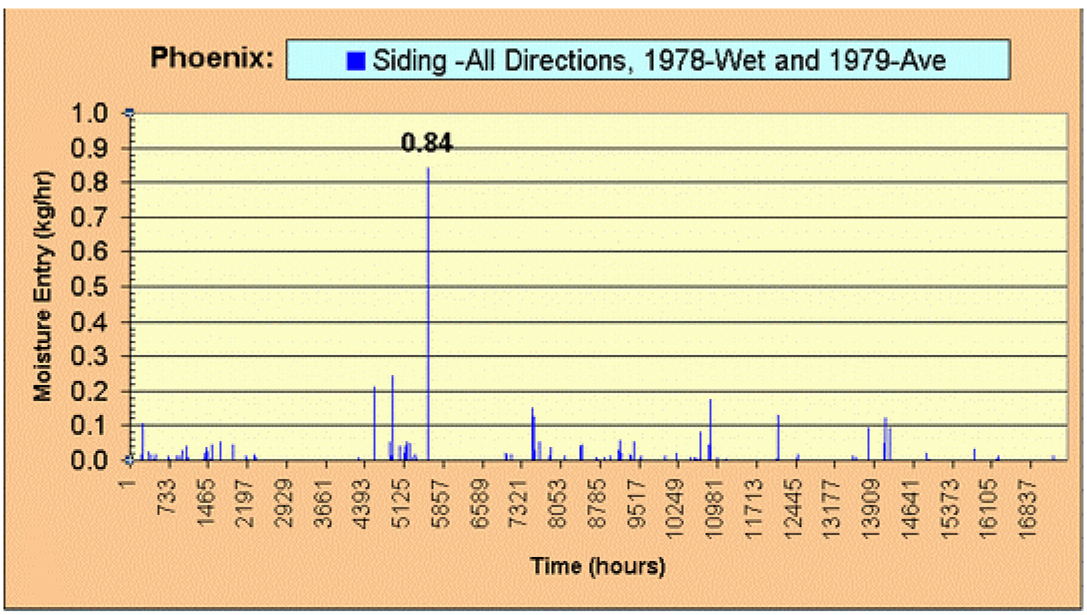


Figure 5.5c) Hourly rates of water entry "injected" in the stud cavity (referred to as "1Q") of siding-clad reference wall for Phoenix for the two years of hygIRC simulation.

Moisture Distribution Within the Stud Cavity

Having established how much water could get into the stud cavity, the next step was to decide where and how to distribute it. As described in Chapter 1, through some computer routines, the modeller deposited the moisture load at the bottom of the stud cavity. The hourly amounts, varying from 0 to a maximum of about 0.8 L (Wilmington NC) were uniformly distributed among several grid points representing a thin layer of stud cavity insulation just above the bottom plate in the wall stud cavity.

Selection of the Region of Focus in the Stud Cavity

The region of focus was selected for its potential to represent a worst-case scenario (see Chapter 1 section 1.7.1 for details). In preliminary simulations a region had been identified as being the wettest portion of the wall assembly most of the time (see Figure 5.6). For all siding simulations, the region of focus was a thin slice (5 mm) of the top surface of the bottom plate, extending 53 mm from the sheathing board.

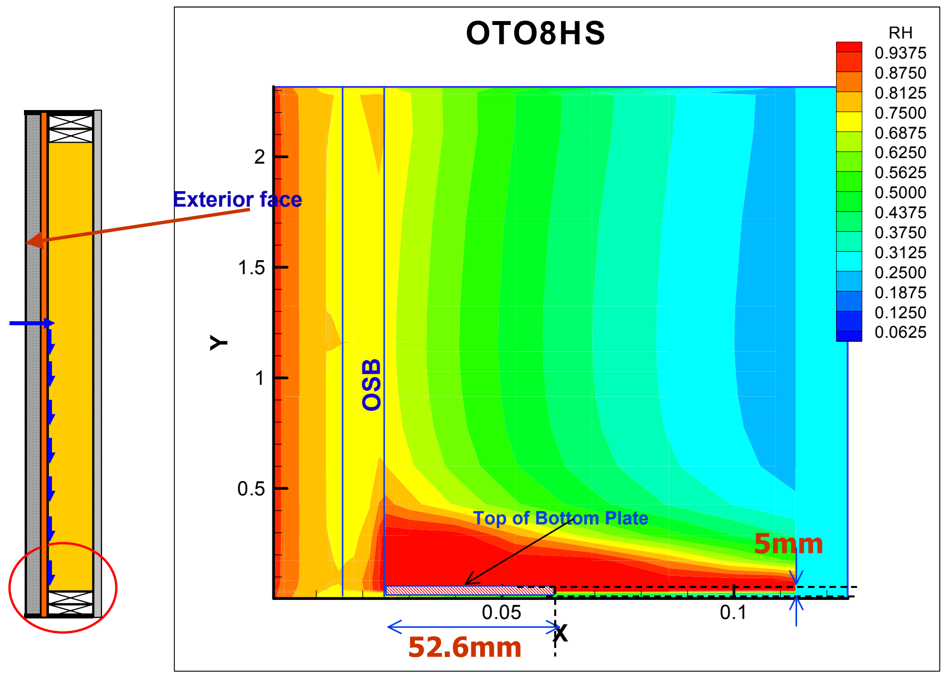


Figure 5.6 shows a typical RH contour plot generated by hygIRC for the reference wall in Ottawa, taken as a snapshot during the two-year simulation. The dark (red) areas are regions for which hygIRC predicted an RH above 87%. The bottom of the stud cavity was predicted to be the wettest portion of the wall assembly most of the time.

5.4 Prediction of the Hygrothermal Response of Hardboard Siding Assemblies

5.4.1 Parameters Investigated

The following parameters were varied to predict their influence on the hygrothermal response of a reference hardboard siding-clad wall assembly (Figure 5.7):

1. Climate severity (7 locations)
2. Material properties
   - 2 sheathing membranes (building paper and polymeric)
   - 3 sheathing boards (OSB, plywood and asphalt-coated fibreboard)
   - 3 vapour barriers (2 membranes and painted interior gypsum board)
3. Characteristics of the assembly
   - Presence of a vented cavity behind the siding
   - With and without a deficiency allowing water leakage into the stud cavity. The rate of accidental moisture entry inside the stud cavity was varied between 0Q, Q/2, Q/4, 1Q, 2Q, 4Q

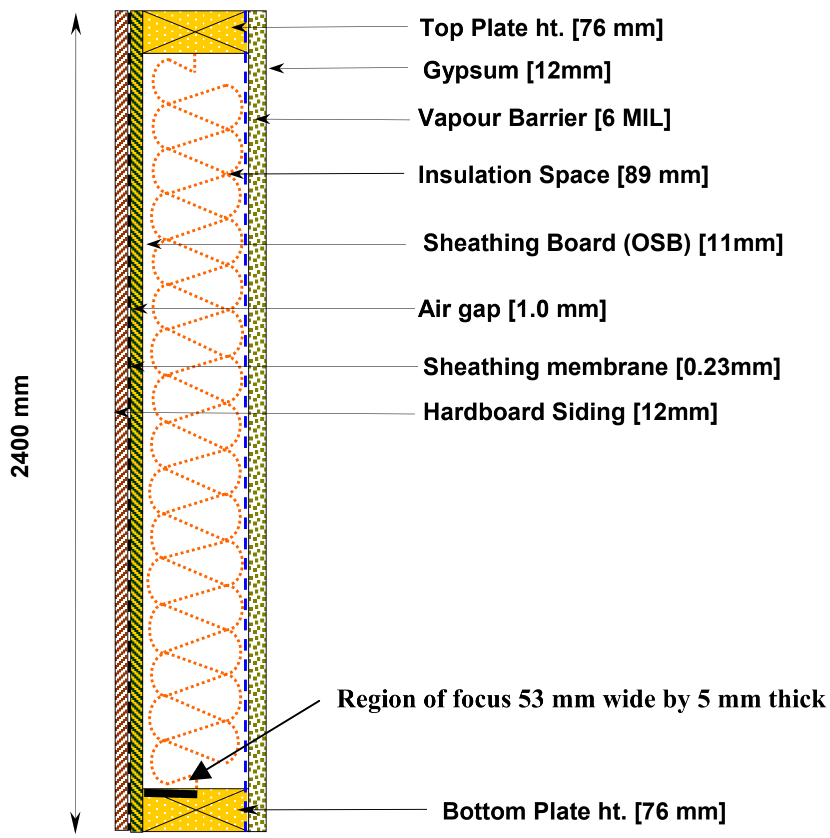


Figure 5.7 A vertical section showing the composition of the siding-clad wall used as the reference for the parametric study.

NB. For the simulation runs, it was assumed that double top and bottom plates in the stud cavity were in place. In practice it is more common to use only a single plate. It is believed that this discrepancy did not affect the interpretation of the results significantly.

5.4.2 Comparative Results

All possible combinations of material types for each of the seven locations with and without moisture entry through a deficiency would yield about a thousand simulations. This was indeed far more than could have been accommodated given the time and resources available for the MEWS project. Hence, after careful consideration and consultation with MEWS partners, it was decided to conduct just enough simulations to predict the major influences of parameters mentioned above (wall construction details and parameters). The simulations presented in this summary represent only a portion of the total number of simulations carried out in this program. Of these, only a handful are singled out for discussion here; two complete sets of results (for RHT(95) and RHT(80)) are provided in Appendix 5.1. Reported in this section are the comparative effects of the parameters listed in section 5.4.1 on the hygrothermal response of the wall expressed using the RHT(95) indicator.

The following nomenclature is used in the subsequent sections to describe the effects of changing various parameters on the wall response:

Decisive: cumulative RHT(95) was reduced to near zero by a single change of parameter.
Substantial: cumulative RHT(95) difference of at least 1000 of the larger value compared.
Small: cumulative RHT(95) difference less than 1000 and higher than 100 of the larger value compared.
Near-zero: cumulative RHT(95) difference less than 100 of the larger value compared

1.0 Effect of Climate Severity on a Wall Assembly Response

Observation: In terms of RHT(95), the hardboard siding-clad wall reference assembly with no deficiency showed no adverse hygrothermal response in any of the seven locations. All other configurations (with the "nominal" deficiency allowing water entry into the stud cavity) registered positive RHT(95) index values, increasing with the climate severity of the location.

Discussion: Figure 5.8 summarizes this observation. The flat blue line for the reference wall assembly shows that the cumulative RHT(95) remained at zero even in climates with a high moisture index (MI) such as Wilmington NC. This was related to the rather high resistance to water of the hardboard siding itself, which reduced water entry into the wall assembly sufficiently to maintain an RHT index response below the threshold of 95%RH at the region of focus in the stud cavity. The green and red curves show the predicted cumulative RHT(95) index value for hardboard siding-clad walls with deficiency, and two different sets of material properties.

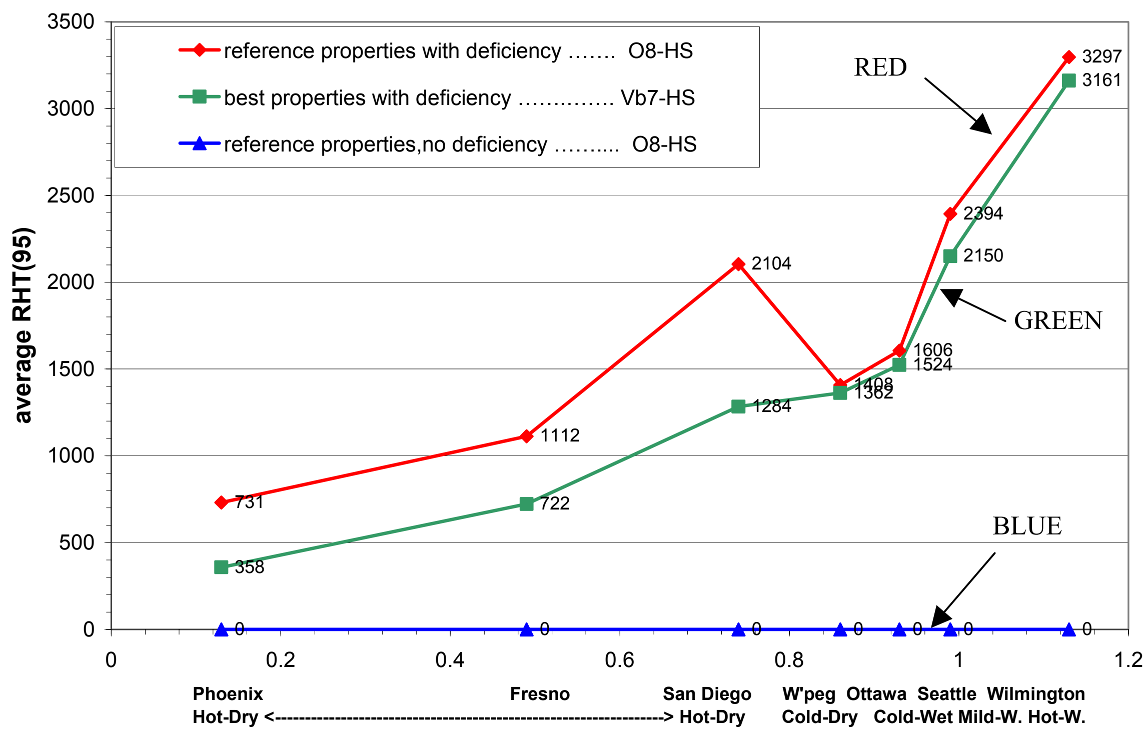


Figure 5.8 Relationship between climate severity and hardboard siding-clad wall response for three scenarios: the reference wall (illustrated in Figure 5.7) with no water entry into the stud cavity (blue line); the reference wall with a 1Q set of hourly moisture loads into the stud cavity (red line); the wall with the best properties of materials and with a 1Q set of hourly moisture loads into the stud cavity (green line).

The upper (red) line has a pronounced upward kink for the San Diego climate. San Diego and Seattle have different climates and different MI, but the RHT(95) response of the wall was about the same. San Diego's climate was drier and warmer than Seattle's, and from the lower **MI**, a lower RHT was expected. To explain this behaviour, one needs to examine the RH and T curves that form the basis for the computation of the RHT values at the region of focus. For the San Diego simulation (Figure 5.9), the wall had two drying spells (with RH at the region of focus below 95%); however, the temperature at the region of focus was always higher than that for the wall in Seattle. For the Seattle simulations, the RH reached about 98% after the first month and stayed there for the rest of the simulation period, but the cooler temperature "slowed down" the accumulation of RHT values (Figure 5.10). The net effect was that, even though the climates of San Diego and Seattle were quite different, their RHT response was about the same because of the combined effects of the relative humidity and the temperature.

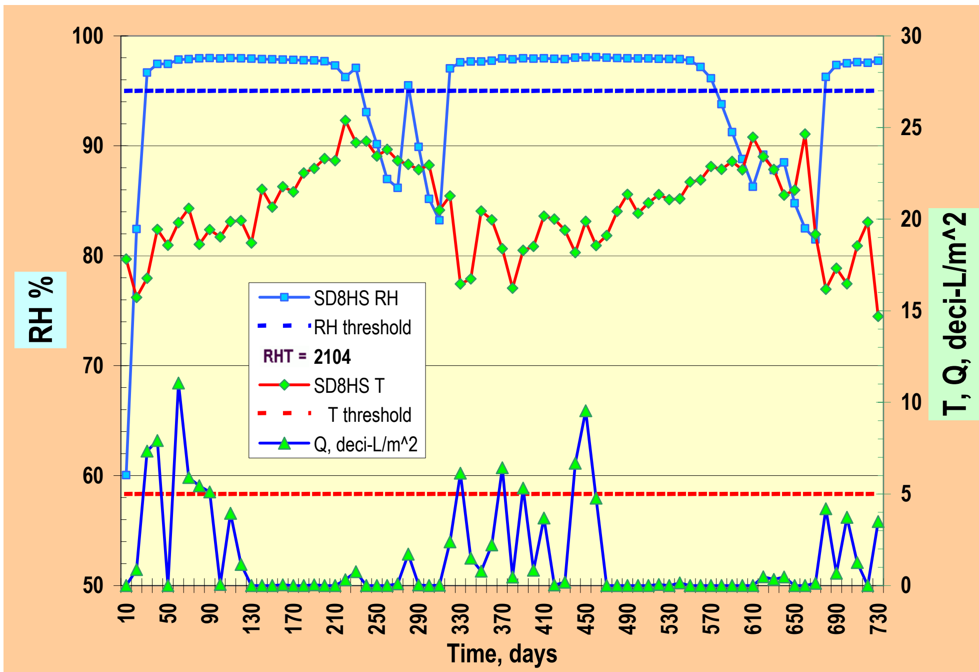


Figure 5.9. RH and T profiles predicted for the reference wall in San Diego. Cumulative RHT(95)= 2104

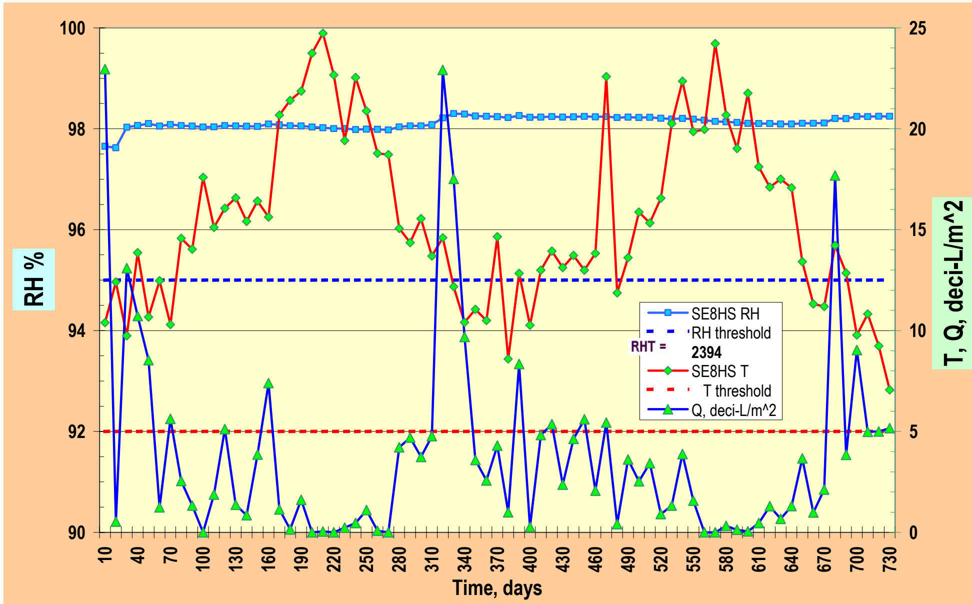


Figure 5.10. RH and T profiles predicted for the reference wall in Seattle. Cumulative RHT(95)= 2394

Climates of Winnipeg and Ottawa had higher MI than San Diego but the reference wall had a lower RHT(95) response in these two cold climates than in San Diego. Figure 5.11 shows the situation for Winnipeg. With the temperature at the region of focus below 5°C, there was no accumulation of RHT(95) for long periods during the winter months. This explains why the two-year cumulative RHT(95) value for the wall exposed in Winnipeg was lower than the same wall exposed to the San Diego climate, even though the indicator of climate severity, MI, for Winnipeg (MI=0.86) was higher than that of San Diego (MI= 0.74). The same observation applied for the Ottawa climate.

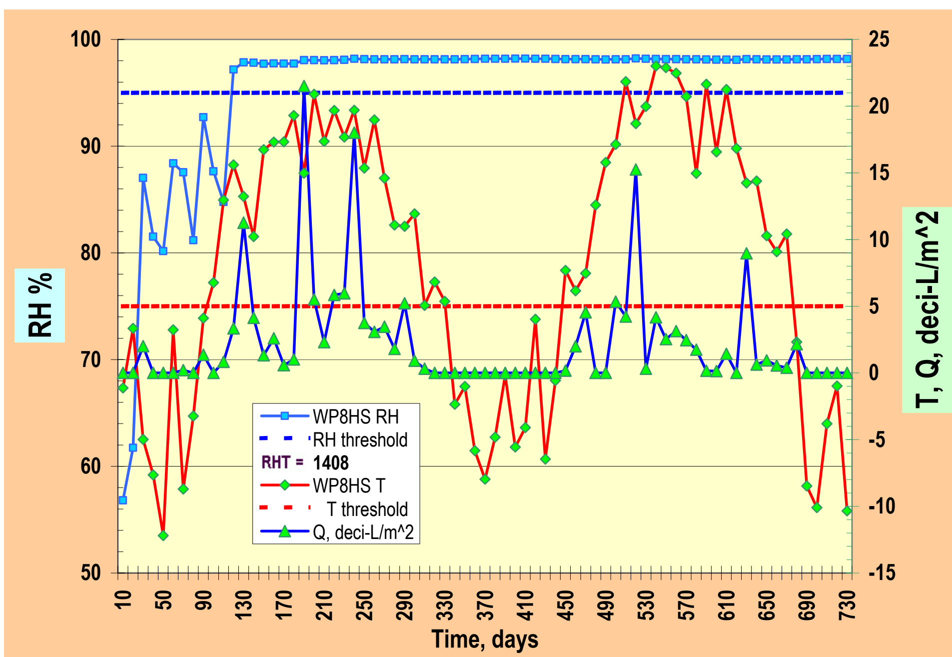


Figure 5.11. Predicted RH and T profile for the reference wall with a 1Q set of hourly water entry rates, exposed to two years of Winnipeg climate years. Cumulative RHT(95)= 1408.

2.0 Effect of the Variation of the Moisture Loads (Q) into the Stud Cavity

Observation No. 1: ***Effect of Q=0.*** hygIRC simulations predicted that the hardboard siding investigated provided a high degree of water resistance, even under severe outdoor moisture loads (Wilmington NC). (Effect: *decisive*)

Discussion: The RHT(95) value for the reference wall not subjected to accidental water entry in the stud cavity, i.e. *zero Q*, was zero for all locations investigated (Table 5.2 and Figure 5.12). When no water bypassed the cladding system, the properties of the cladding material became the dominant factor for the control of moisture ingress. The hardboard cladding exhibited a low liquid diffusivity (Table 5.1), which indicated a high resistance to liquid water flow across the material.

Table 5.2 Cumulative RHT(95) values for several sets of moisture loads in the stud cavity (Q)

Q	Phoenix	Fresno	San Diego	Ottawa	Winnipeg	Seattle	Wilmington NC
0	0	0	0	0	0	0	0
¼	*	60	173	351	746	1110	2466
½	*	468	838	1457	1273	2105	3001
1	731	1112	2104	1606	1408	2394	3297
2	1859	*	*	*	*	*	*
4	3746	*	*	*	*	*	*

An asterisk, *, indicates no simulation run for the specific parameter

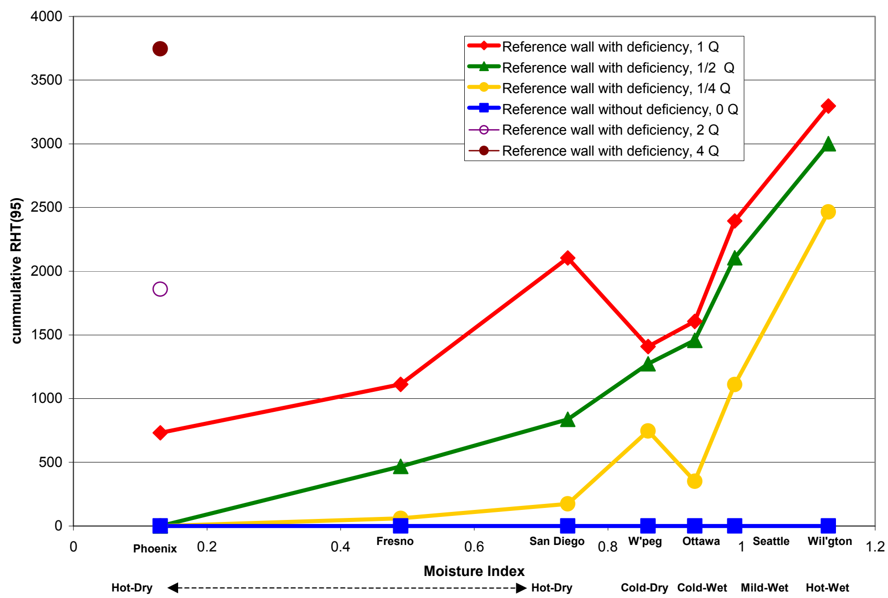


Figure 5.12. Relationship between cumulative RHT(95) values, MI severity and magnitude of Q, the set of hourly moisture loads in the stud cavity

Observation No. 2: ***Effect of Q≠0.*** In all locations investigated, and within the range of sets of hourly moisture loads in the stud cavity (Q) investigated, water leakage into the stud cavity was shown to increase the RHT(95) response of the hardboard siding-clad wall. The hardboard siding-clad assembly was sensitive to moisture entry into the stud cavity. The magnitude of that response was a function of the climate loads, the detailing of the water leakage path and the properties of the materials making up the assembly.

Discussion: All simulation results for several levels of water leakage into the stud cavity (1/4, ½, 1, 2 and 4Q) for several locations predicted that the wall RHT(95) response was above a zero value (Table 5.2 and Figure 5.12). Even in the dry climate of Fresno, and with the lowest selected rate of water entry into the cavity (i.e. 1/4Q), the RHT(95) wall response was positive (value of 61). The deficiency used to estimate the rate of water entry into the stud cavity of the wall specimens consisted of a 1-mm wide by 50-mm long gap in the bead of sealant at the interface between an electrical receptacle cover plate and a siding board. As deficiencies in practice have not been well documented, the range of Qs could be even broader than that covered by this parametric study.

Observation No. 3: ***Effect of Q=1***. Most of this parametric study used a 1Q set of hourly water entry rate in the stud cavity (see examples of hourly rates in Figure 5.5). For the wet and cold climates investigated, a 1Q set of wetting rates of the stud cavity seemed "to flood" the reference wall, i.e. no noticeable drying occurred during the two years of simulation runs. In the drier climates, however, (Fresno, San Diego and Phoenix), that wall was predicted to experience drying periods. (Effect: *decisive*)

Discussion: With a 1Q set of hourly moisture loads in the stud cavity, the wall RHT(95) value reached a low of about 731 in Phoenix and a high of 3297 in Wilmington NC. For the wet and cold climates investigated, the evaporative drying rate offered by the materials in the vicinity of the region of focus and by the outdoor and indoor climates was insufficient to offset the 1Q set of wetting rates of the stud cavity. An examination of the 10-day interval predictions of RH and T in Wilmington NC (Figure 5.13) showed that the region of focus reached an RH of about 97% early on in the simulation run (after about 3 months) and stabilized at that level for the remaining of the simulation. In other words little drying occurred during the simulation period. The temperature prevailing at the region of focus drove the RHT value.

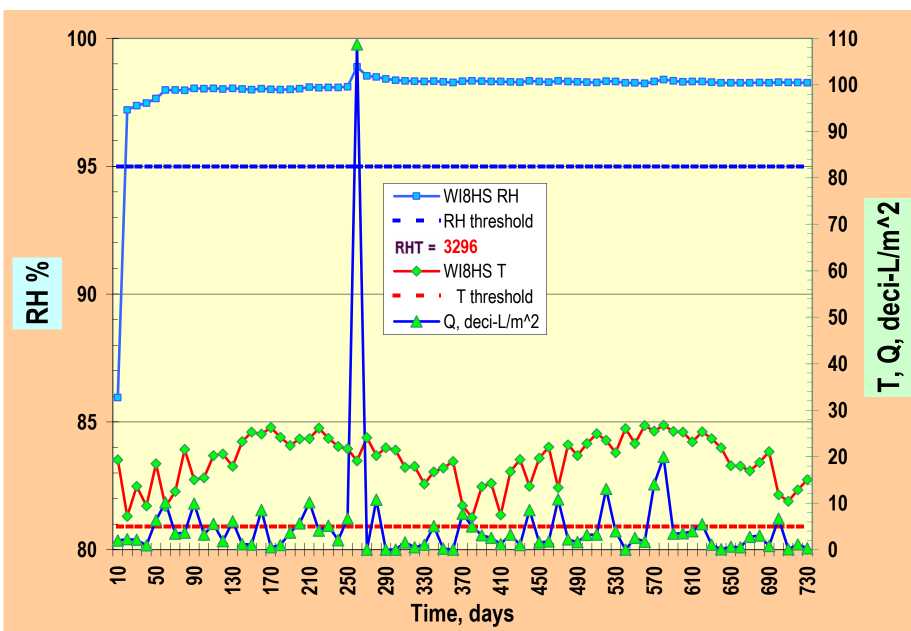


Figure 5.13Predicted RH and T profiles for the reference wall with a 1Q set of hourly moisture loads, exposed to two years of Wilmington climate years. Cumulative RHT(95): 3296

For Phoenix, Fresno and San Diego, the 1Q set of hourly moisture loads into the stud cavity did not “flood” the wall, and a few extended periods of drying were predicted to occur (Figures 5.9, 5.14 and 5.15). The RH dropped down to 50% in Phoenix, 60% in Fresno and 80% in San Diego. The lower moisture loads and the higher drying potential captured by the MI indicator of climate severity can explain the lower RHT values.

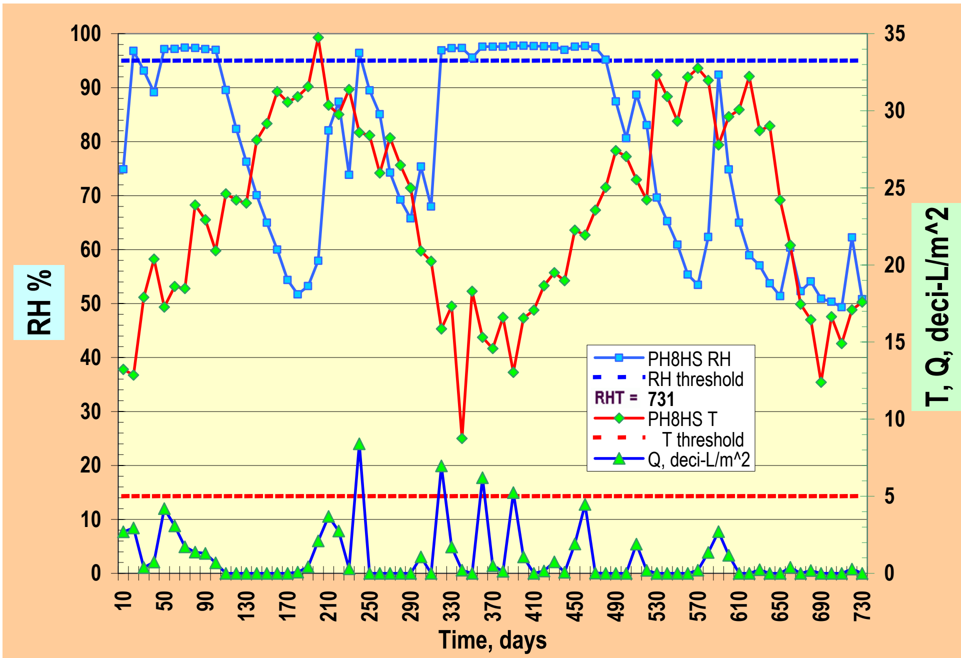


Figure 5.14 Predicted RH and T profiles for the reference wall with a 1Q set of hourly moisture loads, exposed to two different years of Phoenix climate years. Cumulative RHT(95): 731

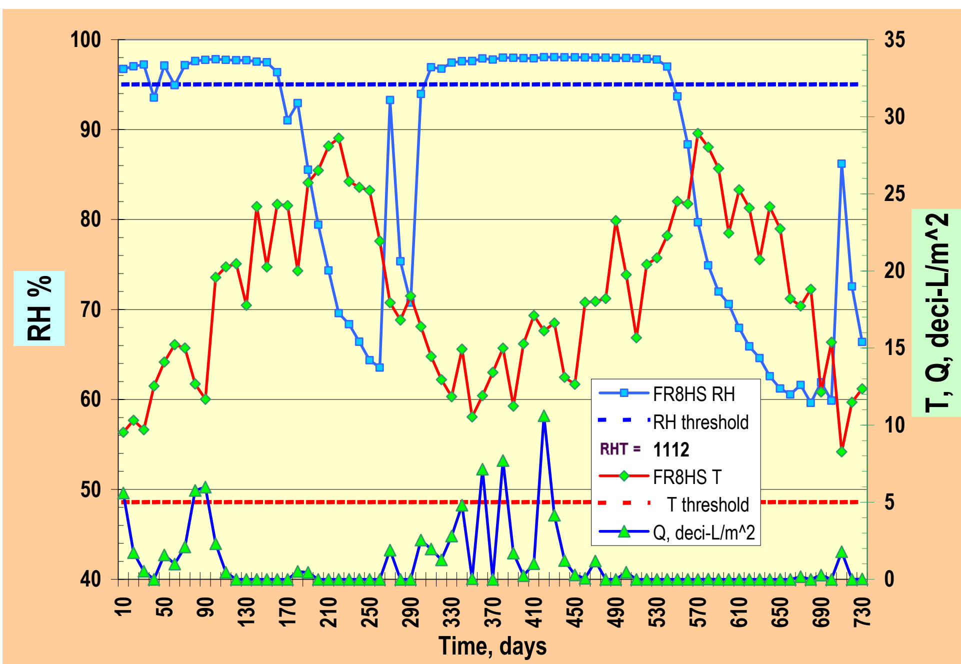


Figure 5.15 Predicted RH and T profiles for the reference wall with a 1Q set of hourly moisture loads, exposed to two different years of Fresno climate years. Cumulative RHT(95): 1112

Observation No. 4: ***Effect of Q between 0 and 1***. When the moisture loads in the stud cavity were reduced to 1/4Q, hygIRC predicted substantially improved hygrothermal response in all locations but Wilmington NC, which showed only a small reduction in RHT(95). Even at a quarter of the original loads and in the favourable climate of Fresno, the drying potential through the layers of material of the reference wall was not sufficient to bring the RHT(95) value to zero. (Effect: *small to substantial*)

Discussion: As mentioned before, allowing water entry into the stud cavity had a major effect on the hygrothermal performance of the wall. How low did Q have to go to obtain a decisive drop in RHT(95)? These hygIRC simulations suggest that Q would have to drop to less than ¼ of the original loads. It is interesting to note that the ½ Q simulation results for locations of higher moisture loads and lower drying potential produced only a small improvement of the RHT(95) value compared to that of 1Q (Table 5.2). An examination of the RH fluctuations at the region of focus of the wall in Wilmington NC(Figure 5.16) and Winnipeg (Figure 5.17) suggested that little net drying effect occurs (the RH was rather stable around 97%). In Fresno and San Diego (i.e. dry climates), simulation results for ½ Q set of moisture loading in the stud cavity produced small-to-substantial changes in RHT(95) for the wall region of focus. For that case the strength of the drying mechanisms overcame that of the wetting mechanisms. For any wall assembly in any given climate, there must be a pivotal value of Q that defines when the moisture balance tipped towards "flooding" or drying. The relationship between cumulative RHT(95) and multiples of Q was not linear in climates with moderate to high moisture loads (Figure 5.18). The slope of the curve decreased as the moisture loads into the stud cavity got past a certain value (1/2 Q in Seattle, Ottawa and Winnipeg; ¼ Q in Wilmington NC).

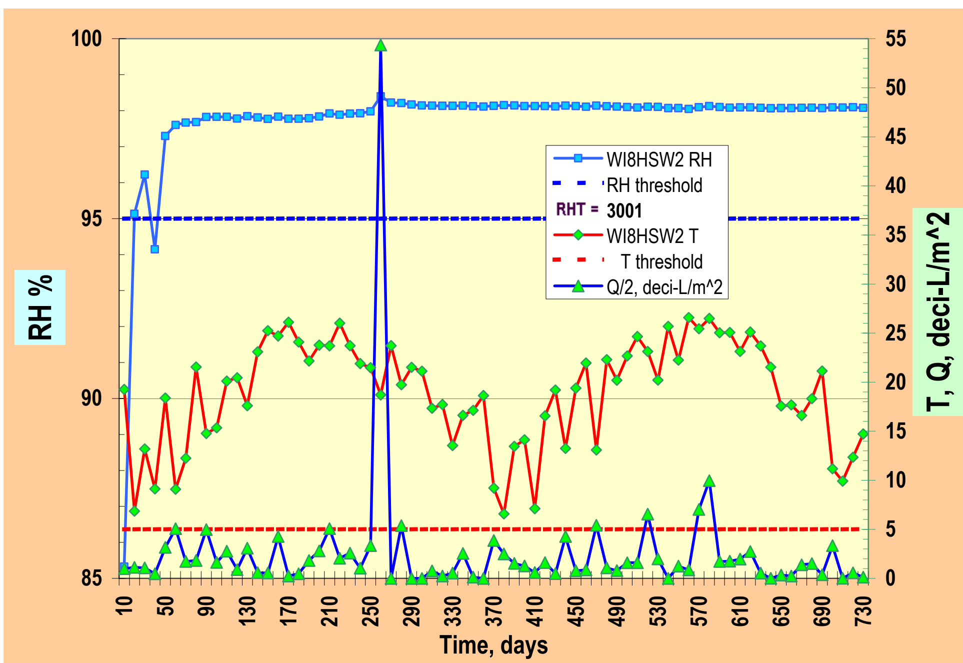


Figure 5.16. Predicted RH and T profile for the reference wall with a ½ Q set of hourly water entry rates, exposed to two different years of Wilmington climate years. Cumulative RHT(95): 3001.

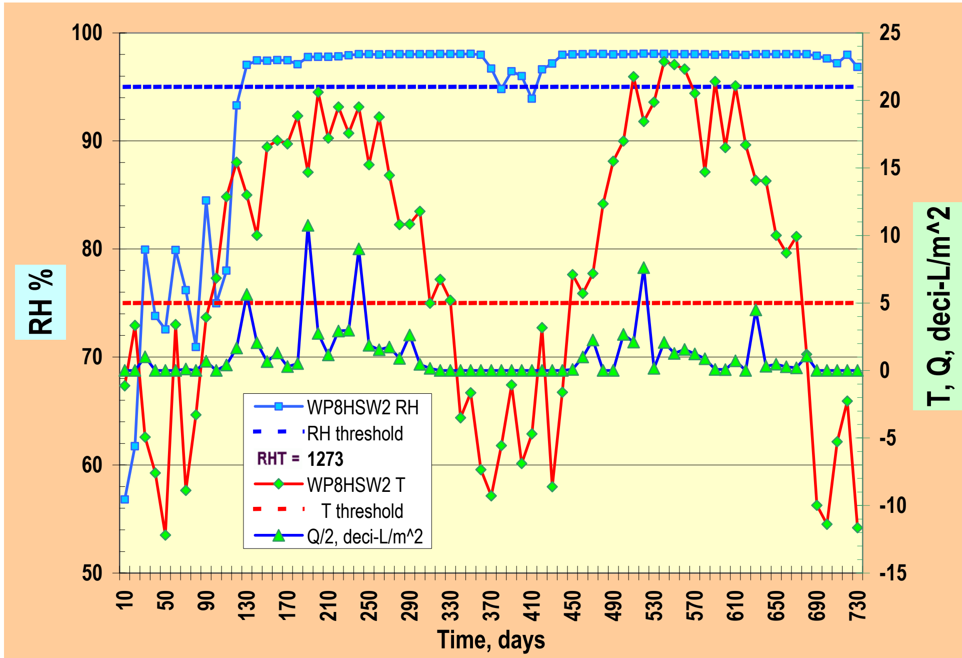


Figure 5.17. Predicted RH and T profile for the reference wall with a ½ Q set of hourly water entry rates, exposed to two different years of Winnipeg climate years. Cumulative RHT(95): 1273.

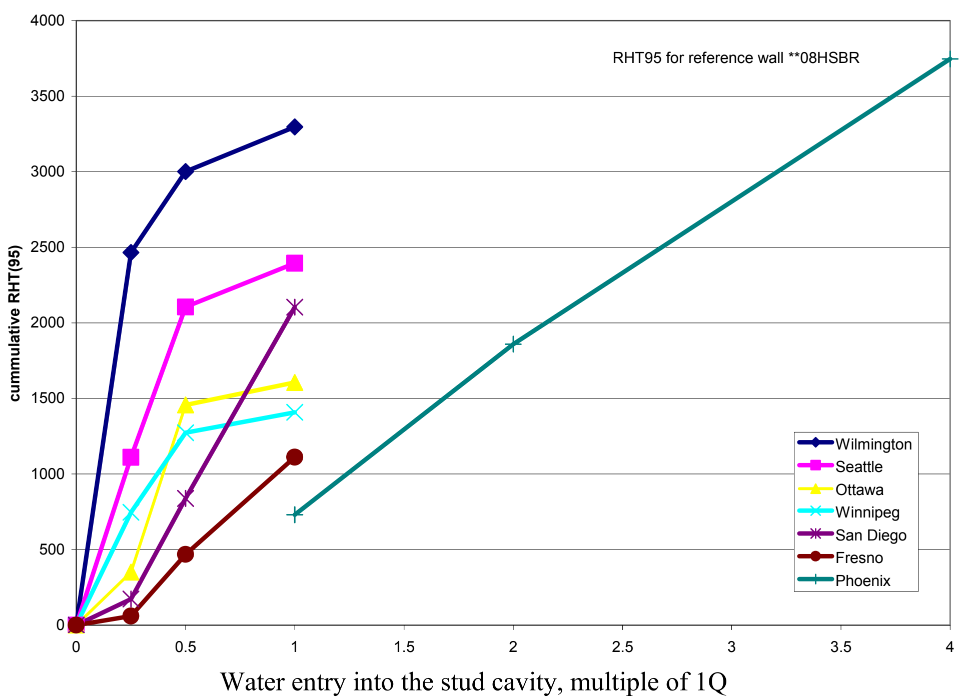


Figure 5.18. Predicted relationship between the magnitude of the set of moisture loads into the stud cavity (Q) and the hygrothermal response of the wall RHT(95), for the seven climates investigated

Observation No. 5: ***Effect of Q>1***. One set of simulation results suggested that the wall RHT(95) response could increase substantially even in a hot, dry climate (i.e. Phoenix) if the moisture loads in the stud cavity were increased sufficiently (e.g. with a severe enough deficiency).

Discussion: For Phoenix, simulation of a 4Q set of hourly moisture loads in the stud cavity of a wall produced an RHT(95) of 3746, higher than the RHT(95) of a wall with a 1Q in Wilmington NC. This highlighted the importance of keeping the magnitude of Q under control, even in forgiving climates. (Effect: *substantial*)

3.0 Effect of Material Properties in a Given Climate

Effect of the Properties of Three Sheathing Boards

Observation: Except for the warm and dry climates investigated (Phoenix and Fresno), hygIRC simulations suggested that the properties of the three sheathing boards included in the parametric study made little or no difference in the hygrothermal response of the reference hardboard siding-clad wall assembly when a 1q set of moisture loads got into the stud cavity. (Effect: *near-zero to small, but for Phoenix and San Diego, small*)

Discussion: The three following sheathing boards were investigated as part of the reference assembly illustrated in Figure 5.7: OSB, plywood and asphalt-coated fibreboard. The hygIRC properties of these materials have been characterized in TG3 and the results are presented in Table 5.1. Table 5.3 provides the RHT(95) response of the reference wall for all locations and sheathing board materials investigated, once water entered the stud cavity at a 1Q set of hourly rates.

For climates experiencing high moisture loads and low drying potential (i.e. Seattle and Wilmington NC), the change in sheathing board did not make much difference in the moisture balance of the region of focus in the stud cavity. This was also the case for the simulation results in Ottawa and Winnipeg climates.

For climates of lower moisture loads and higher drying potential (i. e. San Diego and Phoenix) a small improvement in RHT(95) was shown when the OSB was changed for asphalt-coated fibreboard or plywood.

The properties defined for the asphalt-coated fibreboard used for the simulation (see Table 5.1) showed a higher water vapour permeability (about 4 times, at 100%RH) and a much higher air permeability than the OSB and plywood (about 400 times higher). Asphalt-coated fibreboard contributed to larger evaporative drying, for the low wetting rates of Phoenix and San Diego.

Table 5.3: RHT (95) index comparison for the reference wall using three sheathing boards

	RHT(95) index at a 1Q set of hourly moisture loads in the stud cavity					
board	**Phoenix**	**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
OSB	731	2104	1408	1606	2394	3297
Asphalt-coated fibreboard	305	1449	1253	1474	2207	3099
Plywood	495	1529	1335	1530	2283	3197

Effect of the Properties of the Water Resistive Barrier

Observation: For all climates investigated, hygIRC simulations predicted that the properties of the two sheathing membranes included in the parametric study would have essentially no effect on the hygrothermal response of the reference hardboard siding-clad wall assembly, as the RHT(95) results were almost identical. (Effect: *near-zero*)

Discussion: Two water resistive barriers were investigated: a spun-bonded polyolefin membrane and a 60-minute building paper membrane (see Table 5.1 for their properties). The simulation results are given in Table 5.4. One can see that the properties of these two water resistive barriers were predicted to have essentially no effect on the hygrothermal response of the wall assembly, once a 1Q set of moisture loads has entered in the stud cavity over the two years of simulation runs. The main purpose of the water resistive barrier was to protect the back up wall from further water intrusion once water has penetrated the cladding assembly. In the simulations, water was allowed to bypass the water resistive barrier and the sheathing board and reach the stud cavity (simulating a poor detailing around a through-the-wall penetration). The simulations mainly investigated how the hygrothermal properties of the water resistive barrier can affect on the evaporative drying of the stud cavity, rather than its effect on water ingress into the back up wall.

Table 5.4: RHT (95) index comparison for two water resistive barriers

Location Sheathing membrane	RHT(95) index at a 1Q set of hourly moisture loads in the stud cavity				
	Phoenix	Winnipeg	Ottawa	Seattle	Wilmington NC
SBPO (reference case)	731	1408	1606	2394	3297
60 minute bldg paper	716	1406	1602	2389	3288

Effect of the Properties of the Vapour Barrier

Observation No. 1: For climates investigated other than that of Phoenix, hygIRC predicted that using a vapour barrier membrane with a higher vapour permeance (30 times more permeable at 100%RH) made little improvement in the RHT(95) hygrothermal response of the wall assembly at the region of focus. (Effect: *near-zero to small; for Phoenix, small*)

Discussion: Two vapour barrier membranes were investigated for several locations. The hygIRC properties of these two materials have been characterized by TG3 and a summary of properties can be found in Table 5.1. The relationship between vapour permeability and relative humidity as defined by TG 3 laboratory experiments is illustrated in Figure 5.19.

Table 5.5 provides the predicted RHT(95) response for all locations and vapour barrier materials investigated. Overall, changing from a very tight vapour barrier *membrane* to a more vapour permeable *membrane* (about 30 times) provided a near-zero improvement in the RHT(95) response of the stud cavity of the wall in cold climates, and a very small RHT(95) improvement in wet climates. As examples, take Wilmington NC and Ottawa: the RHT(95) in the area of focus dropped from 3297 to 3161, and from 1606 to 1524 respectively. It may well be that in those climates, the moisture loads in the stud cavity were so high that a small variation in the vapour permeability of the vapour barrier membranes investigated did not allow a fast enough rate of moisture release to the inside to make a difference.

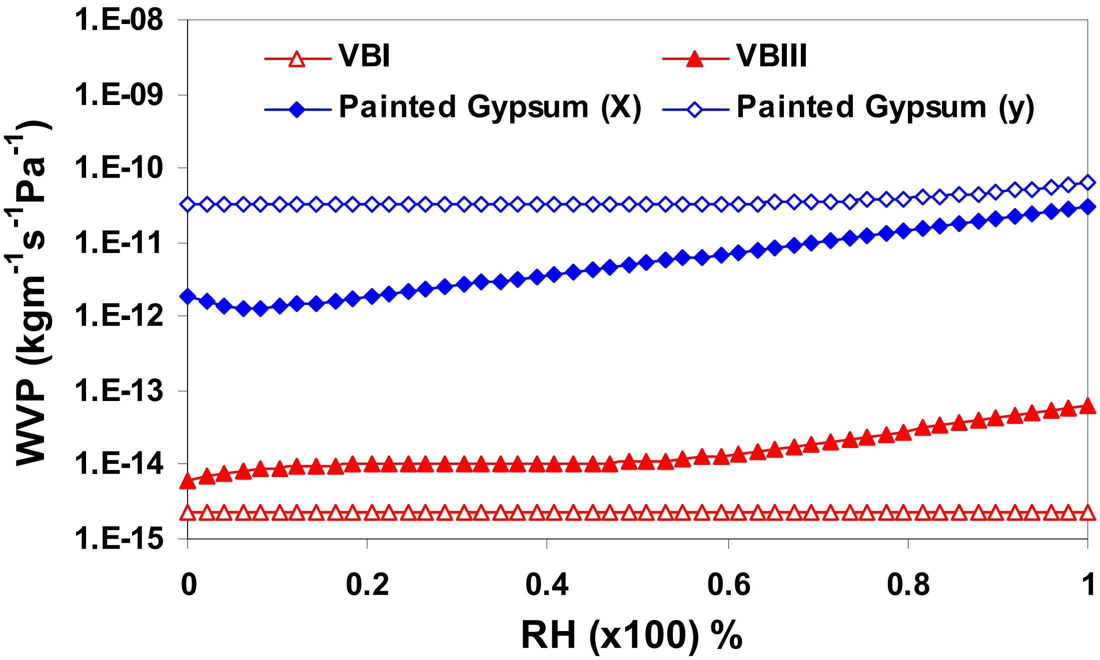


Figure 5.19. Relationship established by TG 3 between vapour permeability and relative humidity of two vapour barrier membranes and one coating on gypsum board. VB I did not change property with changes of relative humidity, while VBIII tended to exhibit an increase in water vapour permeability as a function of relative humidity.

Table 5. 5: RHT (95) index comparison for vapour barriers of different properties

	RHT(95) index for reference wall at a 1Q set of moisture loads in the stud cavity				
Location Vapour barrier membrane	**Phoenix**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington NC**
VB1 membrane	731	1408	1606	2394	3297
VB3 membrane	358	1362	1524	2150	3161
No VB membrane; Painted int. gypsum board	104	851	649	989	1207

Observation No. 2: For all five locations investigated, hygIRC predicted an improvement in RHT(95) at the region of focus in the stud cavity when the vapour permeance of the layer of materials placed on the inside of the stud cavity was increased by a large factor - in this case several thousand times. (Effect: *small to substantial*)

Discussion: For one set of simulations done for 5 locations, the vapour barrier membrane was removed from the reference wall and one coat of primer with two coats of latex paint were added to the unpainted gypsum board interior finish. The vapour permeance of this assembly was much higher than either of the two vapour barrier membranes investigated previously (see Table 5.1 and Figure 5.19). hygIRC predicted that the drying potential offered by materials with relatively high vapour permeance located on the inside face of the stud cavity can be substantial in all five climates, but not sufficient as a single measure to bring the RHT value to the threshold of zero.

Note that the evaporative drying to the inside depended upon the differential vapour pressure between the wet stud cavity and the indoors. The lower the indoor RH, the higher the vapour pressure differential will be, and hence the higher the drying rate. The indoor RH used in the simulations was low (25% RH in winter and 55%RH in summer). In practice however, particularly in warm and wet climates, the indoor RH may be higher, and as a result, the driving force for drying to the inside may be lower than what was simulated.

Effect of Addition of a Vented Cavity Behind the siding

Observation No. 1: For the five locations investigated, hygIRC predicted that a clear cavity (vented top and bottom) behind the siding made essentially no difference in the hygrothermal response of the wall in the region of focus, once water entered the stud cavity at a 1Q set of hourly rates. (Effect: *near-zero*)

Discussion: In that set of simulation runs, a 19 mm cavity was introduced behind the hardboard siding of the reference wall. hygIRC predictions are presented in Table 5.6. These indicated that the introduction of a clear cavity had little effect on the RHT(95) response of the reference wall, once water has entered in the stud cavity at a 1Q set of hourly rates. It must be emphasized that the simulation runs investigated the drying potential offered by the addition of a vented cavity, but did not investigate the ability of a vented cavity to reduce the moisture loading into the stud cavity. In fact for these simulations, the reference wall was subjected to the same 1Q set of hourly moisture loads in the stud cavity, as the reference wall without a vented cavity. The RHT(95) responses suggested that the rates of moisture loading into the cavity was much larger than the rates of moisture withdrawal (evaporation) contributed by the introduction of a vented cavity. To go one step further, another similar set of simulations was done using a ¼ Q (but 4Q for Phoenix) set of hourly rates of water entry into the stud cavity (Table 5.6) (See next point).

Table 5.6: **RHT (95) index comparison for the reference wall with and without a vented cavity behind the siding**

	RHT(95) index for reference wall at a 1Q, ¼ Q and 4Q sets of moisture loads in the stud cavity									
	Phoenix		Winnipeg		Ottawa		Seattle		Wilmington NC	
Cavity behind siding	1Q	4 Q	1Q	¼ Q	1Q	¼ Q	1Q	¼ Q	1Q	¼ Q
No	731	3746	1408	746	1606	351	2394	1110	3297	2466
Yes (19 mm)	732	3402	1481	426	1662	174	2471	721	3142	1073
Effect of adding cavity	None	Small	None	Small	None	Small	Small	Small	Small	Subs-tantial

Observation No. 2: For all locations investigated (except Phoenix), when the set of hourly rates of water entry in the stud cavity (Q) was reduced to ¼ of the original loads, hygIRC predicted that the introduction of a clear cavity (vented top and bottom) behind the siding improved the RHT(95) response of the wall in the region of focus. (Effect: *small to substantial*)

Discussion: Table 5.6 provides the hygIRC predictions when 1Q and ¼ Q moisture loads are injected in the stud cavity. A consistent drop in the cumulative RHT(95) value for the reference wall with a vented cavity behind the siding can be observed in all four locations. This indicates that the vented cavity contributed noticeably to the evaporative drying of the stud cavity, when the rate of wetting of the stud cavity was greatly reduced.

5.5 Prediction of the Hygrothermal Response of Vinyl Siding-clad Assemblies

5.5.1 Parameters Investigated

The following parameters were varied to predict their influence on the hygrothermal response of the vinyl siding-clad wall assembly (Figure 5.20):

1. Climate severity (7 locations)
2. Material properties
    - 2 sheathing membranes (30 minute building paper and polymeric)
    - 2 sheathing boards (OSB and extruded polystyrene (XPS) foam sheathing)
    - 3 vapour barriers (Type I, Type II, and painted interior gypsum board)
3. Characteristics of the assembly
    - With and without a deficiency allowing water leakage into the stud cavity. The rate of accidental moisture entry inside the stud cavity is varied between 0Q, Q/8, Q/6, Q/4, Q/2, and 1Q for all locations.
    - Removal of the sheathing membrane for the XPS foam sheathing
    - Presence of a vented cavity behind the siding for one city (Wilmington NC)

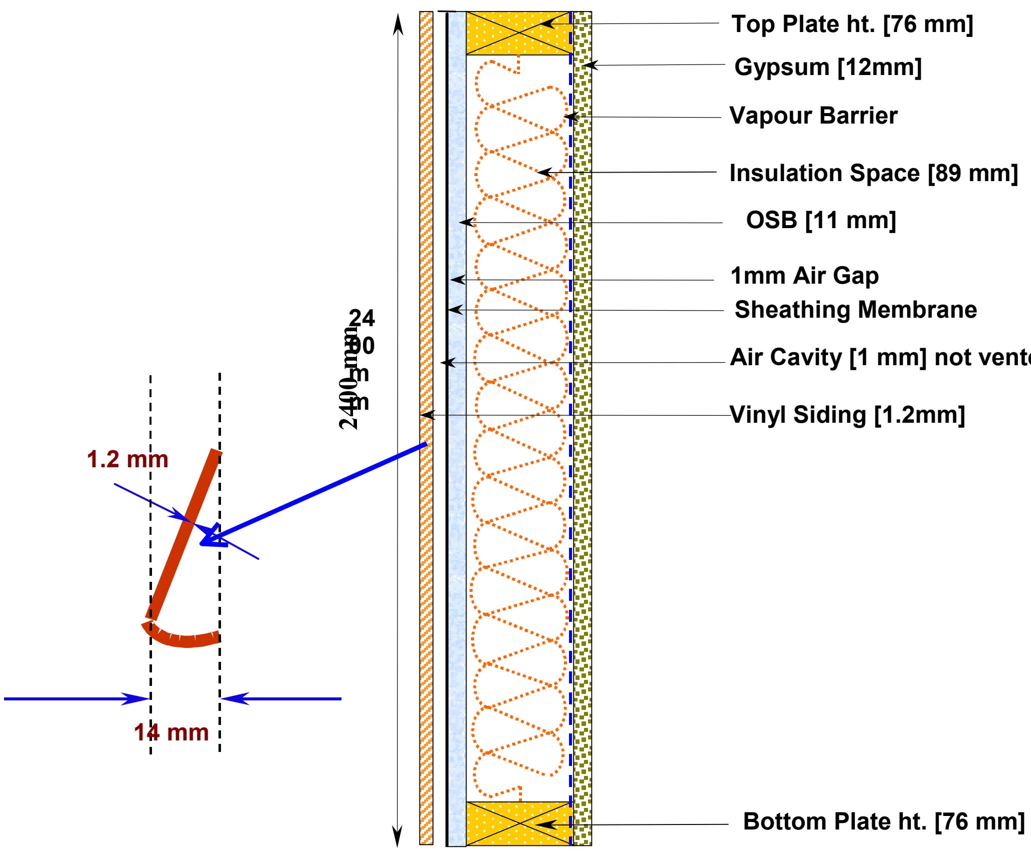


Figure 5.20. A vertical section showing the composition of the vinyl siding-clad wall used as the reference for the parametric study.

NB. For the simulation runs, it was assumed that double top and bottom plates in the stud cavity were in place. In practice it is more common to use only a single plate. It was believed that this discrepancy did not affect the interpretation of the results significantly.

5.5.2 Comparative Results

All possible combinations of material types for each of the seven locations with and without moisture entry through a deficiency would yield about a thousand simulations. This is indeed far more than could have been accommodated given the time and resources available for the MEWS project. Hence, after careful consideration and consultation with MEWS partners, it was decided to conduct just enough simulations to predict the major influences of parameters mentioned above (wall construction details and parameters). The simulations mentioned in this summary represent only a portion of the total number of simulations carried out in this program. Of these, only a handful are singled out for discussion here, but the complete set of results reported for two single indicators of hygrothermal performance, RHT(95) and RHT(80) indices, for each simulation is provided in Appendix 5.2. Reported in this section are the comparative effects of the parameters listed in section 5.5.1 on the hygrothermal response of the wall expressed using the RHT(95) indicator.

The following nomenclature is used in the subsequent sections to describe the effects of changing various parameters on the wall response:

Decisive: cumulative RHT(95) was reduced to near zero by a single change of parameter.
Substantial: cumulative RHT(95) difference of at least 1000 of the larger value compared.
Small: cumulative RHT(95) difference less than a 1000 and higher than 100 of the larger value compared.
Near-zero: cumulative RHT(95) difference less than 100 of the larger value compared

1.0 Effect of Climate Severity on a Wall Assembly Response

Observation: hygIRC predicted that the hygrothermal response of the vinyl-clad reference wall assemblies with the "nominal" deficiency allowing water entry into the stud cavity would have positive RHT(95) index values, increasing with MI of increasing magnitude. (Effect: *decisive*)

Discussion: Figure 5.21 illustrates this effect. The results are also tabulated in Table 5.7. The blue curve or lower curve in Figure 5.21 shows the behavior of the vinyl-clad reference case (**08VSBC) wall without water entry in the stud cavity. For all locations the wall RHT(95) response was zero. The red curve (upper curve) shows the response of the same wall (**08VS) with the 1Q set of moisture loads in the stud space. The value of RHT(95) generally increased monotonically with increasing climate severity as measured by the MI. The exception to this trend was San Diego. The value of RHT(95) for San Diego was higher because of temperature and the amount of water introduced into the stud cavity. A water entry of "1Q" was sufficient in most cases to overwhelm the drying capacity of the vinyl-clad wall in the region of focus. This can be seen in the detailed RH and T plots shown in Figure 5.22 for San Diego, Winnipeg, and Seattle. The response of the walls for the "1Q" case was governed by temperature. The temperature regimes in the region of focus for the San Diego and Seattle walls were similar, yielding a similar cumulative RHT(95). For the colder climate of Winnipeg, the temperature of the region of focus was below the threshold value of 5^oC for a significant part of the year, reducing the accumulation of RHT(95) (see Figure 5.22c).

When too much water entered the stud cavity (i.e. at 1Q), the drying potential of the materials did not affect the wall response. When the water entry was reduced to 1/4 Q, the drying potential of the wall played a significant role in reducing RHT(95) (the pink curve, second from the top in Figure 5.21). Unlike the other three wall systems (stucco, EIFS and masonry), the rest of the vinyl-clad siding simulations were done with 1/4Q moisture loads in the stud cavity. A more detailed discussion is given in the section on varying water entry rates.

The green curve shows the response of the wall made of materials most conducive to drying, specifically the **VB6VSW4 case with a water entry load of 1/4 Q. The shape of the curve is similar to that of the 1/4 Q reference case but its magnitude is attenuated.

The effect of climate can be decisive. Since the amount of water permitted in the stud cavity was, in the case of the assumptions made in MEWS, directly related to the climate severity, it stands to reason that the effect of climate was pronounced. "One Q" in Phoenix represented very little moisture loading combined with a high drying potential while "one Q" in Seattle was a significant load in a climate with a low drying potential. Vinyl-clad walls were sensitive to the amount of water entry into the stud cavity (see the next section). Beyond a certain amount of water entry in the stud cavity, the hygrothermal response of the walls became more sensitive to the temperature of the region of focus rather than the wetting and drying potential of the climate.

Table 5.7 Variation of RHT(95) with Climate Severity in terms of Moisture Index.

Location	MI_{hourly}	RHT(95) Base Case (0Q)	RHT(95) BC + 1Q	RHT(95) BC + 1/4Q	RHT(95) Best materials + 1/4Q
Wilmington	1.13	0	3138	2431	2134
Seattle	0.99	0	2195	1494	975
Ottawa	0.93	0	1477	1118	807
Winnipeg	0.86	0	1284	948	898
San Diego	0.74	0	3192	247	176
Fresno	0.49	0	1752	47	31
Phoenix	0.13	0	1072	0	0

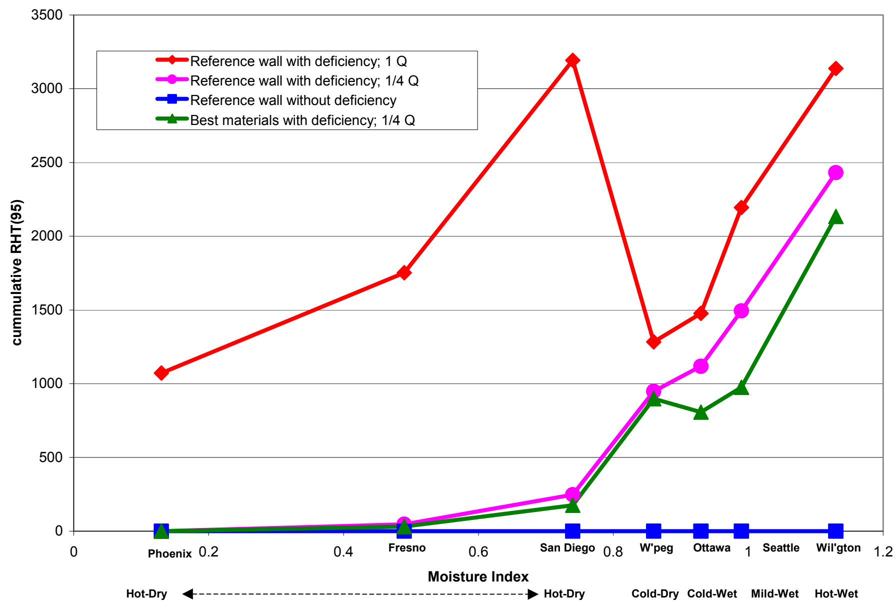


Figure 5.21. Relationship between climate severity and vinyl-clad wall response for four scenarios is shown in the figure. The blue, or lower, curve is the response for a reference wall No. 08VSBC having no water leakage into the stud cavity (no deficiency). The red, or upper, curve is the response of the same wall, No. 08VS however, with a deficiency allowing water leakage into the stud cavity (1Q). The pink curve, second from the top is the response of the reference wall with a water entry of 1/4 Q. The green curve third from the top represents the response of wall number VB6VSW4 (reference wall with a Type II, 60 ng, vapour barrier) having a combination of materials more conducive to drying and with the same deficiency (1/4 Q) as was incorporated in wall No. 08VSW4 (pink or curve second from the top).

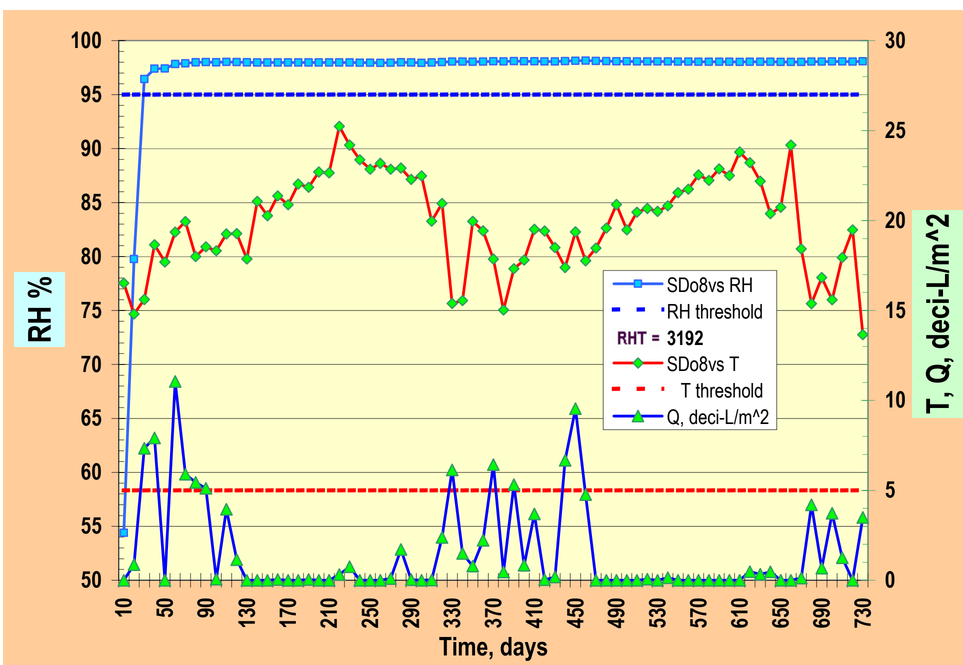


Figure 5.22 a) Reference wall with "one Q" moisture load in San Diego, CA. RHT(95) = 3192. Note the temperature curve. The RH curve is flat above 95%.

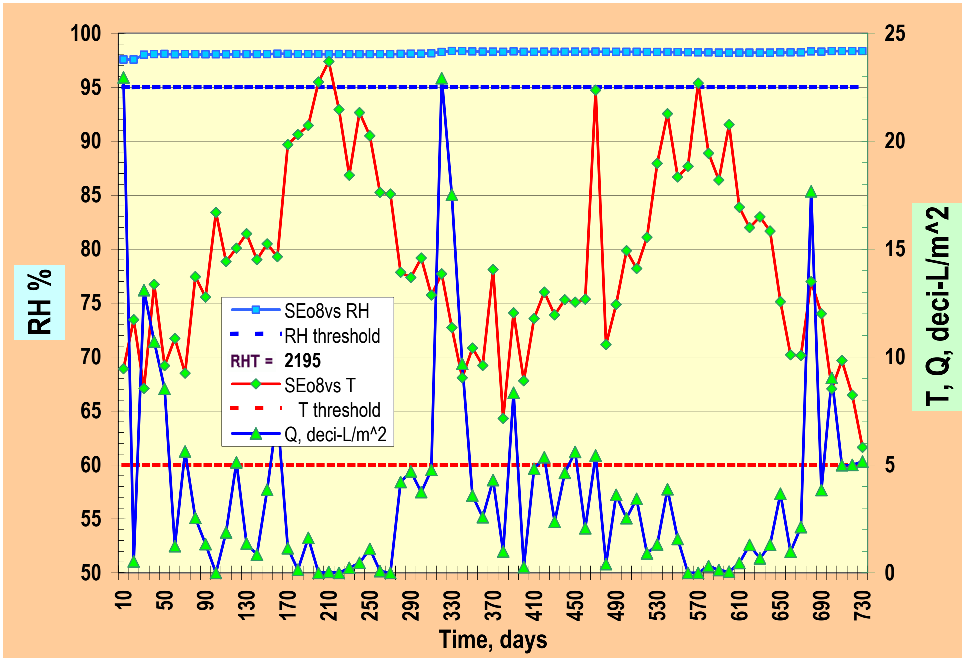


Figure 5.22 b) Reference wall with "one Q" moisture load in Seattle, WA. RHT(95) = 2195. The RH curve is flat above 95% similar to San Diego and Winnipeg. Note the temperature curve and how it compares to San Diego and Winnipeg.

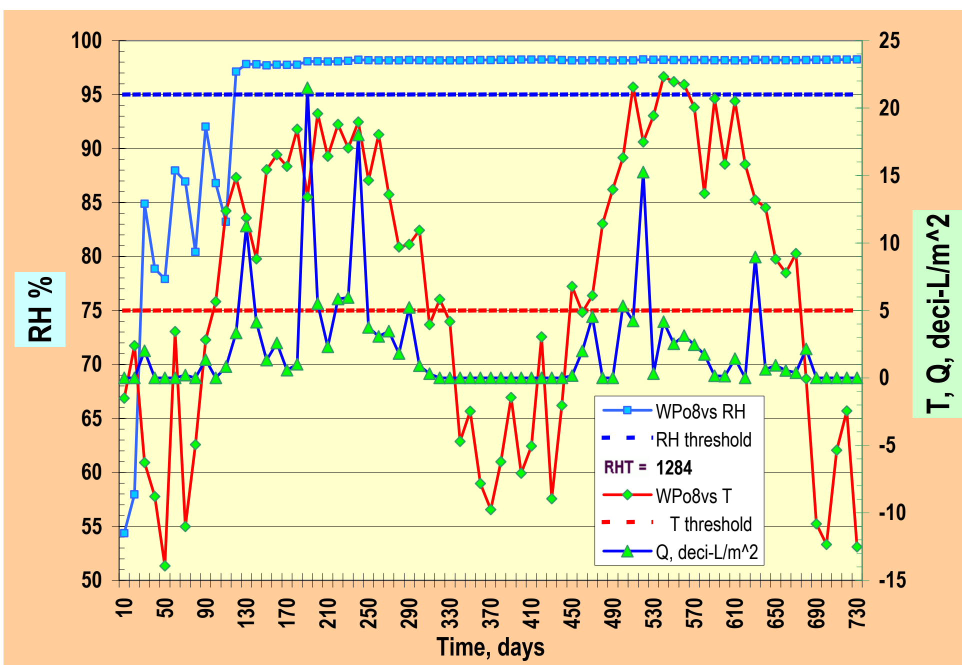


Figure 5.22 c) Reference wall with "one Q" moisture load in Winnipeg, MB. RHT(95) = 1284. The RH curve is flat above 95% similar to San Diego and Seattle. Note the temperature curve and how it compares to San Diego and Seattle.

2.0 Effect of the Variation of the Moisture Loads (Q) into the Stud Cavity

Observation: Simulations predicted that vinyl-clad walls provided a high degree of resistance to water entry, even under outdoor moisture loads as severe as in Wilmington NC, assuming no water leakage into the stud cavity. When water was allowed to enter the stud cavity, the RHT(95) wall response first increased linearly with Q, then beyond a certain value of Q the region of focus was consistently above the RH threshold and the slope of the response curve became less steep. (Effect: *decisive*)

Discussion: In the absence of deficiencies, RHT(95) was zero for all seven climates. When water was allowed to enter the stud cavity, via a leakage path, the RHT response increased sharply with the moisture load Q. At a certain level of Q the amount of water introduced into the stud cavity exceeded the drying capacity of the wall. This effect is shown in Figure 5.23. The results are also tabulated in Table 5.8.

Figure 5.23 plots the 2-year sum of RHT(95) versus percentages of Q, the moisture load in the stud cavity for the seven locations investigated. The figure shows that below a certain moisture load, Q_a, there was no accumulation of RHT(95). Between points Q_a and Q_b, the relationship between the RHT(95) response and the moisture loads in the stud cavity, Q, was somewhat linear for all seven locations. Beyond Q_b the response curve became noticeably flatter. The values of Q_a and Q_b varied from one climate region to another.

The behaviour shown in Figure 5.23 can be best explained by considering the case for San Diego (see Figure 5.24). In this case the temperature in the region of focus was always above the threshold limit of 5°C. At zero Q the RH of the region of focus was governed by the ambient relative humidity and interior moisture loads, which were controlled by the vapour permeance of the materials. When water was introduced into the stud cavity, the RH of the region of focus was raised during rain events. Individual events sometimes raised the RH of the region of focus above the threshold limit, 95%, and RHT(95) increased. As the amount of Q was increased, the length of time required to dry the region of focus increased producing a steep increase in the value of RHT(95). Beyond a certain point however the drying time required for the region of focus exceeded the time between rain events and response became less sensitive to increasing values of Q.

Table 5.8 Cumulative RHT(95) values for seven locations for several sets of hourly moisture loads in the stud cavity (Q)

Q	Phoenix	Fresno	San Diego	Winnipeg	Ottawa	Seattle	Wilmington NC
0	0	0	0	0	0	0	0
1/8	0	0	0	217	5	221	1616
1/6	0	0	0	619	254	829	1869
1/4	0	47	247	948	1118	1494	2431
1/2	66	534	2262	1168	1388	2046	2857
1	1072	1752	3192	1284	1477	2195	3138

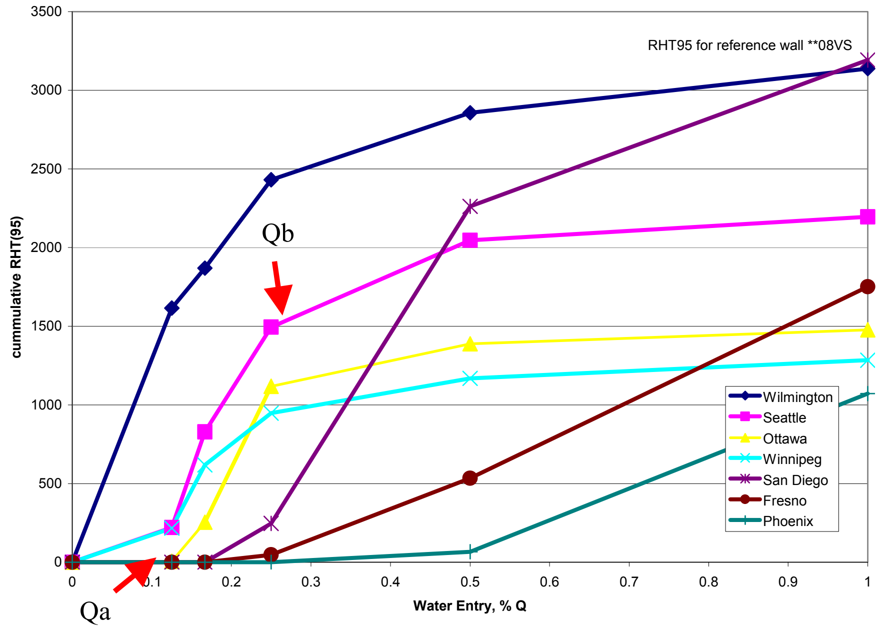


Figure 5.23. Relationship between moisture load, Q, and the severity of wall response for a reference vinyl-clad wall (**08VS) for varying percentages of Q, water entry. Each line shows the RHT(95) wall response for a particular location. The response showed the sensitivity of the reference case vinyl-clad walls to water entry in the stud cavity. Below a certain point, Q_a, rain events can be effectively dried without producing a positive RHT(95) response. At and beyond Q_a individual events caused the RH in the region of focus to exceed 95%, producing a response. The response was linear up to point, Q_b, after which the region of focus remained saturated for extended periods of time and became temperature dependent.

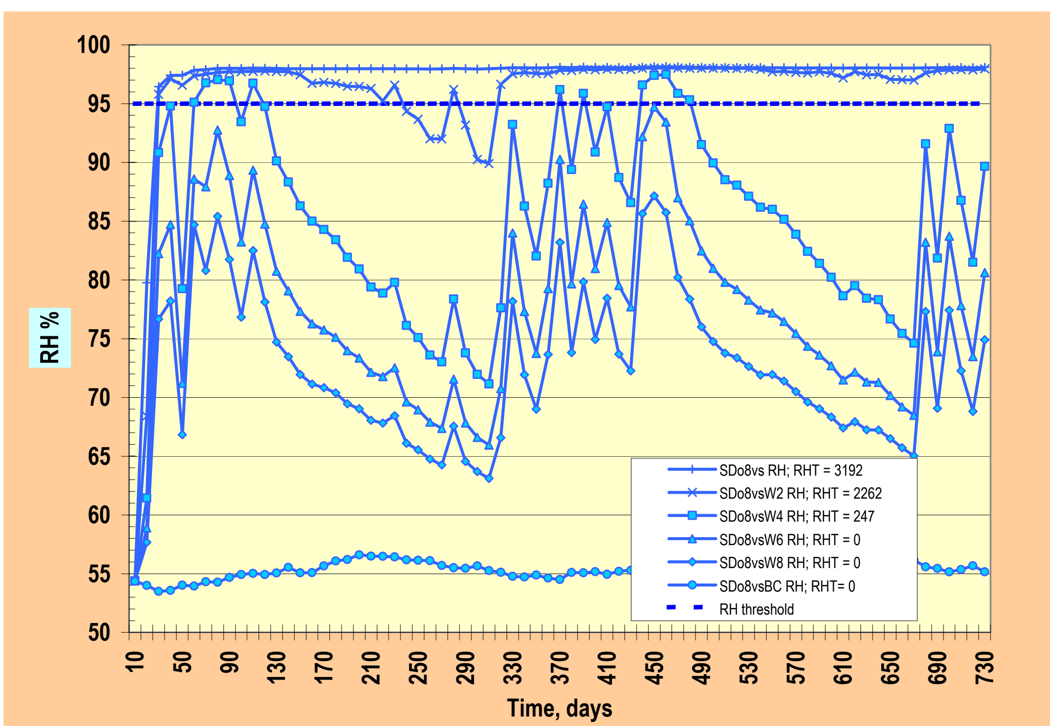


Figure 5.24. RH fluctuations in the region of focus for increasing amounts of Q, from 0 Q to 1 Q. At a certain level of Q the drying time for the region of focus exceeded the time between rain events and the response became insensitive to increased levels of Q.

3.0 Effect of Material Properties in a Given Climate

Effect of the Properties of Two Sheathing Boards

Observation: Substituting XPS insulating sheathing board for OSB exacerbated the RHT(95) wall response to moisture loading. (Effect: *small to substantial)*

Discussion: The results are tabulated in Table 5.9 and on Figure 5.25. XPS foam sheathing had a much lower thermal conductivity than OSB and raised the temperature of the region of focus located in the stud cavity, thus increasing the accumulation of RHT(95) when the RH condition of 95% was satisfied. Figures 5.26 and 5.27 illustrate how the temperature in the region of focus can be affected by the thermal characteristics of these two sheathing boards. For example, in Wilmington NC at the beginning of the second year, the temperature at the region of focus dropped to about 13^{o}C when XPS foam sheathing was used (Figure 5.27) whereas it dropped to 5^{o}C when OSB sheathing was used (Figure 5.26). The hygric properties of the sheathings had a much smaller effect on the RHT(95) wall response, as the RH curves indicated. The effect of adding XPS foam sheathing on the outside of a stud cavity that would get wet due to outdoor water leakage is different from a situation where condensation of indoor water vapour would be the only concern: in the latter case, the presence of an insulating sheathing would be desirable because the increased cavity temperature would shorten the period where it is below the dew point temperature of the indoor air.

Table 5.9: RHT (95) index comparison for the reference wall using two sheathing boards.

Sheathing Board			**San Diego**	**Winnipeg**	**Ottawa**	**Seattle**	**Wilmington**
OSB (Reference wall **08VSW4)	0	47	247	948	1118	1494	2431
XPS Sheathing (**X20VSXW4)	0	291	960	1681	*	2761	3477

An asterisk, *, indicates no simulation run for the specific parameter value.

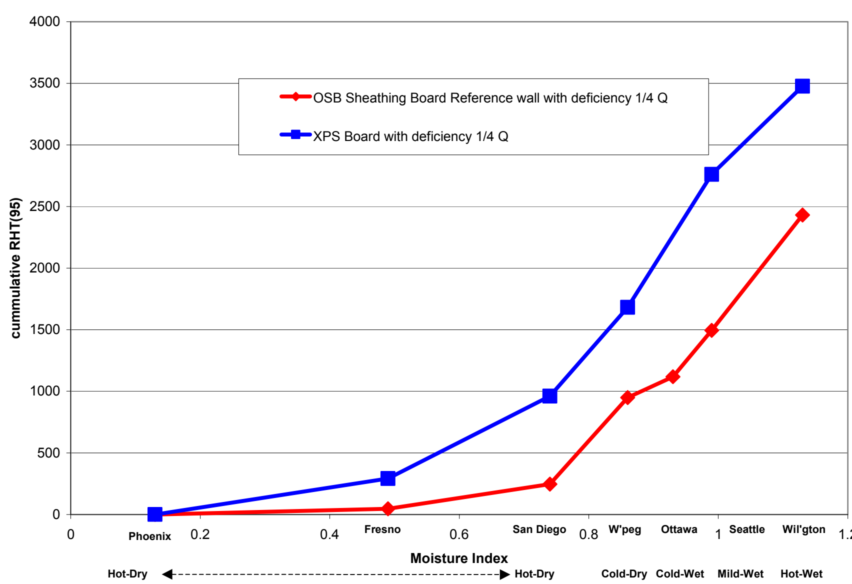


Figure 5.25. Relationship between climate severity and vinyl-clad wall response for two sheathing boards

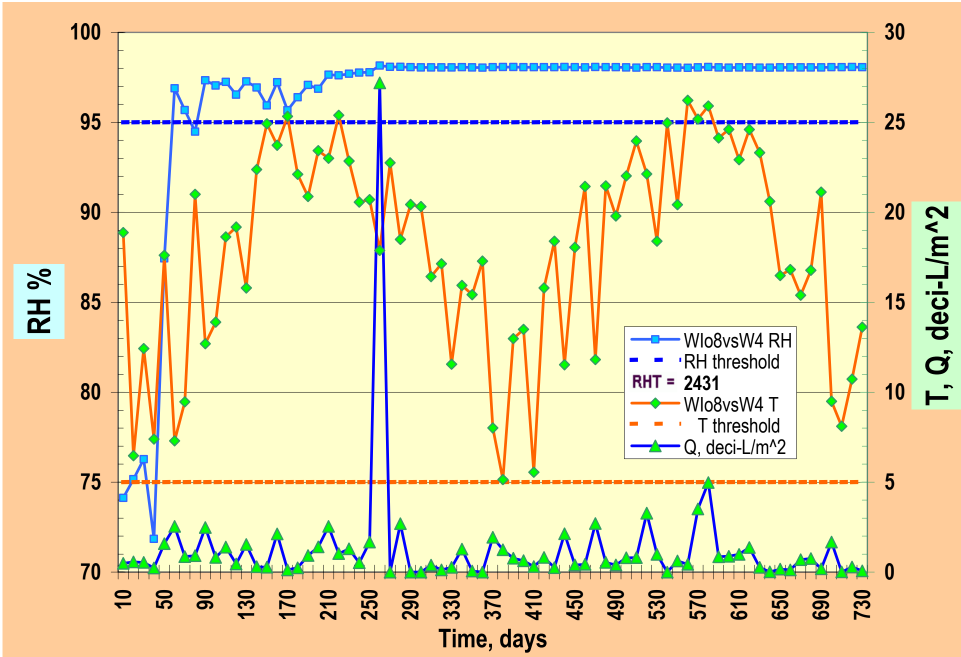


Figure 5.26. Detailed RH and T response for the reference case wall with OSB sheathing and with 1/4 Q, 08VSW4 in Wilmington NC. RHT = 2431. Note the temperature curve and compare to that of the XPS sheathing board case (Figure 5.27).

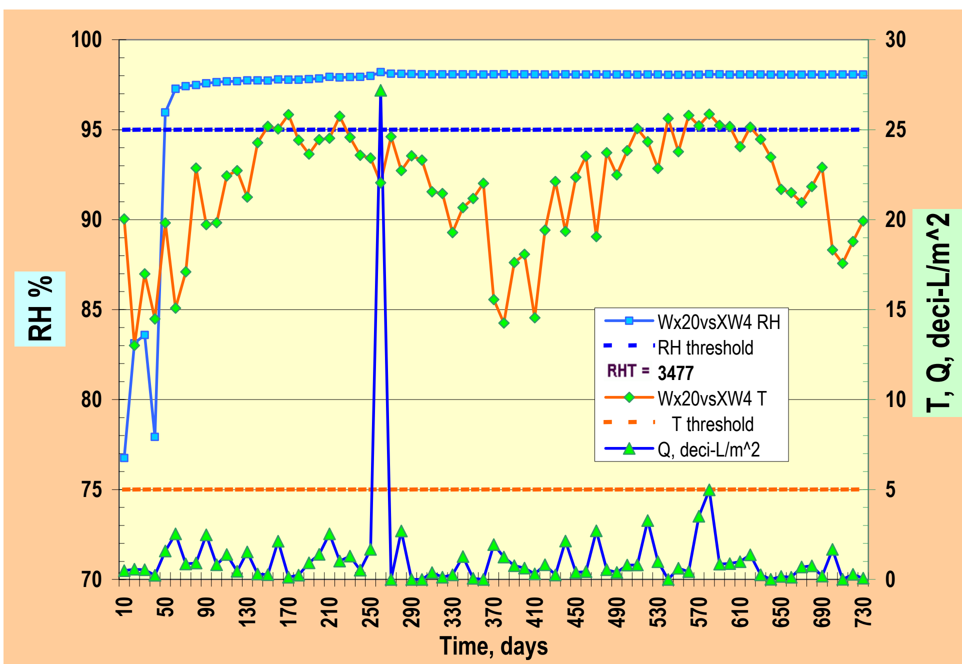


Figure 5.27. Detailed RH and T response for a wall with XPS foam sheathing and with 1/4 Q in Wilmington NC. RHT = 3138. Note the temperature curve. The curve is attenuated and generally higher than the OSB producing an increase in RHT(95).

Effect of the Properties of the Water Resistive Barrier

Observation: Changing the sheathing membrane from 30-minute building paper to a polymeric sheathing membrane had little or no effect on the RHT(95) response of the wall. (Effect: *near-zero*)

.***Discussion***: The results are tabulated in Table 5.10 and shown in Figure 5.29. The water resistive barrier is intended to protect the back up wall from further water intrusion once water has penetrated the cladding. When water was introduced into the stud cavity, it bypassed the water resistive barrier. Thus the water resistive barrier was not allowed to perform its intended function. The exercise was essentially one of examining the effect of the various membranes on the drying potential of the region of focus, as opposed to examining their effect on water ingress into the back up wall. It appeared that even though the liquid diffusivity and water vapour permeabilities of the water resistive barriers were different (see Figure 5.28), these membranes exhibited the same high level of resistance to evaporative drying in comparison to the level of wetting of the stud cavity.

Table 5.10: RHT (95) index comparison for two sheathing membranes.

	RHT(95) index for reference wall at 1/4Q						
Membrane	Phoenix	Fresno	San Diego	Winnipeg	Ottawa	Seattle	Wilmington
30 min. paper (Reference wall **08VSW4)	0	47	247	948	1118	1494	2431
SBPO polymeric **O8SM21VSW 4)	0	45	226	950	1112	1464	2422

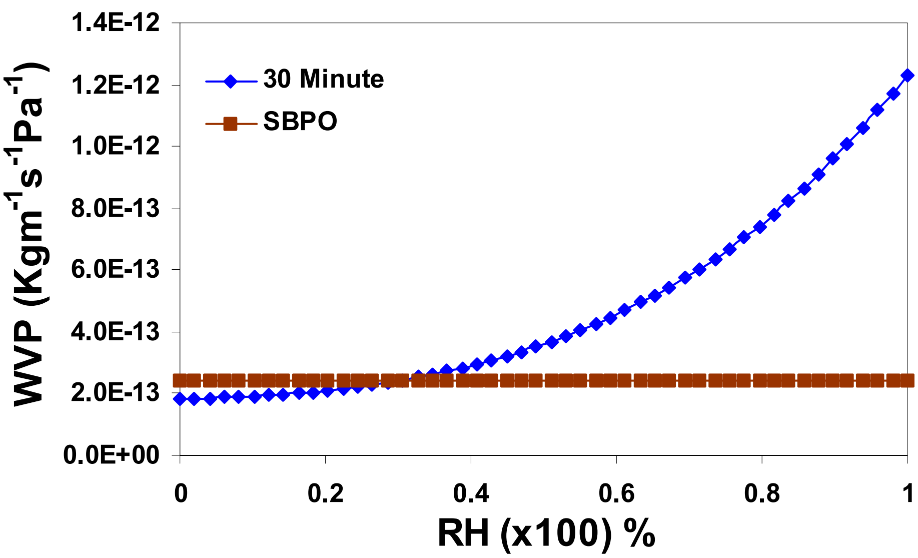


Figure 5.28. The figure shows a comparison of the water vapour permeability of a polymeric membrane and 30-minute building paper for the full range of relative humidities.

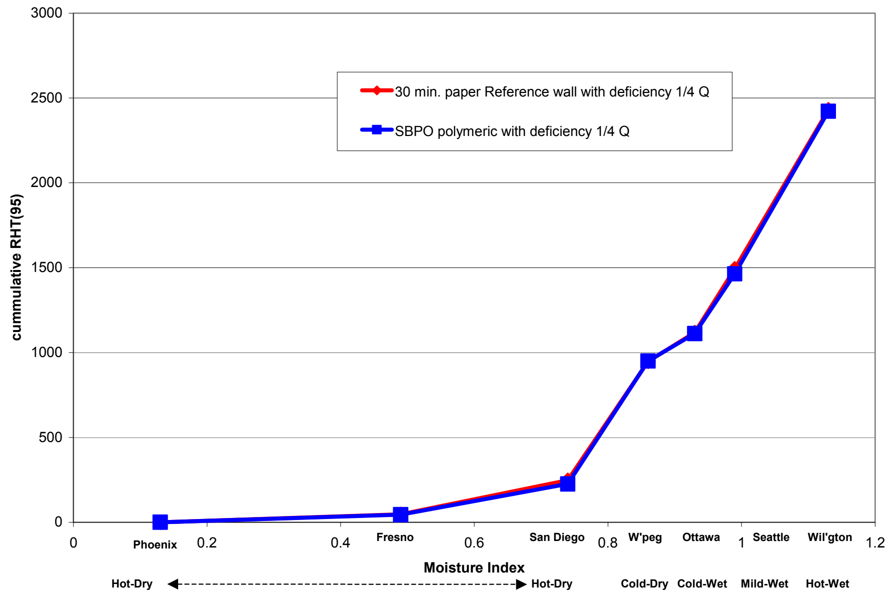


Figure 5.29. Plot of RHT(95) versus MI for two different sheathing membranes having different water vapour permeance (WVP) characteristics. The WVP characteristics are shown in Figure 5.28.

Effect of the Properties of the Water Resistive Barrier for Walls with XPS Sheathing Board

Observation: For all the climates investigated, changing the water resistive barriers on the exterior of an XPS extruded insulation sheathing board had no effect on the RHT(95) response of the wall. (Effect*: near-zero*)

Discussion: Figure 5.30 and Table 5.11 summarize the results. This result is consistent with the results obtained and discussed previously when the water resistive barrier was changed for walls using OSB as the sheathing board. (See the section Effect of the Properties of the Water Resistive Barrier above). Removing the water resistive barrier altogether had no effect on the RHT(95) response either. This can be explained by the similar resistance to evaporative drying offered by the water vapour permeability properties of the XPS sheathing board and the water resistive barriers. Adding or removing another layer against the XPS had no effect on the drying of the wall.

Table 5.11: RHT (95) index for three water resistive barriers for an XPS sheathed wall

	RHT(95) index for XPS sheathed wall at 1/4Q moisture loads in the stud cavity						
Membrane	Phoenix	Fresno	San Diego	Winnipeg	Ottawa	Seattle	Wilmington NC
30 min. paper (XPS wall **08VSW4)	0	291	960	1681	*	2761	3477
SBPO polymeric (XPS wall **SM0VSXW4)	0	295	*	*	2130	2693	3475
No WRB (XPS wall **SM21VSXW4)	0	268	*	1690	2125	2712	3474

An asterisk, *, indicates no simulation run for the specific parameter.

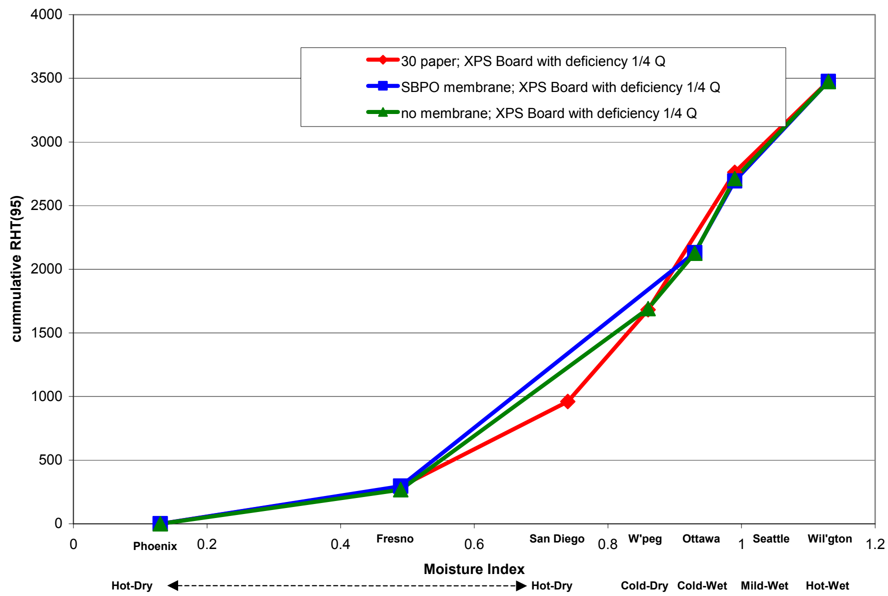


Figure 5.30. Plot of RHT(95) versus MI for two different sheathing membranes with different water vapour permeance (WVP) characteristics. The WVP characteristics are shown in Figure 5.28.

Effect of the Properties of Vapour Barrier

Observation No. 1: Increasing the vapour permeability of the vapour barrier *membranes* included in the parametric study resulted in a small improvement of the RHT(95) response of the wall assembly for climates with higher moisture loads (Ottawa, Seattle and Wilmington NC). For other climates investigated (i.e. Fresno, San Diego and Winnipeg), no effect on RHT(95) wall response was predicted. (Effect: *near-zero to small*)

Discussion: Two vapour barrier membranes were investigated for all locations. Their properties were supplied by TG3 (see Table 5.1). In order of increasing vapour permeability at 0 and 100%RH were vapour barrier Type I and Type II. VB II was about 4 times more vapour permeable than VBI. The relationship between vapour permeability and relative humidity as defined by TG 3 laboratory experiments is illustrated in Figure 5.31.

Table 5.12 and Figure 5.32 provide the RHT(95) hygrothermal response for all locations and vapour barrier materials. The amount and frequency of water introduced into the stud cavity was sufficiently high that attempts at increasing the drying capacity by increasing slightly the water vapour permeability of the vapour barrier membranes had little effect on the RHT(95) wall response. It should also be noted that the RHT(95) response of the region of focus in the stud cavity remained above the threshold value of zero for all cases.

Observation No. 2: For all locations investigated, hygIRC simulations predicted that the RHT(95) wall response would improve when the vapour barrier membrane was removed and the vapour control was provided by painted interior gypsum board. (*Effect: substantial to decisive)*

Discussion: For one set of simulations, the vapour barrier membrane was removed from the reference vinyl siding-clad wall and one coat of primer with two coats of latex paint were added to the unpainted gypsum board interior finish. The vapour permeance of this assembly was much higher than any of the two vapour barrier membranes investigated previously (see Table 5.1 and Figure 5.31). hygIRC predicted that the drying potential offered by such a high vapour permeance assembly located on the inside face of the stud cavity would be substantial in all five climates investigated, but not sufficient as a single measure to bring the RHT value to the threshold of zero.

Note that the evaporative drying to the inside depended upon the difference in vapour pressure between the wet stud cavity and the indoors. The lower the indoor RH, the higher the vapour pressure differential and the higher the drying rate. The indoor RH used in the simulations was low (25% RH in winter and 55% RH in summer).

It should be noted that the apparent improvement in moisture response of the walls with a *loosening* of the vapour barrier should not be taken outside the context of the MEWS parametric simulations. The interior conditions assumed as the internal boundary condition played a large role in the results. The interior RH conditions of 55% in the summer and 25% RH in the winter provided a strong driving force for drying to the interior. The effect might be much less or even reversed if different interior conditions prevail.

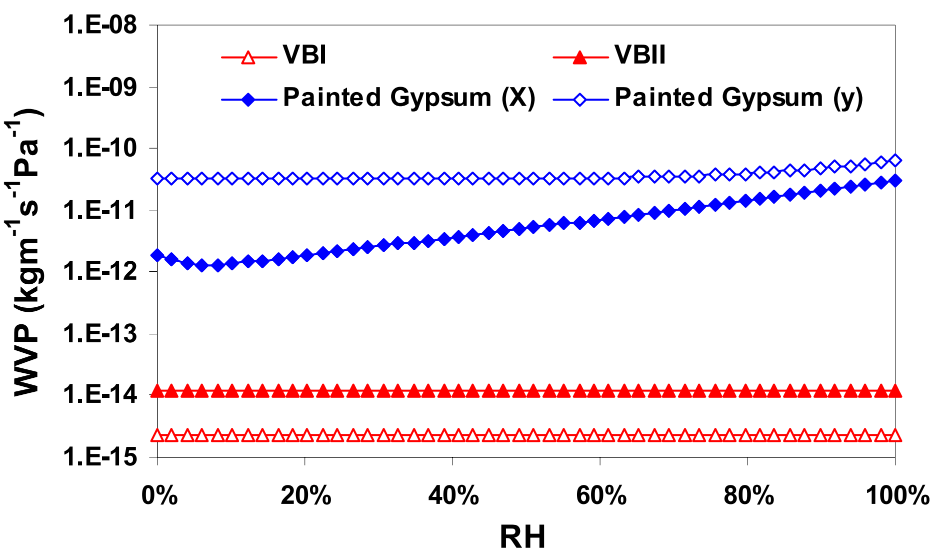


Figure 5.31. Relationship established by TG 3 between vapour permeability and relative humidity of two vapour barrier membranes and painted interior grade gypsum board.

Table 5. 12: RHT (95) index comparison for vapour barriers of different properties

	RHT(95) reference wall response at 1/4Q moisture loading in the stud cavity						
membrane	Phoenix	Fresno	San Diego	Winnipeg	Ottawa	Seattle	Wilmington
Type I - 15 ng (Reference wall **08VSW4)	0	47	247	948	1118	1494	2431
Type II - 60 ng (**VB6VSW4)	0	31	176	898	807	975	2134
Painted Interior Gypsum (**08VSCGW4)	0	*	*	143	59	140	45

An asterisk, *, indicates no simulation run for the specific parameter.

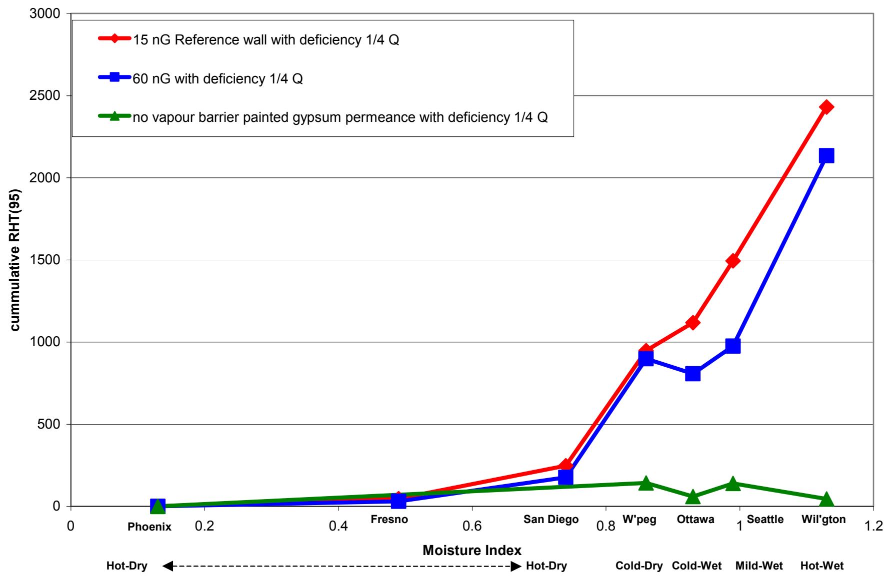


Figure 5.32. Plot of RHT(95) versus MI for vapour barrier materials with different water vapour permeabilities. The effect of *loosening* the vapour barrier was more prominent in wetter climates. Overall however the effect of changing the vapour barrier membrane had a small effect on the RHT(95) wall response. Removing the vapour barrier membrane and replacing it with a latex paint coating produced a decisive improvement. At 1/4 Q there is sufficient drying capacity to deal effectively with water intrusion into the stud cavity (lower curve). These results were strongly tied to the assumed interior conditions and should be treated with caution outside the scope of the assumptions of the MEWS project.

Effect of Addition of a Vented Cavity Behind the Siding

Observation: A clear 19 mm cavity, vented top and bottom, behind the siding improved the RHT(95) hygrothermal response of the wall in the region of focus, once water entered the stud cavity at a 1/4 Q set of hourly rates. (*Effect: Substantial*)

Discussion: In a single simulation run for Wilmington NC, a vinyl-clad wall with a 19 mm vented cavity, simulating furring strips, was modeled. The remaining details of the wall were identical to the reference case. The result is shown in Figure 5.33. It indicates that in a climate with high moisture loads, the introduction of a clear cavity improved substantially the RHT(95) wall response of the reference wall subjected to a 1/4 Q moisture loads in the stud cavity. Still, the water entry rate of 1/4 Q for Wilmington was more than this wall could handle by drying alone, even with a vented cavity.

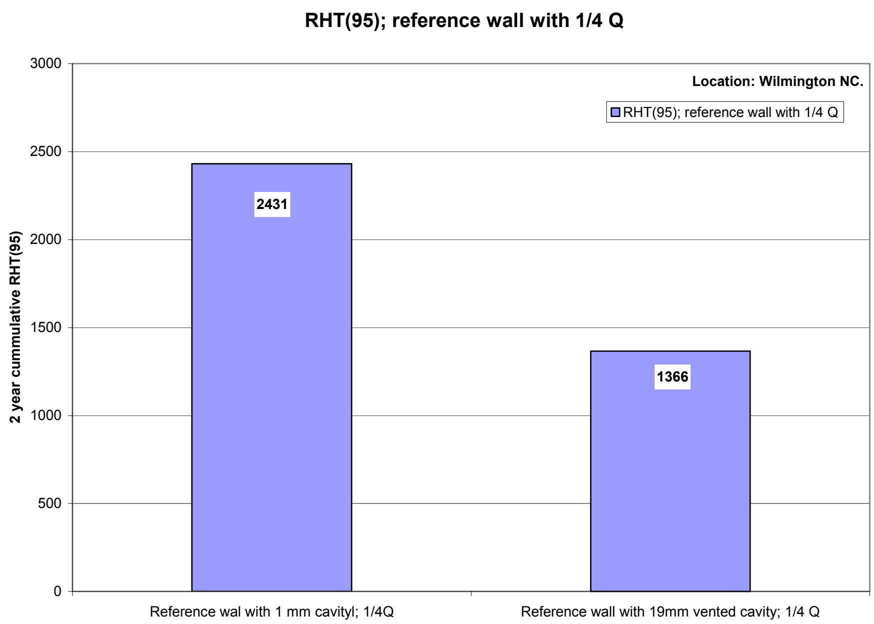


Figure 5.33. The bar chart shows the effect of replacing the 1 mm gap behind the siding in a reference wall with a 19 mm vented cavity (through the use furring strips)

Appendix 5.1 Table of All hygIRC Simulation Results for Hardboard-clad walls
(See the notation at the end)
RHT (95) Indices for Hardboard-clad Walls

Simulation ID	RHT (95) Index
(A) OTTAWA	
OTO8HSBC	0
OTO8HS	1606
OTSM25HS	1602
OTVB7HS	1524
OTO8HSCG	649
OTP18HS	1530
OTF16HS	1660
OTO8HSW2	1457
OTO8HSW4	351
OTO8HSCB	1662
OTO8HSCBW4	174
OTAF26HS	1474
(B) PHOENIX	
PHO8HSBC	0
PHO8HS	731
PHSM25HS	716
PHVB7HS	358
PHO8HSCG	104
PHP18HS	495
PHF16HS	379
PHO8HSW2	1859
PHO8HSW4	3746
PHO8HSCB	732
PHO8HSCBW4	3402
PHAF26HS	305

Simulation ID	RHT (95) Index
(C) SEATTLE	
SEO8HSBC	0
SEO8HS	2394
SESM25HS	2389
SEVB7HS	2150
SEO8HSCG	989
SEP18HS	2283
SEF16HS	2465
SEO8HSW2	2105
SEO8HSW4	1110
SEO8HSCB	2471
SEO8HSCBW4	721
SEAF26HS	2107
(D) WILMINGTON	
WIO8HSBC	0
WIO8HS	3297
WISM25HS	3288
WIVB7HS	3161
WIO8HSCG	1207
WIP18HS	3197
WIF16HS	3337
WIO8HSW2	3001
WIO8HSW4	2466
WIO8HSCB	3142
WIO8HSCBW4	1073
WIAF26HS	3099

Simulation ID	RHT (95) Index
(E) WINNIPEG	
WPO8HSBC	0
WPO8HS	1408
WPSM25HS	1406
WPVB7HS	1362
WPO8HSCG	851
WPP18HS	1335
WPF16HS	1459
WPO8HSW2	1273
WPO8HSW4	746
WPO8HSCB	1481
WPO8HSCBW4	426
WPAF26HS	1253
(F) FRESNO	
FRO8HSBC	0
FRO8HS	1112
FRF16HS	901
FRO8HSW2	468
FRO8HSW4	60
FRVB7HS	722

Simulation ID	RHT (95) Index
(G) SAN DIEGO	
SDO8HSBC	0
SDO8HS	2104
SDP18HS	1529
SDF16HS	1449
SDO8HSW2	838
SDO8HSW4	173
SDVB7HS	1284

RHT (80) Results for Hardboard-clad Walls

(A) OTTAWA

Simulation ID	RHT (80) Index
OTO8HSBC	0
OTO8HS	9548
OTSM25HS	9552
OTVB7HS	9333
OTO8HSCG	6770
OTP18HS	9199
OTF16HS	9893
OTO8HSW2	9146
OTO8HSW4	6648
OTO8HSCB	10223
OTO8HSCBW4	3430
OTAF26HS	9011

(B) PHOENIX

Simulation ID	RHT (80) Index
PHO8HSBC	0
PHO8HS	7668
PHSM25HS	7515
PHVB7HS	5108
PHO8HSCG	2104
PHP18HS	6366
PHF16HS	5361
PHO8HSW2	15534
PHO8HSW4	23994
PHO8HSCB	8162
PHO8HSCBW4	21550
PHAF26HS	5744

(C) SEATTLE

Simulation ID	RHT (80) Index
SEO8HSBC	0
SEO8HS	13939
SESM25HS	13943
SEVB7HS	13373
SEO8HSCG	8079
SEP18HS	13439
SEF16HS	14311
SEO8HSW2	13349
SEO8HSW4	10217
SEO8HSCB	14753
SEO8HSCBW4	7219
SEAF26HS	13212

(D) WILMINGTON

Simulation ID	RHT (80) Index
WIO8HSBC	0
WIO8HS	18772
WISM25HS	18766
WIVB7HS	18449
WIO8HSCG	12837
WIP18HS	18365
WIF16HS	18971
WIO8HSW2	18177
WIO8HSW4	17209
WIO8HSCB	18458
WIO8HSCBW4	11901
WIAF26HS	18158

(E) WINNIPEG

Simulation ID	RHT (80) Index
WPO8HSBC	0
WPO8HS	8377
WPSM25HS	8380
WPVB7HS	8244
WPO8HSCG	7008
WPP18HS	8029
WPF16HS	8604
WPO8HSW2	8019
WPO8HSW4	6706
WPO8HSCB	8935
WPO8HSCBW4	5123
WPAF26HS	7793

(F) FRESNO

Simulation ID	RHT (80) Index
FRO8HSBC	0
FRO8HS	9017
FRF16HS	7434
FRO8HSW2	4941
FRO8HSW4	1758
FRVB7HS	6187

(G) SAN DIEGO

Simulation ID	RHT (80) Index
SDO8HSBC	0
SDO8HS	16579
SDP18HS	14431
SDF16HS	11682
SDO8HSW2	9033
SDO8HSW4	3719
SDVB7HS	10780

Notation

**O8HSBC :	Base case; No moisture entry; OSB sheathing Board
**O8HS :	Same as **O8HSBC but with moisture entry
**SM25HS :	Same as **O8HS but SBPO polymeric sheathing membrane is replaced by 60 minute building paper
**VB7HS :	Same as **O8HS but Type I vapor barrier is replaced by a vapor barrier that has vapor permeance variable with relative humidity
**O8HSCG :	Same as **O8HS but with no vapor barrier and with painted/coated interior gypsum board.
**P18HS :	Same as **O8HS but with OSB sheathing board is replaced by plywood
**F16HS :	Same as **O8HS but with OSB sheathing board is replaced by fiberboard
**O8HSW2 :	Same as **O8HS but with half of the normal moisture entry (only exception is Phoenix with double moisture entry)
**O8HSW4 :	Same as **O8HS but with quarter of the normal moisture entry (only exception is Phoenix with quadruple moisture entry)
**O8HSCB:	Same as **O8HS but with a 19mm cavity behind the siding

** : PH - Phoenix; FR - Fresno; SD - San Diego; WP - Winnipeg; OT - Ottawa; SE - Seattle; WI :- Wilmington

Appendix 5.2 Table of All hygIRC Simulation Results for Vinyl Siding-clad walls

RHT (95) Indices for Vinyl-clad Walls

Simulation ID	RHT (95) Index
(A) OTTAWA	
OTO8VSBC	0
OTO8VS	1477
OTO8VSW2	1388
OTO8VSW4	1118
OTO8VSW6	254
OTO8VSW8	5
OTSM21VSW4	1112
OTVB6VSW4	807
OTO8VSCGW4	59
OTSM21VSXW4	2125
OTSM0VSXW4	2130
(B) PHOENIX	
PHO8VSBC	0
PHO8VS	1072
PHO8VSW2	66
PHO8VSW4	0
PHO8VSW6	0
PHO8VSW8	0
PHSM21VSW4	0
PHVB6VSW4	0
PHO8VSCGW4	0
PHX20VSXW4	0
PHSM21VSXW4	0
HSM0VSXW4	0

Simulation ID	RHT (95) Index
(C) SEATTLE	
SEO8VSBC	0
SEO8VS	2195
SEO8VSW2	2046
SEO8VSW4	1494
SEO8VSW6	829
SEO8VSW8	221
SESM21VSW4	1464
SEVB6VSW4	975
SEO8VSCGW4	140
SEX20VSXW4	2761
SESM21VSXW4	2712
SESM0VSXW4	2693
(D) WILMINGTON	
WIO8VSBC	0
WIO8VS	3138
WIO8VSW2	2857
WIO8VSW4	2431
WIO8VSW6	1869
WIO8VSW8	1616
WISM21VSW4	2422
WIVB6VSW4	2134
WIO8VSCGW4	45
WIO8VSCBW4	1366
WIX20VSXW4	3477
WISM21VSXW4	3474
WISM0VSXW4	3475

Simulation ID	RHT (95) Index
(E) WINNIPEG	
WPO8VSBC	0
WPO8VS	1284
WPO8VSW2	1168
WPO8VSW4	948
WPO8VSW6	619
WPO8VSW8	217
WPSM21VSW4	950
WPVB6VSW4	898
WPO8VSCGW4	143
WPX20VSXW4	1681
WPSM21VSXW4	1690
(F) FRESNO	
FRO8VSBC	0
FRO8VS	1752
FRO8VSW2	534
FRO8VSW4	47
FRO8VSW6	0
FRO8VSW8	0
FRSM21VSW4	45
FRVB6VSW4	31

Simulation ID	RHT (95) Index
FRX20VSXW4	291
FRSM21VSXW4	268
FRSM0VSXW4	295
(G) SAN DIEGO	
SDO8VSBC	0
SDO8VS	3192
SDO8VSW2	2262
SDO8VSW4	247
SDO8VSW6	0
SDO8VSW8	0
SDSM21VSW4	226
SDVB6VSW4	176
SDX20VSXW4	960

Table A.5.2.2: RHT (80) Results for Vinyl-clad Walls

Simulation ID	RHT (80) Index
(A) OTTAWA	
OTO8VSBC	0
OTO8VS	8672
OTO8VSW2	8438
OTO8VSW4	7868
OTO8VSW6	6246
OTO8VSW8	3690
OTSM21VSW4	7859
OTVB6VSW4	7490
OTO8VSCGW4	2237
OTSM21VSXW4	13764
OTSM0VSXW4	13771
(B) PHOENIX	
PHO8VSBC	0
PHO8VS	12076
PHO8VSW2	2280
PHO8VSW4	0
PHO8VSW6	0
PHO8VSW8	0
PHSM21VSW4	0
PHVB6VSW4	0
PHO8VSCGW4	96
PHX20VSXW4	1403
PHSM21VSXW4	1303
PHSM0VSXW4	1329

Simulation ID	RHT (80) Index
(C) SEATTLE	
SEO8VSBC	0
SEO8VS	12620
SEO8VSW2	12257
SEO8VSW4	11314
SEO8VSW6	8451
SEO8VSW8	5637
SESM21VSW4	11214
SEVB6VSW4	9499
SEO8VSCGW4	3461
SEX20VSXW4	18251
SESM21VSXW4	18030
SESM0VSXW4	17977
(D) WILMINGTON	
WIO8VSBC	0
WIO8VS	17581
WIO8VSW2	16995
WIO8VSW4	16137
WIO8VSW6	14091
WIO8VSW8	11876
WISM21VSW4	16145
WIVB6VSW4	15510
WIO8VSCGW4	3376
WIO8VSCBW4	12315
WIX20VSXW4	21222
WISM21VSXW4	21222
WISM0VSXW4	21239

Simulation ID	RHT (80) Index
(E) WINNIPEG	
WPO8VSBC	0
WPO8VS	7548
WPO8VSW2	7253
WPO8VSW4	6499
WPO8VSW6	5619
WPO8VSW8	4665
WPSM21VSW4	6507
WPVB6VSW4	6386
WPO8VSCGW4	3925
WPX20VSXW4	11436
WPSM21VSXW4	11412
(F) FRESNO	
FRO8VSBC	0
FRO8VS	13556
FRO8VSW2	5234
FRO8VSW4	1194
FRO8VSW6	218
FRO8VSW8	0
FRSM21VSW4	1100
FRVB6VSW4	934

Simulation ID	RHT (80) Index
FRX20VSXW4	4187
FRSM21VSXW4	4026
FRSM0VSXW4	4146
(G) SAN DIEGO	
SDO8VSBC	0
SDO8VS	19197
SDO8VSW2	17808
SDO8VSW4	6965
SDO8VSW6	1969
SDO8VSW8	483
SDSM21VSW4	6404
SDVB6VSW4	4536
SDX20VSXW4	11435

Notation

**O8VSBC :	Base case; No moisture entry; OSB sheathing Board
**O8VS :	Same as **O8VSBC but with full moisture load entry
**O8VSW2 :	Same as **O8VSBC but with 1/2 (half) moisture load entry
**O8VSW4 :	Same as **O8VSBC but with 1/4th (quarter) moisture load entry
**O8VSW6 :	Same as **O8VSBC but with 1/6th (one sixth) moisture load entry
**O8VSW8 :	Same as **O8VSBC but with 1/8th (one eighth) moisture load entry
**O8SM21VSW4 :	Same as **O8VSW4 but 30 minute building paper sheathing membrane is replaced by SBPO membrane
**O8VB6VSW4 :	Same as **O8VSW4 but Type I vapour barrier replaced by Type II vapour barrier
**O8VSCGW4 :	Same as **O8VSW4 but with no vapour barrier and with painted/coated interior gypsum board.
**O8VSCBW4 :	Same as **O8VSW4 but 1mm air gap behind the siding is replaced by a 19mm cavity.
**X20VSXW4 :	Same as **O8VSW4 but OSB sheathing board is replaced by XPS foam sheathing.
**SM0VSXW4 :	Same as **X20VSXW4 but 30 minute building paper sheathing membrane is replaced by SBPO membrane
**SM21VSXW4 :	Same as **X20VSXW4 but 30 minute building paper sheathing membrane is removed (i.e. no sheathing membrane)

** : PH - Phoenix; FR - Fresno; SD - San Diego; WP - Winnipeg; OT - Ottawa; SE - Seattle; WI :- Wilmington

Chapter 6. Trends in the Hygrothermal Response to Moisture Loading for the Wall Systems Investigated

In this project on Moisture Management of Exterior Wall Systems (MEWS), a methodology was developed and applied to four types of cladding systems for wood-frame construction in North America. Building practices were reviewed, climate parameters were analyzed, building material properties were determined and full-scale wall specimens were exposed to simulated driving rain conditions in the laboratory. Information from all these activities was used to generate a set of realistic inputs to a hygrothermal model called hygIRC. The model has been separately benchmarked against data from controlled drying experiments on full-scale wall specimens. The model hygIRC was subsequently used for parametric analyses of the hygrothermal responses of all the wall types included in MEWS. The following sections highlight the major observations from the project.

6.1 Summary of Parameters Investigated in MEWS Parametric Study

MEWS hygIRC simulations are more extensive than what has been presented in this report. Task Group 7 final report on the parametric study provides more details on the parametric study. Table 6.1 provides a summary of the parameters investigated and presented in Chapters 2-5, for each wall system investigated.

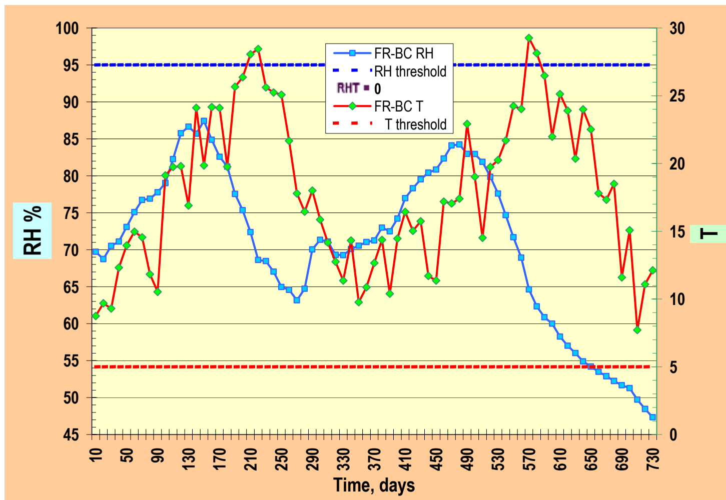
Table 6.1 Summary of parameters investigated in Chapters 2-5

	Stucco	**EIFS**	**Masonry**	**Siding**
Properties of cladding material	YES (3 stucco)	YES (3 thickness of lamina)	YES (3 types of masonry units)	YES (hardboard and vinyl sidings)
Properties of water resistive barriers	YES	YES	YES	YES
Properties of sheathing boards	(OSB, plywood, uncoated fibreboard)	OSB, glassmat gypsum board, plywood	OSB, XPS foam board, asphalt-coated fibreboard	OSB, XPS foam board, asphalt-coated fibreboard, plywood
Airflow through assembly	YES	YES		
Moisture loads in the stud cavity (Q)	YES Parametric study done at 1Q	YES Parametric study done at 1Q	YES Parametric study done at 1Q	YES Parametric study done at 1Q for hardboard, and at ¼ Q for vinyl siding
Properties of wall inner layers of materials (VB membrane & drywall)	YES	YES	YES	YES
No insulation in the stud cavity		YES		
Change of region of focus		YES At mid-height of the wall		
With a vented cavity behind cladding	YES 19 mm		YES 25 mm	YES 19 mm
Increasing the size of vented cavity			YES From 25 to 50 mm	
Increase in indoor RH	YES	YES		
Change the severity of second simulation year		YES From average to dry		

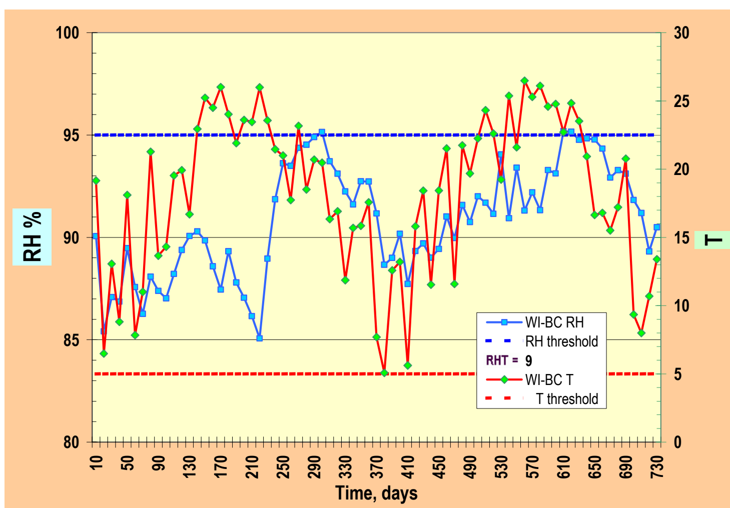
6.2 Highlights on the Wall Hygrothermal Responses

Effect of Climate Severity

The magnitude of the wall hygrothermal response varied primarily with the severity of the outdoor climate. When no water leakage into the stud cavity occurred, the RHT(95) index showed no variation in the hygrothermal response of the four wall systems investigated, because the RH and T conditions remained below the thresholds selected in this parametric study. This is valid for all North American locations investigated in MEWS. Figure 6.1 shows two examples of similar cumulative RHT(95) response for a given wall exposed to two different climates (Fresno and Wilmington NC)



FRESNO



WILMINGTON NC

Figure 6.1 Comparison of a RH and T response of a wall with no water leakage in the stud cavity, exposed to two different climate severities. Fresno, on the left has an MI of 0.49 while Wilmington NC has an MI of 1.13. The RHT(95) response for Fresno (MI 0.49) and Wilmington (MI 1.13) was about the same; however the RH and T prevailing in the region of focus of the wall in Wilmington were higher than it is in Fresno.

When water entered the stud cavity, the RHT(95) response increased steadily with the increase in MI, with a few exceptions. One expects a characteristic curve as illustrated in the red upper curve of Figure 6.2; however some exceptions to this trend have been noted. The slope of the curve varies with the properties of materials and the characteristics of the assembly. The lower the slope of the curve, the better evaporative drying potential is offered by the wall assembly.

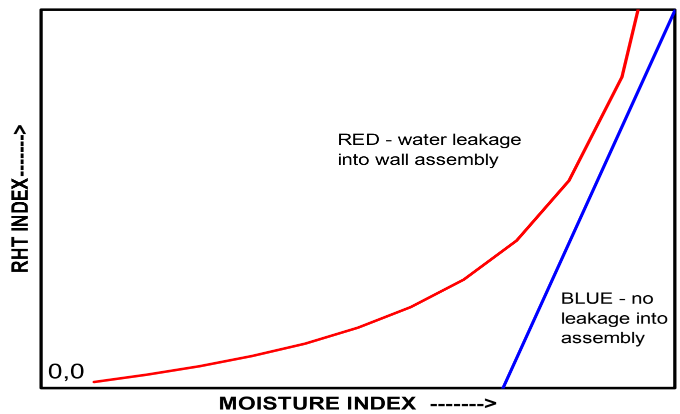
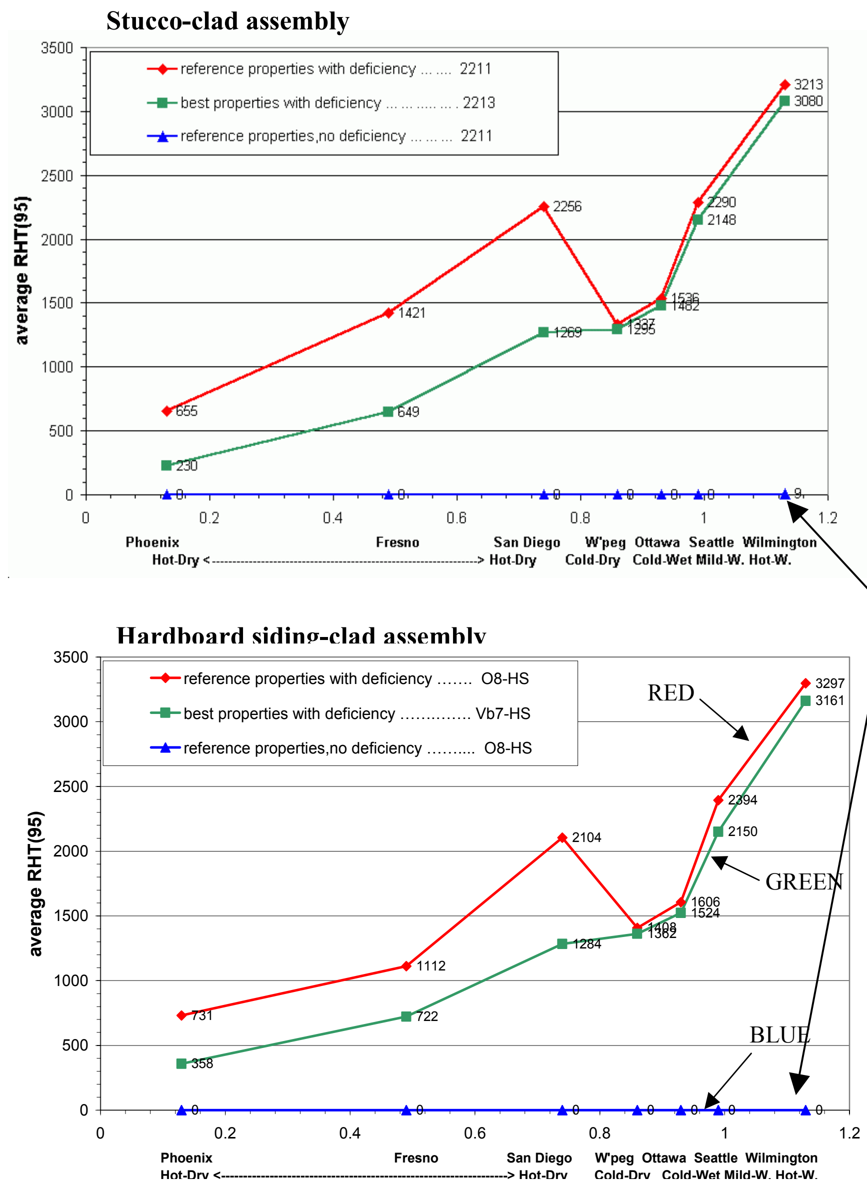


Figure 6.2 Characteristic model curves for RHT(95) index vs. climate severity (MI)

Figure 6.3 shows some examples of such exceptions to the trend: RHT(95) response for cold climates of Winnipeg and Ottawa were lower than the wall RHT(95) response for San Diego. Examinations of several similar cases indicated that when the outdoor climate or the characteristics of the wall allowed the region of focus in the stud cavity to drop below the 5°C threshold for prolonged periods (as in cold climates) while its RH was above 95% (frequent for a 1Q set of moisture loads in the stud cavity), the cumulative RHT value for the wall in that cold climate was lower than it was predicted to be in a warmer climate (Examine the red curves). In other words, when the RH threshold condition was met, the temperature at the region of focus drove the computation of the RHT(95) value. In cold climates, the region of focus in the stud cavity was maintained at lower temperature and this tended to reduce the accumulation of RHT index. When the RH conditions at the region of focus were lower (check green curve), this effect disappeared.



The flat blue curve at the bottom is the RHT(95) wall response when no leakage occurs in the stud cavity for porous (top graph) and non porous (bottom

Figure 6.3 RHT(95) wall response for two wall assemblies as a function of the climate severity (MI) and moisture loading in the stud cavity

Effect of Wetting of Cladding, with No Water Leakage into the Stud Cavity (Q=0)

hygIRC simulations showed that the walls with the porous and non-porous cladding systems investigated had the same RHT(95) response of zero or near-zero, even in climates of high moisture loads as defined by the Moisture Index (Figure 6.1). Cladding materials with higher liquid diffusivity such as the three stucco plasters used in the study had RHT(95) responses similar to those of impervious materials like vinyl siding, indicating that their water resistance level was sufficient to resist the climate loads investigated. Note that the simulations assumed that the joints between cladding elements were as water resistant as the elements themselves. In practice this may not be the case, as the design, construction and aging of joints between cladding elements (e.g., boards of siding or masonry/mortar interfaces) may reduce the overall water resistance of the cladding assembly.

Effect of Water Leakage into the Stud Cavity (Q ≠ 0)

It was evident from the predicted RHT(95) wall responses that all four wall systems were sensitive to the introduction of moisture loads into the stud cavity, as the wall RHT(95) hygrothermal response raised above a value of zero[1] (see middle and top curves in figures 6.3 a and b).

The increase in the RHT(95) wall response was based on the severity of the outdoor climate, the characteristics of the deficiency providing the water leakage path inwards and the characteristics of the wall assembly (for wetting and drying balance). The parametric study investigated the effect of changing Q between 0, ¼Q, ½Q, 1Q, 2Q and 4Q on the RHT(95) wall response. The general pattern observed was as illustrated in Figure 6. 4, and it fell into these stages: a near zero rate of increase of the RHT(95) response for lower Q loads (0 to point A) (i.e. low slope), high increase rate of RHT(95) response for higher Q loads (between Points A and B) (i.e. steeper slope), and low rate of RHT(95) increase for the highest Q loads investigated (between Points B and C), and no change (beyond Point C).

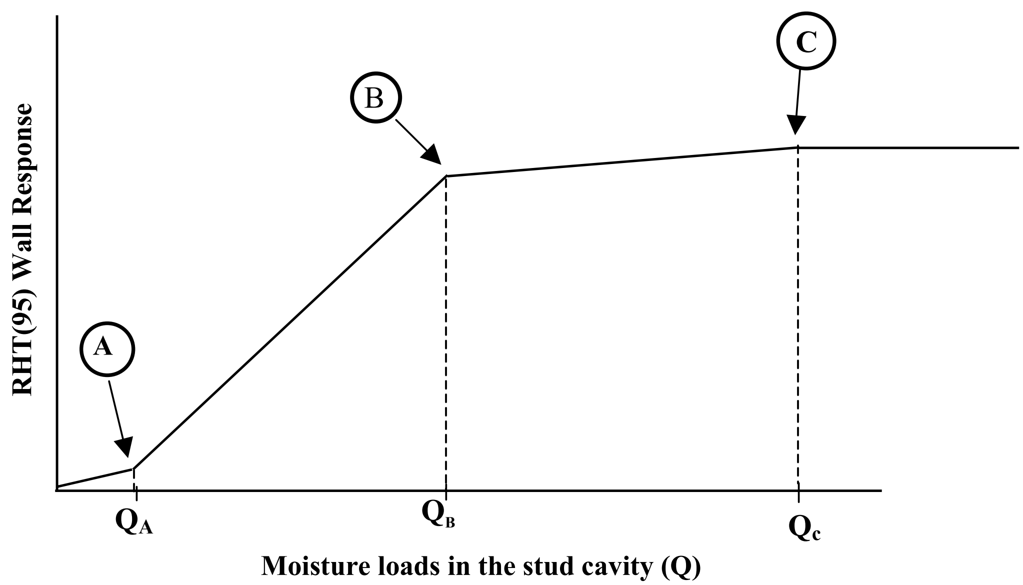


Figure 6.4 Generic pattern for the relationship between RHT(95) wall response and the moisture loading of the stud cavity (Q), for a given climate

[1] RHT(95) value above zero was selected in this parametric study as the indicator of potential wood decay

When no moisture load was injected into the stud cavity, the RHT(95) response was at its lowest; this can be zero or a positive value. As mentioned before, in the case of the wall systems investigated in this study, the RHT(95) response was at zero or near zero for all climates investigated. Other systems or the same systems with different material characteristics or exposed to more severe climate loads could exhibit a positive RHT(95) value. The line does not necessarily pass through the origin of the plot.

Up to a Q_A set of hourly moisture loads in the stud cavity, the RHT(95) wall response can be zero or positive and increasing at a low rate. In that case, over the two years of simulation, periods of wetting alternated with periods of drying, resulting in a near-zero to small positive cumulative RHT(95) value. The slope of the line varied with the climate severity and the drying drive offered by the wall assembly. The lower the slope, the lower the climate moisture loads or the higher the drying potential of the assembly. Using material properties that offered higher drying potential tended to prolong the period of RH below 95%, at the region of focus hence improving the RHT(95) hygrothermal response of the wall.

When Q increased further (between Points A and B) due to, for example, an increase in deficiencies, the wall started to show signs of "losing the battle", as the slope of the RHT(95) response became steeper. The cumulative periods of excessive wetting were increasingly longer than the drying periods. The wall drying ability could not manage the increasing wetting loads, and as a result the RH remained above 95% even between rain events. Even though the drying drive offered by the wall materials was unchanged from situations with lower Qs, the simulation results on the effect of changing the material properties did not provide insight into the potential improvement offered by materials with higher drying characteristics.

When Q was at or beyond point B, the rate of wetting of the stud cavity far exceeded the rate of drying offered by the wall assembly. The wall was overloaded with water, and the RH level at the region of focus stabilized around 98-99%. Beyond Point C, the RHT(95) response eventually became insensitive to the increase of the moisture loads, as it cannot register more than 100% RH.

The deficiency considered in MEWS was a continuous path that allowed rainwater to penetrate into the stud cavity. This resulted in one specific form of "unintentional moisture load" for the wall to manage. This unintentional load can be from any other source (for example, exfiltration of humid indoor air and subsequent condensation in wall assemblies during the heating period), but these general observations from the MEWS project will still be valid. There will always be a behaviour similar to that shown in Figure 6.4, associated with any specific wall assembly at any specific geographical location. The design, construction and maintenance of the exterior walls need to aim at keeping 'Q' substantially below Point B of Figure 6.4.

Effect of Material Property

The climates (indoor and outdoor) provided the moisture loads as well as the drive for evaporative drying, while the material properties and assemblies determined the resistance to flow in or out. An important assumption for the design of this parametric study has been that water was allowed to bypass the first and second lines of defence of the wall against moisture entry (i.e. cladding and water resistive barrier) and to be deposited onto the moisture-sensitive materials of the walls (i.e. in the stud cavity). With these assumptions, the ability of the moisture management strategy in place on the outside part of a wall was not thoroughly investigated in this parametric study. For example the presence of a cavity behind the cladding was not examined for its effectiveness at reducing moisture loads on the backup wall. The ability of the materials on both sides of the stud cavity to promote evaporative drying of a stud cavity that gets frequently wetted by a deficient outside joint was the main focus of this parametric study. For example, hygIRC predicted the effect of adding a vented cavity behind the stucco cladding on the drying of a wet stud cavity material, not its effect to reduce the moisture loads entering the stud cavity. Large-scale experiments in the laboratory investigated the effectiveness of a drained cavity at reducing the wetting of a stud cavity.

hygIRC predictions suggested that evaporative drying through several layers of materials with little airflow in between them can be a slow process. Changing the properties of cladding materials, water resistive barriers and non-insulating sheathing boards has not made a “substantial” difference in the RHT(95) wall response when the moisture loads in the stud cavity were set at 1Q. In fact it appeared that in cold, or warm and humid climates, a 1Q set of loads “oversaturated” the stud cavity in most instances. Under these circumstances, changes in properties of common materials could not begin to result in a substantial reduction in the wall RHT(95) hygrothermal response. To see any significant improvement in this instance, Q should have been reduced substantially below ‘Point B’ in Figure 6.4.

Another factor had to do with the current relatively small variations in moisture transport brought about by variations in the material properties investigated. Several building materials of one generic type tended to exhibit values for a given property within a relatively small range. For example, two materials may have a water vapour permeance (WVP) in the 10^{-9} g/m.s.Pa range: one may have twice or three times the WVP of the other, but it remains that both materials have very low WVP values. For this reason, in several cases changing the properties of a generic material did not substantially affect the outcome of the RHT(95) wall response.

A very large increase in the vapour permeance of the materials placed on the indoor side of the stud cavity (drywall and vapour barrier) was predicted to make a noticeable improvement in the RHT(95) wall response at certain geographic locations. However the results are premature for the following reasons. Most of the parametric study has been done using conservative indoor temperature and relative humidity (based on ASHRAE guidelines). The drive for evaporation towards the interior between a “moderately dry” indoor and a wet cavity was large, so with a large drive and low resistance to moisture transfer, some significant drying of the stud cavity to the inside can be predicted. It can be argued that in low-rise residential buildings, the indoor conditions may not be that well controlled in practice. Further investigation of the effect of the indoor climate on the drying ability of a wet stud cavity for different levels of water vapour permeance of the interior layers of the walls is necessary prior to making general statements.

The presence of an exterior insulating sheathing on the outside of the stud cavity was predicted to exacerbate the wall RHT(95) response when the stud cavity was accidentally wetted with a 1Q set of moisture loads. During seasons where the outdoor temperature was below indoor temperature, an insulating sheathing on the outside of the stud cavity raised the temperature of the region of focus in the stud cavity above what it would be with a non-insulating sheathing. As the temperature in the stud cavity was higher for longer periods than it would be with a non-insulating sheathing in place, the cumulative RHT(95) for the wall with the exterior insulating sheathing also tended to be higher (so long as the RH threshold condition was met). This effect was different from a situation where condensation control would be the only concern; in that case, the presence of an insulating sheathing would be desirable because the increased cavity temperature shortens the time below the dew point temperature of indoor air.

Effect of Airflow Across the Wall Assembly

In this parametric study, the reference walls used for comparison included no openings to allow airflow through the wall assemblies. The only airflow occurring in this reference wall was based on the air permeability of each material. In practice walls are not completely free of unintentional cracks and openings that would allow some through-flow of air in the presence of a force like wind, stack effect or mechanical ventilation. This airflow can have an effect on the wetting and the drying of a wet assembly. A small number of simulations for two of the wall systems investigated predicted that adding an airflow to the reference wall could result in a small reduction in RHT(95) for the wall. Further investigation into the positive and negative effects of various rates of air leakage on the moisture deposition and moisture removal capacity of airflow through a wall assembly in different climates is required prior to making general statements.

Effect of a Vented Cavity behind the Exterior Cladding

The effect of a vented cavity on the RHT(95) hygrothermal response of a wall experiencing water leakage in the stud cavity was examined in the parametric study as well as in a laboratory investigation of large-scale wall specimens subjected to water spray and air pressure, simulating wind-driven rain. The laboratory study indicated that a drained cavity behind the cladding contributed to reduce the moisture loads in the stud cavity. This observation was taken into account in some aspects of the design of the parametric study, as the mathematical function to estimate the rate of moisture load in the stud cavity (Q) for each wall system was based on the laboratory test results. For example, the function for the masonry wall (Figure 1.9) indicated that less water entered in the stud cavity than other wall systems, and the presence of a drained cavity in all four masonry specimens tested had an influence on that. In other respects, the parametric study did not account for the effect of a drained cavity behind the cladding on the magnitude of the moisture loads in the stud cavity. For example, in the parametric study, the same moisture loads (Q) were injected in the stud cavity of the siding-clad walls, whether a furred cavity was in place behind the cladding or not. The parametric evaluation of the vented cavity was designed to compare the effect of the addition of a cavity behind the cladding on the evaporative drying of the stud cavity for given sets of moisture loads in the stud cavity, regardless of the probability of that moisture load occurring.

The results of the parametric study suggested that the reduction in RHT(95) due to the addition of a vented cavity behind the cladding depended on the magnitude of the moisture loads in the stud cavity and the hygrothermal properties of the material(s) separating the wet stud cavity from the vented cladding cavity. The simulations done on hardboard siding and stucco-clad walls indicated that the addition of a 19 mm vented cavity behind the cladding made a small and near-zero reduction in RHT(95) respectively, when a 1Q set of moisture loads was injected in the stud cavity. However when this moisture loads was reduced to ¼ Q, as was the case for hardboard and vinyl siding-clad walls, the RHT(95) reduction was larger (i.e. small to substantial, and substantial respectively). When 1Q moisture loads were injected in the stud cavity, the wall was overloaded with moisture and the wall response was located somewhere beyond point B of Figure 6.4. When Q was reduced to ¼ of the original loads, the wall response became more responsive to the presence of a vented cavity (somewhere between Points A and B). In the case of the brick veneer which included a 25 mm vented cavity, the observation of interest related to the benefits of increasing the air and vapour permeances of the sheathing board used in conjunction with a vented cavity. For all seven climates investigated, the results of a single simulation run suggested that the reduction in RHT(95) can be substantial when a sheathing board with such properties was used, even with a 1Q moisture load in the stud cavity. Further investigation into this issue is required prior to making general statements.

6.3 Design Considerations

The results of the parametric study support the following design considerations for management of exterior moisture in exterior walls.

Know Your Climate

The first question that comes to mind when initiating a wall design for a certain use in a certain climate should be: how severe is the exposure of the building? One does not design the walls of an indoor swimming pool or arena the same way as the house or the office adjacent to it. The same applies for the outdoor climate. The more severe the outdoor climate, the more effective or redundant the moisture management strategies need to be in order to obtain a durable assembly. The MEWS project has produced a provisional mapping of North America that combines how wet it gets with its potential for drying. The higher the Moisture Index (MI), the more severe the climate. The response of the wall to the moisture load, including unintentional moisture entry, increases first gradually and then exponentially with MI. Hence at the higher end of the MI scale, additional precautions to control and reduce the moisture load should be considered

Know Your Four Ds

The basic Four Ds summarize current strategies to reduce the exterior moisture loads into the walls: Deflect, Drain, Dry and use Durable materials. The parametric study has concentrated on the drying potential of assemblies that get accidental water entry into the stud cavity. This scenario is not unlikely, as field surveys have indicated that through-the-wall penetrations can allow water to bypass the cladding and the water resistive barrier to reach the stud cavity. The study indicates that the evaporative drying of the materials can be very limited. Other design strategies such as minimizing the moisture loads in the stud cavity through careful design and detailing of interfaces may be much more effective at controlling the hygrothermal response of a wall assembly.