# Application of hygrothermal analyses to optimize exterior wall design

Mukhopadhyaya, P.; Kumaran, M. K.; Rousseau, M. Z.; Tariku, F.; van Reenen, D.; Dalgliesh, W. A.

# Application of hygrothermal analyses to optimize exterior wall design

Mukhopadhyaya, P.; Kumaran, K.; Rousseau, M.;
Tariku, F.; van Reenen, D. ; Dalgliesh, W.A.

NRCC-46100

A version of this document is published in / Une version de ce document se trouve dans:
Research in Building Physics, Leuven, Belgium, Sept. 14-18, 2003, pp. 417-426

# Application of hygrothermal analyses to optimise exterior wall design

Phalguni Mukhopadhyaya, Kumar Kumaran, Madeleine Rousseau, Fitsum Tariku & David van Reenen

*Institute for Research in Construction, N R C Canada, Ottawa, Ontario, Canada*

Alan Dalgliesh

*Consultant, (formerly Research Officer, Institute for Research in Construction, NRC Canada), 237 Valley Ridge Green N. W. Calgary AB, Canada T3B 5L6.*

ABSTRACT: The design of exterior walls in a building envelope for optimum moisture management is a challenging task. Many conventional methods or local practice guidelines are available for this purpose, based primarily on regional traditions and with limited performance assessment records. In recent years, new wall systems and unconventional materials have been introduced in every part of North America for reasons such as aesthetic appeal, cost-effectiveness etc. However, neither the long-term moisture management performance of these new wall systems nor the uses of unconventional materials have been assessed rigorously. The primary reason for this lack of such assessment is the absence of a design-oriented technical routine to perform the task. Recent studies at the Institute for Research in Construction (IRC) / National Research Council (NRC) of Canada, show that such an assessment is possible with the use of an advanced hygrothermal modelling tool, such as *hygIRC*, developed in-house at IRC. This paper presents results from hygrothermal modelling and discussion on walls with the four different cladding systems: stucco, exterior insulated finish systems (EIFS), masonry and siding. These walls were virtually exposed to several North American climates. Their hygrothermal responses were assessed with a novel indicator, called the RHT index, which is derived from relative humidity and temperature. The results and discussion presented in this paper clearly show the need and usefulness of an integrated design methodology for the moisture management of exterior wall systems that can help to optimise various design considerations.

## 1 INTRODUCTION

The role of a building envelope is to protect the indoor environment from external hazards arising from outdoor weather loads. The exterior walls are primarily subjected to moisture and thermal (i.e. hygrothermal) load gradients in addition to wind loads. The magnitude and nature of the hygrothermal loads vary with time and the hygrothermal response of building materials and wall systems are also time dependent. Unwanted moisture accumulation inside the wall assembly can cause severe functional damage to the structure and environment. In order to avoid such eventualities designers and building envelope practitioners had used various manual analytical tools (TenWolde, 2001) such as the Dew Point Method, Glaser Diagram, and Kieper Diagram, to predict the condensation plane in the exterior wall assembly based on steady-state calculation of heat and moisture transfer. It is quite obvious that outputs from these tools are not time dependent and hence, have limited utility for the long-term moisture response assessment of the wall assembly. However, in the recent past, with the advent of modern computers and advanced numerical algorithms, the prospect of using hygrothermal modelling tools with the capacity to perform transient heat and moisture transfer calculations has become a reality (Trechel, 2001). These models have many advanced features such as use of recorded field weather data for defining boundary conditions, variable material properties, and other useful inputs. The outputs from these modelling tools can be used to identify moisture and temperature distribution patterns in the wall assembly over a period of time. The transient nature of the calculations and outputs provides a designer a real opportunity to assess the long-term moisture performance of the exterior wall assembly. More specifically it gives the opportunity not only to identify the wettest area of the wall assembly but also the duration of the wetting period. However, this is only a first step towards the long-term moisture performance assessment of the wall assembly. During the design process usually the performance of a material or system is expressed in terms of 'reference values' (Hendricks & Hens 2000) or a yardstick value. Hence, it is necessary to further analyse the hygrothermal simulation results so that the performance of various wall components, construction techniques and wall systems can be done in an objective manner that can help to optimise various design considerations for exterior wall assembly.

This paper presents a technique that uses a numerical modelling tool called *hygIRC* that was developed at the National Research Council (NRC) Canada to predict the hygrothermal response of the building envelope and its components at defined intervals over a period of time. The outputs from these numerical simulations are further analysed using a novel moisture response indicator, called the RHT index (Kumaran et al. 2002 and Mukhopadhyaya et al. 2002) which is derived from relative humidity and temperature. This analysis compares the relative effects of various materials and construction types on the long-term hygrothermal response of building envelopes. This novel approach of using a modelling tool and a moisture response indicator for parametric analysis potentially has major applications in the building envelope construction industry.

### 1.1 *Background*

At the Institute for Research in Construction (IRC), National Research Council (NRC) of Canada, a research consortium project called MEWS (Moisture Management for Exterior Wall Systems) was initiated to support the development of guidelines for moisture management strategies applicable to low-rise wood-frame exterior wall systems in North America.

MEWS is a joint research project between IRC-NRC Canada and the following external partners: Louisiana Pacific Corporation, Marriott International Inc., Fortifiber Corporation, EIFS Industry Members Association, EI DuPont de Nemours & Co., Canadian Wood Council, Fiberboard Manufacturers Assn., Canada, Masonry Canada, Canadian Plastic Industry Association, Canada Mortgage and Housing Corp. and Forintek Canada Corporation.

The project has now resulted in a novel methodology that leads to design considerations for improved moisture management strategies for any exterior wall assembly at any geographic location. This methodology effectively integrates (Fig. 1) information from a variety of sources, including:

1. Review of field practices (Rousseau et al., 2002);
2. Measurements of hygrothermal properties of building materials (Kumaran et al., 2002);
3. Definition of environmental loads (Cornick et al., 2002);
4. Laboratory experiments on wind-driven rain penetration (Lacasse et al., 2002);
5. Parametric analysis using a benchmarked hygrothermal model called *hygIRC* (Maref et al., 2002, Mukhopadhyaya et al., 2003).

The detailed description of this methodology has been published elsewhere (Kumaran et al. 2002, 2003).

This paper describes the role of parametric analysis in developing a methodology for comparing the relative performance of various materials as components of exterior wall systems with various wall assemblies in different climatic conditions. In particular, this paper focuses on the parametric analyses carried out on wood-frame stucco-clad walls. Limited results from other types of wall assemblies with different cladding systems (i.e., exterior insulated finish systems (EIFS), masonry and siding) are also presented in a systematic manner.

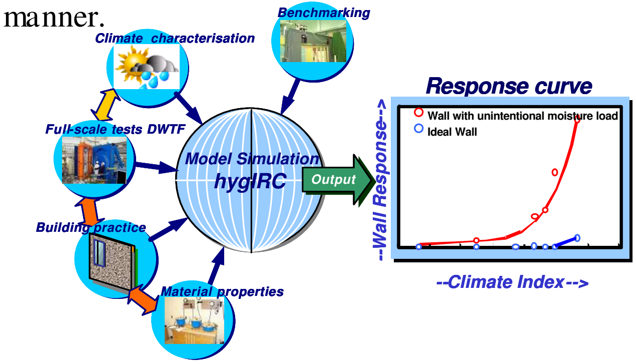


Figure 1. Integration of information

## 2 HYGROTHERMAL MODELING USING *hygIRC*

Hygrothermal models are mathematical tools that can be used for moisture design of building envelopes (Hens 1996). IRC's/NRC's modelling tool for hygrothermal simulation, *hygIRC*, is continuously evolving as a research tool. Interested readers can refer to the publications by Karagiozis, 1993,1997; Karagiozis et al., 1996; and Djebbar et al., 2002a,b for further details. These documents outline the formulation of the combined heat, air and moisture transport equations used in *hygIRC* and the techniques used to solve them numerically. The reliability of *hygIRC* outputs has been established through laboratory measurements and benchmarking exercises (Maref et al. 2002).

This tool accommodates many advanced features, such as transient heat, air and moisture (liquid and vapor) transport, 2 -dimensional spatial formulation, variable material properties with moisture content and temperature, air flow through building materials, effect of solar radiation, presence of moisture source inside the material, freeze-thaw effect, as well as other useful features.

In addition, *hygIRC* can define accidental moisture entry of any quantity into the wall assembly as a function of time at any location on the wall. This feature has been used extensively in this study.

To define the construction of the wall system, *hygIRC* has a pre-processor that allows the user to divide a wall into a number of layers, both in the horizontal and vertical directions.

The effective use of these types of advanced numerical tools to analyse and obtain meaningful results, however, demands a proper physical understanding of the problem, an appropriate definition of input parameters and the ability to judiciously interpret the results.

There are a number of major input parameters required for *hygIRC* simulation, such as:

1. Wall construction details
2. Material properties
3. Boundary conditions
4. Exposure duration
5. Initial moisture content and temperature
6. Accidental moisture entry, quantity and location

The following paragraphs detail these major input parameters.

### 2.1 *Wall construction details*

Figure 2 shows the basic construction details for wood-frame stucco, EIFS, masonry and hardboard-siding walls.

### 2.2 *Material properties*

Simulation using *hygIRC* requires eight sets of material properties: air permeability, thermal conductivity, dry density, heat capacity, sorption characteristics, suction pressure, liquid diffusivity and water vapour permeability. These properties were taken from the MEWS material property database (Kumaran et al. 2002). They were carefully determined in IRC's Thermal and Moisture Performance Laboratory following standard test procedures. The materials considered are also representative of currently available building materials commonly used in North America.

### 2.3 *Boundary conditions*

The two main boundary conditions are the outdoor/exterior condition and the indoor/interior condition.

The exterior boundary condition is defined by specific weather data and has seven components: temperature, relative humidity, wind velocity, wind direction, radiation (direct, diffused and reflective components), horizontal rainfall, and cloud index.

Three typical weather years, representing a *Wet*, *Average* and *Dry* year, were selected for this study. The selection methodology for these years is described in the publication by Cornick et al. (2002).

The interior boundary conditions considered are the indoor temperature (T) and the indoor relative humidity (RH). A summer and winter setting of RH and T were simulated in accordance with ASHRAE recommendations (ASHRAE Handbook of Fundamentals, Chapter 3) as:

25% RH (constant) for winter
55% RH (constant) for summer

The summer and winter seasons were identified according to the criteria specified in "Specifications to National (Canada) Energy Code for Houses, (Swinton & Sander, 1994)", are defined as follows:

Mean monthly outdoor temperature < 11ºC for winter
Mean monthly outdoor temperature > 11ºC for summer.

### 2.4 *Exposure duration*

This study considers a total of three years of exposure duration. In all cases, the first two years are wet years (same year repeated), while the third year is an average year. The exposure duration for each year started on 1st January and ended on 31st December.

### 2.5 *Initial moisture content and temperature*

In any hygrothermal simulation, the user defines the initial moisture content of each wall component at the beginning of the first year. It is assumed in this study that the initial moisture content of each wall component is equivalent to the corresponding relative humidity of 50 percent, derived from the sorption isotherm of the respective materials. The first year of the simulation is considered to be an initial conditioning period, and all the observations are made on the basis of the hygrothermal response of the wall assembly during the second and third years. Similarly, the initial temperature across the entire wall cross section is assumed to be 20°C.

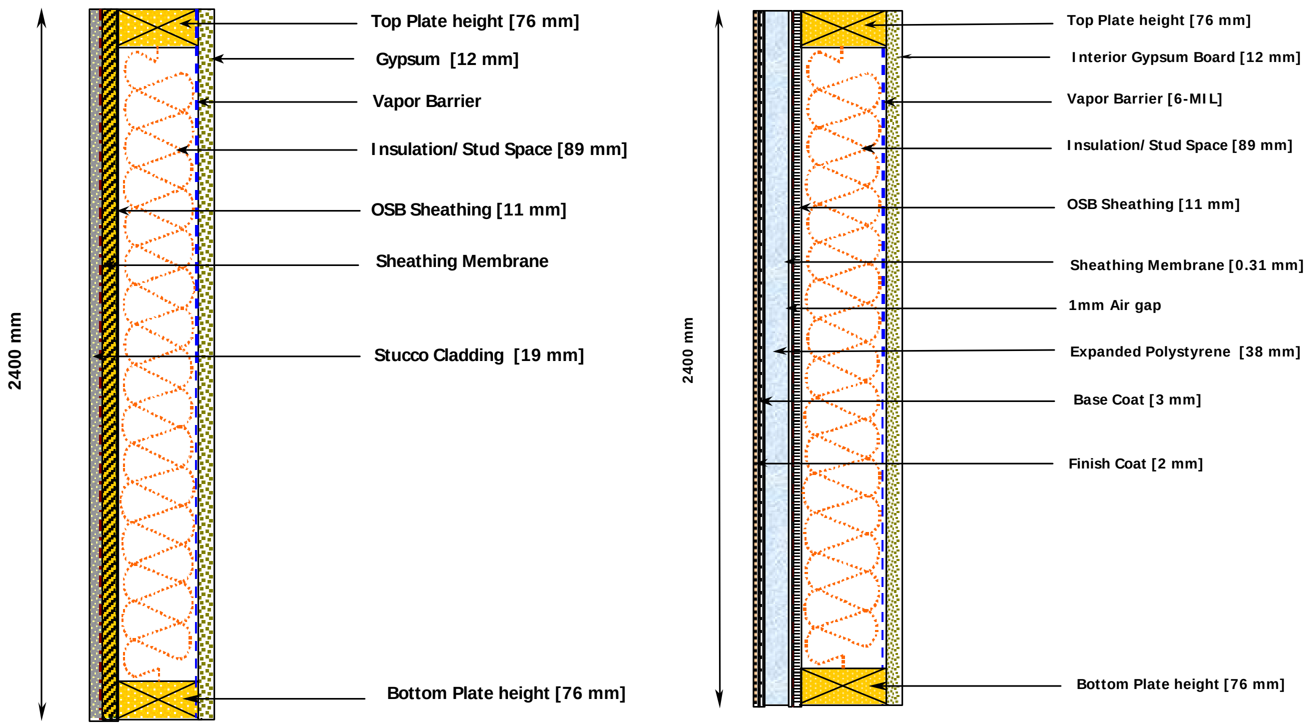
### 2.6 *Accidental moisture entry, quantity and location*

*hygIRC* has the capability to inject a certain quantity of moisture that has entered accidentally at any location of the wall and at any time (hourly). The quantity of accidentally entered moisture inside the wall and its location were determined from the output of full-scale and small-scale laboratory tests done in MEWS (Lacasse et al. 2002), and external weather data (rain fall, wind speed and wind direction). The fundamental relationship used to determine the quantity of accidental moisture entry is,

$$Q = Rp \times f(\Delta p) \qquad (1)$$

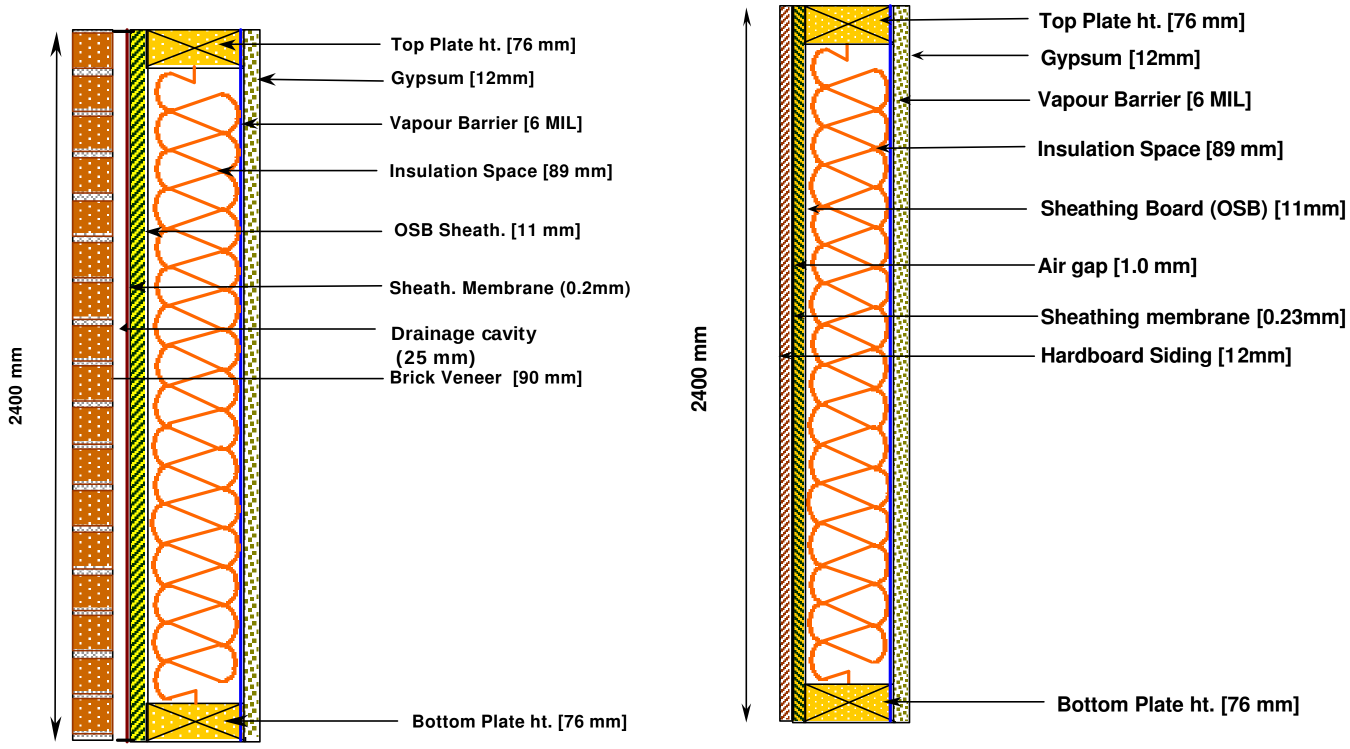
where, $Q$ = water/moisture entry; $Rp$ = spray rate / wind-driven rain; and $\Delta p$ = pressure difference across the wall assembly.

As observed in the full-scale and small-scale tests, the worst-case scenario location of accidentally entered moisture is at the bottom of the insulated stud cavity. Hence, the quantity of accidentally entered moisture determined from equation (1) is injected at the bottom of the stud cavity, on the top of the bottom plate, at every hour.



(a) Stucco wall

(b) EIFS wall



(c) Masonry wall

(d) Siding wall

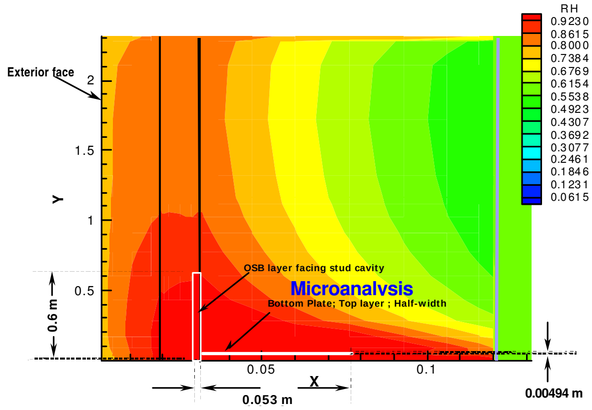
Figure 2. Various wall systems

## 3 RESULTS FROM THE SIMULATIONS

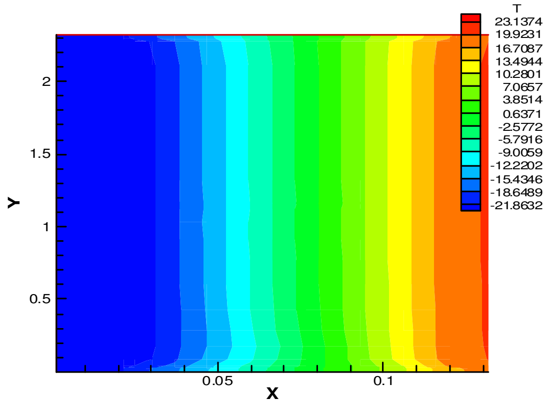
Approximately 450 simulations were done for the parametric study on four types of walls (i.e. stucco, EIFS, masonry and siding walls). A significant amount of data were generated from *hygIRC* and subsequently post-processed for the detailed evaluation of the simulated hygrothermal response of the wall through parametric analyses. However, this paper will discuss only selected results from the stucco walls in detail, touching briefly on the results from other wall systems (i.e. EIFS, masonry and siding walls).

### 3.1 *Typical outputs from hygIRC*

The basic outputs considered for the parametric analyses are the relative humidity (RH) and temperature (T) contour plots (Fig. 3) across the wall assembly cross-section (vertical). These contour plots were generated at midnight, every 10-day for the entire duration of the simulation/exposure period.



(a) Typical relative humidity (RH) contour plot



(b) Typical temperature (T) contour plot

Figure 3. RH and T contour plots (width of the wall expanded)

### 3.2 *RHT index*

This study uses a novel long-term moisture response indicator called the RHT index derived from the RH and T contour plots (Fig. 3) over a period of time for any specific area of the wall cross-section. RH and T are given linear weight in the RHT index. It is to be noted here that in real life for many materials this may not always be the case for the true reflection long-term moisture performance. A different weight for RH and T can be determined only through controlled long-term experiments. IRC/NRC would conduct investigation to generate these information in the coming days (Mukhopadhyaya 2003). Hence, in the mean time, the RHT index as defined in this study is:

$$\textit{Cumulative } (2^{nd} \ \& \ 3^{rd} \textit{ year}) \ RHT=\sum(RH-RH_X)\times(T-T_X), \qquad (2)$$

*for* $RH>RH_X\%$ and $T>T_X°C$ at every 10 days interval.

During any time step when either or both $RH \leq RH_X\%$ and $T \leq T_X°C$, the RHT value for that time step is zero.

User-defined threshold values for $RH_X = 95\%$ and $T_X = 5°C$ have been chosen for this parametric study.

The "region of focus" is the area for which the RHT index is calculated. This area should be the wettest portion of the wall assembly most of the time (Fig. 3a).

For all simulations presented in this paper, the "region of focus" is a thin slice (5 mm) of the top surface of the bottom plate, extending 53 mm from the sheathing board (Fig. 3a).

The parametric analyses presented in the following section use the cumulative two-year RHT index as the long-term single-number moisture response indicator. Higher RHT index value indicates greater potential for moisture-related deterioration.

## 4 PARAMETRIC STUDIES AND DISCUSSION

The following are the major parameters considered in this study for wood-frame stucco walls.

1. Accidental moisture entry inside the wall
2. Quantity of accidental moisture entry
3. Different geographic locations
4. Exterior cladding (three different stucco plaster)
5. Sheathing membrane (three types)
6. Sheathing board (three different oriented strand board (OSB))
7. Vapour barrier (three types)

For all these studies on wood-frame stucco wall, stucco II, sheathing membrane II, sheathing board (OSB) I and vapour barrier I were used for reference wall construction. Further details about these materials and their key properties are described in the related section on parametric analyses.

In addition, this study also discusses moisture response of walls with different cladding systems.

## 4.1 *Accidental moisture entry inside the wall*

Given the nature of building practice, it is not unlikely that in certain instances water can breach the second line of defence and bring about unwarranted effects. The accidental water entry inside the wall, as described in section 2.6, results in higher RHT index (i.e. severe hygrothermal response) at all geographic locations considered in this study (Table 1). Hence, it can be said that the prevention of moisture entry inside the wall system leads to a better moisture management strategy.

All the simulations done for the parametric studies, as presented in the following sections, included accidental moisture entry at the bottom of the insulated stud cavity.

Table 1. Effect of accidental moisture entry

| Location | RHT Index | |
|---|---|---|
| | No moisture entry | Moisture entry (Q) |
| Wilmington, NC | 9 | 3213 |
| Seattle | 0 | 2290 |
| Ottawa | 0 | 1536 |
| Winnipeg | 0 | 1337 |
| Phoenix | 0 | 655 |

## 4.2 *Quantity of accidental moisture entry*

The amount of moisture intrusion inside the wall's insulation cavity was determined from experimental observations in the laboratory (see section 2.6) and their co-relation with simulated wind-driven rain (Lacasse et al. 2002). It is imperative to note that the quantity of accidentally entered moisture can vary widely. To investigate the effect of such variation, simulations were done with a full quantity of accidental moisture entry, given as Q in equation (1), and done with entry of Q/2 and Q/4.

The results from the simulations (Fig. 4) show that the RHT index value reduces with the reduction in the quantity of accidentally entered moisture.

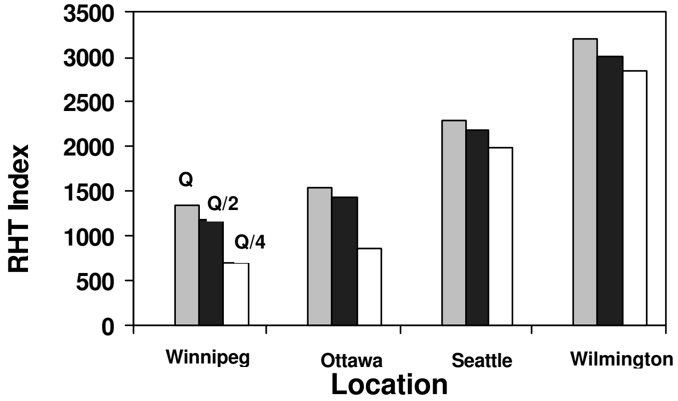


Figure 4. Quantity of accidental water entry

## 4.3 *Different geographic locations*

The moisture management strategy for a wall system is climate specific. Five North American locations are presented in this paper for the parametric studies. These locations were selected on the basis of moisture load characteristics. The moisture characteristic of any geographic location is expressed in terms of moisture index or MI and is derived from an analysis of recorded weather data (Cornick et al. 2002). MI describes the climatic moisture load and it 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. The WI is based on annual rainfall while the DI is based on annual potential evaporation. MI is independent of wall characteristics and design strategies that might be used to manage moisture loading. To assign rankings on the basis of climate analysis at any location in North America, the following definition is used (Cornick et al. 2002):

$$MI=\sqrt{WI_{normalized}^{2}+(1-DI_{normalized})^{2}} \qquad (3)$$

The MI values for these five selected cities vary over a wide range as shown in Table 2.

Table 2. Moisture Index (MI) of locations

| Location | Moisture Index (MI) |
|---|---|
| Wilmington, NC | 1.13 |
| Seattle | 0.99 |
| Ottawa | 0.93 |
| Winnipeg | 0.86 |
| Phoenix | 0.13 |

The variation of the RHT index value with the change in MI indicates a pattern of increasing order as shown in Figure 5. As the severity of the climate moisture load increases, so does the hygrothermal response of the wall. Without accidental moisture entry into the stud cavity, the RHT index value becomes greater than zero when the MI of a location is larger than a certain threshold value. The stucco-wall with accidentally entered moisture shows a higher RHT index when compared with the same wall without any accidentally entered moisture in each five North American locations. The relationship between RHT index and the MI is the basis for the MEWS methodology, the further details of which can be found in other MEWS publications (Beaulieu et al., 2002, Kumaran et al., 2002).

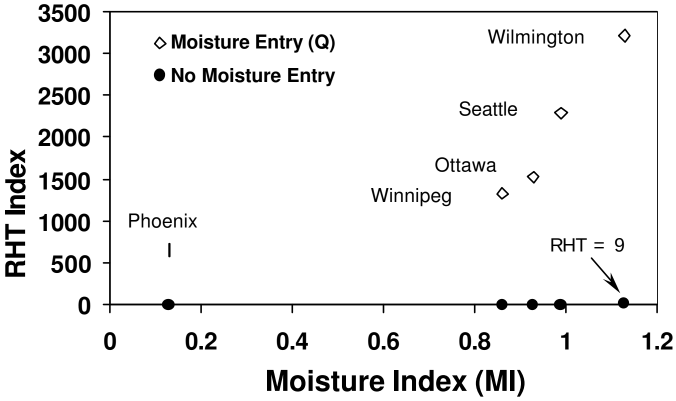


Figure 5. RHT index varies with MI

## 4.4 *Exterior cladding (three different stucco plasters)*

Stucco cladding is the first component of the wall assembly to protect the indoor environment from the outdoor or external climate. Three stucco materials (Stucco I, II and III) were chosen for this parametric study. Figures 6-7 show the water vapour permeability and liquid diffusivity of the three stucco materials.

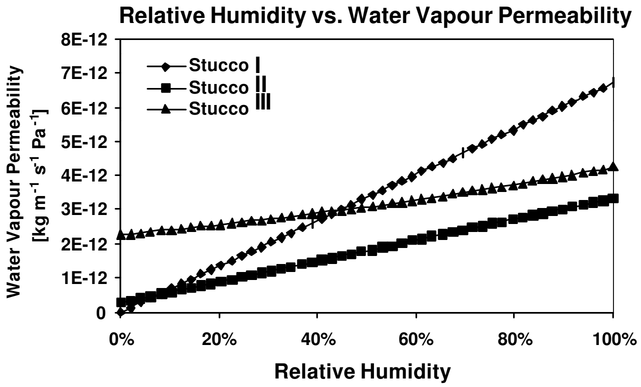


Figure 6. Water vapour permeability of stucco

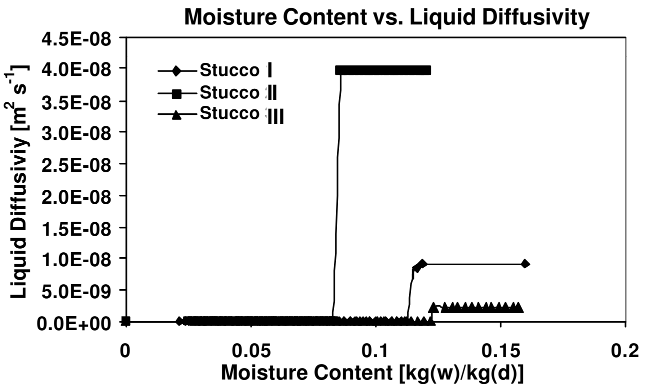


Figure 7. Liquid diffusivity of stucco

The effects of variation in stucco material properties are reflected on the RHT index values are given in Table 3. The properties have a near-zero effect in all locations but Phoenix. This is due to the overwhelming wetting effect of water entry into the stud cavity, and the limited evaporative drying effect of the external layers of the wall assembly. In Phoenix, this effect is small. Stucco III with the lowest liquid diffusivity had caused the lowest RHT values (i.e. the least severe hygrothermal response) in Phoenix.

Table 3. Three different stucco materials

| Location | RHT Index with 1Q moisture entry | | |
|---|---|---|---|
| | Stucco I | Stucco II | Stucco III |
| Wilmington, NC | 3186 | 3213 | 3168 |
| Seattle | 2289 | 2290 | 2281 |
| Ottawa | 1528 | 1536 | 1530 |
| Winnipeg | 1334 | 1337 | 1335 |
| Phoenix | 427 | 655 | 326 |

## 4.5 *Sheathing membrane (three types)*

The sheathing membrane located behind the stucco cladding, is the second element in the wall assembly that offers protection against the outdoor climate. Three sheathing membranes are considered for this parametric study, referred to as sheathing membrane I, II and III. It is to be noted that the water vapour permeability of sheathing membrane I and II increases in a non-linear pattern with the increase of relative humidity (Fig. 8). The water vapour permeability of sheathing membrane III, however, remains constant with the lowest value of water vapour permeability (Fig. 8) among the selected sheathing membranes.

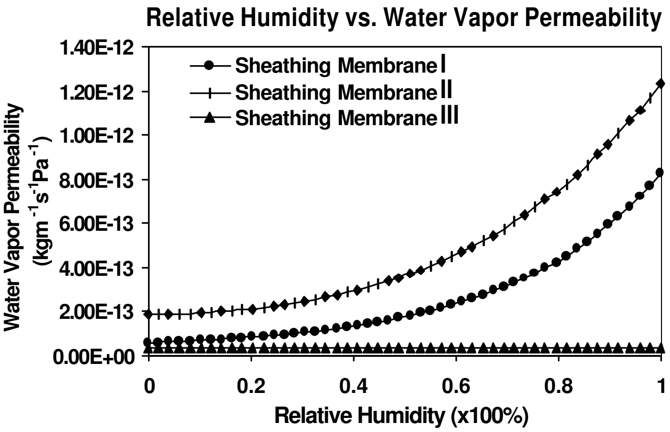


Figure 8. Water vapour permeability of sheathing membranes

The water vapour permeances of three sheathing membranes are:

Sheathing membrane I - between 290 ng/Pa.s.m$^2$ and 4150 ng/Pa.s.m$^2$;

Sheathing membrane II - between 920 ng/Pa.s.m$^2$ and 6180 ng/Pa.s.m$^2$; and

Sheathing membrane III - 280 ng/Pa.s.m$^2$ (constant).

It can be seen from Table 4, that offers a summary of RHT values in relation to membrane type and given locations, that the effects of using different types of sheathing membrane on the overall moisture response of the wall and its components are minimal. However, the use of sheathing membrane III resulted in slightly higher RHT values particularly in Phoenix. This observation is believed to be due to the lower water vapour permeability of sheathing membrane III, which allows a smaller amounts of accidentally entered moisture to be transferred to the outside of the insulation cavity.

Table 4. Three different sheathing membranes

| Location | RHT Index with 1Q moisture entry | | |
|---|---|---|---|
| | Sh. Mem. I | Sh. Mem II | Sh. Mem III |
| Wilmington, NC | 3212 | 3213 | 3217 |
| Seattle | 2292 | 2290 | 2294 |
| Ottawa | 1537 | 1536 | 1538 |
| Winnipeg | 1338 | 1337 | 1338 |
| Phoenix | 666 | 655 | 713 |

## 4.6 *Sheathing board (three different oriented strand board (OSB))*

Three OSBs (OSB I, II and III) are considered in this study. Figures 9-10 show their water vapour permeability and sorption characteristics.

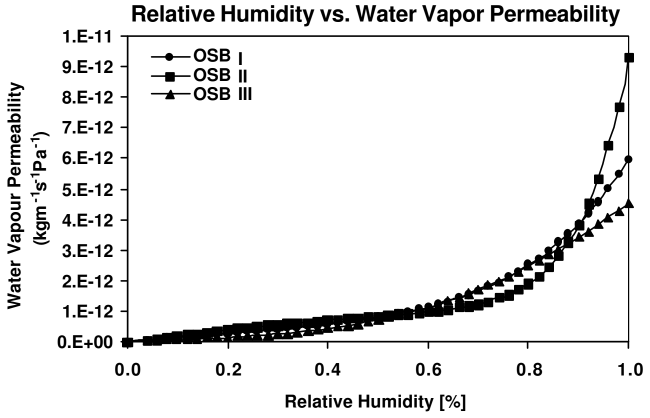


Figure 9. Water vapour permeability of OSBs

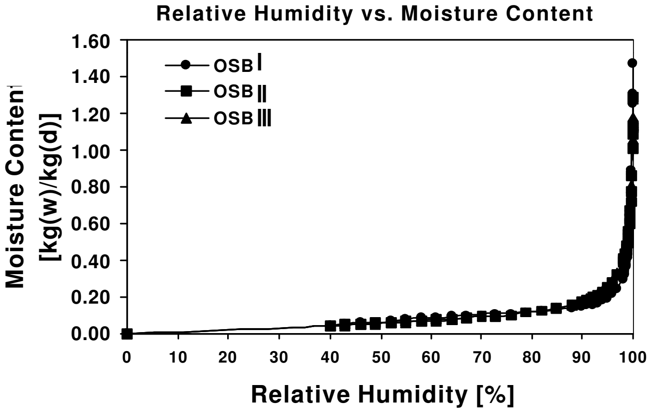


Figure 10. Sorption isotherm of OSBs

The results in Table 5 show that among the three OSB products, OSB II produced the lowest RHT indices. Incidentally, OSB II has the highest water vapour permeability. It is important to note that in the case of sheathing board, however, water vapour permeability alone does not govern the overall hygrothermal response of the wall. Equilibrium moisture content and other related properties, together with the water vapour permeability, influence the moisture response of the wall. The results from the parametric study show that RHT index can help assess the combined effect of variation in all of these properties on the overall moisture response of the wall.

Table 5. Three different OSBs

| Location | RHT Index with 1Q moisture entry | | |
|---|---|---|---|
| | OSB I | OSB II | OSB III |
| Wilmington, NC | 3213 | 3168 | 3180 |
| Seattle | 2290 | 2244 | 2260 |
| Ottawa | 1536 | 1506 | 1515 |
| Winnipeg | 1337 | 1310 | 1320 |
| Phoenix | 655 | 562 | 585 |

## 4.7 *Vapour barrier (three types)*

The vapour barrier is the last effective component of the wall in protecting the indoor room environment from the influence and fluctuation of the moisture content in the outdoor climate. This study considers three vapour barriers (I, II and III), representing three different water vapour diffusion control levels (Fig. 11).

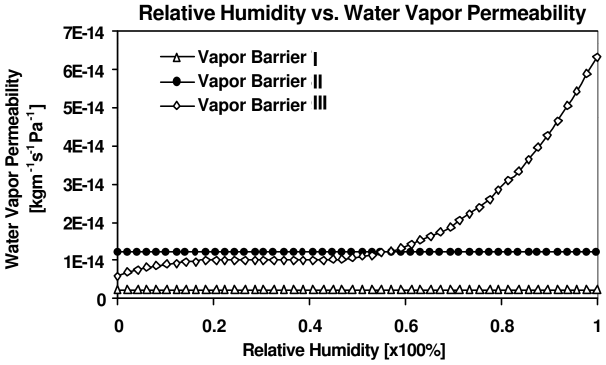


Figure 11. Water vapour permeability of vapour barriers

The water vapour permeances of the three vapour barriers are as follows:

Vapour barrier I has a constant water vapour permeance of 15 ng/Pa.s.m$^2$;

Vapour barrier II has a constant water vapour permeance of 60 ng/Pa.s.m$^2$; and

Vapour barrier III has a water vapour permeance value as a function of relative humidity and varying between 30 and 320 ng/Pa.s.m$^2$.

The RHT values obtained from the simulations (Table 6) clearly indicate that the change of vapour barrier type has a distinct influence on the overall moisture response of the wall and its components. Vapour barrier III, with the highest value of water vapour permeance, resulted in the lowest RHT index values. These results indicate that there is a scope to optimise the water vapour permeance characteristic of the vapour barrier at various locations. Higher water vapour permeance of the vapour barrier may also change the indoor relative humidity condition significantly. Further investigation is required on this issue.

Table 6. Three different vapour barriers

| Location | RHT Index with 1Q moisture entry | | |
|---|---|---|---|
| | Vap. B I | Vap. B II | Vap. B III |
| Wilmington, NC | 3213 | 3161 | 3080 |
| Seattle | 2290 | 2245 | 2148 |
| Ottawa | 1536 | 1517 | 1482 |
| Winnipeg | 1337 | 1321 | 1295 |
| Phoenix | 655 | 389 | 230 |

### 4.8 *Different wall systems*

The parametric evaluation presented in the preceding paragraphs deal solely with wood-frame stucco walls. However, similar parametric studies were conducted on other wall systems as well. While it is beyond the scope of this paper to present all of the information generated from those analyses. Figure 12 shows a general applicability of the MEWS methodology to different wall systems.

Figure 12 indicates that a relationship exists between the hygrothermal response of the wall and the characteristics of the external climate. This relationship has a general pattern and is applicable to all the wall systems considered in this study (i.e. stucco, EIFS, masonry and siding walls, see Fig. 2). Note, however, that the results shown in Figure 12 are derived from different wall systems subjected to different accidental moisture entry loads. Hence, any unqualified comparisons between different wall systems based on these observations would not be appropriate.

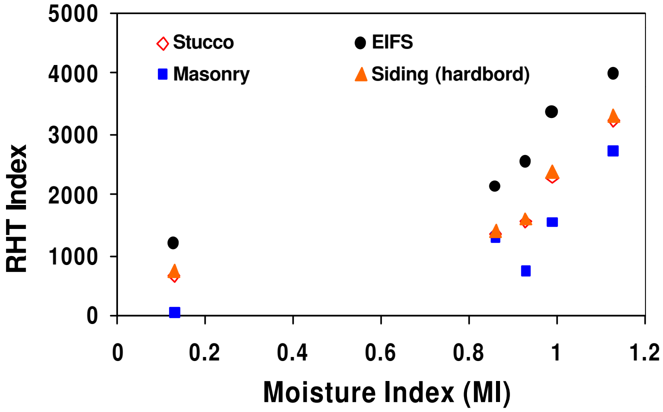


Figure 12. RHT vs. MI for different wall systems

## 5 SUMMARY OF OBSERVATIONS

The results and discussion presented in this paper on parametric studies can be summarised with several observations.

(1) Parametric analyses using a hygrothermal modelling tool can lead to better understanding of the moisture management problem in the exterior building envelope and optimisation of wall design considerations.

(2) A novel hygrothermal response indicator, called the RHT index, has been introduced that can be used as the yardstick for parametric evaluation.

Important features of RHT index include:

(i) Temperature (T), Relative Humidity (RH) and duration effects are all reflected in a single value indicator.

(ii) The user defines the threshold values for T and RH, as well as duration

(iii) Hygrothermal response at any location on the wall assembly can be assessed using the RHT index.

(v) The higher RHT index values indicate an increased severity of the hygrothermal response.

(3) In terms of RHT index, the long-term moisture response of all the wall assemblies considered in this study can be related to the moisture index (MI) of various geographic locations.

(4) Parametric evaluation with the RHT index can assist the building envelope designer in assessing new, selecting appropriate materials and identifying suitable construction techniques.

(5) In general this study indicates that rain infiltration inside the stud cavity or any part of the wall without adequate drainage capability should be prevented by all means.

## 6 REFERENCES

ASHRAE Applications Handbook, 1999. Chapter 3 - Commercial and Public Buildings.

Beaulieu, P. Cornick, S.M. Dalgliesh, W.A. Djebbar, R. Kumaran, M.K. Lacasse, M.A. Lackey, J. Maref, W. Mukhopadhyaya, P. Nofal, M. Normandin, N. Nichols, M. O'Connor, T. Quirt, J.D. Rousseau, M.Z. Said, M.N. Swinton, M.C. Tariku, F. & van Reenen, D. 2002. MEWS Task 8 Report, Institute for Research in Construction, National Research Council, Ottawa, Canada.

Cornick, S. M., Dalgliesh, W. A., Said, N. M., Djebbar, R., Tariku, F. & Kumaran, M. K. 2002. Task 4- Environmental conditions. Institute for Research in Construction, National Research Council, Ottawa, Canada, (NRCC-45222), pp. 1-106.

Djebbar, R. Kumaran, M.K. Van Reenen, D. & Tariku, F. 2002a. Hygrothermal modelling of building envelope retrofit measures in multi-unit residential and commercial office buildings. *IRC/NRC,* National Research Council, Ottawa, Canada, Client Final Report B-1110.3, pp. 187.

Djebbar, R. Kumaran, M.K. Van Reenen, D. Tariku, F. 2002b. Use of hygrothermal numerical modelling to identify optimal retrofit options for high-rise buildings. *12th International Heat Transfer Conference*, Grenoble, France, Aug, 2002, (NRCC-45215), pp. 1-6.

Hendriks, L. & Hens, H. 2000. Building envelopes in a holistic perspective - Methodology. *International Energy Agency Annex 32, Task A,* Amsterdam, Netherlands.

Hens, H. 1996. Heat, Air and Moisture Transport, Final Report, Vol. 1, Task 1: Modelling. *International Energy Agency*

*Annex 24*, Laboratorium Bouwfysica, K. U.-Leuven, Belgium.

Karagiozis, A. Salonvaara, M. & Kumaran, M. K. 1996. Numerical simulation of experimental freeze conditions in glass fibre insulation. *Building Physics in the Nordic Countries*, Finland, August.

Karagiozis, A. 1993. Overview of the 2-D hygrothermal heat-moisture transport model LATENITE. Internal IRC/BPL Report, *IRC/NRC,* National Research Council Canada, Ottawa.

Karagiozis, A. 1997. Analysis of the hygrothermal behavior of residential high-rise building components. Client report A-3052.4, *IRC/NRC*, National Research Council Canada, Ottawa.

Kumaran M. K., Mukhopadhyaya P., Cornick S. M., Lacasse, M. A., Maref W., Rousseau M., Nofal M., Quirt J. D. & Dalgliesh W. A. 2002. A methodology to develop moisture management strategies for wood-frame walls in North America: application to stucco-clad walls. *6th Nordic Building Physics Symposium 2002*, Trondheim, Norway, pp. 651-658.

Kumaran M. K., *Mukhopadhyaya P.*, Cornick S. M., Lacasse, M. A., Maref W., Rousseau M., Nofal M., Quirt J. D. & Dalgliesh W. A. 2003. An integrated methodology to develop moisture management strategies for exterior wall systems. *9th Conference on Building Science and Technology*, Vancouver, Canada, pp. 16. (In Press).

Kumaran, K. Lackey, J. Normandin, N. van Reenen, D. & Tariku, F. 2002. Summary report from Task 3 of MEWS project. Institute for Research in Construction, National Research Council, Ottawa, Canada, (NRCC-45369), pp. 1-68.

Lacasse, M. A. Beaulieu, P. O'Connor, T. & Nicholls, M., 2002. Experimental assessment of water entry into wood-frame wall assemblies. *IRC/NRC*, National Research Council, Ottawa, Canada.

Maref, W., Kumaran, M. K., Lacasse, M. A. Swinton, M. C. & van Reenen, D. 2002. Advanced hygrothermal model-hygIRC: Laboratory Measurements and Bench Marking. *12th International Heat Transfer Conference*, Grenoble, pp. 1-6.

Mukhopadhyaya, P., Goudreau, P., Kumaran, M. K. & van Reenen, D. 2002. Influence of material properties on the hygrothermal response of an ideal stucco wall - Results from hygrothermal simulations. *6th Nordic Building Physics Symposium 2002*, Trondheim, Norway, pp. 611-618.

Mukhopadhyaya, P., Kumaran, M. K., Tariku, F. & van Reenen, D. 2003. Long-term Performance: Predict the Moisture Management Performance of Wall Systems as a Function of Climate, Material Properties, etc. Through Mathematical Modelling. MEWS Task 7 final report. *IRC/NRC*, National Research Council Canada, Ottawa.

Mukhopadhyaya, P. 2003. MEWS project produces long-term moisture response indicator *Construction Innovation* Volume 8, No. 1, pp. 6-7.

Rousseau, M., Bomberg, M. T. & Desmarais, G. 2002. Review of Common Approaches for Exterior Moisture Management. MEWS Task 2 final report. *IRC/NRC*, National Research Council Canada, Ottawa.

Swinton, M.C. & Sander, D.M. 1994. Trade-off compliance for houses: specifications for calculation procedures for demonstrating compliance to the National Energy Code for Houses, (NRCC-39861), pp. 46.

TenWolde, A. 2001. Manual Analysis Tools. Moisture analysis and condensation control in building envelopes. *American Society for Testing and Materials. MNL40*. West Conshohocken, PA, USA, pp. 107-115.

Trechsel, H. R. (editor) 2001. Moisture analysis and condensation control in building envelopes. *American Society for Testing and Materials. MNL40*. West Conshohocken, PA, USA. **x**