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An Integrated Methodology to Develop Moisture Management Strategies for Exterior Wall Systems

M K Kumaran[1], P Mukhopadhyaya[1], S M Cornick[1], M A Lacasse[1], M Rousseau[1], W Maref[1], M Nofal[1], J D Quirt[1], and W A Dalgliesh[2]

ABSTRACT

At the Institute for Research in Construction, N R C Canada, a consortium project called MEWS (Moisture Management for Exterior Wall Systems) has resulted in an integrated methodology to assess the long-term performance of exterior wall systems with regard to moisture management. The methodology includes the integration of information from a review of field practices, extensive measurements of hygrothermal properties of building materials, definition of environmental loads, investigation on damage functions, large-scale experiments on wind-driven rain penetration and detailed parametric analyses using a benchmarked and advanced hygrothermal model called hygIRC.

The paper presents the methodology and the salient features of each module in the methodology. It also presents the highlights from its applications to assess the performance of several types of wood-frame constructions in North American climatic conditions and discusses the design considerations that result from the selected applications.

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1. Research Officer, Institute for Research in Construction, NRC Canada, Ottawa ON, Canada K1A 0R6.

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

INTRODUCTION

Uncontrolled moisture accumulation in the building envelope reduces the structural integrity of its components through mechanical, chemical and biological degradation. Damage induced by moisture includes rotting of wood studs and other wood-based products, efflorescence and spalling of masonry systems, and rusting of wall fasteners. Also, excessive moisture in the envelope may affect the health of occupants directly and through the potential for breeding harmful organisms. From the user's point of view, buildings become "unfit-for-use" whether it is due to questionable structural integrity of the envelope or due to unhealthy indoor environment. In addition, moisture can also adversely affect non-health and safety performance factors such as the effectiveness of thermal insulation and aesthetic appearance. 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, which does enter, so that no component in the system stays 'too wet' for 'too long'. But what is "too wet" and "too long"?

At the Institute for Research in Construction, National Research Council of Canada, a research project called MEWS[1] (Moisture Management for Exterior Wall Systems) was initiated to answer the above questions. The project has now resulted in a methodology that leads to design considerations for improved moisture management strategies for any wall assembly at any geographic region in North America. The methodology includes the integration of information from a review of field practices [1], extensive measurements of hygrothermal properties of building materials [2], definition of environmental loads [3], investigation of damage functions [4], experiments on wind-driven rain penetration, [5] and a detailed parametric analysis [6] using a benchmarked hygrothermal model called **hygIRC** [7-9]. This paper attempts only to summarize the methodology and lists some of the observations from its application to wood-frame walls, with several types of cladding. A full description of each module in MEWS methodology is beyond the scope of this paper [2].

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[1] 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 Association, Canada, Masonry Canada, Canadian Plastic Industry Association, Canada Mortgage and Housing Corporation and Forintek Canada Corporation

[2] Readers interested in further details are welcome to read the collection of Research Reports from IRC . The Final report from MEWS, IRC-RR-118 is now available at www.nrc.ca/irc/ircpubs

THE METHODOLOGY

The long-term performance of any wall assembly of a building is considered as the consequence of the hygrothermal responses of the wall as a whole and localized responses of any of its components and material layers; these responses are specific to each geographic location and to the indoor climate. In MEWS context, the long-term performance of wood and wood-based materials determines the long-term performance of the wall.

The project makes full use of IRC's mathematical model hygIRC, benchmarked against many sets of laboratory experiments [7-9], for predicting the hygrothermal response of the wall as a whole, as well as at a localized vulnerable area of the wall. New knowledge was required on the following fronts:

- Climate characterization for North America, in terms of moisture loads imposed on a wall
- Typical practice of design and construction of walls with different cladding systems in place
- Estimation of quantity and distribution of water ingress into the wall assembly in relation with climatic loading
- Characterization of hygrothermal properties of materials
- Selection of indicators of the hygrothermal response of the wall

The following sections highlight the outcome in each of these fields of activities.

Estimation of the Climatic Moisture Loads in North America

North American locations are characterized using a Moisture Index (MI) that can range from zero to 1.414. This index is a combination of a Wetting Index, which represents the amount of rain to which a wall can be exposed, and a Drying Index, which represents the drying potential offered by the climate through evaporation [10]. Based on MI classification, North American locations are grouped in five weather zones.[3] The higher the MI, the more severe the moisture loads. Weather data from more than 300 locations in North America were analyzed in detail and 41 locations were selected to represent the full range of North American climates. The MI for each of these 41 locations is listed in Table 1.

Review of Typical Practice in the Design and Construction of the Walls

The project scope included the following four types of wall assemblies, based on their cladding systems: stucco-clad, EIFS-clad, masonry-clad and siding-clad wall assemblies. Information was gathered on the field practice for these four wall systems. For example, for stucco-clad walls, it was found that in Canada and USA, the moisture management strategy commonly includes the application of a water resistive membrane behind the cladding (concealed weather barrier wall). Wall assemblies that include a drained furred cavity behind the cladding were starting to be used in Canada. Both types of walls were examined in the project, with more

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[3] The details of the calculation of MI, development of weather zones and selection of moisture reference years for hygrothermal analyses are explained in Reference 3 and in a companion paper at this conference (Cornick et. al.). See also pages 1-5 to 1-9 of IRC-RR-118.

emphasis on the concealed weather barrier wall assembly. Various material layers, the sequence of each layer and the dimensions of each layer in the wall assembly as well as types of deficiencies that can be found in these systems were documented for later use in laboratory evaluations of water ingress as well as the hygIRC simulations.

Table 1: Moisture Index for selected cities in North America

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

Properties of Materials

A detailed database on hygrothermal properties of a variety of building materials was developed at the Institute during the past decade. A number of new building products were included in MEWS project and their properties were measured using well-established experimental and analytical procedures. An updated database was thus developed. This new database was used to define the range of properties for each generic material available in the North American market(see Ref. 2) that included the following hygrothermal properties:

- Thermal conductivity of the dry material as a function of temperature
- Water vapour permeability and permeance as a function of relative humidity
- Equilibrium moisture content as a function of relative humidity and suction
- Moisture diffusivity as a function of moisture content
- Water absorption coefficient
- Air permeability and permeance

Estimation of Water Ingress into the Wall Assembly

Based on the information gathered in the Review of Practice activity, seventeen 2.44-m by 2.44-m test specimens of the wall assembly were built and subjected to a testing protocol that included tests under air pressure differential, simultaneously combined with water spray (simulating wind-driven rain). Each specimen included three penetrations: a window, a vent duct and an electrical outlet. Certain deficiencies were included at the interface between these components and the wall. These deficiencies provided a path for water ingress into the stud cavity. For example, the deficiency selected for the development of an equation to estimate water entry rate into the stud cavity as a function of the spray rate and the pressure difference consisted of a 1-mm by 45-mm crack (referred to as a nominal deficiency in this paper) at the interface between an electrical outlet cover plate and the cladding. The responses of each wall specimen were measured in terms of air leakage rates and quantity of water that penetrated through the deficiencies and reached the inside face of the sheathing board. These measurements provided experimental data to derive mathematical relations that correlate the quantity of rainwater entry with wind speed, and precipitation according to weather data from any geographic location[4].

Parametric Analyses and Hygrothermal Responses

Using the hygIRC model

The computer model hygIRC was used to investigate the hygrothermal responses of wall assemblies. The model predicts (not in absolute terms but on a relative basis) real-time response of the wall to changing environmental conditions and hygrothermal loads. It simulates simultaneous heat, air and moisture transfer. The corresponding governing equations are documented by Djebbar et.al (11) For each combination of the parameters, hygIRC provided the hygrothermal response of the wall assembly, at each hour. These responses at any selected point were quantified in terms of a temperature, a moisture content (or RH) and a pair of airflow velocity vectors. The following four mechanisms of moisture transfer were considered in hygIRC analyses:

- Vapour diffusion due to vapour pressure differences across the wall, as defined by the weather records and indoor conditions.
- Wind-driven rain impinging on the exterior face of the cladding, as defined by the weather records and a prediction method to convert vertical rainfall to rain deposition on a vertical surface due to the prevailing wind.
- Unintentional rainwater leakage into the stud space, as derived from testing of full-scale wall specimens in a dynamic wall test facility and adjusted to the weather records.
- Vapour transport that accompanies natural and unintentional airflow across the wall, as defined by the weather records and through specified airflow paths respectively.

Input data

Based on the review of practice, the vertical cross-section of a full-scale one-storey wall (2.4-m high) was generated. The cross section included all the material layers as well as top and bottom plates, at their nominal thickness. This 2-dimensional cross-section was defined within hygIRC as a matrix of several hundred rectangular sections and grid points. This definition allowed for the calculation of the spatial and temporal distribution of various hygrothermal responses.

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[4] All details on the development of these relations are given in Reference 5. The equations developed for different walls may be found in the final project report, IRC-RR-118 page 1-15.

Seven specific locations from Table 1 were selected to represent the broad spectrum of MI found in North America and the five climatic zones: Phoenix (MI 0.13); Fresno (MI 0.49); San Diego (MI 0.74); Winnipeg (MI 0.86); Ottawa (MI 0.93); Seattle (MI 0.99) and Wilmington (MI 1.13).

From multi-year weather data files (up to 30 years), two years were selected for each location. These two years of climate data defined the exterior environmental conditions prevailing at each location for the parametric analyses. One of these was called a "*wet*" year to represent the highest rain load and the other an "*average*" year to represent an average rain load, characteristic of the location. Hourly weather records from these two years were put together to define a three-year weather cycle in the following sequence: *wet-wet-average*.

The interior environmental conditions considered were temperature and relative humidity. A summer and winter setting of RH and T were simulated in accordance with ASHRAE recommendations.

Out of the database of material properties, three sets of properties for each generic material were selected; the mean value and the lower and upper limits were used as parameters in the analyses.

Simulation Runs

Before the parametric simulation runs started, a year was used to "condition" a given simulated wall to a *wet* year of local weather and hence only subject it to the natural hygrothermal loads. Each material in that wall started with equilibrium moisture content that corresponded to an exposure to an environment of 50% RH and the assembly did not include any deficiency that could lead to water leakage into the stud space. Thus, one year into the simulation, the wall assembly attained a state natural to the wettest local weather, however with no deficiency. The subsequent *wet* year and *average* year of simulation were then used to assess the response of the walls for two years. At this stage of the simulation the walls may have included a deficiency that allowed water leakage into the stud cavity; the local weather conditions determined the rate of water leakage. Snap shots of the wall responses from these two years of the weather sequence were recorded every ten days. This yielded 73 records of temperature, moisture content (or RH) and airflow velocities throughout the wall for each simulated case.

Analysis of the Hygrothermal Responses

The wood framing and the sheathing board were looked upon as the critical layers most susceptible to the detrimental effects of undesirable moisture accumulation during the service life of the wall. A segment on the upper surface of the bottom plate, 5 mm thick and 52 mm long, was identified as the region of focus for the entire sets of the "73 records" of responses obtained from the hygIRC simulations. This was based on consistently higher moisture content in that segment than at any other location in the assembly, for wood and wood-based materials.

A novel concept called RHT Index (see Appendix I) was used to quantify and compare the localized response at the selected segment mentioned above. This index captures the duration of the coexistence of moisture and thermal conditions above a set of threshold levels, during an exposure period of two years. The threshold levels depend on the physical process that is of interest in regard to the durability of any selected material in the wall. Two sets of threshold levels were considered in MEWS. A combination of 95 % RH and 5 °C temperature (called RHT95) averaged along the segment was selected given the potential relevance of these conditions to the growth of wood decay fungi. The second combination considered for MEWS was 80 % RH and 5 °C temperature (called RHT80) averaged along the segment as this combination has potential relevance to corrosion processes. Discussions in this paper refer to the cumulative values of the RHT index, over the two-year simulation period, obtained from all the 73 records.

The graphical representation of the RHT response of a wall after two years of simulated exposure to the local weather is presented in Figure 1. The dashed line closer to the X-axis

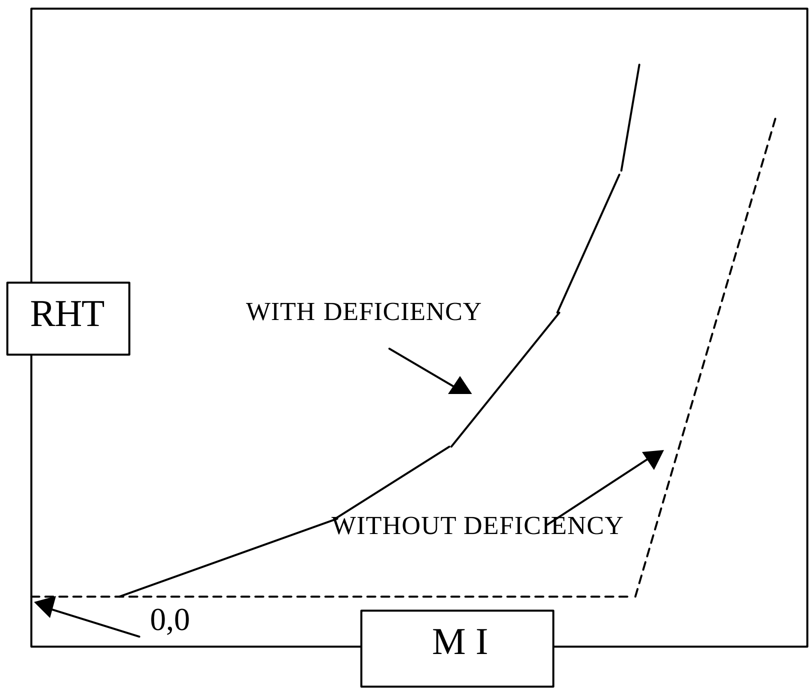

Figure 1: Relationship between Climate, Moisture load and Hygrothermal response.

shows the behaviour of a wall with no deficiencies (or zero rainwater entry behind the sheathing), in response to the hygrothermal loads imposed by two years of local weather and indoor conditions. This line is characteristic of a given wall assembly with a given set of material properties. The curve above the line shows the wall response when an additional moisture load is present, for example in the form of water leakage into the same wall through a deficiency. This latter curve will vary in shape and location on the RHT-MI plane, depending on the magnitude of that additional load.

Evaluation of the Wall Response

As indicated by the results from the parametric analyses, any strategy that brings the two curves in Figure 1 closer to zero RHT is a design consideration for better moisture management.

These considerations can be any one or a combination of the following:

- Selection of materials with properties resulting in less wetting and/or better drying
- Development and use of innovative materials with even better properties than the ones currently available and used in the simulations
- Use of a drainage plane or drained and ventilated cavity between the cladding and the sheathing
- Implementation of design details that reduce the potential for deficiencies or their resultant effects
- Sheltering of the wall to reduce the moisture load on it
- Changes in the basic design of the wall system, as a last resort when other alterations are not sufficient

WATER LEAKAGE INTO THE STUD CAVITY AND RHT RESPONSE

The most important generalization of all the results from over 450 simulations using hygIRC is summarized in Figure 2. The magnitude of the RHT 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 (the empirically estimated moisture load in the stud cavity that corresponded to the nominal deficiency) between 0, ¼Q, ½Q, 1Q, 2Q and 4Q on the RHT wall response. The general pattern observed is illustrated in Figure 2, and is characterized by these stages:

- a near zero rate of increase of the RHT response for lower Q loads (0 to point A) (i.e. low slope);
- high increase rate of RHT response for higher Q loads (between Points A and B) (i.e. steeper slope), and;
- low rate of RHT increase for highest Q loads investigated (beyond Point B)
- little or no change in wall response with an increase in moisture load to the stud cavity (beyond point C).

When no moisture load was injected into the stud cavity, the RHT response was at its lowest; this can be zero or a positive value, for higher MI. In the case of the wall systems investigated in this study, this RHT95 response was at zero or near zero for all climates investigated. Other systems or the same systems with different characteristics or exposed to more severe climate loads could exhibit a positive RHT95 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, for a given MI, the RHT 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 are alternating with periods of drying, resulting in a near-zero to small positive cumulative RHT95 value. The slope of the line will vary with the climate severity and the drying propensity offered by the wall assembly. The lower the slope, the lower the climate moisture loads or the higher the drying propensity of the assembly. Using material properties that offer higher drying potential tends to extend the period of RH conditions at the region of focus below 95%, hence improving the RHT95 hygrothermal response of the wall.

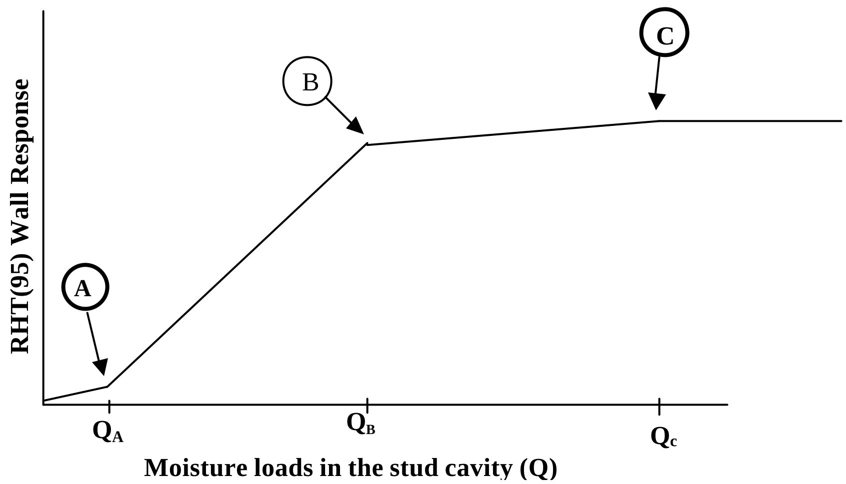

Figure 2: Generic pattern for the relationship between wall response and quantity of unintentional moisture entry

When Q increases some more (between Points A and B) due to, for example, an increase in the size or number of deficiencies, the wall starts to show some signs of "losing the battle", as the slope of the RHT response becomes steeper. The cumulative periods of excessive wetting are increasingly longer than the drying periods. The drying ability of the wall cannot manage the increased wetting loads, and as a result the RH in the region of focus remains above 95% even between rain events. Even though the drying propensity offered by the wall material is the same as the previous situation, a parametric analysis of the effect of change in the material properties does not showcase the maximum improvement offered by materials with higher drying characteristics.

When Q is at or beyond point B, the rate of wetting of the stud cavity far exceeds the rate of drying obtainable by the wall assembly. The wall is over saturated with water, and the RH level at the region of focus stabilizes around 98-99%. The RHT95 response eventually becomes insensitive to the increase of the moisture loads (Q_c), as it cannot register more than 100% RH. Any design considerations, other than to drastically reduce Q, are ineffective.

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 the general observations derived from MEWS project will still be valid. There will always be a response similar to that shown in Figure 2, associated with any specific wall assembly at any specific geographical location. The design, construction and maintenance of the exterior walls need to concentrate on keeping 'Q' substantially below Point B in Figure 2.

SELECTED APPLICATIONS OF MEWS METHODOLOGY

In the MEWS project the methodology described above has been applied to four wall types: Stucco-clad, EIFS-clad, Masonry-clad and Wood/Vinyl siding. The basic cross sections of each wall used in hygIRC simulations may be found in Appendix II. The details of the outcomes from application of the methodology to these wall types are documented in the final project report: IRC-RR-118. Only the highlights from the simulations are provided below.

Application to Stucco-clad Walls

- The stucco claddings investigated exhibited a level of water resistance that significantly reduced the amount of water getting through the field of the wall. The RHT95 wall response was zero for all climates but Wilmington NC, which was at near-zero (less than 100[5]).

- When the same stucco-clad wall included the nominal deficiency that allowed direct water entry beyond the water resistive barrier, i.e. into the stud cavity, the RHT95 response of the wall was quite different. On a relative scale, the RHT95 hygrothermal predicted responses that varied from a value of 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 this amount of water entering the stud cavity (corresponding to the nominal deficiency) 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.

- The outdoor climate played an important role in the RHT95 hygrothermal response of the 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 on in the simulation period, the stucco-clad wall appeared overwhelmed by the moisture loads imposed on it and did not get relieved during the course of the simulation run. In mild climates, the moisture loads are low and the drying potential high. In such instances (i.e. low MI) hygIRC predicted large swings of wetting and drying of the wall resulting in much lower cumulative RHT95 wall response than in climates such as Wilmington NC and Seattle.

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[5] The unit of RHT index that is used in MEWS is "% °C".

- When the moisture load into the stud cavity was reduced to ¼ of the original load from the nominal deficiency, a small reduction in the RHT95 wall response index was predicted to occur in cold and warm climates having high moisture loads. This suggests that even a ¼ of the original moisture load to the stud cavity cannot get eliminated by evaporation through the materials in place. Using a 1 Q set of hourly moisture loads into the stud cavity hygIRC predicts that the following variations makes a near-zero to small difference in the RHT95 response of the 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 some improvement of the RHT95 hygrothermal response of the wall. One specified air leakage path was evaluated at selected geographic locations. This appeared to assist in the drying of the wet stud cavity. Further investigation of the benefits and drawbacks of uncontrolled airflow through a wall assembly is required prior to offering general statements regarding the effect of airflow on drying out any wetted regions of the stud cavity.

- A large increase in the vapour transmission characteristics of the interior layer of the wall assembly (i.e. vapour diffusion control is achieved by the use of a coating on interior gypsum board, with no other vapour barrier membrane present) was predicted to result in a substantial reduction (over 1000) of RHT95 wall response. However, for some geographic locations and for certain levels of indoor humidity conditions, the degree of reduction in wall response was not enough to eliminate unintentional moisture accumulation. 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 in this regard.

Application to EIFS-clad Walls

- The EIFS lamina investigated exhibited a level of water resistance that significantly reduced the amount of water getting through the field of the wall. The characterization of the material properties indicated that the liquid diffusivity of the EIFS lamina – the measure of the capacity of liquid water to pass through a material - is relatively low. hygIRC simulations indicated that when no water was allowed to enter into the wall assembly (i.e. no deficiency), the RHT95 hygrothermal response of the reference EIFS-clad wall was predicted to be zero, even in a climate of severe moisture loads like Wilmington NC.

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* The parametric study investigated the evaporative drying potential offered by the vented cavity but does not take into consideration the potential for drainage of any inadvertent water entry beyond the cladding by way of the cavity.

- When the same EIFS-clad wall included a small deficiency (nominally 1-mm by 45-mm) that allowed direct water entry beyond the water resistive barrier, i.e. into the stud cavity, the RHT95 response of the wall was quite different. The RHT95 hygrothermal responses predicted vary 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 (moisture loads from the nominal deficiency) 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 affect the wall response. The presence of the exterior insulating sheathing (EPS insulation) dampens outdoor temperature swings in the stud cavity: in the heating season the temperature in the stud cavity is higher compared to that in a wall with no exterior insulating sheathing, and in the cooling season, it is lower. Higher temperature in the region of focus resulted in higher RHT95 values, when the RH condition of 95% was met. Secondly, the outer and inner layers of the walls offer 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 RHT95 hygrothermal response of the wall having a deficiency, in two ways: it defined the wetting potential of the cladding and the stud cavity, as well as the propensity for evaporative drying. 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 on, the EIFS-clad wall appeared overwhelmed by the moisture loads imposed on it and did not get relieved during the course of the simulation run. In mild climates, the moisture loads are low and the drying potential high. In these instances, hygIRC predicted large swings of wetting and drying in the region of focus (i.e. low MI) of the wall resulting in much lower cumulative RHT95 wall response than in climates such as Wilmington, NC and Seattle.

- When the moisture load into the stud cavity was reduced, by incorporating a less significant deficiency, a reduction in the RHT95 wall response was predicted to occur. A substantial drop (over 1000) in RHT95 response was predicted in all climates investigated when ¼ of the original moisture loads was injected into the stud cavity. This moisture load reduction brought the wall RHT95 to a near-zero value in Fresno whereas the same wall in Wilmington NC reached, on a relative scale, an RHT value approaching 3000. When the load in the stud cavity was reduced by half, a small reduction in RHT95 was predicted for cold as well as for warm and humid climates (i.e. Winnipeg, Ottawa, Seattle and Wilmington NC) whereas the RHT95 drop was substantial in Fresno and San Diego.

- The parametric study was carried out using a 1 Q set of hourly moisture entry loads that correspond to the nominal deficiency. Under this condition, hygIRC predicts that the following variations makes little difference in the RHT95 response of the 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 RHT95 wall response for all climates investigated. The drying potential offered by their vapour permeance was not sufficient to offset the wetting due to the 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 was substituted for three coats of paint on the interior finish gypsum board) results in a noticeable drop in the RHT95 wall response. However the interior conditions used in the simulation favoured drying to the inside. Hence the simulation results should not be generalized without further analyses of other sets of indoor conditions.

- In all climates investigated, hygIRC predicted that the wall ***with*** insulation in the stud cavity obtains a substantially ***lower*** RHT95 value than did the same wall without insulation in that location. 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 different RH response could be related to a "wicking" effect of the cavity insulation in contact with the bottom plate, 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 RHT95 response of the EIFS-clad wall, for both the full (corresponding to the nominal deficiency) and ¼ 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 in this regard.

- Based on one simulation run for Ottawa, changing the location of the water deposition into the wall, 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 RHT95 value for the respective region of focus in question. The pattern of moisture distribution was, however, somewhat different.

Application to Masonry-clad Walls

- The masonry-clad walls simulated in this study exhibited a level of water resistance that significantly reduced the amount of water getting through the field of the wall. The resistance is 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 RHT95 index was not detectable, even in a climate of severe moisture loads such as Wilmington NC.

- When the same wall included a deficiency that allowed direct water entry beyond the water resistive barrier, i.e. into the stud cavity, the RHT95 response predicted for the wall varied, on a relative scale, 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. Changes in RHT95 near zero on a relative scale were not of great concern, considering the variability of climate conditions and other parameters, but RHT95 changes were substantial for three of the four wettest climates (Winnipeg, Seattle and Wilmington NC). In these three cases, RHT95 indicated water intake clearly exceeded the evaporative drying potential offered by the properties of the materials in the 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 nominal deficiency (1-mm by 45-mm opening). Although the amount (say Q) so defined establishes a starting point, two other water intake rates were also simulated for the wall, to better reveal its drying potential under different service conditions. When the hourly rate of water entry into the stud cavity was varied in steps from 1 Q to zero Q, the RHT95 index in the region of focus (i.e. top of bottom plate) was reduced linearly, reaching zero at rates below ¼ Q for all the climates examined.

- Changing the sheathing board can 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 RHT95 over oriented strand board (OSB) sheathing, likely because of its higher vapour and air permeance. On the other hand, extruded polystyrene (XPS) foam sheathing revealed a large increase in RHT95 in comparison to OSB. By providing extra insulation on the outside of the stud cavity, XPS foam sheathing raises the temperature of the region of focus (base of stud cavity).

- Increasing the water vapour permeance of the vapour barrier membrane showed some decrease in the value of RHT95, 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 RHT95 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 is circumvented if water enters the stud cavity through deficiencies. In any case, the vapour permeances of water resistive membranes investigated 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 rest of the wall by a 25 or 50-mm vented cavity, leaving no strong transfer mechanism between the masonry elements and the rest of the wall assembly.

- Increasing the width of the vented cavity behind the cladding had little effect on the values of RHT95. 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 certain width of the cavity, however no further benefits for the hygrothermal performance of the wall were apparent in the predicted values of RHT95.

Application to Wood/Vinyl siding Wall

- 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 seems to be largely because the liquid diffusivity – the measure of the capacity of liquid water to pass through a material - of the siding material is low.

- When the wall assembly included a deficiency that allowed water leakage into the stud cavity, the predicted hygrothermal response using the RHT95 indicator for the region of focus (a 5-mm slice of the top layer of the bottom plate) varied, on a relative scale, as follows:
    - 731 for hardboard siding to 1072 for vinyl siding, in a hot and dry climate of Phoenix
    - 3297 for hardboard siding to 3138 for vinyl siding, for the warm and wet climate of Wilmington, NC.

  This indicated that hourly moisture loads into the stud cavity from the nominal deficiency (Q) are 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.

- For the hardboard siding-clad wall, interchanging vapour barrier membranes was predicted to have a near-zero-to-small effect on the RHT95 response of the wall.

- Introducing a clear and vented (top and bottom) cavity behind one of the hardboard siding walls did not result in a significant difference in the RHT95 response at the bottom plate once water entered the stud cavity at a 1Q set of hourly rates. When the moisture load Q was reduced to ¼ Q an effect was however obtained (small to substantial). This suggests that in the case where moisture loads of 1 Q were applied to a hardboard siding wall incorporating a clear and vented cavity, such loads can not be managed by the evaporative potential of the assembly (e.g. between Points B and C of Figure 2) but these can be managed at a reduced load of ¼ Q. It is possible that the water vapour permeance of the sheathing board used for the hardboard siding-clad wall will also affect the moisture redistribution and egress from the stud cavity although this effect is likely to be more important at lower moisture loads as compared to higher ones. Further investigations would necessarily be useful to clarify the situation in regard to the relative importance of a vented cavity in siding-clad walls.

CONCLUDING REMARKS

The MEWS research project has resulted in an integrated methodology for assessing and predicting the hygrothermal response of any wall assembly at any location in North America. The methodology has now been applied to wood-frame construction with stucco-clad, EIFS clad, masonry-clad and wood or vinyl siding and several design considerations have been reviewed. This same approach can be applied to a variety of situations where unintentional moisture accumulation occurs in building envelope components from which different moisture management strategies can then be developed given any climatic region of interest.

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APPENDIX I

Definition of RHT Index as used in MEWS

MEWS introduced a novel long-term moisture response indicator called the RHT index derived from the RH and T contour plots provided by hygIRC, over a period for any specific area of the wall cross-section (region of focus). The RHT index as defined in this study is:

Cumulative (2^{nd} & 3^{rd} year) $RHT = \sum (RH-RH_X) \times (T-T_X)$, *for* $RH > RH_X$ and $T > T_X$ at every 10 days interval.

During any time step when either or both $RH \leq RH_X$ and $T \leq T_X$, 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. Hence the unit of RHT index is "% °C".

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 .

Further details can be seen in IRC-RR-118, pages 1-20 to 1-23.

APPENDIX II

Basic cross sections of the four types of walls that have been investigated in MEWS.