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Development of a Wall Performance Classification System

CIB T5S1 Performance Concepts and Requirements

ABSTRACT

This paper is derived from ongoing research conducted into the multi-attribute performance evaluation of wall assemblies. The diversity of wall assemblies available to building designers has increased dramatically as new combinations of methods and materials are introduced into the global construction marketplace. Issues of cost, durability, hygrothermal performance and energy efficiency are among the many parameters that must be carefully considered in design. Additional requirements, such as susceptibility to mould growth and environmental sustainability, further complicate the decision making process. The complexities and risks associated with wall designs are not expected to become more manageable unless a reliable means of narrowing down candidate assemblies is made available to designers.

A hygrothermal performance classification system is one means of addressing this building envelope design issue. It is not intended to address all aspects of building envelope system design, rather it aims to reduce the number of alternatives to those systems meeting prescribed levels of performance in terms of heat, air and moisture management. This paper proposes an efficient means of classifying wall assemblies according to climate, exposure and indoor environment (occupancy) based on hygrothermal computer simulations, acknowledging that a wide range of related factors, such as durability, energy efficiency, economy and environmental impacts, must also be reconciled in professional practice.

The approach advanced in this paper recognizes that a wall classification system cannot be expected to be a substitute for professional judgment and expertise, however, it can significantly reduce the number of alternatives to be considered, improve the reliability of selecting appropriate wall assemblies, and advance the implementation of objective-based codes and standards.

One of the significant relationships emerging from the research is that when the hygrothermal performance requirements for exterior walls have been satisfied, the other requirements are either simultaneously satisfied, or more easily satisfied, than if hygrothermal behaviour is not addressed at the outset. This relationship provides practitioners with a more efficient means of designing innovative wall assemblies, and further supports the importance of a consensus wall classification protocol based on hygrothermal performance.

The work presented in this paper forms part of an ongoing research project that is aimed at providing practical guidance to designers based on normative criteria encountered in practice. It presents a logical approach to simplifying a complex multi-attribute decision process that often requires considerably more expertise than is immediately available to the average practitioner. The methodology integrates past and emerging research and published best practices, and in so doing also identifies critical areas of future research needed to support the more complete and robust development of a wall performance classification system.

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INTRODUCTION

The design of buildings is growing more complex with the introduction of new materials and methods. At the same time, the context for building performance is evolving to include issues such as occupant well being and sustainable development. This expansion of performance parameters, coupled with escalating societal expectations, has dramatically increased the demands on professional practice. Objective-based models for codes and standards, along with sophisticated simulation tools, have become necessary to aid in the integration of innovative technologies to achieve well performing building systems.

This paper recognizes its limited scope, and focuses on the development of a hygrothermal performance classification system for opaque exterior walls. Acknowledging that the performance of opaque walls is significantly influenced by detailing, intersections with other components, and quality of workmanship, it is the intention of this paper to address the basic selection and arrangement of materials constituting an opaque environmental separator. The main idea is to avoid performance problems stemming from fundamental incompatibilities corresponding to climate, exposure and indoor environmental conditions. This does not undermine the importance of detailing and workmanship factors, instead it addresses the initial selection of an exterior wall system typology within the context of a growing number of innovative materials and methods that have not yet exhibited acceptable past performance. It also recognizes the importance of applying limit states design to building envelopes (enclosures).

An enclosure, or part of an enclosure, is considered unfit for use or to have failed when it exceeds a particular state, called a limit state, beyond which its performance or use is impaired. Ultimate limit states are those concerning health and safety. Serviceability limit states are those which restrict the normal performance, use and occupancy, or affect durability. It is the responsibility of the designer to determine all of the limit states which apply to the enclosure being designed, and to ensure that for each limit state the factored resistance provided is not less than the effect of the factored loads, considering all applicable loads and load combinations.

[Adapted from Keenan, Fred J., 1986. *Limit States Design of Wood Structures*, Faculty of Forestry, University of Toronto.]

WALL PERFORMANCE OBJECTIVES AND PARAMETERS

The requirements for wall performance were outlined some half a century ago (Hutcheon 1953). The major considerations were identified as:

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

Since Hutcheon's time, additional objectives have been adopted, such as consideration of the environmental impacts associated with building methods and materials. The objectives or requirements for acceptable wall performance were implicit within traditional methods and materials of construction. With the advent of modern building science, these objectives became more explicit in response to technological innovation. Currently, with the development of objective-based codes and standards, a formal hierarchy is being introduced to foster consensus standards and methodologies for the design and assessment of all aspects of building performance. Table 1 summarizes contemporary performance requirements and their corresponding assessment parameters. It is now apparent that Hutcheon's originally proposed performance framework has expanded and reached the point where considerable time and expertise is needed to properly address wall system design, let alone whole building systems integration.

REQUIREMENT	PARAMETERS	
Structural Strength/Rigidity	▪ Loadbearing/Non-loadbearing ▪ Wind Loading	▪ Seismic Loading ▪ Thermal Effects
Control of Heat Flow	▪ Effective Thermal Resistance	▪ Thermal Bridging
Control of Air Flow	▪ Stack and Wind Pressures ▪ Normalized Leakage Area	▪ HVAC Influences ▪ Internal Partitioning
Control of Moisture Flow	▪ Rain Penetration ▪ Vapour Diffusion	▪ Air Leakage ▪ Condensation Potential
Control of Solar Radiation	▪ Opacity/Emissivity ▪ Solar Orientation	▪ Fenestration ▪ Shading Devices
Control of Sound Transmission	▪ Airborne Sound	▪ Vibration
Control of Fire	▪ Fire Rating	▪ Combustibility
Durability*	▪ Ultraviolet Degradation ▪ Corrosion ▪ Carbonation ▪ Freeze/Thaw ▪ Abrasion ▪ Fatigue ▪ Instability/Incompatibility	▪ Biological Attack (mould, insects, animals, plants) ▪ Chemical Attack (soils, contaminants, pollutants) ▪ Efflorescence ▪ Subflorescence ▪ Spalling
Economy	▪ Initial Cost ▪ Maintenance Cost	▪ Operating Cost ▪ Life Cycle Cost
Environmental Impacts	▪ Resource Depletion ▪ Environmental Degradation ▪ Reduction of Biodiversity	▪ Greenhouse Gases ▪ Pollutants
Buildability (Ease of Construction)	▪ Seasonality ▪ Tolerances	▪ Coordination ▪ Sequencing
Aesthetics	▪ Visual ▪ Tactile	▪ Acoustic ▪ Olfactory
* Another aspect of durability related to envelope assemblies is differential durability (Kesik 2002), a term used to describe how useful service life differs - both between components, and within the assemblies comprising components.		

Table 1. Performance requirements for exterior walls and their corresponding assessment parameters.

PERFORMANCE OBJECTIVES HIERARCHY

The relationship of hygrothermal performance to other broad categories of building requirements is depicted in Figure 1. The relationship is hierarchical with requirements for health and safety taking precedence. The ordering of the remaining three categories may vary, depending on cultural attitudes towards buildings. Each category of requirements is at a different stage of evolution.

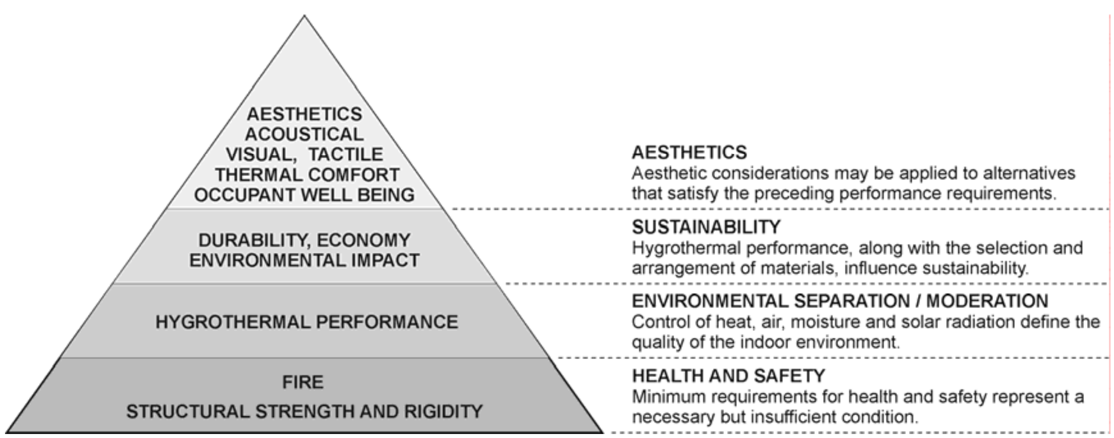

Figure 1. Performance hierarchy based on a building science approach to systems integration.

Requirements for health and safety are much better developed than those associated with hygrothermal performance. Structural engineering practices have evolved sophisticated approaches to analysis and design, and these continue to be adopted within codes and standards. Similarly, the fire safety of building assemblies has enjoyed decades of research and testing to the point where agencies such as ULC Canada publish directories of ratings for materials and assemblies, a sub-set of which appears in appendices of Canadian building codes. Satisfying minimum requirements for health and safety in exterior wall assemblies is a well defined process. As will be further discussed in the next section, requirements for hygrothermal performance are not as straightforward or standardized. However, from the modern consumer perspective, acceptable environmental separation/moderation is a common and rising expectation. Issues of sustainability are difficult to assess in the absence of reliable hygrothermal performance parameters. Durability is directly associated with hygrothermal performance and estimates of service life (CSA 1995). Hence life cycle costs are directly limited in accuracy by our ability to predict hygrothermal performance. Aesthetic requirements benefit from a long history of civilization and architectural precedents. Maintaining the aesthetic performance of exterior walls remains a long-term challenge, largely dependent on hygrothermal performance and durability.

The current state of wall design is such that minimum requirements for health and safety are well understood, and the tools and methods of analysis and design are highly reliable and accessible. Hygrothermal performance continues to elude codes and standards because it is evolving and has not reached the level of maturity associated with structural and fire engineering. But without a reliable assessment of hygrothermal performance, means for satisfying sustainability and aesthetic requirements are severely impaired. This relationship has been confirmed in previous research (Kesik 2001) and explains the hierarchical arrangement depicted in Figure 1.

It may be argued that the fatal flaw in earlier modern building design stems from a disregard for any rational process that embodies a phenomenological hierarchy. Many of the buildings that have been constructed since the time traditional methods and materials were abandoned, represent a process where aesthetics were considered initially and primarily, and then reconciled only with minimum requirements for health and safety. Hygrothermal performance and sustainability objectives were not explicitly addressed through any formal methodology, thereby compromising the quality and robustness of much of the preceding century's building stock.

Advances in tools and methods for assessing hygrothermal performance and sustainability requirements are beginning to influence today's building design processes. The next section looks at issues arising from contemporary efforts to better predict hygrothermal performance.

HYGROTHERMAL PERFORMANCE ASSESSMENT MODELS, METHODS AND THRESHOLDS

The variety and sophistication of heat, air and moisture (HAM) or hygrothermal models has dramatically evolved since the introduction of the Glaser method in 1958. An overview of available models and methods are well documented and readily accessible by practitioners (Straube and Burnett, 2001). Essentially, the sophistication of models is dependent on the consideration of:

- Physical dimensionality (1, 2 or 3 dimensional model);
- Time (steady state, bin or dynamic model);
- Quality and availability of information (input data);
- Stochastic nature of data set (material properties, weather, construction quality); and
- Validation of the models through laboratory and/or in-situ testing/monitoring.

Methods for applying these various models have also been developed and published in the literature. More recently, initiatives to standardize the application of these methods through the development of consensus guidelines are being undertaken (ASTM Standardization News 2003). Thresholds for deterioration mechanisms such as mould, corrosion, freeze-thaw and subflorescence remain a significant challenge to the reliable application of hygrothermal analysis within the context of a limit states design process. It is important to note that practical approaches have been advanced, however, concerns for liability among design professionals has not abated. A selective review of issues associated with critical hygrothermal thresholds is presented to reinforce these concerns.

Moisture Mechanisms

Figure 2 depicts moisture mechanisms in buildings, and it should be recognized that no single model currently exists that deals with all of these mechanisms. Further, stochastic data for many of the sources and processes is only beginning to emerge. This translates into a situation where even if the moisture thresholds (limit states) were known, it would be difficult to determine if they were exceeded by moisture loads. This remains the largest liability concern for practitioners assessing hygrothermal performance.

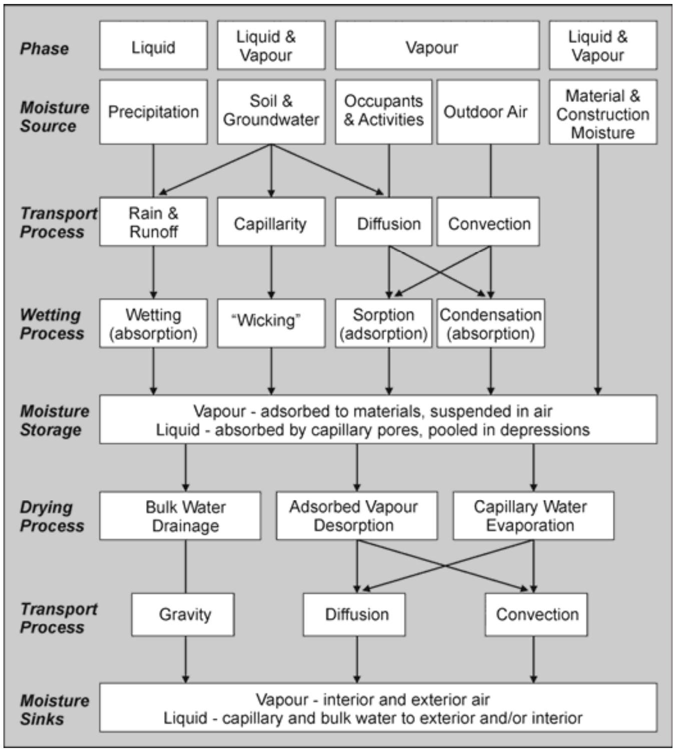

Figure 2. Moisture sources, processes, storage and sinks. [Adapted from J. Straube, 2002. *Moisture in Buildings*. ASHRAE Journal, January 2002.]

Corrosion

The primary factors affecting the corrosion rates of ferrous metal are the availability of moisture, the presence of chlorides and acids, time, and temperature. The ISO 9224 Standard provides likely corrosion rates for common metals as functions of these variables. The most important variable is the time of wetness (TOW), which is the number of hours/year above 80% RH and freezing at the metal surface. Corrosion rates from ISO 9224 are typically initial rates and assumptions must be made for service life predictions (i.e., the corrosion rate to use throughout the material's life). The analysis is more complicated for metal components embedded in mortar or concrete as it is difficult to predict: how long embedded metal components are protected from the initially high pH (passive oxidation layer) when in contact with chlorides/acid rain; and the carbonation effect on the passive oxidation layer - carbonation occurs most rapidly at RH between 50% and 80% without liquid water immersion (Rostam 1986).

Mould

There are many published thresholds for mould growth. The conditions supporting fungal growth are well agreed upon, however, estimates of susceptibility to mould and decay in actual building assemblies are more varied. Recently, an isopleth model has been presented to determine favourable temperature and moisture conditions (Sedlbauer 2002). While this research considers mould growth rates on various substrates, not all available building materials have been examined. Other unresolved parameters are the effects of temperature and relative humidity cycling on mould growth. The relative importance of RH, substrate quality, temperature and time on mould growth were identified in previous research (Krus et al. 2001). This remains a critical and controversial performance threshold.

Freeze-Thaw Risk

Freeze-thaw damage can occur in materials with more than 90% free saturation and below freezing temperatures. Factors such as the rate of cooling, temperature regime, salts, and air entrainment can all affect this process. From a practitioner's perspective, the risk of freeze-thaw damage is a common threshold of concern in cold climates. The use of hygrothermal analysis by computer simulation is among the more recent methods for assessing free-thaw risk (Sedlbauer and Kunzel 2000). Researchers have found that the outside air temperature level cannot be used as the only criterion, but that the combination of the number of freeze-thaw cycles in the building element's interior, and the moisture content in the material at those times, must also be considered. In practice, this involves subdividing exterior materials into fine layers (5 to 10 mm) during analysis, then filtering simulation data to find out how many yearly freeze-thaw cycles may occur in these layers. At present, a freeze-thaw cycle is defined as a zero degree crossing where the moisture content is greater than 90% free saturation. This approach enables a comparison of the number of freeze-thaw cycles for various alternatives/options to determine preferred solutions to minimize freeze-thaw deterioration risks. It is also possible to change material water absorption and vapour permeance properties to explore the effects of water-repellent coatings on freeze-thaw deterioration risks. Despite the sophistication of available techniques, the ability to model micro-environments, where water can accumulate in crevices or at joints, is a critical limitation that is currently addressed more by experience rather than simulation.

Subflorescence

Large expansive forces can occur when salt crystals form inside porous materials. The presence of surface salts (efflorescence) is usually obvious, however, crystallization behind the surface structure of porous materials is difficult to predict. The effect of dissolved salts on moisture transport has not been widely studied across a variety of porous construction materials, and this phenomenon is extremely difficult to predict by any method of hygrothermal analysis.

Current State of Practice

This cursory review of limitations associated with hygrothermal performance thresholds clearly establishes the significant risks facing practitioners. It is not intended to be critical, but rather seeks to clarify the following issues influencing the current state of practice:

- Decisions regarding the design of buildings will always involve lesser or greater degrees of uncertainty, and there are significant uncertainties associated with building envelopes;
- At present, the limit states design of wall systems is confined to structural requirements. Until research leads to consensus standards for applying factored loads and resistances for hygrothermal phenomena, experience and judgement will dominate design and assessment in professional practice. Hence concerns for professional liability may be expected to escalate.
- Hygrothermal analysis by computer simulation is here to stay, and there is no going back. How to best improve and ensure the accuracy and reliability of simulation software is a big question.
- On a comparative basis with other branches of building design, expertise in wall system design and assessment is highly arcane and limited to a relatively small proportion of building design professionals. It is generally found only in large urban centres and academic/research institutions.

Recognizing that buildings will continue to be constructed using all types of innovative material arrangements, it is essential that the results of research on hygrothermal performance be transferred to designers, builders and material manufacturers in a format that is timely, and harmonized with other performance requirements, such as fire and sound transmission ratings. Classification systems are means of simplifying complexity for practical purposes, in this case to achieve acceptable performance. They form an essential means of addressing objective-based codes in practice by listing acceptable solutions to functional requirements that otherwise involve sophisticated methods for demonstrating that quantitative performance criteria have been satisfied. The next section proposes a means of bridging the issues and concerns raised in this paper.

TOWARDS A HYGROTHERMAL PERFORMANCE CLASSIFICATION SYSTEM

It is generally recognized that hygrothermal performance responds to conditions of outdoor climate, exposure to moisture (precipitation) and indoor climate. These three variables have been described and/or defined in various manners by different international organizations and jurisdictions. In this paper, one of the earliest approaches (Lstiburek 2001) forms the basis of the discussion which follows.

Based on Lstiburek's approach, North America's hygrothermal climate regions were defined as:

Severe Cold - A region with approximately 4500 heating Celsius degree-days or greater.

Cold - A region with approximately 2500 heating Celsius degree-days or greater and less than 4500 heating Celsius degree-days.

Mixed-Humid - A region that receives more than 500 mm annual precipitation, has approximately 2500 heating Celsius degree-days or greater, and where the monthly average outdoor temperature drops below 7 degrees Celsius during the winter months.

Hot-Humid - A region that receives more than 500 mm annual precipitation, and where the monthly average outdoor temperature remains above 7 degrees Celsius throughout the year.

Hot-Dry/Mixed-Dry - A hot-dry region receives less than 500 mm annual precipitation, and the monthly average outdoor temperature remains above 7 degrees Celsius throughout the year. A mixed-dry region receives less than 500 mm annual precipitation, has approximately 2500 heating Celsius degree-days or less, and the monthly average outdoor temperature drops below 7 degrees Celsius during the winter months.

Precipitation exposure categories were defined using annual amounts of precipitation:

Extreme - Over 1500 mm.

High - 1000 to 1500 mm.

Moderate - 500 to 1000 mm.

Low - Under 500 mm.

Indoor climate classes were defined based on the degree of environmental control:

Class I - Temperature moderated, vapour pressure uncontrolled, air pressure uncontrolled.

Class II - Temperature controlled, vapour pressure moderated, air pressure moderated.

Class III - Temperature controlled, vapour pressure controlled, air pressure controlled.

It is recognized that many other approaches to defining hygrothermal climate regions and precipitation exposure have been developed, and that a significant effort is underway to internationally standardize these important measures. Recent research in Canada (Cornick and Dalgliesh, 2003) has adopted the concept of moisture index (MI). The modeling and validation of indoor environmental conditions has been recently explored (Aoki-Kramer and Karagiozis 2003). There are also efforts to quantify micro-climatic effects related to building orientation, geometry and the driving rain index, as well as micro-environmental effects (e.g., the underside of an overhang, or below a window sill, sometimes referred to as nano-climate). While it may be expected that research will continue to advance knowledge regarding the modeling of these phenomena, it is also reasonable to assume that climate, exposure and indoor environment will remain the primary variables driving hygrothermal behaviour.

Figure 1 depicts one approach to a hygrothermal classification typology that considers climate, precipitation exposure and indoor climate class. It is important to note that the various notations should be based on whatever consensus conventions are adopted in the hopefully not too distant future.

HYGROTHERMAL CLASSIFICATION TYPOLOGY

WALL TYPE
based on
3 parameters

CLIMATE (Hygrothermal Region)	**PRECIPITATION EXPOSURE***	**INDOOR CLIMATE CLASS**
Any/All	**E**xtreme	Class **I**
Severe **C**old	**H**igh	Class **II**
Cold	**M**oderate	Class **III**
Mixed-**H**umid	**L**ow	
Hot-**H**umid		
Hot-**D**ry / **M**ixed-**D**ry		

EXAMPLE CLASSIFICATIONS

Type A-E-III
Conducive to all climates, extreme precipitation exposure, and fully controlled indoor environment.
Example application: standardized, multi-national, pharmaceutical research/manufacturing facilities to be constructed in numerous international locations.

Type SC-M-II
Conducive to severe cold climate, moderate precipitation exposure and partially controlled indoor environment.
Example application: low-rise housing in the northern Great Lakes region.

Type C-L-I
Conducive to cold climate, low precipitation exposure and moderated indoor environment.
Example application: farm equipment shed in the mid-western United States.

* Precipitation exposure is a function of geographic location, micro-climate, orientation and building height/geometry.

Figure 3. Proposed typology of a hygrothermal classification system for exterior wall assemblies.

Globalization will eventually demand an internationally recognized system of performance classification for buildings, similar to what is taking place in the electronic, automotive and pharmaceutical industries. Hygrothermal performance of wall assemblies represents a reasonable starting point.

INTEGRATING CLASSIFICATION SYSTEMS

In professional practice, it is critical to properly assess the various performance requirements for exterior wall assemblies within a particular context. In some cases, a technically superior wall assembly may not be selected in favour of an assembly that has a higher likelihood of being properly assembled by local trades. As was noted earlier, structural and fire safety must also be carefully considered, along with economic and environmental constraints. Viewed from this perspective, a hygrothermal classification system is one among many classification systems that must be reconciled using professional judgment and experience.

Various techniques for dealing with this type of decision process have been developed. One approach involves multi-attribute decision analysis (MADA) where a means of dealing with quantitative, qualitative and monetary attributes is made possible (Norris and Marshall 1995). Another increasingly popular approach involves knowledge-based expert systems (KBES). This particular approach has demonstrated suitability to decisions involving material selection and arrangement (Trethewey et al. 1998).

Major barriers to these integrative techniques include the reliability of performance prediction and the narrowing of possible outcomes to a practically finite set of feasible alternatives. Hygrothermal performance assessment guidelines combined with consensus classification systems hold the potential to overcome current barriers to the implementation of ‘best practices’ for wall system analysis and design.

FUTURE RESEARCH DIRECTIONS

The development of a hygrothermal performance classification system for exterior walls is dependent on research conducted by the international building science community. Preparation of this paper has suggested the need for the following research:

1. Development of an electronically accessible database containing comprehensive material properties that indicate variations with environmental conditions and exposure (see Kumaran 2001). Studies are required to determine how material properties vary with age, temperature, and with chemical interactions among adjacent materials.
2. Ongoing testing programs to verify the variability of material properties based on origin or manufacturing process. These programs will generate factors similar to material resistance factors in limit states design of structures.
3. Consensus standards development is needed to more accurately define moisture-related performance thresholds so that modeling software can incorporate modules that post-process the output data against the various performance thresholds.
4. Improved availability of weather data for hygrothermal analyses is vital. Hourly weather data (global horizontal solar radiation, diffuse horizontal solar radiation, cloud index, air temperature, relative humidity, wind speed/direction and normal rain) is not readily available. Complete weather data for only a limited selection of cities currently exists.
5. Validation of hygrothermal models and procedures to improve the reliability of limit states design guidelines, similar to recently demonstrated approaches (Kalamees and Vinha 2003).

As future research efforts proceed, the development of a hygrothermal classification system for exterior wall assemblies of residential buildings is viewed as one of the more appropriate initiatives, given the traditionally low involvement of design professionals providing sophisticated analyses to home builders. It is foreseeable that manufacturers will seek hygrothermal performance ratings from testing agencies for wall assemblies incorporating their materials, similar to what is now available for fire and sound ratings. This will allow for a wider variety of prescriptive alternatives (acceptable solutions) within objective-based codes, and encourage construction innovation. Eventually this trend may extend to commercial and institutional building construction for many standard applications, but it is more likely that refinements to hygrothermal design and assessment guidelines will foster more affordable and accessible design consulting for uniquely responsive building envelopes.

CONCLUSIONS

Development of a hygrothermal classification system for exterior wall assemblies is a necessary means of reducing the complexity of logically integrating whole building system performance. This paper concludes with the following insights on hygrothermal classification systems:

1. The development of hygrothermal classifiction systems addresses the implementation of objective-based codes, while encouraging construction innovation.
2. Hygrothermal ratings for wall assemblies represent the weak link in an integrated '*systems approach*' to exterior wall design and performance assessment.
3. A robust and reliable hygrothermal classification system would facilitate a more efficient deployment of limited design resources, preferably toward the appropriate detailing of wall assemblies.

The research and practice issues presented in this paper reinforce the importance of technology transfer from researcher, to practitioner, to builder. The goal is to render well performing buildings within the grasp of the many, through the intelligent and focused efforts by the few.

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