Importance of Moisture Control in Building Performance

Achilles N. Karagiozis
Oak Ridge National Laboratory
Building Technology Center
Oak Ridge, TN, 37831-6070
karagiozisan@ornl.gov

ABSTRACT

The number and frequency of moisture-related premature failures in exterior wall systems has called into question current design and construction practice, materials use, and building code requirements. Many questions have been raised as to whether more rugged materials, more robust assemblies, and revised building codes are needed for climate regions subject to higher moisture loads.

A Seattle research project titled, "Building Enclosure Hygrothermal Performance Study" has been initiated by the moisture-damage committee formed by the Department of Design, Construction and Land Use (DCLU) for the city of Seattle. This committee will assess the performance of current and past typical wall constructions. In the first phase of this project, we analyzed heat, air, and moisture performance of a set of (primarily stucco-clad) wall systems.

A new "moisture engineering approach" was adopted in the project. Moisture engineering analyzes hygrothermal loads from vapor, water, heat, and pressure. In addition to these loads, water penetration data are also included to provide realistic assessments of the performance of building envelope systems.

This paper reports on moisture engineering as performed using Oak Ridge National Laboratory's (ORNL's) state-of-the-art hygrothermal model, MOISTUTE-EXPERT. Transient two-dimensional analysis was performed using hourly weather and interior environment data. Data on the sensitivity of water penetration are also shown for a few selected walls in the Seattle research project. This paper describes only part of the overall project that investigated the response of the walls as a function of weather-resistive barriers, wall venting or ventilation, and the influence of interior moisture generated by the building's inhabitants. The research results also have implications for the need to re-evaluate building codes and their influence on building material durability.

INTRODUCTION

Controlling the accumulation of moisture in building enclosures has been a topic of growing interest, especially over the past 15 years. Changes in building standards and codes immediately preceding that period were initiated by governmental and environmental groups who were concerned about conserving energy. Customer demands for improving interior comfort also contributed to development of tighter building envelopes and increasing insulation levels. The focus on improving the building envelope's thermal performance has affected other aspects of building enclosure performance, most notably moisture performance. Experienced building scientists and professionals frequently share anecdotal evidence that as building enclosure tightness and insulation levels have increased over time, so have the number of premature building enclosure failures due to moisture accumulation. Older buildings simply do not fail at the same rate as newer buildings. Both old and new buildings experience moisture intrusion, but we do not fully understand what is causing newer buildings to incur moisture damage at a much faster rate than older buildings. Moisture accumulation seriously compromises not only the life span of building enclosures, but also degrades indoor air quality and thermal performance.

In response to growing moisture-damage problems in the Seattle area, members of Seattle's Construction Codes Advisory Board (CCAB)[1] began investigating moisture intrusion and damage problems in July 1998. Based on their experience, CCAB members have seen a disproportionate number of relatively new (built since 1984) multistory, multifamily residential structures experience premature building enclosure failures

---

[1] The Construction Codes Advisory Board (CCAB) is the City of Seattle's advisory board for the technical construction codes. The CCAB comprises 13 members representing the construction industry, property owners, and the general public.

caused by moisture accumulation. The CCAB established the moisture-damage committee (an ad hoc committee of CCAB members, concerned state and local agencies, and community building professionals) to advise and guide CCAB's investigation of moisture-damage issues. From November 1998 to March 1999, the Seattle Department of Design, Construction and Land Use (DCLU) and the moisture-damage committee conducted an informal survey of multifamily residential structures to assess the approximate number of moisture-damaged structures in Seattle, the causes of moisture intrusion, and the cost to fix the damage. DCLU received 71 completed surveys representing 74 multifamily residential buildings constructed from the early 1900s to the mid-1990s. Two-thirds of the surveys represented structures built between 1984 and 1998. Fifty-one structures reported construction material and labor cost that totalled approximately $98 million to repair these buildings. This cost did not include costs for investigation, attorneys, or tenant/owner relocation.

As was found previously in the moisture-damage surveys taken in Vancouver, B.C., interface details were listed as the primary source of water intrusion (CMHC 1996). The survey also found that moisture damage was not limited to exterior insulated finish systems (EIFS) clad walls, but affects all cladding types. Because participation in the survey was voluntary and surveys were sent to only a small percentage of apartment owners/condominium associations, the survey results do not necessarily indicate increased moisture-damage problems in newer multifamily buildings. However, the moisture-damage committee members note that in addition to the 38 moisture-damaged structures for which they completed surveys, they have begun investigations into another 150–200 moisture-damaged structures in Seattle and the greater metropolitan area, most of which were built within the past 15 years. Based on DCLU permit tracking data, which shows that approximately 938 multifamily structures were built between 1984 and 1998, moisture damage appears to affect approximately 20% of the multifamily structures built in the Seattle area over the past 15 years. After hearing presentations from Canadian building scientists and the Oak Ridge National Laboratory (ORNL) Buildings Technology Center (BTC) staff, the moisture-damage committee members recommended seeking assistance from ORNL BTC staff to help understand factors that affect the hygrothermal performance of the western Washington/Seattle area building enclosures. DCLU agreed to provide funding to support the damage committee's study proposal and to provide staff support. The Washington State University Cooperative Extension Energy Program (WSU Energy Program) agreed to be a partner in the research by providing library research services and technical support. The results of the research will be used by the state and local partners to develop technical guidance documents and, if necessary, proposals for building code changes.

The strategy taken in this study was to refine and apply a moisture-engineering evaluation to develop engineering assessments that did not favor particular materials—claddings, insulation materials, weather-resistive barriers or even interior vapor control strategy—but to examine the performance of the wall in terms of the system's total moisture performance. The moisture performance of the walls was tracked in terms of its total hygrothermal response to thermal, moisture and pressure loads.

Within the particular design of a building envelope, all kinds of considerations and priorities may exist. The purpose of this work is to develop a better understanding of all processes affecting the performance of the wall. At the same time, we set out to demonstrate an innovative approach on how an engineer/architect may apply a safety factor towards the design of a particular wall for hygrothermal loads. This is a first attempt to employ such an analysis for moisture design of wall systems in Seattle.

MOISTURE DYNAMICS

Moisture may be transported by diffusion, capillary and convection processes, as well as by unintended water penetration. Moisture can be present in any wall system in three thermodynamic physical states: solid (ice), liquid, and vapor. Indeed, all three may be present concurrently in a wall system. This creates complex fundamental transport interactions within a construction material. Understanding the overall performance of building envelope systems with respect to heat, air and moisture (HAM) excluding durability, is a formidable task. During the transport of moisture, some materials may store and accumulate water in the porous structure. Mechanical, biological, and chemical damage may occur, depending on the amount of water stored, environmental conditions, history, and intrinsic material properties of a material. In any envelope, some construction materials may be more prone to ageing and damage due to moisture transport than others. Understanding and predicting moisture movement within and through the envelope is therefore of fundamental importance to predicting and improving performance, particularly durability.

Recently, several models have been developed to predict the hygrothermal performance of building systems. These models vary significantly and can be ranked in terms of both mathematical sophistication and inclusions of building system and subsystem performances according to the new *ASTM Manual of Moisture Analysis*, chapter 6 (Karagiozis 2001). This classification approach allows models to differentiate in terms of simplified design and research tools. In the past few years, simplified models are being used less, as user-friendly hygrothermal design tools have become available (Karagiozis et al. 2001). However, more sophisticated research models such as MOISTURE-EXPERT (Karagiozis 2001) can be employed in the development of design guidelines for the long-term performance of building systems.

Currently, a standard approach does not exist for the use of hygrothermal modeling, whether this is at the preliminary investigative stage or at the final design optimization stage. This makes the interpretation of the results generated from simulation models (advanced or simplified) by a building consultant dependant on the level of understanding of the inputted building dynamics. Misapplications of hygrothermal modeling may develop design recommendations that have little value or may result in recommendations that do not address the moisture-control problem or that may create a worse problem. As with any building design activity, use of such analysis should be conducted by qualified individuals with appropriate background in heat and mass transfer such as mechanical engineers, civil engineers, and architectural engineers.

To capture and predict the "real" moisture dynamics that include the response of the building to heat, air, and moisture excitations, input must reflect realistic loads. In a majority of past hygrothermal simulations, key elements of real envelope behavior have not been included. For example, the input parameters for the development of the air barrier guide for CCMC (1996) did not include the influence of wind-driven rain, night sky radiation, the dynamic interior environment, and the sorptive capacity of the exterior cladding. In addition, this CCMC barrier guide did not determine moisture design criteria based on exterior environmental loads, and most critically it assumed only vapor flows. No liquid transport was included in the CCMC analysis, this alone can critically limit the value of the results. Unfortunately, recommendations have already been implemented in the National Building Code, and are already being adopted by others.

In another recent example, the role of the weather-resistive barrier on the hygrothermal performance of a wall was examined using an advanced hygrothermal model by a research group. A set of recommendations was developed and published that diminished the importance of the weather-resistive barrier by totally ignoring the function of the barrier to shed water and to provide a drainage plane for incidental water entry. As only the vapor transmission characteristics were examined by the research group, the results could mislead architects and engineers if the conclusions from this study are adopted.

This paper will present preliminary results using the advanced (ASTM 2001) hygrothermal model, MOISTURE-EXPERT (Karagiozis 2001) to investigate the moisture performance of stucco-clad walls in Seattle. Results are preliminary because hygrothermal material property data are being currently measured at ORNL for many construction materials, interior environmental data are being collected, and a state-of-the-art "test facility" is being built in Seattle. The test facility will have more than 10 wall sections that will be monitored. As the field testing of the building envelope system and subsystem characterization is analyzed, this performance data will be incorporated into the model. A moisture engineering approach will allow the generation of stucco wall design guidelines through use of integrated hygrothermal material property, field system and subsystem characterization, and advanced modeling.

MOISTURE-EXPERT:Advanced Hygrothermal Model

This model was developed at the Oak Ridge National Laboratory by Dr. Karagiozis (ASTM, 2001) to predict the complex heat, air, and moisture transport in building envelope systems. This model incorporates the latest understandings of the physics of hygrothermal processes and allows extension of this model to durability predictions. Each transport process has been developed in an object-like representation, where specific indexes store the linkages of the process to other actions or performances. The type of representation allows direct interaction of the magnitude/strength, occurrence, and frequency of various hygrothermal potentials to durability processes. In this regard, this model is unique.

The model is capable in predicting the 1-D and 2-D heat, air, and moisture transport in building envelope geometries. The model treats vapor and liquid transport separately. The moisture transport potentials are vapor pressure and relative humidity, and temperature for energy transport. The model includes the capability of handling temperature-dependent sorption isotherms and liquid transport properties as a function of drying or wetting processes.

The MOISTURE-EXPERT model includes porous airflow through insulation by solving a subset of the Navier Stokes equations–the Darcy's equations. The

MOISTURE-EXPERT model accounts for the coupling between heat and moisture transport via diffusion and natural and forced convective air transport. Phase change mechanisms due to evaporation/condensation, freezing/thawing are incorporated into the model. The model includes the capability of handling internal heat and moisture sources, gravity-driven liquid moisture, and surface drainage. The model also captures experimentally determined system and subsystem performances and anomalies of the building envelope. One of the model's unique features is its capability to include temperature-dependent sorption isotherms, and directional and process-dependent liquid diffusivity. Currently, the model incorporates subsystem drainage performance from a field drainage study performed by Straube et al. (2000).

The moisture transfer equation, including contributions from liquid, vapor, air flow, and gravity-assisted transfer is

$$\dot{m}_M = -D_\phi(u,T,x,y)\nabla\phi - \delta_p(u,T)\nabla P_v + v_a\rho_v + K(u)\rho_w\vec{g}$$

Where:

$\dot{m}$ = Mass flux, kg/m^2·s
D_ϕ = liquid moisture transport coefficient, m^2/s
u = moisture content, kg_w/kg_d
T= temperature, ^{o}C
δ_p = vapor permeability, kg/s·m·Pa
P_v = vapor pressure, Pa
v_a= velocity of air, m/s
ρ_v= density of vapor in the air, kg/m^3
K= moisture permeability, s
ρ_w= density of liquid water, kg/m^3
g= acceleration due to gravity, m/s^2

Purpose of Seattle Wall Research

The purpose of this research project was to

- assess the effect that building enclosure components have on the transmission of heat and moisture into and out of western Washington/Seattle area building and
- assess the relative thermal efficiency and hygrothermal performance of older (pre-1984) western Washington/Seattle area building envelopes versus new (1999) building envelopes.

To accomplish the stated objectives, this project required state-of-the-art advanced computer modeling and expert consulting services from ORNL to study the predicted hygrothermal performance of the range of western Washington/Seattle area building enclosures.

The analysis sought scientific evidence to support or refute widely held beliefs regarding hygrothermal performance differences between older and newer structures. The analysis would also determine the role building, ventilation, and energy codes have played, if any, in affecting hygrothermal performance. The research also analyzed specific reasons for any differences in hygrothermal performance of buildings and suggested improvements to Washington's residential construction codes.

Conceptual Approach for Moisture Control and Drying Potential of Envelope Systems

Any wall system can be characterized as comprising a few basic subsystems. The exterior most subsystem is identified as the cladding or façade system. Others include the weather-resistive barrier system, the sheathing system, the insulation system, the framing system, the vapor-diffusion control system, and the air-barrier system. A multitude of variations may exist among these fundamental systems. In some cases, the functions of several systems can be accomplished by one system if proper performance criteria can be satisfied. The drying capability of a building envelope system with initial construction moisture and recurring water penetration critically depends on the climatic conditions in which the wall is placed, and on the system and subsystem performances of these wall systems and components. The drying-rate mechanisms by which walls redistribute and transport moisture must be incorporated directly into the wall designs. When a wall is not properly designed with adequate drying capacity, the potential for moisture-induced damage significantly increases. The drying potential then becomes a distinct property of each wall system and can be ranked.

The challenge is to develop building envelope designs that incorporate high drying potentials. This may be achieved by allowing the wall systems to dry towards both the outside and inside whenever possible. Several successful walls systems have been implemented for centuries that allow and control moisture flow using no restrictive elements. In the past, such wall systems typically require a tremendous amount of energy to heat the space bounded by the walls. Today, the challenge is to design walls that include features to enhance energy efficiency.

This approach was developed in a generic fashion and has been applied to other building envelope systems (Karagiozis 2001). Because water is a solvent, all walls will eventually have water leaks. Some walls will leak as soon as they have been built while others (e.g., heavy masonry systems) may take a considerable time. However, no matter how and why water penetrates through the wall, each wall has a distinct rate of drying. The drying rate of a wall depends on the loads to which the wall is exposed. The wall's drying rate performance characteristic was used in this project, which is dependent not on one element but on all elements combined to assess the total hygrothermal performance. Subsequently, a wall-ranking system was developed and used to rank the walls in terms of their efficiency in handling incidental water penetration.

Conventional moisture design of building envelopes essentially considers transport mechanisms caused only by vapor diffusion. At best, this conventional approach captures a very small portion of the possible "real moisture loads" in residential construction. Indeed, the loads present caused by air leakage may be 60–100 times those caused by vapor transport, while loads caused by wind-driven rain may contribute 10–100 times those caused by vapor transport. Walls in the past have been designed using steady-state models that assumed that material properties were constant, and in almost all cases, did not take into account the sorption capabilities of the materials. Rain, wind, solar irradiation, air and vapor pressure, and sky radiation were never used as driving potentials for moisture transport. Designs also assumed perfect systems—walls that never leaked air or water. These types of assumptions clearly illustrate the limitations of some existing and past design approaches, as the designs never included the "real" loads that actually dictate the moisture behavior of walls.

The approach adopted in this work is state-of-the-art. It includes contributions from hygrothermal loads caused by wind-driven rain, solar irradiation, sky radiation, mechanical pressures, wind pressures, stack effect, vapor diffusion, liquid diffusion, sorption and suction storage, and temperature-dependent sorption capabilities. In addition, freezing, thawing, and evaporation-condensation characteristics were included in the analysis. At all times, the thermal transport was fully coupled to moisture transport.

In addition to these loads, the effect of water penetration was also included, based on the possible paths for water entry. The water penetration in the walls can be interpreted in two ways. It can be viewed as a possible construction/contractor index that is directly related to the level of workmanship or it can be viewed as an inherent feature of the wall. This inherent feature of the wall may represent the level of complexity in making the wall air tight or water tight. If water penetration is viewed as an inherent feature of the wall, then the wall may be related to the quality and durability of the materials involved. Materials and their associated mechanical, chemical, and hygrothermal properties may change as a function of time and the environment to which they are exposed.

For example, the enhancement in the evaluation approach used to assess the hygrothermal performance of stucco-clad systems recognizes that such walls need to resist more than just vapor diffusion loads. The stucco walls also need to resist influences of wind-driven rain, air leakage, and water penetration. This approach makes the results from this preliminary Phase I parametric study unique in North America and elsewhere. A complete report on this activity is available from ORNL (Karagiozis 2002).

Reality Check

System and Subsystem Performance

The water penetration performance data for the stucco-clad wall simulations were generated at the JJAC test house of at the Building Science Corporation in Boston. The weather-resistive drainage characterization and the water penetration performance of several building papers was examined in the JJAC test house. A simple test program was devised by Drs. Lstiburek, Straube, Karagiozis, and Mr. Schumacher to investigate drainage in full-scale walls clad with stucco and horizontal vinyl siding. Figure 1 depicts the octagonal test house of eight 4-ft wide and 8-ft high 2 x 4 framed walls. The eight walls comprised seven test panels and one door.

The flow leakage rates and paths were forensically determined. In Figure 2, the drainage capability of single- vs multiple-layered building paper was examined, and the effect of the adherence of the building paper to the stucco façade is depicted. Various water leakage contact with the sheathing were also monitored and recorded. These important field performance attributes of the weather-resistive sheathing barrier were included in the model.

Figure 1: JJAC water drainage/penetration set-up.

Figure 2: Drainage capability of multilayers of building paper.

Boundary Conditions and Initial Conditions

The analysis was conducted while subjecting the exterior boundary of the wall to real weather data (temperature, vapor pressure, wind speed and orientation, solar radiation, wind-driven rain, sky radiation, and cloud indexes). A 10% cold and 10% hot year was developed for Seattle from 30 years of hourly data from the National Climatic Data Center. This approach is currently being proposed by ASHRAE SPC 160P (ASTM 2001) and has been examined in detail by IEA Annex 24. All wall systems investigated in this paper were subjected to the same climatic conditions of Seattle, Washington. Interior conditions were also allowed to vary depending on the time of day and exterior conditions, and by adding additional moisture sources. All material layers of the wall were assumed to be in equilibrium at 20° C and with a relative humidity (RH) of 85%.

Material property

Prior to initiating the simulation exercise, the author solicited material properties from several building material manufacturers. The basic material properties required in the modeling analysis are as follows:

- Water vapor permeance as a function of relative humidity
- Liquid diffusivity as a function of moisture content
- Sorption + suction isotherm as a function of temperature
- Thermal conductivity, density and heat capacity

These properties are not single valued; they may also depend on time, history, or other dependent variables. The change in material property performance was not taken into account. Directionally dependent material properties were employed for the wood-based and insulation materials. Because the existence and reporting of basic material properties varied widely from manufacturer to manufacturer, the material properties employed in these simulations were taken from Kuenzel (1995) and Kuenzel et al. (2001).

Simulation Cases

The basic stucco-clad wall as shown in Figure 1, was composed of the following layers starting from the outside to the inside:

- 1/8 in. acrylic stucco
- 7/8 in. convention cement stucco
- 15 # felt paper
- ½ in. oriented strand board (OSB)
- 6 in. fiber glass insulation
- polyethylene sheet
- ½ in gypsum board

The exterior was exposed to hourly Seattle weather conditions, while the interior was exposed to relative humidities and temperatures that were dependent on outside conditions and the number of inhabitants. The wall was assumed to be centrally located in the middle of a two-story building. The inside surface of the gypsum board was coated with a vapour permeable paint (permeance approximately 400 ng/(m2sPa) or 8 perms).

The oriented strand board moisture content was assumed to be in equilibrium with 85% relative humidity initially. This represents initial moisture condition in the OSB layer that would be above acceptable moisture contents permitted by building inspectors. The simulations were carried out for a two-year exposure starting on the 1st of July.

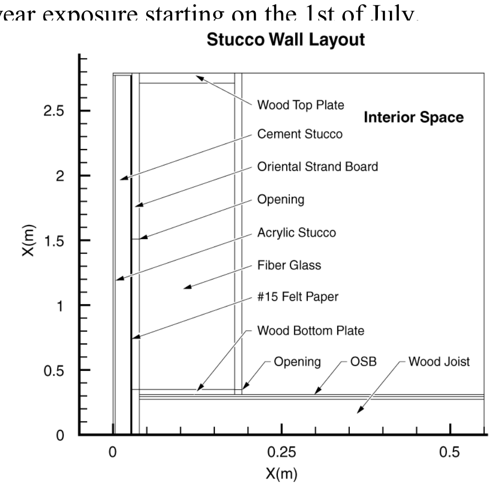

Figure 3: Stucco Clad Wall System

The solar radiation and long-wave radiation from the outer surfaces of the wall were included in the analysis. Air flow was also modeled as needed. The effect of water leakage was included based on the field drainage data test. A representative value of 1% was assumed, and this value was incorporated into the model. The rain penetrated at the interface of the building paper and sheathing board, as found in the field test by Lstiburek et al. (2000). It is expected that as more data are developed, better estimates can be assigned to the model. Drainage was modeled using the surface tension of the paper, the size of the gap, and the use of either single or double building paper in the wall assembly.

SIMULATION RESULTS

This paper presents only two aspects of the Seattle study. These deal with the effect of building interior vapor-control strategy and the effect of building paper type (weather-resistive membrane) on the hygrothermal performance of stucco-clad walls.

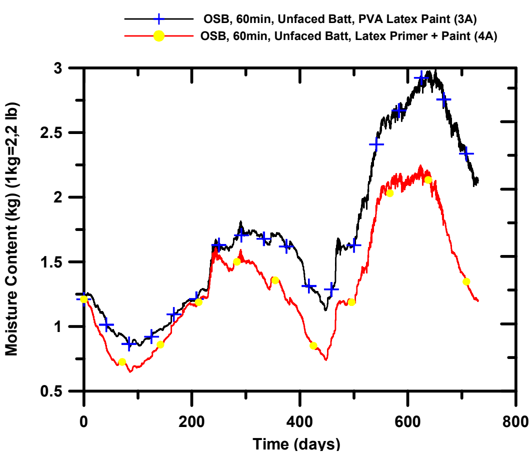

Figure 4: Interior vapor-control strategy

Effect of Building Interior Vapor Control Strategy

In Figure 4, the effect of interior vapor-control strategy is shown for two stucco-clad walls. The total moisture content (kg) in the exterior sheathing board is plotted out for a period of two years. In the first walls, a vapor retarder paint is used in addition to the latex primer and paint, while in the other case, a latex primer and paint were used. Both walls had two layers of 60-min building paper installed on the exterior. The walls' drainage capability was improved with the use of two layers of 60-min building paper. The results clearly depict the detrimental effect of the use of PVA (62 ng/s m^2 Pa) as an interior vapor-control strategy when interior relative humidity is kept within a healthy range of 30–60%. The vapor-open strategy (latex paint and primer) performed best in terms of moisture control. A parallel set of simulations were performed where high interior relative humidities (yearly average of 65 and 70% RH) were employed. The results clearly depict the importance of interior vapor control and strongly suggest the use of a low vapor-permeance system. But under high interior load conditions, the indoor air quality also deteriorated .

Effect of Building Paper Type (Weather-Resistive Membrane)

Figure 5 shows the comparison of the use of a single- vs multiple-layer building paper using the same stucco-clad wall. The moisture performance as a function of time (moisture content) is shown for the OSB layer. The primary enhancement shown for a wall with two layers of sheathing paper was caused by better performing drainage. The additional vapor resistance of the building paper did not significantly affect the drying performance of the wall. However, the performance differences are significant. The effective OSB sheathing board vapor resistance was several times higher, providing a limiting value for drying out.

CONCLUSIONS

Advanced research tools such as ORNL's MOISTURE-EXPERT can assist in evaluating the performance of various building envelope systems and can optimize "real systems."

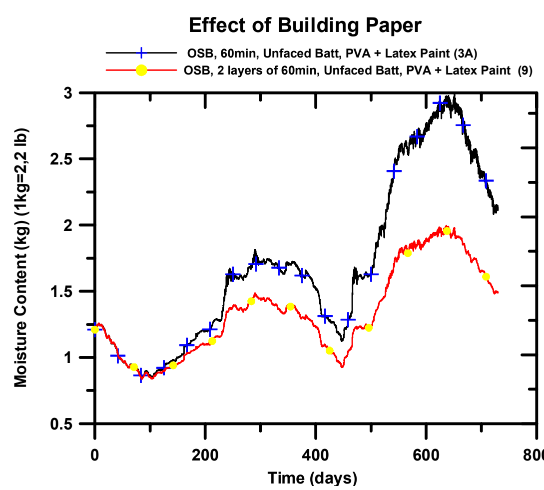

Figure 5: Effect of building paper.

A model is only a tool, and requires appropriate loads for inputs. The development of any guideline requires understanding of the wall system first, performing field tests that give insight to the system and subsystem performance, and then examining the drying-rate performance. Improving the performance of building envelopes through design can be achieved only when the tools used are capable of analyzing liquid flows, water penetration, drainage, air flow, and actual material (e.g. temperature-dependent sorption).

Interior vapor control systems are important and must be designed using inhabitant information. If the relative humidities are maintained below 60%, then the use of a latex primer and paint may perform better than the use of PVA or even of a polyethylene sheet. When the interior environment is maintained at higher relative humidities, then stricter interior vapor control is required.

Multilayered building paper was experimentally shown to enhance the drainage capability of the stucco walls in a set of preliminary drainage tests. The simulation results indicate the beneficial influence of such an arrangement with respect to changing exterior environmental conditions. The effectiveness of the building paper depends on the type of interior vapor-control strategy being used on the interior. The results have shown that two layers of 60-min paper performed better than a single layer of 15# paper. In general, weather-resistive building papers play a very important role in a stucco-clad wall system. Vapor diffusion control is only part of what these membranes offer.

ACKNOWLEDGEMENTS

The author is grateful to Department of Energy (DOE) manager Arun Vohra for his continued support of ORNL's Building Technology Center Moisture Management Program. The author would like to thank Drs. Straube and Lstiburek and Mr. Shumacher for the development of a drainage testing methodology. Finally, thanks are due to Michael Aoki-Kramer from City of Seattle DCLU and Chuck Murray from WSU for their support in Seattle's first moisture engineering project.

REFERENCES

ASTM. 2001. Ed. H. R. Trechsel. *Moisture Analysis for Buildings, Manual 40*, Chapter 6: Advanced Hygrothermal Models for Hygrothermal Research, American Society for Testing and Materials, West Conshohocken, PA.

CMHC. 1996. *British Columbia Building Envelope Study,* Canada Mortgage and Housing Corporation.

Karagiozis, A.N. 2001. *Advanced Hygrothermal Model MOISTURE-EXPERT*, Oak Ridge National Laboratory, Report I. Oak Ridge, TN.

Karagiozis, A.N. 2002. "Building Enclosure Hygrothermal Performance Study Phase I," ORNL/TM-2002/89, Oak Ridge National Laboratory, Oak Ridge, TN.

Karagiozis, A.N. 2001. "Advanced Hygrothermal Modeling of Building Materials using Moisture-Expert 1.0," 35th International Particleboard/ Composite Materials Symposium, Pullman, Washington.

Künzel, H.M. 1995. *Simultaneous Heat and Moisture Transport in Building Components. - One- and two-dimensional calculation using simple parameters.* IRB Verlag.

Künzel, H.M. 1998. "More Moisture Load Tolerance of Construction Assemblies Through the Application of a Smart Vapor Retarder," Thermal Performance of the Exterior Envelopes of Buildings VII, Clearwater, FL, pp.129–132.

Künzel, H.M., Karagiozis, A.N., and Holm A.H. 2001. *Moisture Analysis for Buildings, Manual 40*, Chapter 9, A *HygrothermalDesign Tool for Architects and Engineers (WUFI-ORNL/IBP)* . American Society for Testing and Materials, West Conshohocken, PA.

Straube, J., J. Lstiburek, A.N. Karagiozis, and C. Shumacher. 2001. *Investigation of Water Drainage in Walls Systems.* Building Science Corporation Report