# Activity 3: Advanced Moisture Engineering/Modeling

In this activity, the ORNL MOISTURE-EXPERT hygrothermal model (Karagiozis, 2001) was employed in developing a parametric analysis of the performance of permeable wall systems without mechanical ventilation. A series of 2-D simulations were performed. The 2-D simulations allowed us to determine the hygrothermal performance of the walls with the influence of infiltration/exfiltration air dynamics. In these 2-D simulations, the influence of air flow through the wall system was evaluated as a function of hourly wind pressures. As 1-D simulations do not include air flow dynamics in walls, a decision was taken to limit the number of simulations conducted, but to carry out all the simulations in 2-D. In Table 1 a review of the parametric analysis is given. This decision was beyond the initial intent of the project, as 1-D simulations were proposed.

A decision was made by the research team (BSC and ORNL) to select two climate conditions. The particulars regarding the selection of the two climates were presented in Activity 2 section of this report. The climates chosen were weather stations located in Minneapolis and International Falls. Two climatic years representing the 10% percentile cold and 10% percentile warm year were determined from the 30 year hourly data, as currently proposed by ASHRAE SPC160P. From the series of parametric simulations, the hygrothermal performance was tracked and assessed. A mold growth model was also used to assess possible durability problems. This moisture engineering approach allows a fair assessment of the hygrothermal influences that affect design decisions such as those proposed in this work. The combined effects of both vapor and air permeable wall systems can be effectively compared against those with imbedded moisture control elements. The ASHRAE SPC 160P proposed methodology to compute the interior environment load (moisture conditions) was also used in this project. The indoor air quality requirements set by ASHRAE 62.2 were also considered and addressed in the simulations. The SPC160P methodology (recently presented at Performance of Exterior Envelopes of Whole Buildings VIII in Clearwater FL, 2001 by TenWolde and Walker) was adopted for determining the indoor moisture conditions. The approach was discussed in detail in Activity 2 of this report.

Building Science Corporation staff (including Mr. Ueno, Project Manager, and Mr. Armin Rudd), assisted in the development of data used to characterize the air leakage of Category 2 buildings in Minnesota. The results were based on measured single residential as well as multi-family housing data that were collected using blower door testing. A value of 4 ACH of leakage at 50 Pa pressure difference was chosen for Minnesota housing stock with a floor area of 1400 $ft^2$. The ASHRAE Handbook of Fundamentals (1997) was used to determine the distribution of air leakage through the building envelope wall elements. Approximately 35% of the air leakage was assumed to flow through the walls. This was used to develop the effective leakage characteristic of a wall opening. Overall leakage data were used to calculate the interior environmental loads and the corresponding interior vapor pressure and relative humidity conditions as proposed by ASHRAE SPC 160P.

Table 1: Parametric Analysis Variables

| Envelope Systems | Climate | | Indoor Conditions (Moisture Production Rates, kg/day) | | Mechanical and Non-Mechanical Ventilation (Pressure Pa ) | | |
|---|---|---|---|---|---|---|---|
| Wall1 | Minneapolis | International Falls | 6.8 | 16.8 | 0 Pa | 3 Pa | -3Pa |
| Wall2 | Minneapolis | International Falls | 6.8 | 16.8 | 0 Pa | 3 Pa | -3Pa |
| Wall3 | Minneapolis | International Falls | 6.8 | 16.8 | 0 Pa | 3 Pa | -3Pa |
| Wall 4 | Minneapolis | International Falls | 6.8 | 16.8 | 0 Pa | 3 Pa | -3Pa |
| Total Number of 1-D Simulations: 4 walls x 2 Climates x 2 Indoor Conditions x 3 Ventilation = 48 simulations | | | | | | | |

In this project the ORNL research hygrothermal model MOISTURE-EXPERT version 1.0 (Karagiozis 2001) was employed to parametrically investigate the moisture performance of the selected wall systems. Four wall systems selected by Building Science Corporation and approved by the Minnesota Energy Department, were employed in the study.

The four wall systems selected by the Building Science team were sent to Mr. Hernick (Director/Manager of the Minnesota Department of Administration, Building Codes and Standards Division) for approval. As time constraints were mounting, nearly all recommendations were accommodated. The four wall systems are described in layers going from inside to outside as follows:

1. "Standard" Wall (polyethylene vapor retarder)

½” Gypsum wallboard w. 1 coat latex paint, 6 mil polyethylene vapor retarder, 2x6 studs w. R-19 unfaced fiberglass batt insulation, OSB, housewrap, vinyl siding.

2. Permeable Wall A (no polyethylene vapor retarder)

½” Gypsum wallboard w. 1 coat latex paint, 2x6 studs w. R-19 unfaced fiberglass batt insulation, OSB, housewrap, vinyl siding.

3. Permeable Wall B (no polyethylene vapor retarder, vented rainscreen battens)

½” Gypsum wallboard w. 1 coat latex paint, 2x6 studs w. R-19 unfaced fiberglass batt insulation, OSB, housewrap, 1x4 battens installed vertically over studs with 3/4" air space, wood siding (back primed).

4. Modified Permeable Wall B (no PE, vented rainscreen battens, EPS interior)

½” Gypsum wallboard w. 1 coat latex paint, ½” expanded polystyrene board (EPS), 2x6 studs w. R-19 unfaced fiberglass batt insulation, housewrap, 1x4 battens installed vertically over studs with 3/4" air space, wood siding (back primed).

Wall 3 is meant to be similar to the wall proposed by the state representative who is a builder; the wall is a permeable flow-through assembly. However, 1x stock was substituted for 2x2s for furring out the air space: this is what is typically used and recommended in vented rainscreen wall applications.

Wall 4 was created because it was theorized that the failure mode of Wall 3 (if it failed) would not be actually moisture accumulation, but instead, low surface temperatures (and high localized humidities) resulting in mold growth at interior corners, etc. The addition of the EPS board raises the wall interior surface temperature, while keeping an overall permeable wall assembly (1/2" EPS = ~1-2 perm range).

For each of these walls, two different interior vapor environments (low and high moisture production loads) and three interior ventilation conditions (mechanical ventilation according to code (+3 Pa, –3 Pa or none) were investigated. While the complete array of parametric simulations is presented in Table 1, a subset of this is needed to respond to the engineering assessment set in the proposal. The present work assessed the moisture engineering performance of this wood frame clad envelope system not only in terms of the development of temperature and relative humidity distributions, but also in terms of the risk for mold growth using results from ORNL’s advanced hygrothermal modeling tool, MOISTURE-EXPERT.

The general inputs required to the model are:

- Material Properties (#1)
- Exterior Environmental Loads (#2)
- Interior Environmental Loads (#3)
- Envelope System and Sub-System Characteristics (#4)

Due to the intent and time constraints of the project, the best available data were used. Item # 4 (Envelope System and Sub-System Characteristics) was developed based on expert advice. In total, the model for a 2-D simulation requires approximately 6,000 inputs, which include the material properties, exterior and interior environmental loads and system characteristics.

## Boundary Conditions & Initial Conditions

The analysis was conducted while subjecting the exterior boundary of the wall to real weather data (including temperature, vapor pressure, wind speed and orientation, solar radiation, wind-driven rain, sky radiation, and cloud indexes) for International Falls and Minneapolis, MN. Wind-driven rainwater was included in the analysis, and the exterior surface was exposed to the amount of rainwater that hits a vertical wall under wind conditions. Two consecutive years of simulations were performed that included the 10% hot and 10% cold years from 30 years of data (NCDC). The hourly solar radiation and long wave radiation from the outer surfaces of the wall were also included in the analysis. This approach is currently being proposed by TenWolde (ASHRAE SPC 160P) and Treschel (ASTM Manual 40, 2001) and has been examined in detail by IEA Annex 24.

Interior conditions were also allowed to vary depending on the time of day and exterior conditions, and by adding additional moisture sources. In Activity 2, results were developed for the dynamic internal conditions, and an hourly moisture production generation schedule was implemented. As no air conditioning during the summer months was used, the temperatures were allowed to float above 20 °C (68° F). The minimum relative humidity was limited to 15% RH, at which time the inhabitants were allowed to turn on humidification equipment. Again, if condensation occurred on a window with a U value of 0.35 IP, then the humidification was turned off. This represents an advance over SPC 160P and is more realistic.

The four wall systems used in this project were assumed to be located on the second floor of the building. The walls were oriented to the west, based on data collected in Activity 2: wind-driven rain was most prominent in this orientation. The heat and mass transfer coefficients for external surfaces were dynamic, varying hourly based on exterior weather wind speed and orientation conditions. No water penetration through the first cladding element was employed in the simulations, even though a moisture engineering analysis requires these loads to be included. The water penetration was assumed nil to provide a fair evaluation of one strategy against another (permeable versus non-permeable). The goal of this study was to determine whether it is feasible to implement (either alone or in combination with a permeable envelope) criteria for non-mechanical ventilation that will ensure satisfactory air quality and envelope durability. Several sets of simulations were performed; ventilation drying was also modeled for all cases, but this was dependent on the wall system.

In the 2-D simulations, the combined effects of infiltration/exfiltration were examined, the effects of mechanical pressure, and the 2-dimensional spatial effects. The cases with 0 Pa represent the case of no mechanical ventilation. The 2-D simulations allowed a better understanding of the attributes of mechanical ventilation, the effect of insulation, interior vapor control strategies, and other variations on the total drying performance of building envelopes parts.

## Material Properties

In this section some additional information is given on the particular moisture properties that are needed in advanced hygrothermal models:

1) Sorption Isotherms:

Most building materials are hygroscopic, which means that they absorb water vapor from the environment until equilibrium conditions are achieved. This behavior can be described by sorption curves over a humidity range of 0 to 95% R.H. For some materials, the equilibrium water content is not very sensitive to changes in temperature; therefore, the sorption curves are called sorption isotherms. In these materials, sorption curves and sorption isotherms from 95% R.H. up to the capillary saturation at 100% R.H. are difficult to measure. In this range the equilibrium water content of a material is still a function of relative humidity. However, this function can no longer be determined by sorption tests in climatic chambers. In these cases, a pressure plate apparatus is necessary in order to complete the sorption curve in the high humidity range. The resulting water retention curve is a prerequisite for simulations including liquid transport. The sorption isotherms are the equilibrium moisture contents of a porous material as a function of relative humidity at a particular temperature. Families of sorption isotherms that encompass both the hygroscopic and capillary regimes are:

- Absorption Isotherm
- Desorption Isotherm
- Hysteresis Isotherms (the equilibrium moisture content curves that span the complete spectrum of moisture equilibrium during both absorption or desorption).
- Temperature-Dependent Sorption Curves (the equilibrium moisture content curves dependent on temperature)

The units for moisture content employed in the sorption isotherms are:

- water content (kg/m$^3$)
- moisture content by mass (kg/kg)
- moisture content by volume (m$^3$/m$^3$)

The hysteresis between absorption and desorption isotherms is usually not very pronounced. Rode (1990) approximated the effect of hysteresis and found that the effect on the calculated water content results was not large. Most models do not incorporate hysteresis and use the absorption isotherm, or, where necessary, an average function of absorption and desorption. Figure 3.1 shows the combined sorption/suction isotherms. Neglecting the hysteresis might not have a great influence on the water content, but it damps the fluctuations in relative humidity within the building assembly. In order to avoid this effect, separate absorption and desorption isotherms and a validated method to interpolate between both curves must be employed.

Nearly all advanced hygrothermal models with the exception of MOISTURE-EXPERT use a single curve to represent the absorption/desorption equilibrium isotherm. MOISTURE-EXPERT uses a set of sorption isotherms at different equilibrium temperatures. This is important when simulating wood based material elements, but is probably less important for mineral-based materials.

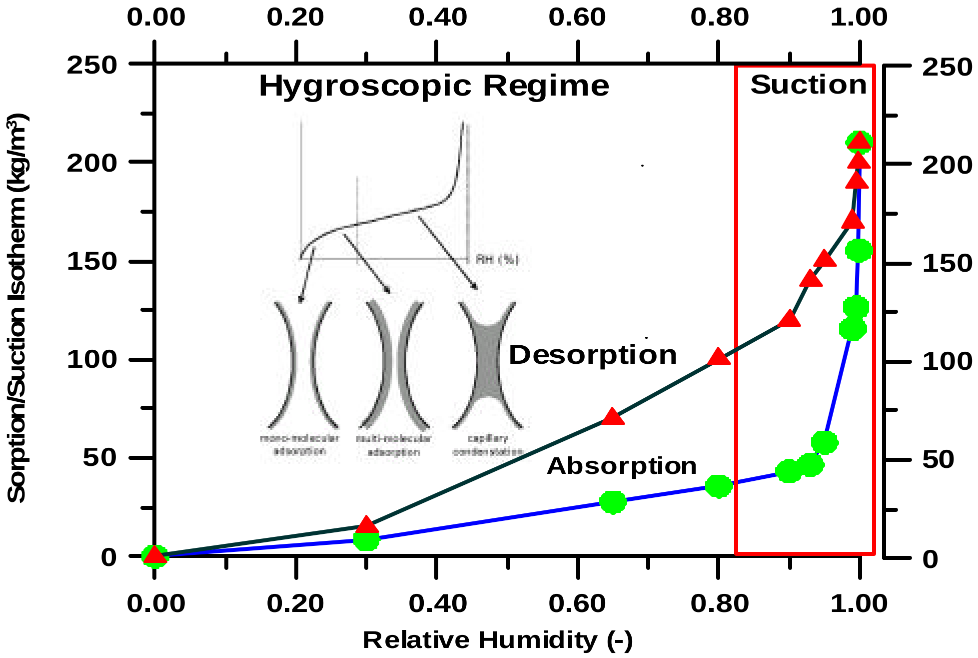

Figure 3.1: Sorption/Suction Isotherm

2) Vapor Permeability

The vapor permeability (kg/m·Pa·s) is defined as the transport coefficient for vapor diffusion in a porous material subjected to a vapor pressure gradient. In most technical publications, vapor permeance is used to characterize the vapor transmission coefficient. Vapor permeance (kg/$m^2$·Pa·s) is defined as the ratio between the vapor flow rate and the magnitude of vapor pressure difference across a slab in steady state conditions. Other expressions for vapor permeability exist, as the transport coefficient under a vapor concentration gradient ($m^2$/s) or as a vapor resistance factor $\mu$ (dimensionless). To determine the vapor permeability of a porous material, ASTM Standard E96 for water vapor transmission of materials may be used. It is important to recognize that the full dependency of the vapor transport coefficient as a function of temperature and relative humidity must be included in the model. Assuming constant values may introduce higher errors in the simulation results than when one includes the correct function curve but has higher uncertainties around these values. In Figure 3.2, the vapor permeability is shown for a vinyl film: a strong functional dependency of the vapor permeability on relative humidity is displayed.

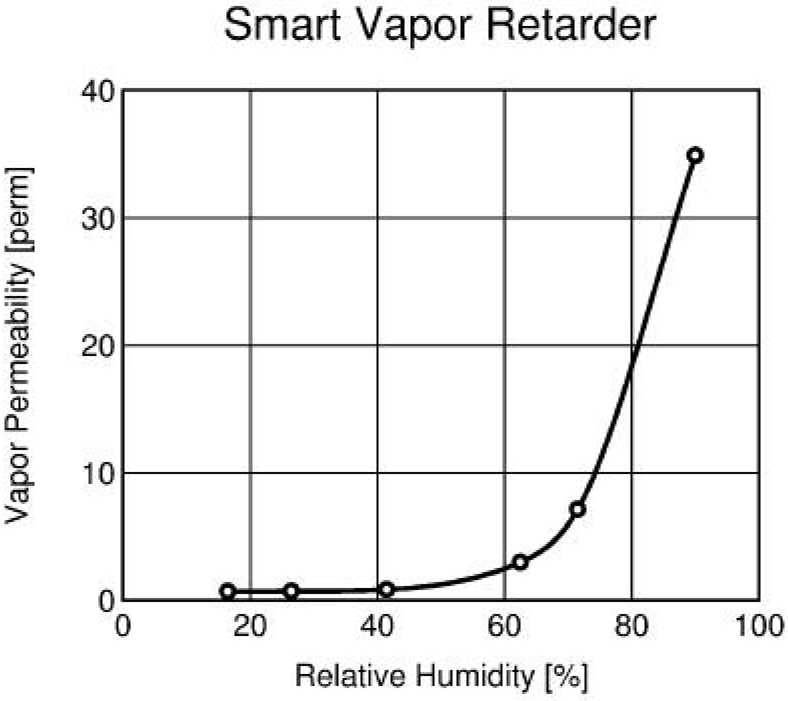

Figure 3.2: Vapor permeability as a function of relative humidity

3) Liquid Transport Properties

The coefficient that describes the liquid flow is defined as the liquid transport coefficient. The liquid flux in the moisture transport equation is only slightly influenced by the temperature effect on the liquid viscosity and consequently on liquid transport coefficients. Most of the time, moisture diffusivity is used, which is the total diffusivity measured. The main reason moisture diffusivity is used is due to the difficulty in determining what part is pure liquid flow and what is enhanced vapor flow. Different moisture dependent liquid transport coefficients exist according to the transport potentials of the advanced models; some are:

- Moisture diffusivity, $D_w$ ($m^2/s$)
- Liquid conduction coefficient, $D_\varphi$ (kg/ms)
- Hydraulic Conductivity, $D_p$ (kg/m·s·Pa)

The transport coefficient for liquid flow can change dramatically from one time step to the other. Several orders of magnitude of change occur in the transport coefficients when rain first strikes a building's exterior façade due to the steep increase of the diffusivity with water content. These large changes may cause numerical stability or convergence problems, and special numerical solution methods are required.

Kuenzel et al (2001) provides an explanation for the differences in diffusivity employed for the wetting and drying (liquid redistribution) process. Indeed, depending on the material, a factor of up to 10 or more may exist between these transport coefficients for the same water content. Only two of the advanced hygrothermal models include this discrimination for the liquid transport process by employing two distinct coefficients, WUFI and WUFI-ORNL/IBP, and recently MOISTURE-EXPERT. It is important to consider that liquid transport may occur at relative humidities as low as 60% for many construction materials.

## Directional Properties

Another important material property consideration in advanced hygrothermal models is that many materials exhibit very different behavior in the x, y, and z Cartesian directions. For example, moisture transport in wood is direction dependent. Thermal properties may also be spatial dependent—such as the thermal conductivity in fibrous materials, depending on the packing arrangement. For the advanced hygrothermal models that include air flow, the spatial properties for air permeability are also of importance. The predictive accuracy of an advanced hygrothermal model depends more on the realistic material properties than those used in simplified models. As more and more transport processes are included in a model, the errors from uncertainties in each process propagates further than in simple lumped models.

To summarize, the following material properties were gathered and included:

- 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 but may also depend on time, history, or other dependent variable. 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 (1994), Kuenzel et al (2001), IEA Annex 24 (Kumaran, 1996) and from the recent 2001 ASTM Manual 40 (Treschel, 2001). A more engineered approach would have been to measure and test these properties, but that was above and beyond both the scope and time constraints of the project.

The MOISTURE-EXPERT model includes the capability of handling internal heat and moisture sources, gravity driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and sub-system performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature dependent sorption isotherms, and directional and process dependent liquid diffusivity.

## Description of the Hygrothermal Model

The MOISTURE-EXPERT hygrothermal model was developed by Karagiozis (2001) at ORNL was used in this work. The model was developed to predict the dynamic 1-dimensional and 2-dimensional 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. MOISTURE-EXPERT model accounts for the coupling between heat and moisture transport via diffusion and natural and forced convective air transport. Phase change mechanisms such as evaporation/condensation and freezing/thawing are incorporated in the model. The model includes the capability of handling internal heat and moisture sources, gravity driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and sub-system performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature dependent sorption isotherms, water penetration, and directional and process dependent liquid diffusivity. For these wall simulations, a majority of the simulations were performed both in 1-D and 2- D enhanced version. The moisture transfer equation, including contributions from liquid, vapor air flow, and gravity assisted transfer is:

$$\dot{m}_M = -D_f(u,T,x,y)\nabla f - d_p(u,T)\nabla P_v + v_a r_v + K(u)\, r_w \vec{g} \qquad \text{(Equation 1)}$$

Where: $\dot{m}_M$ = mass flux, kg/m$^2$·s
$r_0$ = dry density of porous material, kg/m$^3$
$D_f$ = liquid moisture transport coefficient, m$^2$/s
$u$ = moisture content, kg$_w$/kg$_d$
$T$ = temperature, °C
$d_p$ = vapor permeability, kg/s·m·Pa
$P_v$ = vapor pressure, Pa
$v_a$ = velocity of air, m/s
$r_v$ = density of vapor in the air, kg/m$^3$
$K$ = moisture permeability, s
$r_w$ = density of liquid water, kg/m$^3$
$g$ = acceleration due to gravity, m/s$^2$
$f$ = relative humidity (-)

In Figure 3.3, the simulation procedure is detailed for this project. All materials, boundary conditions, and system effects were integrated using the model.

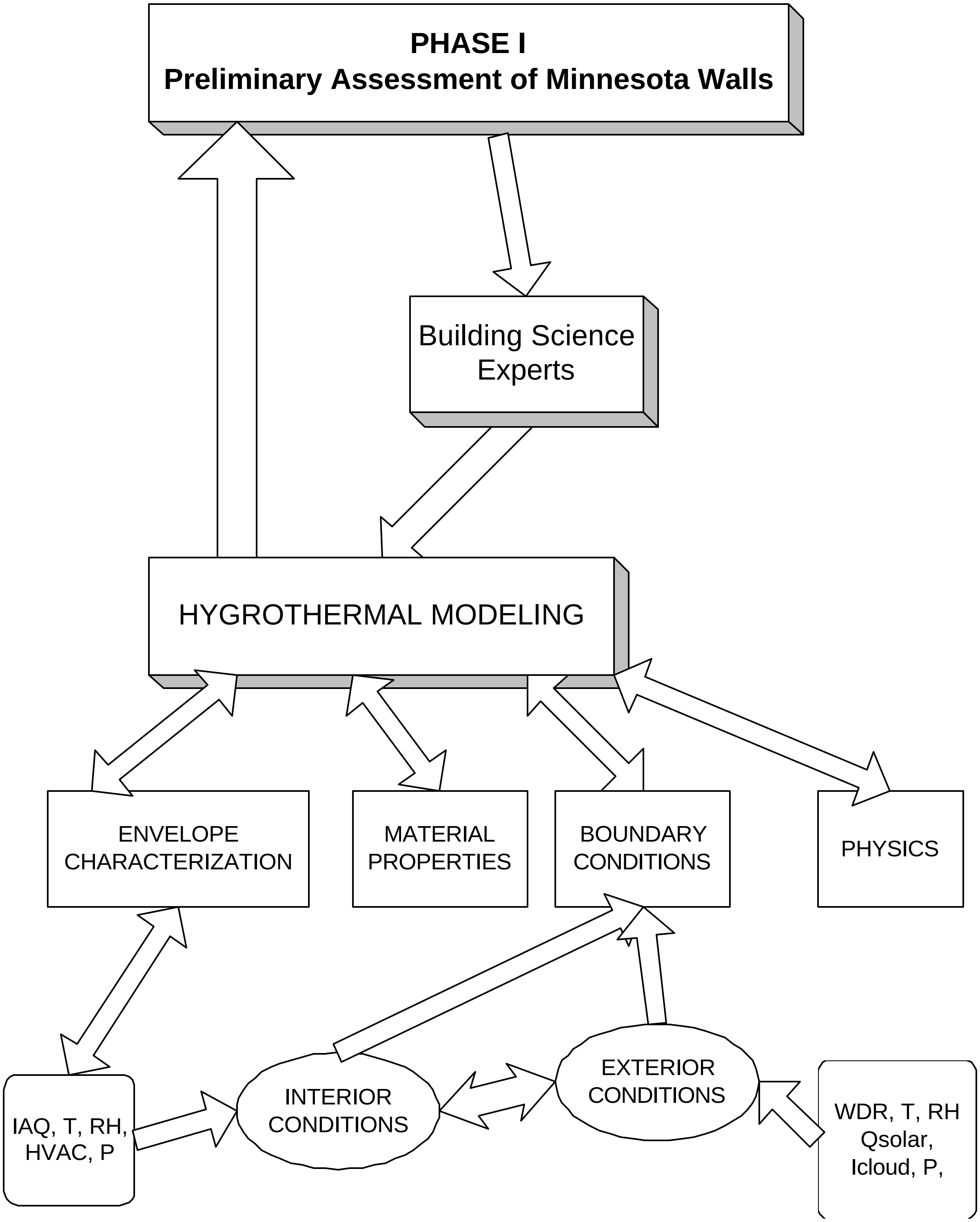

Figure 3.3: Simulation Approach

## Description of Mold Growth Model

The essential ingredients required for the reproduction of molds are as follows: spores, adequate temperature, food source, and moisture. Mold growth in the building structures was estimated using a model equation that employs temperature, relative humidity, and exposure time as inputs. The mold growth model and differential mathematical equations were developed and presented in detail by Hukka and Viitanen (1999), Viitanen (1997a), Viitanen (1997b), and only a short description is given here. Quantification of mold growth in the model is based on the “mold index” first employed in biological experiments during visual inspection (Viitanen, 1996).

The mold growth model is based on mathematical relations for growth rate in different conditions, including the effects of exposure time, temperature, relative humidity and dry interrupt periods. The model is purely mathematical in nature, and as mold growth was only investigated with visual inspection, it does not have any connection to the biology in the form of modeling the number of live cells. Also, the mold index resulting from computations does not reflect the visual appearance of the surface under study, because traces of mold growth remain on wood surface for a long time. The correct way to interpret the results is that the mold index represents the possible activity of the mold fungi on the wood surface. The model makes it possible to calculate the development of mold growth on the surface of wooden samples exposed to fluctuating temperature and humidity conditions, including dry periods. The numerical values of the parameters included in the model are fitted for pine and spruce sapwood, but the functional form of the model can also be reasoned to be valid for other wood-based materials. The mold index scale employed in the analysis is explained in Table 2. The details on the set of equations that are solved for each time step are presented in a paper by Viitanen et al (2000) at the BETEC Bugs, Mold, and Rot III symposium.

The mold index scale employed in the analysis is explained in the following, Table 2.

Table 2: Mold Index Values and Description

| **Index** | **Descriptive meaning** |
|---|---|
| 0 | No growth |
| 1 | Some growth detected only with microscope |
| 2 | Moderate growth detected with microscope |
| 3 | Some growth detected visually |
| 4 | Visually detected coverage more than 10% |
| 5 | Visually detected coverage more than 50% |
| 6 | Visually detected coverage 100% |

### Modeling Assumptions

Several assumptions were implemented at different levels of the input parameters. Input parameters related to weather loads, interior moisture loads, material properties, and system and sub-system performance attributes were used. Assumptions were made that were consistent with the purpose of the project: that was, to provide relative performance of walls in terms of their response to the same hygrothermal loads and inputs.

A few of the assumption made are:

- Air leakage was assumed representative of Category 2 buildings in Minnesota
- Pressure differentials due to mechanical systems were functional 33% of the time (daily cycle)
- Material properties used in the simulations are representative of material used in Minneapolis. Some of the material properties used may not have been measured from one sample, but rather a ‘pick and match’ of several batches or different manufacturers. However, these were available at the present time.
- Weather data were developed from 30 years of hourly data by choosing the 10% cold and hot years. This approach has been developed at IEA Annex 24 and has been used extensively in North America (ASHRAE is proposing this approach for SPC 160P)
- Cavity ventilation rates were assumed. Experimental data are required to provide more quantitative validation data.
- Temperature dependencies were accounted for only in the wood top and bottom plates.
- System imperfections were not included.
- In this project, the effect of ageing of materials was not included due to the lack of any data. Therefore, durability changes and influences were not included in this project.

With any engineering analysis, the loads used are assumed substantially higher than average loads. While this statement is not absolute, and exceptions may exist, imposing higher than normal hygrothermal loads and tracking the performance of the walls is one way to design systems with an added safety factor.

**List of Figures (Activity 3):**

**List of Tables (Activity 3):**