Modeling Enclosure Design in Above Grade Walls Measure Guideline

Building America Report - 1509

November 2015 (rev)

Joseph Lstiburek, Kohta Ueno, Sravanthi Musunuru

Abstract:

This Measure Guideline describes how to model and interpret results of models for above grade walls. It analyzes the failure thresholds and criteria for above grade walls. A library of above-grade walls with historically successful performance was used to calibrate WUFI (Wärme und Feuchte instationär) software models. The information is generalized for application to a broad population of houses within the limits of existing experience.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES OFFICE

Modeling Enclosure Design in Above Grade Walls

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Building Science Corporation

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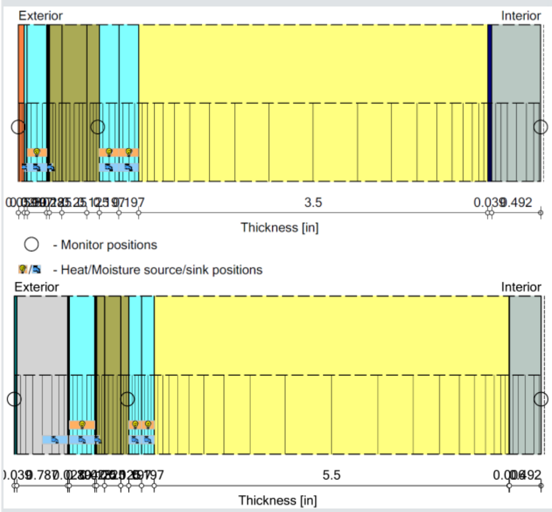

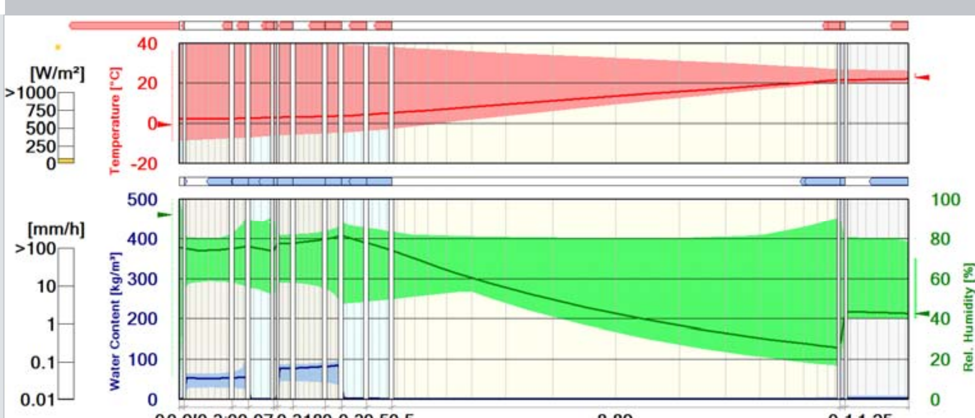

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TO 5: 2.3.3 Modeling Enclosure Design in Above Grade Walls: Final Measure Guideline

Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

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NREL Task Ordering Agreement No. KNDJ-0-40337-00

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Prepared under Task Order No. KNDJ-0-40337-05

November 2015

The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

ACH	Air changes per hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
BA	Building America Program
BSC	Building Science Corporation
CFM	Cubic feet per minute
CZ	Climate zone
DOE	U.S. Department of Energy
IEA	International Energy Agency
IECC	International Energy Conservation Code
MC	Moisture content (wood % by weight)
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
ocSPF	Open-cell spray polyurethane foam
OSB	Oriented strand board
PCF	Pounds per cubic foot
RH	Relative humidity
WUFI	*Wärme und Feuchte instationär*

Abstract

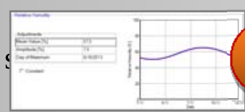
The Measure Guideline describes how to model and interpret results of models for above grade walls. The Measure Guideline analyzes the failure thresholds and criteria for above grade walls. A library of above-grade walls with historically successful performance was used to calibrate WUFI (*Wärme und Feuchte instationär*) software models. The information is generalized for application to a broad population of houses within the limits of existing experience.

Progression Summary

SET UP THE WUFI MODEL

Set up the WUFI model. Set up the WUFI model by defining the wall assembly, its orientation, climate, and appropriate indoor conditions. A north/south pairing is the most informative for interior condensation risks (worst/best case, respectively).

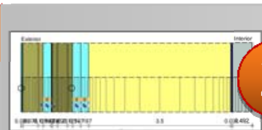
INTERIOR CLIMATE CONDITIONS



1

Set climate conditions. Interior relative humidity (RH) levels can have a strong effect on hygrothermal results; adjust interior RH per local climate, and/or project requirements (e.g., humidified interior conditions, high occupant loading).

ASSIGN MATERIAL DATA



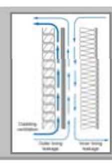
2

Assign material data. Fine-tune the existing material properties or create custom materials for the inclusion of common materials used in North American walls as per the guidance in the report.

Structural sheathing. Moisture risks to sheathing should not be presented as the moisture content (MC) of the entire layer; this only provides the average through the sheathing thickness, and understates risks. Instead, divide the sheathing into three layers: an outer layer, a core layer, and an inner layer (e.g., 1/8 in, ¼ in. 1/8 in). Use the innermost layer to evaluate interior-sourced condensation, and the outermost for rain penetration risks.

Interior paint. Do not model interior paint on interior gypsum board as a separate layer. Instead, model it as a surface transfer coefficient of 10 perms.

ADDRESS AIRFLOW



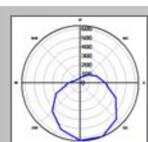
3

Address airflow in WUFI model. Add airflow to the WUFI model, in order to simulate cladding ventilation (drained and ventilated cavities) and "through the assembly airflow," (i.e., air leakage through the wall) per the guidance below.

Model cladding ventilation. Model cladding ventilation by introducing exterior condition air into an airspace between the cladding and water control layer. Flow rate varies depending on cladding type.

Model cavity air leakage. Approximate "through the assembly airflow" by creating two arbitrary 5 mm (3/16 in.) airspaces at the interface of the cavity insulation and the structural sheathing. Couple one airspace to the interior and the other airspace to the exterior.

ADDRESS RAIN



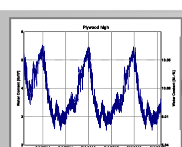
4

Address rain in WUFI model. Model rainwater penetration to reflect water deflection vs. penetration, leakage through exterior cladding (actual wall conditions), and leakage past the water control layer (reflecting small water control failures).

Rainwater Deposition and Cladding Leakage. Assume that 70% of the incident rainfall stays on the cladding, and 30% is shed ("bounces" off). Assume that 1% of this water penetrates through the cladding (using a moisture source/sink term), outboard of the water control layer.

Water Control Layer Leakage. To simulate imperfections/small flashing failures in the water control layer, model 1% of the previous 1% (0.01%) of the incident rainfall as a moisture source/sink at the structural sheathing, inboard of the water control layer. This will show the drying ability of the wall.

RUN ANALYSIS



5

Run Analysis. Run the WUFI analysis over a three year period; this allows drying of construction moisture, and shows longer-term trends. The MC of the innermost sheathing layer can be used to evaluate interior-sourced condensation risks.

1 Introduction

Background

Hygrothermal simulations such as WUFI (Künzel 2002) are coming into increasingly common use among building science researchers and practitioners, architects and designers, and energy analysts. Such simulations have been shown to be powerful and validated tools that predict hygrothermal behavior of enclosure assemblies. Simulation developers have continued to expand the capabilities of such tools over time.

However, with increasing dissemination of these modeling tools – most notably WUFI - less-experienced or less-informed practitioners have run models that provide unrealistic results—typically overly conservative. In some cases, these results clearly contradict extensive field experience and known history of assemblies, showing failure when they do not occur in reality. In other more worrisome cases, models run on assemblies that clearly have not performed historically show successful performance. This has resulted in confusion in the building industry—specifically, problems with advancing knowledge of moisture-safe building enclosure/shell assemblies. Development of moisture-safe enclosure assemblies is a component that will contribute to the Building America target of reducing residential carbon emissions 20% by 2020 and 80% by 2050.

NREL and the Standing Technical Committee on Enclosures presented top priorities for research in their document, "Building America Technical Innovations Leading to 50% Savings – A Critical Path" (NREL 2013). Critical Milestone E4, under Enclosures states:

> *Develop guidance on design methods for enclosure design with a focus on above-grade walls; guidance to be provided for both new construction and retrofits in all U.S. climate zones.*

The Technical Report addresses this priority by modeling typical wall assemblies that have performed well historically, and demonstrating that these models agree with historic experience when modeled correctly. A library of input data and results are provided.

Hygrothermal Models

Hygrothermal analysis is a relatively new field. The fundamentals date back to the 1950's. Analysis was observation and experience based. The major focus was rain and groundwater control. As insulation was introduced into assemblies, energy flows were altered, resulting in materials remaining wetter for longer periods of time. Simultaneously, new building materials were introduced that were inherently more water sensitive. The focus shifted from rain and groundwater to vapor movement in the form of air transport and molecular diffusion. Calculation methods of predicting performance and assessing risk were primitive and typically fundamentally flawed. Analysis remained rooted in observation and experience–i.e., a "build it, wet it, watch what happens" methodology.

In the 1980's with the advent of numerical analysis and computer availability, it was believed that a shift from observation and experience to numerical methods based on physics was possible. Numerous models were developed but none with reasonable predictive capability. In the 1990's this changed based on work done in Canada (Kumaran, M., Mitalas, G. and Bomberg, M.; 1994) and Sweden (Viitanen, H., and A. Ritschkoff; 1991). These models were principally research tools rather than design tools. Work done in Germany in 2000 changed the modeling status quo (Künzel, H.; 2002). However, such design models were limited to mass assemblies typical to Europe. North American assemblies are hollow, multi layered, and dominated by three dimensional air flow networks that have proven problematic to modeling efforts.

The dominant European model has proven to be attractive to North American practitioners. WUFI is popular despite its inability to provide reasonable predictive outcomes unless used by an experienced sophisticated user who already "knows" the correct outcome. In fact, despite the sophistication of the numerical analysis, available research is still dominated by experiment. We still must "build it, wet it and watch it." Then, the observed outcomes are used to "tune" available models. The field remains phenomenologically based, as there is yet no widely accepted theory of combined heat and moisture flow.

2 Moisture Physics Background

State Phases of Water

Water exists in four phases: vapor, liquid, solid, and adsorbate. These phases interact with each other as shown in Figure 1.

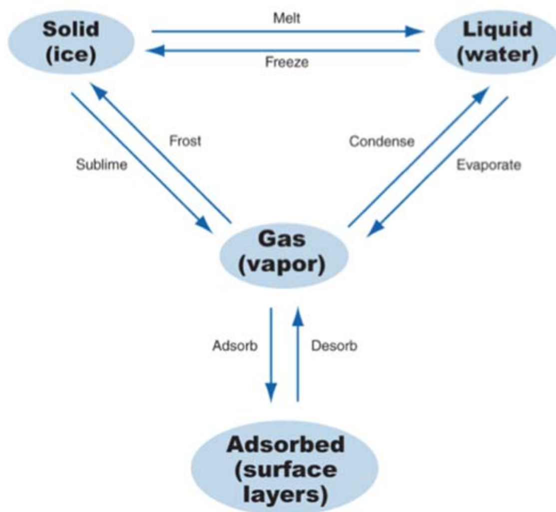


Figure 1: Phases of water (from Kumaran, Mitalis & Bomberg, ASTM MNL 18)

Modeling this interaction in a porous material has proved challenging. Most hygrothermal models simplify the interaction by dropping the interactions with the solid phase. The resultant transport processes and driving potentials are summarized in Table 1.

Table 1. Moisture transport in porous media

Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow Osmosis	Suction Pressure Solute Concentration

Building Enclosure Materials and Layers

Addressing the dynamic interactions in a single material is complex, and is phenomenologically based, as there is yet no widely accepted theory of combined heat and moisture flow. Addressing the dynamic interactions in a single material is challenging on its own (Figure 2) but addressing the dynamic interactions in several materials simultaneously has proved to be an order of magnitude more difficult (Figure 3). Where the materials are in contact with each other, one-dimensional combined heat and moisture flow models provide reasonable correlation with real world examples and measurements. However, the real world is three-dimensional, whereas the models are one-dimensional. Where the materials are not in direct contact with each other (Figure 4) one-dimensional models tend to break down as they are ill-equipped to handle airflow and the resultant convective flow.

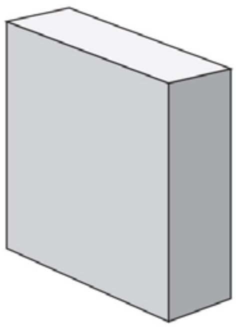


Figure 2: Single material

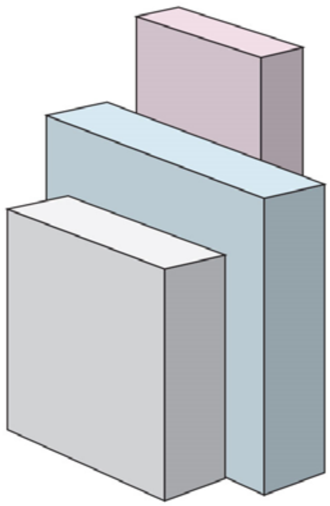


Figure 3: Several materials in contact

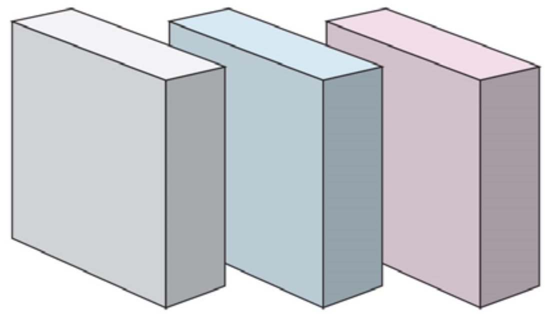


Figure 4: Several materials not in contact (air gap)

Rain and Airflow

European building assemblies historically tend to be solid mass systems with little or no convective air flow. In these cases, one-dimensional combined heat and moisture flow models have proven useful in analyzing performance and predicting performance. North American building assemblies, however, are multi-layer systems with complex three-dimensional airflow pathways. One-dimensional combined heat and moisture flow models have provided less than ideal results in these types of assemblies, due to the complexity added by the airflow component.

Both European and North America building assemblies are exposed to rain—this of course is obvious. That rain is a significant moisture load is also obvious. As such, this moisture transport mechanism needs to be considered by hygrothermal models for the models to be useful. Modeling the rain transport mechanism—a three dimensional phenomena in a multi-layer system—adds more complexity.

The challenge for a one-dimensional combined heat and moisture flow model is addressing the rain and airflow component. Figure 5 summarizes the modeling question.

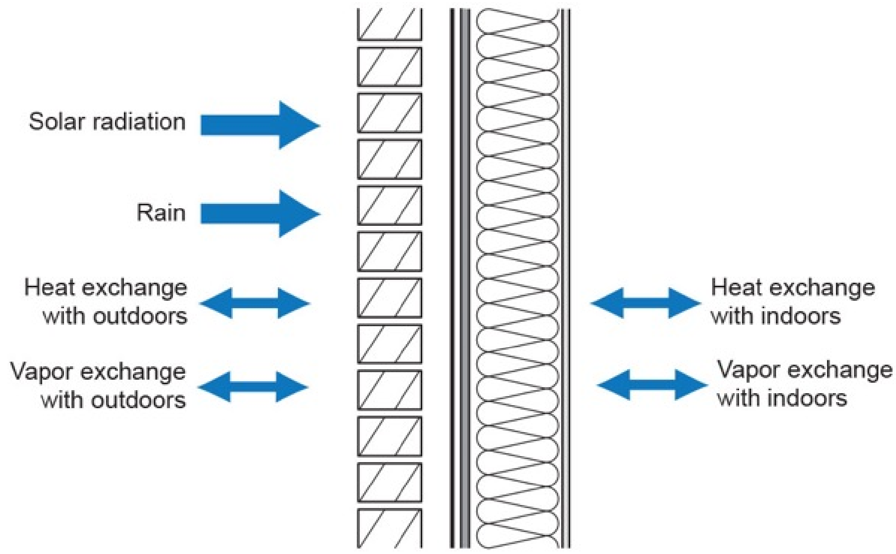


Figure 5: One-dimensional combine heat and moisture flow model

Table 2 summarizes transport processes and driving potentials that need to be addressed.

Table 2. Moisture transport in assemblies

Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration
	Gravitational Flow	Height
	Surface Tension	Surface Energy
	Momentum	Kinetic Energy
	Convective Flow	Air Pressure

3 Simulation of Rain and Airflow Assembly Interactions

Addressing Rain

The key question is how much rainwater hits the wall, which is a simple question, but not one that is simple to answer. WUFI software adapts the rainwater exposure models developed by Straube and Künzel to determine the amount of rainwater that impinges on the wall.

Some of this rainwater "bounces" (or is shed) off the wall, while some of this rainwater penetrates the cladding, and finally some of this rainwater penetrates the water control layer. This is summarized in Figure 6.

For modeling purposes, we assume that 30 percent of this water "bounces" off the wall, and that 70 percent stays on the wall (adheres to the cladding surface). The 70 percent that stays on the wall ("retained water") is addressed by liquid conductivity (capillary flow) and vapor diffusion.

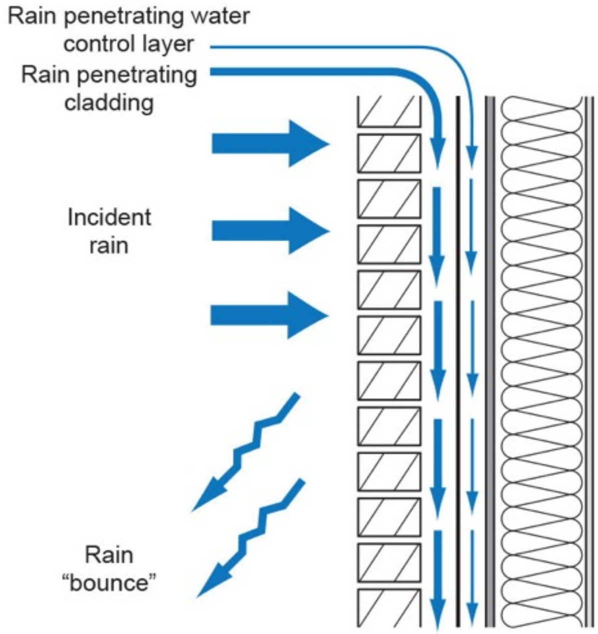


Figure 6: Rainwater penetration in a wall

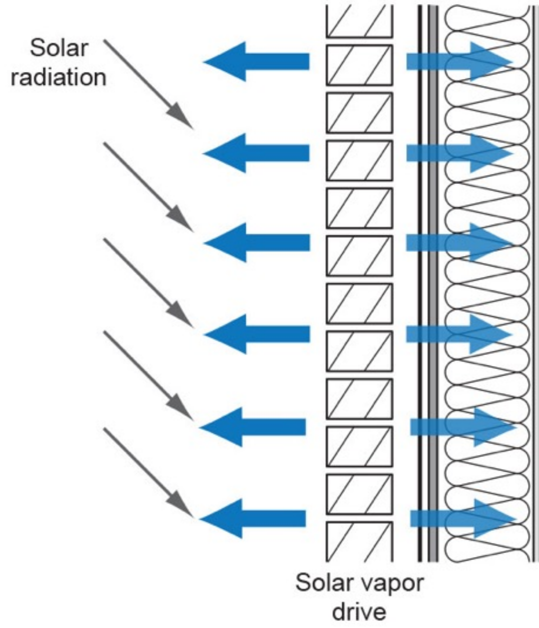


Figure 7: Solar radiation on a wall

The amount of solar radiation incident on the wall affects the liquid conductivity and vapor diffusion (Figure 7). As such model orientation can play a significant role.

For modeling purposes, we assume that 1 percent of the 70 percent (the "retained water') penetrates to the back side of the cladding, and we further assume that 1 percent of the 1 percent penetrates/bypasses the water control layer, and enters into the sheathing. The percentages above are based on the experience of the authors.

Addressing Airflow

Another challenge is to model a complex three-dimensional phenomenon in a one-dimensional model. There are twelve (12) typical airflow pathways that need to be considered in multi-layer systems (Figure 8).

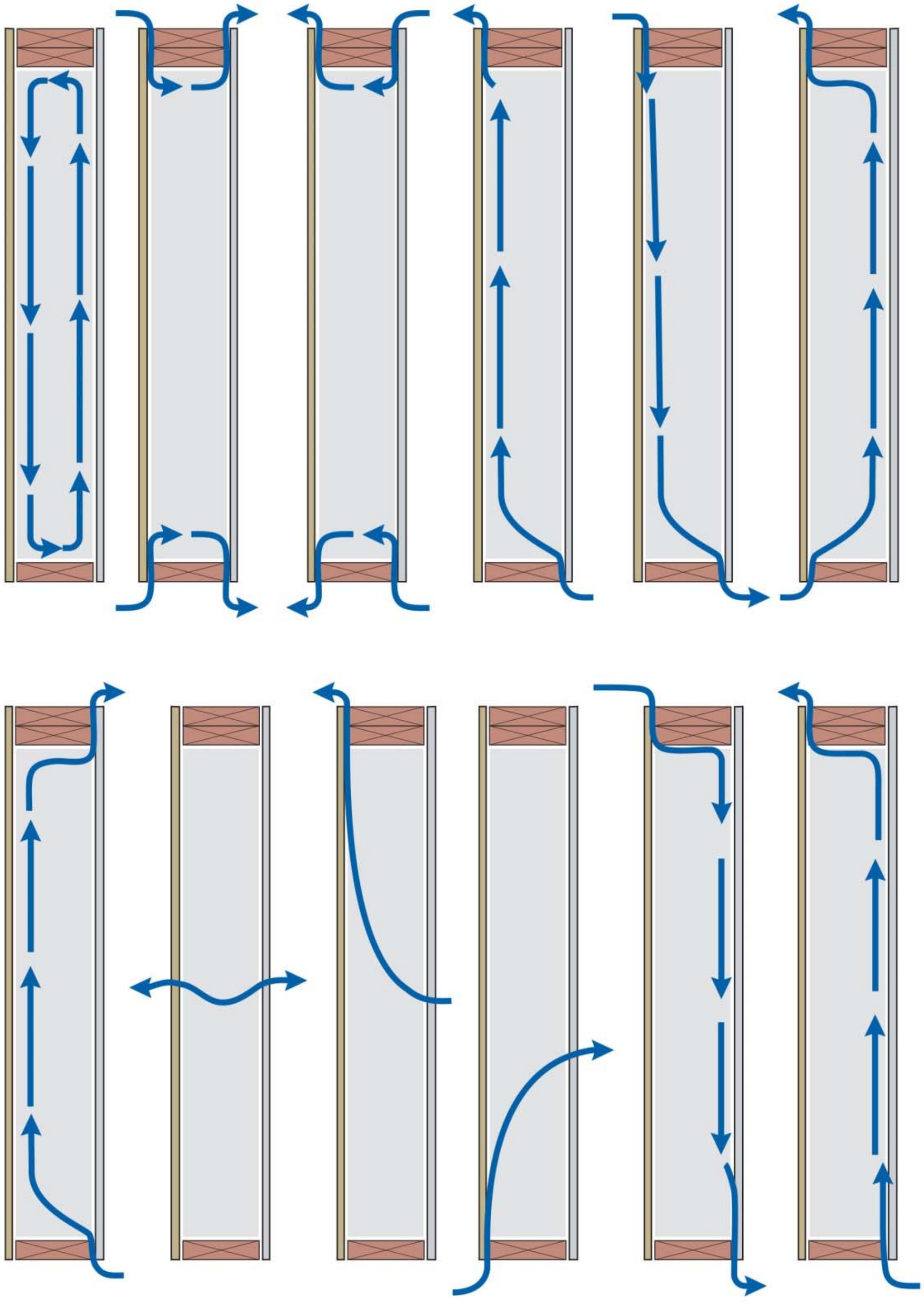


Figure 8: Airflow mechanisms in a wall

These airflow pathways arguably can be combined for modeling purposes as shown in Figure 9. Note the cladding ventilation component that has been added. The flows in Figure 8 can further be simplified as shown in Figure 10. WUFI software is capable of modeling cladding ventilation. Using this capability allows us to approximate the flows in Figure 10, as shown in Figure 11.

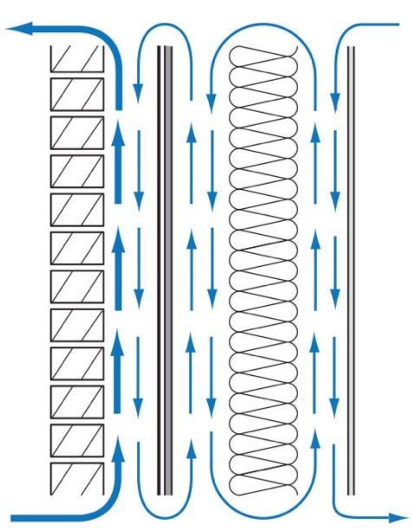


Figure 9: Combined airflow pathways (full level of complexity)

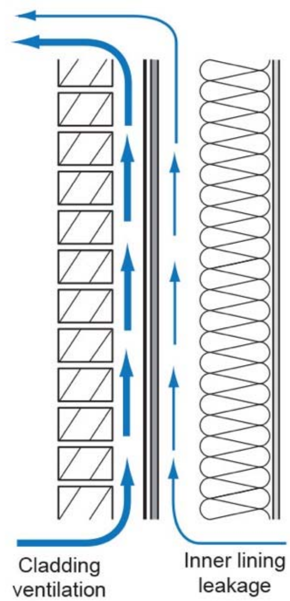


Figure 10: Further simplification of airflow pathways

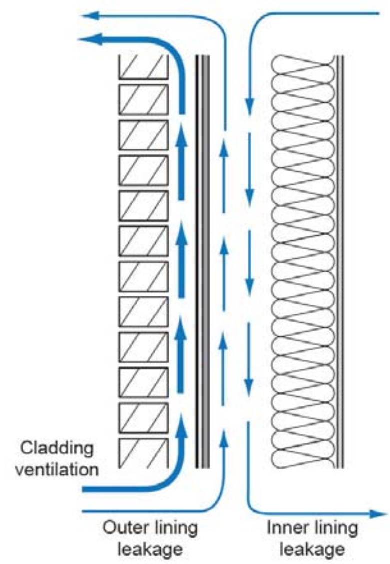


Figure 11: Approximation of flows (for purposes of modeling)

WUFI software is capable of modeling cladding ventilation, by introducing exterior condition air into an airspace within the assembly. This allows for explicit (and correct) modeling of ventilated rainscreen behaviors, including vinyl siding (bypass of vapor-impermeable vinyl material with airflow) or brick veneer construction.

This airflow model within WUFI also allows the analysis of "through the assembly airflow" (i.e., air leakage through typical imperfect assemblies). This flow can be approximated as follows. Two arbitrary 5 mm (3/16 in.) airspaces are created at the interface of the cavity insulation and the structural sheathing. One airspace is coupled to the interior, simulating moves air-transported moisture from the interior to the interior face of the exterior sheathing. The other airspace is coupled to the exterior, and simulates air leakage from the exterior into the cavity. Multiple layers can be addressed in a similar fashion (Figure 12).

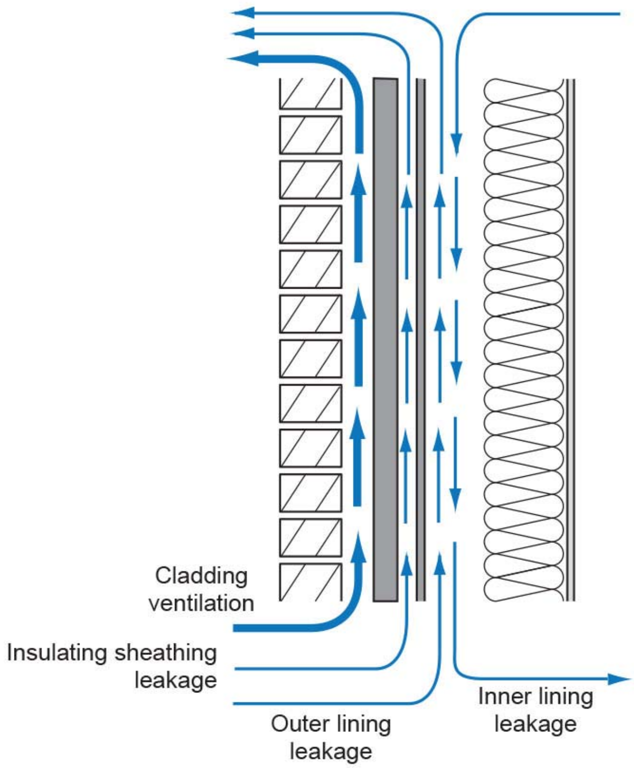


Figure 12: Air space coupling to address through the assembly airflow in WUFI

For modeling purposes, we assume the flow rates, gap sizes and air changes per hour (ACH) as shown in Table 3. The information in Table 3 comes from a combination of published work and unpublished work by the authors.

Table 3. Cladding ventilation/ sheathing ventilation

	Flow Rate	Gap	ACH (1/h)
Wood Siding	0.1 cfm/sf	3/16 in.	20
Vinyl Siding	0.5 cfm/sf	3/16 in.	200
Brick Veneer	0.15 cfm/sf	1 in.	10
Stucco (vented)	0.1 cfm/sf	3/8 in.	10
Stucco (direct applied)	none	none	0
Sheathing flanking flow*	0.05 cfm/sf	3/16 in.	10

* Flanking flow refers to outer lining leakage, inner lining leakage and to insulating sheathing leakage.

4 Material Properties

As discussed in the Building America Expert Meeting on hygrothermal modeling (Ueno and Lstiburek 2014), material properties can have a substantial effect on modeling results. Therefore, guidance is provided below for the inclusion of common materials used in North American walls.

Structural Sheathing (Moisture Content Measurements)

A common practice is to plot the moisture content (MC) of the entire sheathing layer; however, this value is simply the average MC of the sheathing thickness. In reality, sheathing failures are typically associated with high MCs on one face or another—for instance, the interior sheathing face for interior-sourced interstitial condensation, or the exterior face for rain leakage.

Therefore, the sheathing should be divided into three layers: an outer layer, a core layer and an inner layer. For instance, the innermost layer is shown in red in Figure 13, which would be used to evaluate interior-sourced condensation.

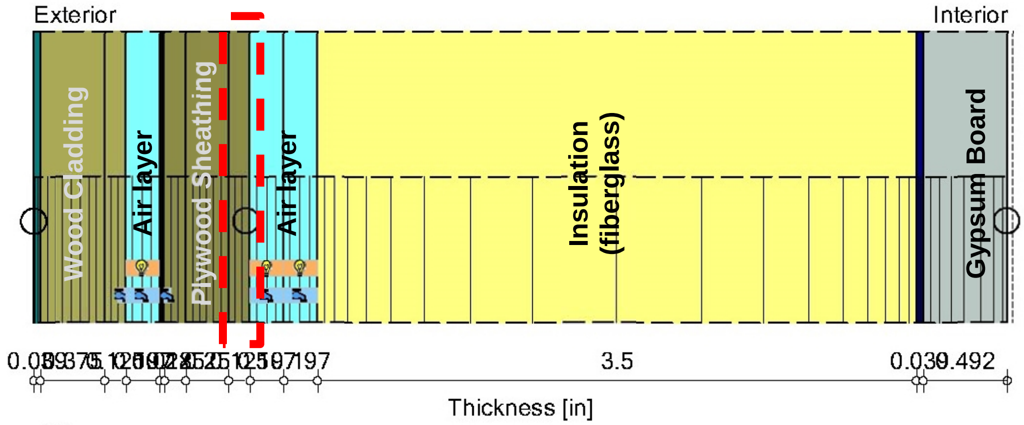


Figure 13: WUFI wall cross-section highlighting sheathing MC interior layer

For typical ½ in. (12 mm) sheathing, these layers should be roughly 1/8 in., ¼ in., and 1/8 in. (3 mm/6 mm/3 mm). When running a WUFI simulation, the sheathing layer can be entered into the model, and then duplicated to ensure identical material properties.

Oriented Strand Board (OSB)

Unfortunately, OSB has substantial variation in material properties, based on manufacturing processes. However, designers seldom have knowledge of the specific brand/type of OSB sheathing that will be used. Therefore, the best recommendation we can provide is to use OSB with a selected density of 36 pounds/cubic foot (PCF). The vapor permeance should be roughly 0.2 perms dry cup, 3.0 perms wet cup, and 6.0 perms at 100% RH.

Fiberglass Insulation

Most fiberglass insulation used in North America is low density, so the values in WUFI must be modified from their default values. For a 2x6 wall, the insulation thickness should be set to 5.5 inches. Then, entering the layer material properties, “unlock properties” should be selected, and the density changed from 1.87 to 1.2 PCF. This also changes the heat capacity of the insulation.

Note that European R-values values are given at 50° F (10° C), while North American values are given at 75° F average temperature.

Stucco

When modeling stucco, note that stucco is typically painted. The paint layer needs to be defined and implemented in the model. Use the generic material characteristics for polyethylene, and modify the layer by assuming a vapor permeance similar to Kraft paper. Use the permeance for Kraft paper as defined by NIST.

The stucco data for new buildings should use regular Portland cement-based stucco, rather than lime based stucco. Lime-based stucco stores more water, the liquid transport is much greater, and the vapor permeability is double that of Portland cement-based stucco. The WUFI default thickness needs to be changed to 0.75 in.

When installing stucco over a drainage mat, the generic materials table should be used. Use an air layer of 3/8 in. (10 mm), "without additional moisture capacity." The original WUFI software implemented air spaces using a fictional moisture storage capacity, in order to improve the stability of the software. This fictional layer avoided crashes when using slow processors and memory limitation in the past. This legacy material has not been deleted, but should not be used in modern simulations.

Gypsum Board

The material to select for interior gypsum board is "Gypsum Board USA." The material "interior gypsum board," which has a higher density (50 PCF vs. 40 PCF) should be selected.

Interior Paint

For interior paint on interior gypsum board, it should not be modeled as a separate layer. Instead, it as a surface transfer coefficient of 10 perms (a conservative value for latex paint). We recommend against using the curve of latex as a database material, as it is not very sensitive at the interior.

5 ASHRAE Standard 160 Limitations and Viitanen Mold Index

Interpreting the results of modeling has been problematic. For example, wall assemblies that have performed well historically in various climate zones “fail” when standardized moisture failure criteria such as that presented in ASHRAE Standard 160 are applied.

This section covers preliminary research conducted by Glass et al. (2015) on the limitations of the moisture failure criteria presented in ASHRAE Standard 160. This work was summarized in the press by Holladay (2015).

Standard 160 Background

ASHRAE Standard 160 (ASHRAE 2009) provides guidance on moisture analysis for building envelope design, including the moisture performance evaluation criteria. The failure criteria (defined as the risk of mold growth) were redefined in addendum (a) (ASHRAE 2011), as follows:

> ***6.1 Conditions Necessary to Minimize Mold Growth.*** *In order to minimize problems associated with mold growth on the surfaces of components of building envelope assemblies, condition shall be met: a 30-day running average surface RH < 80% when the 30-day running average surface temperature is between 5°C (41°F) and 40°C (104°F).*
>
> *Materials that are naturally resistant to mold or have been chemically treated to resist mold growth may be able to resist higher surface relative humidities and/or to resist for longer periods as specified by the manufacturer. The criteria used in Addendum a to Standard 160-2009 the evaluation shall be stated in the report.*

One issue with these criteria is that they are based on IEA Annex 14 (IEA 1991). Annex 14 presented mold risk criteria for interior and exterior surfaces (e.g., mold growth in a cold corner of a room), rather than within a building enclosure assembly (i.e., interstitial mold growth).

Chicago Brick Veneer Wall Simulations

WUFI simulations were used to examine an established wall commonly used in climates such as Chicago, IL (CZ 5A). The wall assembly is a brick veneer with a ventilated cavity (10 air change per hour in a 1 in. airspace), #30 felt, OSB sheathing, 2x4 stud wall with R-13 insulation with Kraft facer (Class II vapor retarder), and interior gypsum board with latex paint. Interior conditions were run at a seasonal sinusoidal cycle (73-75°F, 30-60% RH, winter to summer). Incident rain (1%) was introduced on the #30 felt (water control layer) surface, to simulate water penetration through the brick cladding. Additional rain (0.01% of incident rainfall) was introduced inboard of the #30 felt, to simulate a rain leakage failure past the water control layer.

The resulting temperature and RH conditions at the insulation-sheathing interface (30 day running averages) are shown in Figure 14. The temperature and RH risk ranges discussed above are superimposed on the data, and periods when both risk criteria are met are indicated by a black dot (“Failing Hours”). The analysis demonstrates that this wall assembly—which has a long and established history of acceptable performance in this climate—is at high risk of failure and mold growth, according to ASHRAE Standard 160. This conclusion contradicts common knowledge of local practitioners and builders.

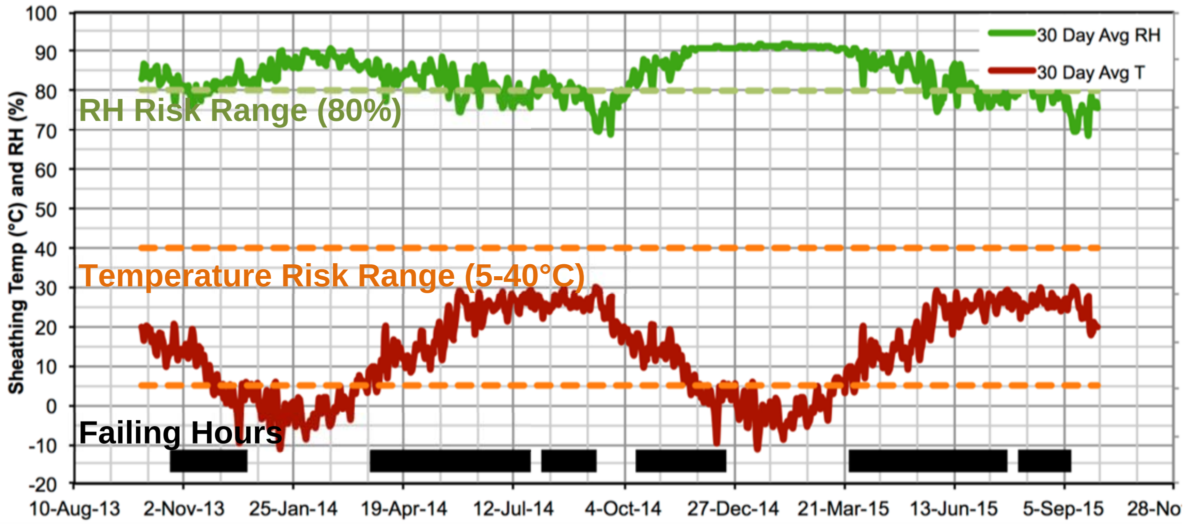


Figure 14: Chicago wall, insulation-sheathing interface conditions and ASHRAE Standard 160 failures

Comparisons with Measured Data (Double Stud Walls CZ 5A)

Ueno and Lstiburek (2015) monitored moisture conditions in double stud wood frame walls in CZ5A over three winters. These assemblies included open cell polyurethane spray foam (ocSPF) and dense-pack cellulose insulation, interior vapor control was provided by latex paint on gypsum board.

Instrumentation indicated that the dense-pack cellulose wall showed high risks of moisture damage, with extended winter periods at high sheathing moisture content and RH, as well as possible liquid water condensation. The ocSPF walls also had risks, but less severe. These problems were the worst during the second of three winters, when interior RHs were high (40-50%), due to inoperative ventilation equipment.

This work was followed by disassembly of the walls, to assess their condition, as shown in Figure 15.

The sheathing, framing, and insulation conditions were surprisingly intact. No signs of moisture damage or mold were visible; there was slight grain raise on the cellulose wall sheathing, as well as some rusted fasteners.

Figure 15: Sheathing conditions at south (left) and north (right)-facing walls

The instrumentation results were then used to perform ASHRAE Standard 160 analysis of conditions at the insulation-sheathing interface. The results for the north-facing walls are plotted in Figure 16: hours that fail ASHRAE Standard 160 are denoted by points; outdoor temperature and the sheathing temperature (30-day rolling average) are plotted for reference.

The results show that all three walls fail ASHRAE Standard 160 requirements during all three winters, and that the cellulose wall (N2) has the worst performance according to these criteria. In addition, winter 2012-2013 (high humidity winter) has more failing hours: the cellulose wall (N2) fails ASHRAE Standard 160 from mid-September through mid-November, and then April through late June. It is interesting to note that failures occur in the walls in fall and spring. During the winters, sheathing temperatures drop below the 41°F/5°C lower limit, even though the RH criterion is exceeded. Overall, based on an ASHRAE Standard 160 analysis, the walls do not dry rapidly enough to avoid problems

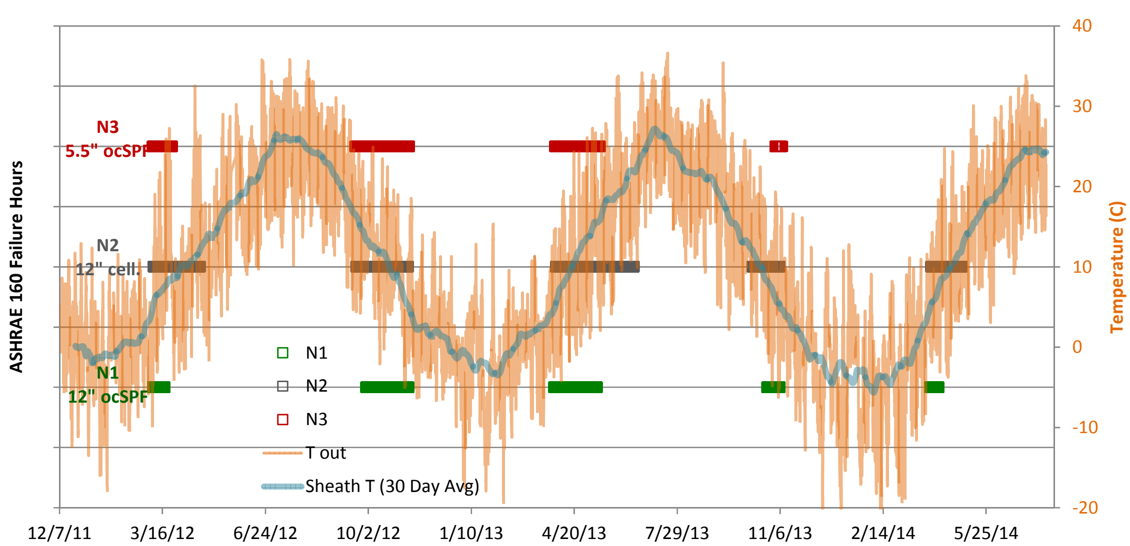


Figure 16: ASHRAE Standard 160 evaluation of north-facing walls, insulation-sheathing interface

Again, this is a clear demonstration that ASHRAE Standard 160 criteria are providing false positives in terms of wall failures, based on monitored assemblies that were visually inspected.

Alternate Mold Growth Criteria (Viitanen Mold Growth Index)

Viitanen and Ojanen (2007) created a mold growth model or index, which instead of a binary pass/fail criteria, has a sliding scale of mold growth to indicate risks. The descriptors of various mold growth levels are shown in Table 4. These mold growth levels vary from 0 (no growth) to 5 (over 50% coverage with visible mold).

Table 4: Mold growth index descriptions (Ojanen, Viitanen, et al. 2010)

Index	Description
0	No growth
1	Small amounts of mold on surface (microscope);initial stages of local growth
2	Several local mold growth colonies on surface (microscope)
3	Visual findings of mold on surface; <10% coverage
4	Visual findings of mold on surface; 10% - 50% coverage
5	Plenty of growth on surface; > 50% coverage

The mold index is calculated using the temperature and relative humidity at the surface being examined (e.g., insulation-sheathing interface); the index will rise and fall based on conditions. Temperature and relative humidity can be plotted against each other to create a plot (Figure 17) of the lowest (critical) RH to sustain mold growth, as a function of temperature (the isopleth line shown in green). Conditions below this RH are too dry. Temperatures between 32°F-122°F (0°C–50°C) are required for growth as well.

In comparison, the ASHRAE Standard 160 criteria (relative humidity over 80%, temperature between 41°F/5°C and 104°F/40°C) are also plotted in this manner, in grey in Figure 17. ASHRAE Standard 160 criteria state that failure occurs in any hour with conditions inside the grey box. In contrast, the Viitanen mold growth index simply increases the index upward on a varying basis when conditions are above the green curve, showing finer-grain sensitivity.

Ojanen, Viitanen, et al. (2010) further refined the model, adding factors such as sensitivity classes for various building material substrates (very sensitive, sensitive, medium resistant, and resistant), as well as a “die off” factor (mold index falls under less favorable conditions).

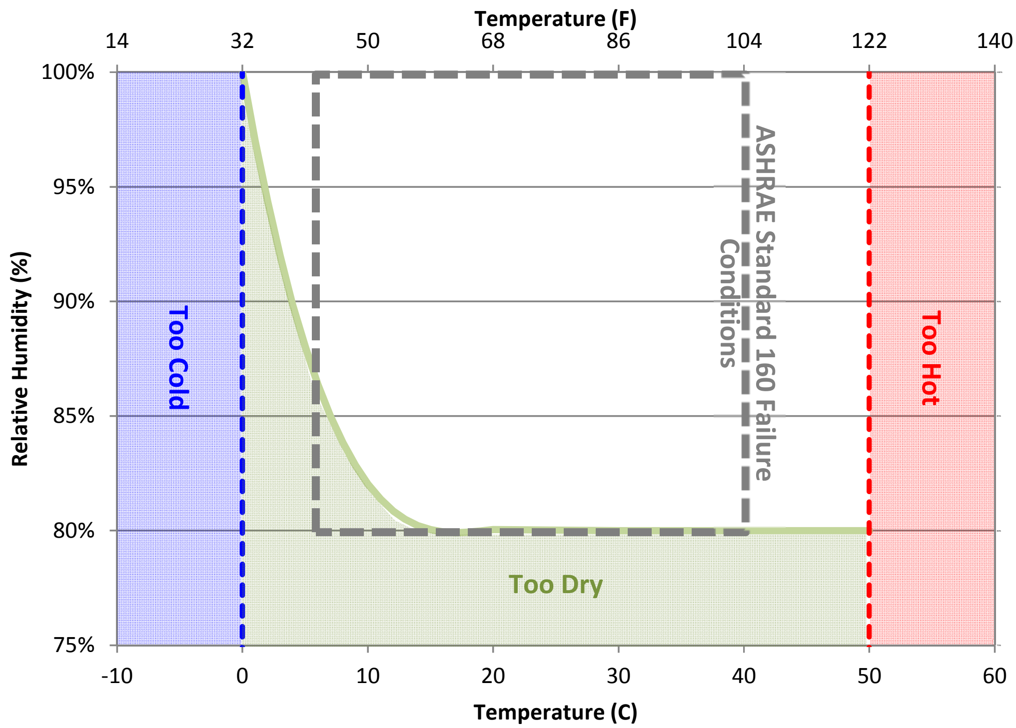


Figure 17: Temperature/humidity conditions for mold growth, from Viitanen and Ojanen (2007), with ASHRAE Standard 160 criteria

This mold index model is a more promising methodology compared to *ASHRAE Standard 160*; the data from the double stud work (Ueno and Lstiburek 2015) were reanalyzed using the Viitanen mold index, as shown in Figure 18. It shows that the mold index in the ocSPF wall remains below 2 (microscopic growth), and in the cellulose wall below 3 (visual mold under 10% of surface). These observations are more consistent with the wall disassembly observations.

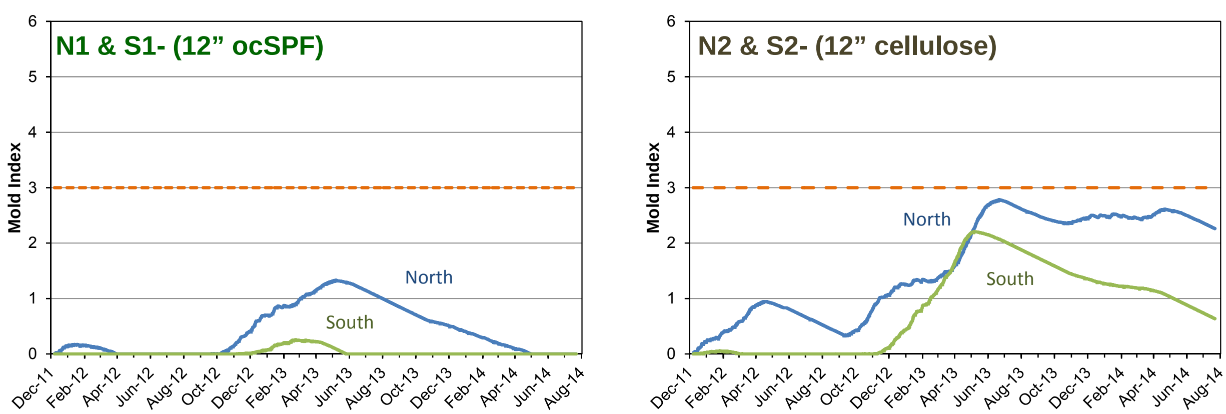


Figure 18: Mold growth index calculations for ocSPF (left) and cellulose (right) double stud walls

Comparisons with Measured Data (Vented and Unvented Roofs CZ 4C)

Schumacher and Reeves (2007) monitored conditions in an unvented cathedral roof/ceiling assembly insulated with ocSPF, in Vancouver, BC (CZ 4C). Their measurements indicated high sheathing moisture contents (20%+) on the north side in winter, which is often considered a risk case for mold growth. However, disassembling the roof assembly after these measurements showed no mold growth. The temperature and RH measurements were compared with ASHRAE Standard 160 criteria and mold index models; both options indicated no risk of mold growth, consistent with field observations.

A field test facility was constructed in Coquitlam, BC (CZ 4C) (Figure 19 left) with monitored roof and wall assemblies; this facility is described by Lstiburek (2012) and Grin and Smegal (2013). One section of the building had a vented attic (insulation at the flat ceiling plane, attic ventilated with outdoor air; Figure 19 right).

Figure 19: Coquitlam test facility (left), and vented attic

ASHRAE Standard 160 criteria were calculated for the roof sheathing, indicating long periods (late fall/early spring) with failing hours (Figure 20). However, examination of the roof sheathing at 2 and 9 years revealed no sign of mold growth.

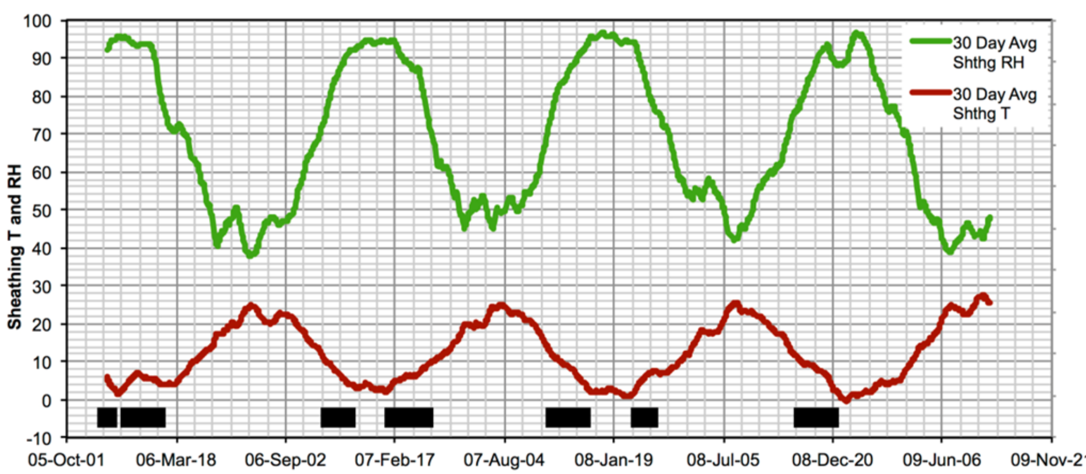


Figure 20: Coquitlam vented attic ASHRAE 160 results

These observations are consistent with the mold index model (Figure 21), which shows a seasonal cycle that peaked just over 1 (microscopic mold growth).

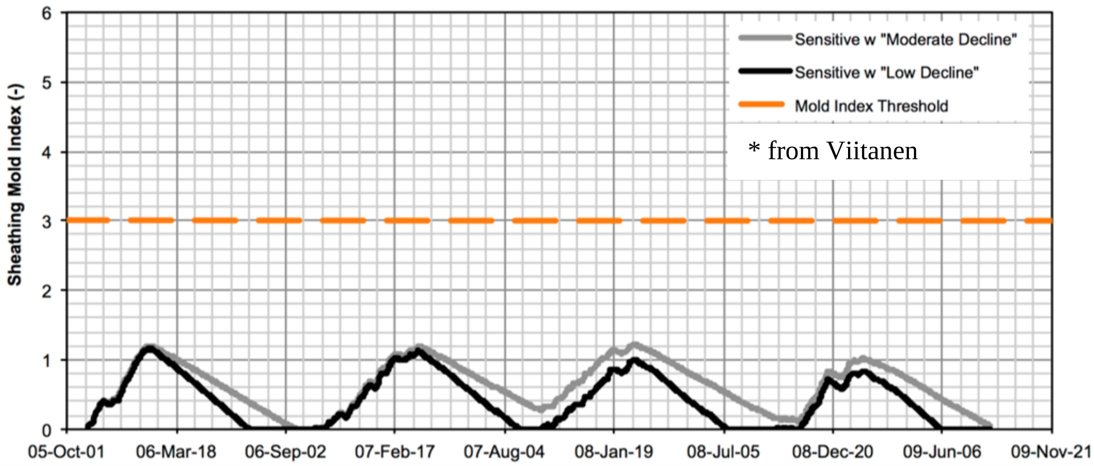


Figure 21: Coquitlam vented attic mold index results

In the same Coquitlam test facility, unvented cathedralized roof assemblies (asphalt shingle, OSB sheathing, ocSPF insulation) were constructed and monitored (Figure 22, left).

Figure 22: Unvented cathedralized attic in Coquitlam test facility, and sheathing MC measurement

Similar analysis was done, and again, the roof sheathing failed *ASHRAE Standard 160* criteria, but had a mold index than remained under the visible mold range (3), as shown in Figure 23. The sheathing was examined by removing the insulation (Figure 22, right), and no mold was seen, again indicating that the mold index provides more valid conclusions than the *ASHRAE Standard 160* criteria.

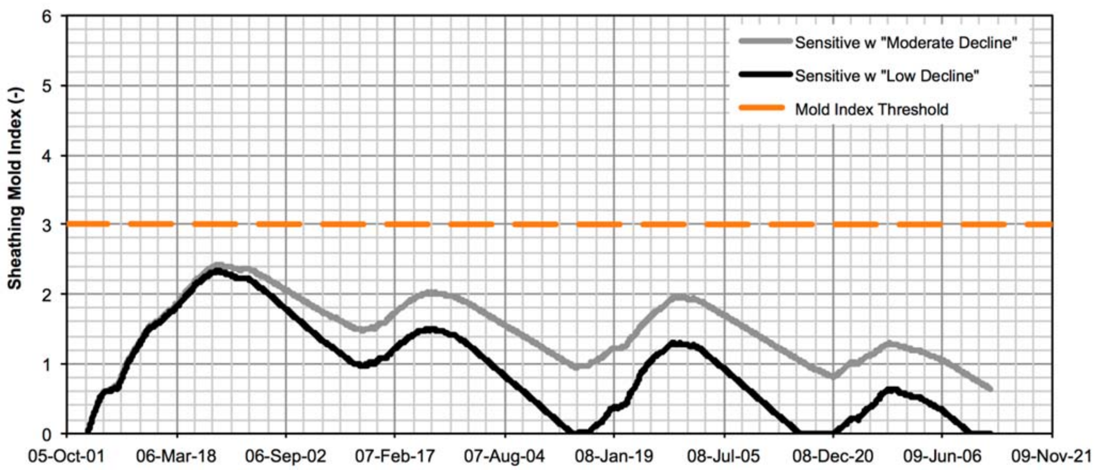


Figure 23: Coquitlam unvented cathedralized mold index results

ASHRAE 160 Conclusions and Further Work

The analysis of existing data indicates that the mold index model provides much more reasonable correlation with observed mold growth (or lack thereof), compared to the *ASHRAE Standard 160* criteria. An addendum to the standard will be released soon for public review, which will include the mold index model.

However, one important piece of work left outstanding is to analyze data in cases where visual mold growth was observed. So far, the field data analysis has addressed the false positives (of mold growth) of *ASHRAE Standard 160*. There is some risk that the mold growth index might result in false negatives (i.e., mold growth occurs in reality, but none shown in model); this analysis should be done to ensure this is not the case.

6 Conclusions

The Measure Guideline describes how to model and interpret results of models for above grade walls. The Measure Guideline analyzes the failure thresholds and criteria for above grade walls. A library of above-grade walls with historically successful performance was used to calibrate WUFI *(Wärme und Feuchte Instationär)* software models. The provided information can be generalized for application to a broad population of houses, within the limits of existing experience.

The WUFI software model was calibrated or "tuned" using wall assemblies with historically successful performance. The primary performance criteria or failure criteria establishing historic performance was moisture content of the exterior sheathing. The primary "tuning" parameters (simulation inputs) were airflow and specifying appropriate material properties. "Rational" hygric loads were established based on experience – specifically rain wetting and interior moisture (RH levels). The "tuning" parameters were limited or bounded by published data or experience.

The WUFI software model is a one-dimensional combined heat and moisture flow model. Typical building assemblies are multi-layer systems with complex three-dimensional airflow pathways. One-dimensional combined heat and moisture flow models have proven difficult to use for analysis in these types of assemblies due to the complexity added by the airflow component.

One challenge for a one-dimensional combined heat and moisture flow model is to address the rain and airflow components.

Rain is a significant moisture load: modeling the rain transport mechanism—a three dimensional phenomena in a multi-layer system—adds more complexity. The WUFI rain modeling inputs had the following assumptions:

- 30 percent of this water bounces off the wall and 70 percent is retained on the wall
- 1 percent of the 70 percent (the "retained water') is assumed to penetrate to the back side of the cladding
- 1 percent of the 1 percent is assumed to penetrate the water control layer and enter into the sheathing.

WUFI software is capable of modeling cladding ventilation, by introducing interior or exterior condition air into an airspace within the assembly. This allows for explicit (and more correct) modeling of ventilated rainscreen behaviors, including vinyl siding (bypass of vapor-impermeable vinyl material with airflow) or brick veneer construction.

This airflow model within WUFI also allows the analysis of "through the assembly airflow" (i.e., air leakage through typical imperfect assemblies). This flow can be approximated as follows. Two arbitrary 5 mm (3/16 inch) airspaces are created at the interface of the cavity insulation and the structural sheathing. One airspace is coupled to the interior, simulating moves air-transported moisture from the interior to the interior face of the exterior sheathing. The other airspace is coupled to the exterior, and simulates air leakage from the exterior into the cavity.

Running the rainwater and airflow “tuned” WUFI software model generated the library of input data and results presented. The results agree with historical experience of these assemblies constructed in the climate zones modeled.

Comparisons between *ASHRAE Standard 160* and measured data coupled with visual observations indicated that *ASHRAE Standard 160* criteria are providing false positives of wall failures, based on disassembly and examination of enclosure assemblies.

The same measured data and observations were compared to the Viitanen Mold Growth Index model. The analysis indicates that the Viitanen Mold Growth Index model provides much more reasonable correlation with observed mold growth (or lack thereof), compared to the *ASHRAE Standard 160* criteria.

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About this Report

This report was prepared with the cooperation of the U.S. Department of Energy's Building America Program.

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