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Guidance on Modeling Enclosure Design in Above Grade Walls: Expert Meeting Report

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Kohta Ueno and Joseph Lstiburek

Abstract:

Hygrothermal simulations such as WUFI 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. However, with increasing dissemination of these types of modeling tools–most notable 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.

Therefore, Building Science Corporation led a Building America Expert Meeting on "Guidance on Modeling Enclosure Design for Above-Grade Walls." Presenters from national laboratories, consulting firms, and building material manufacturers presented on their research, which matched field measurements of wall hygrothermal behavior to simulations. This was followed by a group discussion on various topics, including required expertise for running WUFI, education requirements, and the need for material property testing.

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

BUILDING TECHNOLOGIES PROGRAM

Guidance on Modeling Enclosure Design in Above Grade Walls: Expert Meeting Report

K. Ueno and J. Lstiburek

June 2014

Building America U.S. Department of Energy

Prepared by Building Science Corporation
For the U.S. Department of Energy Building Technologies Program

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Prepared by:

Building Science Corporation

3 Lan Drive, Suite 102

Westford, MA 01886

NREL Technical Monitor: Cheryn Metzger

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Unless otherwise noted, all figures were created by Building Science Corporation

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Definitions

ACH	Air changes per hour
ACH 50	Air changes per hour at 50 Pascals
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BA	Building America Program
BPI	Building Performance Institute, Inc.
BSC	Building Science Corporation
BSCI	Building Science Consulting Inc.
ccSPF	Closed-cell Spray Polyurethane Foam
CZ	Climate Zone (DOE, ASHRAE)
EPS	Expanded polystyrene
HERS	Home Energy Rating System
ICC	International Code Council
MC	Moisture content
NAHB	National Association of Home Builders
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
OSB	Oriented strand board
PHIUS	Passive House Institute US
RH	Relative humidity
RESNET	Residential Energy Services Network
USDA	United States Department of Agriculture

VTT	VTT Technical Research Centre of Finland
WRB	Water-resistive barrier
WUFI	Wärme- Und Feuchtetransport Instationär
XPS	Extruded polystyrene

Executive Summary

Hygrothermal simulations such as WUFI 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. However, with increasing dissemination of these types of modeling tools–most notable 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.

Therefore, Building Science Corporation led a Building America Expert Meeting on "Guidance on Modeling Enclosure Design for Above-Grade Walls" on May 12, 2014 at the Westford Regency Inn and Conference Center in Westford, MA. Invited speakers presented on the following topics:

Christopher Schumacher, as an experienced user of WUFI, regularly fields questions from less-experienced users who are setting up models. He has helped these practitioners tune their models closer to reality; walked through a typical exchange with a new practitioner. Some key weaknesses he found in his interactions is that there is limited or uncertain material property information, many users are use default configurations due to ignorance instead of choice, and many do not understand the underlying physics. He recommended more education to users, better material properties, and more field experience/monitoring.

Lois Arena covered work monitoring high-R (double stud) walls, simulations of these walls, and interactions with ASHRAE Standard 160. In multiple projects, including both field monitoring and simulation, ASHRAE 160 showed that assemblies were failing, while no such endemic failures occur in practice or were in evidence in measured moisture contents. The ASHRAE 160 committee is considering changes to the standard, including adoption of the VTT Finland mold index. In addition, Arena noted that the initial condition (80% RH) recommended in ASHRAE 160 seemed consistently high.

Vladimir Kochkin presented results from monitoring sheathing moisture contents in a broad survey of houses (20+ homes in multiple climate zones), and test hut monitoring work in Maryland (Zone 4A). Many of these walls had exterior foam, to meet requirements in the 2012 IECC. One general pattern that "safer" designs (more exterior continuous insulation/less cavity insulation) generally had lower wintertime moisture contents, but with some exceptions. The results also allay builder concerns that exterior foam impedes drying; drying to the interior was in evidence. He also questioned ASHRAE 160 criteria as being overly conservative. In addition, he questioned the common wisdom of 20% moisture content as a risk condition; it is known that no damage will occur under 20% MC, but the inverse (damage will occur above 20%) is not as clear. This is consistent with the field disassembly conducted of walls that hit 20% MC in wintertime. Test hut work indicated, among other items, that walls with Kraft-faced batt (Class II) were less sensitive to interior RH; controlling interior RH is critical if Class III vapor retarders are being used.

Samuel Glass covered WUFI simulations on the test hut data discussed previously; results were examined to see if they correctly captured general wetting and drying trends; it was not intended as a model validation effort. Key research covered OSB response to interior RH conditions, north vs. south wall orientation, and Kraft facing vapor retarders (Class II) vs. latex paint (Class III). Correlations between simulations and measured data were reasonable, with some exceptions. In general, high interior humidity levels (40-50% in winter) resulted in significant moisture accumulation (20%+) in walls with a Class III vapor retarder (latex paint), particularly north-facing walls, and moisture accumulation was not significant in walls with an interior Kraft vapor retarder (Class II). Also, simulations tend to under-predict OSB MC during summer, particularly for stucco and manufactured stone veneer (simulation drier than reality).

Achilles Karagiozis first explained that ASHRAE Standard 160 should not predict typical interior or enclosure conditions in the field; instead, the intent of 160 is to provide design or worst-case conditions. It is entirely possible that they are currently too high (and should be less stringent), but the ultimate intent is to provide a safety factor when designing building enclosures. He stated that the ASHRAE 160 simplified method produces unrealistic results, but the intermediate method produced better results. He then covered the role of WUFI, stating that is used by experts to create useful results—but ultimately, "the tool is only as knowledgeable as the user." Others in the audience questioned the level of expertise being proposed here: a high bar would limit practitioners to a small fraction of the current users.

Joseph Lstiburek then covered BSC's upcoming work under Building America (Task Order 5), which is to generate a series of WUFI files of common North American wall assemblies that have historically provided good performance. The behavior of these assemblies can then be examined, to determine appropriate failure criteria based on this historic record. This is intended to counter much of the common, existing modeling which shows that walls known to perform well (historically) do not meet various failure criteria. Each of these wall assemblies will be accompanied by a short case study, which explains the history of the wall, how it works (hygrothermally), the function of each component (air barrier vs. vapor retarder vs. water control), and the thought process behind the design.

This was followed by a group discussion on various topics. One topic was WUFI and the user base's expertise, and training. The general consensus was that trying to limit access to WUFI is a non-starter. Instead, the correct approach is to provide education; the template files described above are a step in the right direction. In addition, a fundamental issue is that this field needs to determine who is qualified to make these engineering judgments. There was broad support for better material property data; the key question is how industry will support the funding of the material property testing, and dissemination of the data. Failure criteria were discussed; in addition to ASHRAE 160 criteria, the VTT mold index, sheathing moisture content, and WUFI moisture year-to-year trend data were brought up as options.

1 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.

Therefore, Building Science Corporation led a Building America Expert Meeting on "Guidance on Modeling Enclosure Design for Above-Grade Walls." 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). This expert meeting will directly support Critical Milestone E4, under Enclosures:

> *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 meeting began with presentations from various stakeholders, providing background information on the current state of hygrothermal modeling, including interactions with ASHRAE Standard 160. The meeting then focused on proposed guidance for design methods for enclosure design for above-grade walls. The intent was to examine this topic with viewpoints from the various stakeholders, such as builders, architects, developers, modelers, and anyone asked to design an above-grade wall assembly. The meeting was organized around the following topics:

1. Review wall assemblies and conditions that provide proven performance in each climate zone.
2. Review ASHRAE Standard 160 (ASHRAE 2009) and WUFI (Künzel 2002) analysis of these wall assemblies and conditions.
3. Review modeling boundary conditions and failure thresholds.

2 Meeting Information

Building Science Corporation held an Expert Meeting on "Guidance on Modeling Enclosure Design in Above Grade Walls Interior," on May 12, 2014 at the Westford Regency Inn and Conference Center in Westford, MA.

There were 26 in attendance; participants included building science researchers, product manufacturers representatives, and representatives of the press. Invited speakers gave presentations in their particular area of expertise. The presentations were followed by an open discussion moderated by Joseph Lstiburek of BSC, on the topics of where hygrothermal modeling resources should be directed to increase accuracy and applicability of simulations, as well as BSC's planned research work for Building America TO5 (calendar year 2014).

Figure 1: Photo taken during expert meeting

The invitation and agenda for the meeting is listed in Appendix A. The presentations are included in Appendix B through F.

A list of attendees is included in Table 1; presenters are highlighted in italics.

Table 1: Expert meeting participants

Name	Organization	Email Address
Alexander 'Andy' Bell	Energy Vanguard	andy[at]energyvanguard[dot]com
Marcus Jablonka	Cosella-Dörken	mjablonka[at]cosella-dorken[dot]com
Peter Yost	Building Green	peter[at]buildinggreen[dot]com
Warren Barber	National Gypsum Services Company	warrenb[at]nationalgypsum[dot]com
Theresa Weston	DuPont	Theresa[dot]A[dot]Weston[at]dupont[dot]com
Rockford Boyer	Roxul	rockford[dot]boyer[at]roxul[dot]com
Danko Davidovic	Huber Engineered Woods	danko[dot]davidovic[at]huber[dot]com
Michael Gestwick	NREL	Michael[dot]Gestwick[at]nrel[dot]gov
Chris Rosemond	BASF	chris[dot]rosemond[at]basf[dot]com
Roderick Jackson	ORNL	jacksonrk[at]ornl[dot]gov
Tom Kositzky	APA	tom[dot]kositzky[at]apawood[dot]org
Mac Sheldon	Demilec	mac[at]demilec[dot]com
Andre Desjarlais	ORNL	desjarlaisa[at]ornl[dot]gov
Layla Thomas	MASCO	Layla[dot]Thomas[at]mascohs[dot]com
Duncan Prahl	IBACOS	dprahl[at]ibacos[dot]com
Katrin Klingenberg	PHIUS	Katrin[at]passivehouse[dot]us
Christine Cronin	WJE	CCronin[at]wje[dot]com
Betsy Pettit	Building Science Corporation	betsy[at]buildingscience[dot]com
Kohta Ueno	Building Science Corporation	kohta[at]buildingscience[dot]com
Peter Baker	Building Science Corporation	pbaker[at]buildingscience[dot]com
Phil Kerrigan	Building Science Corporation	phil[at]buildingscience[dot]com
Ken Neuhauser	Building Science Corporation	ken[at]buildingscience[dot]com
Honorata Loomis	Building Science Corporation	honorata[at]buildingscience[dot]com
Achilles Karagiozis	*Owens Corning*	*Achilles[dot]karagiozis[at]owenscorning[dot]com*
Samuel V Glass	*Forest Products Laboratory*	*svglass[at]fs[dot]fed[dot]us*
Lois Arena	*Steven Winter Associates*	*larena[at]swinter[dot]com*
Joseph Lstiburek	*Building Science Corporation*	*joe[at]buildingscience[dot]com*
Chris Schumacher	*Building Science Consulting Inc.*	*chris[at]buildingsciencelabs[dot]com*
Vladimir Kochkin	*Home Innovation Research Labs*	*Vkochkin[at]nahbrc[dot]com*

3 Meeting Objectives and Agenda

The meeting began with presentations from various stakeholders, providing background information on the current state of hygrothermal modeling, including interactions with ASHRAE Standard 160. The meeting then focused on proposed guidance for design methods for enclosure design for above-grade walls. The intent was to examine this topic with viewpoints from the various stakeholders, such as builders, architects, developers, modelers, and anyone asked to design an above-grade wall assembly.

3.1 Research Questions

Building Science Corporation posed the following research questions relevant to this area of study:

- What are some proven performance wall assemblies in each climate zone?
- What are the modeling boundary conditions and failure thresholds?
- Are there failure modes other than rain, air, construction moisture, vapor, and interior relative humidity?

3.2 Agenda of Presentations & Discussion

The agenda for the presentations and discussions is shown below, and also in Appendix A.

Table 2: Expert meeting agenda

Time	Speaker	Topic
8:30 to 8:45 am	Joseph Lstiburek	Introduction
8:45 to 9:30 am	Chris Schumacher	Modeling a Historically Proven Wall
9:30 to 10:15 am	Lois Arena	Monitoring and Modeling Issues Associated with ASHRAE 160
10:15 to 10:30 am		Break
10:30 to 11:15 am	Vladimir Kochkin	Moisture Performance of Energy Efficient Walls
	Samuel Glass	Simulated and Measured OSB MC in CZ 4 Wall Assemblies
11:15 to 12:00 pm	Achilles Karagiozis	What is WUFI?—The Building Science Tool
12:00 to 1:00 pm		Lunch
1:00 to 2:45 pm	Joseph Lstiburek	Moderated discussion between presenters and attendees
2:45 to 3:00 pm		Break
3:00 to 4:00 pm	Joseph Lstiburek	Moderated discussion between presenters and attendees
4:00 to 4:15 pm	Joseph Lstiburek	Closing Remarks

3.3 Presenter Biographies

3.3.1 Joseph Lstiburek

Joseph Lstiburek is a principal of Building Science Corporation. Dr. Lstiburek's work at BSC ranges widely, from investigating building failures to overseeing research and development projects, to writing articles and books as well as educating industry professionals. A building science pioneer, particularly in the areas of air barriers, vapor barriers, and vented and unvented assemblies, he has had a lasting impact on building codes and practices throughout the world. Dr. Lstiburek founded BSC in 1991, and has been a key figure in establishing it as one of the most influential and respected building science firms in North America.

Dr. Lstiburek is one of the world's foremost authorities on energy efficient construction techniques and heads one of the Building America program teams for the U.S. Department of Energy. Through the program, Dr. Lstiburek has forged partnerships with designers, builders, developers, materials suppliers and equipment manufacturers to build higher performance buildings across the U.S. Dr. Lstiburek has been a licensed Professional Engineer in the Province of Ontario since 1982 and is an ASHRAE Fellow.

3.3.2 Christopher Schumacher

Christopher Schumacher is a principal of Building Science Consulting Inc. He is recognized as an expert in the field of building monitoring, as well as enclosure and building systems testing. He has led the design, installation, and analysis of monitoring systems for a variety of research programs and demonstration projects, both in the lab and in field locations around the globe. Chris' formal education in architecture and engineering is balanced by almost two decades of experience in design, computer simulation, physical testing, and forensic investigation.

At BSCI, Chris regularly conducts field investigations and large-scale retrofit assessments. He has a special interest in historical buildings and has consulted on many projects for universities and other industrial/commercial/institutional facilities. He also oversees much of the work done through BSCI's research division, Building Science Laboratories. Examples of his research work include the Thermal Metric Project and the Vancouver Test Hut Project. He has extensive experience in product testing and development and thrives on the challenge of inventing novel solutions to client and industry questions.

3.3.3 Lois Arena

Lois Arena is a Senior Mechanical Engineer at Steven Winter Associates, Inc., where she works on the Department of Energy's Building America program and conducts advanced systems research. She received her M.S. in engineering from the University of Colorado's Building Science Program and holds Passive House, BPI and RESNET certifications.

She possesses over 15 years' experience in the building science field. She has extensive experience with new and existing residential buildings including on-site testing and diagnostics, design assistance and energy modeling. Awards presented to her clients include the New Millennium Builder Award and Gold Energy Value Housing Award from the NAHB. Lois has co-authored and presented training programs about energy efficient building practices to professionals in all sectors of the building industry.

3.3.4 Vladimir Kochkin

Vladimir Kochkin is the Director of the Applied Engineering Division of Home Innovation Research Labs; there, he oversees engineering research programs on structural, environmental, and energy performance of residential construction. He also manages the ANSI process for the development of the National Green Building Standard (ICC-700). In his tenure at Home Innovation, Vladimir's work has spanned analytical and experimental studies on the performance of buildings in natural disasters with focus on development of innovative engineering solutions.

Experimental projects included measuring the performance of various structural systems and materials including conventional and panelized systems for wood, cold-formed steel, and concrete construction. He has authored multiple research reports and guides for builders and product manufactures, and contributed to the development and implementation of product certification programs based on advanced quality management practices. Vladimir also works with product manufacturers on obtaining code acceptance for innovative construction technologies. He participates in the building code development process and serves on several standard development committees on structural performance of building systems including wall bracing. Vladimir holds a master's degree in Timber Engineering from Virginia Tech, and a B.S. in Civil Engineering from Vyatka State Technical University, Russia.

3.3.5 Samuel Glass

Samuel Glass is a Research Physical Scientist at the USDA Forest Products Laboratory. There, he leads the Building Moisture and Durability Research Team, one of four teams within the Durability and Wood Protection Research Work Unit at the Forest Products Laboratory. His work focuses on extending the service lives of buildings and wood products used in buildings by advancing a moisture performance based design approach and by promoting awareness of proper construction and operation practices. His primary research objectives include characterizing building envelope moisture performance in a variety of climates; developing and evaluating moisture management strategies to improve building envelope performance; quantifying moisture sources in buildings; and understanding moisture dynamics from the molecular level to the scale of whole buildings.

Dr. Glass is an ASHRAE member and participates in technical committees and development of standards related to building envelope performance and moisture control. Prior to joining the Forest Products Laboratory in 2005, Dr. Glass completed a Ph.D. in physical chemistry at the University of Wisconsin-Madison."

3.3.6 Achilles Karagiozis

As the Global Director of Building Science at Owens Corning, Dr. Karagiozis' role encompasses global accountability for Owens Corning's building science strategy. He is responsible for leading, shaping, driving, educating, and training others in energy efficiency and green building science, transforming building science into a growth engine aimed at accelerating energy efficiency improvements in the built environment.

Dr. Karagiozis is one of the leading building scientists in North America. Prior to joining Owens Corning, Karagiozis worked at the prestigious Oak Ridge National Laboratory, where he was a distinguished research engineer and hygrothermal project manager. He was instrumental in the launch of a number of innovative construction material and system products, and in the development of design guidelines, software tools, and code changes. He was formerly the owner of a building science consulting firm, which specialized in construction litigation and the development of design solutions for thermal and moisture control issues. He is the US representative for the new International Energy Agency (IEA) Annex 55 on Reliability of Energy Efficient Building Retrofitting. After his Ph.D., he joined the Institute for Research in Construction, NRC, and developed his unique competencies in whole building analysis and moisture engineering analysis. As an expert in the area of Moisture Engineering, he has solved many hygrothermal designs and retrofit challenges, and has developed multiple design guidelines for various enclosure systems and software tools.

In addition to his work with the IEA, Dr. Karagiozis is an active member of ASTM and ASHRAE. He is also an Adjunct Professor at the University of Waterloo and the author of more than 120 technical papers and reports related to building science.

4 Presentation Summaries

Five presentations were given covering current research and knowledge in hygrothermal behavior of building assemblies, and hygrothermal simulation of these assemblies.

4.1 Chris Schumacher: Modeling a Historically Proven Wall

4.1.1 Presentation

Schumacher first questioned the purpose of developing "guidance on modeling enclosure design"—both the target audience, and what form the guidance should take. More importantly, *ASHRAE Standard 160* is intended to fulfill this exact role, including analytical procedures, inputs, and evaluation of outputs (pass/fail criteria)—but is not providing realistic results.

Schumacher, as an experienced user of WUFI, regularly fields questions from less-experienced users who are setting up models. He has helped these practitioners with models that indicate that well-known, historically common wall assemblies demonstrate failure, despite the extensive historical success in the field with these assemblies. He walked through a typical exchange with a new practitioner, to "tweak" or tune a model closer to reality.

The modeled assembly was a Chicago-area wood stud frame wall with fiber cement cladding; as provided, the simulation showed peak moisture contents of 40-50% at the interior side of the exterior plywood sheathing in winter (Figure 2), which was far outside of the realistic range.

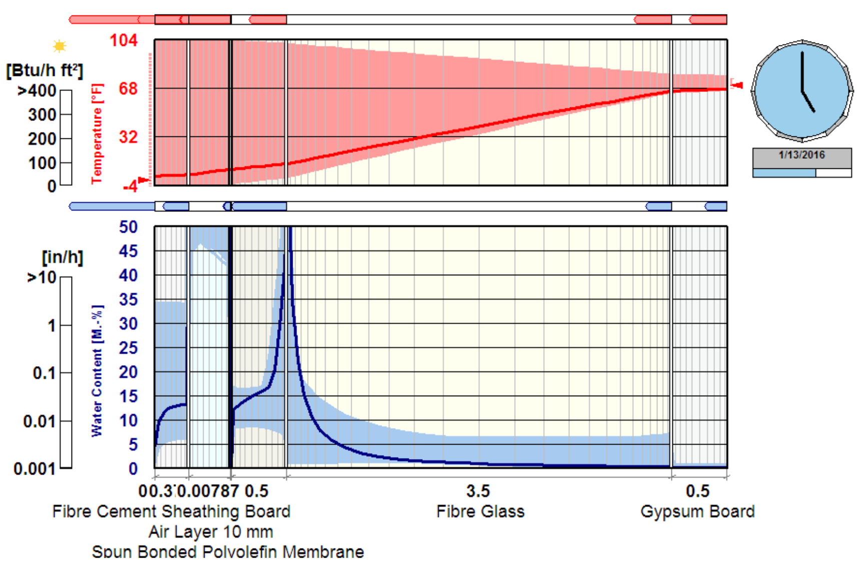

Figure 2: Initial WUFI results for Chicago wall, pre-tuning (Schumacher 2014)

Schumacher then walked through, step-by-step, the choices made by the practitioner and problems encountered while building the model:

- Materials selection and assembly construction:
    - Some materials are not available in the database (fiber cement siding)—fiber cement sheathing board can be substituted, but it is not clear whether the

properties are actually correct. Manufacturers seldom provide the detailed material data required by WUFI, and many have never generated this information themselves.

  - Air spaces can be a source of confusion due to the options and numerical simulation work-arounds.

  - Other materials (plywood, fiberglass batt, gypsum board) have multiple options available in the database: the typical practitioner does not necessarily understand which material(s) will provide reasonable results.

  - Overall, the practitioner was confident in only one of the six materials selected in the assembly cross-section.

- Surface Transfer Coefficients: these can provide significant differences in calculation results, but are poorly understood by many practitioners; they are often left at the default conditions, without any deeper understanding.

- Exterior and Interior Climate: selecting a North American climate from the database was straightforward; however, interior climate was set to ASHRAE 160 conditions. This interior condition can lead to problems, but typical practitioners are unaware of this fact.

- Initial conditions, calculation period, and numerics were all left at default values.

Schumacher then walked through various modifications to the model, to increase accuracy and realism:

- The plywood sheathing layer was split into multiple sub-layers or "study layers," so that peak moisture contents are accurately captured in quick graphs.

- Interior conditions were changed from ASHRAE 160 to a "low moisture load" sine curve (30% lowest interior RH), for "tuning" purposes.

- Ventilation was added to the air space (rainscreen cavity between the cladding and the WRB). Background materials for determining ventilation flow rates (ASHRAE Research Project 1091; see Burnett et al. 2004, Karagiozis 2004, Shi et al. 2004, and Straube et al. 2004) were covered, with 10 air changes per hour (ACH) selected for this assembly. However, this did not noticeably change the sheathing peak moisture content, even when ventilation was increased to 200 ACH.

- A different plywood material from the database was selected, which drastically dropped peak moisture contents (~40% MC to ~22% MC), bringing it down to the range of expected behavior, when combined with cladding ventilation. This demonstrated that the plywood was likely the drying bottleneck, given the low vapor permeability in the original material data.

- However, a small exterior-to-cavity air leak could result in a similar type of reduction in sheathing wetting, as demonstrated by the addition of a source-sink term.

- Small reductions in interior water vapor permeance (from 10 perms to 7 perms) had a strong effect on sheathing moisture content.

- Other items were not modified, but could have an effect on results, including paint on the exterior of the cladding, back-priming of the cladding, rain water penetration, and the explicit radiation balance calculation.

Overall, this exercise demonstrated that there are a vast number of "knobs" to modify the model. It is unclear which of these knobs—acting alone or in combination—is necessarily the "correct" modification.

In conclusion, Schumacher pointed out that many of these less-experienced practitioners do not understand the program, the underlying building physics, and/or ways to evaluate results. He recommended more college education and continuing education (for professionals) to try to increase knowledge levels, as well as more measurement and field experience. Other problems Schumacher noted were lack of accurate material properties, lack of field data of boundary conditions, and lack of field experience with newer enclosure assemblies.

4.1.2 Discussion

In further discussion, Schumacher asked whether WUFI should be used as a demonstration or learning tool, a scoping tool, a forensic tool, or as a design tool. It has been used successfully in many of these applications, but unsuccessfully as well.

In terms of being a demonstration or learning tool, WUFI is an excellent resource: it increases intuition and understanding of the underlying building science, and forces the user to learn more about the physics.

WUFI can be used as a scoping tool when designing an experimental program with a limited budget: it can suggest some key variables, to winnow down the experiments to key variables.

Joseph Lstiburek pointed out that his takeaway from this presentation is that WUFI is a fantastic hygrothermal simulation engine, but more often than not, its best use is not truly predictive. Instead, given the number of unknown variables, it is often most useful for analysis of collected field data, when the model is tuned to fit the (known) data.

Andre Desjarlais pointed out that not knowing a key material property (e.g., paint permeance) is analogous to not knowing the R value of an assembly: a key value that is typically necessary to obtain correct answers. Schumacher also noted that a precise energy model can be off by 20%, resulting in greater or lower energy consumption in reality—while hygrothermal simulations can determine success or failure of an assembly.

Chris Schumacher pointed out that although measurement (i.e., field data collection) trumps modeling (which can be misleading), measurement is expensive and time consuming, and can also be misleading. He considers both modeling and measurement as necessary components to advance building science research.

4.2 Lois Arena: Monitoring and Modeling Issues Associated with ASHRAE 160

4.2.1 Presentation

Arena started the presentation admitting that she is one of the practitioners described by Schumacher: trying to understand the WUFI inputs with difficulty, even though she has been modeling since 2008 and has taken multiple training classes. Given this level of uncertainty, she could only imagine that there are many practitioners with far less knowledge. In addition, she echoed Schumacher's sentiment on the lack of manufacturers' material property data.

Arena presented on Steven Winter Associates' work on moisture monitoring of walls, comparisons between modeling and measurement, her team's experience with ASHRAE 160, and proposed changes to ASHRAE 160.

She explained the original (pre-Addenda) ASHRAE 160 standard, including inputs and failure criteria (30-day, 7-day, and 24-hour running average maximum RH values). Her team's 2008 field monitoring showed that interior temperatures were lower in winter and higher in summer, and relative humidity levels were higher in winter and lower in summer than those calculated by ASHRAE 160. In addition, she has found that the starting condition (80% RH equilibrium moisture condition) is too high.

In 2011, her team ran simulations for the Spray Polyurethane Foam Alliance (SPFA), examining "flash and batt" (spray foam and fibrous hybrid insulation) wall insulation levels. The research question was whether the insulation ratios were sufficient to avoid moisture failures when using a Class III vapor retarder. WUFI simulations were run in Climate Zones 4 through 7, with a total of over 90 runs; all walls failed the ASHRAE 160 criteria. In addition, the simulations showed likely mold growth on the interior walls, which is clearly not a common occurrence. ASHRAE 160 conditions were examined in more detail: the "intermediate method" results in 90% interior RH, even with interior cooling; this unrealistic input caused the prediction of interior mold growth. For following work, an interior T/RH sine curve was used.

In 2011 through 2013, her team monitored a high-R (double stud and cellulose) wall in Devens, MA (Zone 5A), followed by WUFI simulations informed by the measurements. They found that modeling reasonably reflects performance. In addition, the walls performed well, but failed ASHRAE 160 criteria. The interior conditions during the monitoring period included 20% interior RH in wintertime, which would tend to not stress wall assemblies; this is consistent with existing housing stock (not superinsulated/airtight), as well as properly ventilated airtight construction.

When the monitoring results were compared with simulations, the south side had reasonably good correspondence. However, on the north orientation, simulations predicted lower sheathing moisture contents than measured, even with modifications of interior and exterior vapor permeability. Reasonable correlation could be achieved, though, by assuming a 1% driving rain leak at the OSB surface (Figure 3).

When measured and simulated results were subjected to ASHRAE 160 criteria, both options failed, in north and south orientations. One objection to ASHRAE 160 is that the failure criteria might be too strict, with a single 30-day average above the limit constituting a failure of the entire assembly.

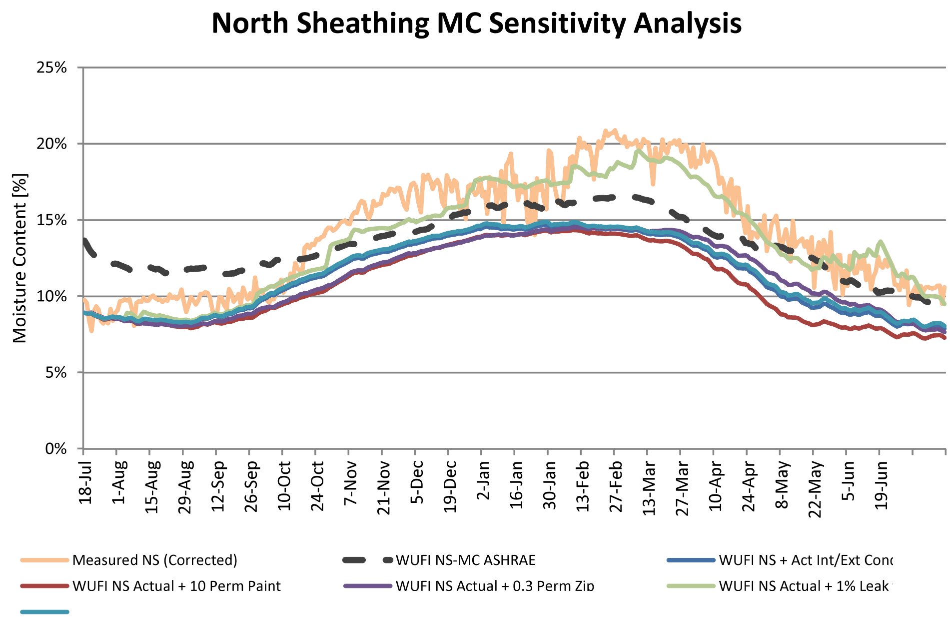

Figure 3: Devens double stud north side sheathing MC vs. WUFI simulations (Arena 2014)

Arena then discussed the 2011-2012 addenda to ASHRAE 160. Addendum a eliminated the 7-day and 24-hour running average failure conditions; Addendum b reduced interior moisture generation rates (and thus interior RHs) and capped interior RH at 70%; and Addendum c simplified the calculation methods for driving rain/wind-driven rain. She noted that with Addendum b, ASHRAE 160 interior RH predictions were reasonably close to measured values.

She then continued with her team's current (2014) NYSERDA monitoring and modeling project: two double stud walls in Climate Zone 6 (Ithaca NY), one with 12" of cellulose, and the other with a "hybrid" or "flash and batt" assembly (3.5" ccSPF and 8.5" cellulose). Both of these walls fail ASHRAE 160 criteria, but are measured to be performing very well (wintertime moisture contents under 15%).

Monitored data showed 100% RH conditions at the sheathing-insulation interface throughout most of the winter, even in the spray foam wall; of course, this fails ASHRAE 160 criteria. Again, this raises questions of whether failure criteria are too strict: for instance, it does not account for mold-resistant condensing interfaces, such as the spray foam-to-cellulose interface. In addition, most of the simulated failures were in the first year at the beginning of the modeling period, which suggests that initial conditions might be overly wet. In addition, most walls with Class III interior vapor retarders fail the ASHRAE 30-day criterion.

The ASHRAE 160 committee is considering changes to the standard, including adoption of the VTT Finland mold model or mold index (Viitanen and Ritschkoff 1991), and eliminating airtightness/air leakage calculations.

4.2.2 Discussion

Initial Conditions: Arena questioned the realism of the ASHRAE 160 starting conditions (80% RH): handheld moisture content measurement of the above-grade walls at the start of the work measured 8-9% MC (equivalent to 45-50% RH, vs. 16% MC at 80% RH). Achilles Karagiozis agreed that this is a worthwhile step if the model is being tuned to data, but for design purposes, this 80% RH starting condition is a good conservative assumption.

Mold Growth Conditions: In the Devens work, the home was sealed up right after completion and the air conditioning system completely turned off. SWA visited the site to install the data logging equipment one month after and found the interior conditions were 70F/80% in the basement. Major amounts of mold were found on the exposed basement framing. However, all above-grade exterior walls had low moisture contents and no mold growth, which belies some of the failure criteria used in ASHRAE 160. Chris Schumacher also noted that in climate chamber work, he found that sustained 80% RH was not sufficient to grow mold on building materials; however, with the introduction sufficient liquid water, mold growth was rapid. Achilles Karagiozis responded that the ASHRAE 160 standard is moving away from the current 80% threshold, instead adopting the VTT mold index. Joseph Lstiburek and Chris Schumacher, though, noted that it is a flawed tool, even if it is the best available today, and perhaps it should not be introduced to cause further problems.

Design vs. Validation: Joseph Lstiburek argued that to obtain believable results from WUFI, tuning the model to measured data might be the only realistic option—which means that it is not a very suitable design tool (given the unknowns and lack of measured data in design). Achilles Karagiozis argued that WUFI has been fully validated and can be used for design, but Lstiburek countered that validation (agreement with physics) is different than tuning (modifying model inputs to reflect measured data).

PHIUS Perspective and Building Science Education: Katrin Klingenberg noted that PHIUS uses WUFI and WUFI-Passive as design tools. Students are introduced to these tools, but training time is limited, and it is unknown how students will continue their education. One response of the Passive House community is to move away from more moisture vulnerable walls (using OSB sheathing or "flash and batt"), instead preferring safer or more "hygrothermally foolproof" vapor-open (or "flow through") walls.

Peter Yost followed up to this comment, noting that he has often communicated with or heard about architects who use WUFI as a substitute for building science education and understanding of the physics. He found this trend exceptionally dangerous and worrisome.

4.3 Vladimir Kochkin: Moisture Performance of Energy Efficient Walls

4.3.1 Presentation

Kochkin presented the results of Home Innovation Research Labs' recent hygrothermal monitoring work: a broad sample survey of wall moisture contents (20+ homes in multiple climate zones), and test hut monitoring work in Maryland (Zone 4A). The following presentation (Samuel Glass) covered hygrothermal simulations of the Maryland test hut work.

The "broad sample" survey was intended to prepare for the wall assemblies that will be required under the 2012 International Energy Conservation Code (ICC 2012); many of the options involve exterior foam continuous insulation, which makes many builders concerned due to potential moisture accumulation issues. A set of 22 homes across Climate Zones 2 through 6 had walls monitored for sheathing moisture content, temperature, and relative humidity with wireless battery-powered sensors. All houses were substantially airtight (2-4 ACH 50 typical), and all had ventilation systems. A variety of wall assemblies were monitored (typically ranging from R-13 to R-30+), based on the builder's preferences and current practices.

A huge data set was generated: to create a builder-digestable form of the information, bar graphs were created to summarize key takeaways from the first winter, first summer, and second winter. An example is shown in Figure 4: the sets of 3 bars represent average seasonal moisture contents in the first winter (dark blue), first summer (yellow), and the second winter (light blue). The pink bars represent the peaks or spikes of data. The graph shows the general trend that "safer" designs (more exterior continuous insulation/less cavity insulation) have generally lower wintertime moisture contents, but with some exceptions. All walls had gypsum board and latex paint (Class III vapor retarder) on the interior; it was measured at 30 perms.

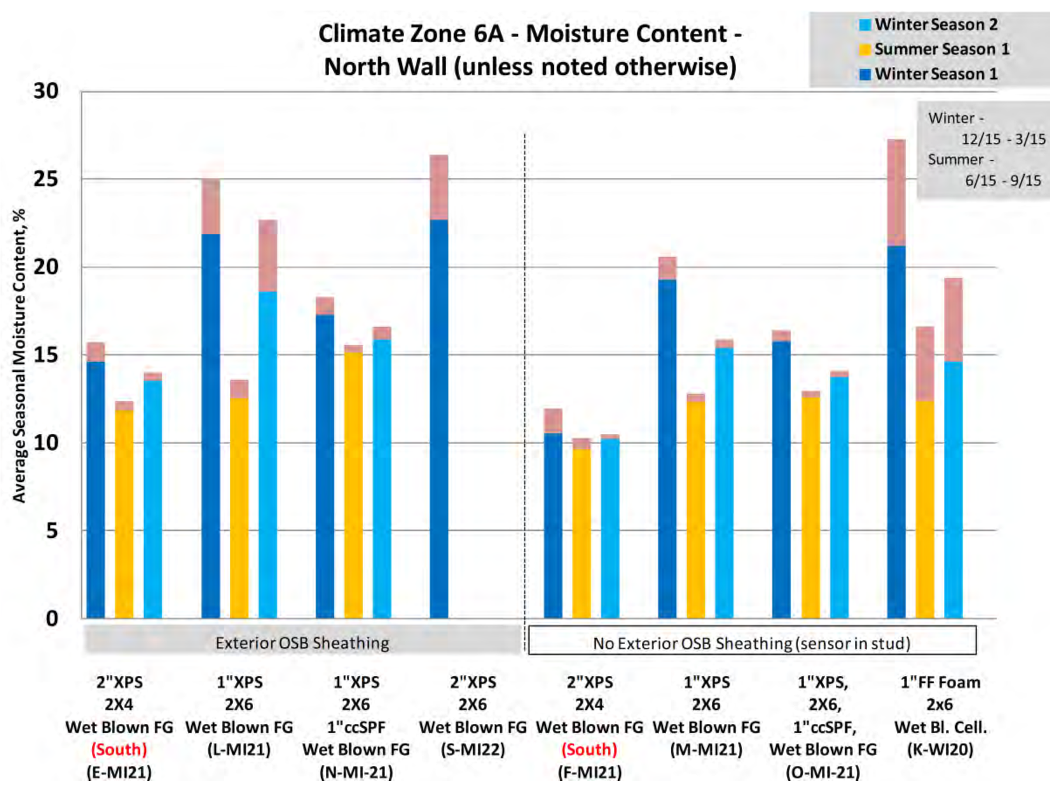

Figure 4: Summary of Zone 6A moisture content survey data (Kochkin 2014)

One concern raised by the builders was that exterior foam will eliminate drying to the exterior, and that the wall will remain wet. The results show that the second winter consistently has lower moisture contents than the first winter, showing drying to the interior. The results in Figure 4 also indicate that 1" of foam on a 2x6 wall has some risk: a greater thickness of foam would be safer, but many builders prefer 1" of foam (vs. 1-½" or 2") for buildability reasons. Kochkin proposed that adding a variable permeability ("smart") vapor retarder on the interior might address these concerns. 1" of exterior foam and ccSPF provided good performance; however, the OSB sheathing "trapped" between the two vapor-impermeable foams would be at high risk in the case of bulk water leakage.

ASHRAE 160 criteria were exceeded in almost all cases, including commonly accepted walls in Climate Zones 4 and 5, providing another data point questioning the conservatism of the standard.

In addition, Kochkin questioned the common wisdom of 20% moisture content as a risk condition; it is known that no damage will occur under 20% MC, but the inverse (damage will occur above 20%) is not as clear; he saw no reason to reject many of these walls. To wit, his research team disassembled and examined some Climate Zone 4A (MD) walls after two years with 20%+ sheathing MC peaks; the OSB looked essentially pristine.

Other conclusions from this research included the fact that 2" exterior foam provides excellent protection from inward-driven moisture on the south orientation. High moisture contents were seen in damp-spray cellulose walls in the first winter; continued monitoring was recommended to capture the duration of risk. Simplified condensation calculations tend to overly predict risk, but ASHRAE 160 failure conditions were often exceeded.

The test hut results were recent work that compared multiple north- and south-facing wall assemblies in Climate Zone 4A (MD). The walls were all 2x4 construction with various types of R-5 exterior insulation materials (XPS, EPS, polyisocyanurate, rockwool), and fiberglass cavity insulation (both unfaced batt and Kraft-faced batt). The research quantified the impact of vapor diffusion vs. air leakage on OSB moisture content, as well as the impact of interior RH with an interior Class III (latex paint) vapor retarder. The interior relative humidity was controlled to ASHRAE 160 target conditions; it was at 40-60% through most of the winter. When the walls were disassembled after a winter, mold and rust were noticeable in the cavities, due to vapor diffusion and/or air leakage of the high interior moisture conditions. Walls with Kraft facing were less sensitive to interior RH; controlling interior RH is critical if Class III vapor retarders are being used.

4.3.2 Discussion

Chris Schumacher pointed out that latex paint and primer (Class III) has changed significantly over the last 50 years; his team has measured:

- Oil paint (on drywall): under 1 perm
- Roller-applied latex: 2-7 perms
- Spray applied latex: 15+ perms

The reason for the high permeability of spray applied (even back-rolled) paint may be microscopic pinholes in the paint coating. Samuel Glass noted that his permeance measures corroborated Schumacher's.

Schumacher also noted that the physically large moisture content sensors used in the "survey" research displace a noticeable amount of cavity insulation, which might result in higher sheathing surface temperatures (and thus lower moisture contents) than in the main field of the wall.

4.4 Samuel Glass: Simulated and Measured OSB MC in CZ 4 Wall Assemblies

4.4.1 Presentation

Samuel Glass covered the Forest Products Laboratory work done in cooperation with Home Innovation Research Labs, performing WUFI simulations on the test hut data discussed previously. The simulations were examined to see if they correctly captured general wetting and drying trends; it was not intended as a model validation effort. Key research covered OSB response to interior RH conditions, north vs. south wall orientation, and Kraft facing vapor retarders (Class II) vs. latex paint (Class III). No air leakage or liquid water leaks were introduced into the simulated walls. Actual measured interior and exterior boundary conditions were used in the simulations.

Material data were taken from the North American database, but certain properties were adjusted using measured values. Latex paint (primer + two coats paint) was set at 35 perms. Asphalt-coated Kraft paper (interior vapor retarder) was set as an RH-dependent curve based on measured values at 0.6 perm dry cup/1.0 perm wet cup (Figure 5). Achilles Karagiozis stated that Kraft's wet cup permeance is higher (8-10 perms). Glass agreed that previous measurements have ranged from about 0.3 to 1 perm at low RH and from about 3 to 8 perms at high RH (literature data are shown in Figure 5). For reference, dry cup measurement is at 25% RH, and wet cup at 75% RH.

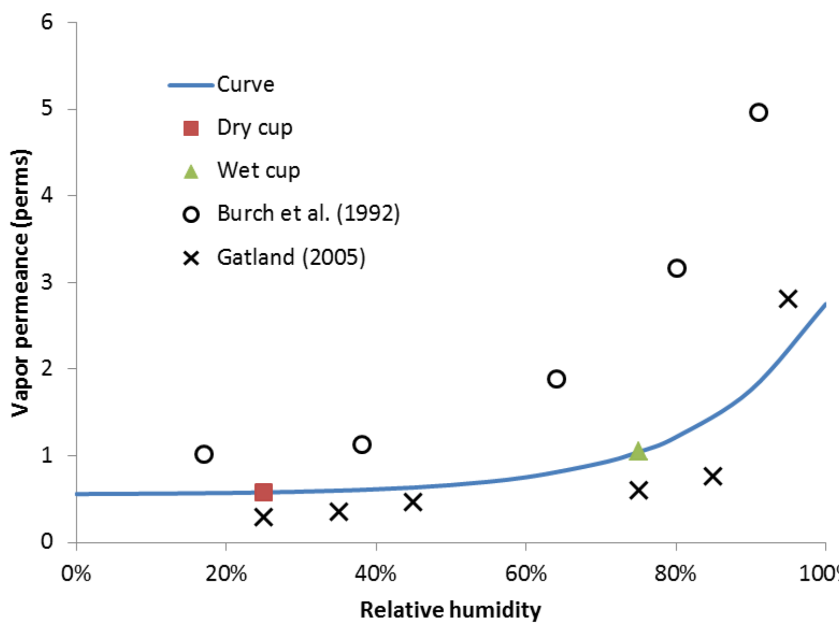

Figure 5: Kraft facing permeance as a function of humidity (Home Innovation Research Labs 2013)

Resistance-based moisture content sensors were calibrated against gravimetric MC measurements; the 95% confidence interval was calculated. The sensors went out of range high at roughly 25% MC.

Glass then presented a series of comparisons between measured and modeled data. The comparison for the 2x6/R-21 wall with vinyl siding is shown in Figure 6. The correlations between measurements and simulations are reasonable; the north unfaced MC measurements show “clipping” at 25%. The simulation underpredicts peak MCs with the Kraft-faced batt walls; this may be a function of the permeability used in the simulation. The plotted results are for the fully thickness of the OSB sheathing (as opposed to an interior “slice”), which would tend to underreport peak MCs, compared to field measurements.

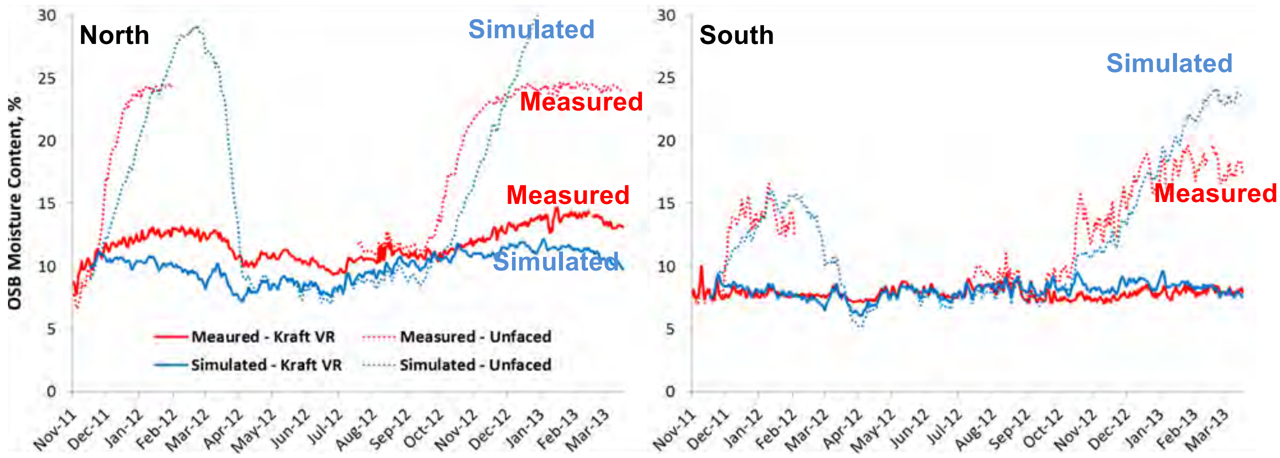

Figure 6: Measured vs. modeled OSB MC, 2x6 w. vinyl siding (Glass 2014)

An XPS-sheathed wall was measured with and without an added “crinkled” WRB; differences were insignificant.

The manufactured stone veneer and stucco walls showed higher summertime measurements than simulations, especially in summer (15% measured/8% simulated). Glass suggested this might be ion migration into the wood sheathing (affecting the electric resistance response), but other practitioners (Chris Schumacher, among others) did not find this likely.

The brick veneer wall again raised the topic of limitations in the material database: the material “Brick (old)” was selected from the North America database even though it does not include the effect of mortar joints (which are included in “Solid Brick Masonry” from the Fraunhofer-IBP database), but little other information was known or available. Assuming a 10 ACH ventilation rate, the correlations were reasonable (better on south than north).

Key conclusions included:

- High interior humidity levels result in significant moisture accumulation (20%+) in walls without an interior Kraft vapor retarder (i.e., Class III/latex paint), particularly north-facing walls.
- Moisture accumulation was not significant in walls with an interior Kraft vapor retarder (Class II).
- R-5 exterior XPS had a marginal improvement of moisture content of OSB sheathing in walls with vinyl siding and an interior Kraft vapor retarder (Figure 7).
- Simulations capture the general timing of seasonal increase and decrease of OSB MC.

- Simulations tend to under-predict OSB MC during summer, particularly for stucco and manufactured stone veneer (simulation drier than reality).

- Simulations tend to under-predict OSB MC during winter for the same cladding types with an interior Kraft vapor retarder.

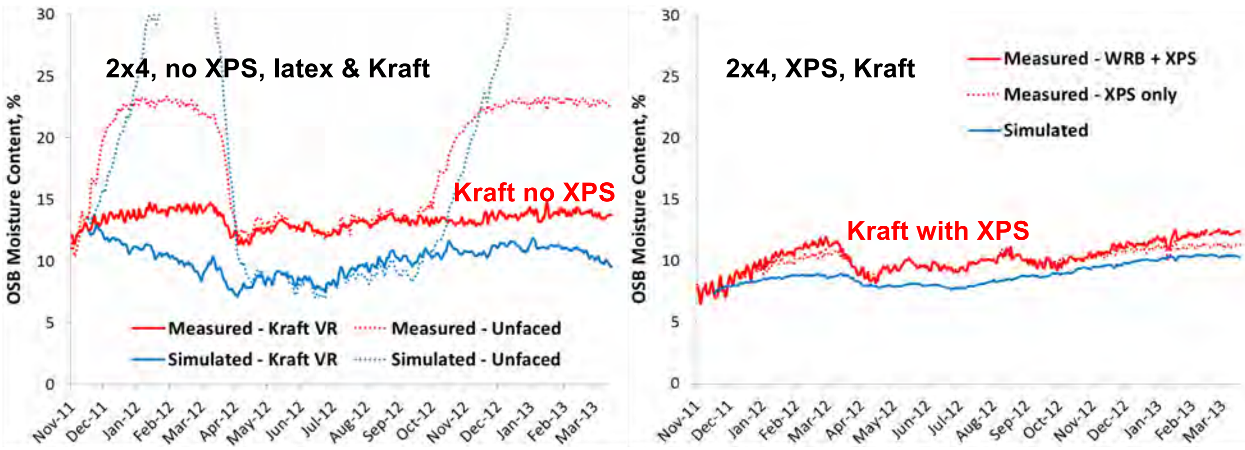

Figure 7: Measured vs. modeled OSB MC, 2x4 with/without XPS (Glass 2014)

Previous simulation work included sensitivity analysis looking at drying capabilities of various assemblies, ability to survive wind-driven rain penetration, and moisture accumulation by air leakage and vapor diffusion. Future test hut work will include drying capabilities of 2x4 assemblies with various types of exterior insulation (XPS, EPS, polyisocyanurate, rock wool) in response to water injections and quantifying the relative impact of air leakage versus vapor diffusion on OSB MC in 2x6 walls.

4.4.2 Discussion

Chris Schumacher noted that in some cases, the interior RH conditions were the same in the two winters, but there were differences in the resulting sheathing moisture content. He suggested that the material properties of OSB may be changing over time, after it experiences wetting and drying cycles, per Timusk's (2005) work. He also noted that there was similar evidence of this OSB behavior in his monitoring of roofs insulated with open-cell spray foam in the Vancouver area (Schumacher and Reeves 2007).

4.5 Achilles Karagiozis: What is WUFI?—The Building Science Tool

Karagiozis' presentation was a consistent back-and-forth discussion with the audience, so the description below is broken up by topic, as opposed to a presentation followed by a discussion.

4.5.1 ASHRAE Standard 160

First, Karagiozis pointed out that ASHRAE 160 should not predict typical interior or enclosure conditions in the field; instead, the intent of 160 is to provide design or worst-case conditions. It is entirely possible that they are currently too high (and should be less stringent), but the ultimate intent is to provide a safety factor when designing building enclosures.

In addition, he noted that ASHRAE 160 is intended to produce consistent results/outputs between various consultants performing similar analysis. He noted that there has been substantial work put into the standard, but more needs to be done—and more importantly, that the standard has a vital and needed role. He asked the audience that instead of criticizing the standard, they should help work to fix it.

ASHRAE 160's interior relative humidity levels are highly critical to the results; in some simulations (e.g., WUFI Plus/WUFI Passive), after entering inputs (# occupants, activity level, ventilation, and airtightness), the resulting outputs have been consistent with measured interior RH data. He recommends this method of calculation over the simplified, intermediate, or advanced models.

Karagiozis then discussed interior condition monitoring work done under the U.S. Department of Housing and Urban Development (Arena et al. 2010). The team collected a full year of indoor temperature and humidity data for a sample of 60 homes across three different climate regions—the hot and humid Southeast (Zone 2), the cold Northeast (Zone 5), and the marine Northwest (Zone 4).

When monitored results were compared to the ASHRAE 160 simplified method, unrealistically high interior humidity conditions were predicted in cold (Zone 5) climates. In Zone 2, summertime RHs were underpredicted, and in the Pacific Northwest (Zone 4C), RHs were overpredicted. Shifting to the intermediate method brought calculations closer to measured data. The upshot was to propose a method adding 5.2°F/2.9°C to the interior setpoint.

The moisture generation rates in ASHRAE 160 were reduced by 25-30% (typically) by addendum b in 2012 (Figure 8), in Table 4.3.2 Residential Design Moisture Generation Rates. Although the results are still on the high side, it should not overpredict RH levels excessively, per the previous version.

Number of Bedrooms	Number of Occupants	Moisture Generation Rate		
1 bedroom	2	~~8~~ 7 L/day	~~0.9~~ 0.8 x 10^{-4} kg/s	~~0.7~~ 0.64 lb/h
2 bedrooms	3	~~12~~ 9 L/day	~~1.4~~ 1.0 x 10^{-4} kg/s	~~1.1~~ 0.83 lb/h
3 bedrooms	4	~~14~~ 10 L/day	~~1.6~~ 1.2 x 10^{-4} kg/s	~~1.3~~ 0.92 lb/h
4 bedrooms	5	~~15~~ 11 L/day	~~1.7~~ 1.3 x 10^{-4} kg/s	~~1.4~~ 1.0 lb/h
Additional bedrooms	+1 per bedroom	+1 L/day	+0.1 x 10^{-4} kg/s	+0.1 lb/h

Figure 8: ASHRAE Standard 160 addendum b Table 4.3.2 (ASHRAE 2012)

Joseph Lstiburek agreed that ASHRAE 160 originally had serious flaws, but it is far more reasonable as wintertime RH levels are dropped.

4.5.2 WUFI as a Building Science Tool, and the User Base

Karagiozis started the discussion by stating that WUFI is a building science tool; it is used by experts to create useful results—but ultimately, "the tool is only as knowledgeable as the user." Also, he stated that out of all the hygrothermal tools currently available, WUFI is the best, has excellent validation (including North American work), and is the de facto industry standard.

Over time, building materials (stucco, wood products, and building papers) have changed: modeling is a useful tool to determine whether this will have an overall effect on building durability. In addition, it is often the only cost-effective tool that can predict performance of newly developed products in assemblies.

He also pointed out that moisture analysis is fundamentally different from energy analysis: moisture analysis is more complicated, given the range of inputs that can have substantial effects on outputs. For instance, OSB material properties are complicated—the "skin" vs. "core" properties are not the same. Theresa Weston pointed out that most practitioners do not have that level of information available to them. Karagiozis continued, stating that any design tool will provide false negatives and false positives; a safety factor should be set that brings false positives to a reasonable rate.

Karagiozis returned to his previous point, that WUFI should be used as a tool for experts, run by those who understand building science. Duncan Prahl countered, though, that it seems like "experts" are a small minority, perhaps 1%, of those running WUFI today. Karagiozis replied that those who are not qualified should not be doing these simulations, or create designs based on those simulations.

Peter Yost has taken multiple WUFI courses, but despite that training, when asked a simple question—"When I am building a double stud wall, how close to 'the edge' (of failure) am I?"—he could not provide a positive answer. This reflects the complexity inherent to this hygrothermal model. Katrin Klingenberg reiterated her point that PHIUS is recommending completely moisture safe "flow through" walls that are far from 'the edge.' Another fundamental problem is the number of U.S. building science practitioners: in a country of roughly 300 million, the number of qualified practitioners is likely below 100. In contrast, Finland (a country of 5 million) likely has five times the number of experts at this level.

Katrin Klingenberg mentioned the use of templates as a useful tool. In the WUFI Plus software package, these templates provide an easier way to start building energy simulations, and help determine whether targets are being met. This is in line with BSC's proposed research work (covered below), which will provide WUFI templates for common, historically successful wall assemblies. The risk, as posed by Christine Cronin, is that less-experienced users will again modify these templates in an incorrect manner. Joseph Lstiburek responded that templates will be provided, but with clear limits on the amount of modification allowed (such as a maximum percentage change)—analogous to fire rated assemblies.

Karagiozis wrapped up his presentation mentioning that third-party plug-ins would be a powerful way to make WUFI more useful to the community at large, and that the authors of the software are amenable to these modular additions. Examples would include modules that would calculate ventilation airflow in cavities from environmental and geometry parameters, or a corrosion tool (commonly calculated in post-processing).

5 Discussion

The discussion among the speakers and audience members is broken down roughly by topic in the sections below.

5.1 BSC TO5 Work: Above Grade Wall WUFI Templates and Case Studies

Joseph Lstiburek and Chris Schumacher explained BSC's upcoming work under Building America (Task Order 5), which is to generate a series of WUFI files of common North American wall assemblies that have historically provided good performance. The behavior of these assemblies can then be examined, to determine appropriate failure criteria based on this historic record. This is intended to counter much of the common, existing modeling which shows that walls known to perform well (historically) do not meet various failure criteria. In short, if WUFI had been available to model these historic walls, nothing would have been built.

The primary focus of this work is residential (not commercial/steel stud-gypsum sheathing) walls. There is no intent to simulate walls with known failures or risks, as a negative case. There is no intent to simulate high-R walls (double stud, foam sheathing, etc.) in this research. Some walls will be simulated that do not meet current or upcoming energy codes; this is being done to calibrate the model response based on historic data.

A matrix of roughly eighteen walls has been proposed for BSC's work; a sampling of the assemblies is shown in Table 3. Other claddings to be simulated include brick veneer and stucco; simulations will be run with an interior polyethylene vapor barrier, or 2x6 framing/R-19 cavity insulation, as other variables. Six climate zones will be used for these simulations (Table 4). This matrix of walls will result in roughly 60-70 simulations, at least.

Table 3: Proposed wall assembly examples (1 through 3) for BSC simulation work

Wall (1)	Wall (2)	Wall (3)
Latex painted wood siding	Vinyl siding	Vinyl siding
Asphalt saturated Kraft paper (building paper)	Tyvek	Tyvek
Plywood sheathing	Plywood sheathing	OSB sheathing
2x4 framing	2x4 framing	2x4 framing
Kraft-faced R-13 fiberglass batt	Kraft-faced R-13 fiberglass batt	Kraft-faced R-13 fiberglass batt
Gypsum wall board	Gypsum wall board	Gypsum wall board
Latex Paint	Latex paint	Latex paint

Table 4: Proposed climate zones for BSC simulation work

Climate Locations
Minneapolis (Zone 6A)
Chicago (Zone 5A)
Kansas City (Zone 4A)
Seattle (Zone 4C)
Atlanta (Zone 3A)
Houston (Zone 2A)

The full list of walls will be circulated to the expert meeting participants and other key stakeholders for comments before proceeding.

Each of these wall assemblies will be accompanied by a short case study, which explains the history of the wall, how it works (hygrothermally), the function of each component (air barrier vs. vapor retarder vs. water control; see Figure 9 as an example), and the thought process behind the design. This is intended as a basic primer of the building science of each assembly.

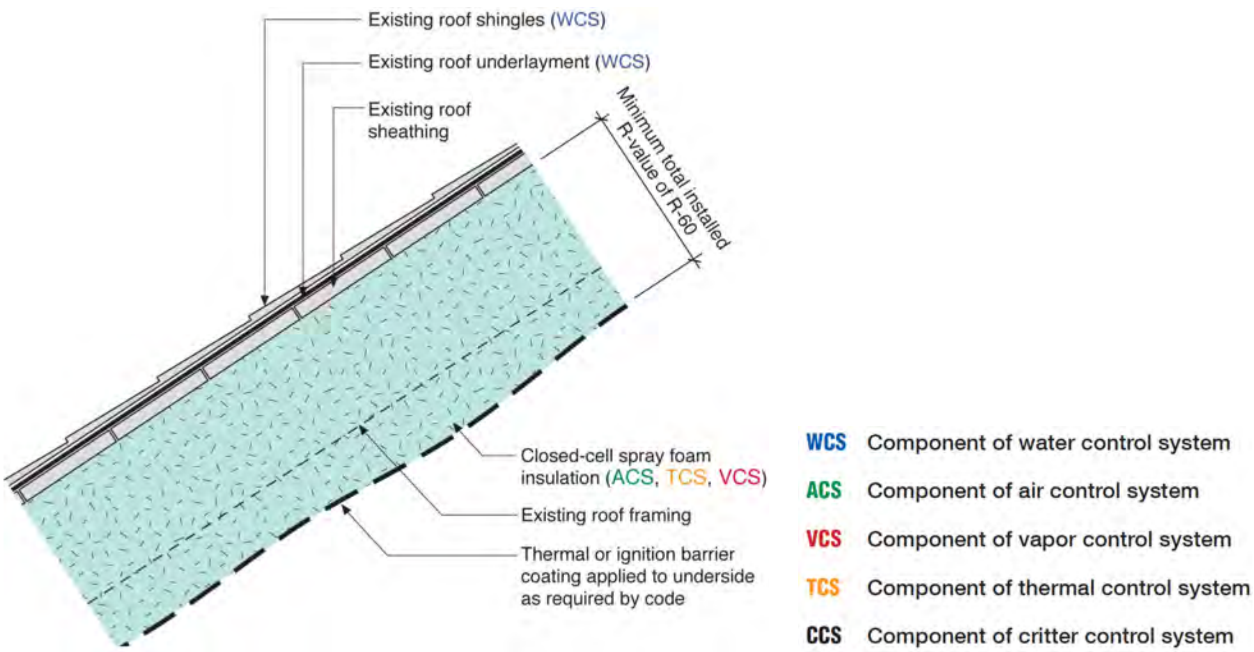

Figure 9: Identification of control layers in an assembly (BSC 2013)

Given that the template files will be released to the public (to be run in WUFI), limits will be given for the acceptable range for modifying variables. The case study could also explain the sensitivities of the assembly, and what types of modifications could push it to failure. The provided WUFI files would be useful to new users, showing (and possibly explaining) reasons for various default settings.

Samuel Glass suggested that a simple index to rank the moisture performance of assemblies would be useful. By way of analogy, the HERS Index provides a simple, one-point indication of energy performance. A builder would want a simple (1 page vs. 20 page) explanation.

Joseph Lstiburek responded that BSC did a similar exercise for high R-value walls (Straube and Smegal 2009), where the walls were rated according to various criteria (cost, buildability, durability, etc.); the criteria weighting could be modified based on a user's preference (Table 5). This would be a useful metric, but the scope/funding of the current project is sufficiently limited that it might not be possible to incorporate it.

Table 5: High R-value wall comparison table with weighting criteria (Straube and Smegal 2009)

	Thermal Control	Durability (wetting/drying)	Buildability	Cost	Material Use	Total
Criteria Weighting	1	1	1	1	1	
Case 1: Standard Construction	1	3	5	5	3	17
Case 2: Advanced Framing with Insulated Shtg	4	4	4	4	4	20
Case 3: Interior Strapping	3	3	3	4	4	17
Case 4: Double Stud	4	3	3	3	2	15
Case 5: Truss Wall	4	3	2	3	3	15
Case 6: SIPs	4	4	3	3	3	17
Case 7: ICF	4	5	4	2	3	18
Case 8: Sprayfoam	5	5	4	2	4	20
Case 9: Flash and Fill (2" spuf and cell.)	4	4	4	3	4	19
Case10: Double stud with 2" spray foam and cell.	5	4	3	3	3	18
Case 11: Offset Framing (ext. Spray foam insul.)	5	5	4	3	2	19
Case 12: EIFS with fibrous fill in space	5	5	4	3	3	20

One method of measuring "moisture resilience" or "moisture safety" of a wall would be to measure its ability to dry; this could be done in simulations by introducing a fraction of the driving rain behind the water resistive barrier. The rate of drying could be used as a metric to compare walls.

One question raised by the audience is what interior conditions will be used, which can have a major effect on results. For instance, a non-functional ventilation system in a tight house can easily raise wintertime interior RH to dangerous levels. Achilles Karagiozis pushed for using ASHRAE 160 conditions, as an overprediction with a large safety margin. Joseph Lstiburek countered that ASHRAE 160 is still flawed, but the response of the wall might provide some feedback on whether the assumed interior RH conditions are reasonable or not.

Danko Davidovic was concerned that these basic case studies might eliminate the need for practitioners to run WUFI simulations; Lstiburek countered that in his experience, providing free information ends up raising more questions. Duncan Prahl noted that the vast majority of users will simply use these case studies as templates. These users are not interested in running simulations; they simply want an answer that they can provide to their client.

5.2 WUFI and User Expertise/Training

Peter Yost noted that Achilles Karagiozis stated that WUFI should only be "run by experts." He was hoping that this could be better quantified or characterized. Kohta Ueno brought up the devil's advocate position, of limiting access to WUFI to those who pass a qualifying examination, similar to HERS raters. Theresa Weston replied that this would require a major amount of infrastructure that does not exist, and possibly to limited benefit. In addition, Vladimir Kochkin noted that there is a large and growing market for REM/Rate simulators; there is no analogous demand for experienced WUFI users.

Peter Baker noted that the fundamental issue is that the field needs to determine who is qualified to make these engineering judgments. By way of analogy, no layperson downloads a free structural analysis program and then sends out structural drawings. In other words, it is not the software tool, but the reputation/licensure of the consultant that needs to drive this issue.

Joseph Lstiburek added that the architect has the ultimate call and responsibility: they may do the analysis themselves if they feel that they are qualified, or they can hire an engineering consultant. But many of the engineering consultants currently being hired (for WUFI analysis) are not truly qualified, despite licensing. On the commercial side, this problem is self-correcting to a degree: if a building fails, the firm will face legal action, and a clearly wrong analysis will reduce the chances the consultant will have future work. But on the residential side, this feedback is not occurring.

He noted that we will not keep people from running the model, but we should help them run it better and more accurately. He hopes that the WUFI templates and case studies might start to address this.

The discussion also covered user knowledge and training. Andre Desjarlais noted that based on users comments he has seen, if the users had simply used the WUFI built-in help feature, they would have answered their own questions. This unfortunately suggests that despite a wealth of available information, many users do not avail themselves of it (and will not when more becomes available)—others in the audience agreed. Ken Neuhauser added that the industry is not in a position to invest in educating practitioners on this tool in depth: other cultures (such as Finland) do, but he is pessimistic about the North American mindset. Christine Cronin added that the inexperienced users are not stupid, but that they have just not been informed—and that the case studies could be a very accessible tool or stepping stone for them to use.

Achilles Karagiozis contributed the idea that continuing education in WUFI (e.g., periodic 6 month refresher courses) might be helpful; others in the audience doubted that training budgets are likely to support this.

Overall, the audience agreed that greater training and a better knowledge base for basic WUFI users will be valuable, if there is a way to put it in practice. As an example, Chris Schumacher's presentation talking about his decision-making process in critiquing a wall simulation would be information worth disseminating.

5.3 Role of WUFI

Joseph Lstiburek pointed out that WUFI can act as an educational tool, a design tool, a research (or validation), or a marketing tool: could it be modified for each of these purposes, based on the associated target audience? Duncan Prahl noted that this discussion has concentrated on research more than the other aspects—but the biggest problems from inexperienced users occur on the design side. Lstiburek later concluded that four different versions of WUFI would likely be more complicated than useful.

Andre Desjarlais noted that the free version of WUFI is clearly labelled for educational use only. Christine Cronin noted that most students would prefer to work with the fully featured version, not a limited educational version; Duncan Prahl responded that universities should invest in an academic site license.

Vladimir Kochkin noted that he is increasingly seeing WUFI recommended or required as a default-response safety measure. Specifically, when judging a net zero student competition, builder judges asked teams whether they had done WUFI analysis, especially on high R-value/high performance wall systems. Lstiburek responded that this increases the impetus for this case study/WUFI template project, to try to avoid requiring assemblies that are overly conservative.

5.4 Material Properties

As seen in Chris Schumacher's presentation, material properties can have a tremendous effect: changing the OSB sheathing material caused major changes in the wintertime moisture content peaks. However, there is a consistent lack of reliable and accurate material property data; many in the audience agreed. If material data were available for across the spectrum of building material manufacturers, many of the associated problems would be eliminated.

Duncan Prahl noted that the vast majority of manufacturers have CAD details (in multiple formats) available on their websites for installation of their product. He questioned why the same could not be done for WUFI-compatible material data. Theresa Weston added that some manufacturers might have this data, but it is likely known to the research and development department, not front line product support. Achilles Karagiozis pointed out that the material data template is available on the WUFI forum, if manufacturers are willing to invest in this testing.

Some pushed to "force manufacturers" to provide this data; others suggested the language of "encouraging manufacturers" to submit data. The problem, of course, is that the regimen of tests required for full material property characterization in WUFI is involved and costly.

Chris Schumacher noted that in Europe, periodic third-party spot checks are done on insulation, which is paid for by a "kitty" funded by insulation manufacturers. He suggested a similar program might work to pay a third party to do material property testing. Danko Davidovic echoed these problems—even working for a building material manufacturer's research & development department, measurements of material properties needed in WUFI analyses was not considered as a justified investment.

Another problem is that although some materials (exterior gypsum sheathing, plywood, OSB) are considered "generic," they might have differing properties between manufacturers. Achilles Karagiozis argued that the way to obtain correct answers is to use the actual materials. However, Joseph Lstiburek pointed out that if we are trying to use WUFI as a design tool, during the design process, we have no ability to specify a given manufacturer's materials. In addition, this is a level of complexity beyond what a novice user would know or understand.

Given the complexity of materials selection, Achilles Karagiozis suggested that a construction materials science course might provide a base of knowledge. Theresa Weston countered, though, that this is not a feasible way to reach across industry, noting that, "We are in a world of one-hour webinars taught over lunch break"—there is a need for this information, but there has to be an alternate way to disseminate the knowledge than a course.

5.5 Failure Criteria

Much of the criticism directed at ASHRAE 160 is that the failure criteria—even when reduced to the single 30-day criterion—makes many common wall assemblies fail. This suggests that alternate failure criteria should be considered. Achilles Karagiozis espoused the use of the VTT mold index, which is built into the latest version of WUFI.

Others posed the idea of using sheathing moisture content or a condensation index as failure criteria. Kohta Ueno surveyed the audience, asking whether they believed many assemblies are reaching 20% MC (a common failure criteria) every winter, but with no detrimental effect (in line with Kochkin's results). Many agreed, showing that 20% MC would likely be too stringent of a failure criterion. Joseph Lstiburek concurred, noting that Canadian building science educators have long taught that all walls in Canada becomes wet every winter without problems. The key was not whether the walls become wet, but whether they can dry in time to avoid issues.

Chris Schumacher noted that we calculate condensation hours or condensation potential in ASHRAE 160 because it is easy to do. Lois Arena asked if a downward moisture trend over years would be a good evaluation tool; Schumacher countered that it could work, but probably not for massive walls (e.g., 16" solid brick masonry) that have substantial moisture storage.

Lstiburek suggested that a graph of monthly vapor pressures (per Max Baker) provides an excellent "snapshot" of relative seasonal risks; he asked whether a similar exercise could be done using WUFI.

Another potential failure to examine is bulk water or rain penetration; this could be done in simulations by introducing a percentage of incident driving rain past the WRB. This is explicitly not done in ASHRAE 160, but many practitioners are curious about the wall's "drying response." Roderick Jackson asked if laboratory testing could be used to validate WUFI drying responses. Chris Schumacher responded that given his extensive experience with test huts and climate chambers, water leakage is even harder to characterize and make consistent than air leakage. Another question, though, was whether the incident driving rain in the climate file is sufficient, or if some other rain metric should be used, to simulate gross flashing errors. Others noted, though, that there is a wetting level that a wall cannot be expected to survive, and should not constitute a failure in this "drying index."

5.6 Final Comments

Joseph Lstiburek asked for a final round of comments based on the day's discussion; the items below are key comments that were not captured in the previous topic summaries.

Table 6: Final comments from expert meeting participants

Commenter	Comment
Samuel Glass	ASHRAE 160 has been heavily criticized at this meeting, but as a point of information, the "intermediate" method has much better accuracy than the "simplified" method, which is likely unrealistic. There will be an upcoming paper on these results. There still needs to be a decision, though, on how severe the interior climate needs to be to provide realistic "design" conditions.
Rockford Boyer	When showing WUFI output to architects, they often respond, "That's a pretty graph, but what does it mean?" Layman guidance on interpreting performance from WUFI outputs could be a useful tool for industry.
Vladimir Kochkin	If we are considering a metric such as a "drying index," by way of analogy, a HERS Index is relative energy performance compared to a reference house. We will need to base the index off of a known wall's drying rate. He is in favor of the proposed idea of case studies.
Lois Arena	Agrees with the consensus that better material data, consistent initial assumptions, and consistent inputs among practitioners will improve the quality of WUFI modeling. Chris Schumacher asked whether a meeting reviewing modeling procedure would be helpful. Joseph Lstiburek suggested that this could be an activity associated with the upcoming Westford Symposium in August 2014.
Roderick Jackson	All of the input parameters in WUFI have a degree of uncertainty; this uncertainty could be examined in more detail by taking a probabilistic approach to assessing the sensitivity.
Layla Thomas	As a representative of the builder community, she asked that the results of this work be couched in the "language of the builder." For instance, a "Builders Guide to Hygrothermal Models" could be a useful primer for that audience.
Christine Cronin	Using prescriptive or legalistic methods to "keep stupid ideas out" from WUFI models are more likely to backfire than not; it is more useful to supply information resources to less experienced users.
Theresa Weston	Reiterated that there are many parts of ASHRAE 160 that are useful; Joseph Lstiburek reassured her that BSC's intent is not to fight or eliminate ASHRAE 160 but to improve it.
Peter Yost	The Building Material Property Table on BSC's website is a useful resource; if BSC could provide a similar online resource for WUFI materials, it would be very useful. (see Information Sheet 500: Building Materials Property Table; http://www.buildingscience.com/ documents/information-sheets/building-materials-property-table)
Chris Schumacher	The current WUFI material library has no text search feature; adding this (e.g., search for "gypsum") would be an excellent improvement.

Commenter	Comment
Ken Neuhauser	When energy models were used to provide predictions of performance, there were, at times problems. We should not be surprised that hygrothermal models have similar issues.
Katrin Klingenberg	The industry should appeal to universities that more building science education is needed to improve the "pipeline" of practitioners. Chris Schumacher countered that in North America, there are insufficient numbers of instructors; industry funding would help improve this issue. But the field has been improving: most major cities now at least have a building science course available at local universities.
Warren Barber	A case study matrix to interpret performance would be useful for manufacturers.
Michael Gestwick	Agreed with previous comment that prescriptive approaches to modeling won't work; we will need to provide better information. This meeting has focused on WUFI users, but one of the drivers is that lending institutions have been asking for WUFI analysis. It might be worthwhile to provide guidance to them, to ask the correct questions of the WUFI modeler, and pull up the level of sophistication in the field.
Danko Davidovic	I strongly support development of the performance matrix with regards to moisture management/durability of modeled wall assemblies which can be incorporated in WUFI. We also need to tweak the industry and encourage the manufacturers to conduct comprehensive material property characterization in order to bring the quality of WUFI simulations to the next level.

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Appendix A (Invitation and Agenda)

Building Science Corporation would like to invite you to attend the **Building America Expert Meeting** on **Guidance on Modeling Enclosure Design for Above-Grade Walls**. The purpose of this expert meeting is to directly support Critical Milestone E6 as identified by the Building America Enclosures Standing Technical Committee:

> *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 meeting will focus on evaluating the progress made on creating guidance on design methods for enclosure design for above-grade walls. The intent is to examine this topic with viewpoints from the various interest groups, such as builders, architects, developers, modelers and anyone asked to design an above-grade wall assembly. The meeting is organized around the following topics:

1. Review wall assemblies and conditions that provide proven performance in each climate zone.
2. Review ASHRAE Standard 160 (ASHRAE 2009) and WUFI analysis of these wall assemblies and conditions.
3. Review modeling boundary conditions and failure thresholds.

The following questions will be addressed during the meeting:

- What are some proven performance wall assemblies in each climate zone?
- What are the modeling boundary conditions and failure thresholds?
- Are there failure modes other than rain, air, construction moisture, vapor and interior relative humidity?
- What is the appropriate format for the guidance document?

Location:
The meeting will be held on Monday, May 12, 2014 at the **Westford Regency Inn and Conference Center** in Westford, Massachusetts from 8:30 am to 4:15 pm.

To attend:
If you would like to attend, please email Honorata Loomis at Building Science Corporation at honorata@buildingscience.com before May 1, 2014.

Agenda:

Time	Speaker	Topic
8:30 to 8:45 am	Joseph Lstiburek	Introduction
8:45 to 9:30 am	Chris Schumacher	Historically proven wall assemblies in each climate zone and associated boundary conditions
9:30 to 10:15 am	Lois Arena	Monitoring and modeling issues associated with ASHRAE 160
10:15 to 10:30 am		Break
10:30 to 11:15 am	Vladimir Kochkin and Samuel Glass	Results of monitoring of wall assemblies in CZ 4 and the capacity of WUFI for predicting the behavior of such assemblies
11:15 to 12:00 pm	Achilles Karagiozis	Recent advances in hygrothermal modeling
12:00 to 1:00 pm		Lunch
1:00 to 2:45 pm	Joseph Lstiburek	Moderated discussion between presenters and attendees
2:45 to 3:00 pm		Break
3:00 to 4:00 pm	Joseph Lstiburek	Moderated discussion between presenters and attendees
4:00 to 4:15 pm	Joseph Lstiburek	Closing Remarks

Appendix B (Christopher Schumacher)

Modeling a Historically Proven Wall

Guidance on Modeling Enclosure Design for Above-Grade Walls

Chris Schumacher

Building America Expert Meeting
May 12, 2014 – Westford MA

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Guidance on Modeling…

- Who is the Guidance for?
  - Researchers?
  - Builders?
  - Architects & Engineers?
  - Building Product Manufacturers?
- What form should the Guidance take?
  - Prescriptive Standard?
  - Performance Standard?

Guidance on Modeling…

- ASHRAE 160
  - The purpose of this standard is to specify perfomance based design criteria for predicting, mitigating, or reducing moisture damage to the building envelope, materials, components, systems, and furnishings, depending on climate, construction type, and HVAC system operation. These criteria include the following:
    a. Criteria for selecting analytic procedures
    b. Criteria for inputs
    c. Criteria for evaluation and use of outputs

Requests for Guidance

- Monthly occurrence
- Requests
  - Scenarios vary greatly
  - ‘User’ backgrounds vary greatly
  - Time varies greatly

Requests for Guidance

- Monthly occurrence
- Requests
  - Scenarios vary greatly
  - ‘User’ backgrounds vary greatly
  - Time varies greatly
- Almost never paid

Modeling a Historically Proven Wall

An example of the conversations that follow a typical ‘Request for Guidance’

The ‘Request’ comes in…

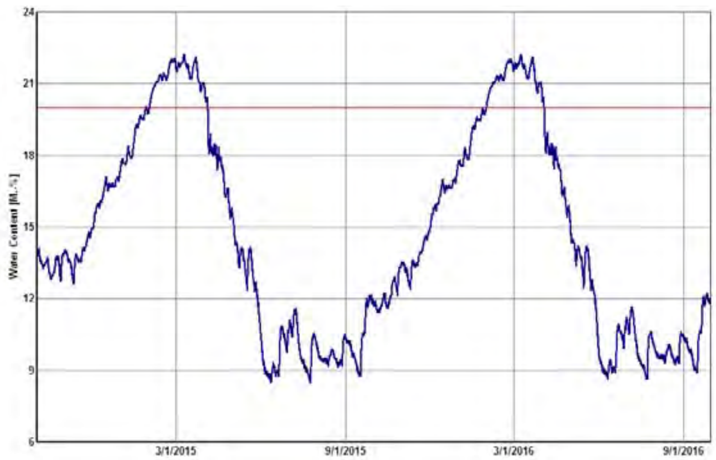
Novice Hygrothermal Model User:

- “HELP !”
- “Something is wrong with my model !!!”

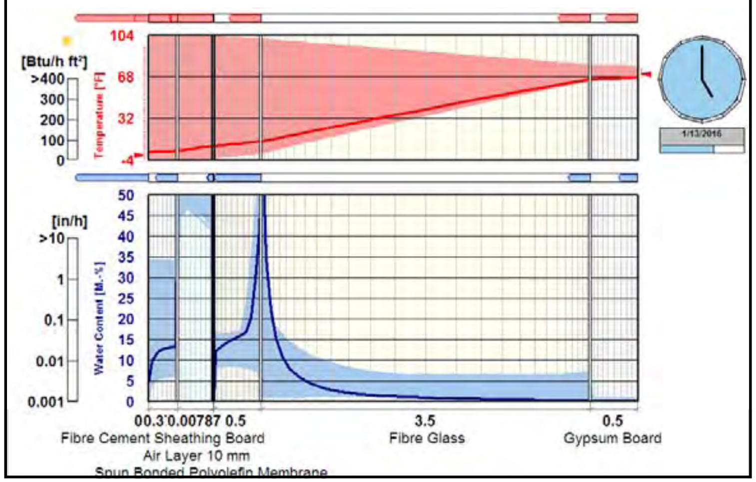
‘Proven’ 2x4 Chicago Wall

- fiber cement siding
- 3/8 in. air space
- ‘house wrap’
- ½ in. plywood
- 2x4 wood frame
- R13 fiberglass batt
- ½ in. drywall
- latex primer and paint

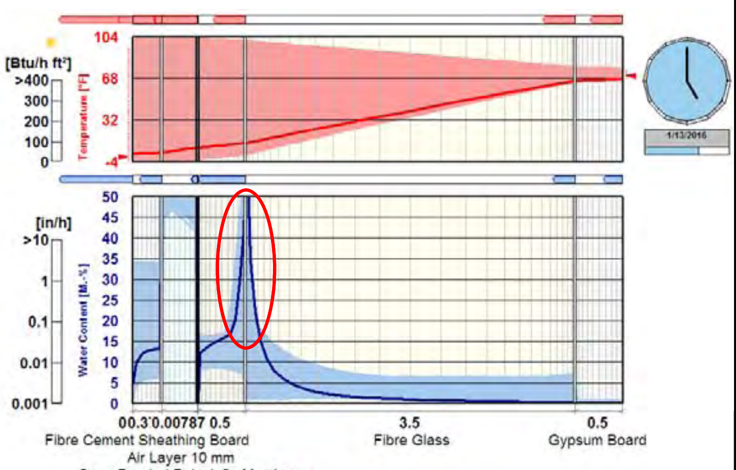
At first plywood MC looked OK but…



…what's happening in the film ?!



…what's happening in the film ?!



Time for a GoToMeeting…

Me :

- "Start from the beginning"
- "Explain how you setup the model"

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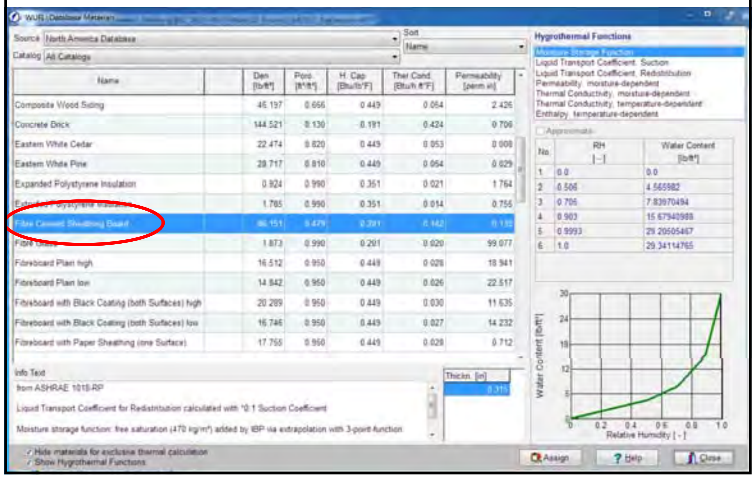
Fiber Cement Siding… N/A?



Fiber Cement Siding → "Fiber Cement Sheathing Board"

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Guidance on Modeling – BA Expert Meeting
May 12, 2014 | Westford, MA

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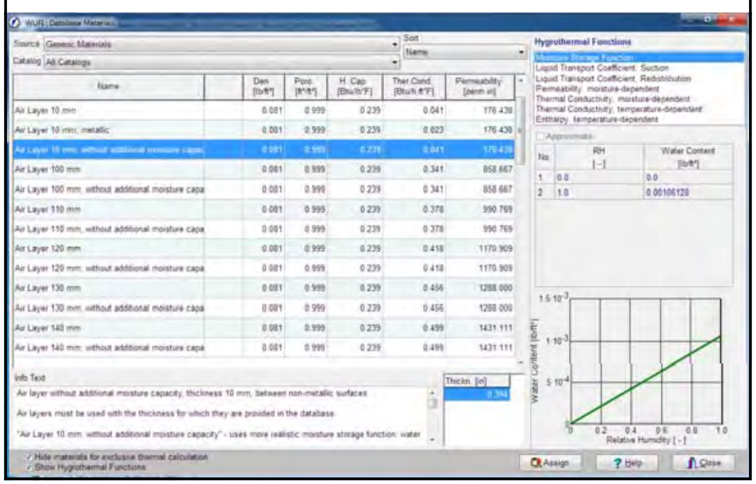
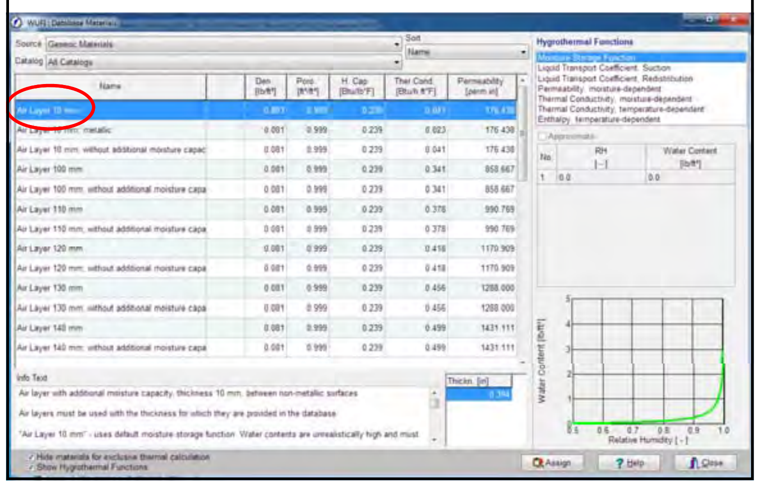
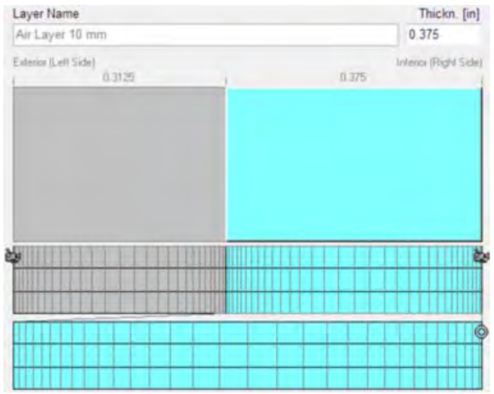
Air Space… Which one ?



Air Space… Which one ?



Air Space… "Air Layer 10 mm"



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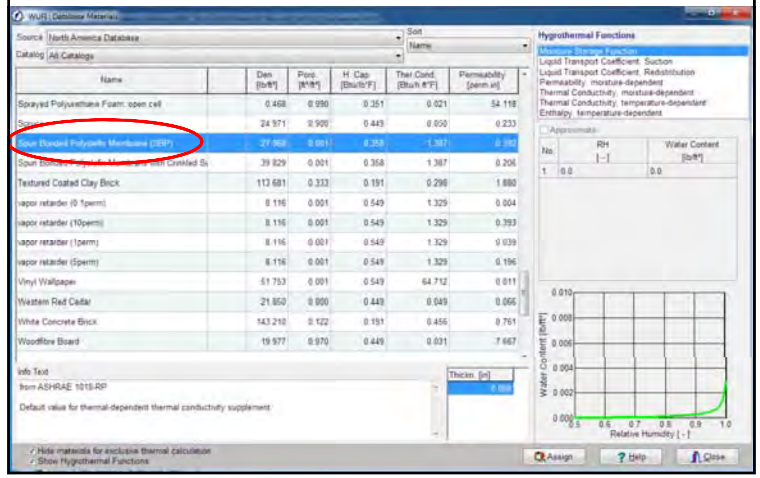
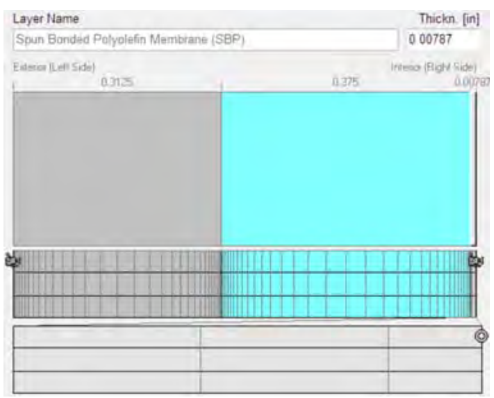
'House Wrap'… Tyvek® ? Found it !



'House Wrap' → "Spun Bonded Polyolefin Membrane (SBP)"



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May 12, 2014 | Westford, MA

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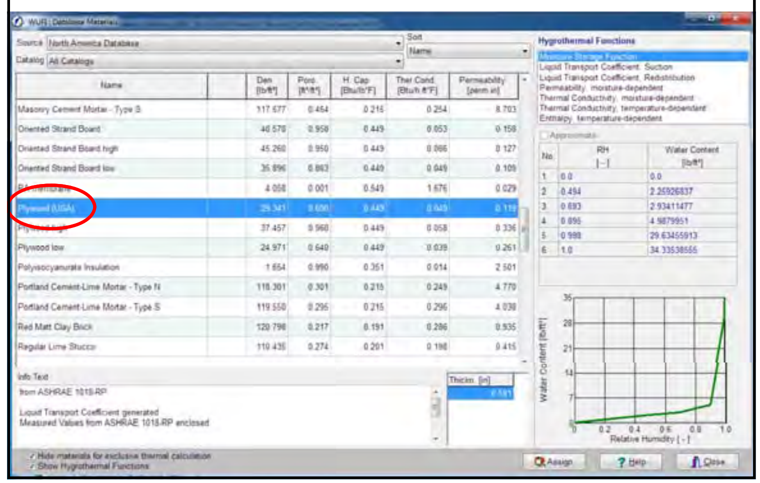
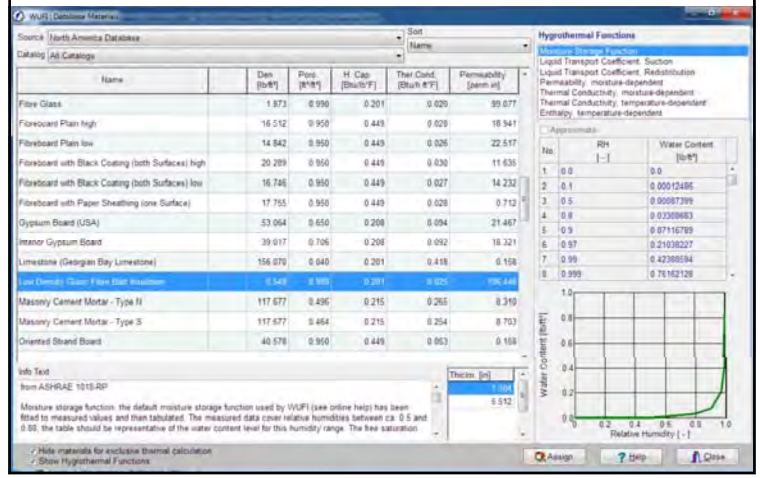
Plywood… Which one ?

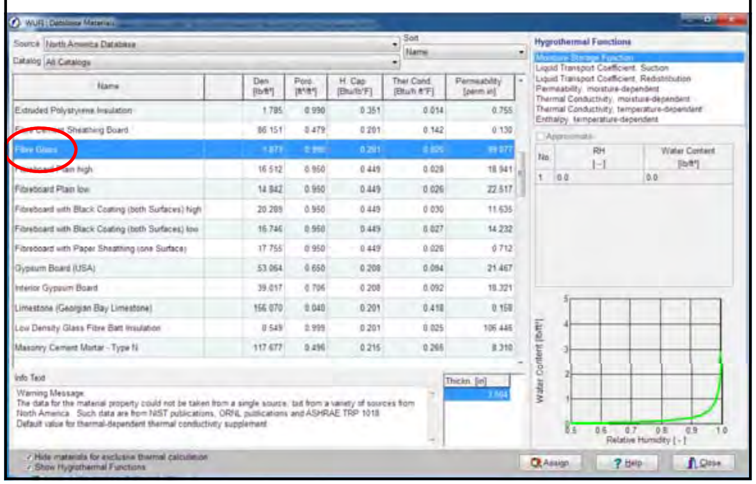


Plywood → "Plywood (USA)"

Fiberglass Batt… Which one ?

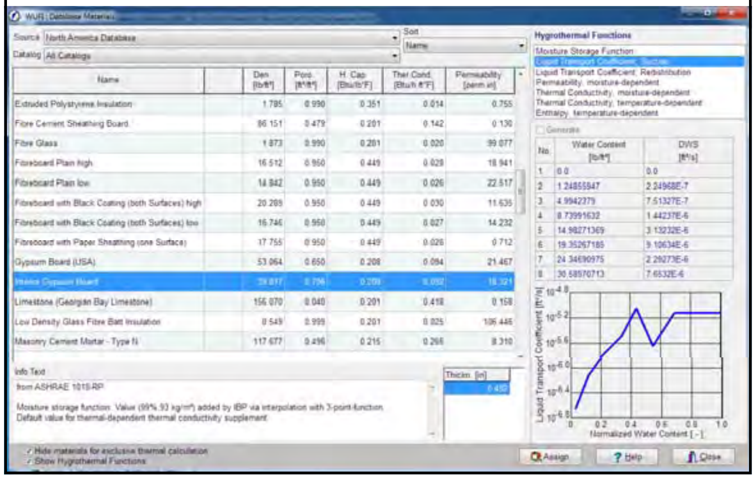


Fiberglass Batt… Which one ?

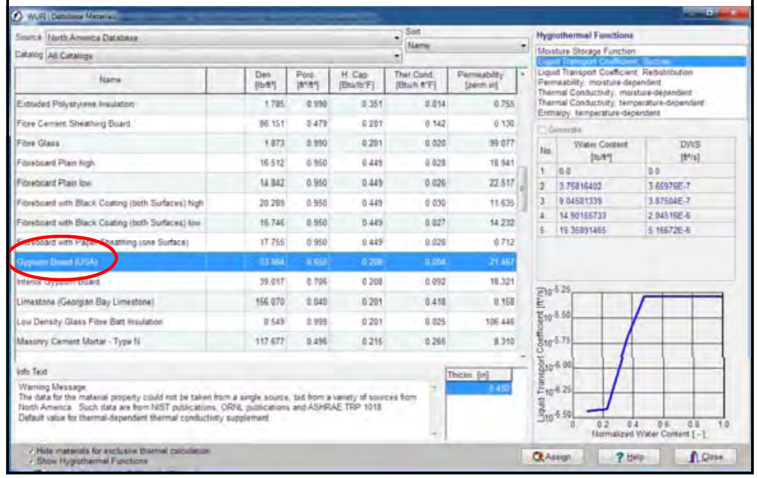


Fiberglass Batt → "Fibre Glass"

Drywall… Which one ?



Drywall… Which one ?



Drywall → "Gypsum Board (USA)"

So the Assembly is defined

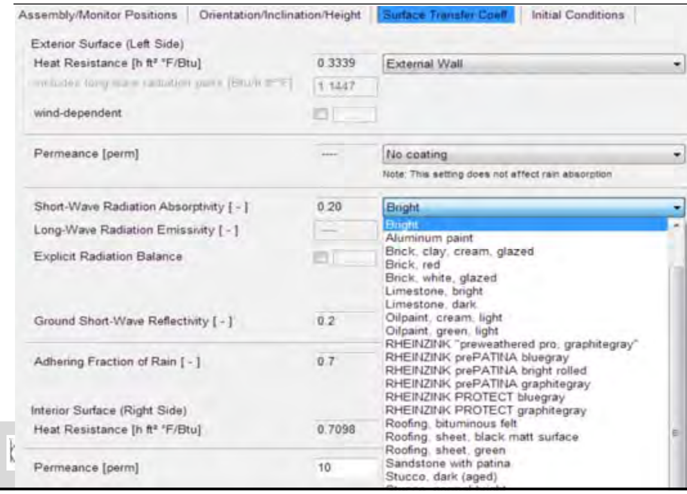
- 6 Layers...
- Novice User was confident in selection of only 1

Moving Along…

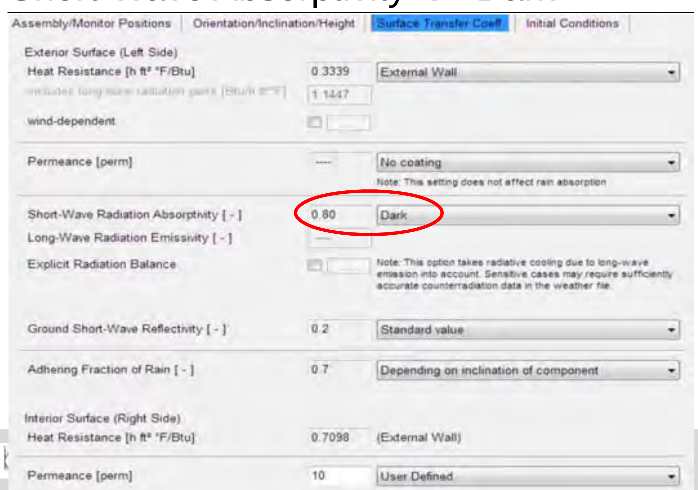
Me :

- “What about Surface Transfer Coefficients?”

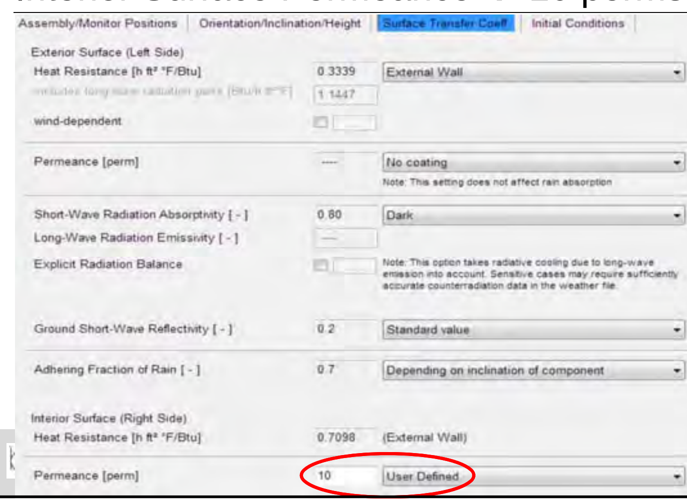
Short-Wave Absorptivity… Which One?



Short-Wave Absorptivity → “Dark”



Interior Surface Permeance → 10 perms



So Surface Transfer Coeffs. are defined

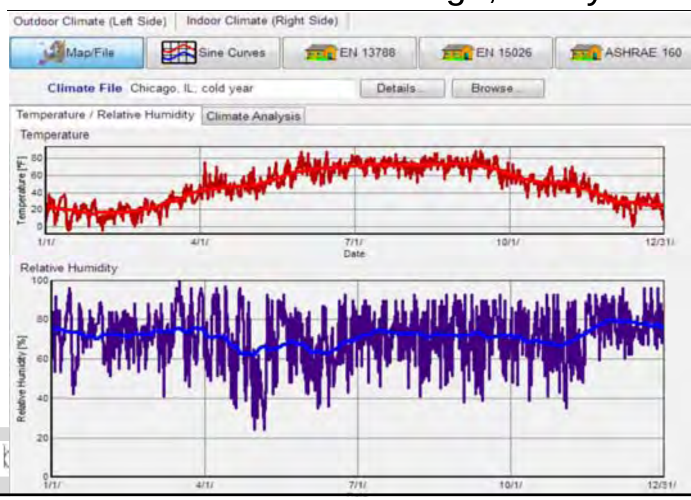
- Novice User ignored most values
  - Only changed 2 things
  - Left the remaining at their defaults
- Not confident in selection of Solar Absorption
- Changed Interior Surface Permeance to 10 because the 'heard' that was the 'right number'

Moving Along…

Me :

- "What did you do with Climate?"

Outdoor Climate → "Chicago; cold year"



Indoor Climate → "ASHRAE 160 w AC"

So Ext. & Int. Climates are defined

- Chicago cold selected for exterior
  - Reasonable for the problem under consideration (sheathing MC on North side)
- Again Novice User ignored most variables
  - Only changed AC
  - Left the remaining at their defaults
- w.r.t. ASHRAE 160: Novice user doesn't know what they don't know

And Finally…

Me :

- "Orientation is North. Driving rain set for a low-rise building. Any other changes ?"

And Finally

Novice User:

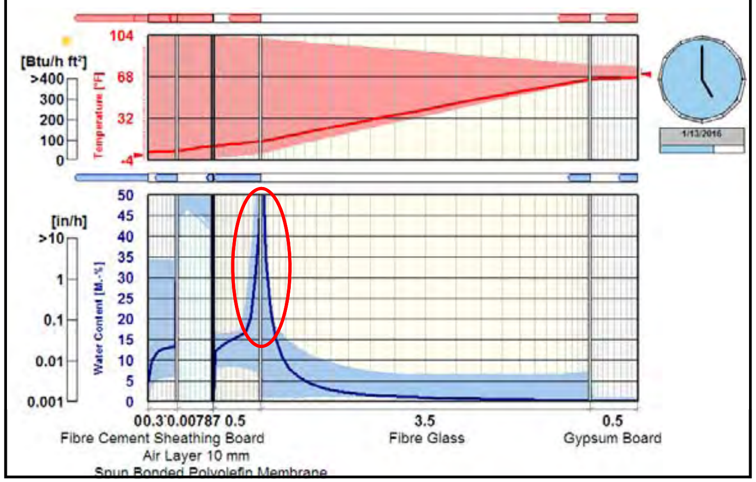
- "No."
- Initial Conditions at defaults
- Calculation Period at defaults
- Numerics at defaults

And Finally

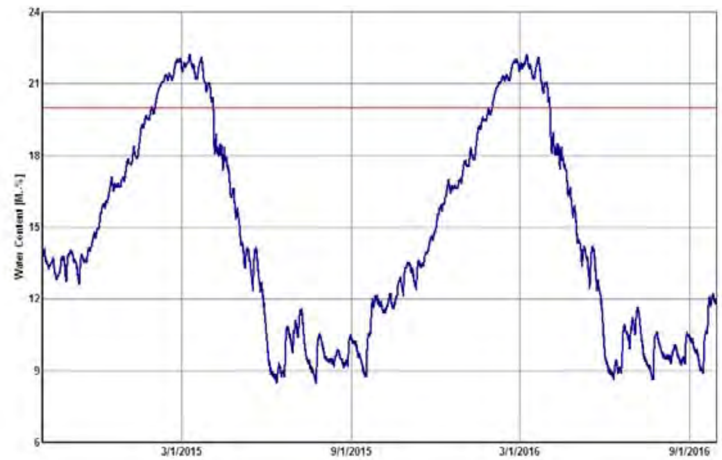
Novice User:

- "No."
- Initial Conditions at defaults
- Calculation Period at defaults
- Numerics at defaults
- User isn't really sure what a lot of this stuff means

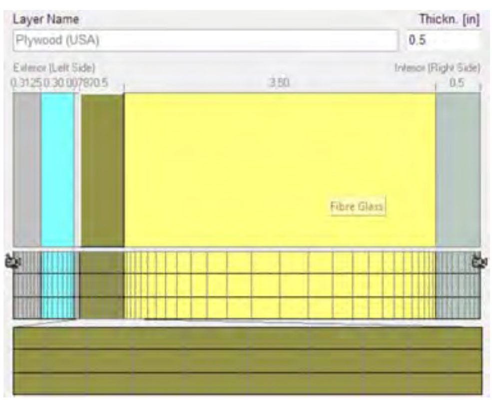
Back to the User's Question



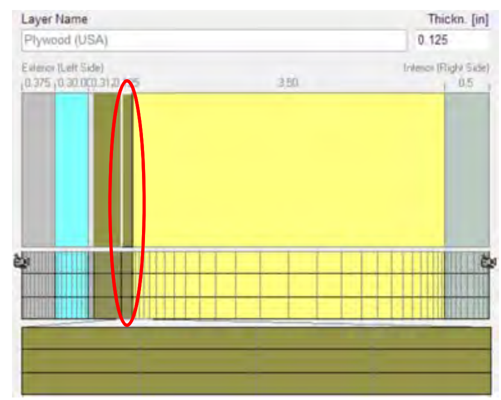
Graph MC vs Film MC ?



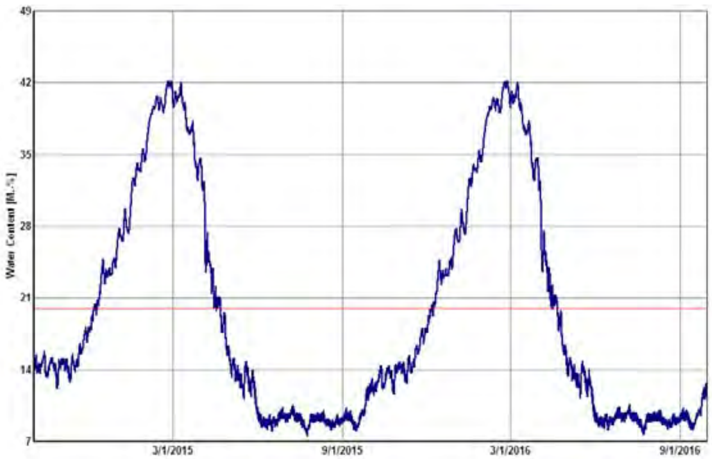
Split Sheathing into 'Study Layers'



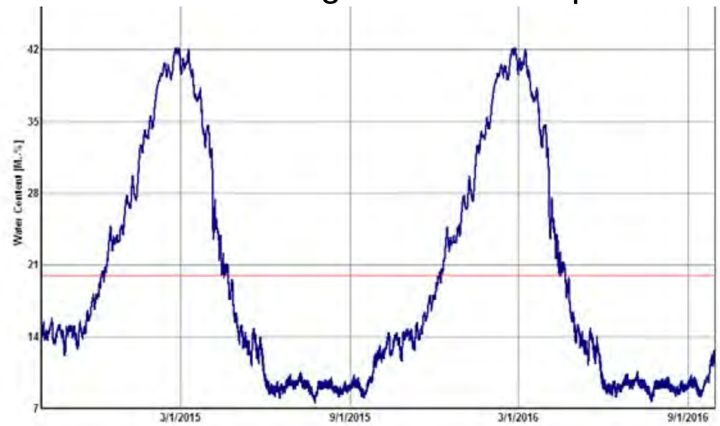
1) Split Sheathing into 'Study Layers'



1) Graph agrees w/ Film now…



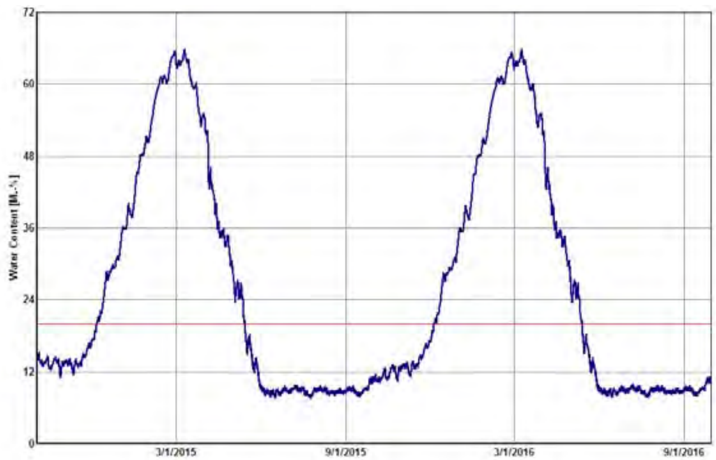
1) Graph agrees w/ Film now…
…but doesn't agree w/ field experience



2) Change ASHRAE 160 to 'Med' Sine

2) Change ASHRAE 160 to 'Med' Sine

2) That's Worse!

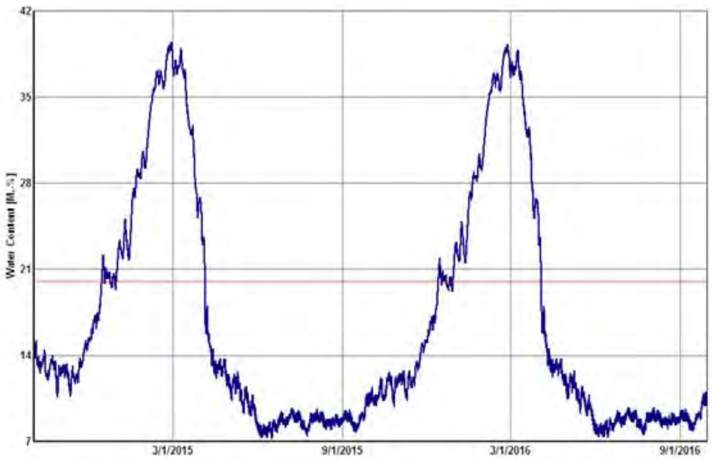


2) That's Worse!
…but easier to understand & tune

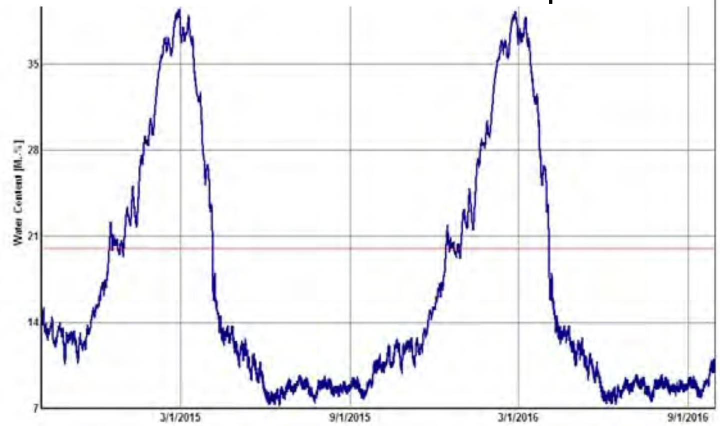
3) Change 'Med' to 'Low' Sine

3) Change 'Med' to 'Low' Sine

3) A little better than where we started?



3) A little better than where we started?
…but easier to understand & explain



4) Add ventilation to the air space

- ASHRAE Research Project 1091

  "Development of Design Strategies for Rainscreen and Sheathing Membrane Performance in Wood Frame Walls"

  - Pennsylvania Housing Research/ Resource Center at Penn State (PHRC/PSU)
  - Building Engineering Group at the University of Waterloo (BEG/UW)
  - Building Technology Center at Oak Ridge National Laboratory (BTC/ORNL)

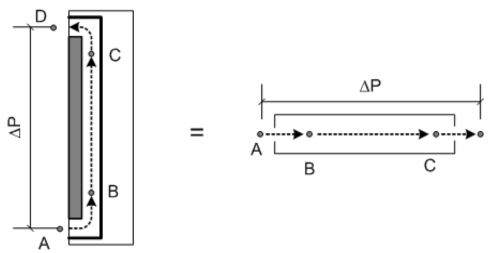
4) Add ventilation to the air space

- ASHRAE Research Project 1091
- Brick Walls: 0 to 90 ACH
  - 1.2m (4 ft) wide x 2.4 m (8 ft) high brick wall with 20 mm (3/4 in) cavity and 2 open head joints at top and bottom
- Vinyl Siding: 0.6 to 2.7 lps/m2 for 1 to 10 Pa
  - 1.2 m (4 ft) wide x 2.4 m (8 ft) high wall with direct-applied vinyl siding

4) Add ventilation to the air space

- ASHRAE Research Project 1091
  - Simplified pressure balance through a ventilated wall cavity:

$$\Delta P_{total} = \Delta P_{entrance} + \Delta P_{cavity} + \Delta P_{exit}$$



4) Add ventilation to the air space

- ASHRAE Research Project 1091
  - For a panel cladding, such as stucco or cement board with continuous slot vents, the pressures can be derived from:

$$\Delta P_{total} = C_{entrance} \cdot 0.5\rho \cdot V^2 + \frac{32 \cdot k_f \cdot V \cdot \mu \cdot L}{\gamma_c \cdot D_h^2} + C_{exit} \cdot 0.5\rho \cdot V^2$$

where

C = flow coefficient for the entrance/elbow/exit, from published literature
ρ = density of air, kg/m^3
V = velocity through the vent or cavity, m/s
k_f = correction factor for a rectangular conduit
μ = dynamic viscosity of air (18.1 · 10^{-6} N·s/m^2 [ASHRAE 2005])
L = cavity length, m
γ_c = cavity blockage factor to account for mortar protrusions, etc.
D_h = hydraulic diameter of the cavity, m

4) Add ventilation to the air space

- ASHRAE Research Project 1091
  - For brick veneers, the vents can be treated as standard sharp edge orifices (Straube and Burnett 1995) and the equation is simplified to:

$$\Delta P_{total} = \left(\frac{Q_{vent1}}{0.6 \cdot h_{v1} \cdot w_{v1} \cdot \gamma_{v1}}\right)^2 + \frac{32 \cdot k_f \cdot V \cdot \mu \cdot L}{\gamma_c \cdot D_h^2} + \left(\frac{Q_{vent2}}{0.6 \cdot h_{v2} \cdot w_{v2} \cdot \gamma_{v2}}\right)^2$$

where

Q_v = airflow through each vent, m^3/s
h_v = vent height, m
w_v = vent width, m
γ_v = vent blockage factor to account for bug screens, obstructions, etc.

4) Add ventilation to the air space

- ASHRAE Research Project 1091
  - Calculate the driving pressures for every hour
  - Thermal & moisture buoyancy

$$\Delta P_{buoyancy} = [\rho_{exterior} - \rho_{interior}] \cdot g \cdot L$$

  - Wind pressure gradients

$$P_{stagnation} = \frac{1}{2}\rho \cdot V_{wind}^2$$

$$P_{ventilation} = C_{pv} \cdot P_{stagnation}$$

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4) Add ventilation to the air space

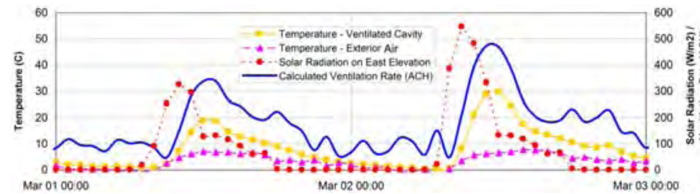
- ASHRAE Research Project 1091

Table 1. Ventilation Cavity and Vent Details for Four Cladding Types

	Cement Stucco on Backer Board on Strapping	Horizontal Wood Siding (or Cement Board) on Strapping	Brick Veneer with Top and Bottom Vents	Metal Panel with Slot Vents
Cavity Notes	19 × 38 mm wood strapping at 400 mm (16 in.) on center	19 × 38 mm wood strapping at 400 mm (16 in.) on center	25 mm (1 in.) open cavity, brick ties as required	12 mm open cavity, steel z-girts at 914 mm (3 ft) on center
Cavity width	362 mm (14.5 in.)	362 mm (14.5 in.)	Continuous, per 1000 mm (3.28 ft) width	914 mm (3 ft)
Cavity depth	19 mm (0.75 in.)	19 mm (0.75 in.)	25 mm (1 in.)	12 mm (0.5 in.)
Cavity weight	2743 mm (9 ft)	2743 mm (9 ft)	2743 mm (9 ft)	2743 mm (9 ft)
Cavity blockage factor, γ (0.01 to 1)	0.9 (assume slight bowing of stucco backer board when stucco is installed)	1.0 (cladding is rigid enough to span between strapping)	0.8 (mortar protrusions in well constructed brick veneer)	1.0 (smooth metal panel)
Vent Notes	Continuous through-wall flashing at floor height top and bottom	Continuous through-wall flashing at floor height top and bottom	Spaced every two bricks top and bottom	Drilled or punched slot vents top and bottom
Vent dimensions	12 mm bottom, 12 mm top, both continuous	19 mm bottom, 19 mm top, both continuous	10 mm × 65 mm spaced at 400 mm	6 mm × 25 mm spaced at 456 mm (1.5 ft)
Vent blockage factor (0.01 to 1)	0.5, mesh bug screen, estimate	0.5, mesh bug screen, estimate	0.1, plastic bug screen insert (Straube 1998)	1.0, open slots, no restrictions

4) Add ventilation to the air space

- ASHRAE Research Project 1091
- Predict hourly ventilation rate?



- OR use constant ventilation rate?

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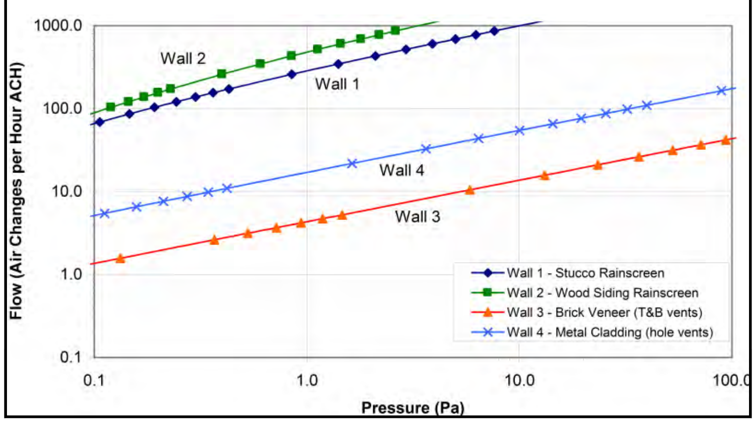
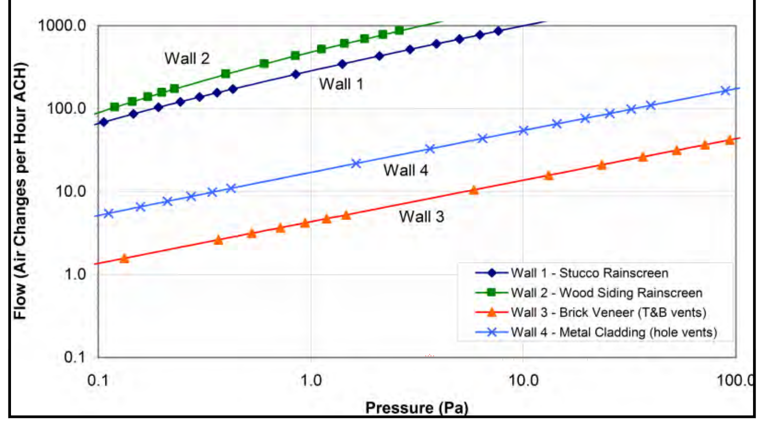
4) Add ventilation to the air space

- ASHRAE Research Project 1091



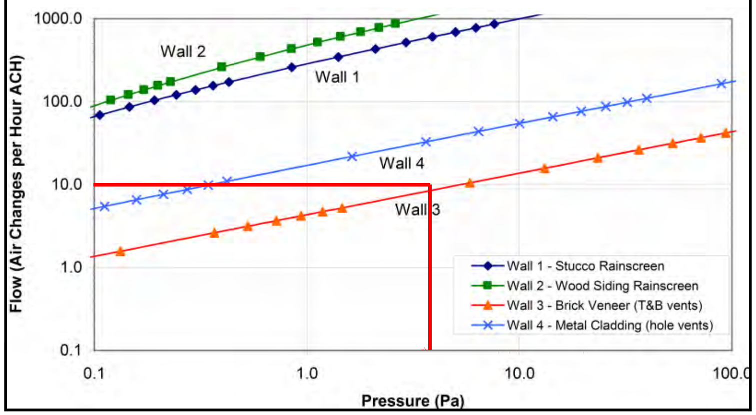
4) Add ventilation to the air space

- ASHRAE Research Project 1091



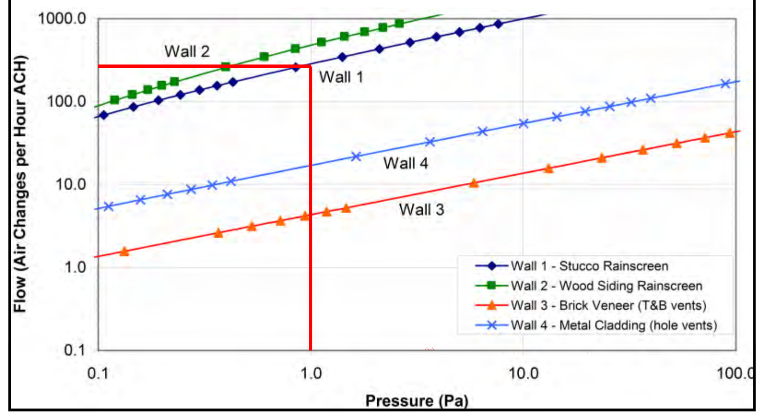
4) Add ventilation to the air space

- ASHRAE Research Project 1091



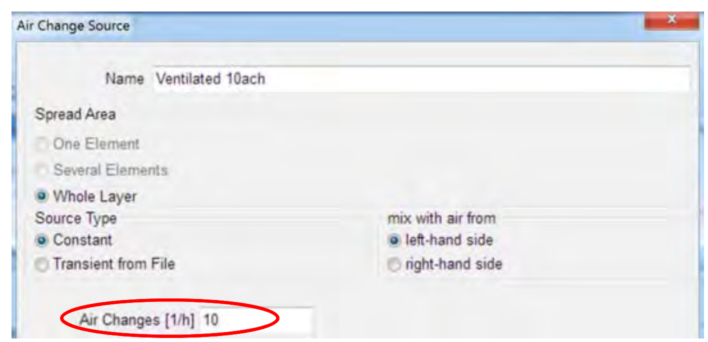
4) Add ventilation to the air space

- ASHRAE Research Project 1091

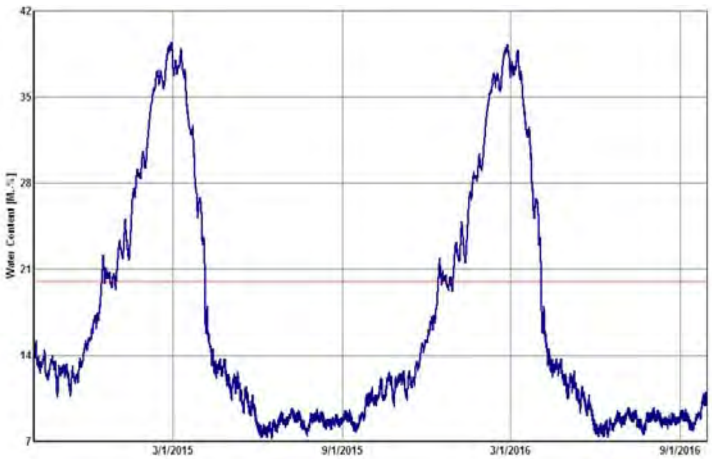


4) Add 10 ach ventilation to the air space

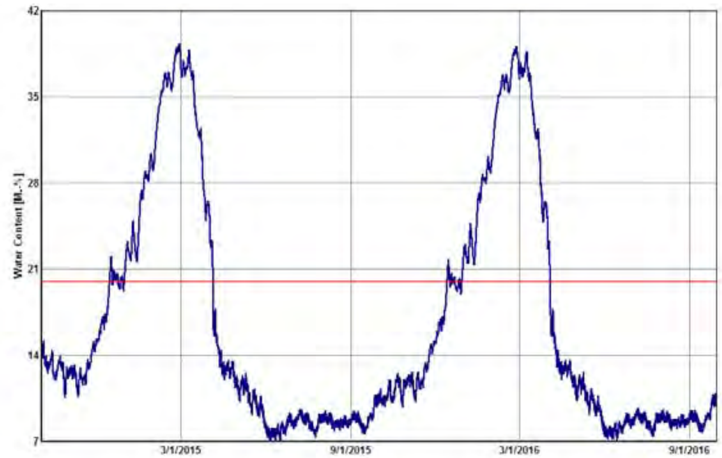
4) Add 10 ach ventilation to the air space



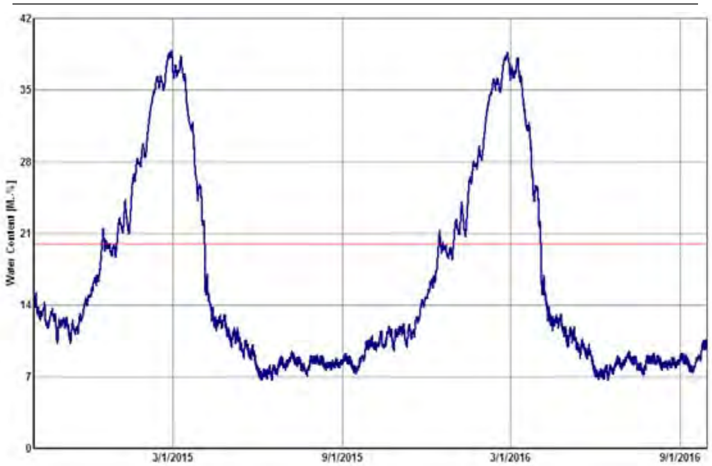
4) Remember where we were after 3…



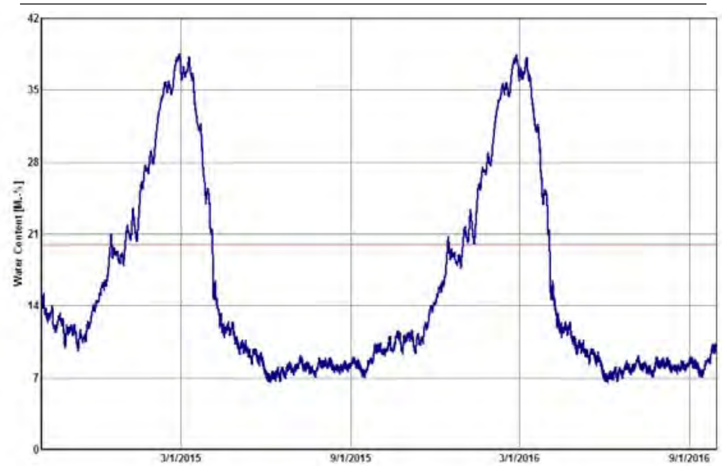
4) 10 ach. Why didn't that do anything?



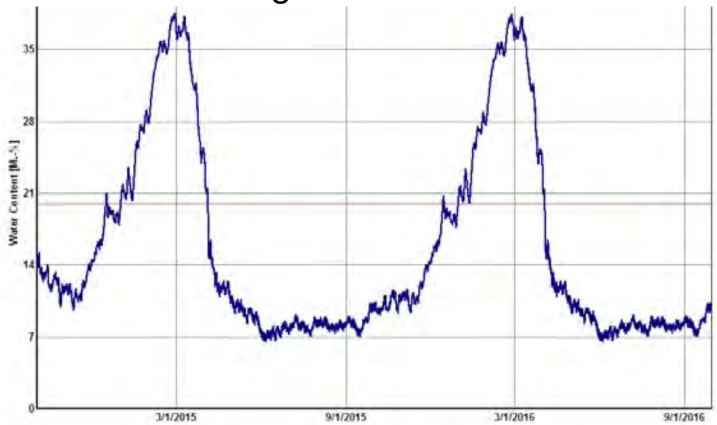
4a) Change 10 to 50 ach. Still nothing?



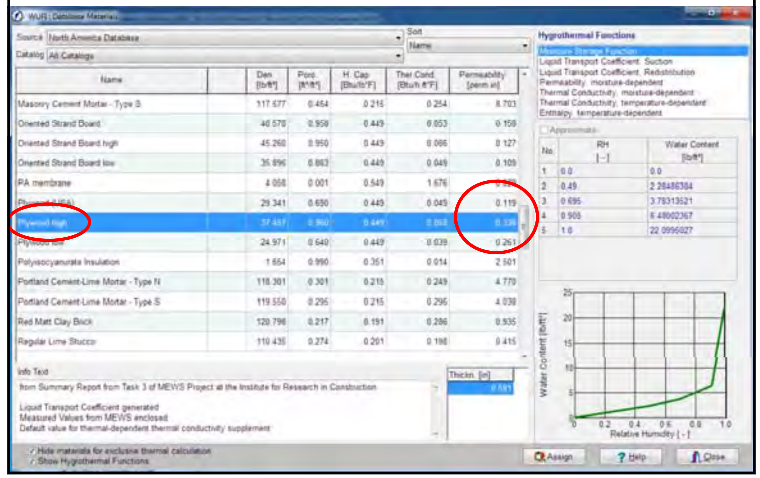
4b) Change 50 to 200 ach. Still nothing?



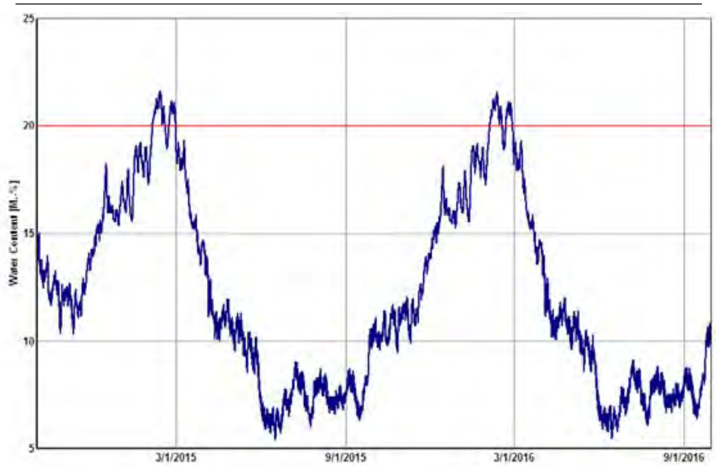
4b) Change 50 to 200 ach. Still Nothing? …Sheathing is the bottleneck?



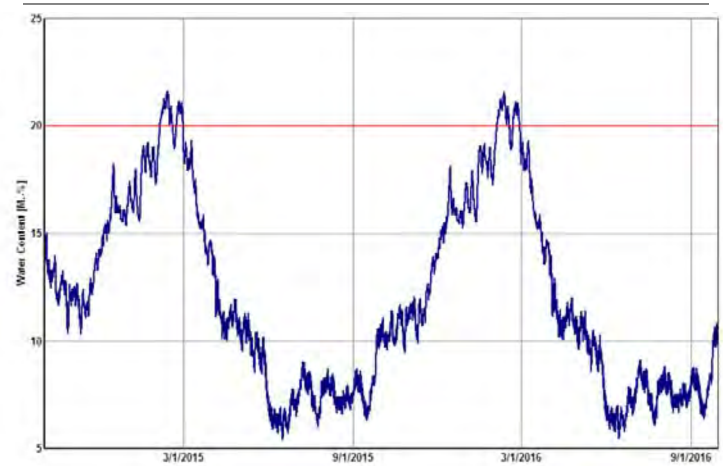
5) Change Plywood USA to High (back to 10 ach)



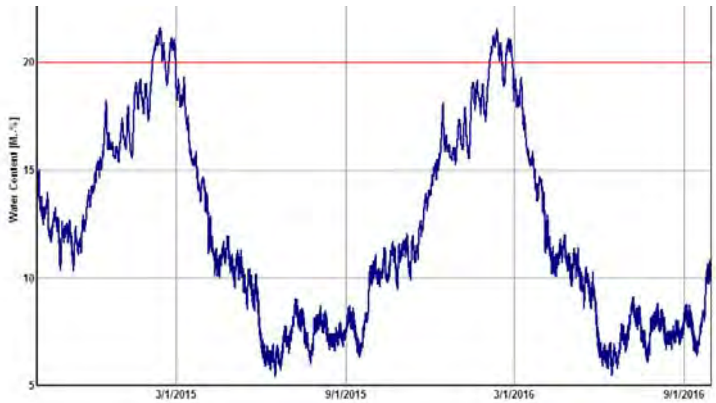
5) Whoa! Agrees w/ field experience…



5) So problem was the Plywood?

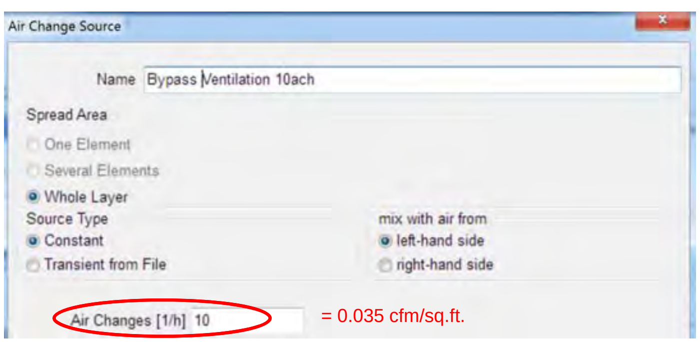


5) So problem was the Plywood?
… Not necessarily…



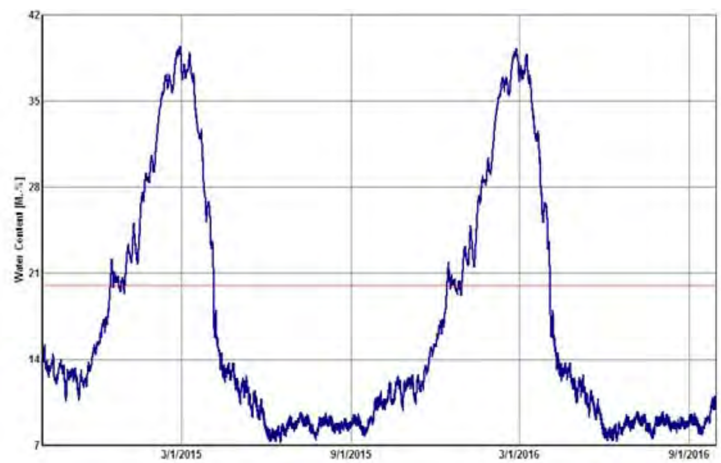
6) Back to Plywood USA, Add Bypass

6) Add Bypass Ventilation (back to Plywood USA)

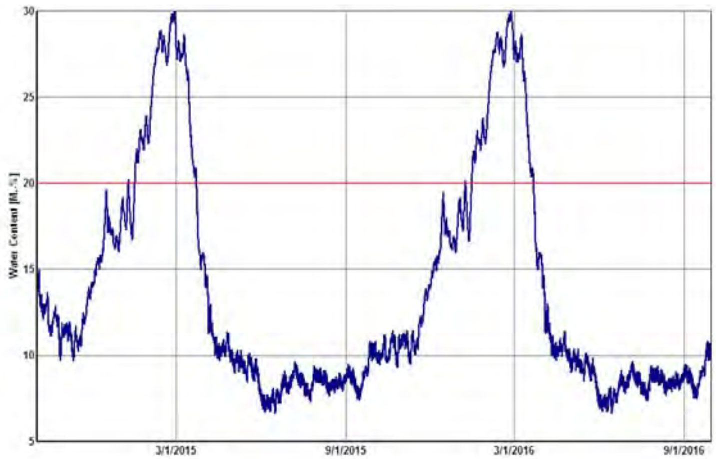


= 0.035 cfm/sq.ft.

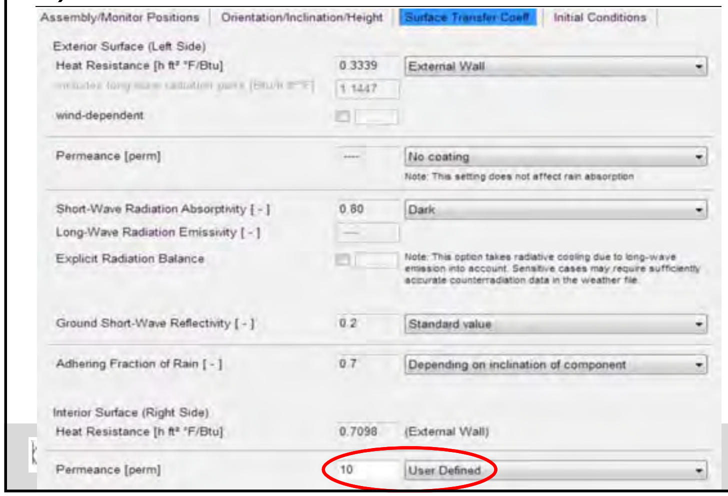
6) Remember where we were after 3…



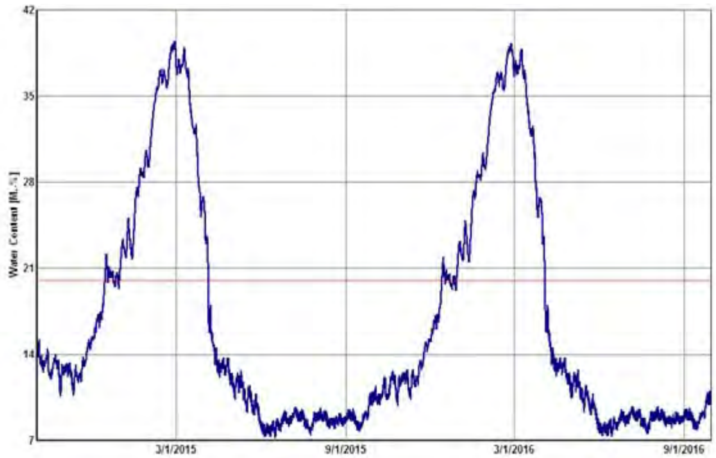
6) Noticeable impact from small Bypass



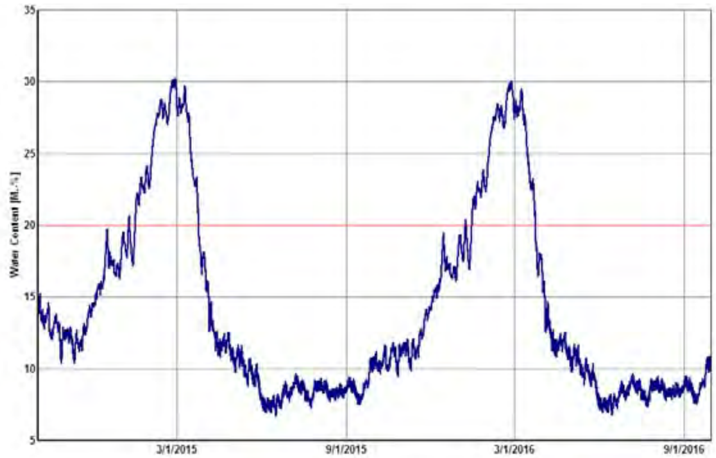
7) What about Int. Surface Permeance?



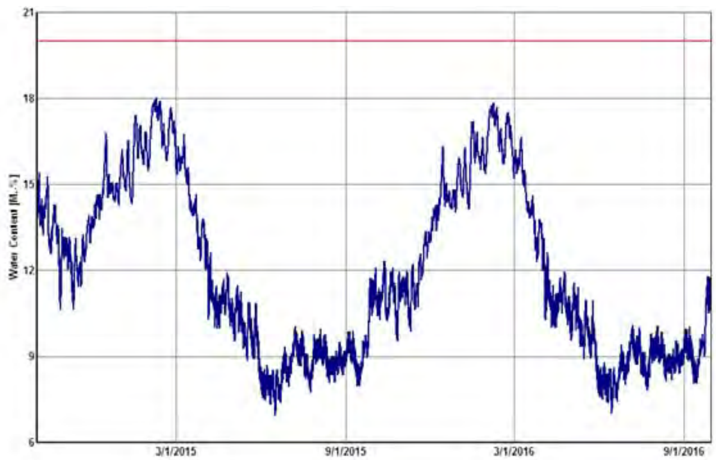
7) Remember where we were after 3…



7) Change Int. Surf. From 10 to 7 perms

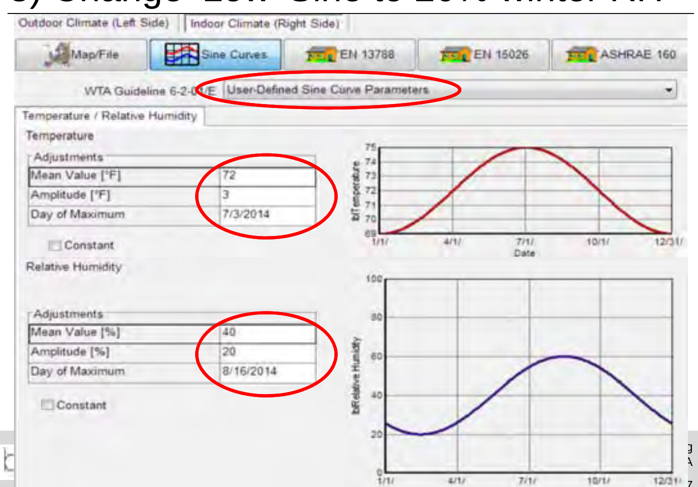


7a) Agrees w/ dry end of field experience

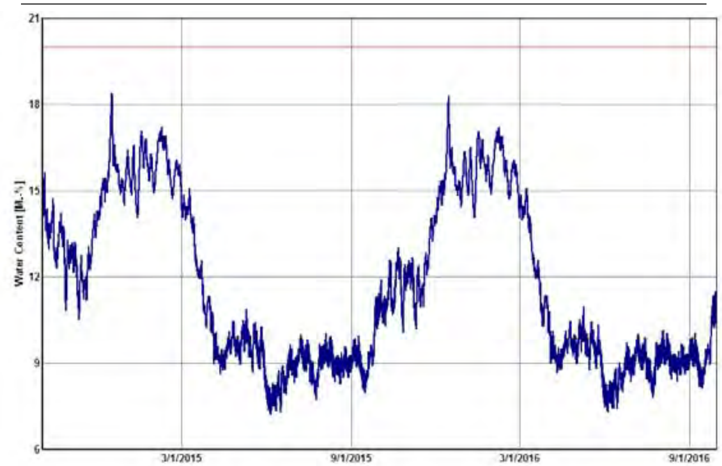


8) Recall Int. Climate from 3…

8) Change 'Low' Sine to 20% winter RH



8) Agrees w/ dry end of field experience



Numerous other things not touched

- Paint on the exterior of the siding
- Back priming on the interior of the siding
- Rain water penetration
- Explicit radiation balance
- Etc…

Modeling a Historically Proven Wall

What have we learned from the conversations that follow a typical 'Request for Guidance'?

50 ways to leave your lover?

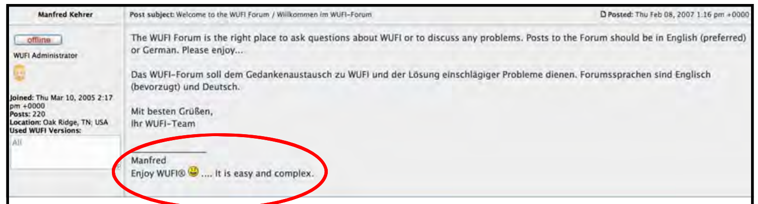
- Often 5 or more ways to reflect reality

User:

- "Which one is right?"

Me:

- "Likely that hygrothermal performance of any pair of walls is influenced different combinations of factors that end up producing similar results"



Manfred Kehrer :

- "Enjoy WUFI® … it is easy and complex"

The Users of Hygrothermal Models?

- Many users don't have the background
  1. to understand the physics
  2. to understand and run the program
  3. to judge the validity of the predicted performance
- Need
  1. more building science education in colleges
  2. more con-ed options for 'experienced' professionals
  3. more measurement and field experience

The Building Science Industry?

- Don't have enough material properties
  - properties are highly variable
  - names and sources are confusing / contradictory
- Don't have enough field data for boundary conditions (especially interior)
- Don't have enough field experience for performance of newer systems
  - need more deconstructive surveys !!!

Guidance on Hygrothermal Modeling

- Use it as a demonstration tool?
- Use it as a learning tool?
- Use it as a scoping tool?
- Use it as forensic tool?
- Use it as a design tool?

Thank You

Reality of our industry

- Modeling can be misleading
- Measurement trumps modeling
- Measurement is time consuming & expensive
- Measurement can be misleading
- Both are necessary. Do them intelligently.

Appendix C (Lois Arena)

Monitoring and Modeling Issues Associated with ASHRAE 160

ASHRAE 160: Modeling and Measured Data

BA Expert Meeting 2014

Steven Winter Associates, Inc.

Overview

- CARB's moisture related research & experience w/ ASHRAE 160
- Monitoring efforts & how they compare /w modeling
- Proposed Changes to 160
- Questions/Discussion

Original 160 Criteria

- Purpose of the Standard
  - Criteria for selecting analytic procedures
  - Criteria for inputs
  - Criteria for evaluation and use of outputs

Original 160 Criteria

- Design Parameters
  - Initial conditions of building materials set to ECM80 (material at equilibrium w/ air at 80% RH & 68F), ECM90 if masonry
  - Indoor temperatures at 70F winter, 75 summer
  - RH determined based on weather file & mechanical systems
  - 1% of driving rain on outside of WRB

Original 160 Criteria

- Running average surface temperature is between 41°F and 104°F
  - 30–day running average surface RH<80%;
  - 7–day running average surface RH<98%
  - 24-h running average surface RH< 100%

Original 160 Criteria

- It is often quoted that that the minimum moisture (MC) content requirement for the growth of fungi is approximately 20% in wood corresponding to about 80%- 90% RH (Siau 1984). Decay generally occurs above 90-95% at 68°F (ASTM MNL 40 2001).

CARB's Moisture Projects

- 2008 HUD field study:
  - collect interior temp and RH data for comparison to 160 design conditions
  - Find correlations between indoor conditions and mold growth
  - Temperatures and RH levels typically lower in winter and higher in summer than 160 design conditions

CARB's Moisture Projects

- 2011SPFA
  - Modeling study to evaluate minimum levels of spray foam in cavities w/ class III VR, Climate Zones 4-7
  - All homes with minimum levels of spray foam in code and class III VR failed the 160 criteria as do homes with FG batts and no spray foam
  - All homes showed the potential for mold growth on the interior walls

CARB's Moisture Projects

- Evaluated160 design parameters and standard sine curve
- RH levels predicted by this method reach 90% regardless of that fact that cooling was assumed.
- WUFI predicted that there is the potential for mold growth on the interior surface of the drywall in all climates
- Sine curve was used instead

Results – Code hybrid

	Sine Wave - (69.8 ± 1.8°F, 50% RH ± 10%)						ASHRAE 160 - Cooling Assumed					
	ASHRAE Criteria	OSB Moisture Content	Assembly Moisture Content	Isopleths Interior	Isopleths MDSPF	Condensation Potential	ASHRAE Criteria	OSB Moisture Content	Assembly Moisture Content	Isopleths Interior	Isopleths MDSPF	Condensation Potential
4A-1	X	√	√	√	X	13%	X	√	√	X	X	36%
4B-1	X	√	√	√	X	19%	X	√	√	√	X	23%
4C-1	X	√	√	√	X	13%	X	X	√	X	X	62%
5A-1	X	√	√	√	X	24%	X	√	√	X	X	49%
5B-1	X	√	√	√	X	27%	X	√	√	√	X	29%
6A-1	X	√	√	√	X	23%	X	√	√	X	X	33%
6B-1	X	√	√	√	X	17%	X	√	√	√	X	10%
7-1	X	√	√	√	X	21%	X	√	√	X	X	8%

CARB's Moisture Projects

- 2011-2013 BA
  - Modeling study on high R walls
  - Monitoring of double stud cellulose walls in Devons, MA
  - Vented cladding necessary
  - Modeling resulted in reasonably accurate predictions of performance
  - Ratios of impermeable to permeable insulation in high R-walls may need to be revisited
  - Walls performed reasonably well, failed 160

Addendum A – 02/2011

In this addendum, the three required conditions for minimizing mold growth are modified by retaining only the most significant condition while eliminating the other two. This change has been made because

1. the condition being retained (item a) is sufficient for determining the onset of mold growth,
2. one of the conditions being deleted (item b) was erroneous, and
3. the other condition being removed (item c) is not germane to determining mold growth. In addition, this change will make the standard easier to use.

Addendum C – 06/2012

SSPC 160 changes Section 4.6 as indicated below. The changes are limited to Table 4.6.1 and the explanation of terms directly below the table.

- The changes are meant to simplify the calculation of wind-driven rain without significantly degrading the accuracy of the calculation.
- Because the calculation has large errors associated with it, the specificity of the old table did not improve accuracy.
- There is also considerable uncertainty about the effect of building height on rain deposition.

Addendum B – 10/2012

- Section 4.3: The SSPC realized that indoor design humidities exceeding 70% RH are excessive and would likely lead directly to indoor mold and should therefore not be allowed for design analysis.
- Table 4.3.2: It has become apparent that the residential generation rates in Table 4.3.2 are very high. Changes to Table 4.3.2 are based on recent analysis of measured indoor humidity and ventilation data.

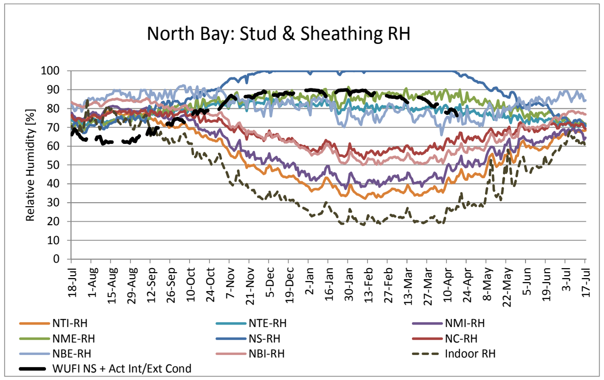
CARB's Moisture Projects

- 2014 NYSERDA
  - Monitoring two high R-walls, Climate Zone 6
  - 12" cellulose wall and 3.5" ccSPF + 8.5" cellulose
  - Fail 160 criteria
  - Performing very well, MC <15%

CARB's Moisture Projects

- In general, predictions using 160 design criteria vs. measured values are very good.
- Predictions using climate files are close to predictions using measured boundary conditions

BA Study



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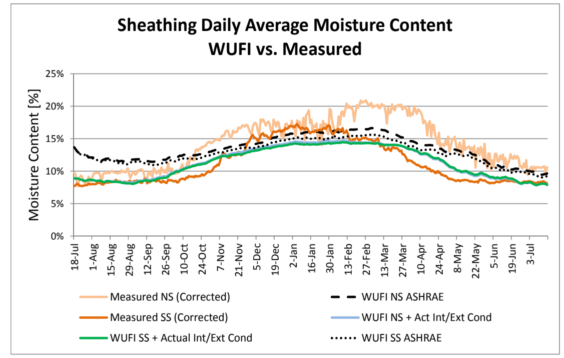
BA Study



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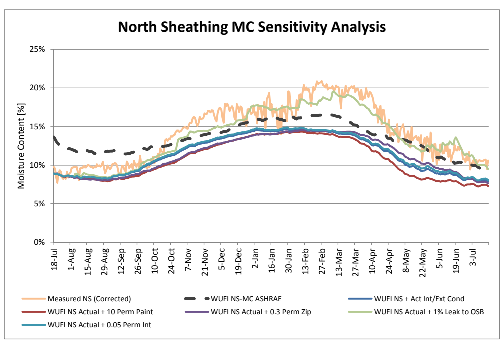

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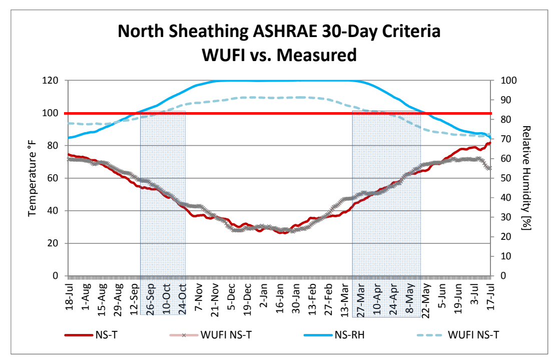

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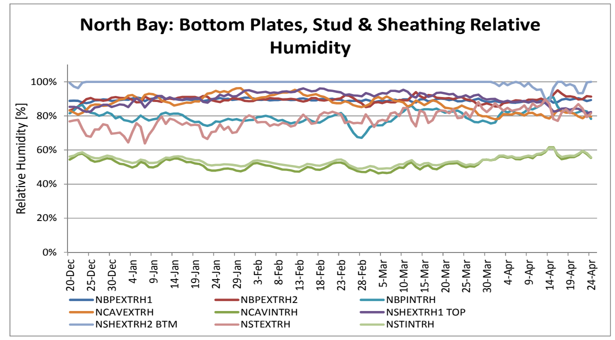
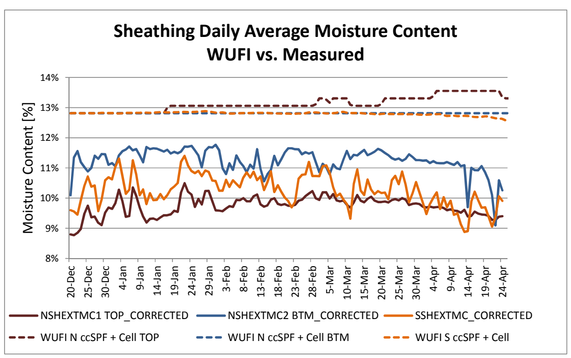
BA Study

Orientation	Case	% of 30-day Averages that Fail (Jul – Mar)[1]	Pass/Fail
North	Measured	23%	Fail
	Predicted	36%	Fail
South	Measured	18%	Fail
	Predicted	54%	Fail

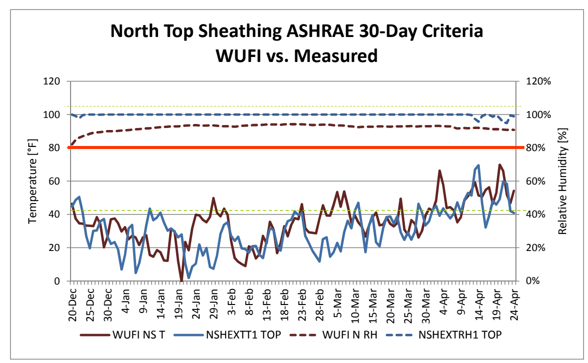
NYSERDA Study



NYSERDA Study



NYSERDA Study



NYSERDA Study

Project	Surface	WUFI Prediction	Measured Data	Pass/Fail
Cellulose Wall N	sheathing	29%	29%	Fail
Cellulose Wall S	sheathing	38%	33%	Fail
Cell + ccSPF N	ccSPF	73%	81%	Fail
Cell + ccSPF S	ccSPF	56%	0%	Pass

Questions for Discussion

- Is the failure criteria too strict?
- What are the alternatives?
- What surfaces should be analyzed
  - Is first condensing surface enough?
  - Should some materials be ignored for mold growth – ie, cellulose, spray foam
- Should the EMC80/90 values be used at the start of the simulation?

Consider the Following

- A significant percentage of the failures occurred in the first year at the beginning of the modeling period.
- It should be noted that almost all walls modeled with the Class III vapor retarder fail the 30 day criteria.

Changes Being Considered

- Possibly using the VTT Finland mold growth model as an option to the current criteria
- Eliminating most of 4.4.1.3 in the existing standard dealing with air tightness values and air leakage rates of materials/assemblies.

Lois B. Arena
Steven Winter Associates, Inc.
www.swinter.com

QUESTIONS?

Appendix D (Vladimir Kochkin)

Moisture Performance of Energy Efficient Walls

Moisture Performance of Energy Efficient Walls

Summary Results of Two Monitoring Programs: Whole-House Project and Test Hut Project

Vladimir Kochkin
May 2014
Building America Expert Meeting
Summerville, MA

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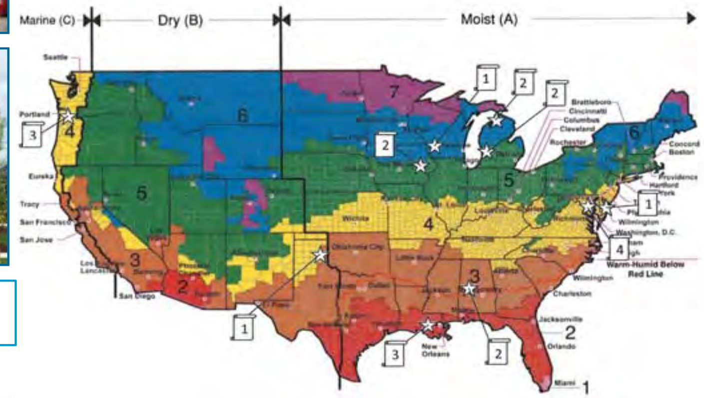
Technical Approach

Cataloguing and monitoring EE wall designs used by builders in various climates



22 Homes

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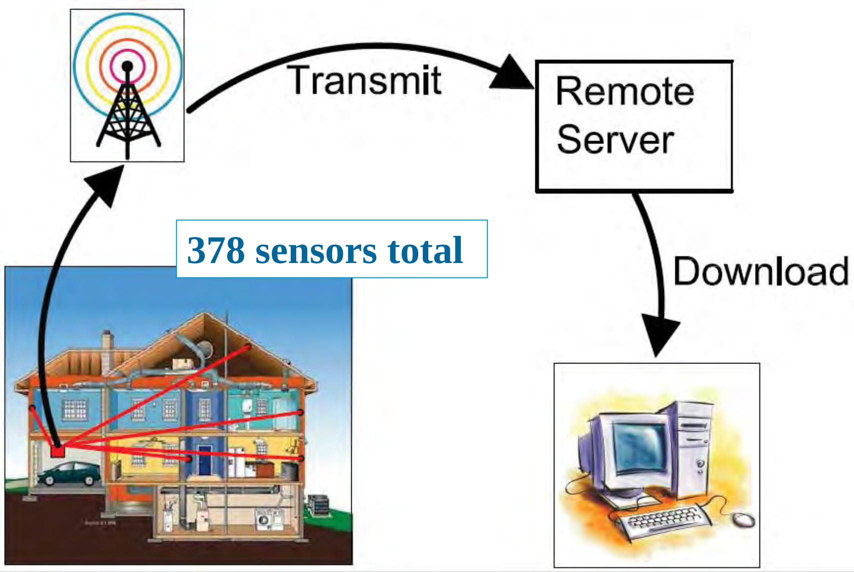
Monitoring System



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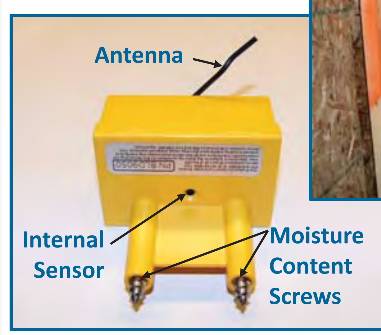
Wireless Sensor – T/RH/MC



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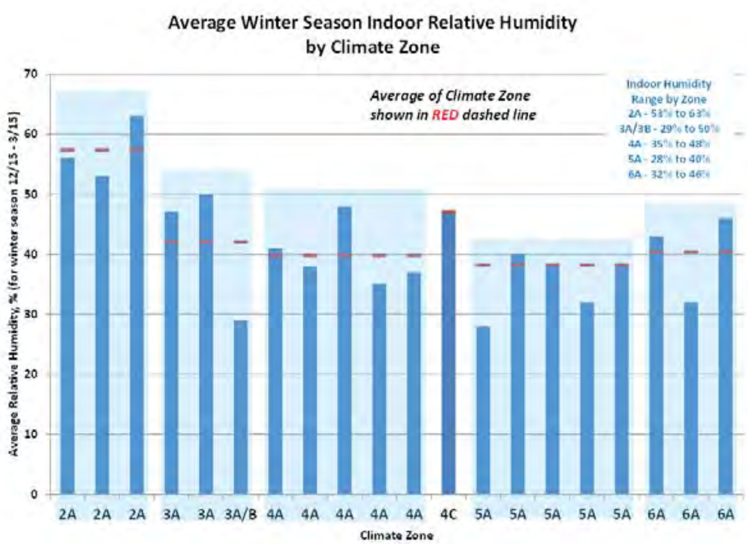
Homes by Climate Zone

CZ	# Homes	# Wall Types
2A	3	3
3A	3	3
4A	5	2
4C	3	1
5A	5	5
6A	3	9
Total	**22**	**23**

22 Homes

Test Site	State	Climate Zone	Cond. Floor Area, sf	Foundation	ACH50	Ventilation	Start Date	Duration
1	Lousiana	2A	1,896	crawlspace	4.39	Exhaust fans	3/30/2012	**1.0**
2	Lousiana	2A	1,896	crawlspace	4.29	Exhaust fans	3/30/2012	**1.0**
3	Lousiana	2A	1,896	crawlspace	2.04	Exhaust fans	3/30/2012	**1.0**
4	Alabama	3A	1,094	slab on grade	1.32	Exhaust fans	2/17/2012	**1.1**
5	Alabama	3A	1,094	slab on grade	2.25	Exhaust fans	2/17/2012	**1.1**
6	Texas	3A	2,115	slab on grade	1.83	HRV	6/30/2012	**0.8**
7	Maryland	4A	4,407	basement	1.90	RA supply	5/24/2011	**1.9**
8	Maryland	4A	4,648	basement	2.30	RA supply	12/8/2011	**1.3**
9	Maryland	4A	4,371	basement	2.40	RA supply	11/10/2011	**1.4**
10	Maryland	4A	4,486	basement	2.30	RA supply	11/9/2011	**1.4**
11	Delaware	4A	4,893	basement	1.03	RA supply	1/26/2012	**1.2**
12	Washington	4C	3,199	slab on grade	3.10	Exhaust fans	11/1/2012	**0.4**
13	Washington	4C	2,735	slab on grade	3.40	Exhaust fans	10/3/2012	**0.5**
14	Washington	4C	2,815	slab on grade	2.20	HRV	4/25/2013	**0.0**
15	Iowa	5A	5,286	basement	<2.0	HRV	11/8/2012	**0.4**
16	Iowa	5A	3,256	basement	<2.0	HRV	12/1/2012	**0.3**
17	Michigan	5A	1,352	basement	3.37	ERV	12/14/2012	**0.3**
18	Michigan	5A	1,352	basement	3.30	ERV	12/14/2012	**0.3**
19	Michigan	5A	1,344	basement	1.48	ERV	1/4/2013	**0.2**
20	Wisconsin	6A	1,368	slab on grade	<4.0	HRV	1/20/2012	**1.2**
21	Michigan	6A	4,318	basement	0.76	ERV	12/17/2011	**1.3**
22	Michigan	6A	1,304	basement	0.88	ERV	12/14/2012	**0.3**

Interior Winter RH



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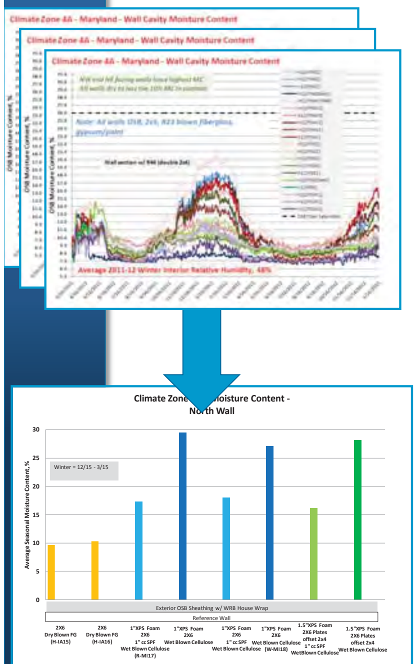
23 Wall Configurations

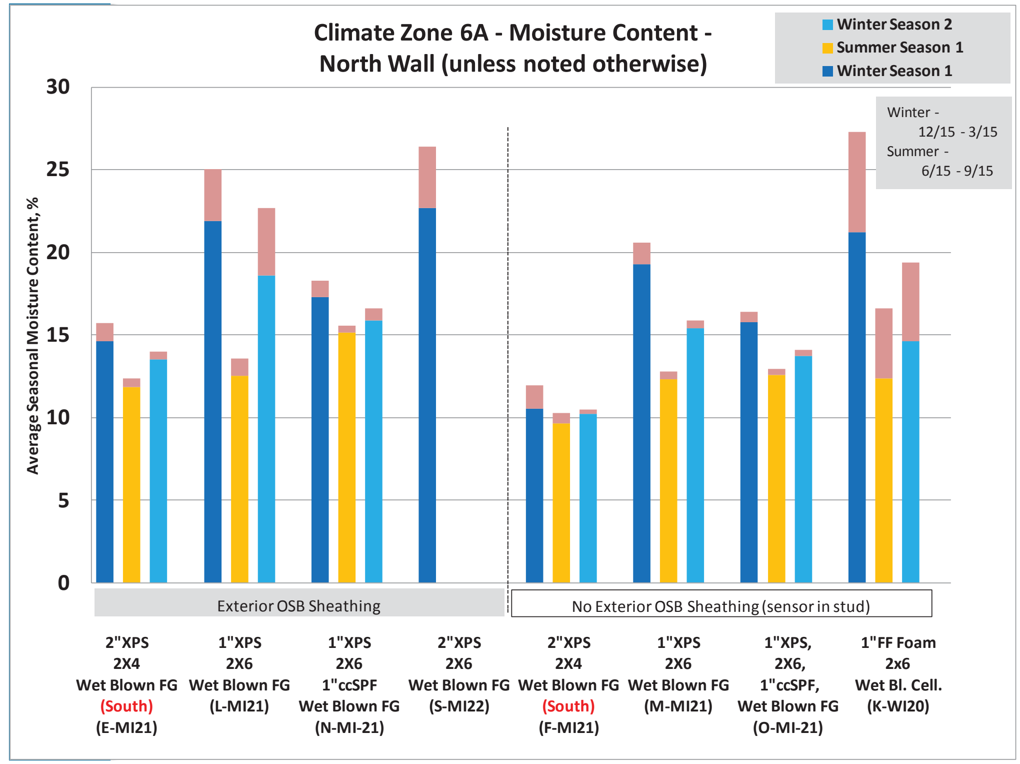
Wall Ref.	Frame	OSB	WRB	Exterior Insulating Sheathing	Cavity Insulation and Nominal R-value[2]	Interior Vapor Retarder/Barrier
A	2x4	Y	Y		Fiberglass Batt (R13)	Gypsum/paint
B	2x4	Y		1/2" Foam (R3)	Spray Cellulose (R15)	Gypsum/paint
C	2x4	Y		1" XPS Foam (R5)	Fiberglass Batt (R13)	Gypsum/paint
E	2x4	Y		2" XPS Foam (R10)	Wet Blown Fiberglass (R20)	Gypsum/paint
F	2x4	N		2" XPS Foam (R10)	Wet Blown Fiberglass (R20)	Gypsum/paint
G	2x4	Y	Y		Closed Cell Foam (R18)	Gypsum/paint
H	2x6	Y	Y		Dry Blown Fiberglass (R23)	Gypsum/paint
i1	2x6	Y	Y		Spray Rockwool (R24)	Gypsum/paint
i2	2x6	Y	Y	Reflective WRB (E/W)	Spray Rockwool (R24)	Gypsum/paint
J	2x6	Y		1/2" Foil Faced Foam (R2.5)	Wet Blown Cellulose (R19)	Vapor barrier paint
K	2x6	N		1" Foil Faced Foam (R5)	Wet Blown Cellulose (R19)	Vapor barrier paint
L	2x6	Y		1" XPS Foam (R5)	Wet Blown Fiberglass (R20)	Gypsum/paint
M	2x6	N		1" XPS Foam (R5)	Wet Blown Fiberglass (R20)	Gypsum/paint
N	2x6	Y		1" XPS Foam (R5)	ccSPF Flash, Wet Bl. FG (R23)	Gypsum/paint
O	2x6	N		1" XPS Foam (R5)	ccSPF Flash, Wet Bl. FG (R23)	Gypsum/paint
P	2x6	Y	Y		Open Cell Foam (R16)	Gypsum/paint
Q	2x4 offset	Y	Y		Offset 2x4 framing, Blown Fiberglass (R24)	Gypsum/paint
R	2x6	Y	Y	1" XPS Foam (R5)	ccSPF Flash, Wet Bl. Cell (R21)	Gypsum/paint
S	2x6	Y	N	2" XPS Foam (R10)	Wet Blown Fiberglass (R20)	Gypsum/paint
T	2x4 offset	Y	Y	1.5" XPS Foam (R7.5)	Offset 2x4 framing, Wet Blown Cellulose (R21)	Gypsum/paint
U	(2) 2x6	Y	Y		Blown Fiberglass (R46)	Gypsum/paint
V	2x4 offset	Y	Y	1.5" XPS Foam (R7.5)	Offset 2x4 framing,ccSPF Flash, Wet Blown Cellulose (R24)	Gypsum/paint
W	2x6	Y	Y	1" XPS Foam (R5)	Wet Blown Cellulose (R19)	Gypsum/paint

- 2x4, 2x6, 2x4 offset
- Cavity (R13-R24)
  - Spray rockwool
  - Wet blown cellulose
  - Wet blown fiberglass
  - Dry blown fiberglass
  - Open cell spray foam
  - Closed cell spray foam
  - Flash & batt
- Ext. Insulation (R3-R10)
  - ½-inch foil faced foam
  - 1-inch XPS
  - 1.5-inch foam
  - 2-inch XPS
- R13-R31, R46 wall

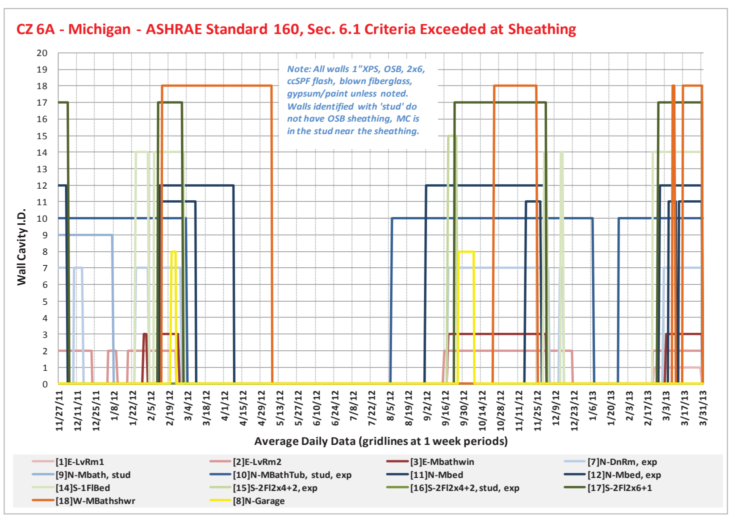
Results



- MC: Season average and daily average
- Organized by season: heating/cooling
- Organized by wall orientation
- Organized by climate zone



ASHRAE 160



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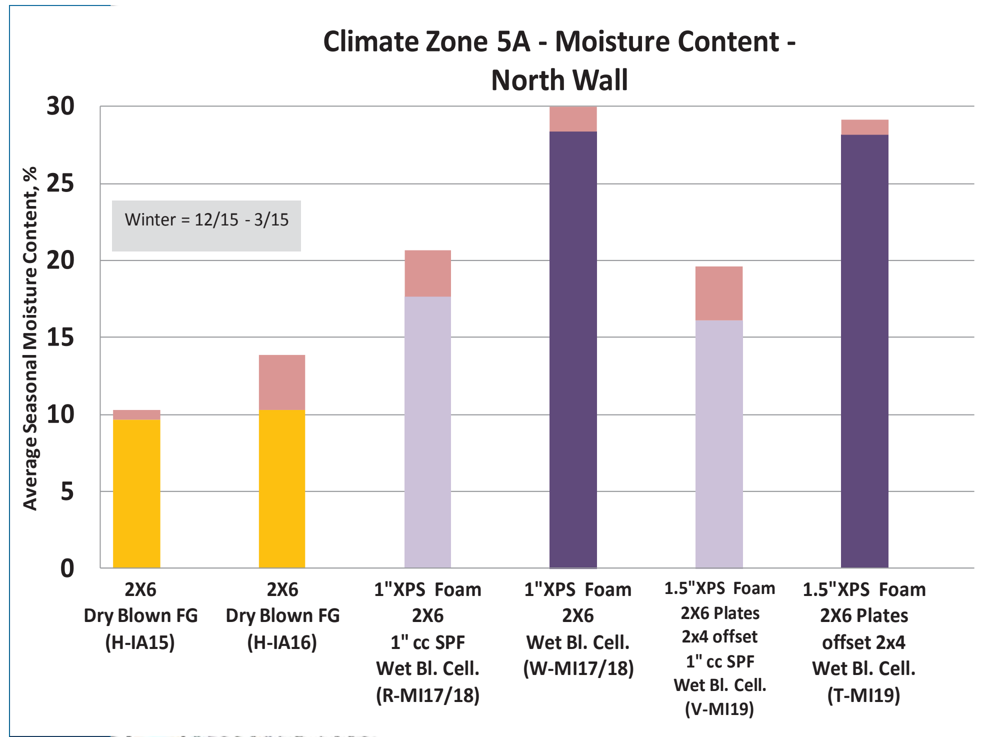
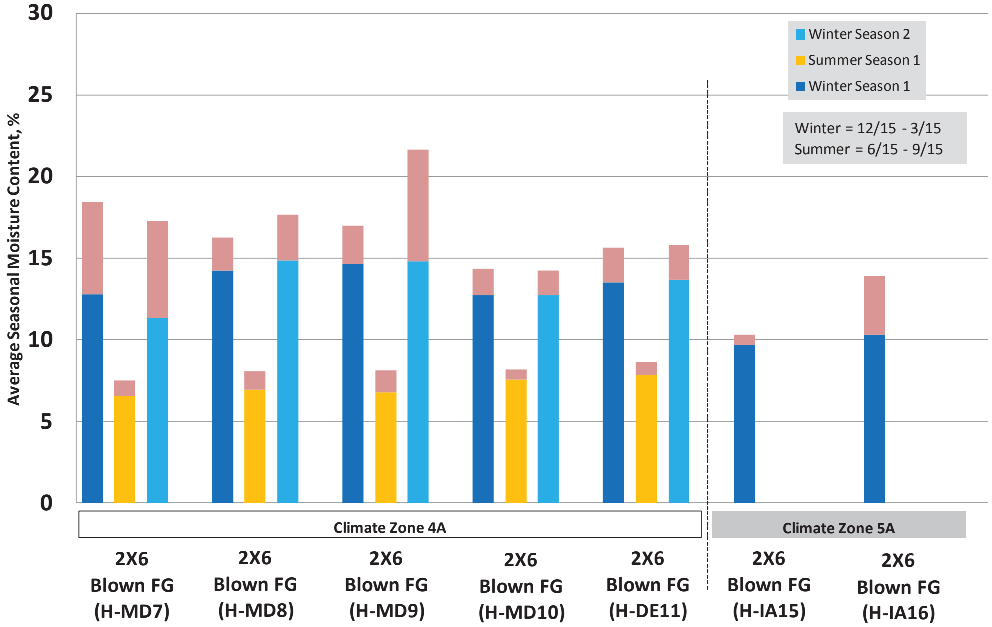


2x6 Walls

Moisture Content - Climate Zone 4A & 5A - North Wall



2x6 Wall Case Study

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2x6 Wall Case Study

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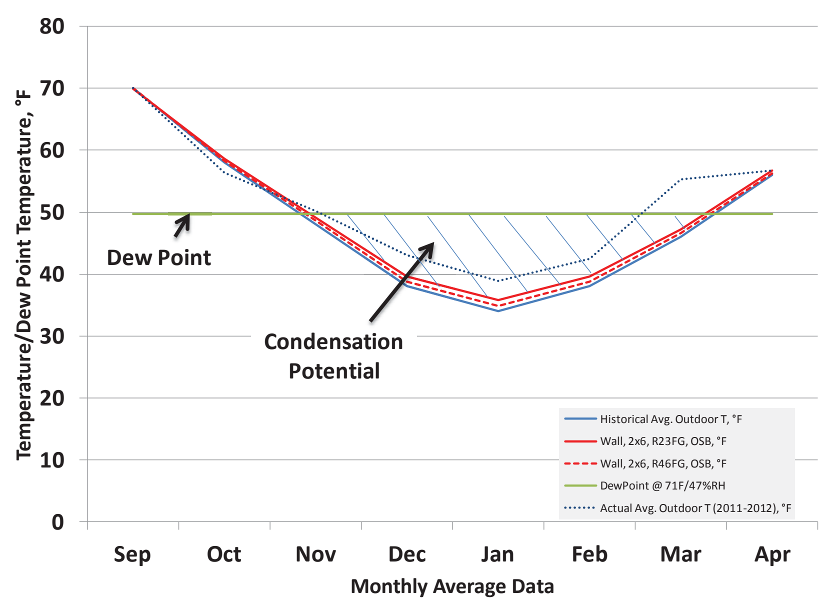
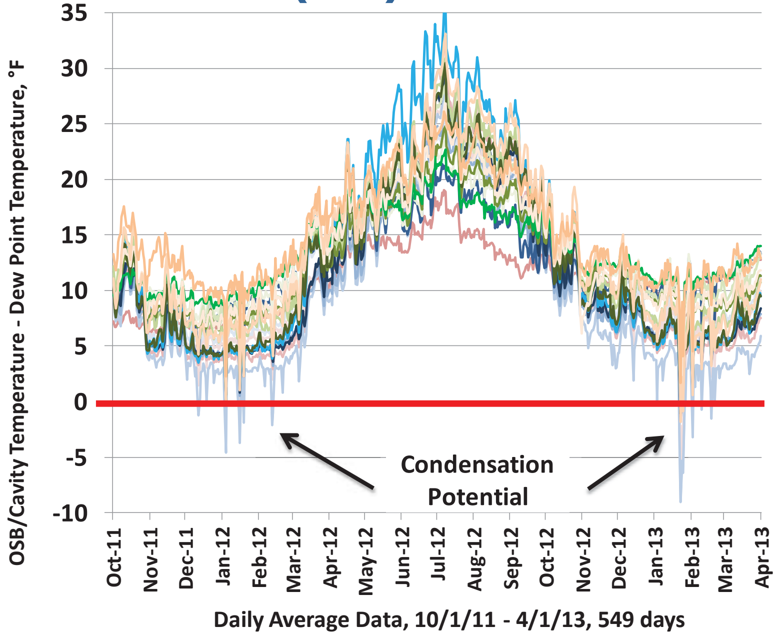
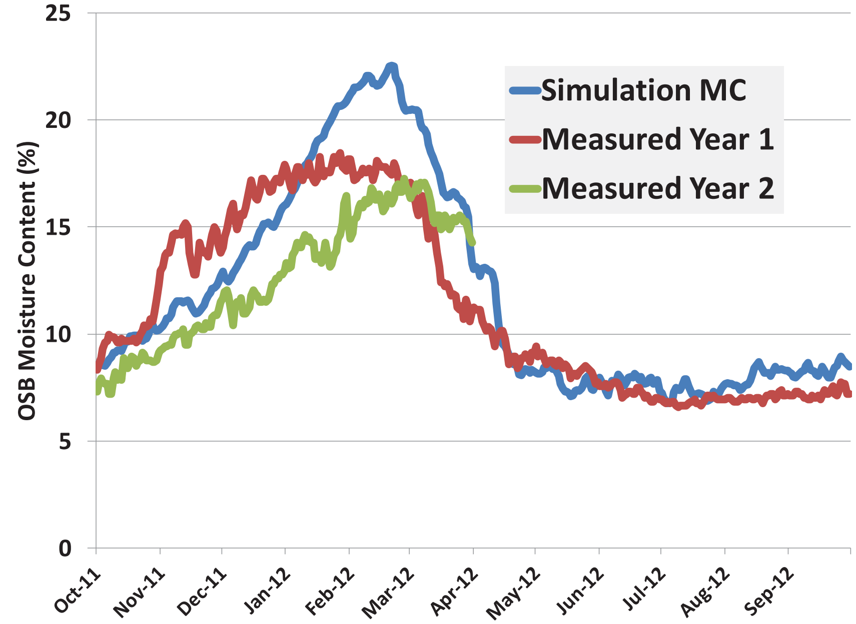
Simplified Dew Point Calc CZ 4 (MD) – 2x6 wall

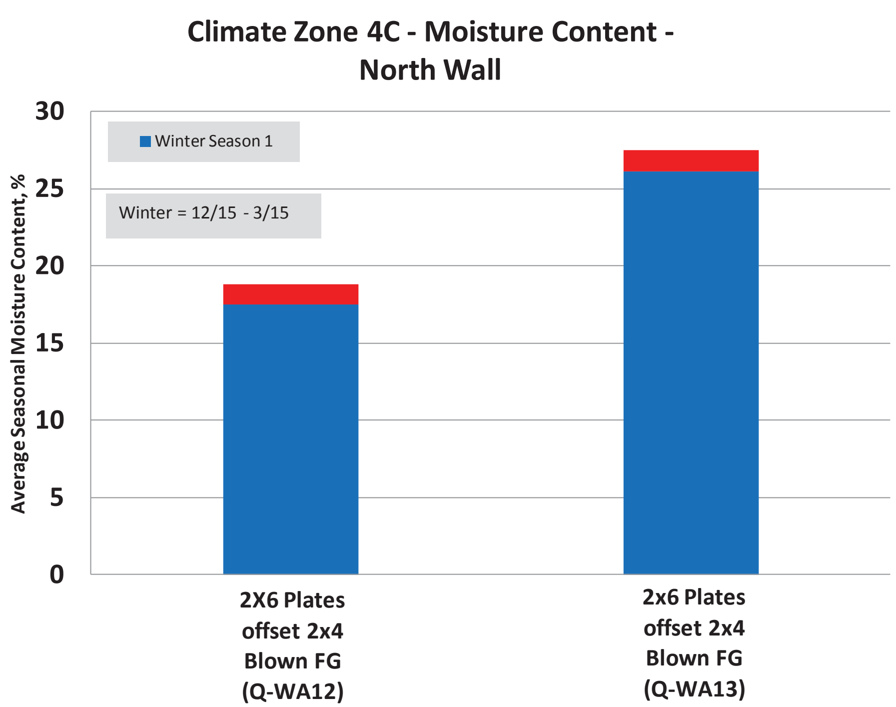


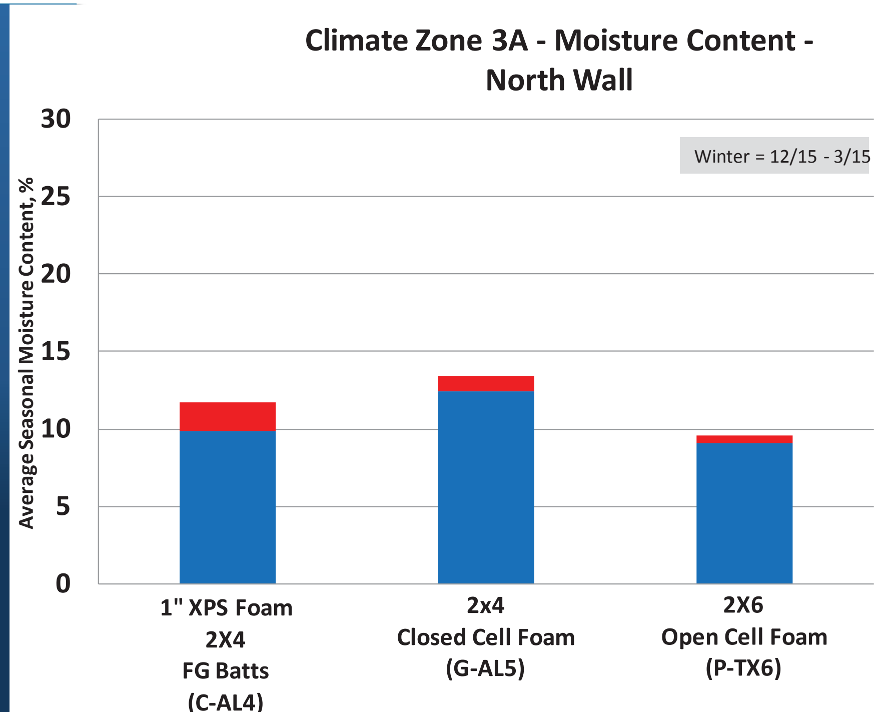
Measured Dew Point Potential CZ 4 (MD) – 2x6 wall

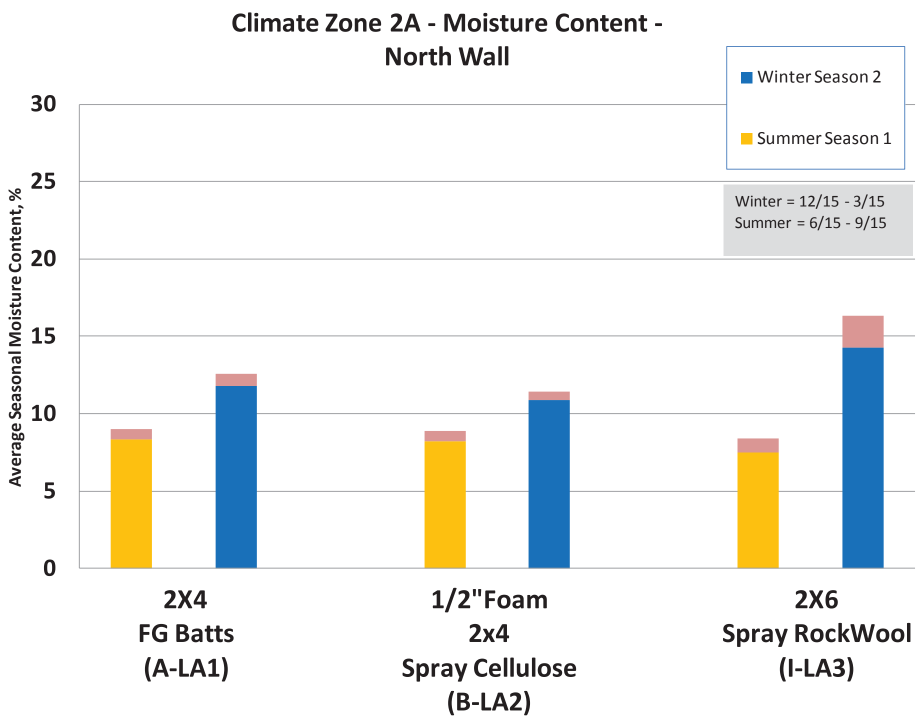


WUFI Modeling









Highlights

- In walls with exterior foam and w/o vapor retarder, summer drying is observed
- 2x6 walls w 1-1.5" ext foam sheathing and w/o an int vapor retarder may not be appropriate for colder climate zones (5 and higher). Variable ("smart") vapor retarder (e.g., kraft paper)?

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Highlights

- 1" ext foam and an interior flash coat of ccSPF is effective at controlling OSB moisture uptake from the interior. However, this system would be susceptible to retaining moisture.
- OSB in 2x6 walls with 2" ext foam w/o an int vapor retarder showed high MC in the first winter following construction.

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Highlights

- South-facing 2x4 walls with 2" ext foam w/o int vapor retarder show low OSB MC – solar vapor drive to the inside. Data is needed for north-facing exposure.
- Wet-blown cellulose used in combination with exterior foam sheathing results in high initial OSB moisture content. Continued monitoring is needed to capture duration of the exposure.

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Highlights

- 2x6 walls in CZ 4 and 4C (w/o a vapor retarder) and CZ 5 (w a vapor retarder) showed good overall performance
- 2x6 walls w/o a vapor retarder showed significant seasonal fluctuations in OSB MC
- In some homes trend with interior RH
- Visual inspection – no observed effects

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Highlights

- A range of EE wall designs in CZ 2 and 3 indicates acceptable performance for all monitored wall types. A relationship b/w the int RH and OSB MC for walls without an int vapor retarder.
- Simplified condensation calcs overly predict risk
- ASHRAE 160 is often exceeded

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Test Huts

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Next Phase

- Comparative evaluation of 2x4 walls with four types of ext insulation (R5): XPS, EPS; Polyiso, Rockwool
- Quantify the relative impact of vapor diffusion versus air leakage on the OSB MC a 2x6 walls
- Evaluate the impact RH on walls without a vapor retarder
- Evaluate Extended Plate and Beam wall system (two air sealing configurations)

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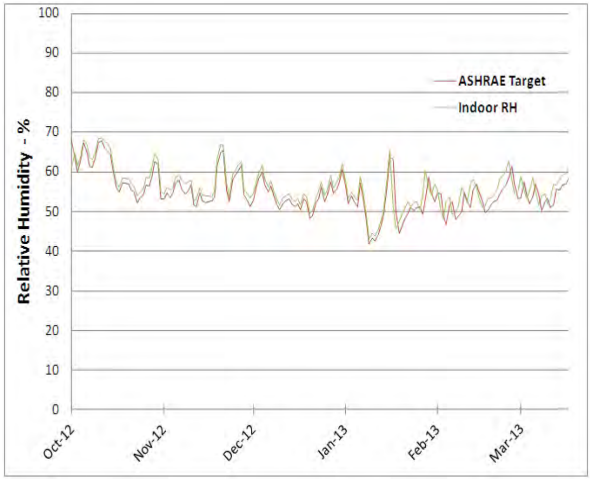
Test Hut (Completed)

RH



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Year/Month	Monthly Average T, °F		Monthly Precipitation, inch	
	30 year average	Measured	30 year average	Measured
2011 Nov	47.0	51.2	3.5	1.8
2011 Dec	37.5	43.7	3.1	5.0
2012 Jan	33.5	39.8	2.9	2.3
2012 Feb	36.0	42.3	2.8	1.9
2012 Mar	44.5	54.6	3.8	1.8
2012 Apr	54.5	56.1	3.6	1.9
2012 May	63.5	68.6	4.3	2.9
2012 Jun	72.5	72.9	4.1	4.6
2012 Jul	77.5	80.3	4.0	2.1
2012 Aug	75.0	76.2	3.7	1.3
2012 Sep	68.0	68.3	4.0	3.6
2012 Oct	56.0	58.1	3.6	16.7[A]
2012 Nov	47.0	43.3	3.5	0.5
2012 Dec	37.5	43.6	3.1	5.0
2013 Jan	33.5	38.6	2.9	3.4
2013 Feb	36.0	36.2	2.8	4.0
2013 Mar	44.5	41.7	3.8	2.8

[A.] Rainfall in the wake of Hurricane Sandy. Analysis of moisture content results did not reveal any definitive uptick in OSB moisture content following the high rainfall.

Summary

Conf.#		Cladding	Water Resistive Barrier	Exterior Insulation	Framing and Ext. Sheathing	Cavity Insulation/ Kraft Facing	Interior Sheathing and Vapor Retarder
1	a	Manufactured Stone	2 layers felt paper	none	2x4 w/ OSB	**R-13 Kraft faced Batts**	The interior surface of all wall specimens was sheathed with ½-inch gypsum board finished with a primer plus two rolled-on coats of latex paint.
	b					**R-13 Unfaced Batts**	
2	a	Stucco	2 layers felt paper	none	2x4 w/ OSB	**R-13 Kraft faced Batts**	
	b					**R-13 Unfaced Batts**	
3	a	**Cedar Siding Solid Planks** over ¾" furring @ 16" oc	House wrap w drainage plane	none	2x4 w/ OSB	R-13 Kraft Faced Batts	
	b	**Cedar Siding Finger-Jointed Planks** over ¾" furring @ 16" oc					
4	a	Vinyl Siding w/2x4 framing	House wrap	none	2x4 w/ OSB	**R-13 Batts Kraft faced Batts**	
	b					**R-13 Batts Unfaced Batts**	
5	a	Brick	House wrap & 1" Air Gap	none	2x4 w/ OSB	**R-13 Batts Kraft faced Batts**	
	b					**R-13 Batts Unfaced Batts**	
6	a	Fiber Cement Siding	House wrap	none	2x4 w/ OSB	**R-13 Batts Kraft faced Batts**	
	b					**R-13 Batts Unfaced Batts**	
7	a	Vinyl Siding	**House wrap w drain. plane**	1" (R-5) XPS Rigid Foam	2x6 w/ OSB	R-21 Kraft Faced Batts	
	b		**Taped foam joints**				
8	a	Vinyl Siding	House Wrap	none	2x6 w/ OSB	**R-21 Batts Kraft faced Batts**	
	b					**R-21 Batts Unfaced Batts**	
9	a	Vinyl Siding	**House wrap w drain. plane**	1" (R-5) XPS Rigid Foam	2x4 w/ OSB	R-13 Kraft Faced Batts	
	b		**Taped foam joints**				

Note: Bold type indicates a variation in the wall panel construction between (a) and (b) subcategories.

Summary

- A combination of three variable can cause sustained high MC:
  - High interior RH
  - High perm vapor retarder
  - Air leakage (further study)
- 1" XPS has a marginal impact on OSB MC in walls with vinyl siding and interior Kraft vapor retarder in Climate Zone 4.

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FG Batts: Faced vs. Unfaced in CZ 4

Summary

- Walls with and without exterior foam showed OSB drying in the spring at a similar rate regardless of use of foam on the exterior.
- Walls with Kraft paper are less sensitive to int RH.
- Int RH is a critical factor walls with painted gypsum as the only interior vapor retarder.

Appendix E (Samuel Glass)

Simulated and Measured OSB MC in CZ 4 Wall Assemblies

Simulated and measured OSB moisture content in Climate Zone 4 wall assemblies

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Advanced Housing Research Center
Forest Products Laboratory
Madison, Wisconsin

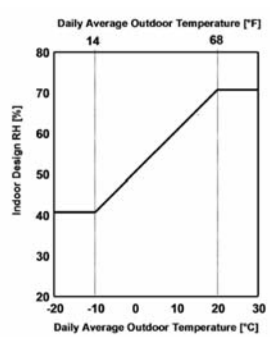
Sam Glass
U.S. Forest Products Laboratory

Building America Expert Meeting | 12 May 2014

Overview

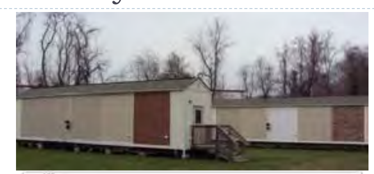
- Do WUFI simulations capture measured OSB wetting and drying trends?
- Emphasis on
  - OSB moisture response to design indoor humidity levels
  - N vs. S wall orientation
  - Kraft vapor retarder vs. latex paint alone
- Not a model validation effort
- No intentional air leakage or liquid water injection

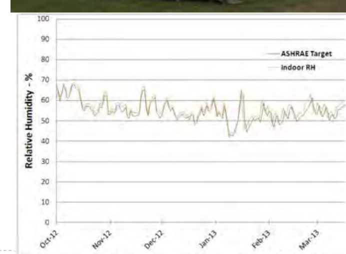
Indoor humidity levels



ASHRAE Standard 160-2009 Indoor Design Humidity, Simplified Method

Indoor humidity levels





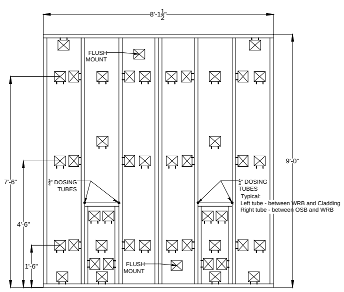
Simulation boundary conditions

- On site measured conditions when available
  - Indoor temperature and RH
  - Outdoor temperature and RH
  - Wind speed
  - Wind direction
  - Solar radiation
- Rainfall data taken from nearest weather station (Andrews Air Force Base, ~10 miles)

Material hygrothermal properties

- WUFI 5.2 North America database for most materials
- Adjusted certain materials using measured properties:
  - Gypsum board/primer/two coats latex paint: **35 US perms**
  - Asphalt-coated Kraft paper: RH-dependent curve based on dry-cup (0.6 perm) and wet-cup (1.0 perm)
  - Extruded polystyrene: 1 perm at 1 inch thick
  - Manufactured stone veneer: thickness, density, and vapor permeability curve based on measured values
  - Cedar siding: thickness, density, and vapor permeability curve based on measured values

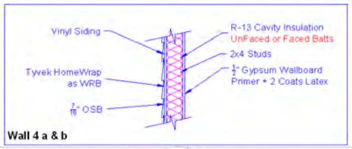
Measuring OSB moisture content



Moisture content sensor uncertainty

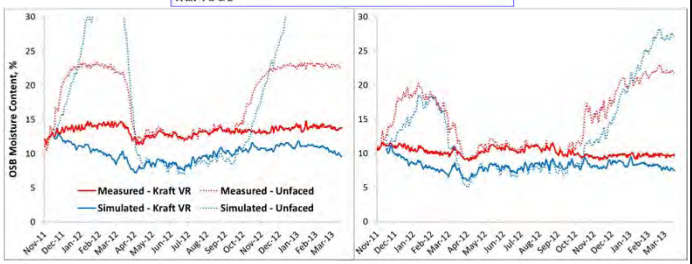
- Sensors were calibrated against gravimetric OSB moisture content in the lab
- 95% confidence band from calibration (depends on MC):
  - ±2% MC at 7% MC
  - ±1.5% MC at 15% MC
  - ±2.5% MC at 25% MC
- Sensors max out at about 25% MC
- Multiple sensors within the same assembly were averaged
- Variation from average was typically ±0.5% to ±1.5% MC

2x4, Vinyl siding



North-facing

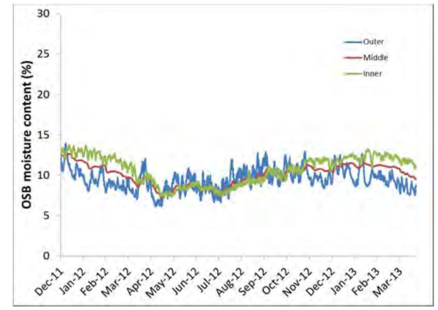
South-facing



 Simulated and measured OSB MC

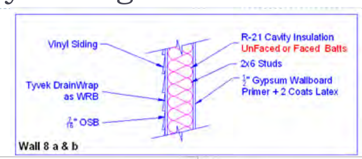
2x4, Vinyl siding

North-facing wall with Kraft VR



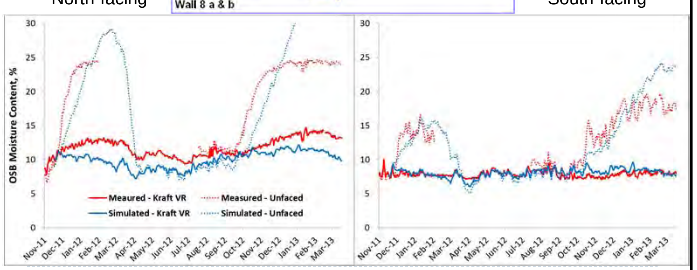
 Simulated and measured OSB MC

2x6, Vinyl siding



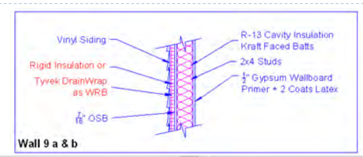
North-facing

South-facing



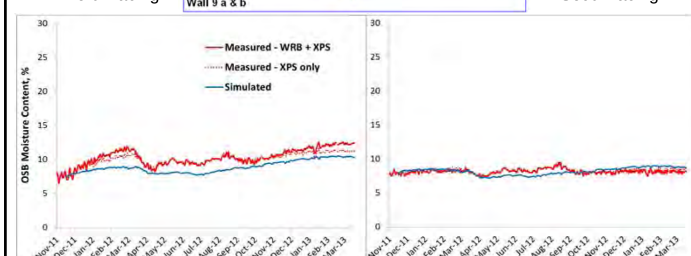
 Simulated and measured OSB MC

2x4 + XPS, Vinyl siding



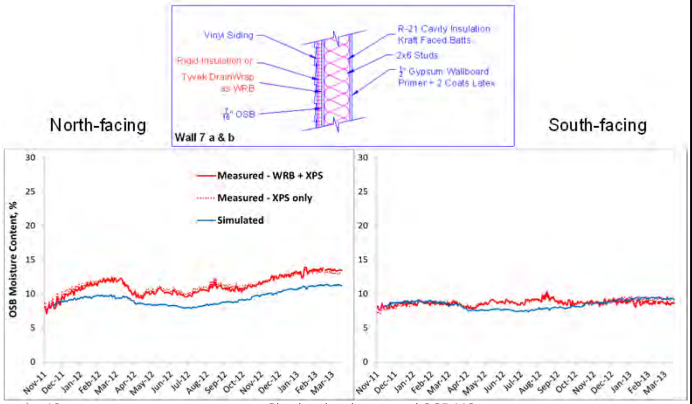
North-facing

South-facing



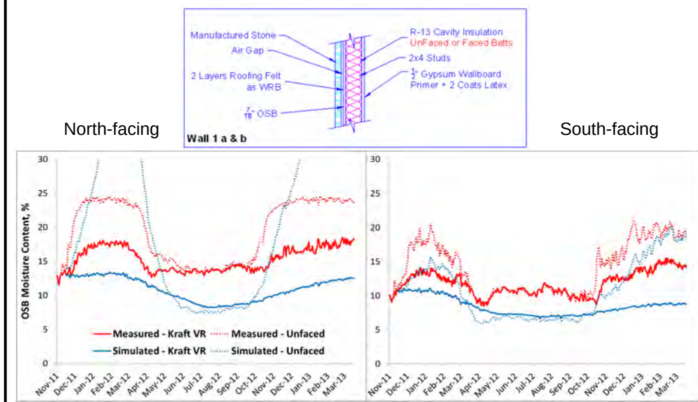
 Simulated and measured OSB MC

2x6 + XPS, Vinyl siding



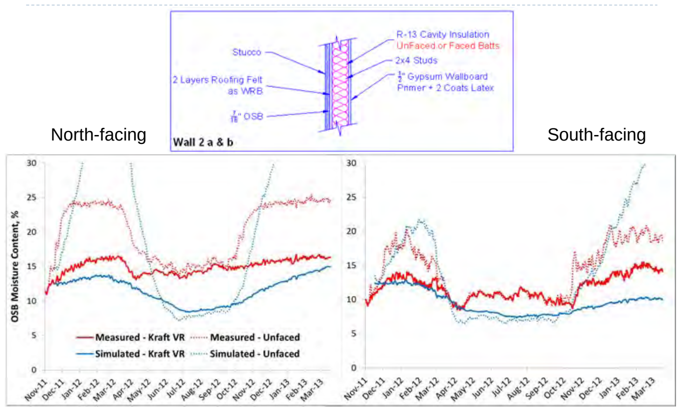
13 Simulated and measured OSB MC

2x4, Manufactured stone veneer



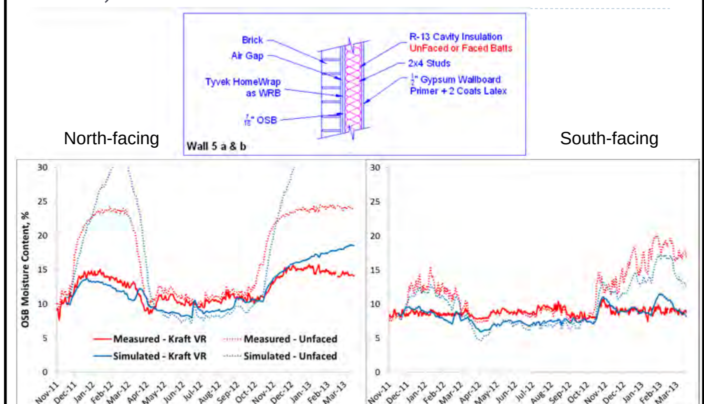
14 Simulated and measured OSB MC

2x4, Stucco



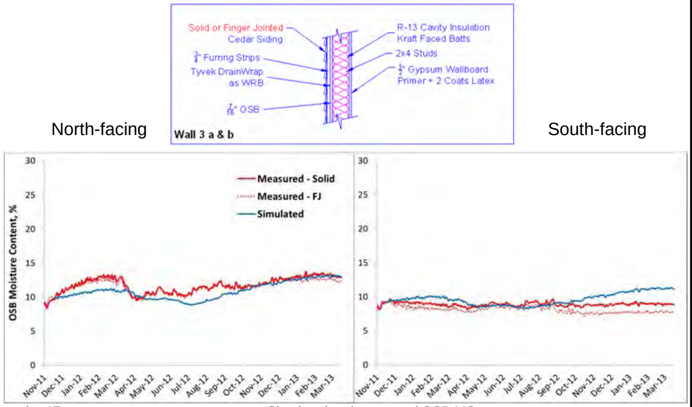
15 Simulated and measured OSB MC

2x4, Brick veneer



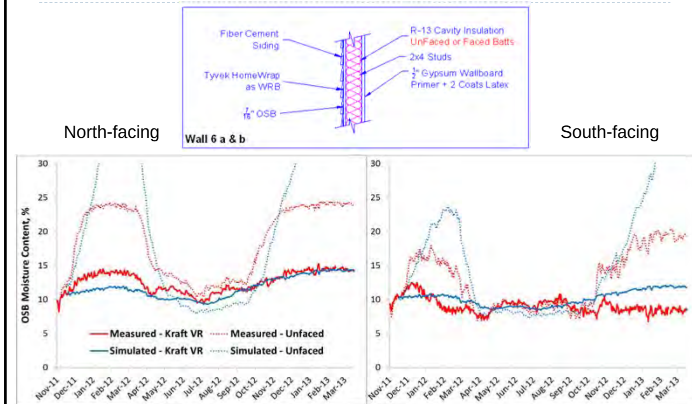
16 Simulated and measured OSB MC

2x4, Cedar siding



17 Simulated and measured OSB MC

2x4, Fiber cement siding



18 Simulated and measured OSB MC

Summary of trends

- High interior humidity levels → significant moisture accumulation in walls without interior Kraft vapor retarder, particularly north-facing walls
- Moisture accumulation not significant in walls with interior Kraft VR
- R-5 exterior XPS has marginal impact on moisture content of OSB sheathing in walls with vinyl siding and interior Kraft VR in Climate Zone 4A
- Simulations capture general timing of seasonal increase and decrease in OSB MC
- Simulations tend to under-predict OSB MC during summer, particularly for stucco and manufactured stone veneer
- Simulations tend to under-predict OSB MC during winter for same cladding types with interior Kraft VR

19 Simulated and measured OSB MC

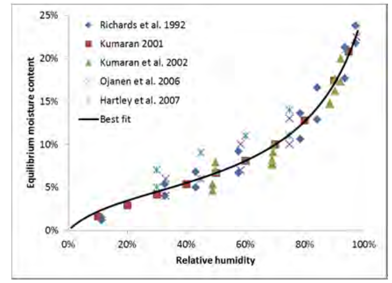
Further parametric modeling

- 10 different assemblies in CZ4
- Performance categories:
  - Drying capability (from high initial MC)
  - Ability to survive wind-driven rain penetration
  - Avoidance of air leakage moisture accumulation
  - Avoidance of vapor diffusion moisture accumulation
- Glass, S.V. 2013. Hygrothermal analysis of wood-frame wall assemblies in a mixed-humid climate. Research Paper FPL-RP-675. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. www.fpl.fs.fed.us

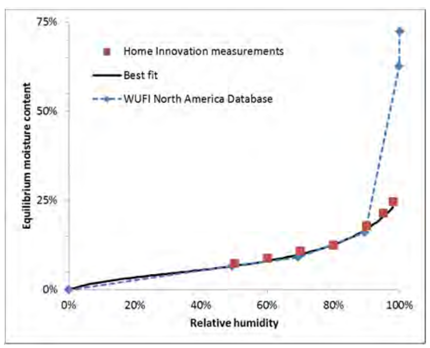
20 Simulated and measured OSB MC

Additional info

OSB sorption isotherm data from literature



OSB sorption curve: WUFI



Appendix F (Achilles Karagiozis)

What is WUFI?—The Building Science Tool

BUILDING SCIENCE INSIGHTS
Physics to the Field™

What is WUFI ? - The Building Science Tool

Building Science Group, Sustainability
Owens Corning

Achilles Disclaimers

WUFI is just a **tool. It is as smart and knowledgeable as the user.**

WUFI is a damn **great tool. It is the best tool that exists for hygrothermal analysis.**

WUFI allows a engineer to do comparatively analyze different building science designs

Translation is always needed between wall installed and wall designed

Education - Education - Education is needed

Purpose of tools ?

- Research (Expand Building Science Field) (Validation)
- Education (As Chris mentioned Radiation too difficult for even Master Degree folks)
- Forensic Studies (Understand the past)
- Design (Design is not field comparison.. Guidance is provided with a safety factor)
- Not take away the bread and butter of uncomputerized experts

Perfect World

WUFI exists

All Interior ... ed

...oads properly used

All durability index criteria known

All material properties known

A perfect SPC 160

But the world is not perfect, Designs need to be evaluated and the world is not going to stop or go backwards

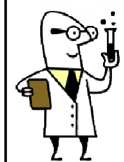
Famous PhD Recommendation

Another Disclaimer **2000**

- Experimental work determining quasi-steady state interstitial air pressures and leakage regimes could be coupled with enhanced heat, air and moisture (HAM) analytical models enhancing the predictability and accuracy of the analytical models. Linking a network model such as CONTAM96 with a moisture model such as WUFFI or MOIST should be possible. CONTAM96 could be modified to contain a numeric module for apportioning leakage areas (as previously described) and also be configured to address interstitial air pressure fields. In this manner CONTAM96 could be used to provide the inputs of leakage areas and pressures to WUFFI or MOIST.

WUFFI

What is Building Science ?



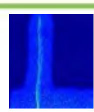
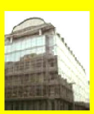
Building Science uses the fundamental laws of physics to understand the response of a component or whole building to exterior or interior conditions.

Building **S**cience deals with:

- Thermal Flows
- Moisture Flows
- Air Flows
- Acoustics
- Fire
- Durability

WUFI Software

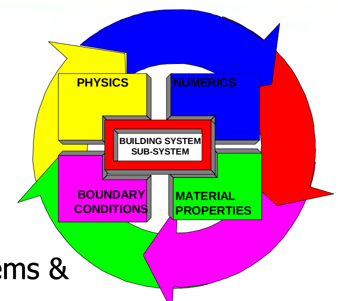
Scales/Levels in Building Physics

Material		Heat, Air, Moisture Transport in Porous Materials	Durability
Building Envelope		Systems, Air Flow, Joints, Ventilation, PV	Energy Efficiency Moisture Control
Building		Inter, Intra Zonal air Transport	Indoor Air Quality Thermal Comfort Energy Consumption
Built Environment		Wind, Rain	Wind Comfort, Wind Energy Polutant Dispersion

Building Science Approach

Building Envelope

- Define Physics
- Define Load Inputs
- Define Material Response
- Define Construction Systems & Sub-Systems



Overview of Models and Codes

Model Name	Capability	Country
WAND	1D Heat-Moisture	BELGIUM
KONVEK	3D Heat+Air+Moisture	
GLASTA	1D Heat+Moisture	
NATKON	2D Heat+Air	
HYGRAN 24	1D Heat+Air+Moisture	
HAM	1D Heat+Air+Moisture	
HMSOLVER	2D Heat+Moisture	
HAMPI	1D Heat+Moisture	CANADA
WALLDRY	1D Heat+Air+Moisture	
WALLFEM	1D Heat+Air+Moisture	
EMPTEDD	1D Heat+Air+Moisture	
LATENITE	2D Heat+Moisture	
MATCH	1D Heat+Moisture	DENMARK
TRATMO2	2D Heat+Air+Moisture	FINLAND
TCCC2D	2D Heat+Air+Moisture	
LTMB	1D Heat+Moisture	FRANCE
CHEoH	2D Heat+Moisture	
TONY	2D Heat+Moisture	
V30	1D Heat+Moisture	
V320	2D Heat+Moisture	
WFTK	1D Heat+Moisture	GERMANY
WUFIZ	2D Heat+Moisture	
JOKE	1D Heat+Moisture	
COND	1D Heat+Moisture	
DIM.5	2D Heat+Air+Moisture	
HYGTHERAN	1D Heat+Moisture	ISRAEL
HYGRO	1D Heat+Moisture	HOLLAND
WISH-3D	3D Heat+Air	
HORSTEN	2D Heat+Air+Moisture	

Model Name	Capability	Country
P1200A	1D Heat+Moisture	SWEDEN
VADAU	2D Heat+Moisture	
AHCONP, ANHCONP	2D Heat+Air	
FUNKT 74.6	1D Heat+Moisture	
ID-HAM	1D Heat+Air+Moisture	
NEV 3	1D Heat+Moisture	SLOVAKIA
BRECON 2	1D Heat+Moisture	U.K.
MOIST	1D Heat+Moisture	USA
FSEC	2D Heat+Air+Moisture	

IEA Annex 24

Need by Architects & Engineers

- Design tool did not exist for North America
- Research tool existed at NRC
- Nothing available to address
  ASHRAE Design Methodology
- Real loads
- Easy to use
- Streamlined Set by Step Approach
- Validated and Upgraded
- Support and Commercial
- Allow innovations in Building Design Options

Past Approach

Trial and Error

Attention to Detail
but
Little Building Science

Worked until:

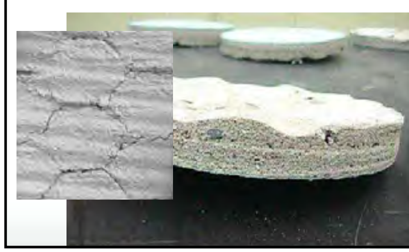
- Enhanced Comfort Requirements
- Energy Conservation
- Material started to Change

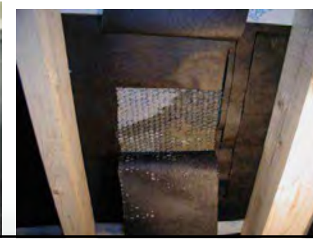
Wood has Changed

What used to be ?

Stucco has changed

Building Papers have changed





System Design Process

1) One needs to design the **system** first.
2) To design the system for proper performance, one needs to understand the LOADS
3) If one underestimates the loads, also material can fail
4) System failed. Design Inadequate

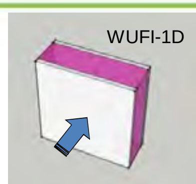
WUFI-1D

WUFI Initials means: **Thermal und Moisture Instationary**

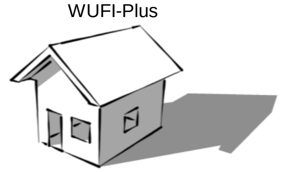
1. It is a hygrothermal model.
2. It is a transient model.
3. Predicts thermal and moisture distribution.
4. Deals with vapor transport, liquid transport.
5. All three phases are present (phase changes).
6. Includes the thermal and moisture capacity
7. Includes the Biohygrothermal damage model
8. Includes the U-value (T, moisture)

WUFI Family of Software

- WUFI-1D
- WUFI-2D
- WUFI-Plus, WUFI-Passive
- Main focus on moisture performance



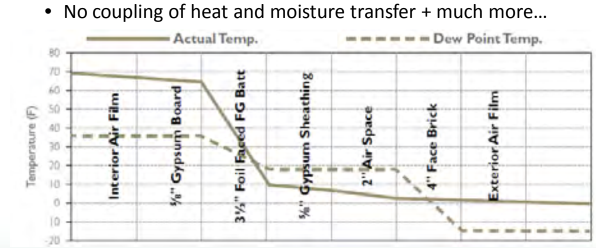
WUFI-Plus



Old Method to Design for Moisture

- Dew Point Method
  - Limits:
    - Only steady-state behavior
    - Only diffusion
    - No heat and moisture storage
    - No coupling of heat and moisture transfer + much more…

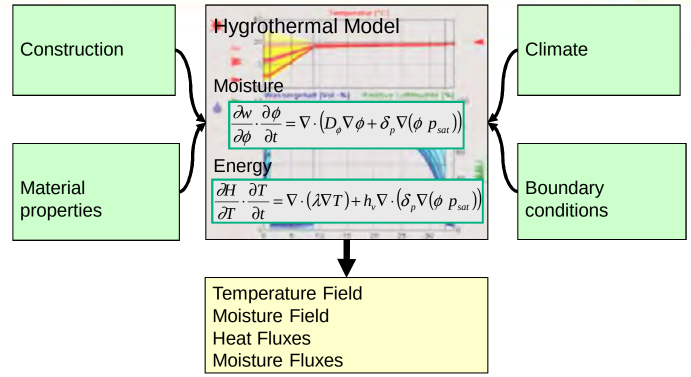
No more recommended by ASHRAE



State-of-the-Art Hygrothermal Modeling

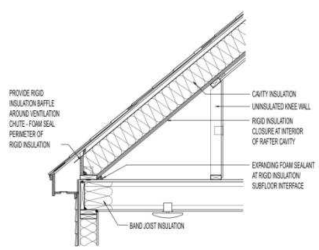
- Dynamics
  - Thermal and moisture storage
  - Hourly calculations
- Material properties
  - Detailed functions, not constants
- Realistic events modeled
  - Solar radiation, Sky radiation
  - Rain, water absorption or intrusion via defects
  - Ventilation of cavities
- Weather and Indoor Climate
  - Hourly data

Models



Construction – From Drawings to Inputs

- Determine
  - Boundaries
  - Exposure and environmental conditions
  - Sub-systems
- Select properties
  - Built-in material database
  - Product specific
    - OC products being tested in detail



Boundary Conditions – Weather/Indoor

- Hourly and location specific weather data
  - Temperature, Humidity, Wind, Solar/Counter radiation, Rain
- Moisture Design Reference Year
  - Different than average energy year
  - Provide safety margin
  - Likelihood of weather being worse <10%
- Indoor Conditions
  - Moisture loads

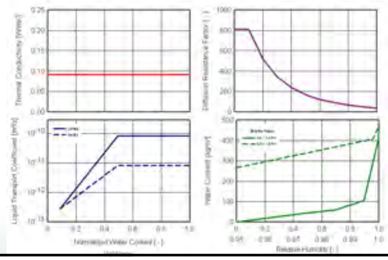
Material Properties

Material : Oriented Strand Board

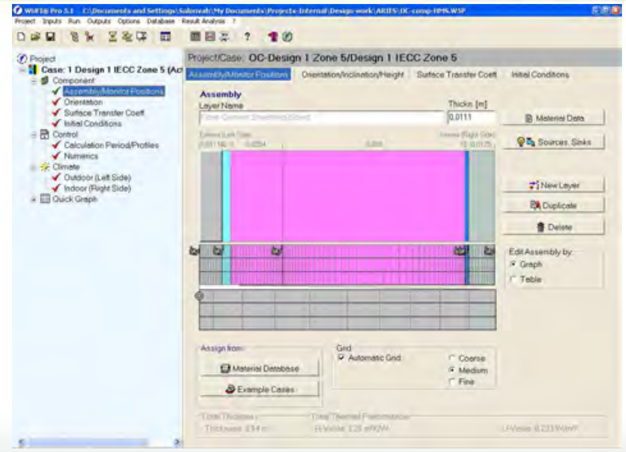
Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	650,0
Porosity	[m³/m³]	0,95
Specific Heat Capacity, Dry	[J/kgK]	1880,0
Thermal Conductivity, Dry ,10°C	[W/mK]	0,092
Water Vapour Diffusion Resistance Factor	[-]	812,8
Reference Water Content	[kg/m³]	83,3
Free Water Saturation	[kg/m³]	470,0
Water Absorption Coefficient	[kg/m²s^0.5]	0,0022
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0,0002

Critical material properties are not constants



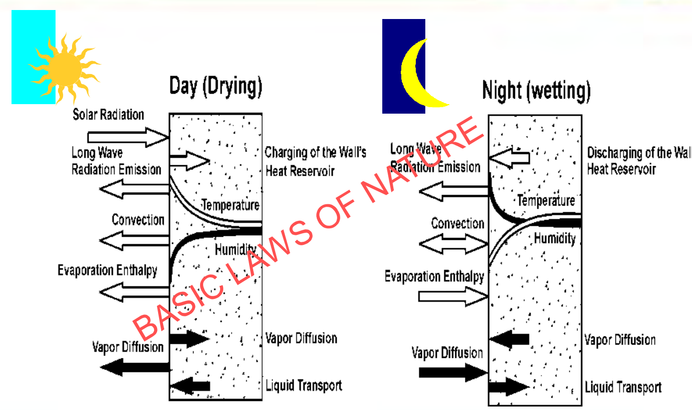
Model Setup - Wall



Modeling Scenarios

- **Sensitivity analyses**
  - Optimized solutions
    - Vapor Retarder options
    - Sheathing Permeance
  - **New energy code requirements**
    - Shingles solar absorptivity
    - Higher R-values
    - Air tightness
- **Impact of environment on performance (probabilistic approach)**
  - Weather/Climate
  - Indoor loads

Hygrothermal Transport



WUFI-1D

WUFI-1D been configured to follow ASHRAE Standard 160. Was customized for USA Designers

It is the **USA Industry Standard for design**

It is the only way you can add a Safety factor to your design

WUFI Development

- Fraunhofer Institute in Bauphysics and Oak Ridge National Laboratory
- Two versions of the software -**Free Version** downloadable from ORNL site: see next page
- **Commercial version** with Fraunhofer support
- Search **WUFI ORNL**
- **Excellent** Help System, & WUFI Forum
- ***Validated with over 100 field monitored wall systems in North America***

What is the Challenge ?

- 4 People worldwide can solve (Heat, Air & Moisture) in building applications
- Very complex numerical integration code + solvers
- Phase Changes and moving front
- Highly anisotropic problems

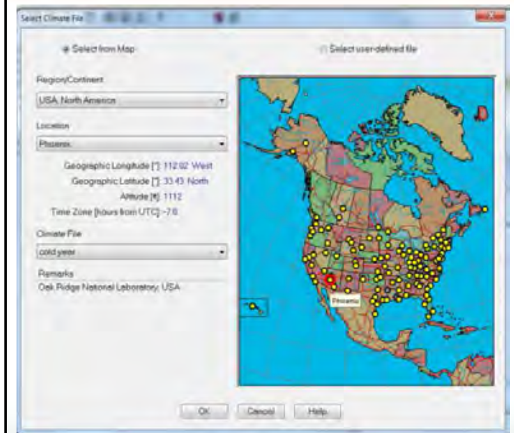
Little Known Fact

- US Code changes in Vapor Retarders were performed by ORNL and Building Science Corporation between 2004 to 2007.
- Over 5000 WUFI simulations were performed for a wide range of wall systems and climate zones.
- WUFI results enabled the IECC then to have the most advanced VR code anywhere in the world.

http://web.ornl.gov/sci/ees/etsd/btric/wufi/

Free education version with full capability

Exterior Loads

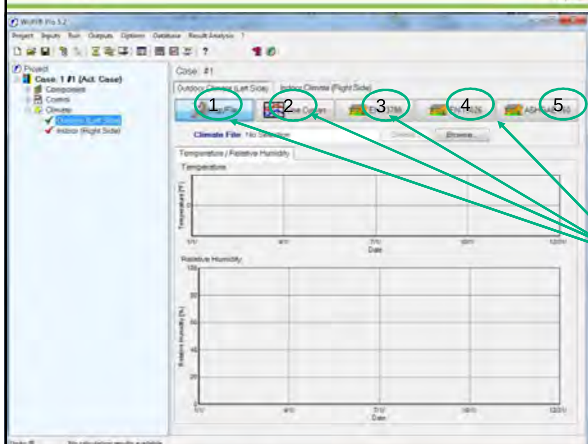


Hourly data

105

Exterior Climate Locations

Interior Loads

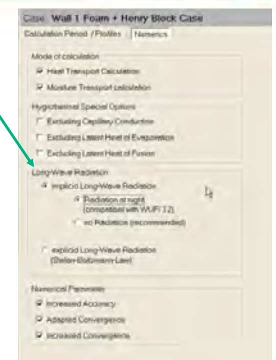


Interior Climate

5 additional Hourly Options

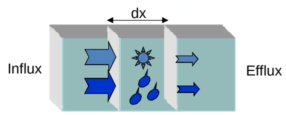
Radiation Transport

- **Night Sky Radiation**



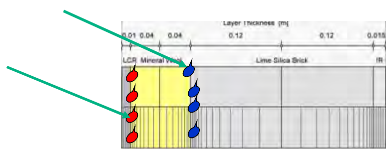
SPC 160 P Sources & Sinks

- Includes impact of sources & sinks
  - Examples



$$\frac{\partial}{\partial t} A = -\vec{\nabla} \cdot \vec{a} + \text{Sources / Sinks}$$

Moisture



Post-Processing

- Courses
- Profiles
- Animations

- Bio-model/Mold growth
- Corrosion
- Freeze-Thaw Cycles

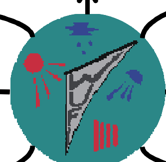
Interpretation of Results

Transfer to different climate zone

Different types of indoor environment

Extrapolation (long-term behavior)

Development and optimization of building products



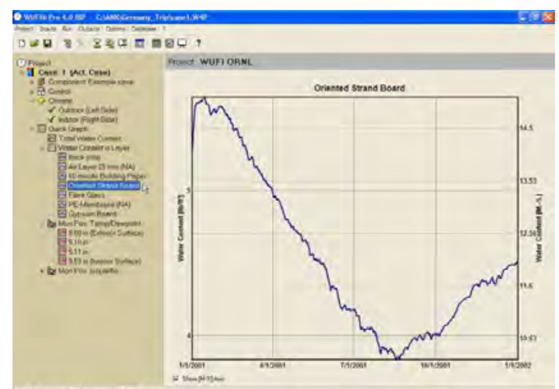
Hygrothermal loads (Wetting/Drying, Moisture Content)

Microbial growth (mold / algae)

Corrosion

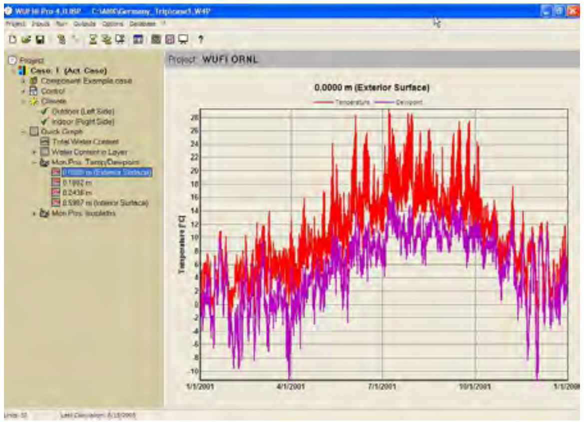
Frost damages

Valuable Plots



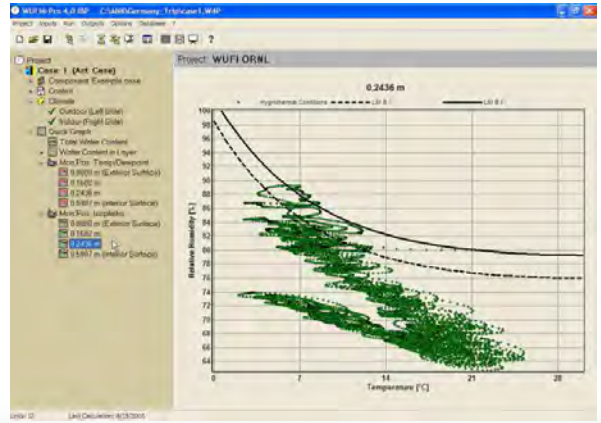
Water Content

Not valuable plots



Dew Point T

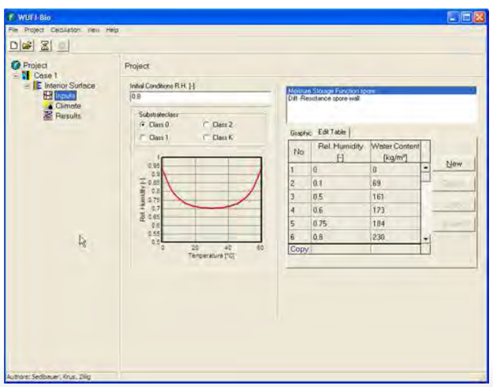
Valuable Plots



Isopleth Data

ADDITIONAL FEATURES

- **WUFI BIO Model**

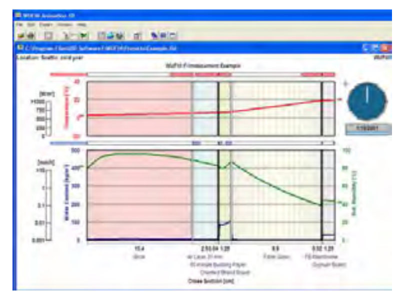


ADDITIONAL FEATURES

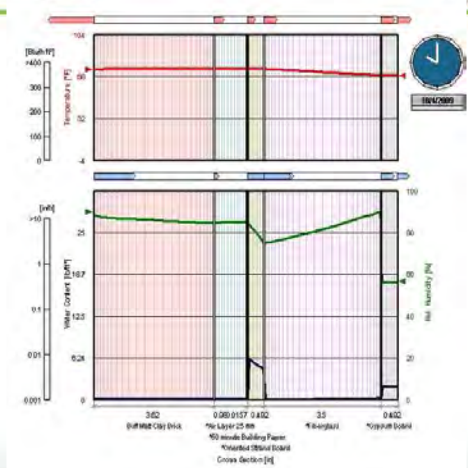
- **NEW WUFI ANIMATION PROCESSOR**

  FEATURES

  - **Zoom in-out**
  - **Backward transient**
  - **New Extracting**
  - **New Properties**
  - **Create *avi movies**



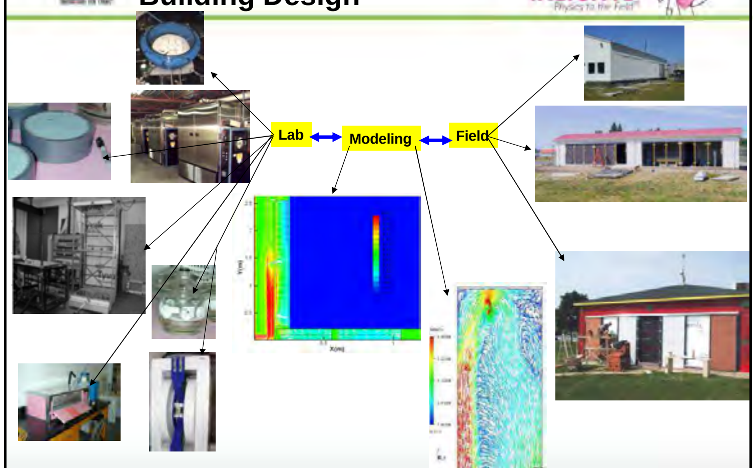
Animations



2012 BuildingGreen Award

- **BuildingGreen** made a modeling software one of our Top Ten Products for the first time - the WUFI hygrothermal modeling software from Fraunhofer IBP and Oak Ridge National Laboratory (http://www2.buildinggreen.com/buildinggreens-top-10-products-2013)

Most Tested Software in Building Design



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Standards and Guides in NA

ANSI / ASHRAE Standard 160-2009:
"Criteria for Moisture-Control Design Analysis in Buildings"

PURPOSE

The purpose of this standard is to specify performance-based design criteria for predicting, mitigating or reducing moisture damage to the building envelope, materials, components, systems and furnishings, depending on climate, construction type, and HVAC system operation. These criteria include:

(a) criteria for selecting analytic procedures

(b) criteria for inputs, and

(c) criteria for evaluation and use of outputs.

Standards and Guides in NA

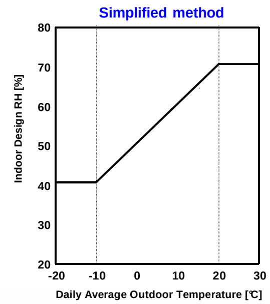
ANSI / ASHRAE Standard 160-2009:

Exterior climate
- **data from 10 consecutive years or moisture reference year**

Interior humidity

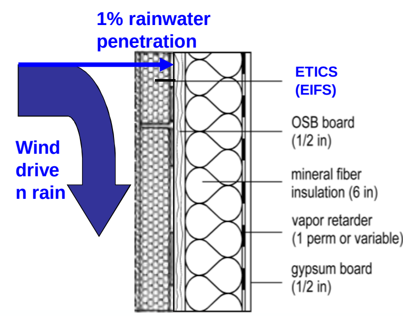
$$p_{indoor} = p_{outdoor} + \frac{cQ_{source}}{VI}$$

P_{indoor}= indoor vapor pressure, Pa
$P_{outdoor}$= outdoor vapor pressure (24h)
c = 1.36·10^5 Pa·m³/kg
Q_{source}= moisture generation rate, kg/s
V= building volume, m³
I = air change rate, s^{-1}



ANSI / ASHRAE Standard 160-2009:

Safety feature: moisture tolerance – drying potential



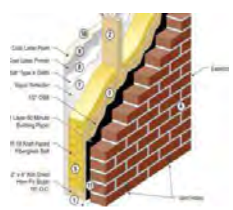
Rainwater penetration:
In the absence of specific full scale test methods and data for the considered exterior wall system, the default value for water penetration through the exterior surface is 1% of the water reaching that exterior surface. The deposit site for the water shall be the exterior surface of the WRB. If a WRB is not provided then the deposit site shall be described and a technical rationale shall be provided.

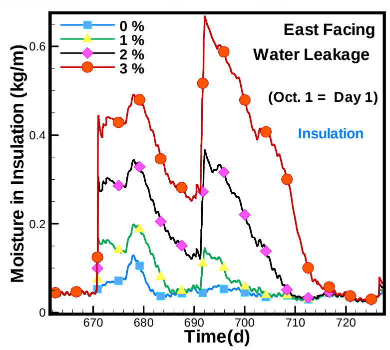
EXAMPLE Source & Sinks

- **Example**

Three levels

Water Penetration

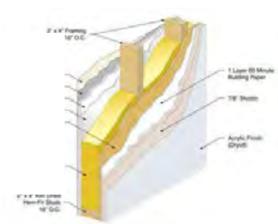


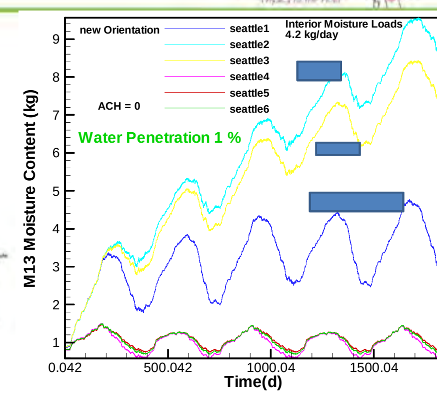


EXAMPLE Source & Sinks

- **Example**

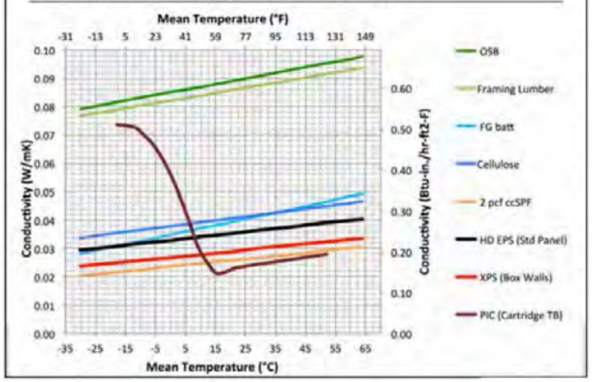
Effects of Vapor Retarder Strategy





Thermal Performance

Realistic Temperature Range



What does this Mean ?

Can WUFI include This information

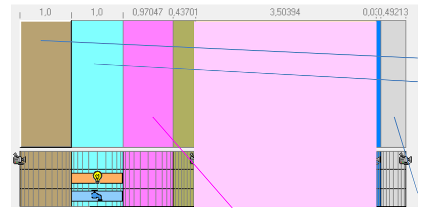
?????

Building Science Corporation Measurements

More…..

Brick Wall with R5 (XPS) exterior insulation

Outside



Inches

Layers from Outside
- -Brick
- -Air
- -XPS
- -OSB
- -Fiberglas
- -Vapor retarder
- -Interior Gypsum Board

Inside

All assemblies to be simulated:

Brick – R5;	Brick – R7.5;	Brick – R10;	Brick – R15
Vinyl– R5;	Vinyl– R7.5;	Vinyl– R10;	Vinyl– R15

→ All 8 cases are simulated once with XPS and once with Polyiso

→ total amount of simulation per city = 16

50

1D comparison – heat flux through a single wall

Input parameters for the 1D simulations
→ Further input parameters

- Simulation period = 2 years → average values are used for comparison
- Inclination = 90°
- Driving Rain coefficients = low (short building)
- Orientation = North → extreme cases for cold temp. (low sun irradiation)
- Initial relative humidity of materials = 80%
- Initial temperature of materials is 68°F

- Weather file type used = Ashrae Year 1

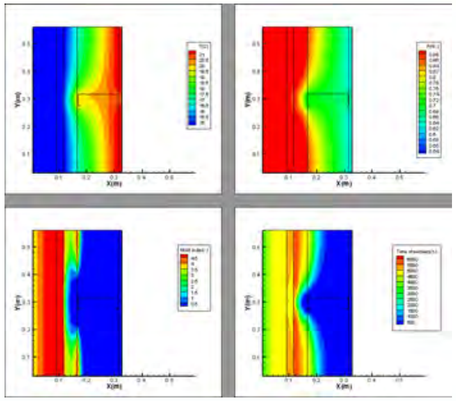
- Thickness of exterior insulation layer is always adapted to the R-value
→ XPS and Polyiso layer have always the same R-value but do not have the same thickness!!!

Comparison of all Cities

Cities	Savings with XPS in Comparison to PIR [% of Btu/sqft*a]
	Average
Albuquerque	7,61%
Atlanta	5,17%
Baltimore	7,32%
Bismarck	14,98%
Boulder	10,95%
Burlington	10,98%
Calgary	17,52%
Chicago	14,22%
Elko	12,68%
Fairbanks	21,45%
Honolulu	-7,38%
Houston	1,65%
International Falls	19,55%
Key West	-5,60%
Miami	-5,69%
Minneapolis	15,96%
Sacramento	-1,35%
San Francisco	-4,58%
Seattle	1,93%
Toronto	13,21%
Tucson	-3,52%
Vancouver	4,24%

2D Contours

T	RH
Mold	TOW



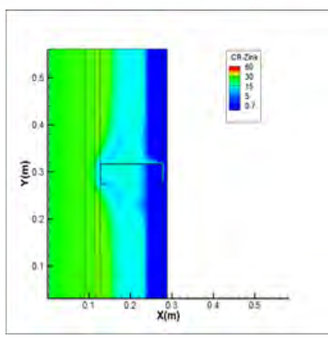
Corrosion

- Time Of Wetness (TOW)
  - Accumulated time at conditions when
    - Temperature >32F
    - Relative Humidity >80%
  - ISO 9223 Corrosion Standard
    - Corrosion rates based on industrial pollution and TOW

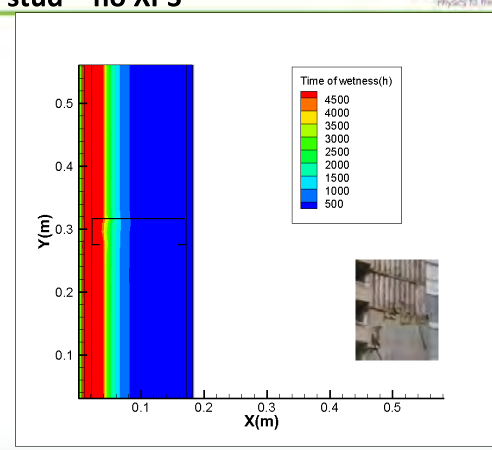
ISO 9223:1992 (E) Corrosion of metals and alloys – Corrosivity of atmospheres – Classification. www.iso.org

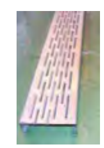
Corrosion Rate

- ½" XPS
- Corrosion rate for zinc (g/m^2a) as a function of
  - Time of Wetness
  - Industrial pollution by sulfur dioxide (SO2 Concentration P_c=12 mg/m^3) and
  - Airborne salinity (Chloride deposition rate= 60 mg/m^2d).



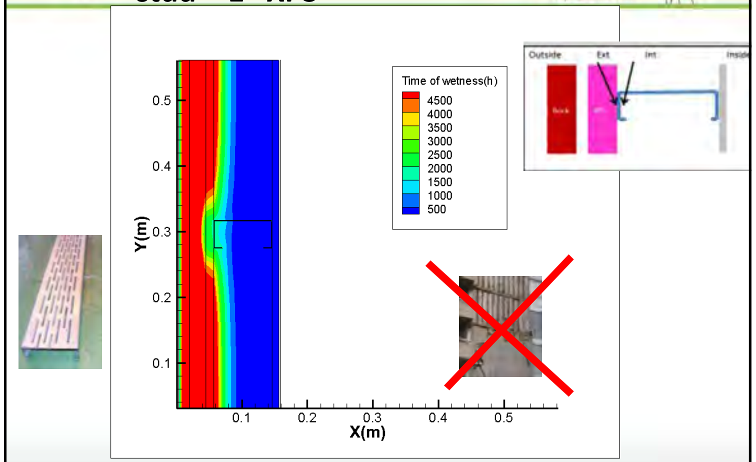
Thermally broken steel stud – no XPS



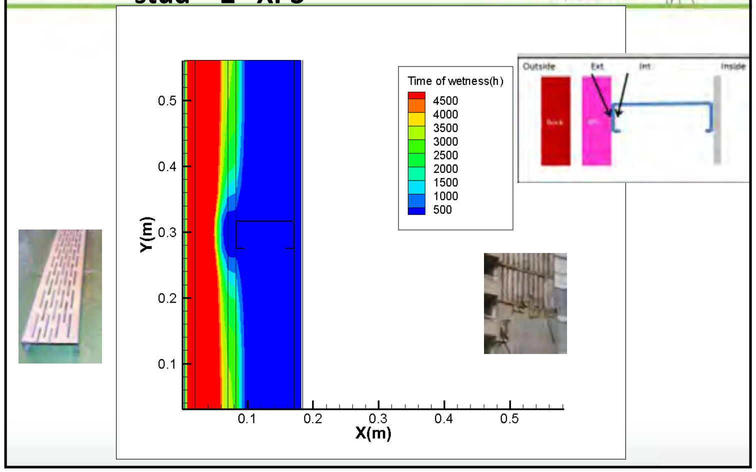


Slotted web to reduce thermal bridging – Thermally equal to wood stud

Thermally broken steel stud – 1" XPS



Thermally broken steel stud – 2" XPS



Mold Growth Model

Two mold growth estimation methods

1. Viitanen model (Technical Research Center of Finland)
   - Refined for material classes
     - Very sensitive (wood)
     - Sensitive
     - Medium Resistant
     - Resistant (glass products)
2. Bio hygrothermal model (Fraunhofer Institute)

Material classes

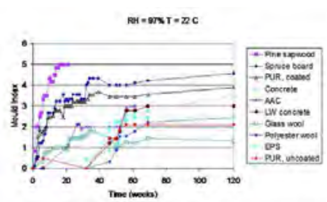
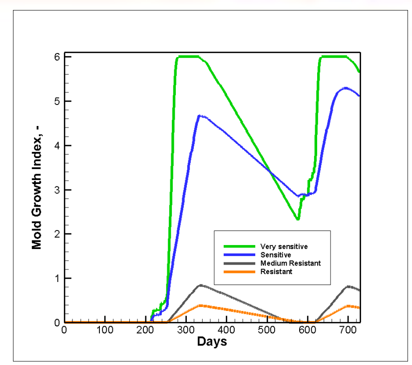


Figure 4 Monitored histories of mold index on the surface of different building materials under constant temperature and humidity conditions (+22°C, 97% RH). Mean values of nine samples.

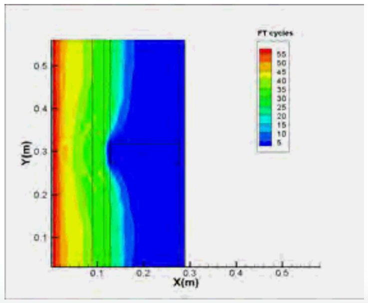
Mold Growth Classes

- Mold Growth as a function of time and material class
  - Very sensitive
  - Sensitive
  - Medium Resistant
  - Resistant



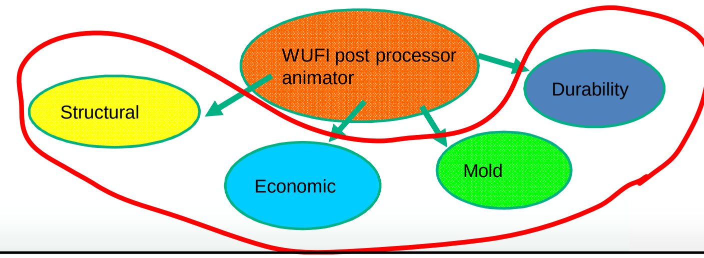
Freeze-Thaw cycles

- Insulating the wall lowers the temperature of the brick cladding
- Moisture in brick can go up, freeze-thaw effects can become critical



OPEN to THIRD Party DEVELOPERS

- **Structural Analysis**
- **Mold growth analysis**
- **Material degradation models (for each material)**
- **Economic analysis models**



Current - Future

- **Three new countries have been added as users of our Software**
  - **FINLAND**
  - **AUSTRIA**
  - **SWITZERLAND**
  - **FRANCE**
  - **NORWAY**
  - **JAPAN**
  - **POLAND**
  - **INDIA**

- **Major upgrades coming in 8 months**
- **We still have a lot to do and ALWAYS welcome & APPRECIATE your feedback**

WUFI your best friend Summary

- Hygrothermal Designs are not generic.
- Material properties are specific.
- DOE/ORNL /Fraunhofer provide a robust tool to Hygrothermal Designer/Builder (DOE Funding Critical to success).
- Valuable Educational Tool.
- Important decision making tool for critical performances especially for High Performance Envelopes (All WRB's are not the same, not all XPS are the same, Not all OSB's the same).
- Differentiation through performance design...

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About the Authors

Joseph Lstiburek, Ph.D., P.Eng. is a principal of Building Science Corporation, Westfords, Massachusetts. Joe is an ASHRAE Fellow and an internationally recognized authority on indoor air quality, moisture, and condensation in buildings. More information about Joseph Lstiburek can be found at www.joelstiburek.com.

Kohta Ueno is a Senior Associate at Building Science Corporation.

Direct all correspondence to: Building Science Corproation, 3 Lan Drive, Suite 102, Westford, MA 01886.

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