



*Just* **Smart** Solutions

## **Buildings XIII Workshop**

December 5th 2016

**Manfred Kehrler**

**Modern Hygrothermal Engineering  
Motivation, Basics, Examples**

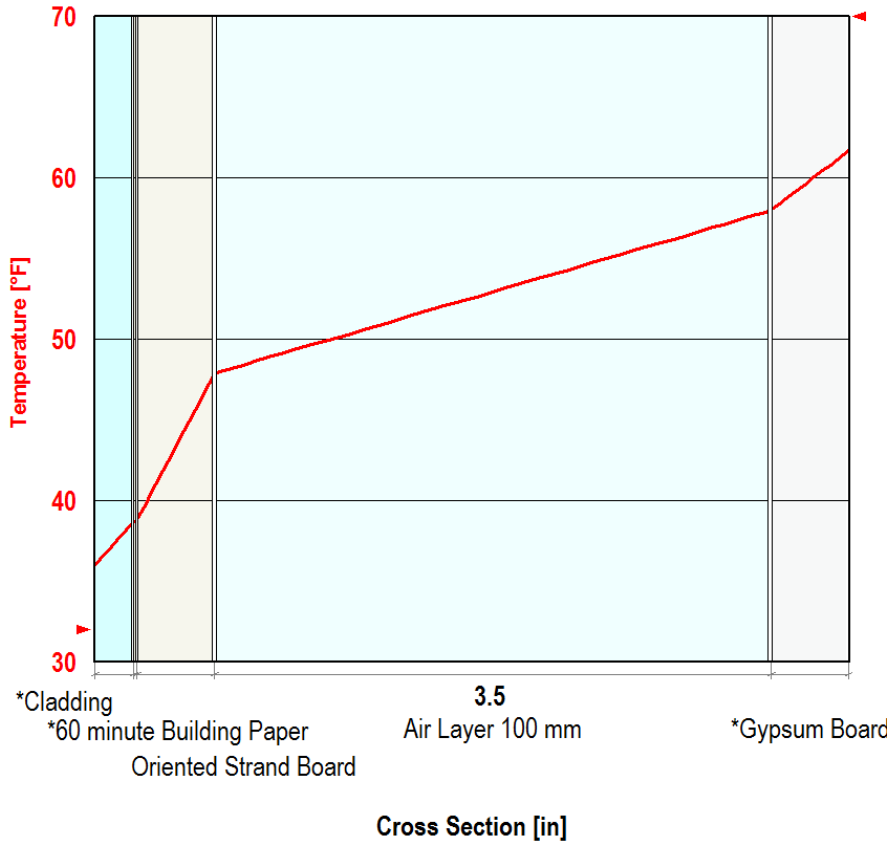
# Why Hygrothermal Engineering?



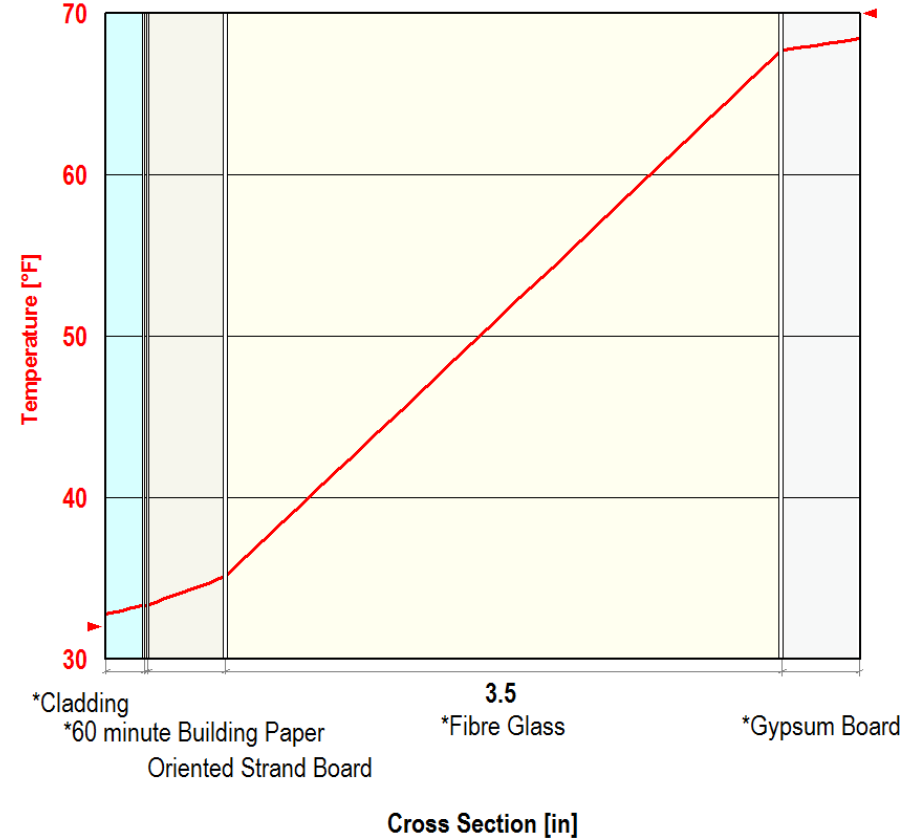
The Price of Energy Efficiency

# Impact of Thermal Insulation on Moisture

## No Cavity Insulation



## Fibre Glass Insulation

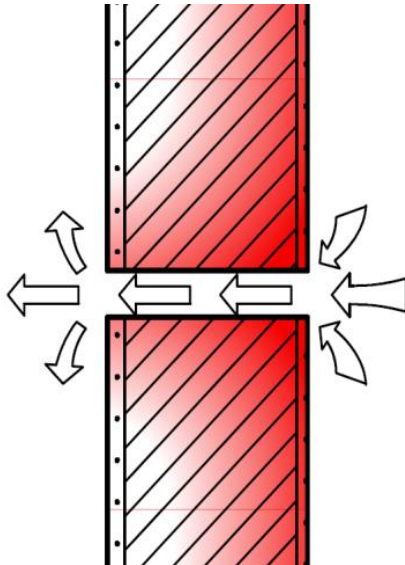


Higher Temperature Gradient has the result that cold spots are closer to warm spots ⇒ **Higher condensation risk in case air tightness is not 100%**

# Impact of Air Tightness on Moisture

Moisture transport due to air infiltration into the envelope

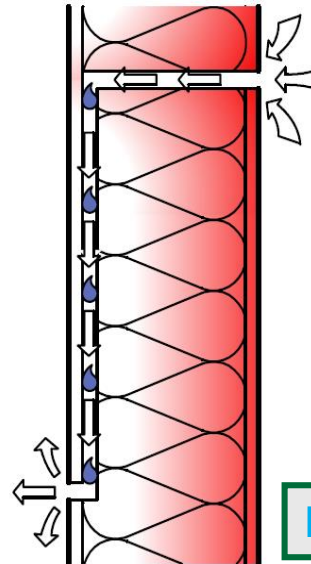
Not Air Tight



## Energy leak

Warming of the leakage area  
in case of strong air flux  
⇒ Only a little condensation

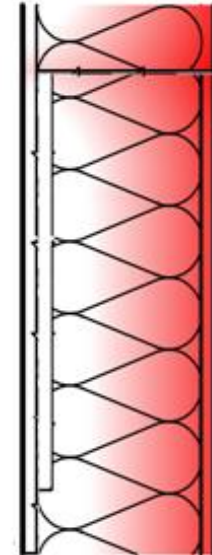
„Air Tight“



## Moisture leak

Cooling of the air in case of  
slow and tortuous air flux  
⇒ Much more condensation

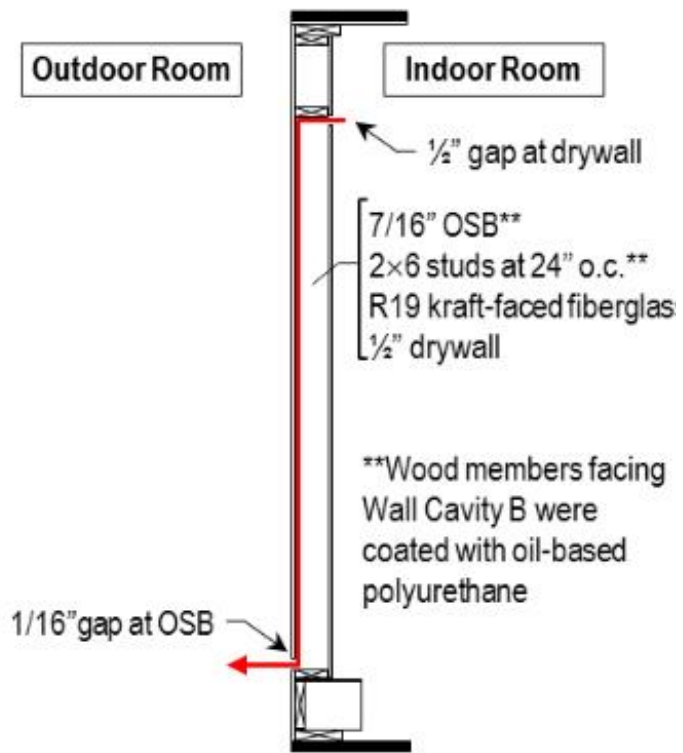
Air Tight



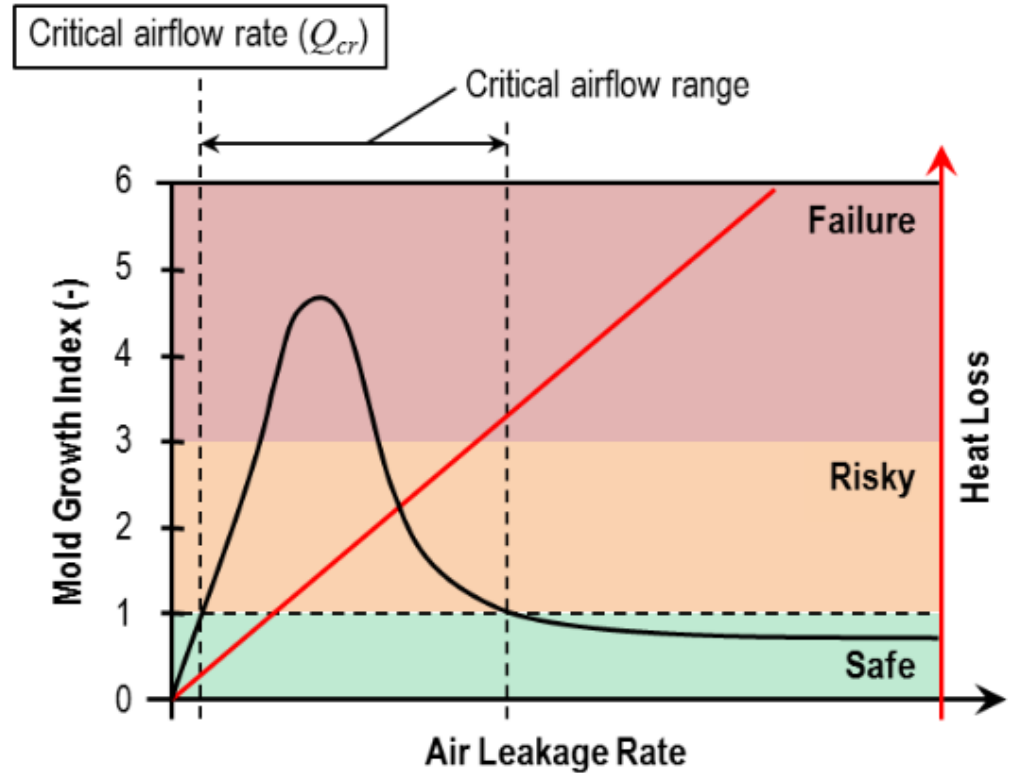
Good luck!

# Impact of Air Tightness on Moisture

## Result of ORNL studies about air flow



Airflow path through Wall Cavities A and B (cross section)



# Importance of Moisture

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ANSI/ASHRAE Standard 155-2009



## ASHRAE STANDARD

### Criteria for Moisture-Control Design Analysis in Buildings

Approved by the ASHRAE Standards Committee on January 24, 2009; by the ASHRAE Board of Directors on January 26, 2009; and by the American National Standards Institute on January 29, 2009.

This standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the standard. The change submital form, instructions, and deadlines may be obtained in electronic form from the ASHRAE Web site, <http://www.ashrae.org>, or in paper form from the Manager of Standards. The latest edition of an ASHRAE Standard may be purchased from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: [orders@ashrae.org](mailto:orders@ashrae.org). Fax: 404-321-5478. Telephone: 404-636-8400 (worldwide), or toll free 1-800-527-4723 (for orders in US and Canada).

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To meet needs of industry on how to predict moisture behavior

But:  
Has to be revised/improved in some particular points

# Importance of Moisture



# Importance of Moisture

## 3.14 Exterior Building Elements

Clearly conceived redundancy against water penetration

Must follow ASHRAE Standard 160

This section establishes design guidelines for exterior elements of the building. These may be individual materials, assemblies of materials, equipment, or assemblies of materials and equipment.

The A/E is responsible for specifying construction materials and systems appropriate to the final design that are lasting, provide enduring quality, and are maintainable.

Selection of construction materials with these factors is critical to building performance.

### Building Enclosure

The building enclosure is an environmental separator for thermal, moisture, air, acoustic, and daylighting properties, and also provides structural protection for blast, seismic, wind, and other hazards.

Since the building enclosure has a major impact on energy conservation and on blast mitigation, the A/E must coordinate all systems selection and design with the requirements in Chapter 4, Structural Engineering, for blast mitigation and Chapter 5, Mechanical Engineering, for building energy analysis.

Exterior wall assemblies must be designed to work in concert with HVAC systems to optimize energy performance. Envelope load criteria are described in ASHRAE 90.1.

### Moisture Control

Design of the above-grade building enclosure must be demonstrated early in the design process. ASHRAE 160, *Criteria for Moisture Control in Buildings* is an acceptable basis of design. Demonstration of the transient hygrothermal behavior of the various multi-layer building components for all critical building enclosure systems must be confirmed through modeling.

Design against water penetration with clearly conceived redundant systems. The A/E is responsible for the integrity of the overall moisture control system.

Construction documents must clearly depict all drainage and air passages. Detail in three dimensions where practical, indicating critical corner terminations, interface of all differing systems, proper sealant methodologies, etc.

### Future Maintenance

The use of different sun control devices to the design and components, their use, and how they are combined on a building must be reviewed for future maintenance needs including replacement, repair, cleaning, weathering, and damage from bird roosts.

Consider the use of steeply sloped surfaces, limited use of horizontal surfaces at window sills, sun control devices or other design features or design approaches to minimize bird roosts.

### Below Grade Systems

#### Ground Water Control

The drainage mat and soil filter should relieve hydrostatic pressure to the clay layer. The drainage mat should be designed to prevent water from entering the building.

3D details to see joints to be sealed properly

Hygrothermal behavior of all critical enclosure components must be demonstrated



# Importance of Moisture

**interface**  
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MARCH 2011 • Vol. XXIX, No. 3

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RCI was chartered, in part, to bridge the gap between the seemingly disparate elements of the roofing profession. It has expanded to include issues of waterproofing and of the entire building envelope. The goal of *interface* is to connect these elements, educate and inform about related topics, establish a common ground for discussion, promote Association programs, and reach out to the industry at large. The articles contained in this publication are intended to provide information that may be useful to readers of *interface*. RCI does not necessarily endorse this information. The reader must evaluate the information in light of the unique circumstances of any particular situation and acceptably determine its applicability. Entire contents, © RCI, Inc.

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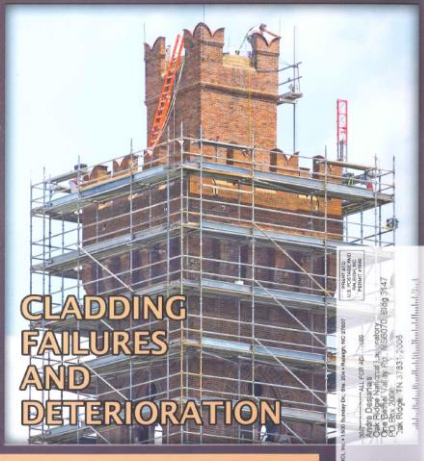
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**interface** The Journal of RCI  
March 2011 • Vol. XXIX, No. 3

**CLADDING FAILURES AND DETERIORATION**



4 out of 5 main articles deal with moisture

**In This Issue:** We examine various cladding failures and deterioration issues, from moisture migration in masonry to curtain wall failure, to problems with wood-framed buildings and issues with drift joints.

**On the Cover:** The masonry tower at the U.S. Penitentiary in Lewisburg, PA, was deteriorating after 75 years of exposure to the elements. Masonry Preservation Services (MPS) performed repairs under difficult conditions. See project profile, page 42.

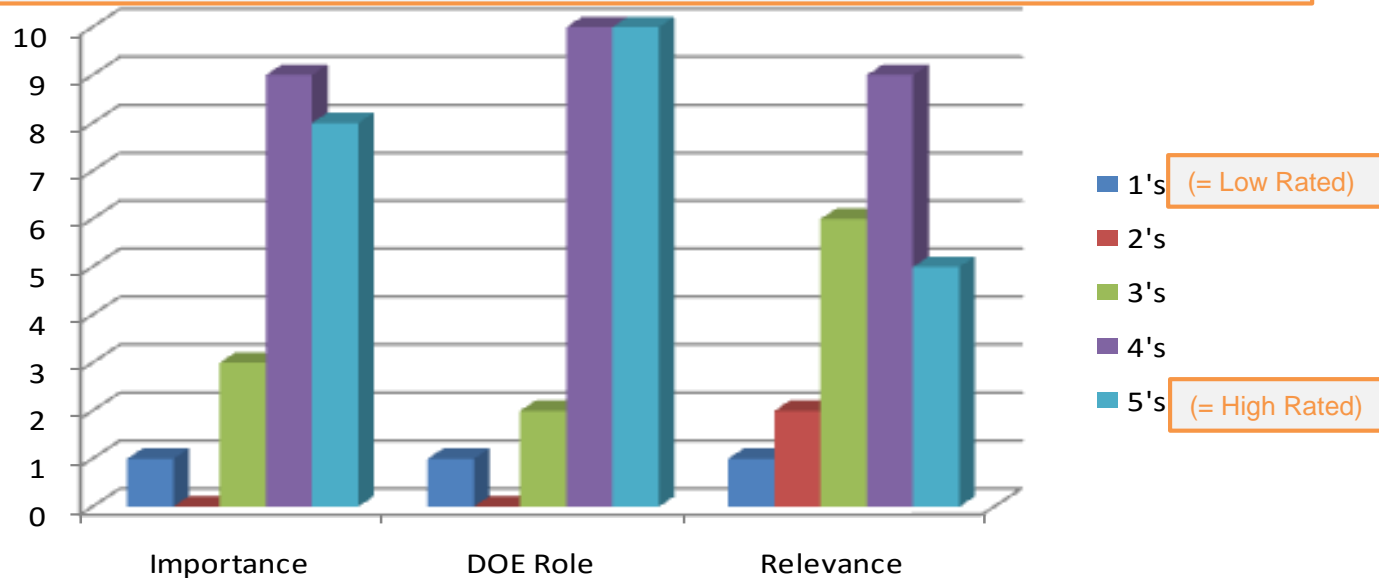
INTERFACE • 1

# Importance of Moisture

Inspection of all papers of “Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference 2010” results in: →

<b>Moisture related Papers</b>	
<b>Practices</b>	<b>61%</b>
<b>Principles</b>	<b>55%</b>

Official Participant's Feedback regarding Moisture Research.



# Moisture Balance

Non Energy Efficient Envelope



Energy Efficient Envelope



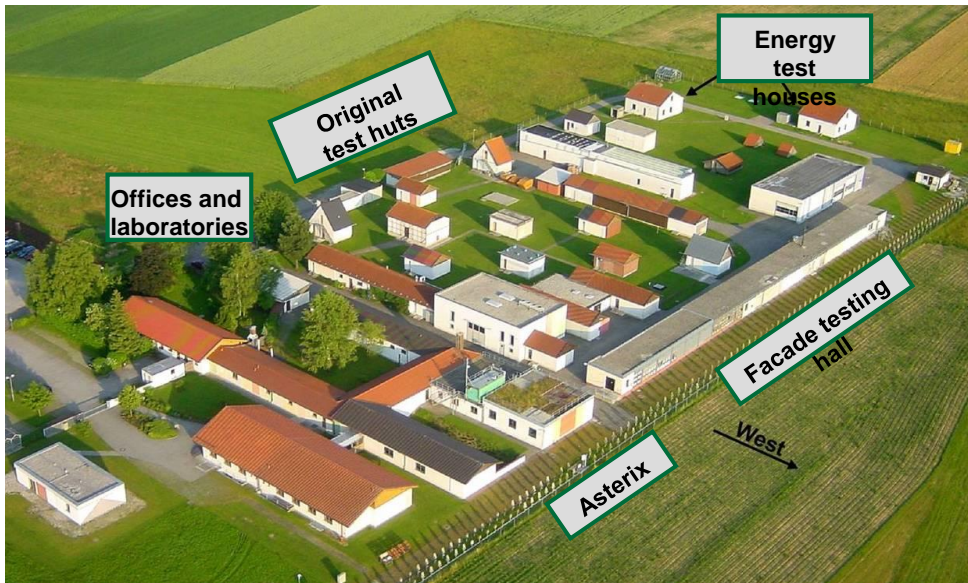
# Previous Assessment

## Field tests:

- Very time consuming
- Very expensive
- Search for alternative ways to investigate hygrothermal performance



Fraunhofer IBP, Germany



# Previous Assessment

## Field tests

- limited transferability to another climate



# Previous Assessment

Field tests: solution to climate dilemma

- new test sites
- search for alternative ways to investigate hygrothermal performance

Field test site in Bangkok



Vliet test building KULeuven



BEG hut Waterloo Canada

# Previous Assessment

Laboratory tests: climate chambers  
(hot box / cold box)

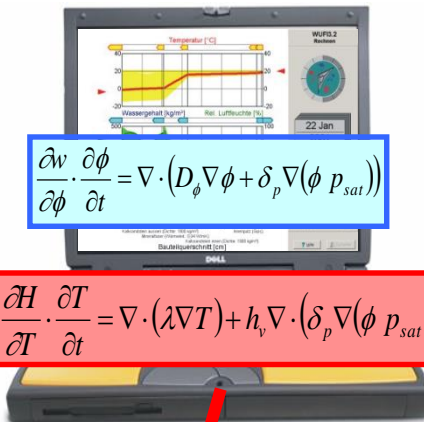
- realistic conditions ( $\theta, \phi$ )
- sky radiation and precipitation difficult to simulate
- limited capacity
- Time consuming
- expensive



# Hygrothermal Modeling

construction details  
orientation  
inclination

initial conditions



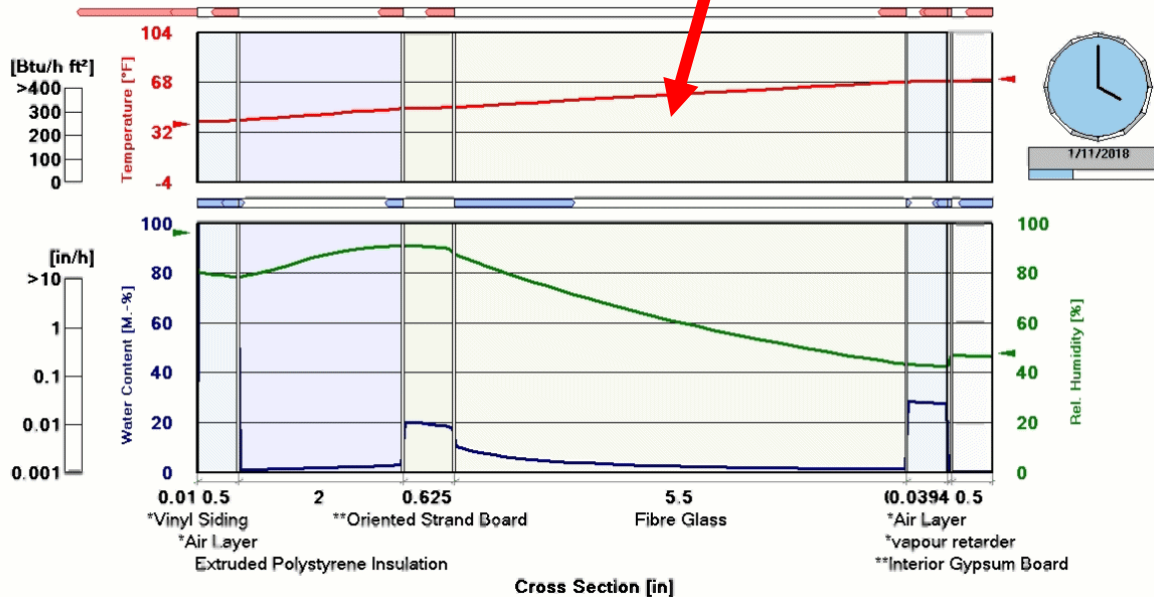
material properties

climate conditions

Location: Chicago, IL; cold year;

Residential High-R Wall Assembly

WUFI®





# Basics

## Heat Calc.

### Total Heat Resistance

$$R = \frac{1}{\alpha_{Ext.}} + \sum_{AllLayers} \frac{d}{\lambda} + \frac{1}{\alpha_{Int.}}$$

### Heat Flux

$$q = \frac{\Delta T}{R}$$

### Temperature Differences

$$\Delta T_{Ext.} = \frac{1}{\alpha_{Ext.}} \cdot q$$

$$\Delta T_{Brick} = \frac{d_{Brick}}{\lambda_{Brick}} \cdot q$$

$$\Delta T_{Int.} = \frac{1}{\alpha_{Int.}} \cdot q$$

## Vapor Calc. (very simplified)

### Total Vapor Resistance

$$R_v = \frac{1}{\beta_{Ext.}} + \sum_{AllLayers} \frac{d}{\delta_p} + \frac{1}{\beta_{Int.}}$$

### Vapor Flux

$$g_v = \frac{\Delta p}{R_v}$$

### Vapor Pressure Differences

$$\Delta p_{Ext.} = \frac{1}{\beta_{Ext.}} \cdot g_v$$

$$\Delta p_{Brick} = \frac{d}{\delta_p} \cdot g_v$$

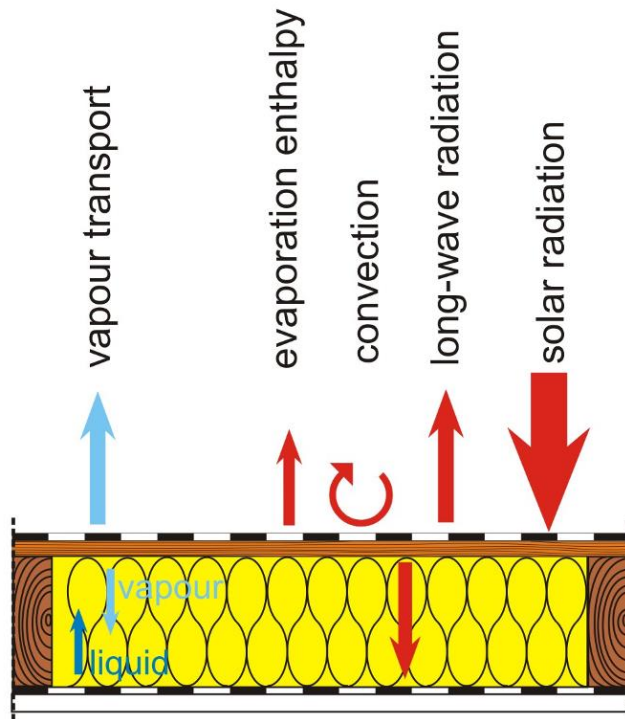
$$\Delta p_{Int.} = \frac{1}{\beta_{Int.}} \cdot g_v$$

# Transient Hygrothermal Processes in Building Envelope

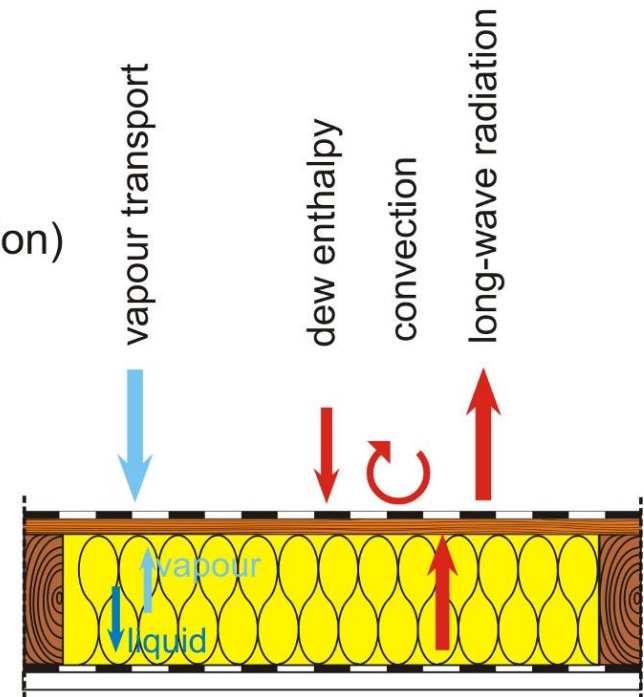
## Example Flat Roof



Day time  
(drying)



Night Time  
(humidification)



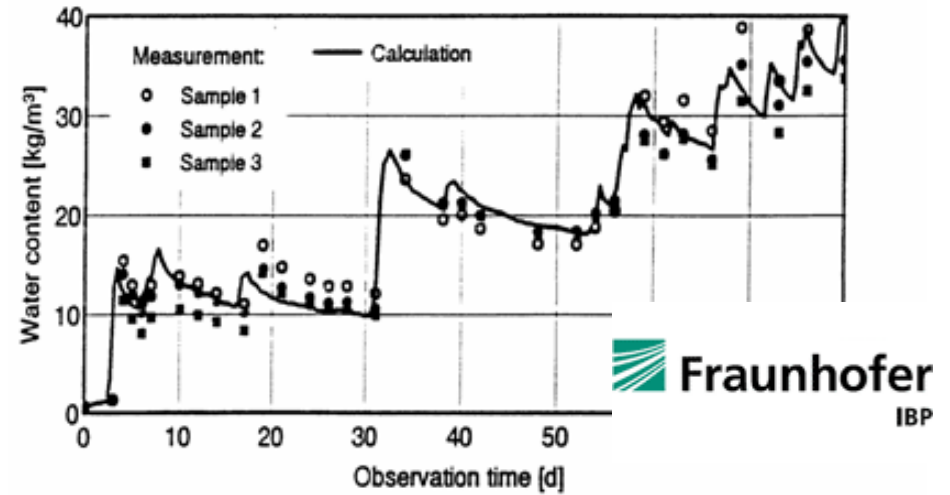
# Material Properties Measurement

The complexity of heat and moisture analysis material properties can be approximated with the following rel. simple and standardized material properties:

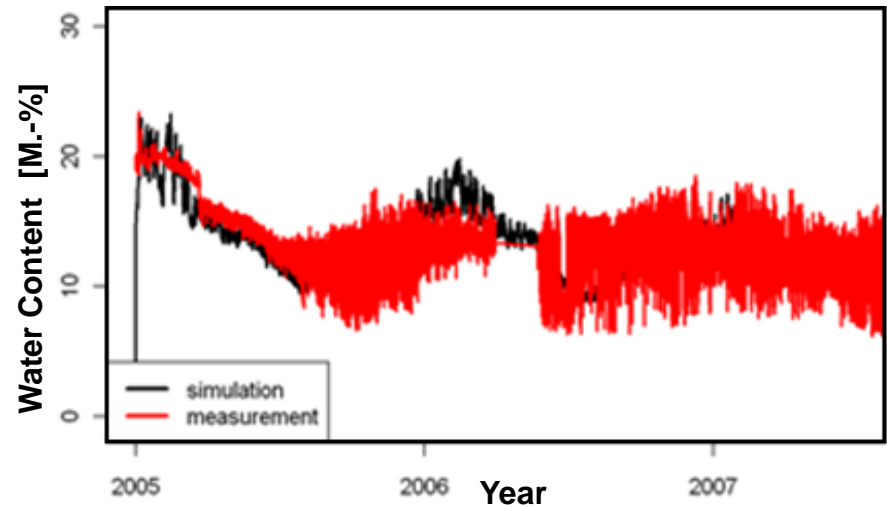
- ⌘ Density
- ⌘ Porosity
- ⌘ Heat Capacity **ASTM (Calorimeter)**
- ⌘ Thermal Conductivity **ASTM C518, C177**
- ⌘ Moisture Sorption Function **ASTM C1498, C1699**
- ⌘ Water Vapor Permeability **ASTM E96**
- ⌘ Free water saturation **ASTM C1699**
- ⌘ Water Absorption Coefficient **ASTM C1794**

# Model Validation

Germany

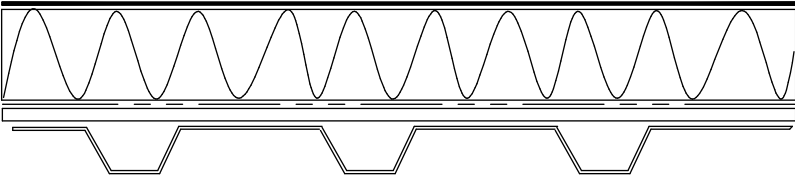


Charleston, SC



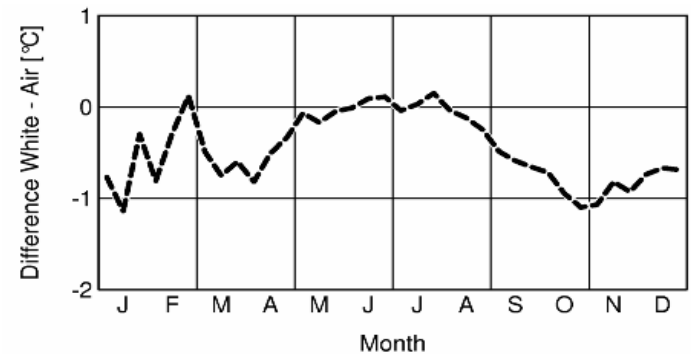
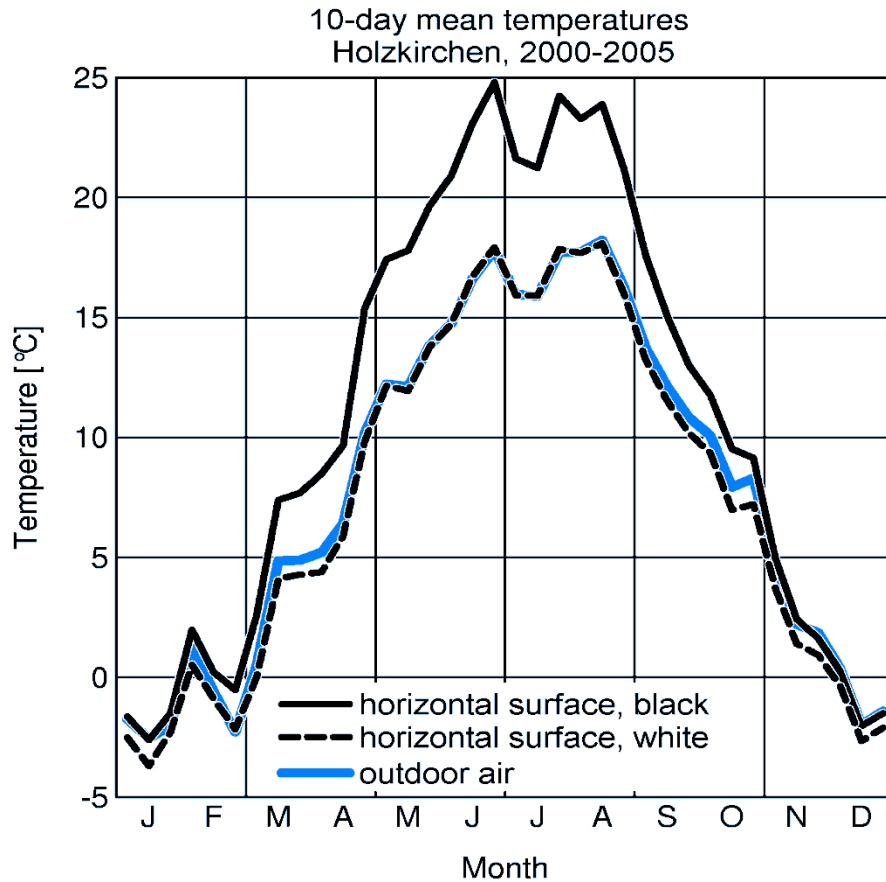
# Condensation Risk of Cool Roofs

## Mechanically attached Commercial Metal Deck Flat Roof

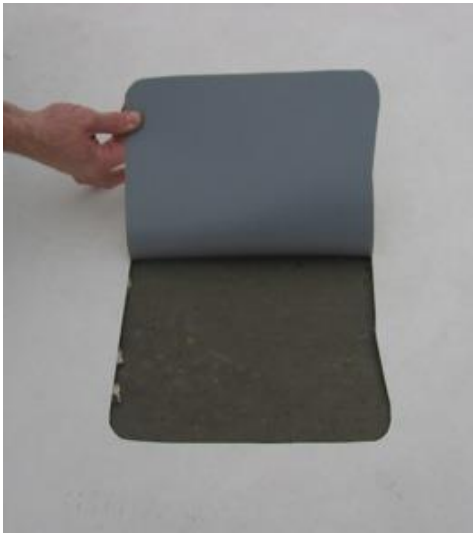


# Analysis of meteorological data

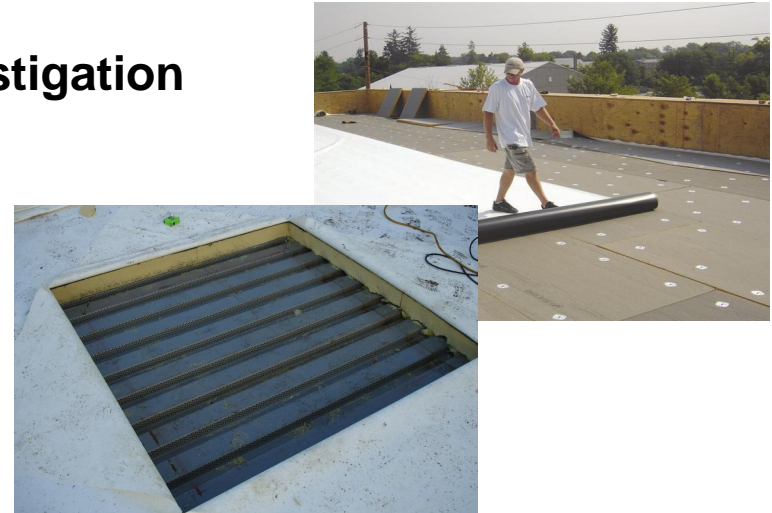
## Solar Radiation Impact



# Condensation Risk of Cool Roofs



## SPRI / ORNL Investigation



- White membranes to reduce the solar heat load
- Black membranes are typically 50 deg F warmer than white membranes on a sunny day
- Theorized impact
  - Location/occurrence of dew point
  - Impact ability of system to dry out

# Cool Roofs: Variation Scenario

## Climate

Zone 4 – Baltimore, MD  
Zone 5 – Chicago, IL  
Zone 6 – Minneapolis, MN  
Zone 7 – Fargo, ND

## Indoor Moisture Supply

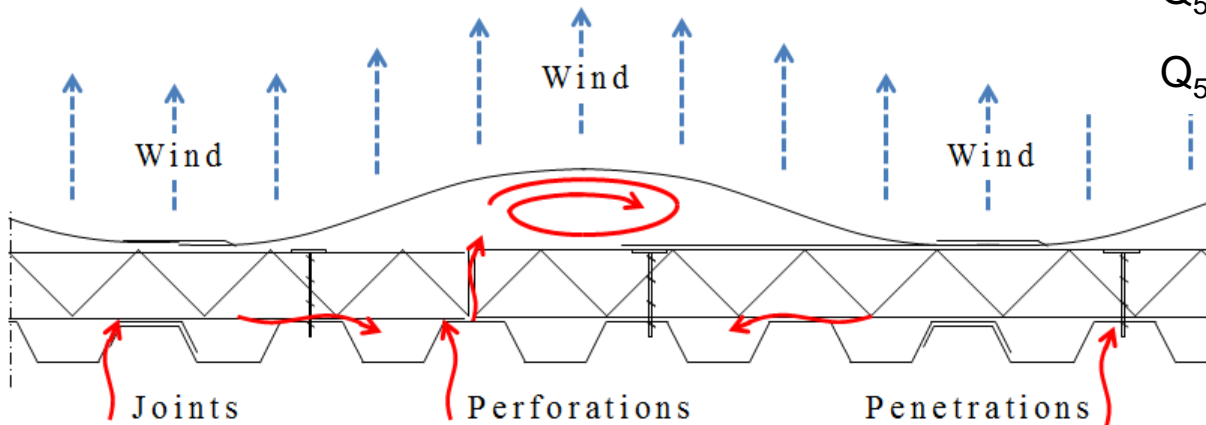
ASHRAE 160, Low  
EN-15026, Normal  
EN-15026, High  
ASHRAE 160, High

## Solar Surface Absorptivity

$\alpha=0.30$  (White Surface)  
 $\alpha=0.85$  (Dark Surface)

## Air Tightness

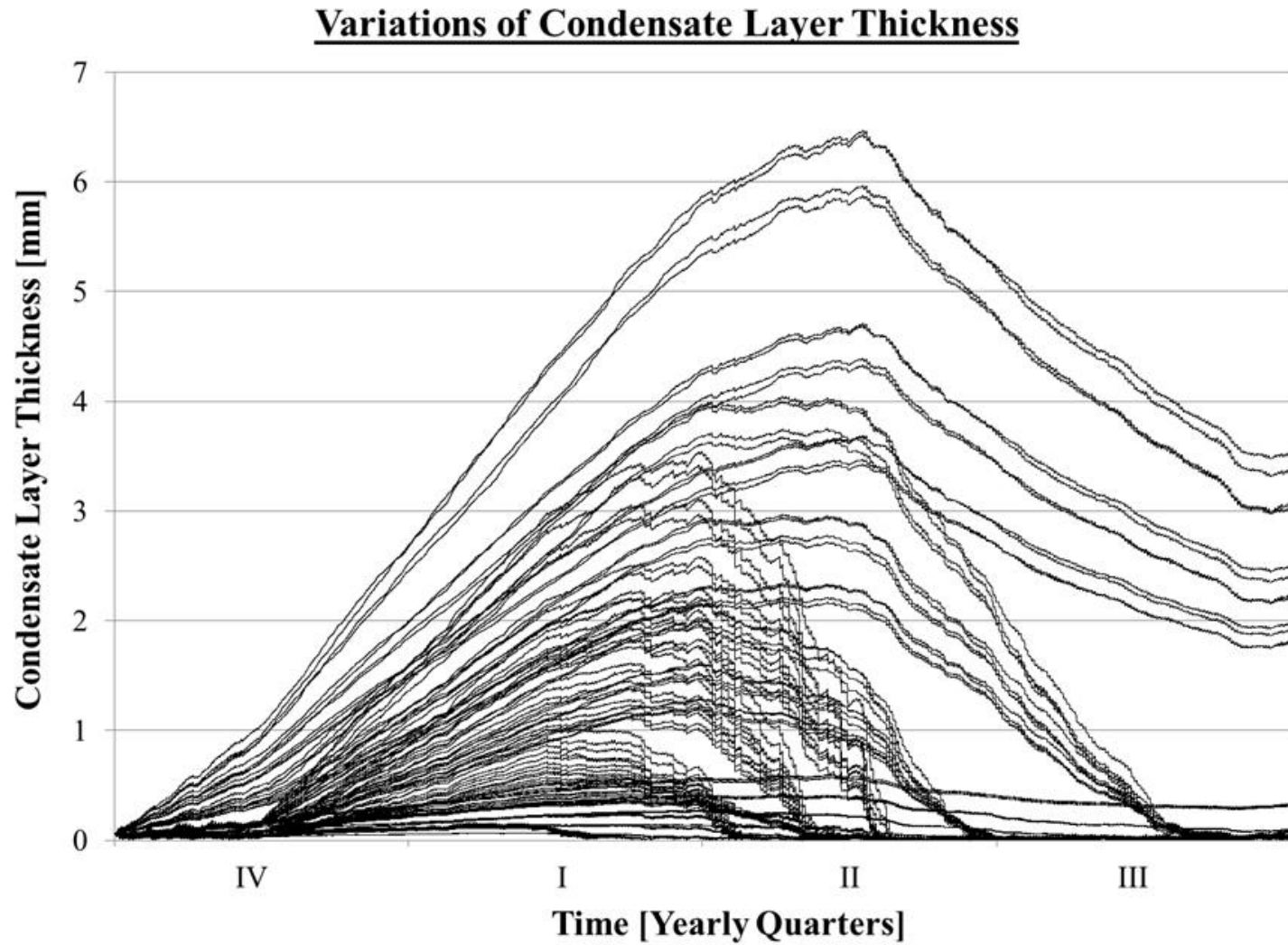
$Q_{50}=0.27$  [l/s,m<sup>2</sup>] – no perforations  
 $Q_{50}=0.56$  [l/s,m<sup>2</sup>] – little leaky  
 $Q_{50}=1.0$  [l/s,m<sup>2</sup>] – average leaky  
 $Q_{50}=2.0$  [l/s,m<sup>2</sup>] – totally leaky



→ Combination:  
128 WUFI Simulations!

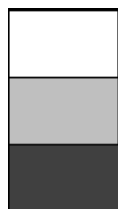


# Cool Roofs: WUFI Results



# Cool Roofs: Final Evaluation of Results

Indicators for the reliability of the roof construction at given conditions.

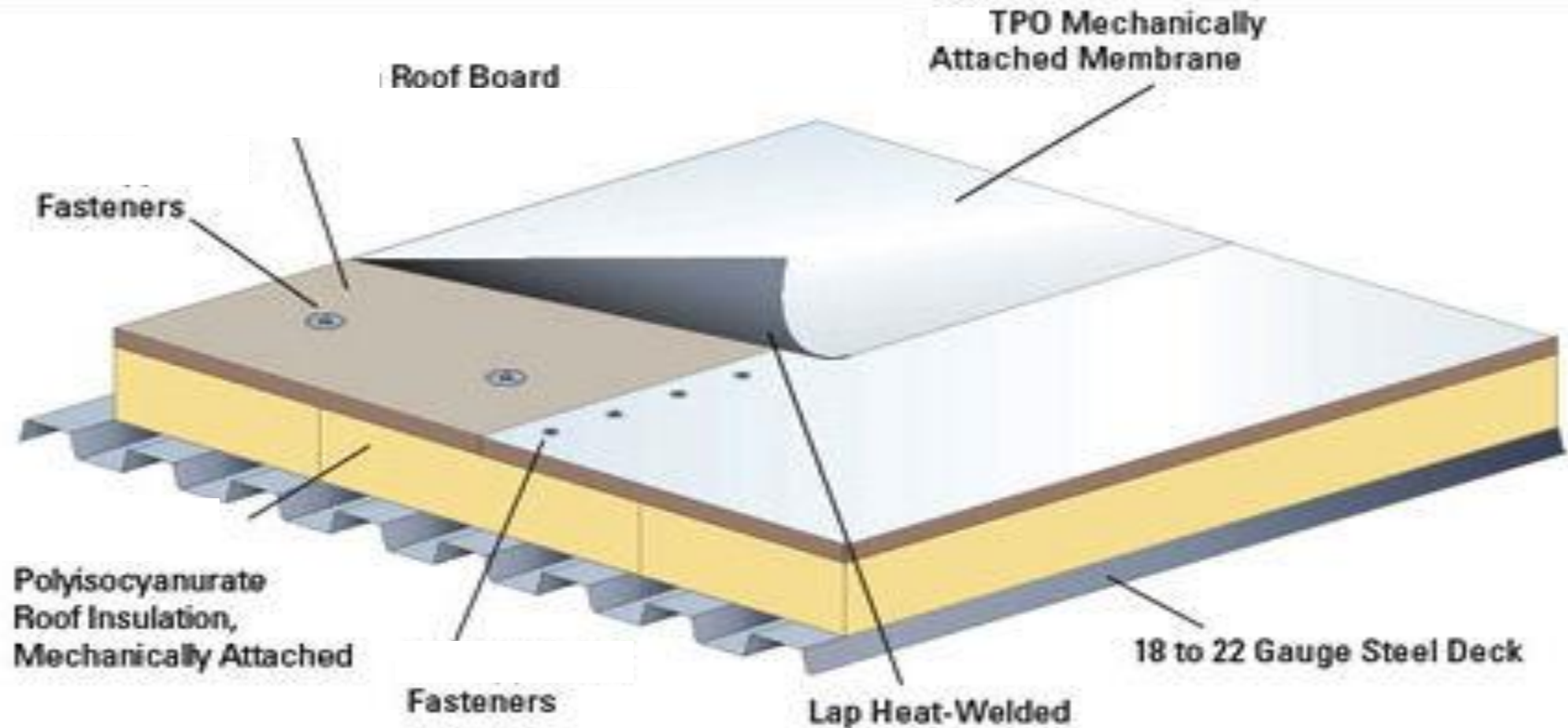


safe roof construction, gray indicates risky construction, dark gray indicates expected failure

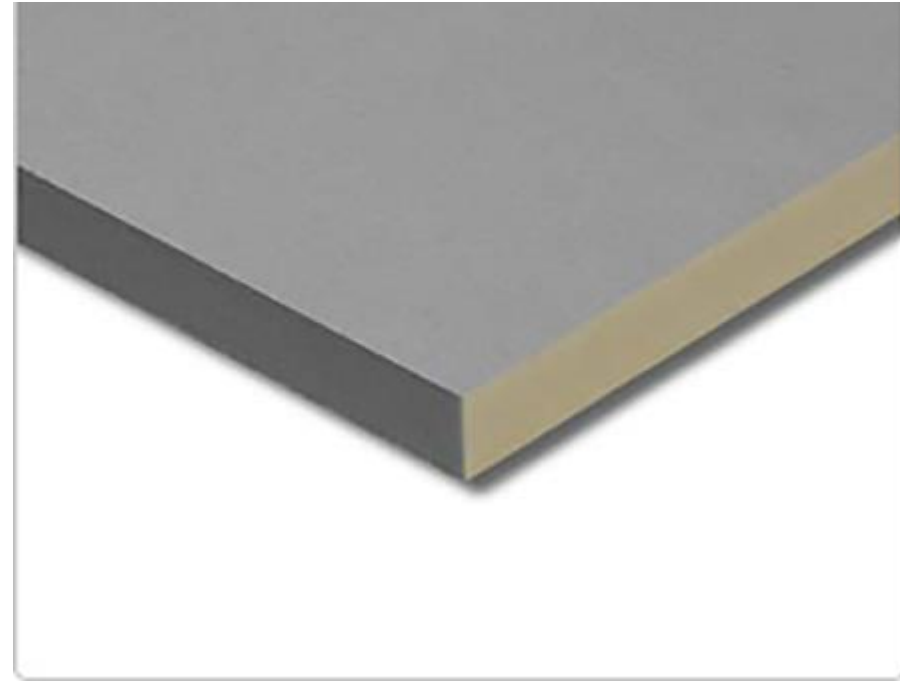
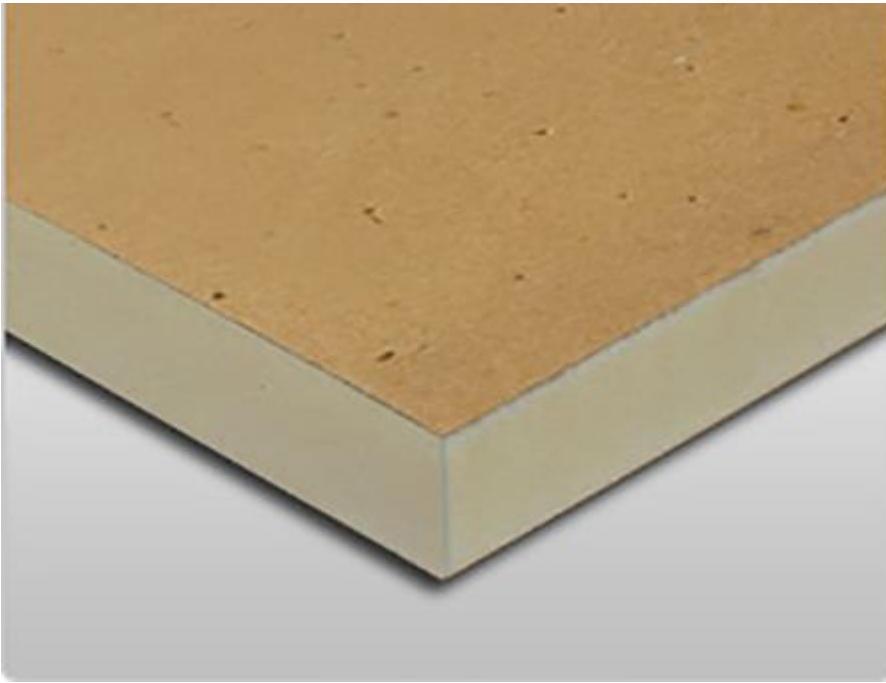
Black Surface  
White Surface

Climate Zone 4								
Indoor moisture supply	Not Leaky		Little Leaky		Avg. Leaky		Very Leaky	
ASHRAE - Low	B	W	B	W	B	W	B	W
EN - Normal	B	W	B	W	B	W	B	W
EN - High	B	W	B	W	B	W	B	W
ASHRAE - High	B	W	B	W	B	W	B	W

# Mech. attached Roof, Sensitivity Analysis



# Mech. attached Roof, Sensitivity Analysis



## Step1: Measurement of Material Properties for

Polyiso, facers separately

Coverboard

TPO

# Mech. attached Roof, Sensitivity Analysis

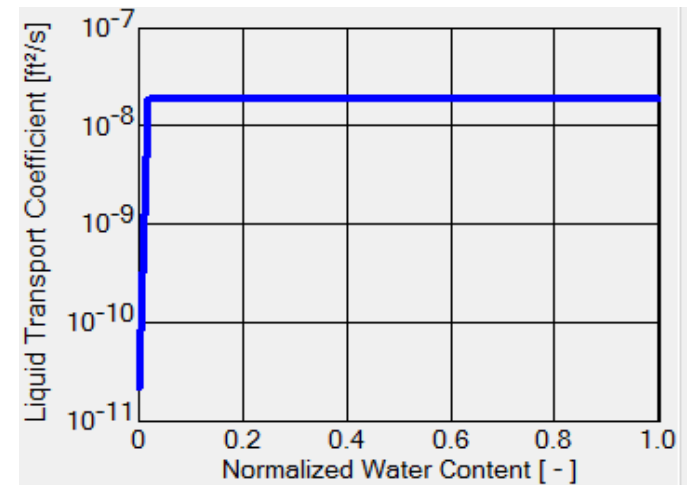
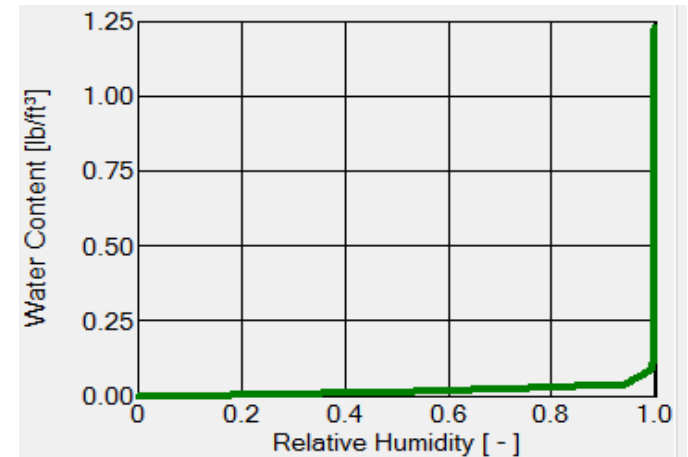
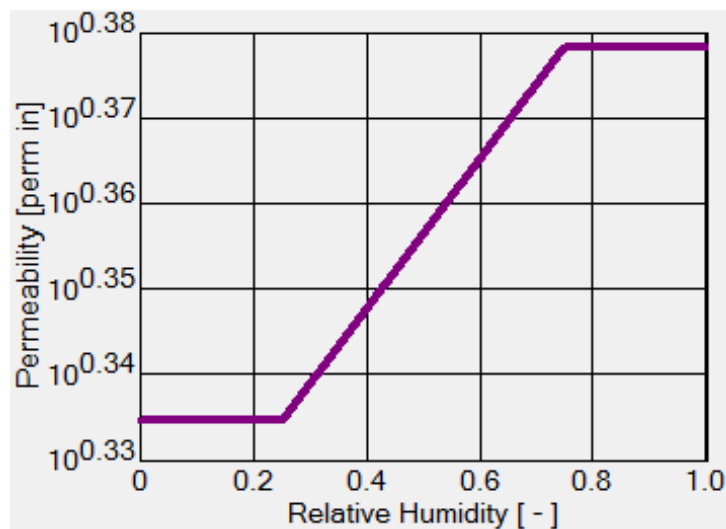
## Measurement Methodology

	Polyiso foam core	Facers	High density polyiso coverboard	Cellulosic coverboard	TPO membrane
Bulk density	ORNL	ORNL	ORNL	ORNL	Manufacturer
Porosity	est	est	est	est	est
Specific heat capacity	est	est	est	est	est
Thermal conductivity	Manufacturer	est	Manufacturer	Manufacturer	est
Water vapor permeability	Manufacturer	Manufacturer	Manufacturer	Manufacturer	Manufacturer
Moisture storage function	ORNL	ORNL	ORNL	ORNL	est
Water absorption coefficient	ORNL	ORNL	ORNL	ORNL	est
Thermal conductivity dependence on temperature	Manufacturer	Manufacturer	Manufacturer	Manufacturer	Manufacturer
Thermal conductivity dependence on moisture	est	est	est	est	est

# Mech. attached Roof, Sensitivity Analysis

## Properties of polyiso insulation board

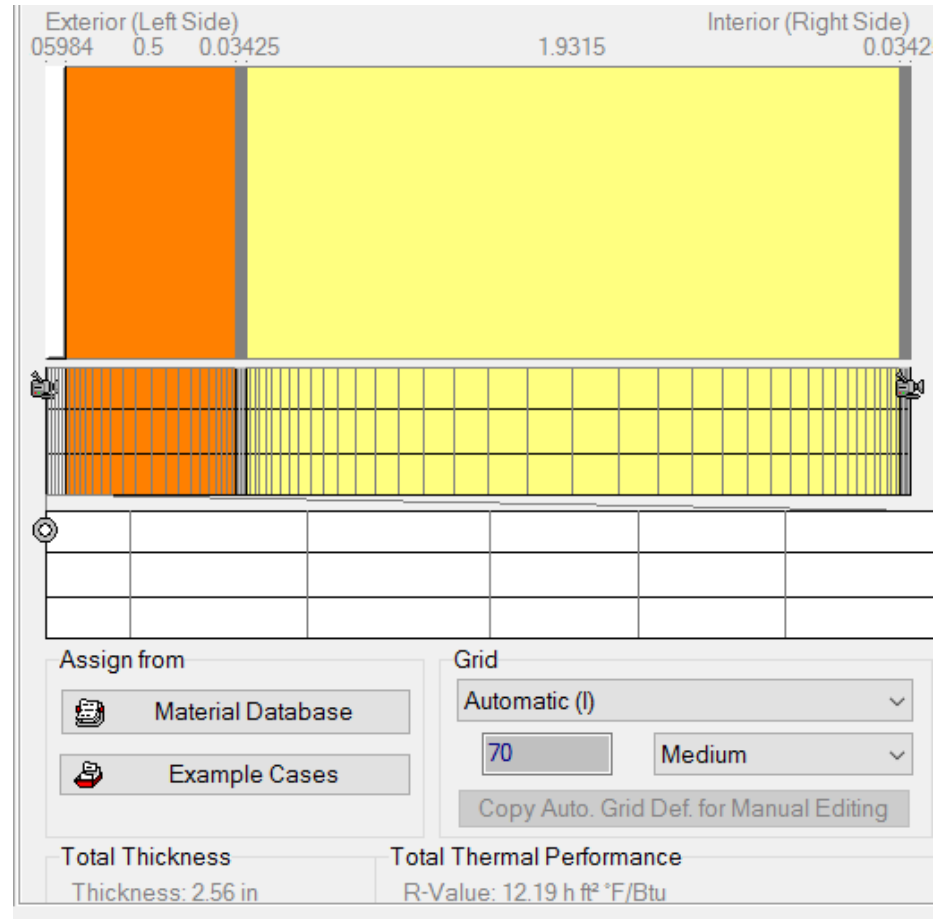
Basic Values	
Bulk density [lb/ft <sup>3</sup> ]	1.6294
Porosity [ft <sup>3</sup> /ft <sup>3</sup> ]	0.98
Specific Heat Capacity, Dry [Btu/lb °F]	0.3511
Thermal Conductivity, Dry, 50°F [Btu/h ft °F]	0.0149
Permeability [perm in]	2.1611



# Mech. attached Roof, Sensitivity Analysis

## Initial and boundary conditions

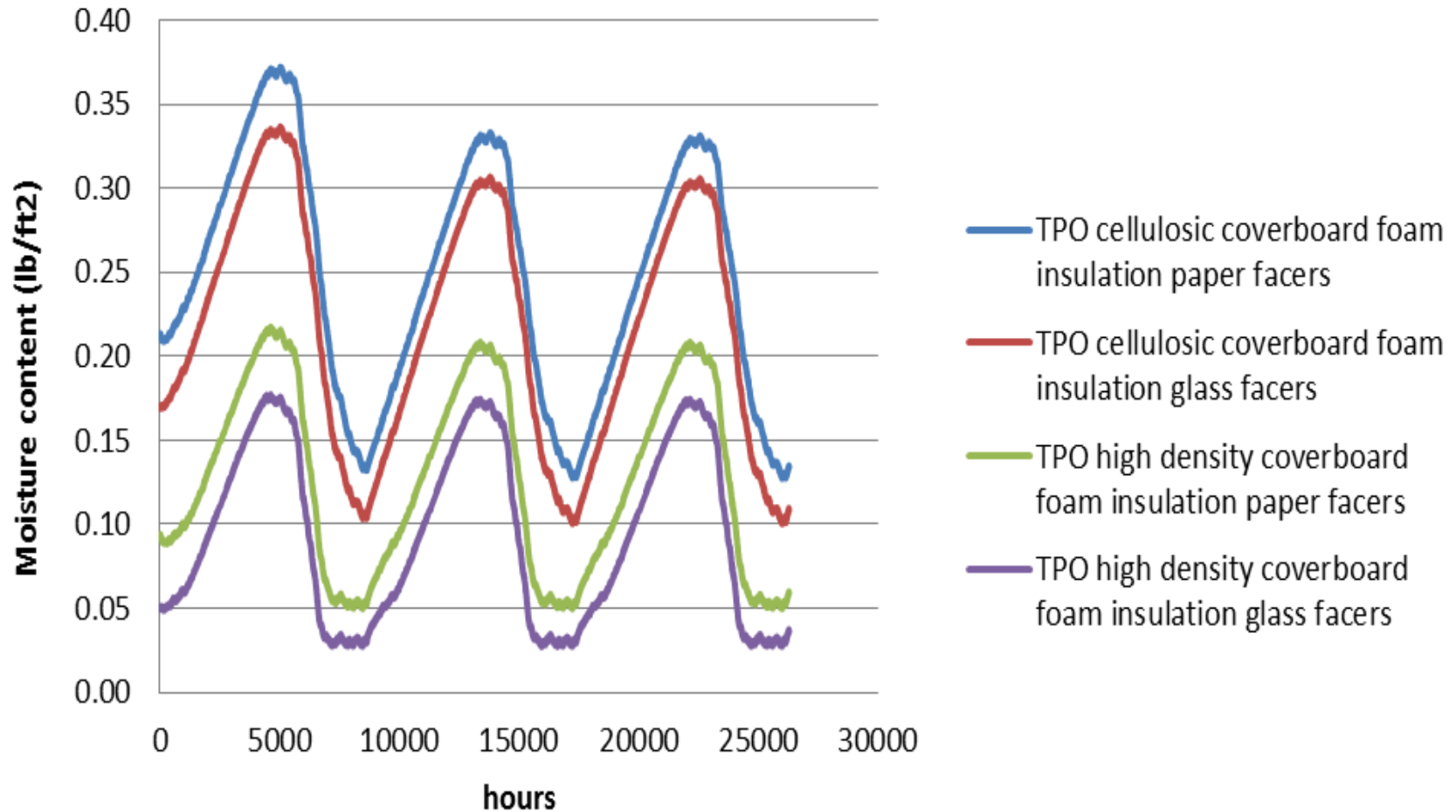
- Horizontal flat roof
- White, reflective roof
- Metal roof deck – 1 perm
- EMC 80 – initial moisture content
- Interior climate: ASHRAE 160



# Mech. attached Roof, Sensitivity Analysis

## Results

### Total moisture content (Chicago)





# Mech. attached Roof, Sensitivity Analysis

## Sensitivity Analysis

- Four systems – Polyiso, TPO, + two coverboards + with two facers
- Two climates – Miami and Chicago
- Properties were varied +/-20%
- Total moisture content maximum in the 3<sup>rd</sup> year compared to baseline

# Mech. attached Roof, Sensitivity Analysis

## Sensitivity Analysis Results

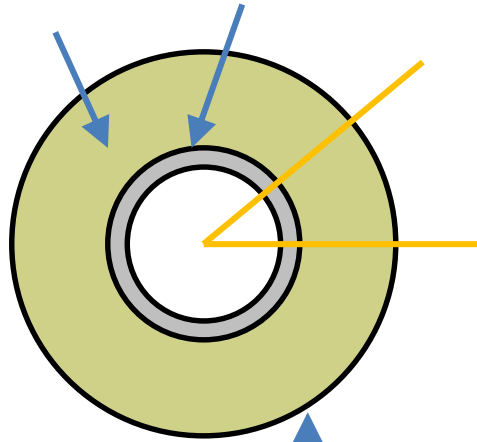
Assembly	High density/paper		High density/glass		Cellulose/paper		Cellulose/glass	
	Chicago	Miami	Chicago	Miami	Chicago	Miami	Chicago	Miami
Density	0.7%	0.0%	0.6%	0.0%	0.0%	0.0%	0.3%	0.0%
Water vapor permeability	6.6%	0.6%	7.8%	0.0%	5.2%	1.4%	5.9%	1.3%
Thermal conductivity	0.7%	0.0%	0.8%	0.0%	0.6%	0.3%	0.6%	0.0%
Moisture storage	7.7%	18.6%	5.9%	18.3%	10.3%	17.8%	9.3%	18.1%
Liquid transport	0.2%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%

Table 8-Variation in total moisture content with a variation of 20% in the measured property

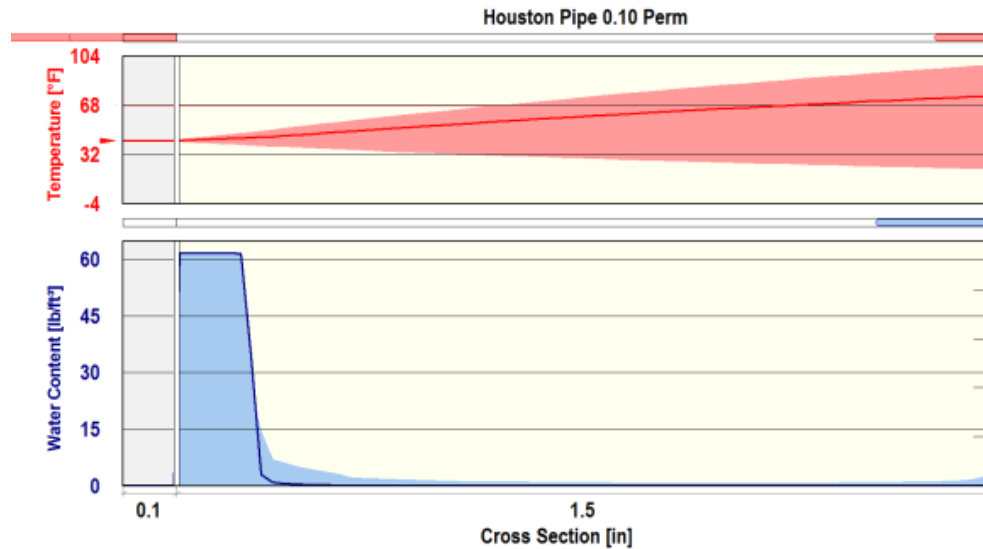
# WUFI Application for Pipe Insulation

Fiber Glass  
Insulation

Steel Pipe



Jacket with  
specified  
Vapor  
Permeance



Geometry

Cartesian

Radially Symmetric

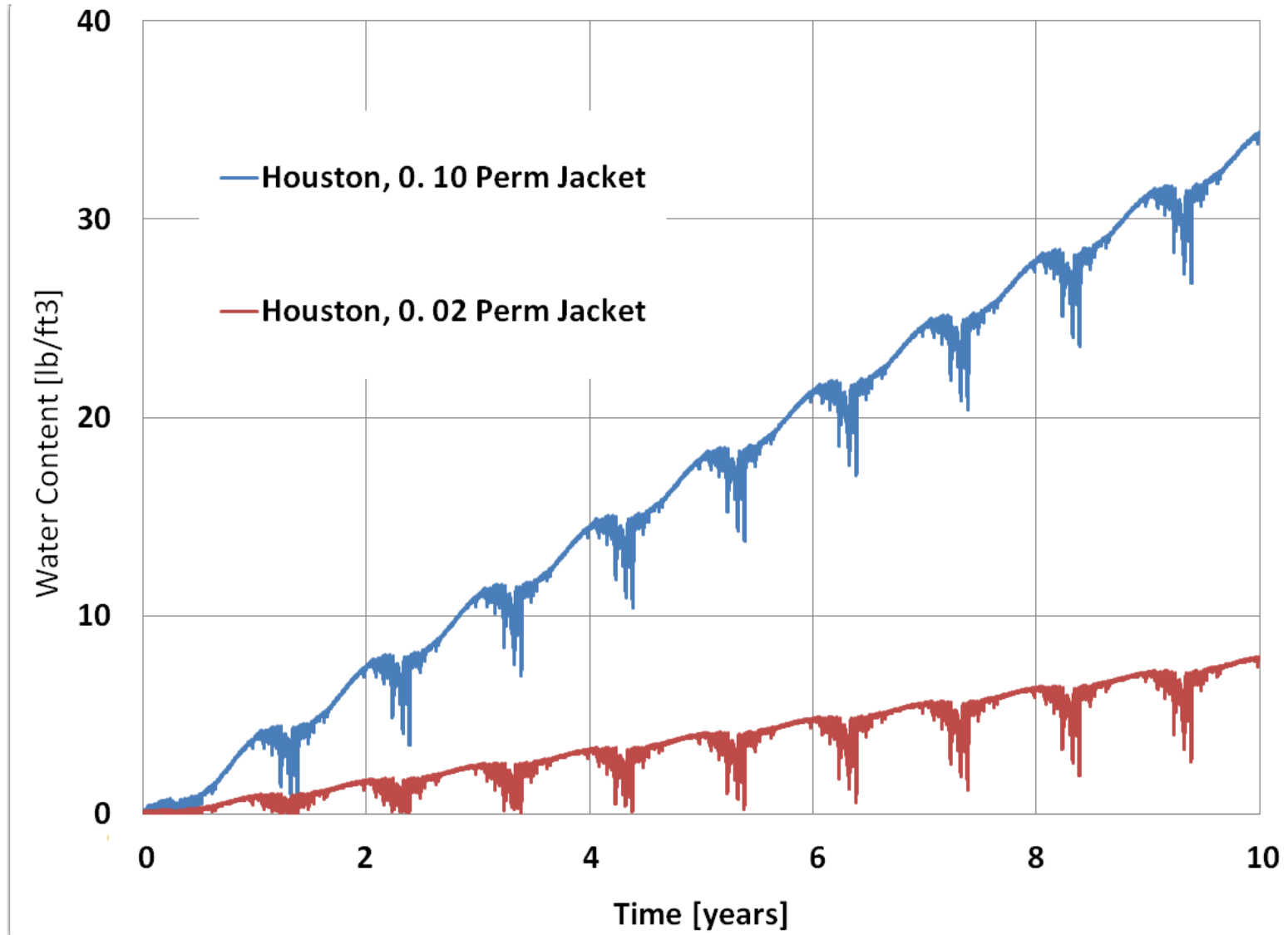
Distance: Left Surface to Symmetry Axis

R0 [in]

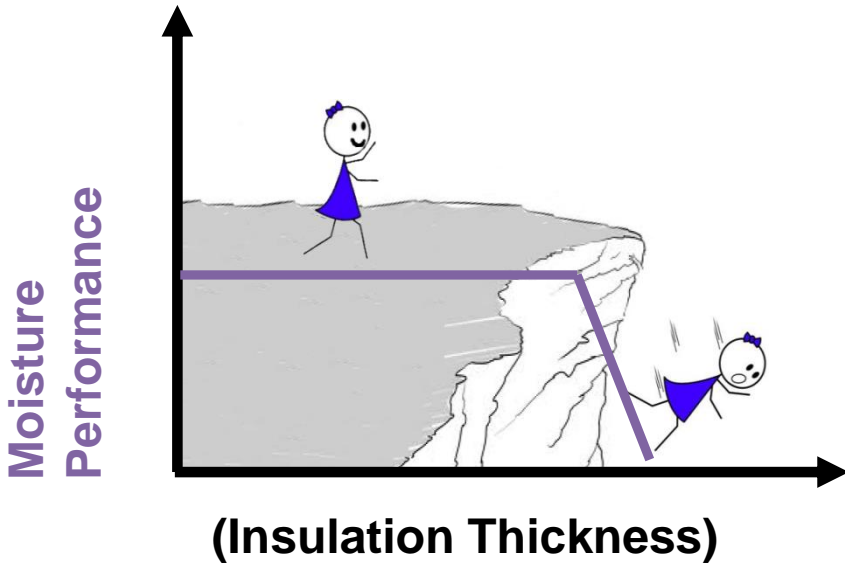
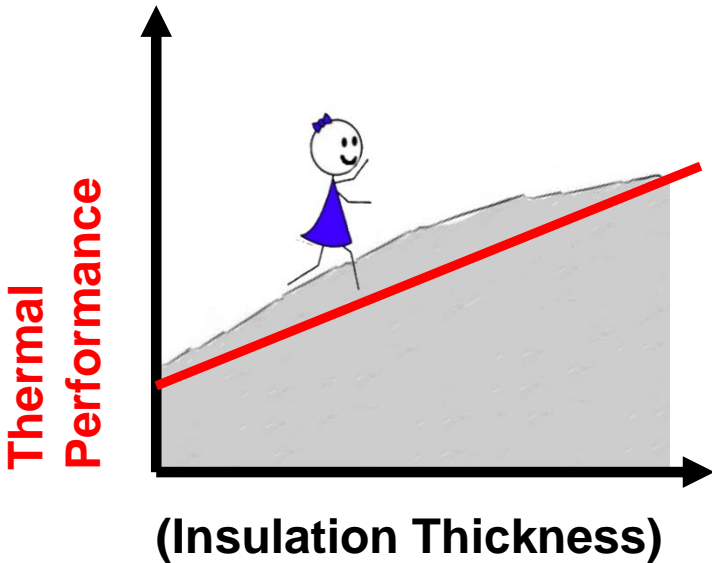
1.5

A diagram of a radially symmetric pipe cross-section, showing a grey pipe and a green insulation layer. A blue arrow labeled  $R_0$  indicates the distance from the left surface to the symmetry axis.

# WUFI Application for Pipe Insulation



# Heat vs. Moisture

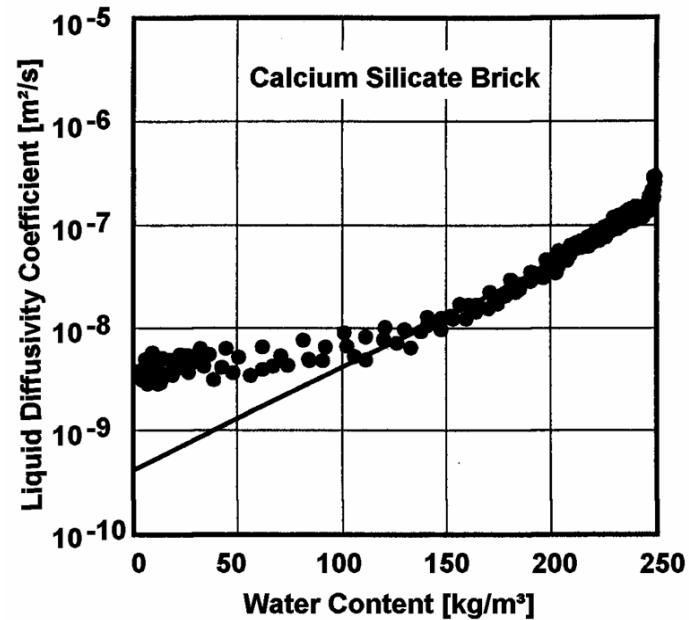
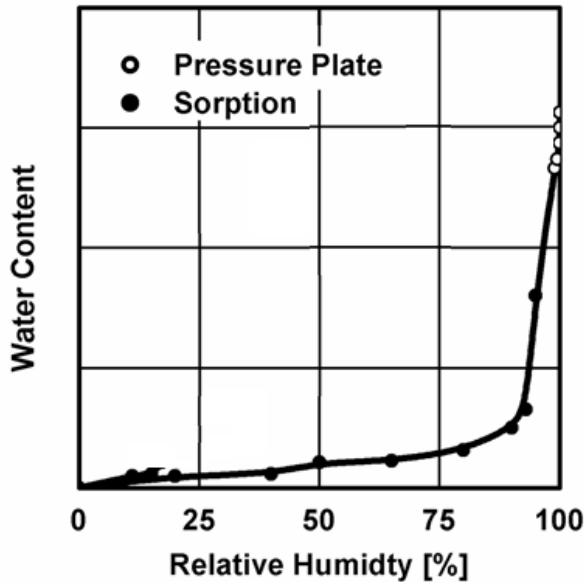
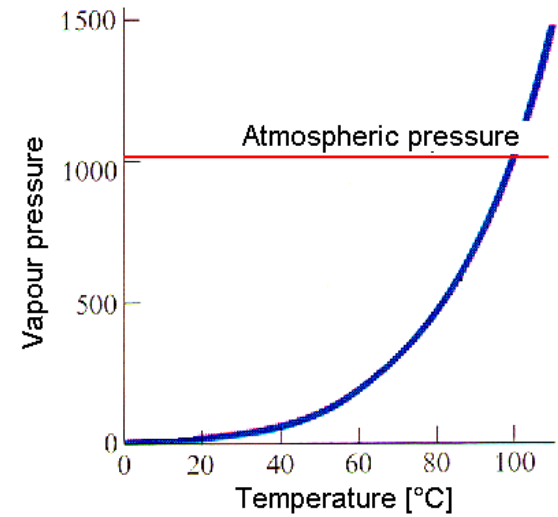


Important for any Insulation!

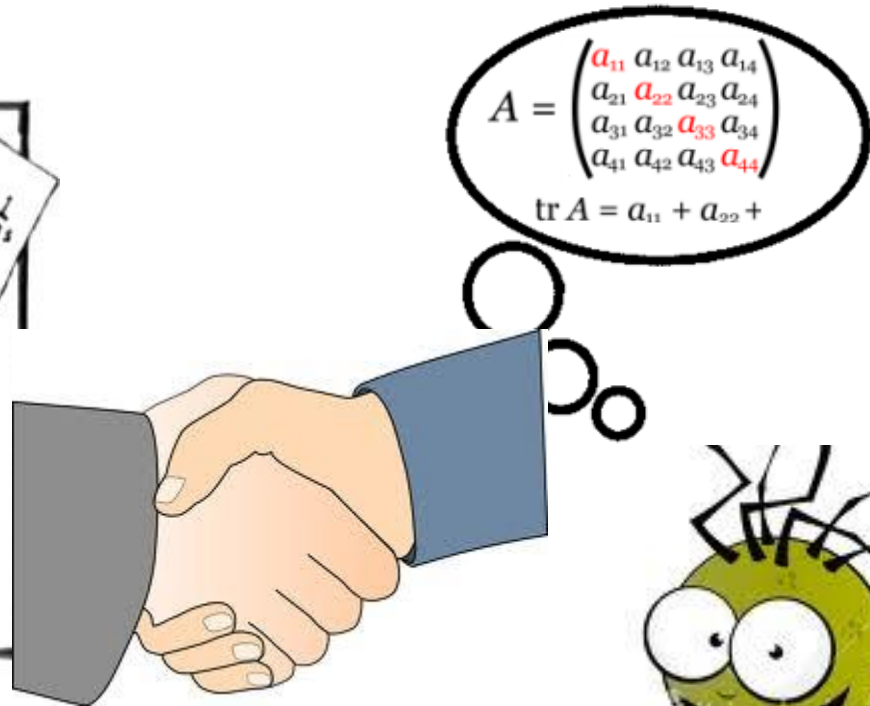
# Heat vs. Moisture

Hygrothermal material properties are highly non-linear.

(unlike thermal material properties)



# Measurement & Calculation





*Just* **Smart** Solutions

## **Buildings XIII Workshop**

December 5th 2016

**Manfred Kehrer**

**Modern Hygrothermal Engineering  
Motivation, Basics, Examples**