Nintendo Engineering: Where are We with Our Modeling?

Dr. Achilles Karagiozis
Distinguished Research & Development Staff
Engineering Science and Technology Division

May 25, 2006

UT-BATTELLE
OAK RIDGE NATIONAL LABORATORY
U. S. DEPARTMENT OF ENERGY

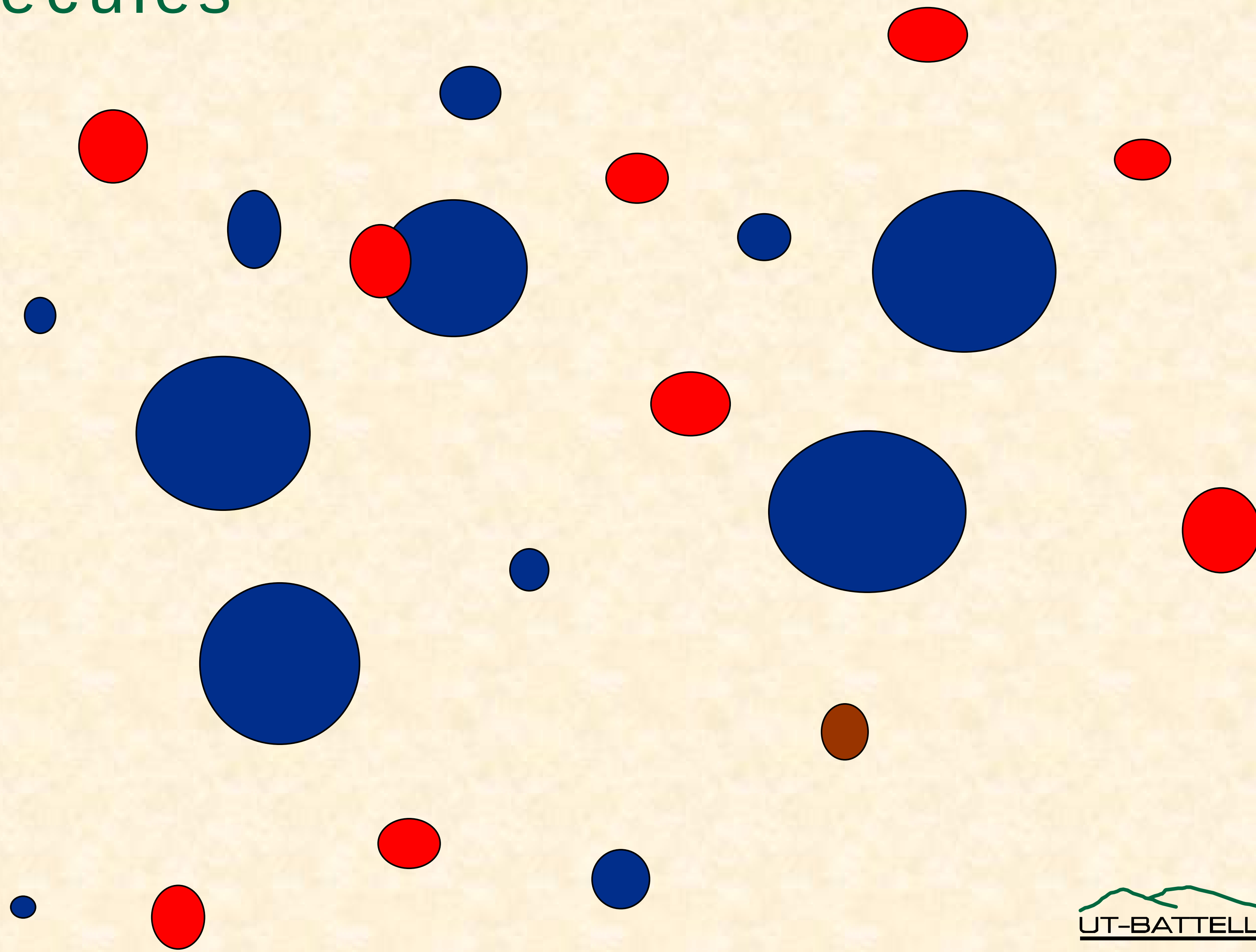
Acknowledgments:

BCBEC

BRITISH COLUMBIA BUILDING ENVELOPE COUNCIL

Moisture Group Incorporated

It all starts with the Theory : Perm Molecules



UT-BATTELLE

Presentation Roadmap

- Current Understanding
- New Standards
- Application
- Future
- Conclusions

Challenge

- **Develop the scientific competencies to analyze complex dynamic heat, air and moisture transport processes in porous media (Hygrothermal)**
- **Develop a framework to evaluate & characterize the performance of building envelopes systems and building stock**
- **Use the scientific competencies & framework to develop guidelines for moisture control, improve Building Codes validate new innovative products & educate building designer & architects**

Why have Envelopes worked well in the Past ?

UT-BATTELLE

Past Approach

Trial and Error

Attention to Detail

but

Little Building Science

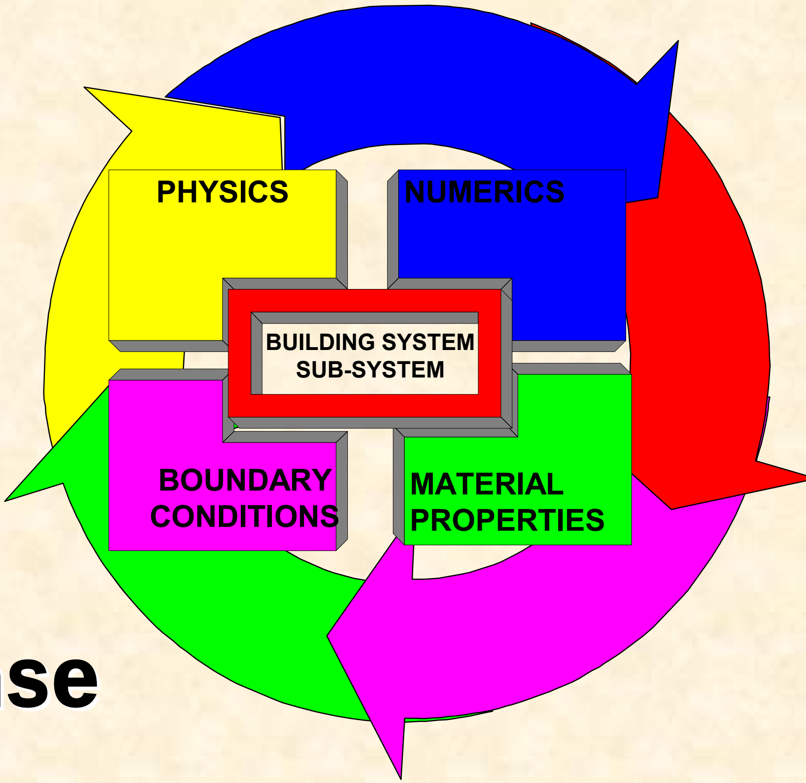
Worked until:

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

What is needed is BETTER DESIGNS

- **Increased drying performance**
  - **Solution : DESIGN**
- **Better Water Management**
  - **DESIGN**
- **More Forgiving Systems**
  - **Innovative Materials**

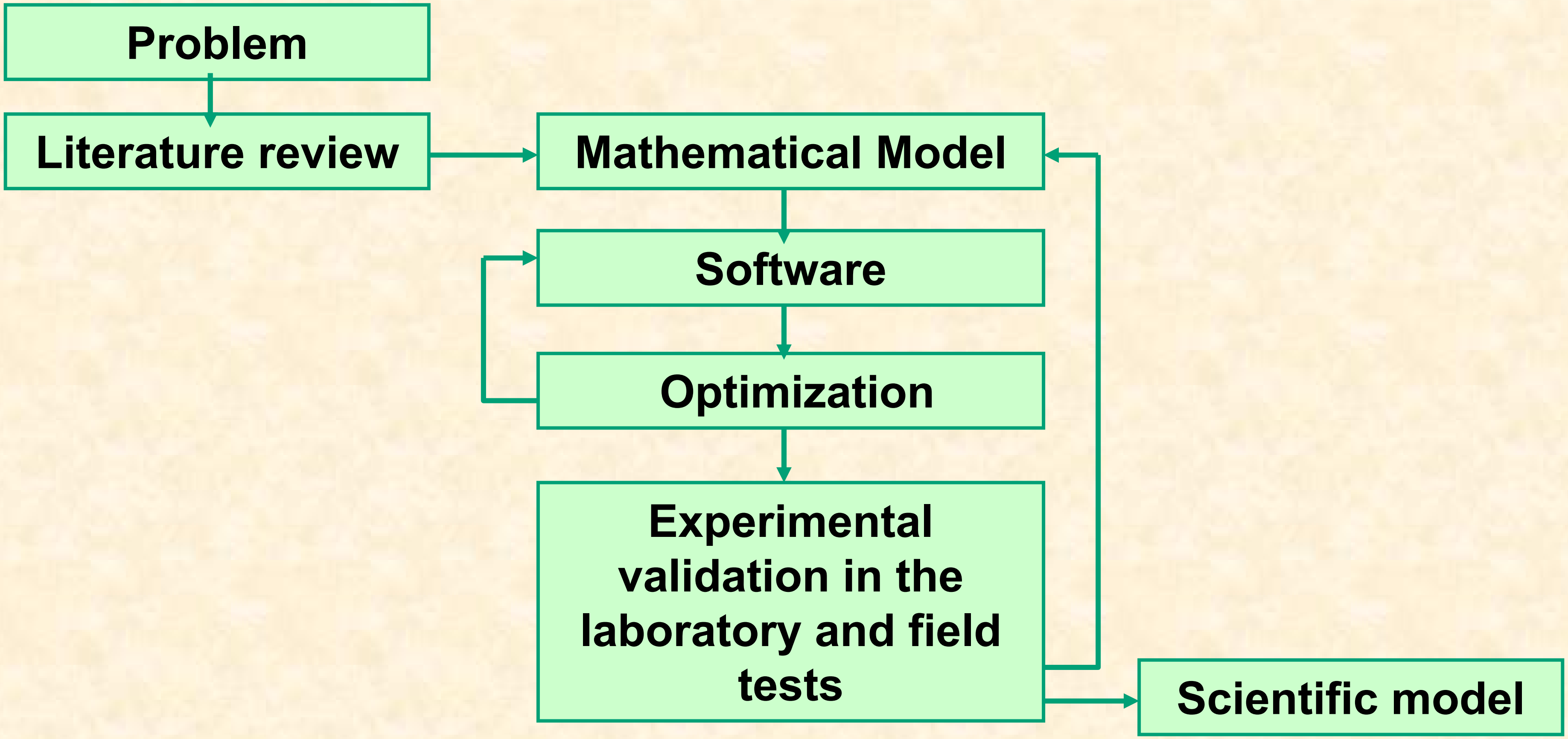
Building Science Approach



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

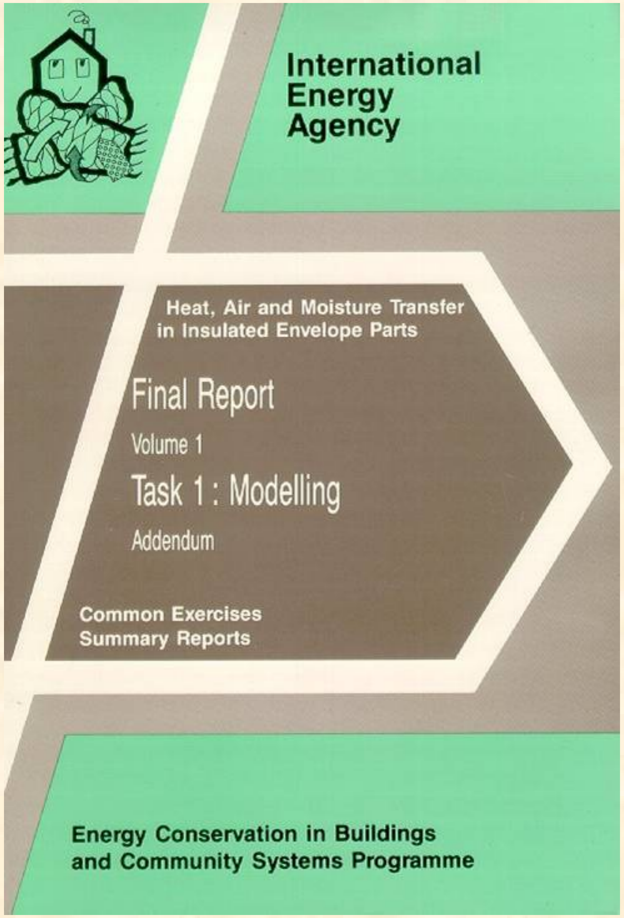
Models

Development of a scientific model



Models

Old Approach



Type	Transport Phenomena	Steady state	Transient	Number of Models
1	- Heat conduction - Vapor diffusion	X X		3
2	- Heat conduction - Vapor diffusion - simplified capillary flow	X X X		2
3	- Heat transport - Vapor diffusion		X X	1
4	- Heat transport - Vapor diffusion - Liquid transport		X X X	17
5	- Heat transport - Convection	X	 X	3
6	- Heat transport - Vapor diffusion - Convection	X X X		2
7	- Heat transport - Vapor diffusion - Convection	X X	 X	1
8	- Heat transport - Vapor diffusion - Convection		X X X	4
9	- Heat transport - Vapor diffusion - Liquid transport - Convection		X X X X	4

IEA Annex 24 - Task 1 (Hugo Hens) 14 countries - 37 models

UT-BATTELLE

Models

New Approach

Type 1
Steady State Glazer Scheme: Heat conduction, vapor diffusion with constant material properties

Type 2
Steady State Glazer Scheme: Heat conduction, vapor diffusion corrected for capillary with constant material properties, thermal-hygric link Psat(T)

Type 3
Transient heat and vapor transfer, variable material properties (moisture ratio), thermal-hygric link Psat(T) equation and latent heat

Type 4
Transient heat, vapor and liquid transfer, variable material properties (moisture content and temperature), thremal-hygric link Psat(T) equation and latent heat

Type 5
Steady and transient heat, air transport, constant material properties, thermal-air link enthalpy transfer and stack effect

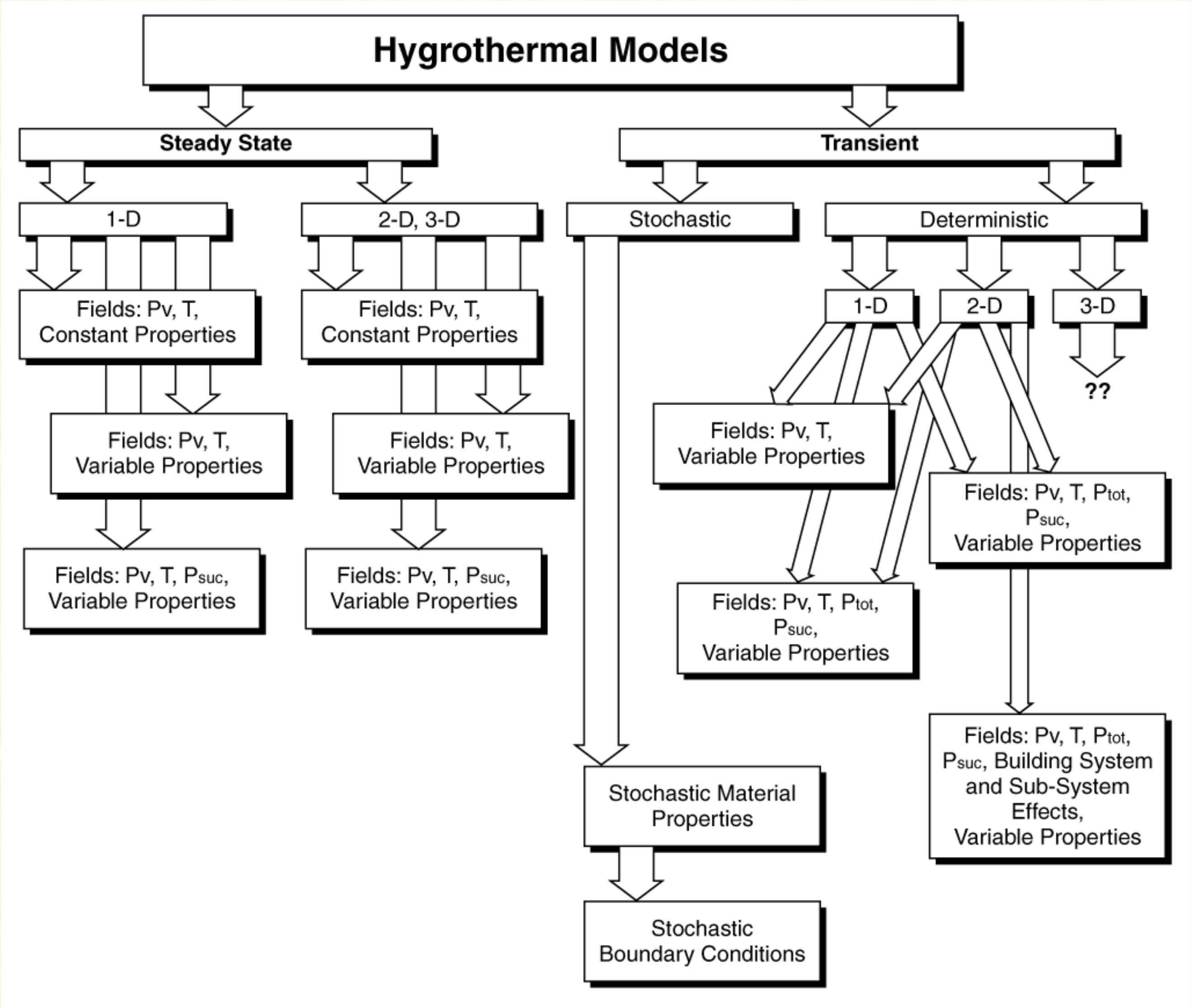
Type 6
Steady heat, vapor and air transport, constant material properties, heat-mass link the Psat(T), latent heat and enthalpy transfer

Type 7
Steady heat, air transport and transient vapor transfer, constant material properties, heat-mass link the Psat(T), latent heat and enthalpy transfer

Type 8
Transient heat, vapor, and air transport, variable material properties, heat-mass link the Psat(T), latent heat, enthalpy transfer and stack effect

Type 9
Transient heat, vapor, liquid and air transport, variable material properties, heat-mass link the Psat(T), latent heat, enthalpy transfer and stack effect

Models



Hygrothermal Models
Steady State
Transient
1-D
2-D, 3-D
Stochastic
Deterministic
Fields: Pv, T, Constant Properties
Fields: Pv, T, Constant Properties
1-D
2-D
3-D
??
Fields: Pv, T, Variable Properties
Fields: Pv, T, Variable Properties
Fields: Pv, T, Variable Properties
Fields: Pv, T, Ptot, Psuc, Variable Properties
Fields: Pv, T, Psuc, Variable Properties
Fields: Pv, T, Psuc, Variable Properties
Fields: Pv, T, Ptot, Psuc, Variable Properties
Fields: Pv, T, Ptot, Psuc, Building System and Sub-System Effects, Variable Properties
Stochastic Material Properties
Stochastic Boundary Conditions

Out of the Date Models

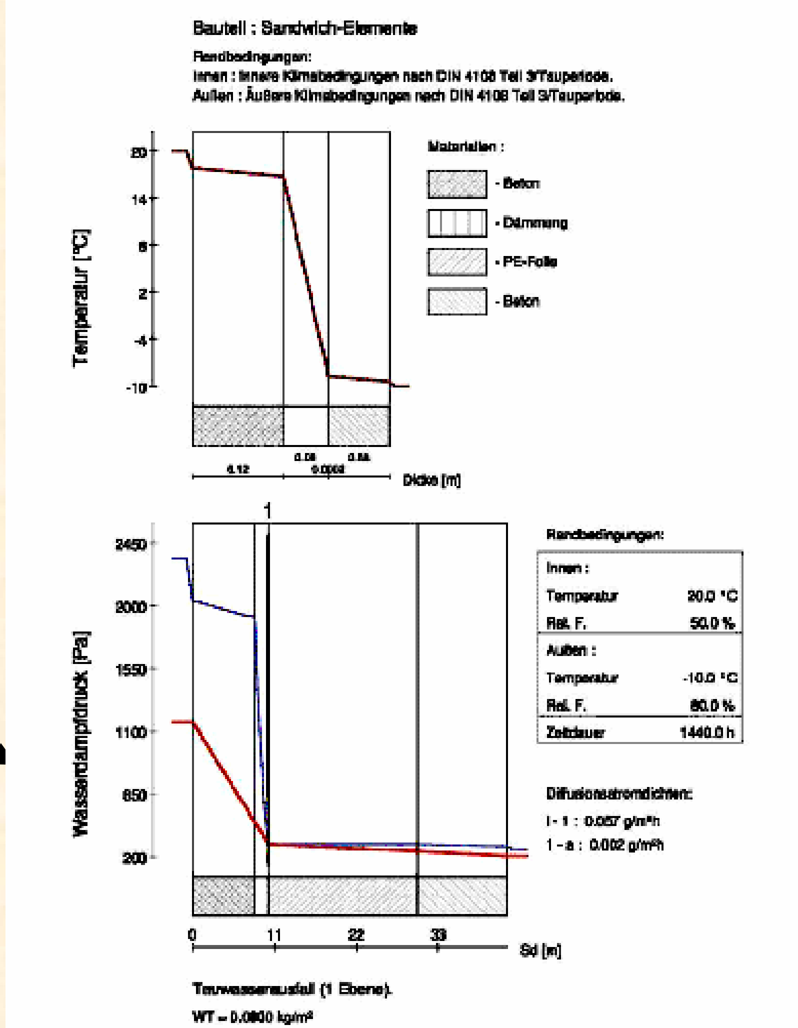
Glaser / Dew Point Method

- **Compute the temperature and saturation vapor press. profile**

- **plot p versus diffusion resistance: risk of condensation**

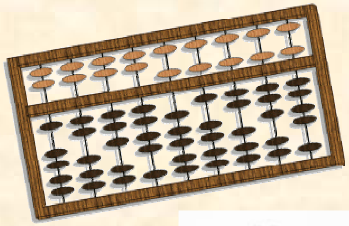
Limits:

- **only steady state behaviour**
- **only diffusion**
- **no heat and moisture storage**
- **no coupling of heat and moisture transfer**



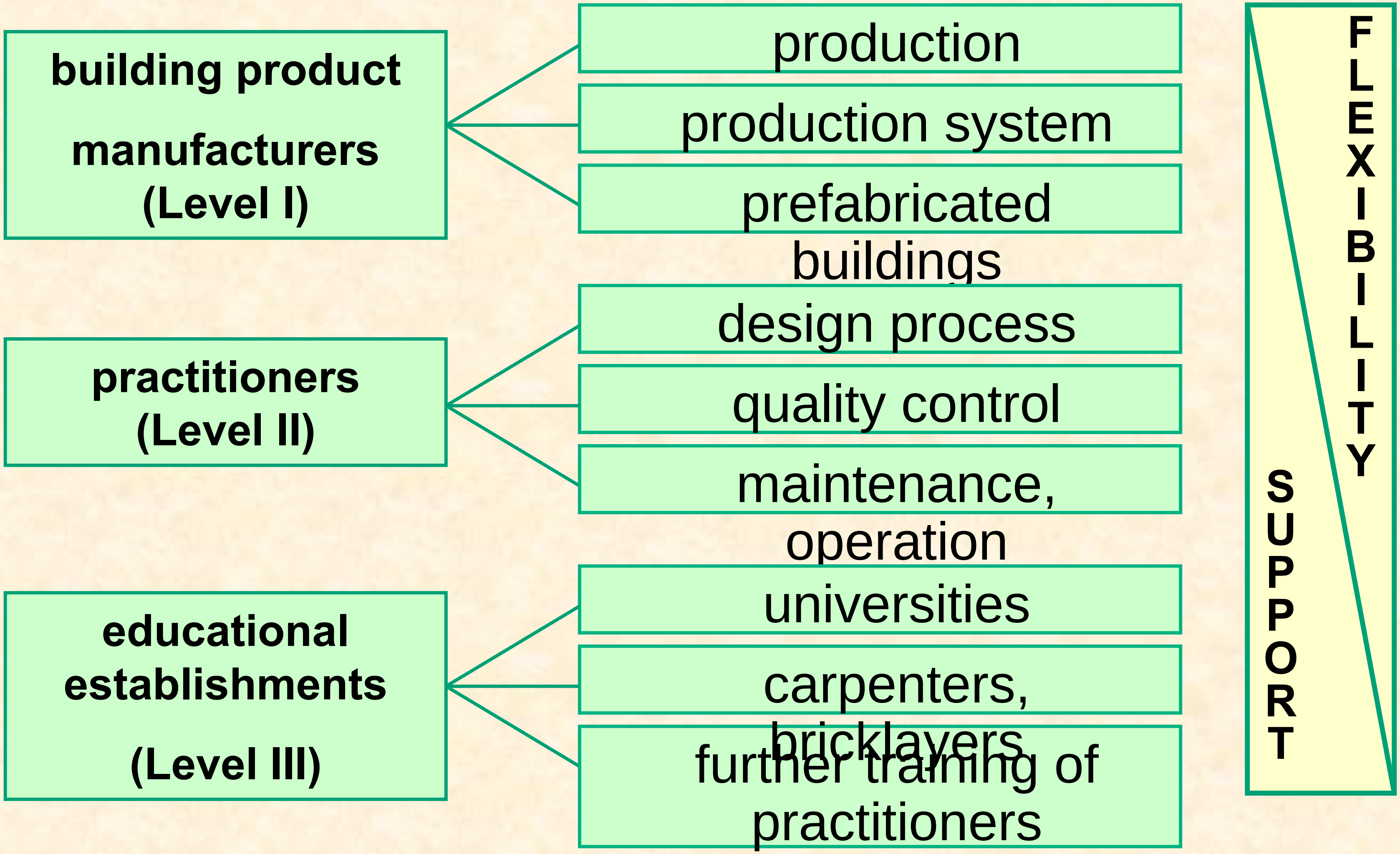
Models

History



	Authors	Models
1856	Darcy	
1957	Krischer	
1957	Philipp & de Vries	
1958	Luikov	
1983	Kießl	
1987	Häupl & Stopp	
1990	Rode	MATCH
1992	Garrecht	
1994	Künzel	WUFI
1994	Karagiozis & Salonvaara	LATENITE
1997	Grunewald	DIM, DELPHIN
1999	Bednar	
1999	Mendes	UMIDOS
2001	Karagiozis	MOISTURE-EXPERT

Trends of Software Developments



Models

Construction

Material properties

Hygrothermal Model

Moisture

$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = \nabla \cdot \left(D_\phi \nabla \phi + \delta_p \nabla \left(\phi \, p_{sat} \right) \right)$$

Energy

$$\frac{\partial H}{\partial T} \cdot \frac{\partial T}{\partial t} = \nabla \cdot \left(\lambda \nabla T \right) + h_v \nabla \cdot \left(\delta_p \nabla \left(\phi \, p_{sat} \right) \right)$$

Climate

Boundary conditions

Temperature Field
Moisture Field
Heat Fluxes
Moisture Fluxes

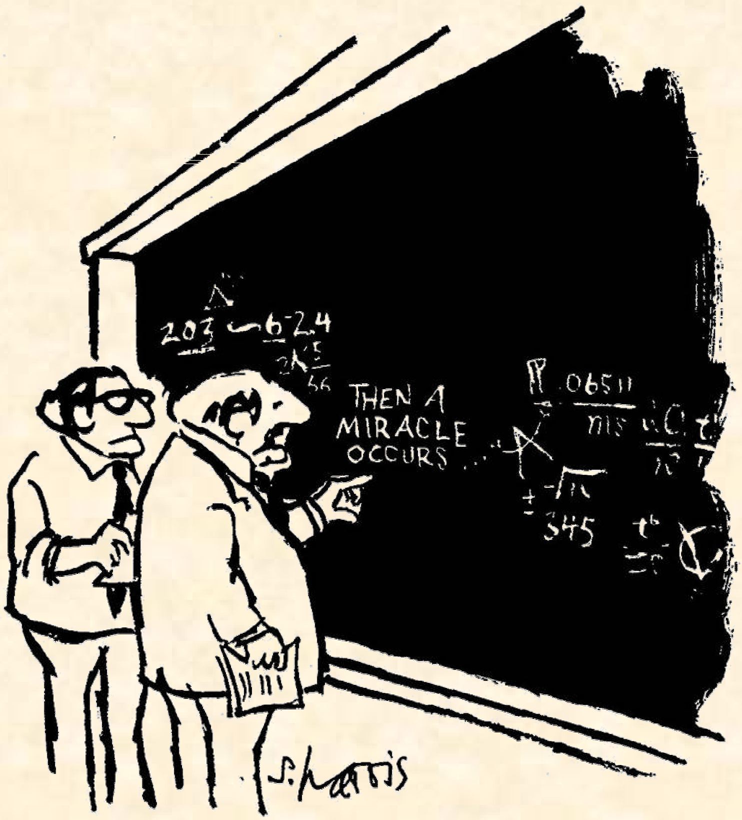
Models

Overview of available HAM-software

Name of the model	Authors	Dimen-sions	Heat conductivity	Diffusion	Capilarity	Luft-strömung	Convection	Enthalphy-ptransport
MATCH	Rode	1	+	+	+	+	+	+
WUFI-ORNL/IBP	Künzel, Karagiozis,	1	+	+	+			+
WUFI-Pro 3.2	Künzel, Schmidt, Holm	1	+	+	+			+
WUFI2d	Künzel, Holm, Eitner	2	+	+	+	+	+	+
Delphin	Grunewald	1 und 2	+	+	+	+	+	+
1d-HAM	Hagentoft, Blomberg	1	+	+		+	+	+
ConDry	Hedenblatt, Arfvidsson	1	+	+	+			+
Umidos	Mendes, Ridley	1	+	+	+			+

Models

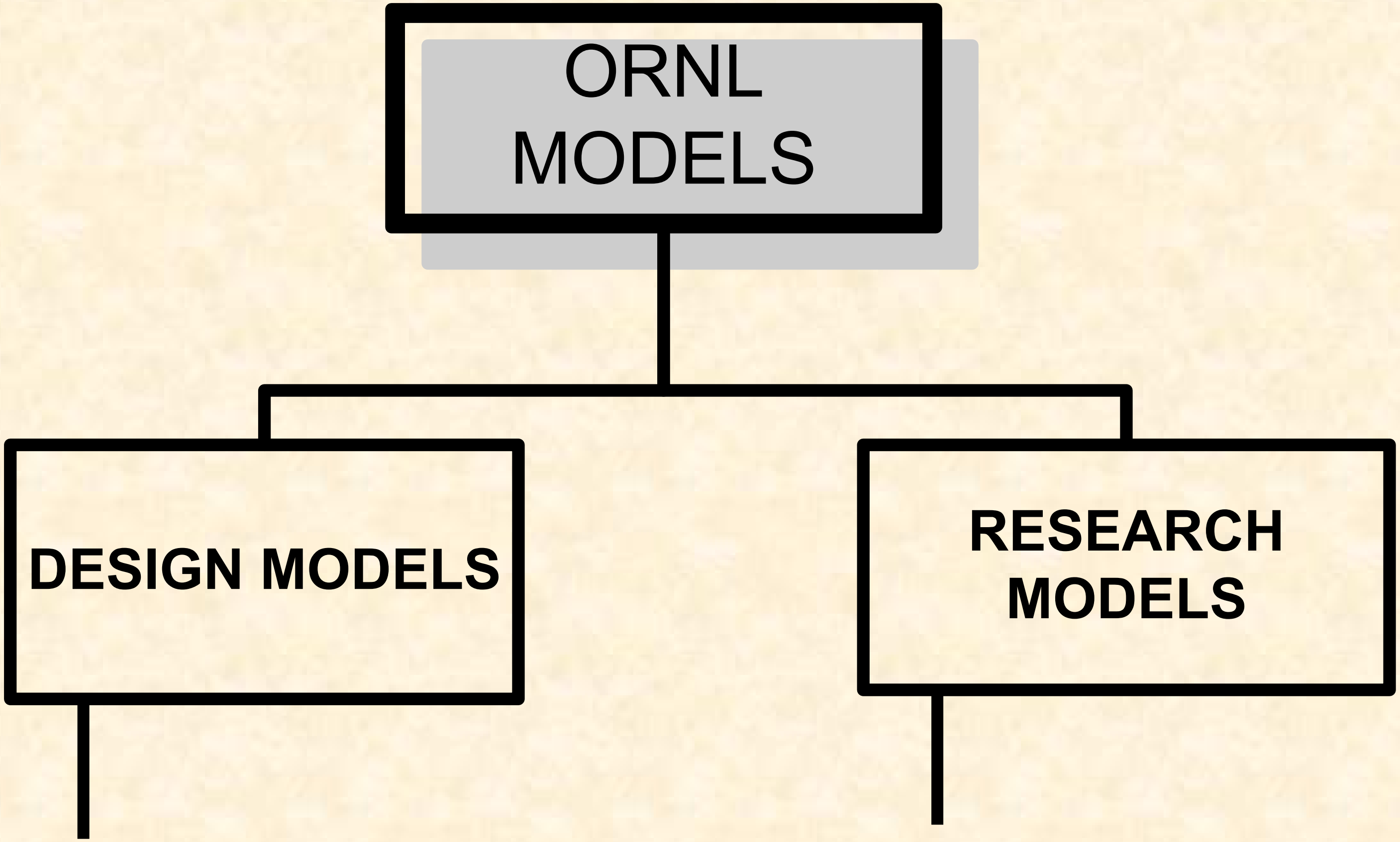
- **The operator requires knowledge, skill, and experience**
- **Important to balance input data and results with engineering experience and judgement**
- **Must understand**
  - **boundary conditions**
  - **material properties**
  - **transport mechanism**
  - **deterioration/damage mechanism**
  - **construction realities**
- **Most models are presently 1-D**



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Harris´ berühmtester Cartoon. „Ich denke, Sie sollten den zweiten Schritt besser erklären"

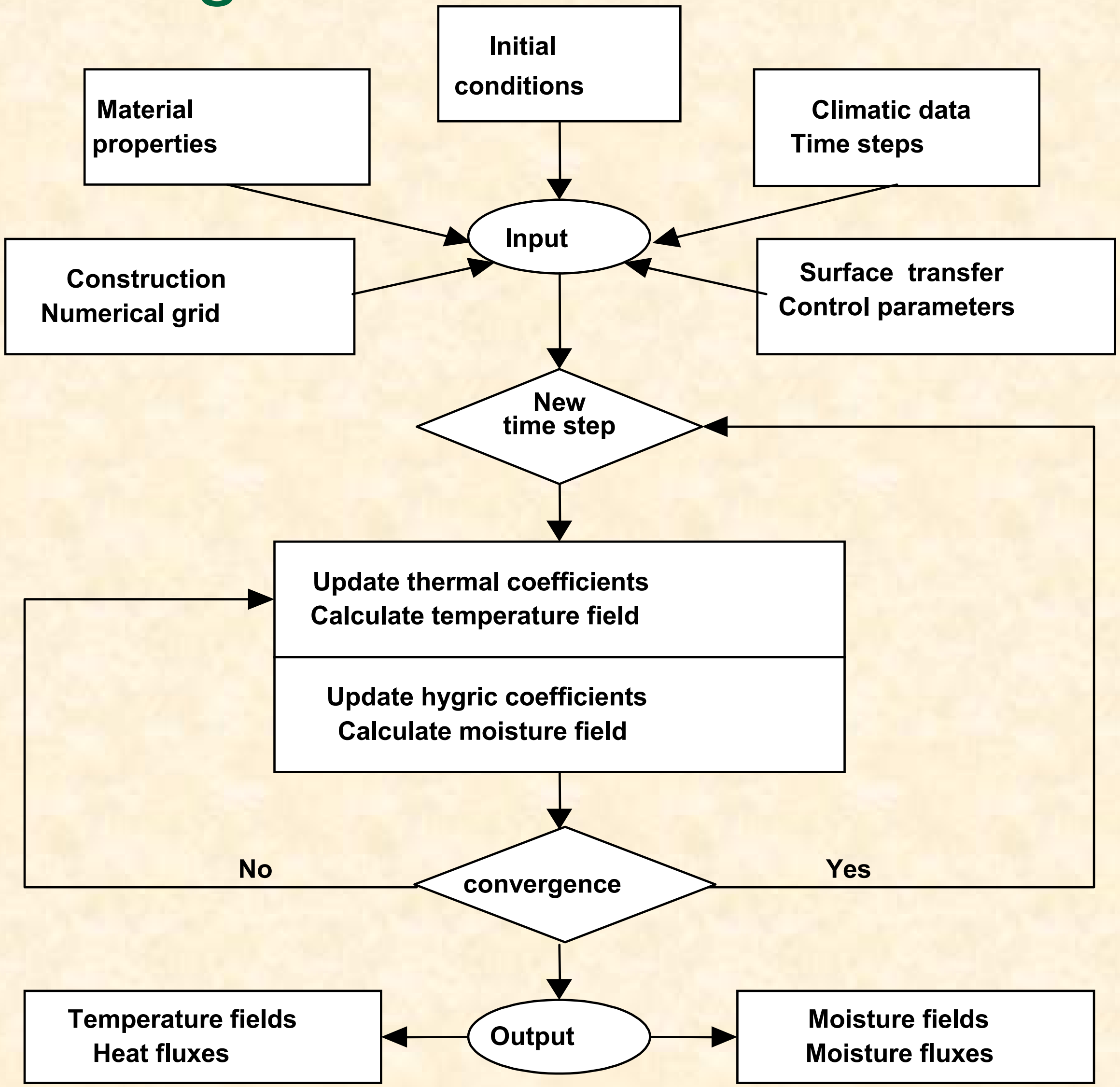
Advanced Hygrothermal Modeling



WUFI- ORNL
WUFI-2D ORNL

MOISTURE-EXPERT
ME-STOCH

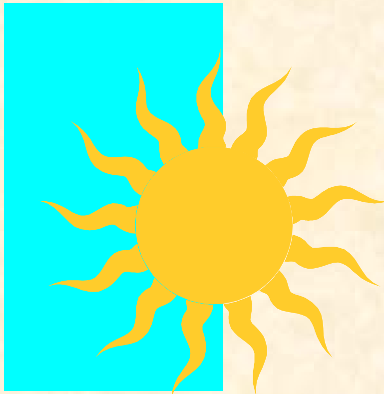
Calculation of coupled Transport: Programming

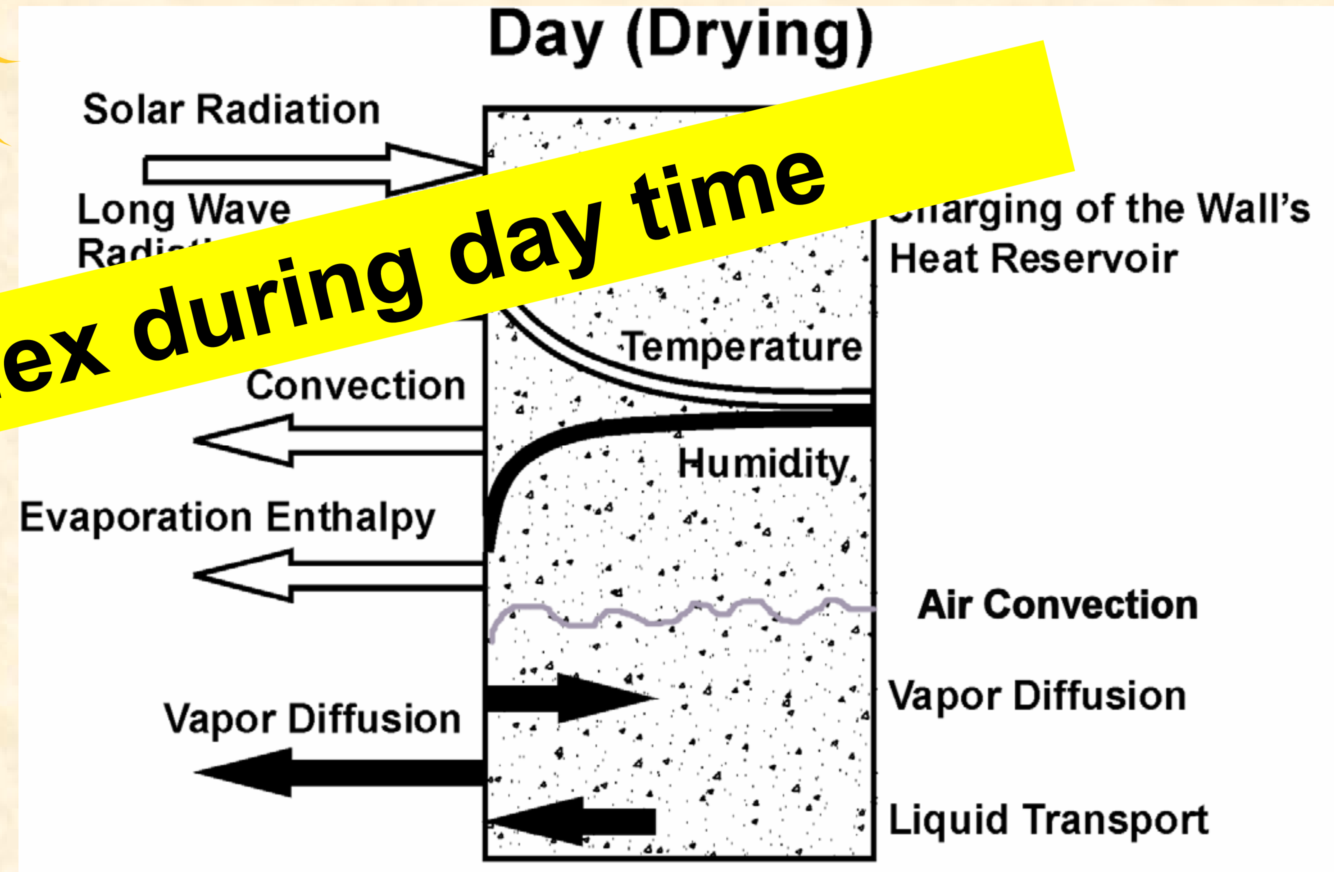


UT-BATTELLE

The Science

Transport Processes

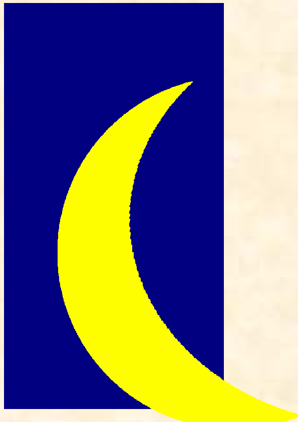


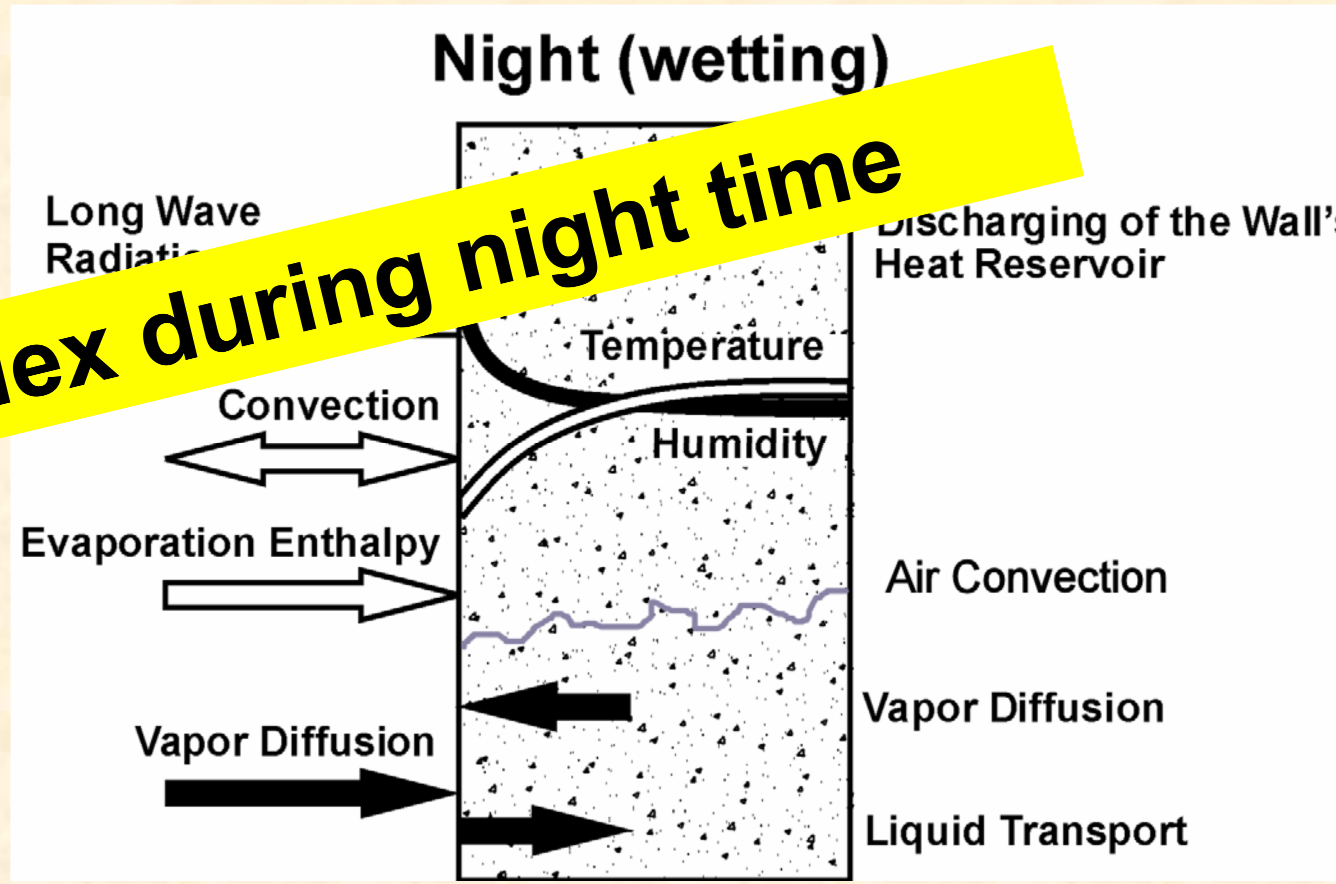


Complex during day time

The Science

Transport Processes





Complex during night time

Engineering vs Physics Analysis (REAL VERSUS IDEAL)

MODEL MOISTURE-EXPERT (Karagiozis, 2001, 2004)

Liquid Flow

Governing Equations

Vapor Flow

Moisture Balance

The moisture transport balance is given as:

Natural & Forced Convection

$$\frac{\partial(\rho_m(T)u)}{\partial t} = \underbrace{-D_\phi(u,T,x,y)\nabla\phi}_{Liquid\ flow} \underbrace{-\delta_p(u,T)\nabla P_v}_{Vapour\ flow} + \underbrace{\rho_v\vec{V}_a}_{Air\ flow}$$

Engineering vs Physics Analysis (REAL VERSUS IDEAL)

Mass Balance

- $$\frac{\partial \rho_a(T)}{\partial t} + \nabla.(\rho_a(T)\vec{v}_a) = 0$$

Momentum Balance

- $$\frac{\partial(\rho_a(T)\vec{v}_a)}{\partial t} + \nabla(\rho_a(T)\vec{v}_a;\vec{v}_a) = -\Delta P_a + \frac{\mu_a(T)}{K_a}\vec{v}_a + \rho_a(T)\vec{g}$$

Energy balance

- $$\rho_m(u,T)C_p(u,T)\frac{\partial T}{\partial t} = \underbrace{-\nabla.(\rho_a C_p(T)\vec{V}_a T)}_{Convection} + \underbrace{\nabla.(k(u,T)\Delta T)}_{Conduction} + \underbrace{L_v.(\delta_p(u,T)\nabla P_v)}_{Evaporation}$$
$$+ \underbrace{L_{ice}.\rho_m(u,T)u\frac{\partial f_l(T)}{\partial t}}_{Condensation}$$

UT-BATTELLE

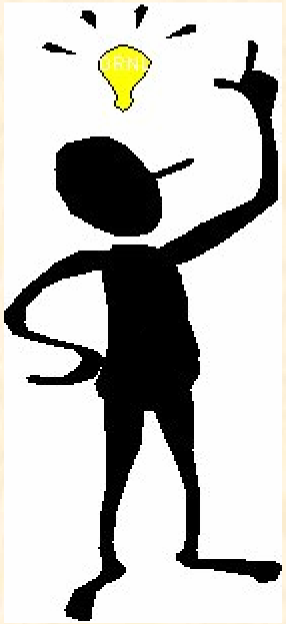
MOISTURE-EXPERT v.2.1.3a

- **2-D Capabilities**
- **Vapor Air Flow**
- **Vapor and Liquid Diffusion**
- **Solar and Sky Radiation**
- **Wind-Driven Rain**
- **Moisture-Thermal Sources and Sinks**
- **Dynamic Stack and HVAC Effects**
- **Temperature Dependent Sorption Processes**

UT-BATTELLE

WUFI, WUFI-ORNL

- **1-D Capable**
- **Vapor Air Flow**
- **Vapor and Liquid Diffusion**
- **Solar and Sky Radiation**
- **Wind-Driven Rain**
- **Moisture-Thermal Sources and Sinks, 2006**
- **Cladding Ventilation (2006)**



Model Validation

- **Very few models have been validated**

- **Different levels of validation exists**
  - **Material level**
  - **Laboratory level**
  - **Field level**

The most validated hygrothermal model worldwide is WUFI, WUFI-ORNL

The most validated research model worldwide is MOISTURE-EXPERT

UT-BATTELLE

Was the model Validated ???

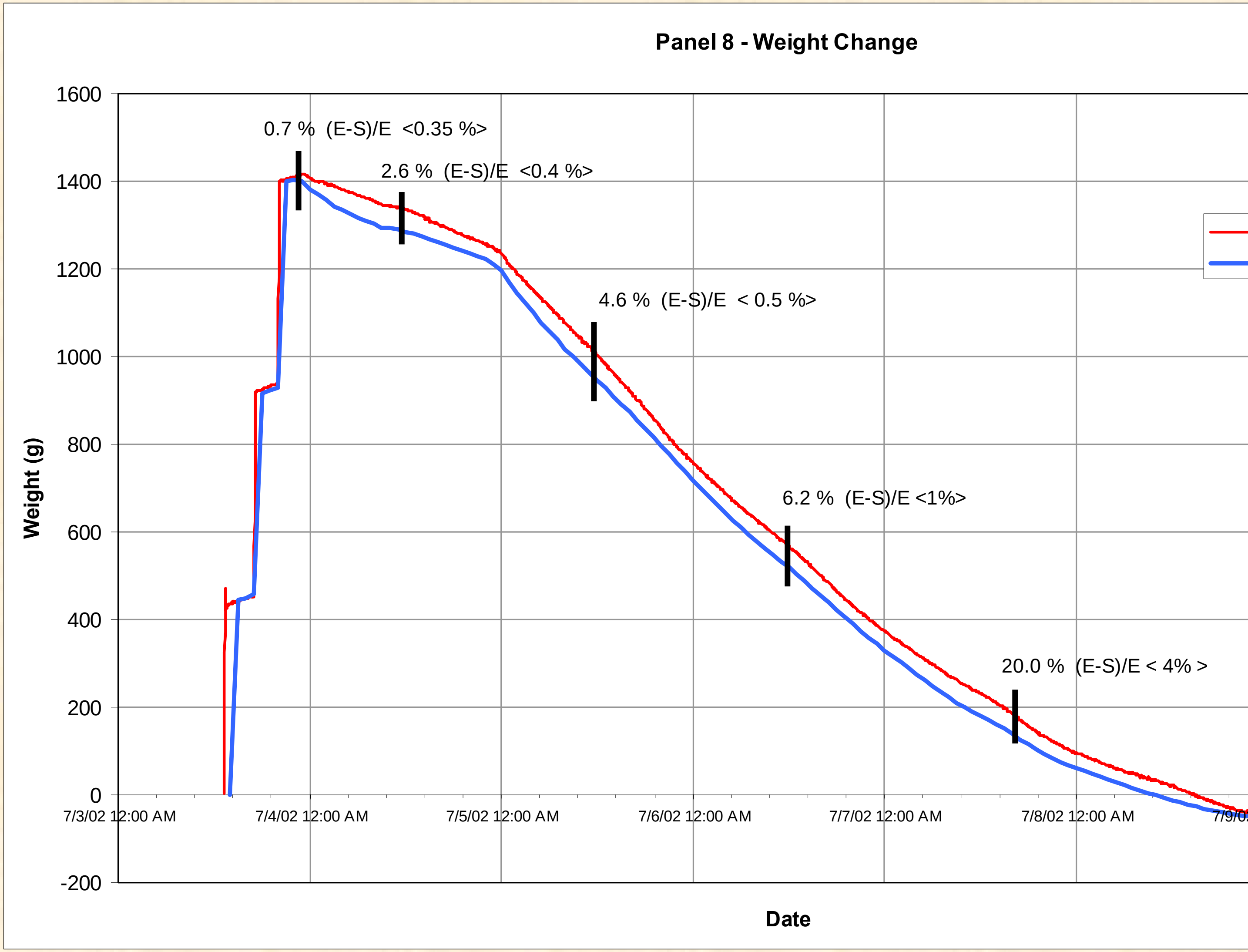
- **Yes.. Yes.. and Yes**

Real Field & Lab Data

  - **ASHRAE TRP 1091 PSU/UW/ORNL**
  - **Seattle WSU/DOE/ORNL Project**
  - **Charleston EIMA/DOE/ORNL**

UT-BATTELLE

Laboratory Validation (0.8 Lps)



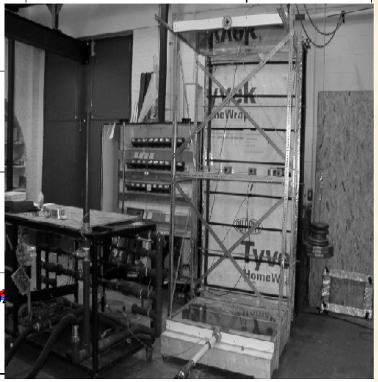


Figure 3. Airflow manifolds connected to test panel on counterbalance system (Burnett et al [2004])

Laboratory Validation (1.6 Lps)

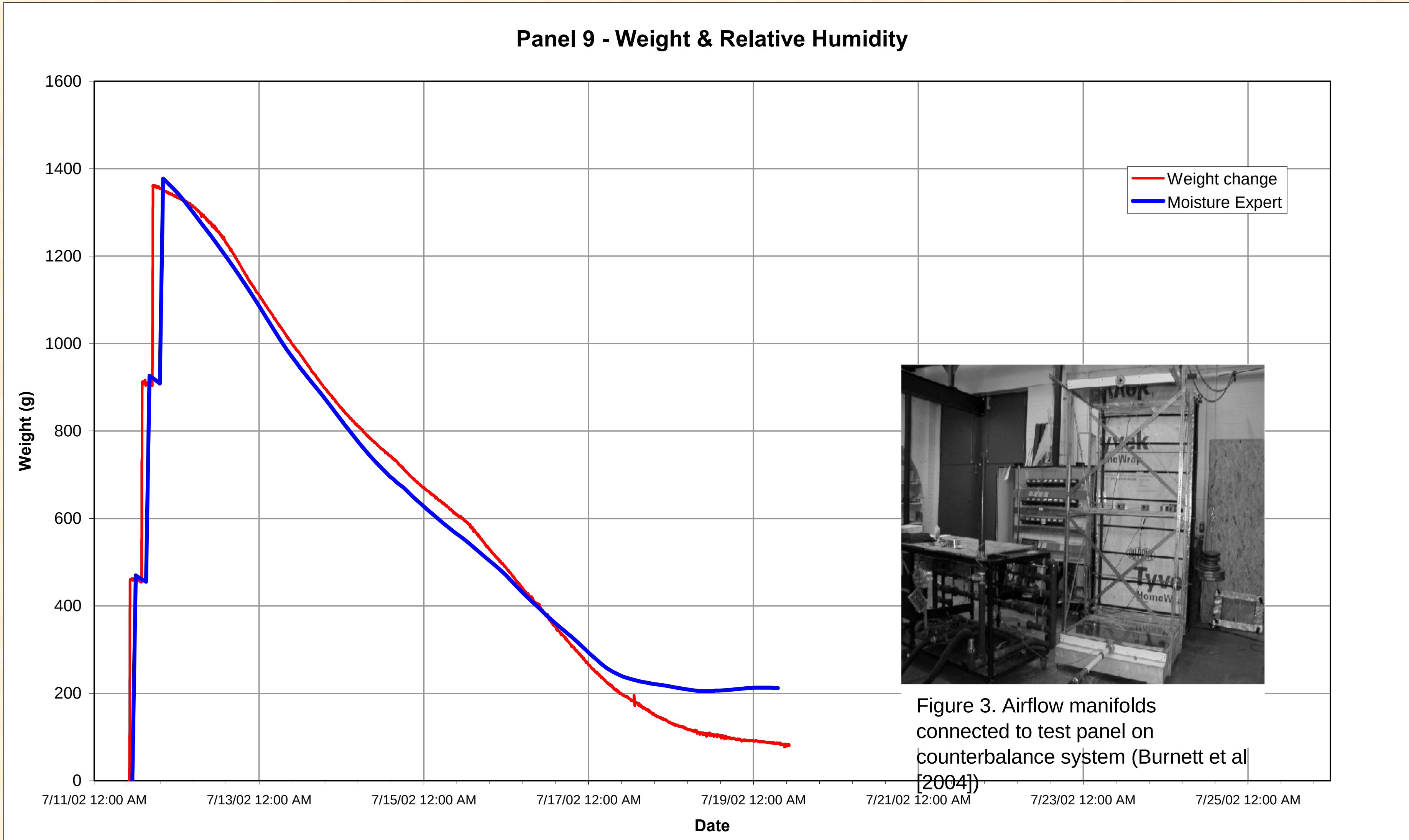
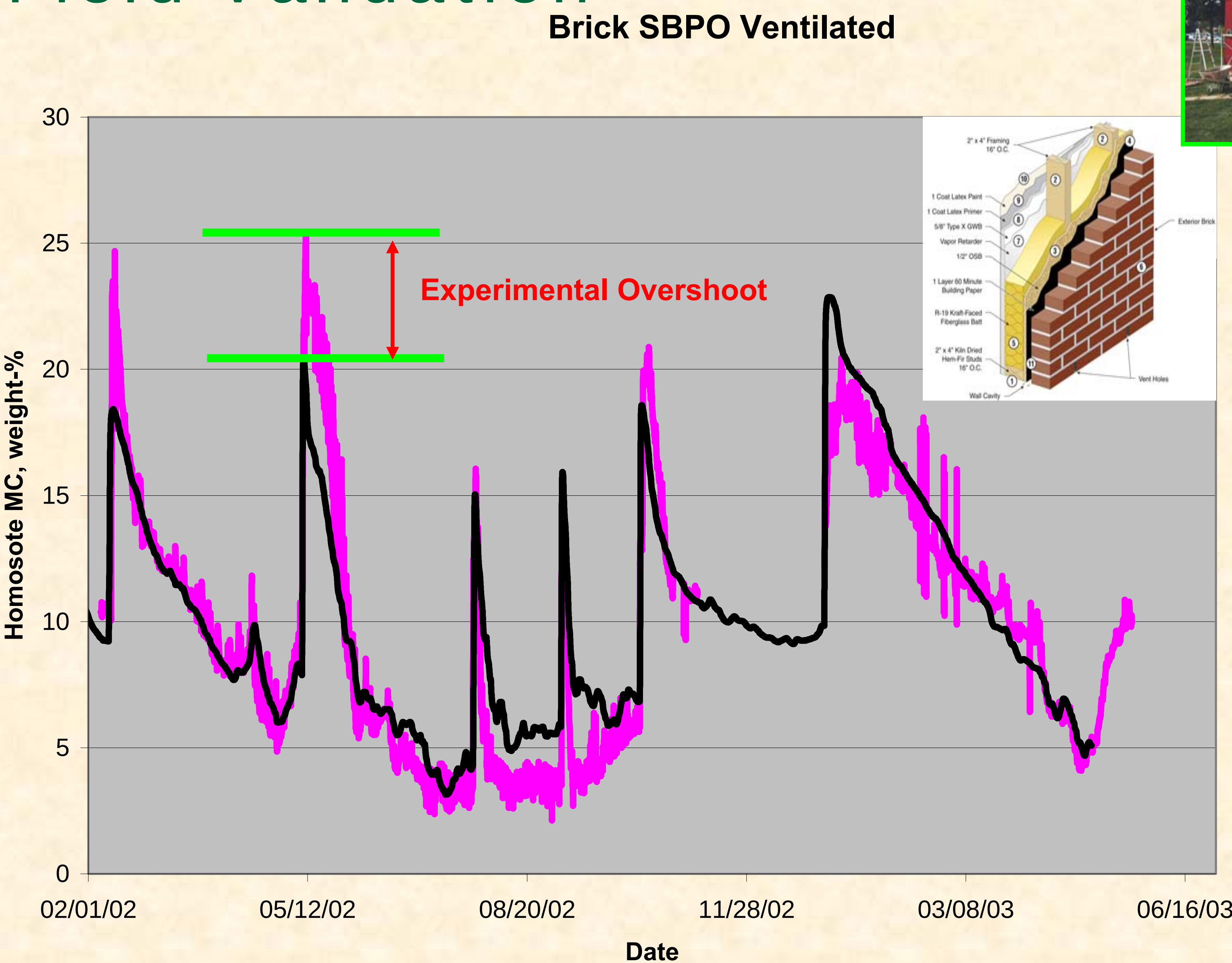
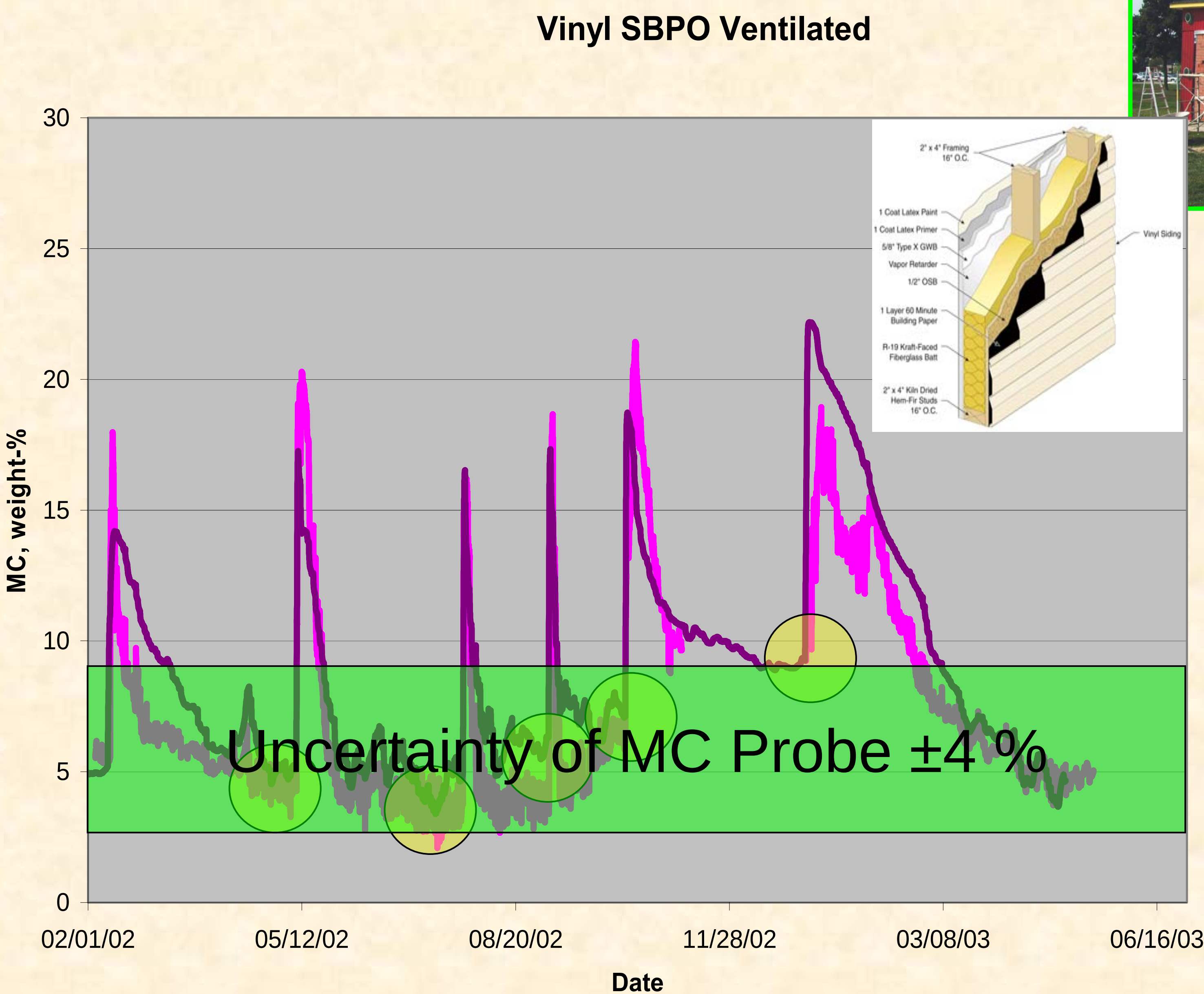


Figure 3. Airflow manifolds connected to test panel on counterbalance system (Burnett et al [2004])

Field Validation



Field Validation

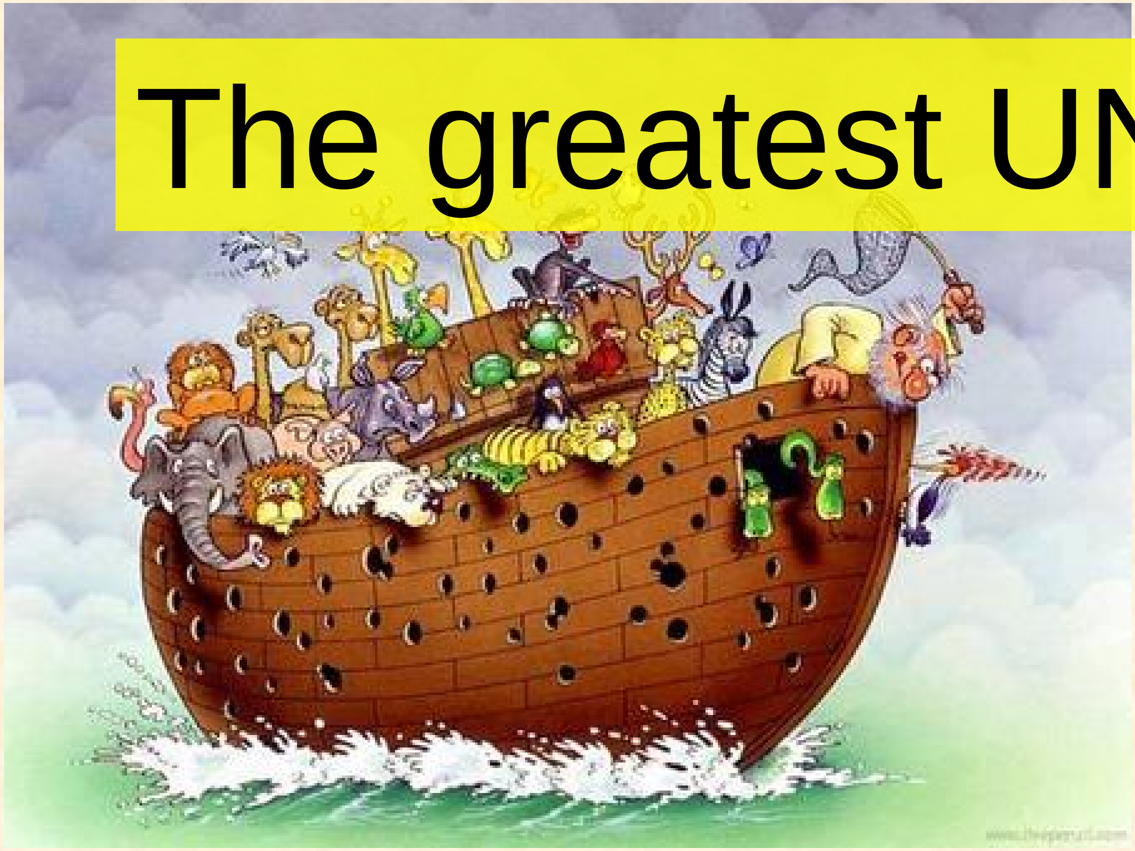


Validation (LAB + FIELD)

- ME has been validated for Brick & Vinyl Walls
- Excellent Agreement was found
- Complex Processes Involved:
  - Liquid Penetration (Incidental Water)
  - Redistribution of Water
  - Ventilation drying
  - Diffusion Transport

UT-BATTELLE

LOADS



The greatest UNKNOWNS

Question :

How much load (water penetration) Does this woodpecker cause ?

LOADS

- Rely on past data: NOPE
- Guess : N
- ASHRAE SPC 160 P Yeap ! (Systems Approach)

Evolution in understanding

Moisture Control: Building System

Application Case

- **IECC Vapor Retarder Recommendation**

Effort by DOE

Building Science Corporation ORNL

UT-BATTELLE

Vapor Retarder Movement

In the USA Millions of Homes are in Trouble

The Confusion

Vapor Guidelines & Codes

- **Vapor Retarders are needed**
- **Vapor Retarders are not needed**
- **Vapor Retarder are imp**
- **Vapor Retard important**

Too many opinions, not enough science

UT-BATTELLE

MOISTURE ENGINEERING

1) **Load Based Analysis (Interior & Exterior)**

2) **Building Envelope System and Sub-systems are needed**

3) **Includes all appropriate physics that describe the transport process**

4) **Incorporates a saftey factor**

UT-BATTELLE

Saftey Factor in Moisture Analysis?? (WOW !!)

Factor of safety (FoS), also known as *Safety Factor*, is a multiplier applied to the calculated maximum load (*vapor, rain,water penetration or a combination*) to which a component or assembly will be subjected. Thus, by effectively "overengineering" the design by strengthening components or including redundant systems, a Factor of Safety accounts for imperfections in materials, flaws in assembly, material degradation, and uncertainty in load estimates. An alternative way to use the safety factor is to derate the performance (strength) of the material/system to get a "design" strength.

Sdesign = Syield / FoS
Sdesign = Sproof / FoS

UT-BATTELLE

Margin of Saftey in Moisture Analysis?? (WOW !!)

An appropriate **factor of safety** is chosen based on several considerations. Prime considerations are the accuracy of load and ageing estimates, the consequences of failure, and the cost of overengineering the component to achieve that factor of safety. For example, components whose **failure** could result in substantial financial loss, serious injury (health consequences or death usually use a safety factor of **four** or higher (often ten). **Non-critical** components generally have a safety factor of **two**. An interesting exception is in the field of Aerospace engineering, where safety factors are kept low (about **1.15 - 1.25**) because the costs associated with **structural weight** are so high. This low safety factor is why aerospace parts and materials are subject to more stringent **testing** and **quality control**.

Factor of safety of **1** implies **no** safety at all. Hence some engineers prefer to use a related term, Margin of Safety (MoS) to describe the design parameters. The relation between MoS and FoS is

MoS = FoS - 1.

UT-BATTELLE

How did we use a Safety Factor

Exterior Load

- **Choose Weather Years in a specific Manner**

Interior Load

- **Investigated three different interior loads**

Wall & Location Specific

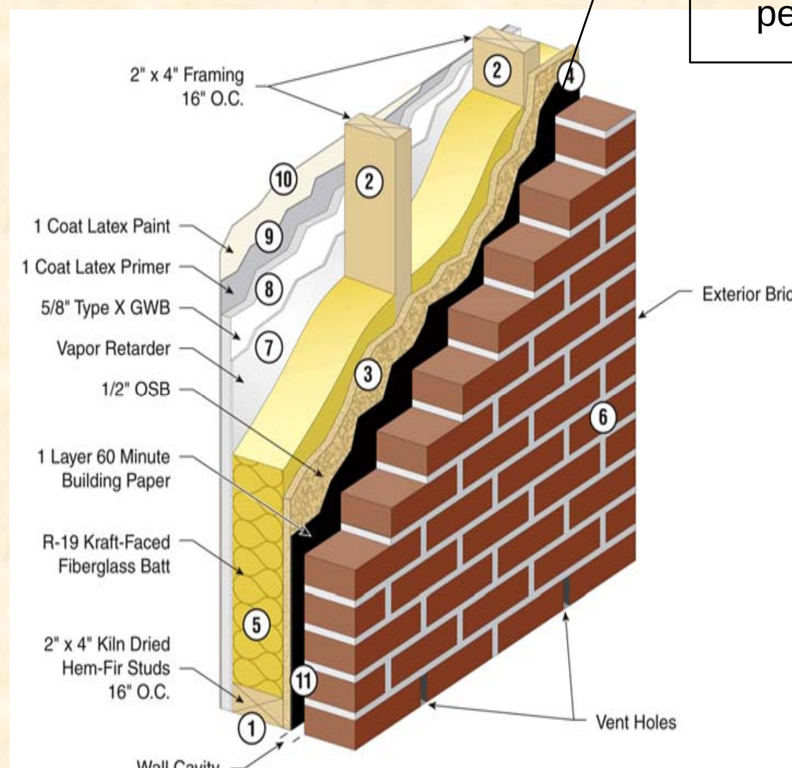
- **Water Penetration in Wall (Dump Water into wall)**

Water penetration: SAFETY FACTOR

SPC 160P

1 % water penetration
On WRB

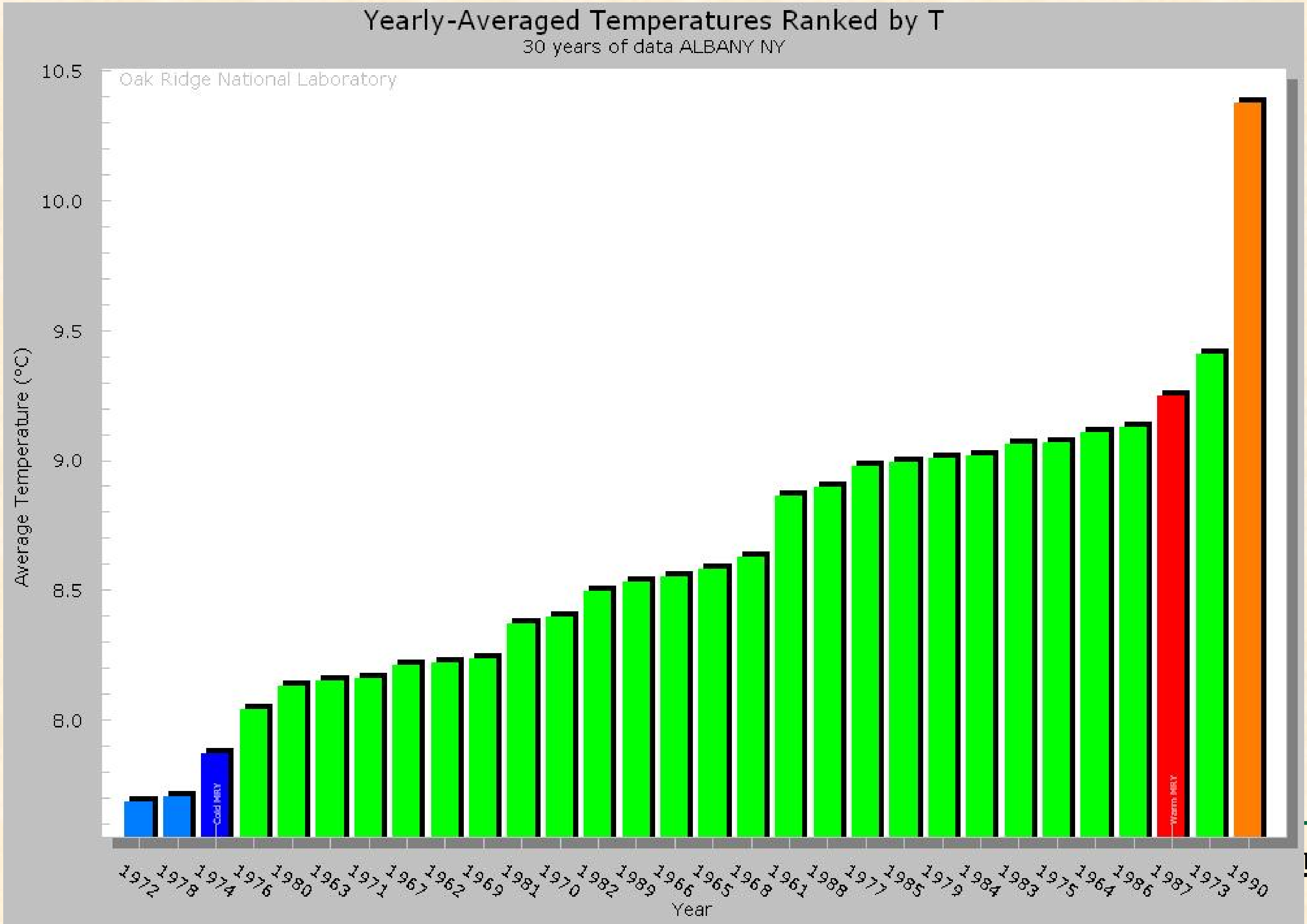
1 % water penetration



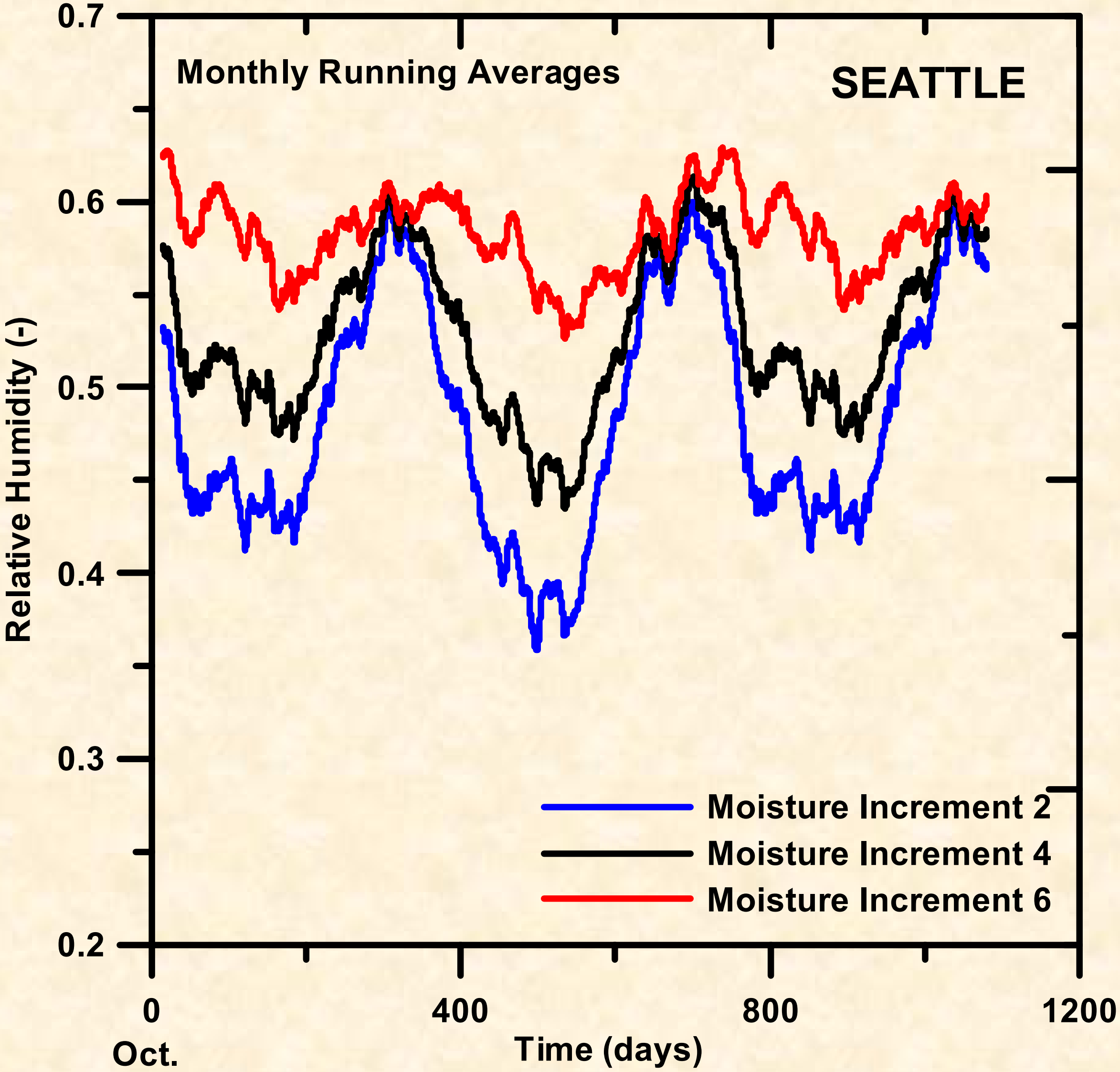
T-BATTELLE

Exterior Loads (SF)

- **Employed IEA Annex 24 (10 % Hot & Cold Years)**



Interior Loads (SF)

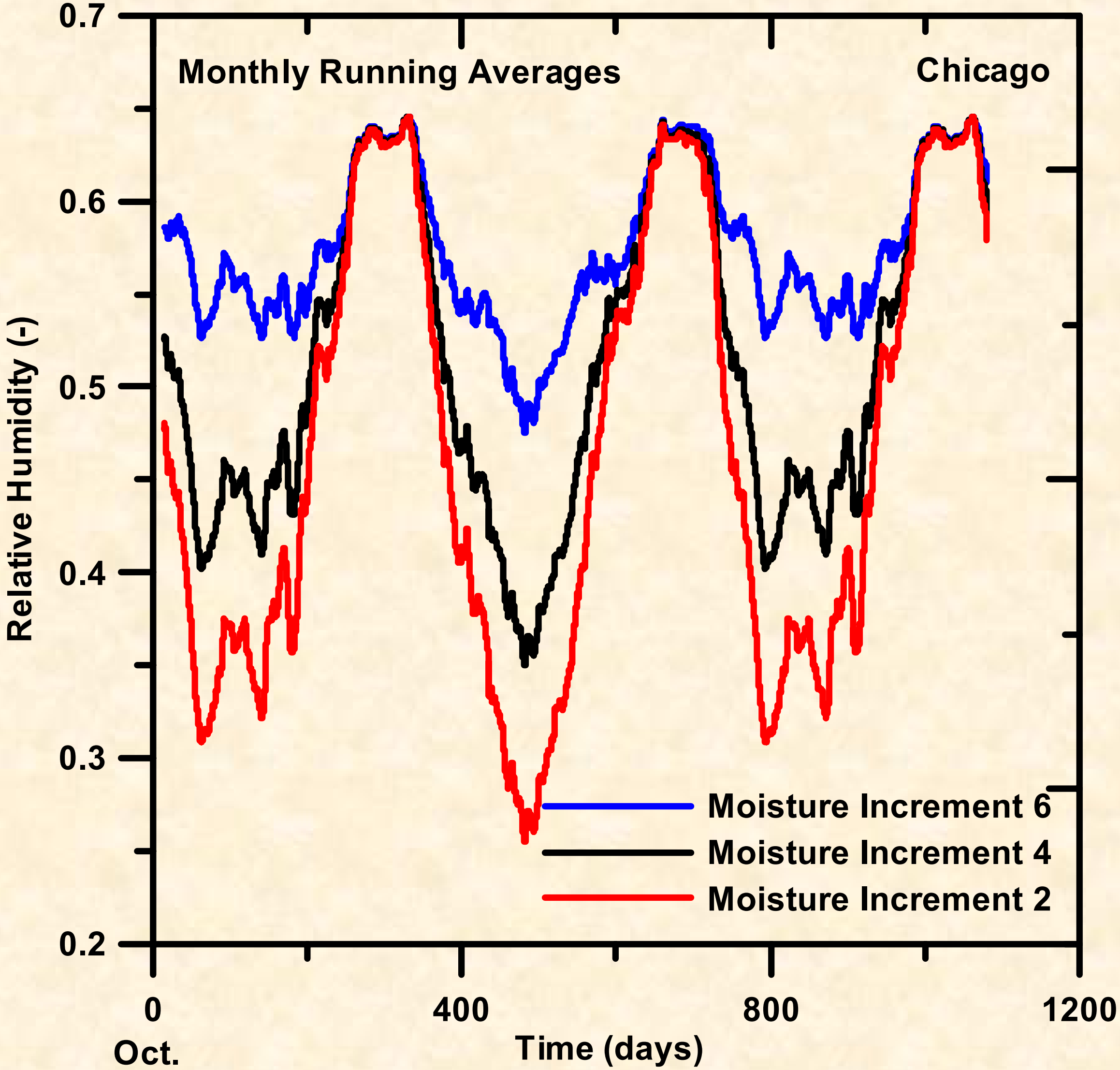


BSC: Approach A

Three Loading Conditions..

UT-BATTELLE

Interior Loads (SF)

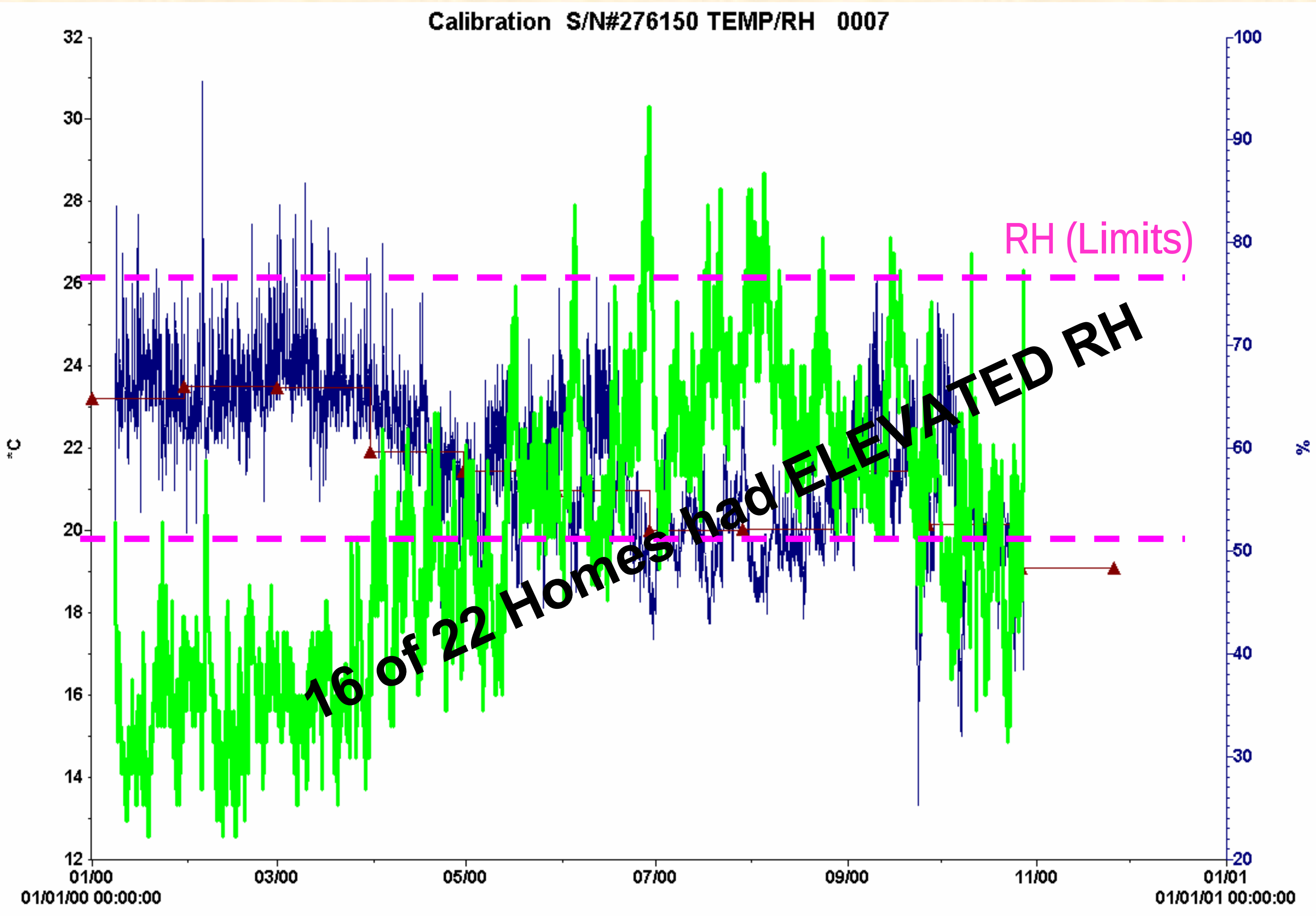


BSC: Approach A

Three Loading Conditions..
(low-normal
mid – average
High – above average)

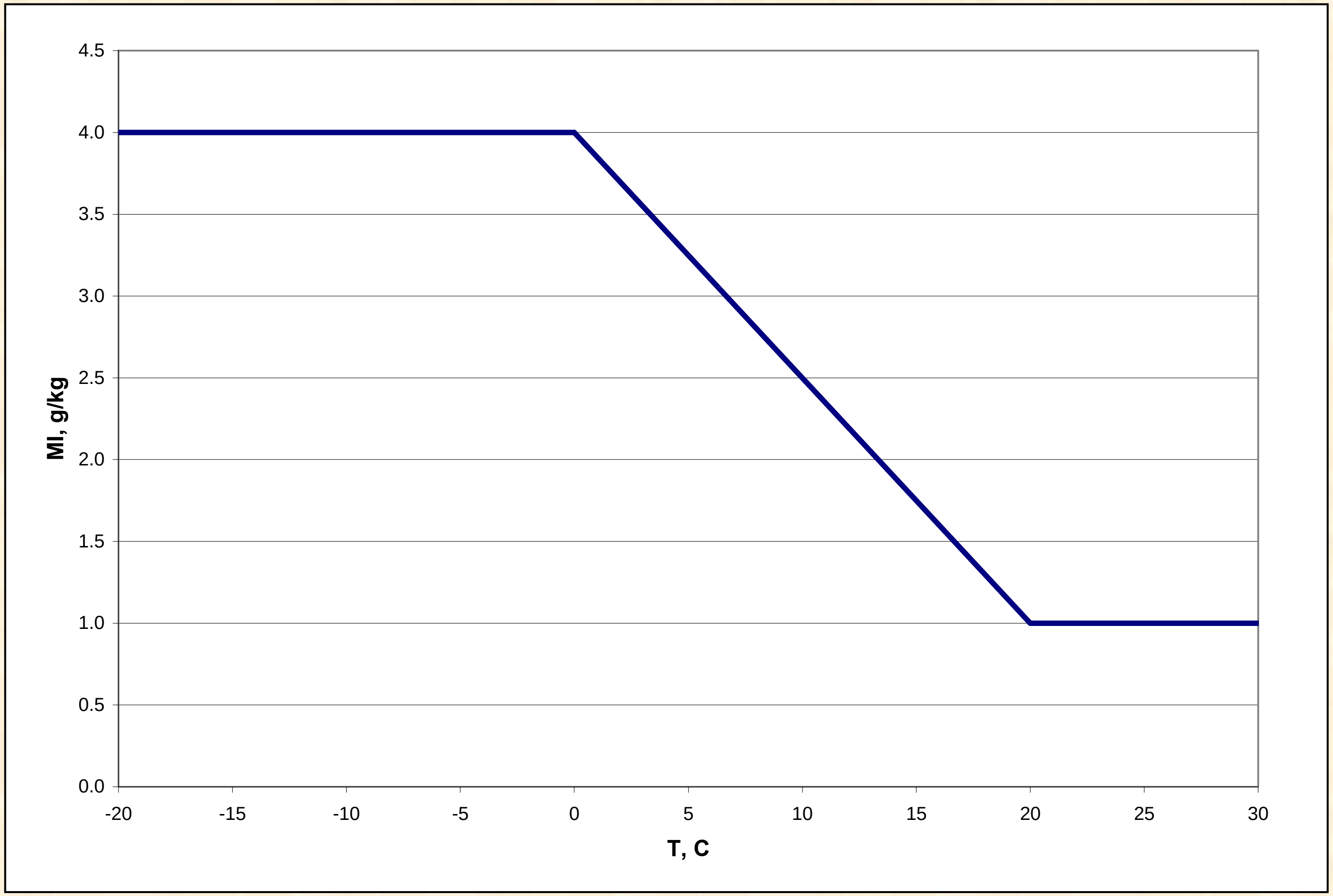
Real Monitored Data

SEATTLE:



DCLU-WSU-(ORNL)

Interior Loads (SF)



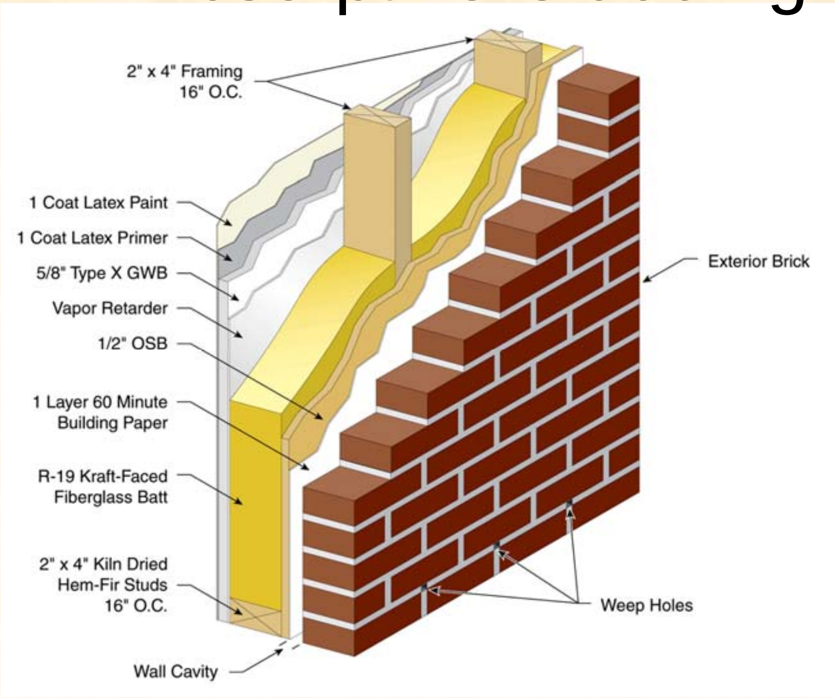
BSC: Approach A

Three Loading Conditions..

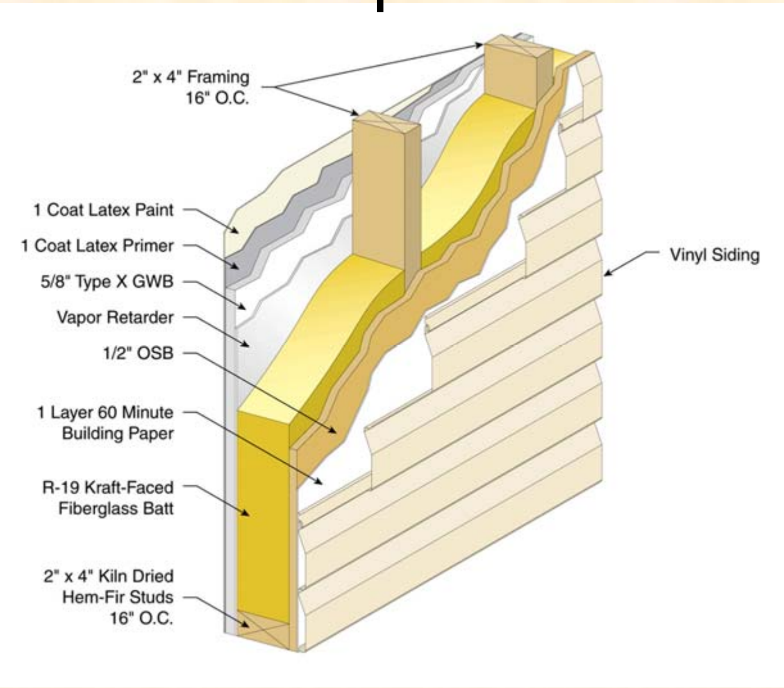
We were not Skimpy with Loads

Simulation Parametric -Part A

Absorptive Cladding

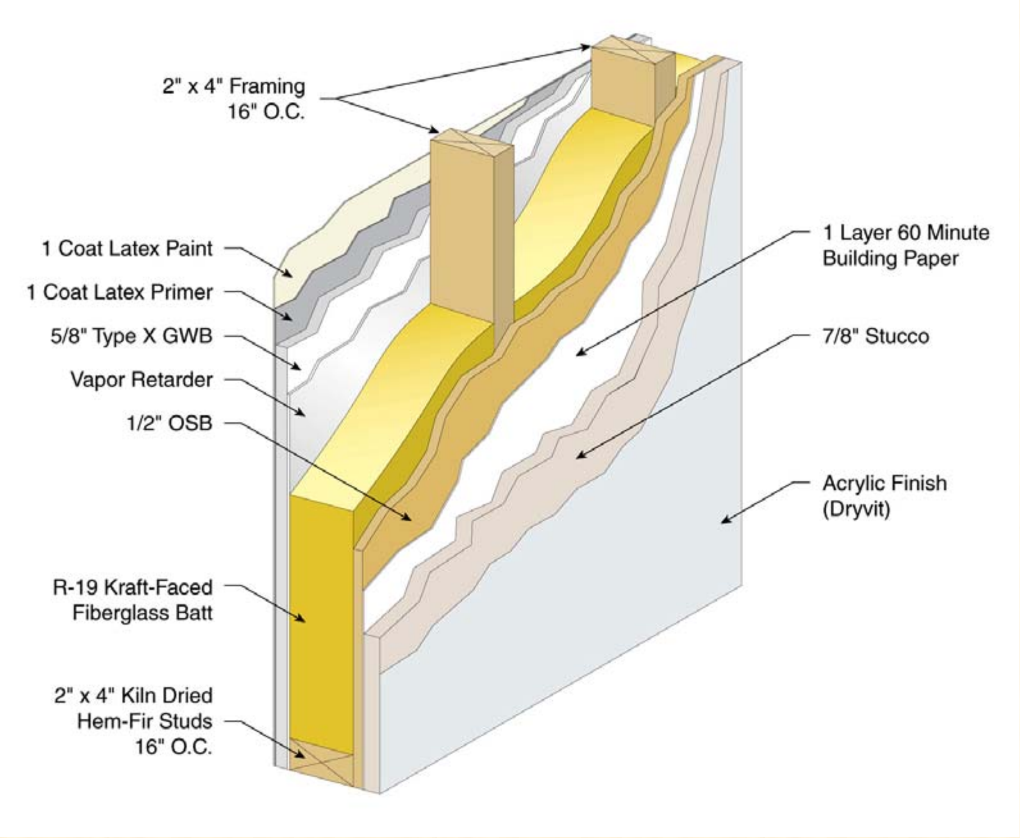


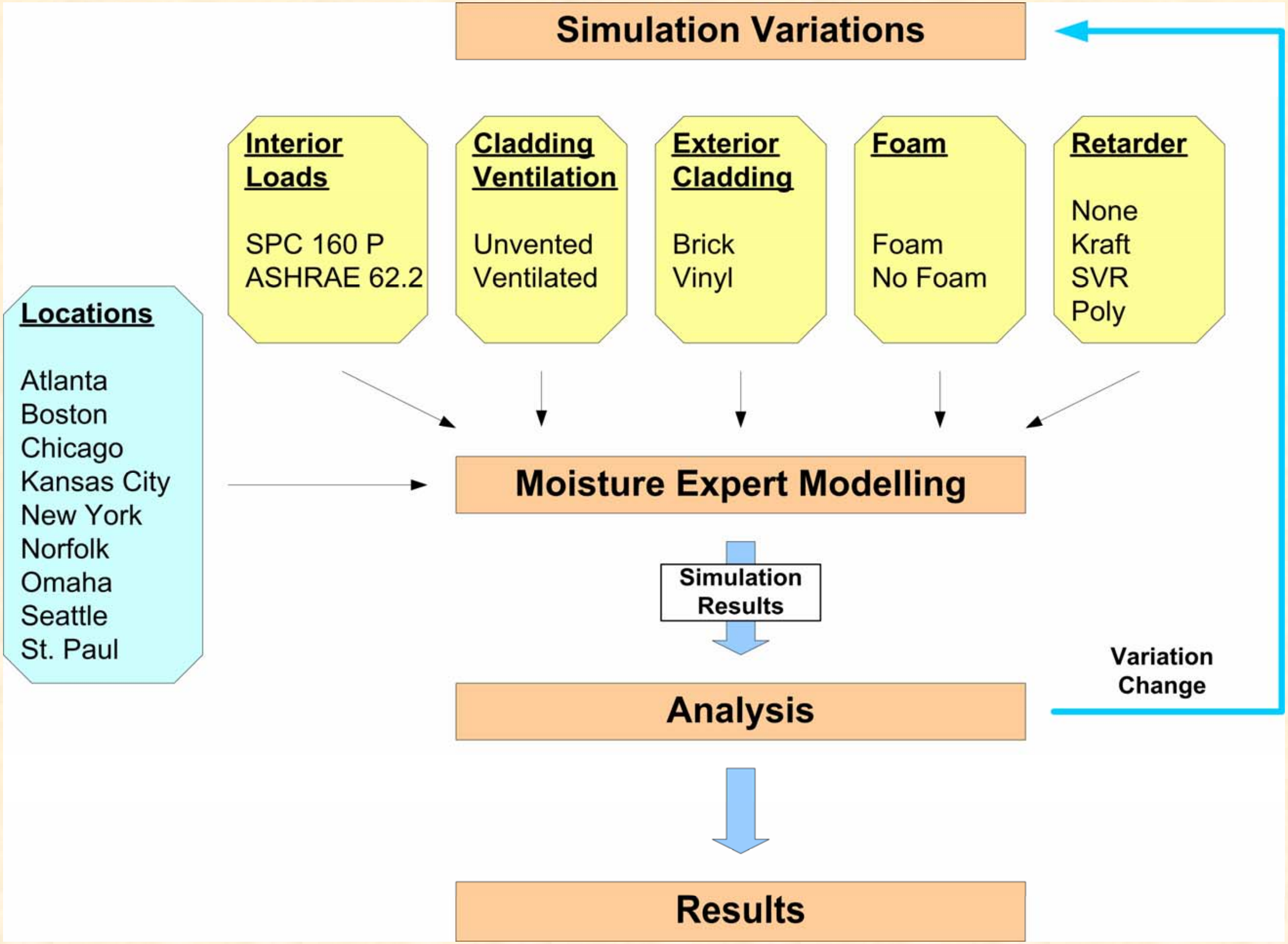
Non Absorptive Cladding



Simulation Parametric – BSC/Building America

Absorptive to Semi Absorptive Cladding

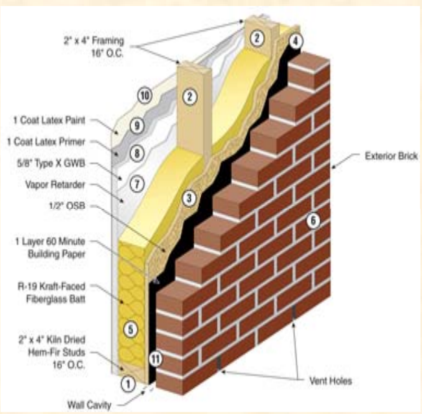


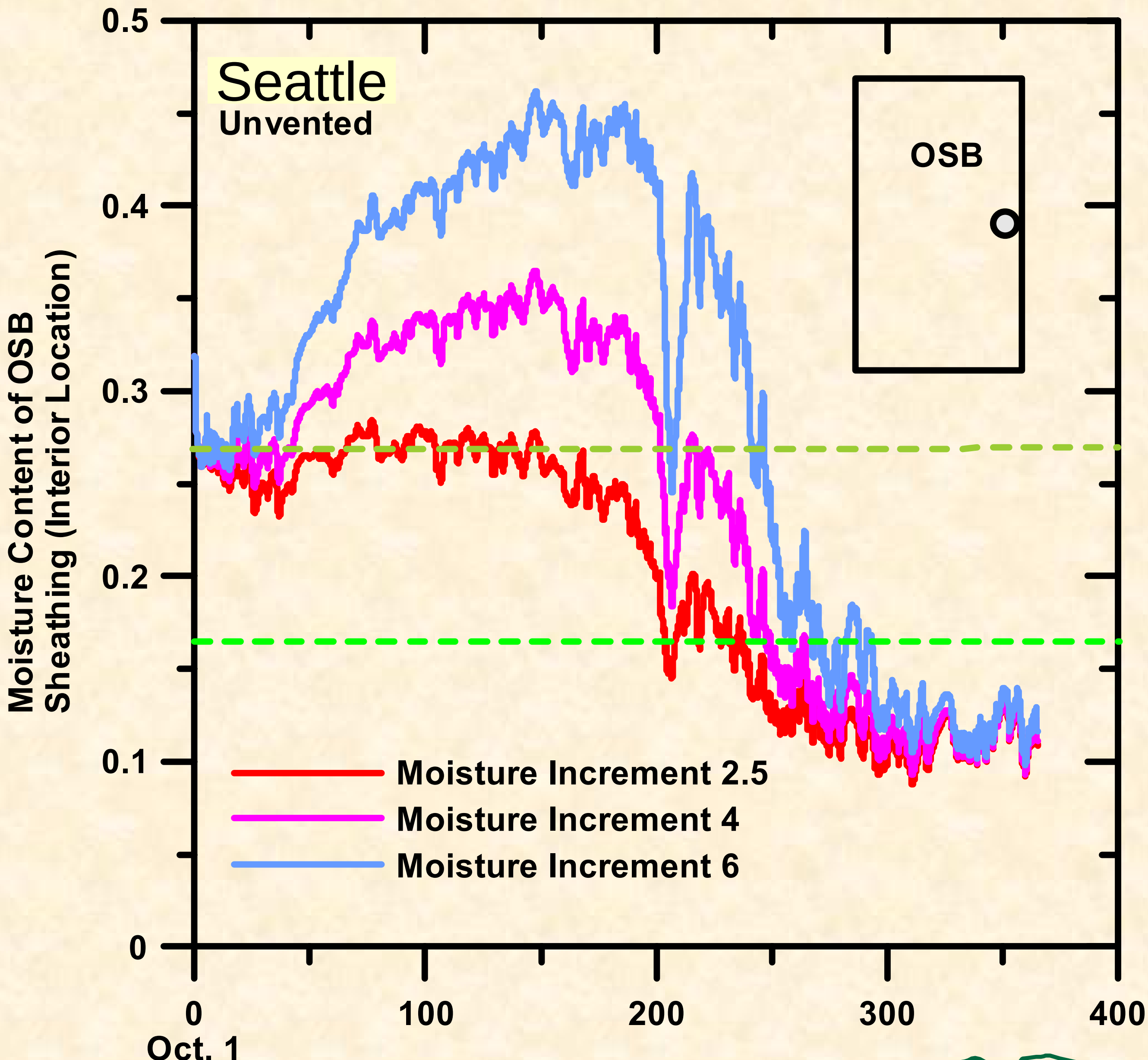

Simulation Variations
Interior Loads
SPC 160 P
ASHRAE 62.2
Cladding Ventilation
Unvented
Ventilated
Exterior Cladding
Brick
Vinyl
Foam
Foam
No Foam
Retarder
None
Kraft
SVR
Poly
Locations
Atlanta
Boston
Chicago
Kansas City
New York
Norfolk
Omaha
Seattle
St. Paul
Moisture Expert Modelling
Simulation Results
Variation Change
Analysis
Results

UT-BATTELLE

Results

Brick Veneer
Interior Coat
8-Perms

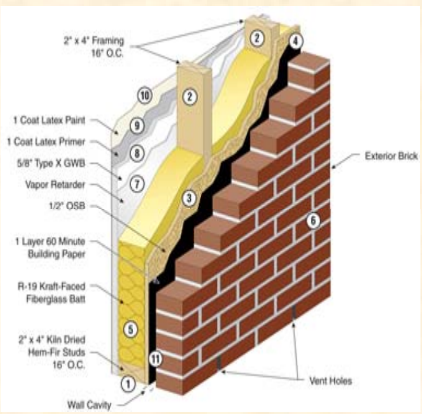


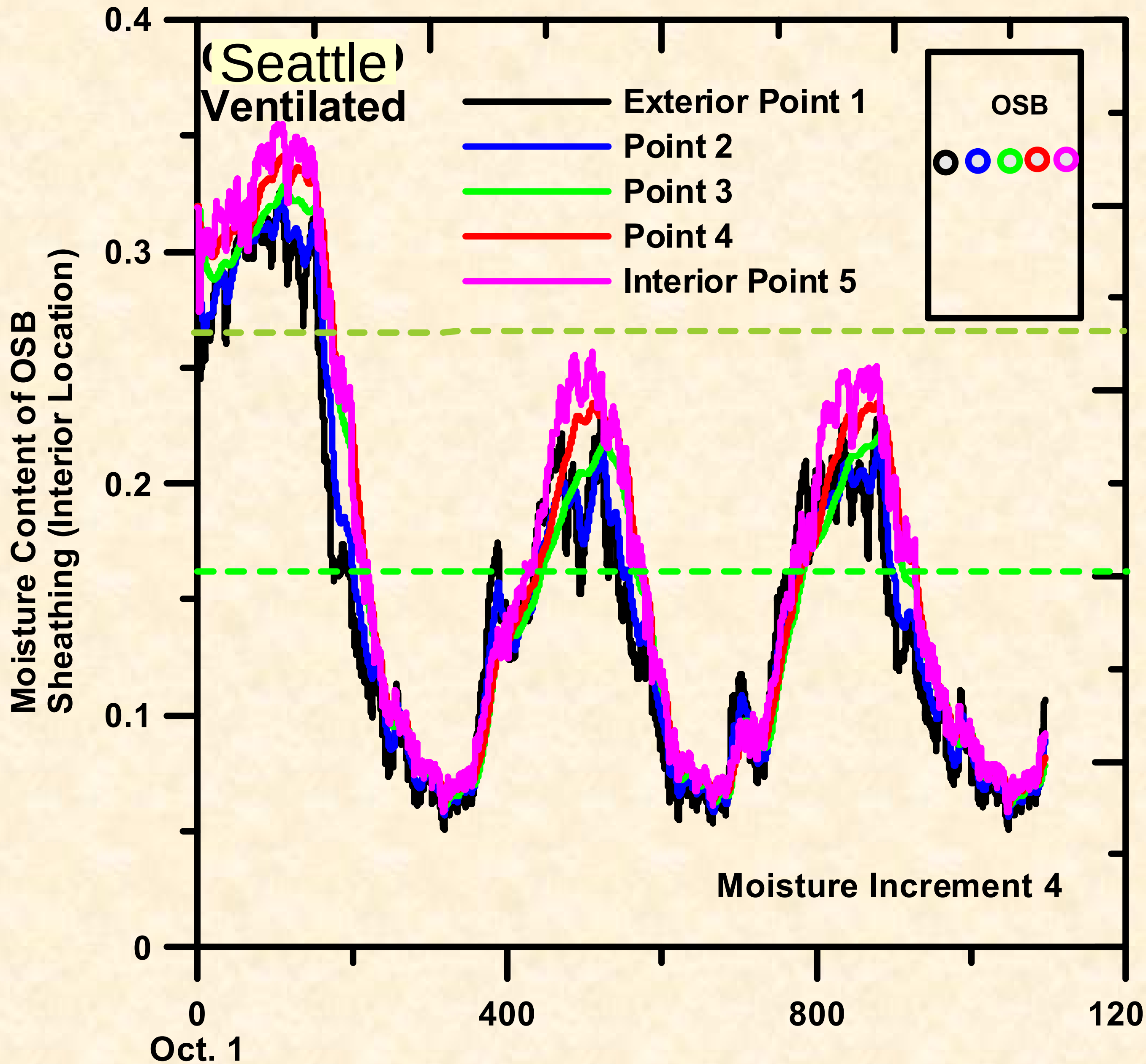


Brick Veneer

Interior Coat

8-Perms

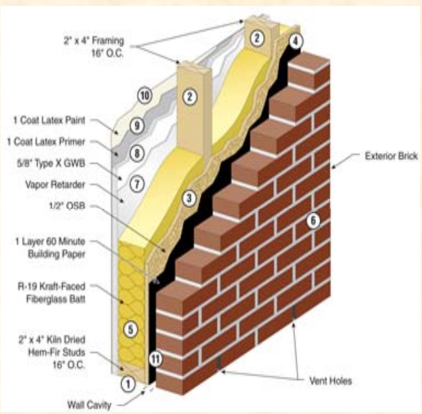


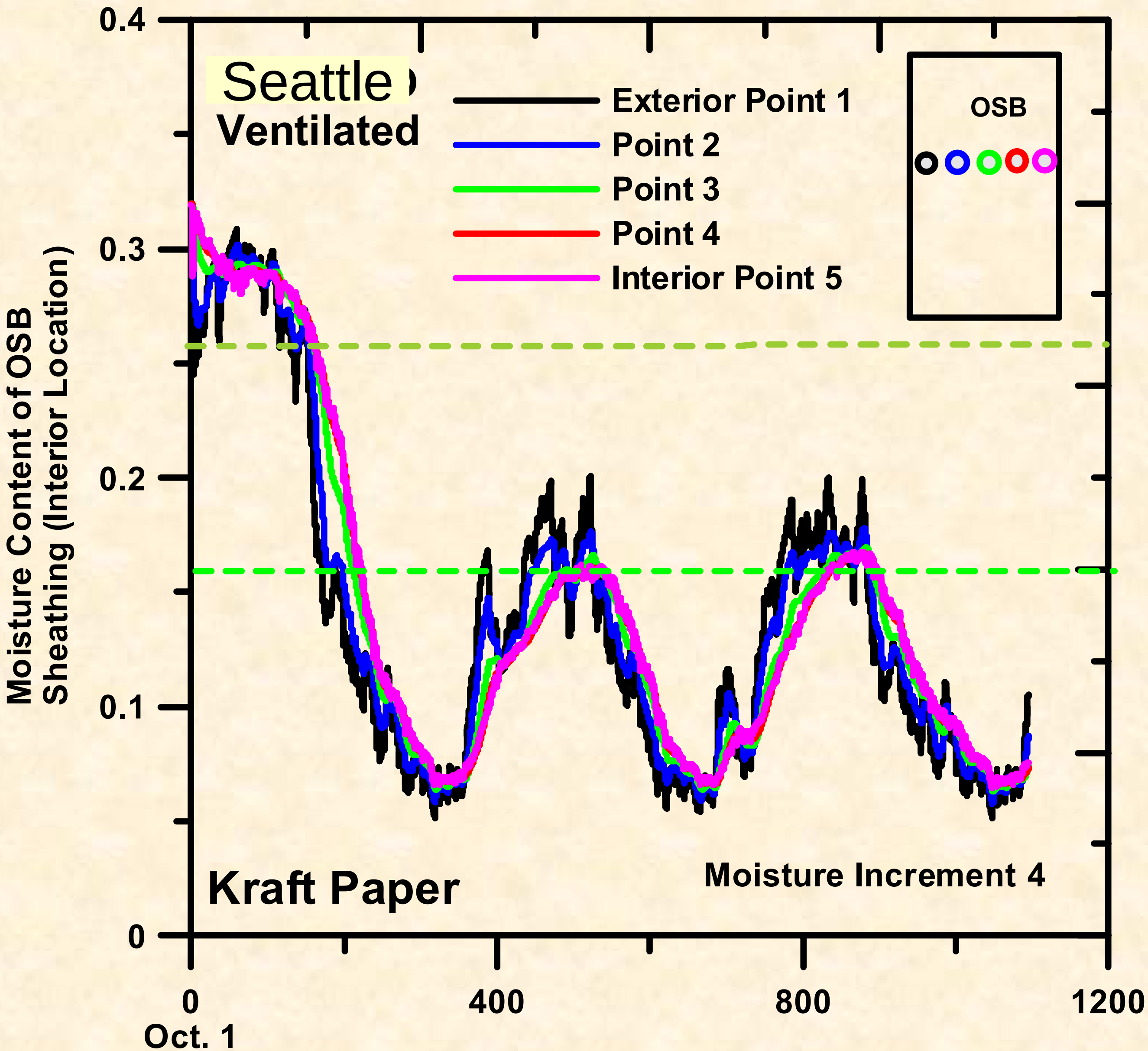


Brick Veneer

Interior Coat

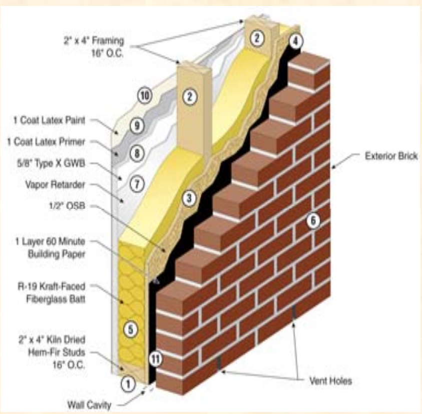
Asphalt-Kraft

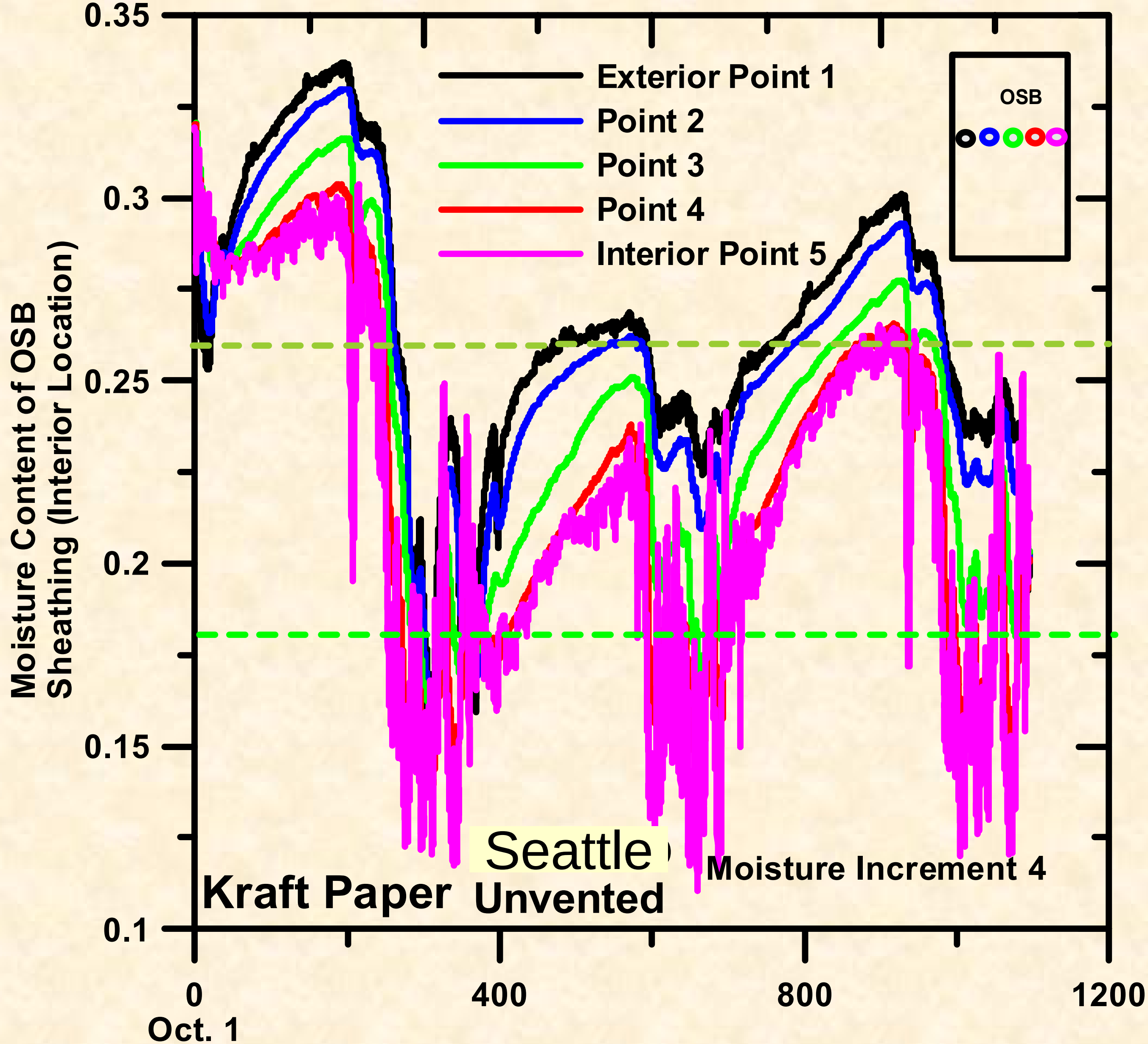




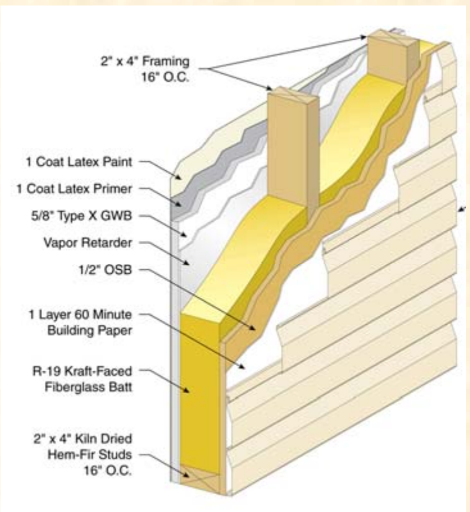
UT-BATTELLE

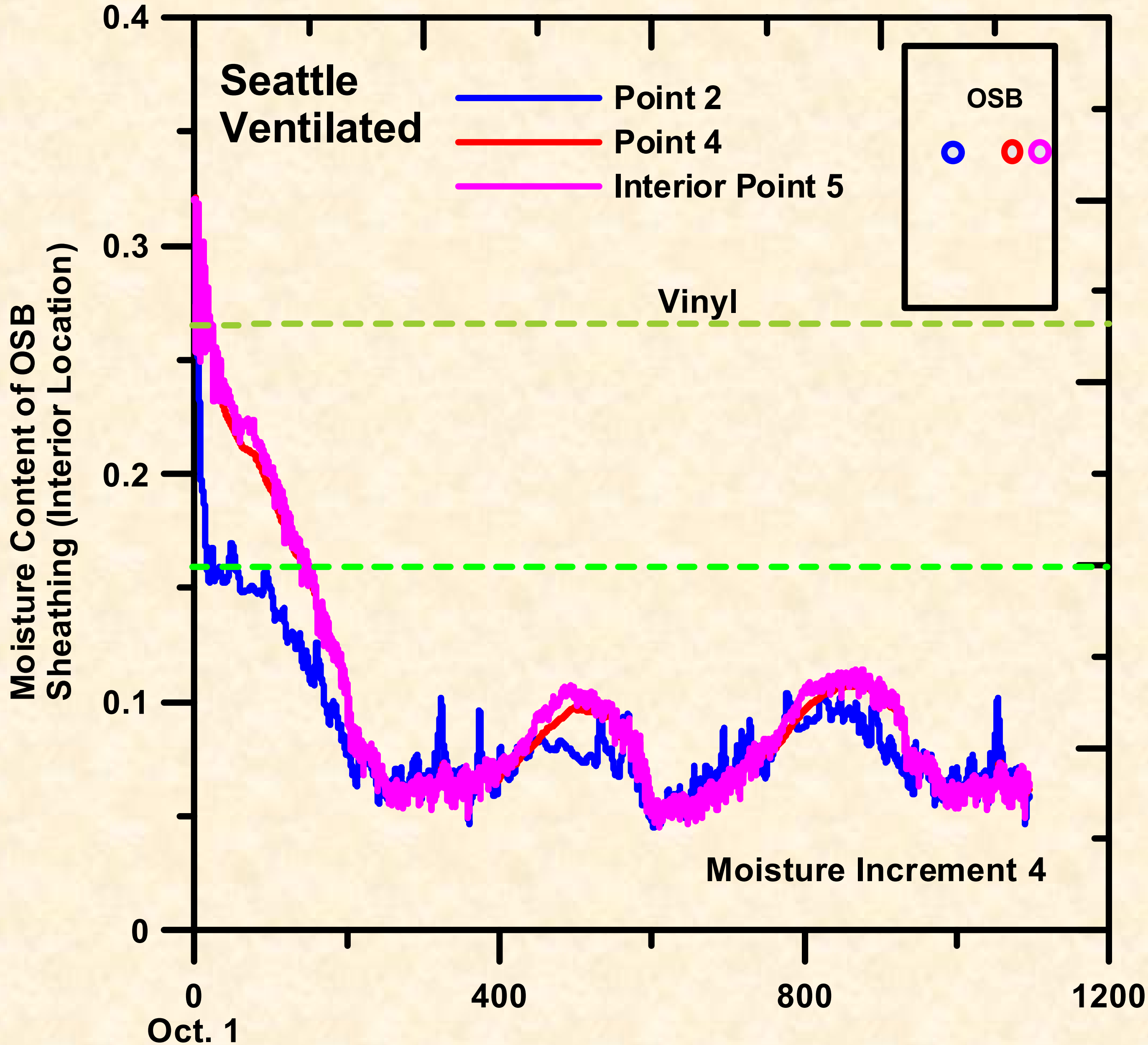
Brick Veneer
Asphalt-Kraft
Unvented





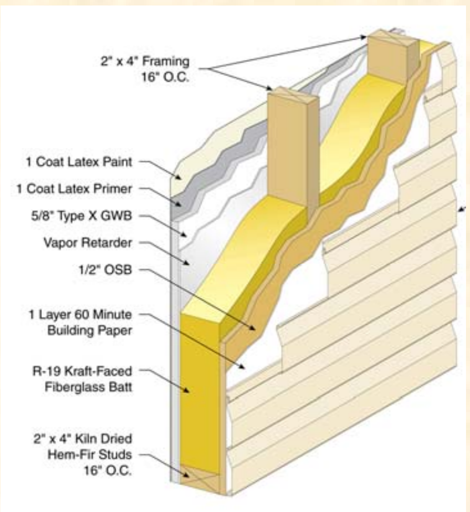
Vinyl
Asphalt-Kraft
Vented

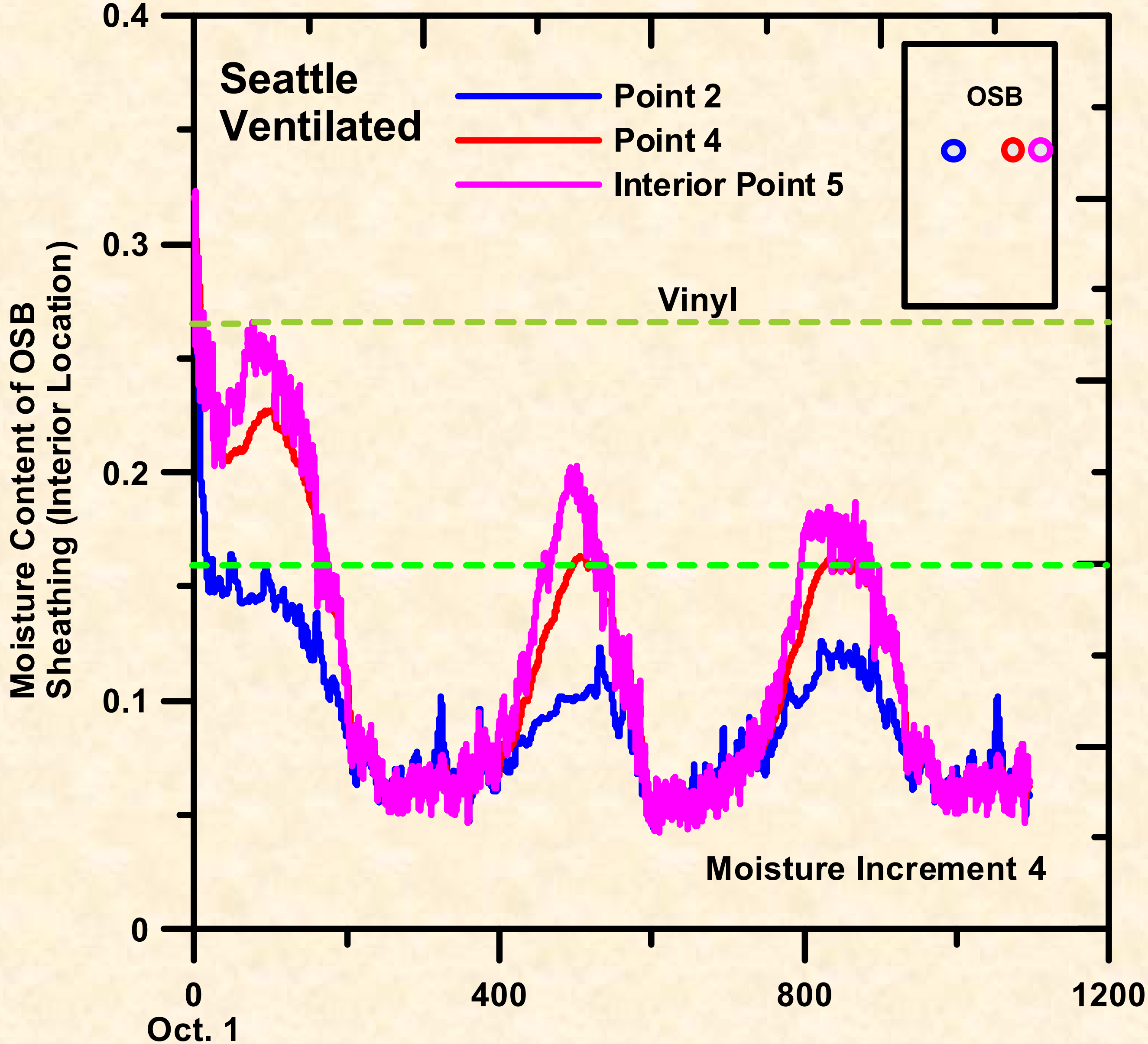




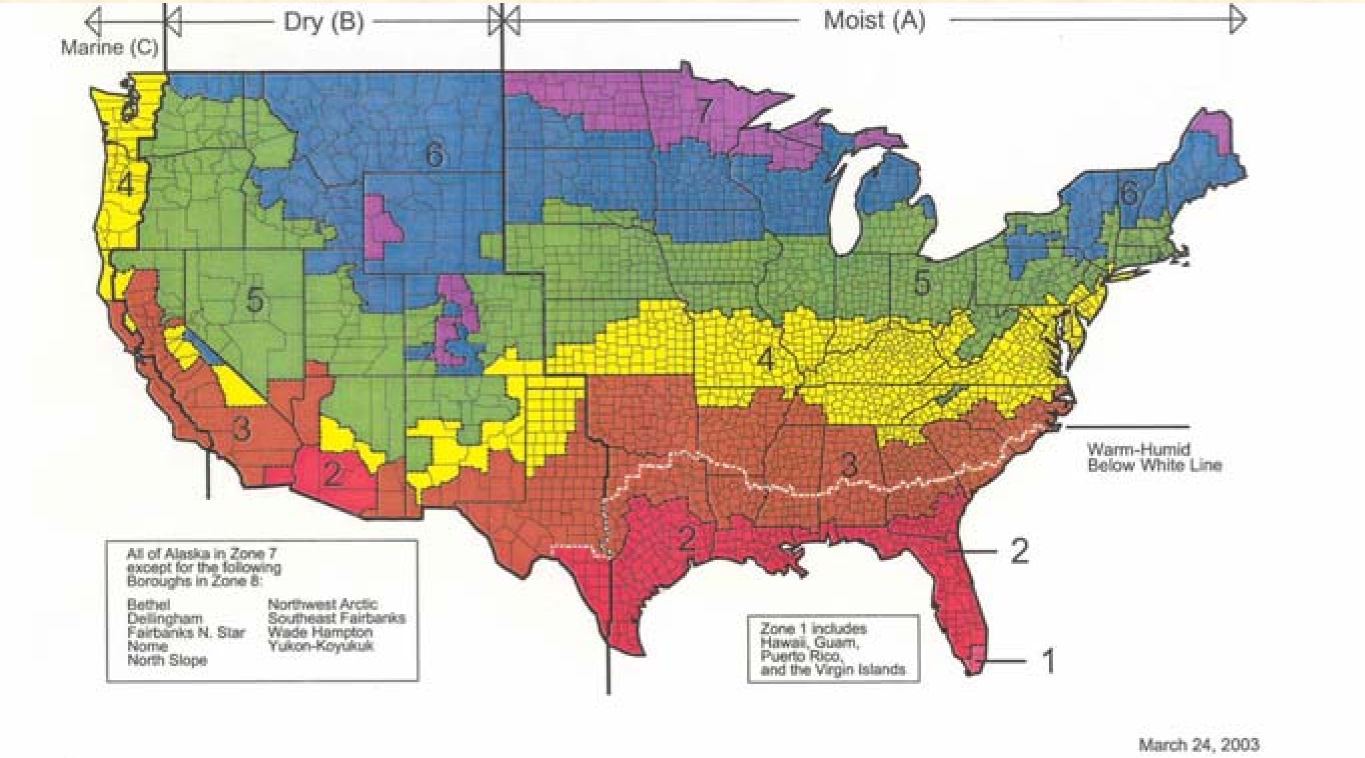
UT-BATTELLE

Vinyl
None (8-perms)
Vented





Vapor Retarder Recommendations



IECC
INTERNATIONAL ENERGY CONSERVATION CODE

Class I	Vapor Retarder:	0.1 perm or less
Class II	Vapor Retarder:	1.0 perm or less and greater than 0.1 perm
Class III	Vapor Retarder:	10 perm or less and greater than 1.0 perm
Class IV	Vapor Retarder	Greater than 10 perm

Test Procedure for vapor retarders: ASTM E-96 Test Method A (the desiccant method or dry cup method)

Class I: Sheet polyethylene
Class II: Kraft facing on fiberglass batts
"Membrane" smart vapor barrier
Typical vapor barrier paint
Class III: Typical latex paint
Class IV: Most building papers and housewraps

Vapor Retarder Recommendations

	Sheathing	Allowable Interior Vapor Resistance Requirements by Class			
		Climate Zone			
		Marine 4	5	6	7
Exterior Covering Unvented	OSB	Class I, II	Class I, II	Class I, II	Class I, II
	Plywood	Class I, II	Class I, II	Class I, II	Class I, II
	Gypsum[4]	Class I, II	Class I, II	Class I, II	Class I, II
	Insulating Sheathing[2]	Class I, II, III (R-2.5 or greater)[3]	Class I, II, III (R-5 or greater)[3]	Class I, II, III (R-7.5 or greater)[3]	Class I, II, III (R-10 or greater)[3]
	Fiberboard	Class I, II	Class I, II	Class I, II	Class I, II
	Other	Class I, II	Class I, II	Class I, II	Class I, II
Notes:					
(2)	When insulating sheathing is installed over other sheathing, requirements for insulating sheathing shall govern				
(3)	Insulating sheathing R-values shown in parenthesis are for 2x4 wall construction. 2x6 walls require insulating sheathing R-values to be increased 50%.				
(4)	When insulating sheathing has a vapor permeance of greater than Class III, requirements for gypsum sheathing shall govern When insulating sheathing having a vapor permeance of greater than Class III is installed over other sheathing, requirements for insulating sheathing shall govern				
(5)	Stucco Brick/Stone/Masonry Veneer Wood/Wood Based/Fiber Cement Panel				

Vapor Retarder Recommendations

Exterior Covering Ventilated[5]	Sheathing	Allowable Interior Vapor Resistance Requirements by Class — Climate Zone: Marine 4	5	6	7
	OSB	Class I, II, III	Class I, II, III	Class I, II	Class I, II
	Plywood	Class I, II, III	Class I, II, III	Class I, II	Class I, II
	Gypsum[4]	Class I, II	Class I, II, III	Class I, II, III	Class I, II
	Insulating Sheathing[2]	Class I, II, III (R-2.5 or greater)[3]	Class I, II, III (R-5 or greater)[3]	Class I, II, III (R-7.5 or greater)[3]	Class I, II, III (R-10 or greater)[3]
	Fiberboard	Class I, II, III	Class I, II, III	Class I, II, III	Class I, II
	Other	Class I, II	Class I, II	Class I, II	Class I, II

Notes:

(2) When insulating sheathing is installed over other sheathing, requirements for insulating sheathing shall govern

(3) Insulating sheathing R-values shown in parenthesis are for 2x4 wall construction. 2x6 walls require insulating sheathing R-values to be increased 50%.

(4) When insulating sheathing has a vapor permeance of greater than Class III, requirements for gypsum sheathing shall govern
When insulating sheathing having a vapor permeance of greater than Class III is installed over other sheathing, requirements for insulating sheathing shall govern

(5) Stucco (3/8 inch clear airspace with 3/8 inch continuous slot vent openings at the top and bottom of each wall)

Brick (2 inch clear airspace with 3/8 inch x 2.5 inch openings (or equivalent net free area per opening) every 3rd brick at the bottom and top course of each wall)

Stone/Masonry Veneer (2 inch clear airspace with 1 square inch of vent opening every 24 inches of wall length at the bottom and top of each wall)

Wood/Wood Based/Fiber Cement Siding (1/4 inch clear airspace or alternatively 1/4 inch gap between horizontal siding laps

Panel Siding (3/8 inch clear airspace with 3/8 inch continuous slot vent openings at the top and bottom of each wall)

FIELD ANALYSIS VALIDATION

- **Models Need Experimental Data to Validate Their Performance**
- **Natural Exposure Test Facility or NET Constructed for this Purpose**

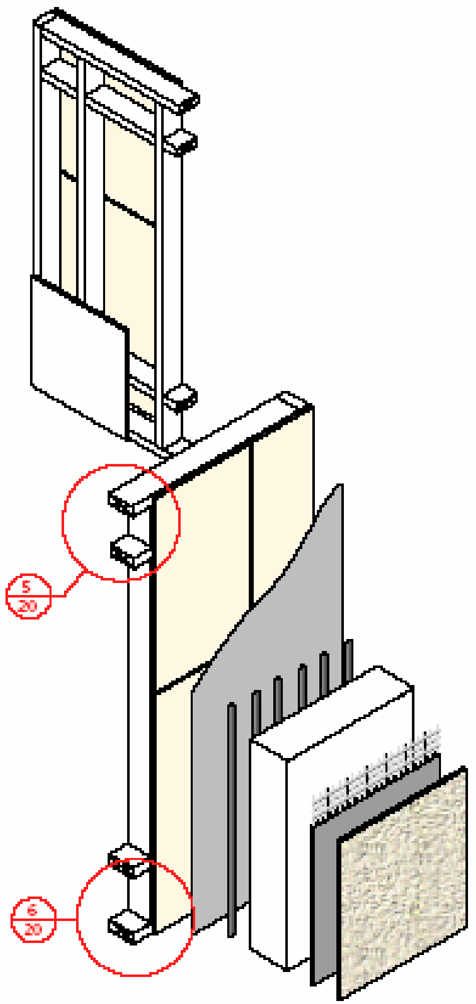
MODEL VALIDATION (Cont)

Initial Efforts Focus on Stucco Claddings

- Potential for Increased Energy Efficiency
- Overcome Negative PR Regarding Hygric Problems of Energy Efficient Structures

UT-BATTELLE

PANEL S8: EIFS/NO CAVITY INSULATION



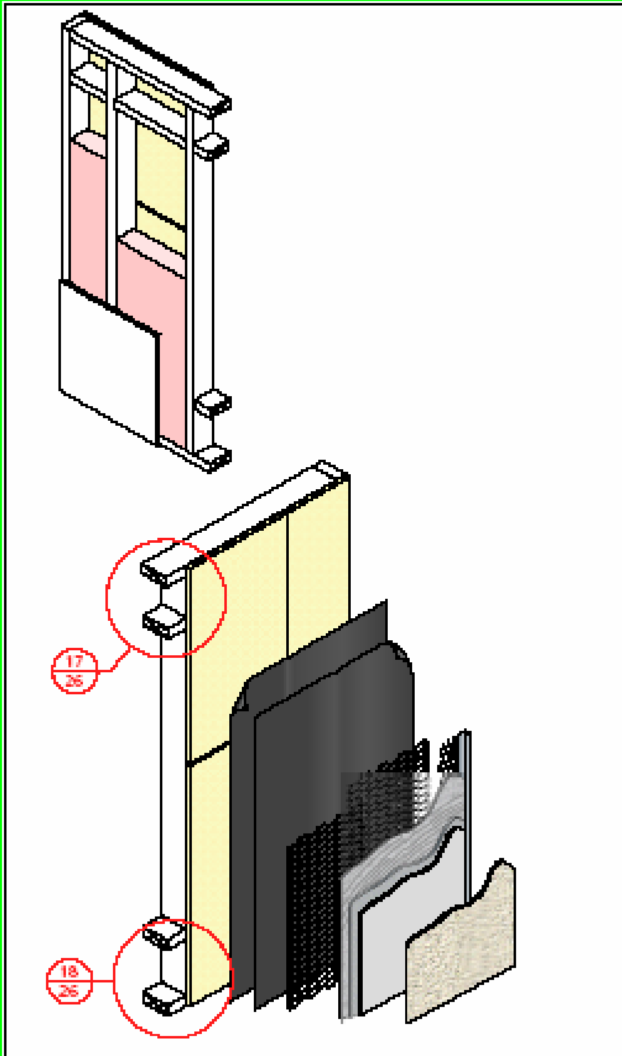
Notes:

1] Interior:
- No insulation in stud cavity
- No vapor barrier
- GWB taped & primed
- Paint

2] Exterior:
- Plywood sheathing
- Liquid applied weather barrier
- Adhesive attachment
- Vertical ribbons
- 4" EPS Insulation
- Base coat, mesh and finish

Details prepared:
22 August 2004

WSU PANELS : THREE COAT PLASTER



Notes:

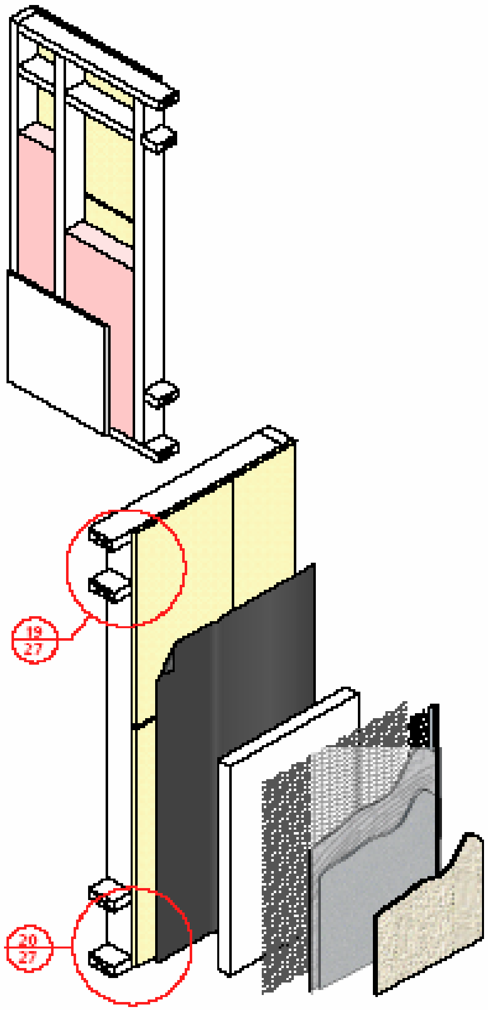
1) Interior:
- R-11 Unfaced batts
- No vapor barrier
- GWB taped & primed
- Paint

2) Exterior:
- 2 x 4 wood frame
- Oriented Strand Board (OSB) sheathing
- 2 layers, Grade D 60 minute paper
- G-60 galvanized, expanded metal, self-furring, 3.4 #/yd², lath mechanically fastened
- 3 coat Portland cement plaster
- Textured acrylic coating (white)

Details prepared:
22 August 2004

UT-BATTELLE

WSU PANELS: ONE COAT STUCCO



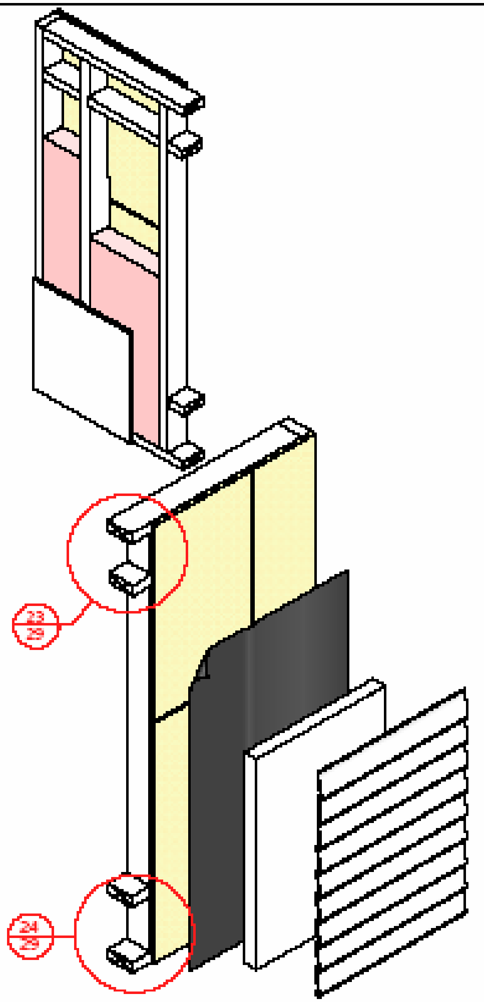
Notes:

1] Interior:
- R-11 Unfaced batts
- No vapor barrier
- GWB taped & primed
- Paint

2] Exterior:
- 2 x 4 wood frame
- Oriented Strand Board (OSB) sheathing
- 1 layer, Grade D 60 minute paper
- Woven-wire, galvanized, 1 x 20 ga. Plaster base mechanically fastened
- One Coat Portland cement plaster
- Textured acrylic coating (white)

Details prepared:
22 August 2004

PANELS : FIBER CEMENT SIDING



Notes:

1) Interior:
- R-11 Unfaced batts
- No vapor barrier
- GWB taped & primed
- Paint

2) Exterior:
- 2 x 4 wood frame
- Oriented Strand Board (OSB) sheathing
- 1 layer, Grade D 60 minute paper
- 1" EPS insulation
- Hardie Plank Siding

Details prepared:
22 August 2004

UT-BATTELLE

Limitation of Experimental Study

1) **Reliability of Moisture Content Sensors (+/- 5 % MC)**

2) **Reliability of MC sensing [illegible] (+/- 20 % of MC)**

3) **No calibration data f[illegible], Plywood used**

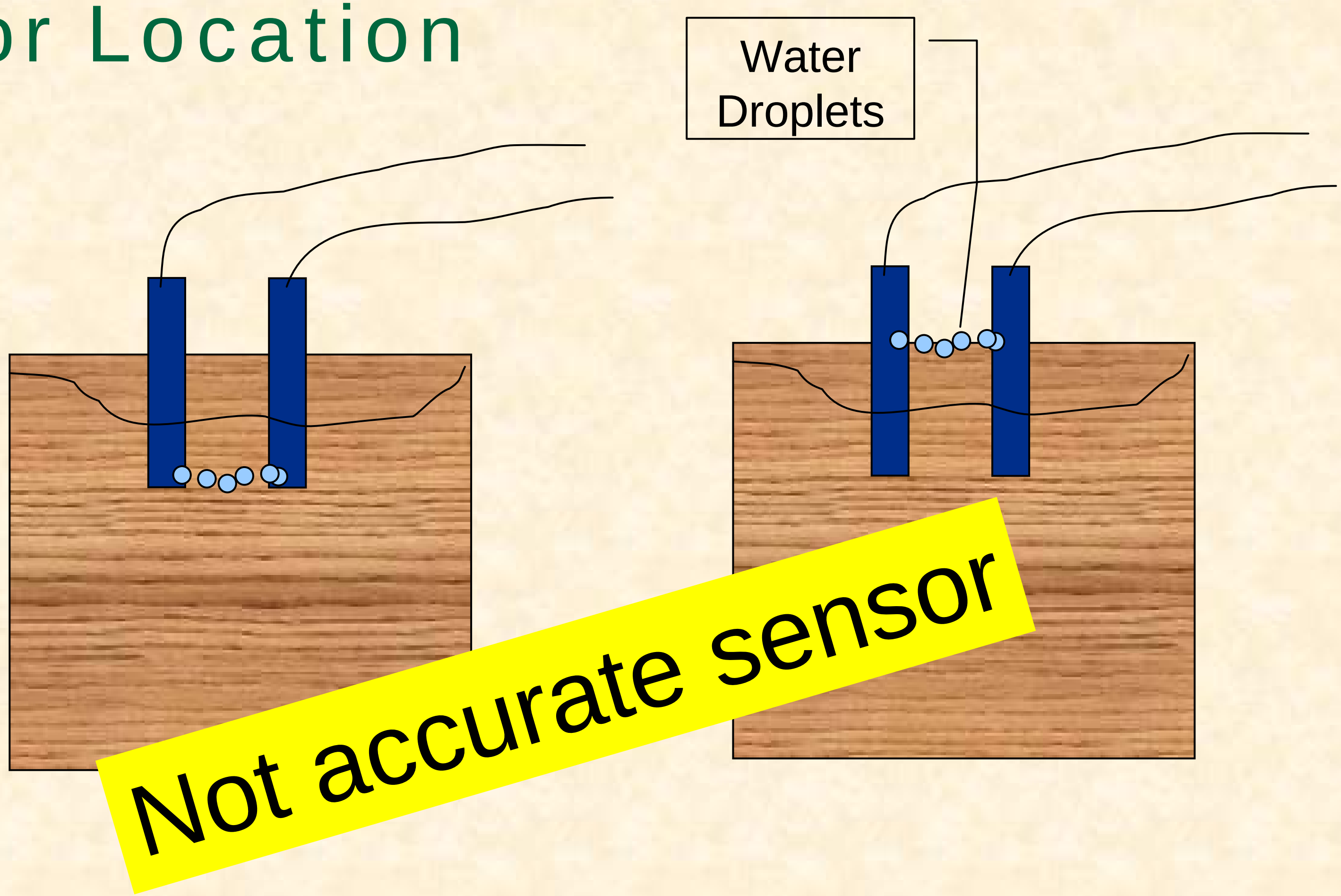
4) **Reliability of R[illegible]ors (+/- 7 %) or higher if exposed to [illegible] zones**

5) **Reliab[illegible] (+/- 1.8 C)**

6) **Wetting Variation large (Unknown liquid distribution), free water dripping unknown.**

Still state-of-the-art

Sensor Location



Not Possible to describe the exact location for MC measurement

1 Year Results

- **Period Oct. 2003 – Oct. 2004**

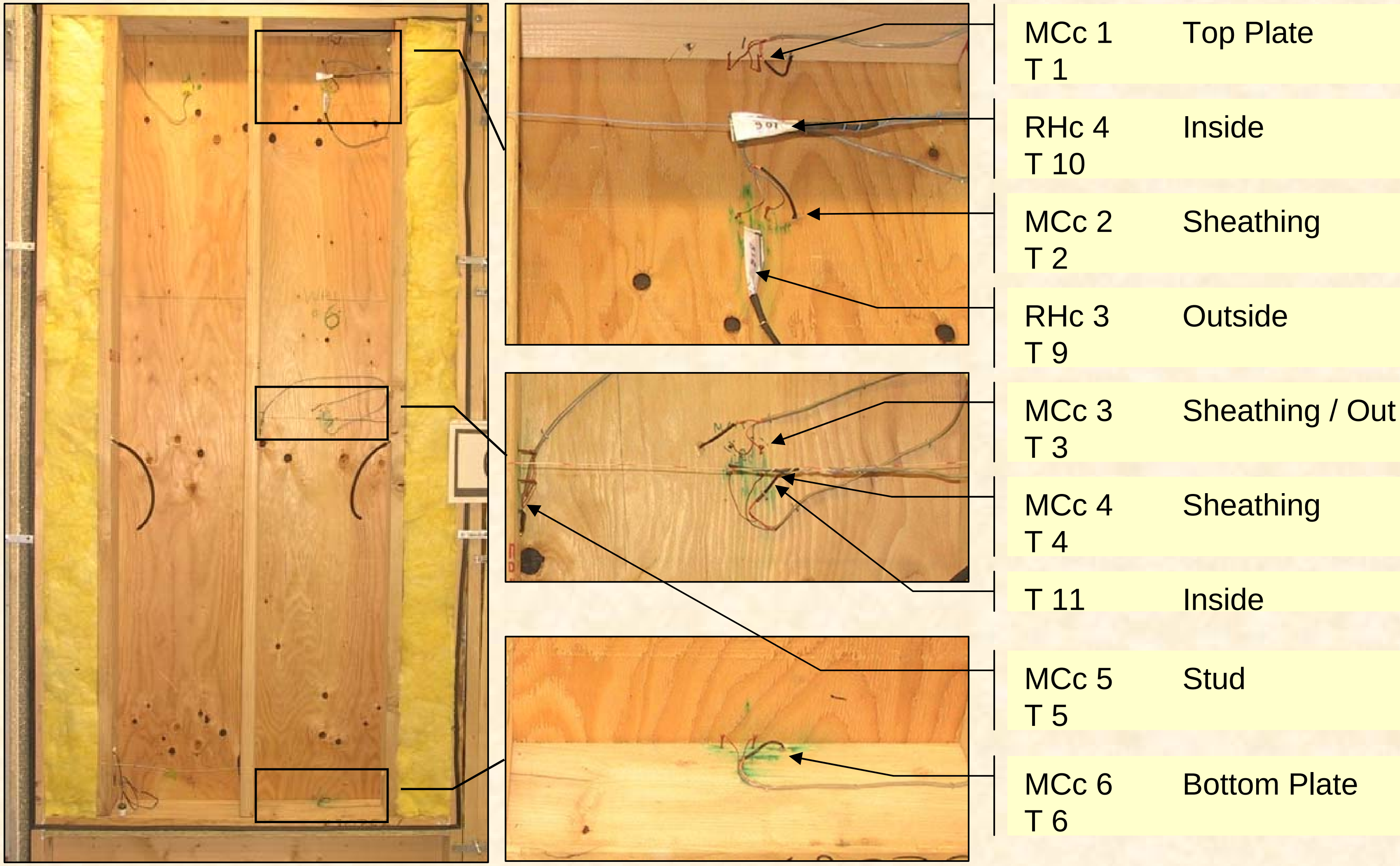
YEAR 1

Test Wall Matrix 2003-2004
WSU Natural Exposure Test Facility, First year testing.

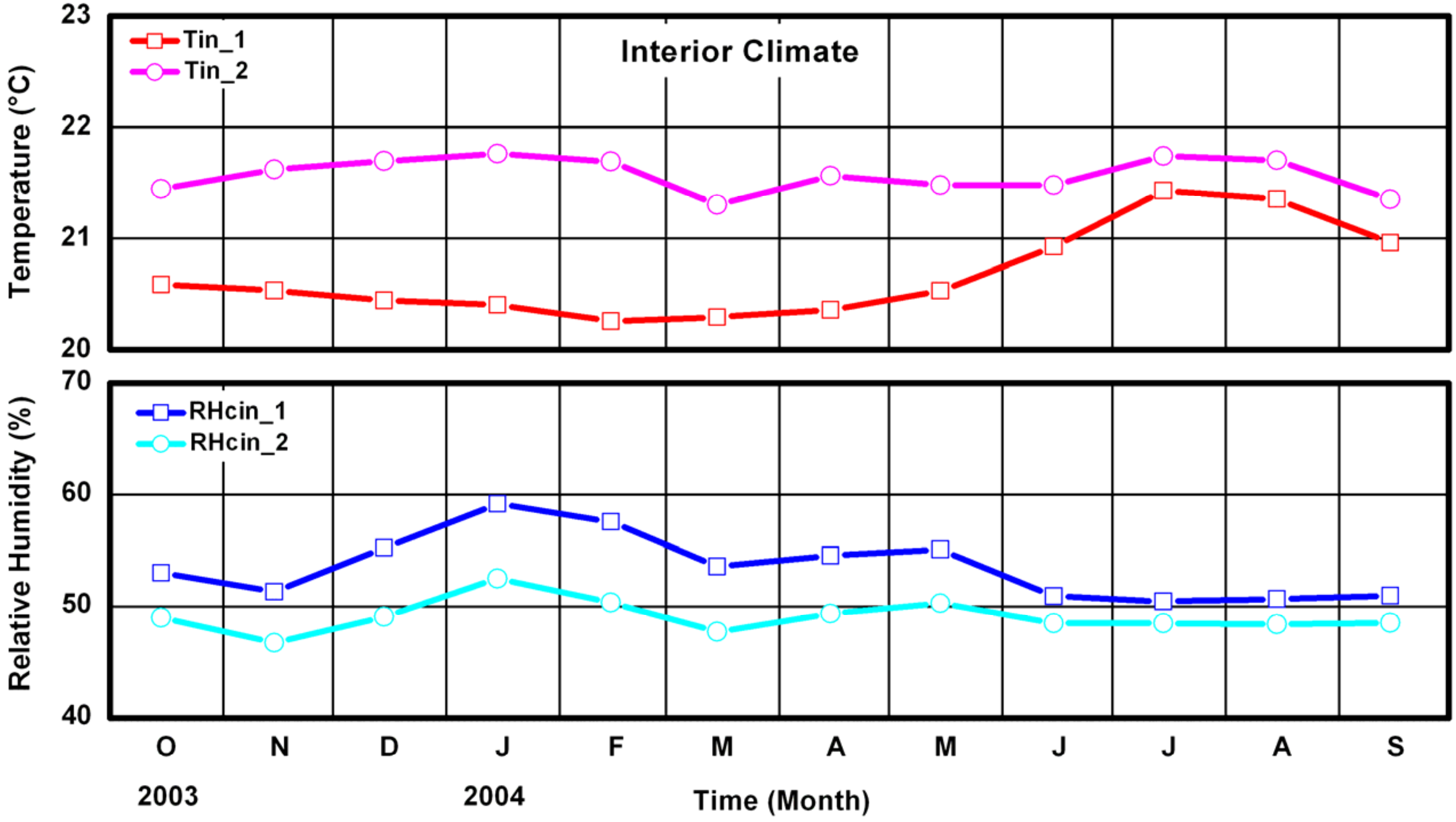
Wall#	Ext Finish	Siding	Ext. Venting	WRB	Sheathing	Ext Insulation	Cavity Insulation	Frame	Vapor Retarder	Int Board	Int Paint	Location
1	Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	South 1
2	Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	MemBrain®	Drywall	Latex	South 2
3	Cement	Stucco 7/8"	Vented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	South 3
4	Cement	Stucco 7/8"	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	South 4
5	Cement	Stucco 7/8"	Unvented	2x 60 min	Plywood		R-11	2X4	Kraft	Drywall	Oil	South 5
6	Cement	Stucco 7/8"	Unvented	2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	South 6
7	Cement	Stucco 7/8"	Unvented	2x 60 min	OSB		R-21	2X6	None	Drywall	Latex	South 7
8	Cement	Stucco 7/8"	Unvented	2x 60 min	OSB	Foam - 1"	R-13	2X4	MemBrain®	Drywall	Latex	South 8
9	Latex	lap	Unvented	2x 60 min	Plywood		R-21	2X6	Poly	Drywall	Latex	South 9
10	Latex	lap	Vented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	South 10
11	Latex	lap	Ventilated	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	South 11
12	Latex	lap	Unvented	2x 60 min	OSB		R-21	2X6	Poly	Drywall	Latex	South 12

OSB	7/16"	Aspen
Plywood	15/32"	4 Ply Doug Fir
Unvented		Siding direct applied over sheathing and weather resistive barrier.
Vented	3/4"	Cavity behind exterior sheathing open at the bottom of the panel only
Ventilated	3/4"	Cavity behind exterior sheathing open at the top and bottom of the panel
WRB		Weather Resistive Barrier
2x 60 min		2 layer 60 minute building paper.
MemBrain®		CertainTeed smart vapor retarder
Drywall	1/2"	Standard drywall taped and finished
Foam	1"	Expanded Poly Styrene R-5

UT-BATTELLE


MCc 1 T 1 Top Plate
RHc 4 T 10 Inside
MCc 2 T 2 Sheathing
RHc 3 T 9 Outside
MCc 3 T 3 Sheathing / Out
MCc 4 T 4 Sheathing
T 11 Inside
MCc 5 T 5 Stud
MCc 6 T 6 Bottom Plate

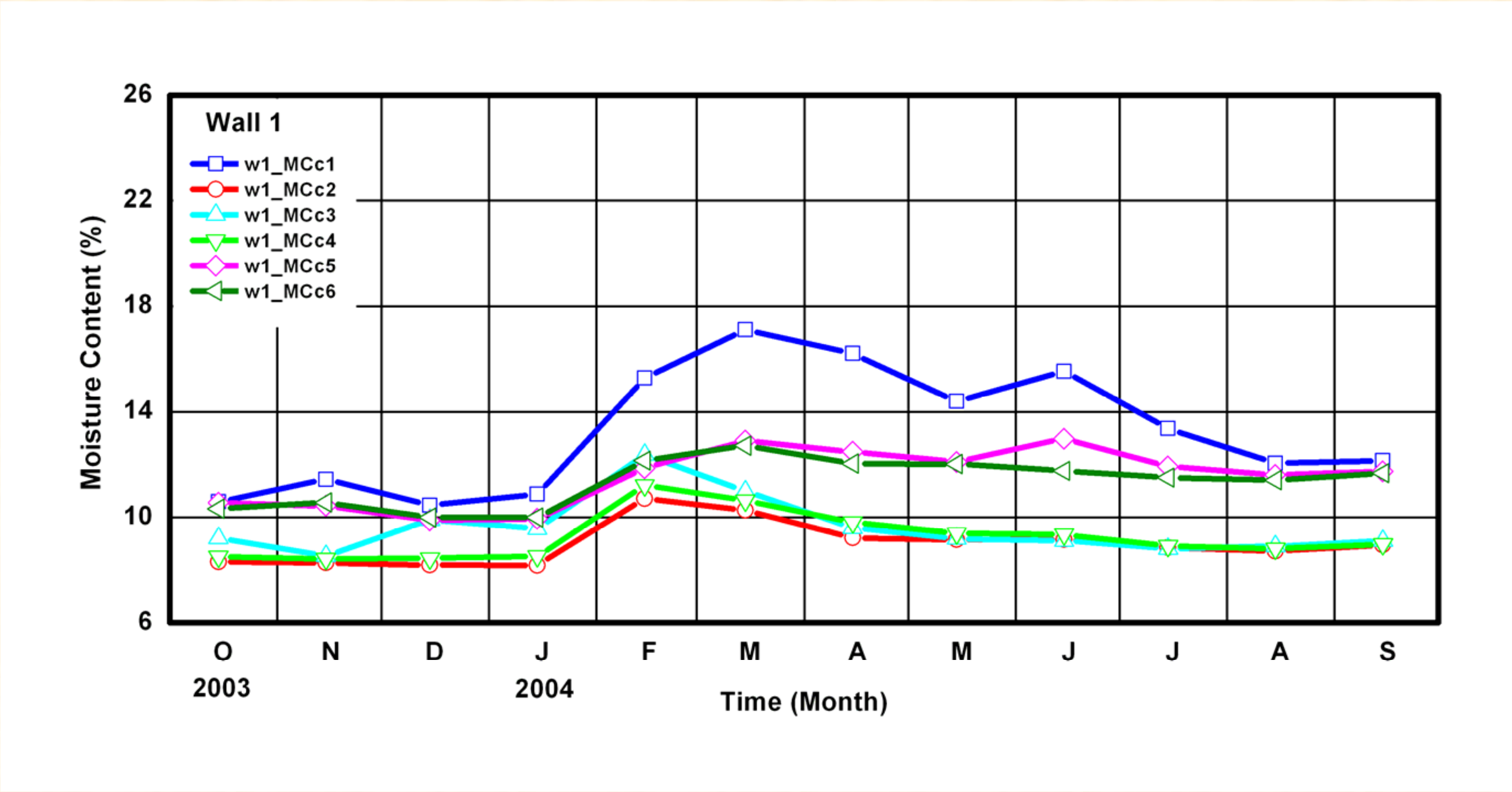
Results: Exterior & Interior Loads



UT-BATTELLE

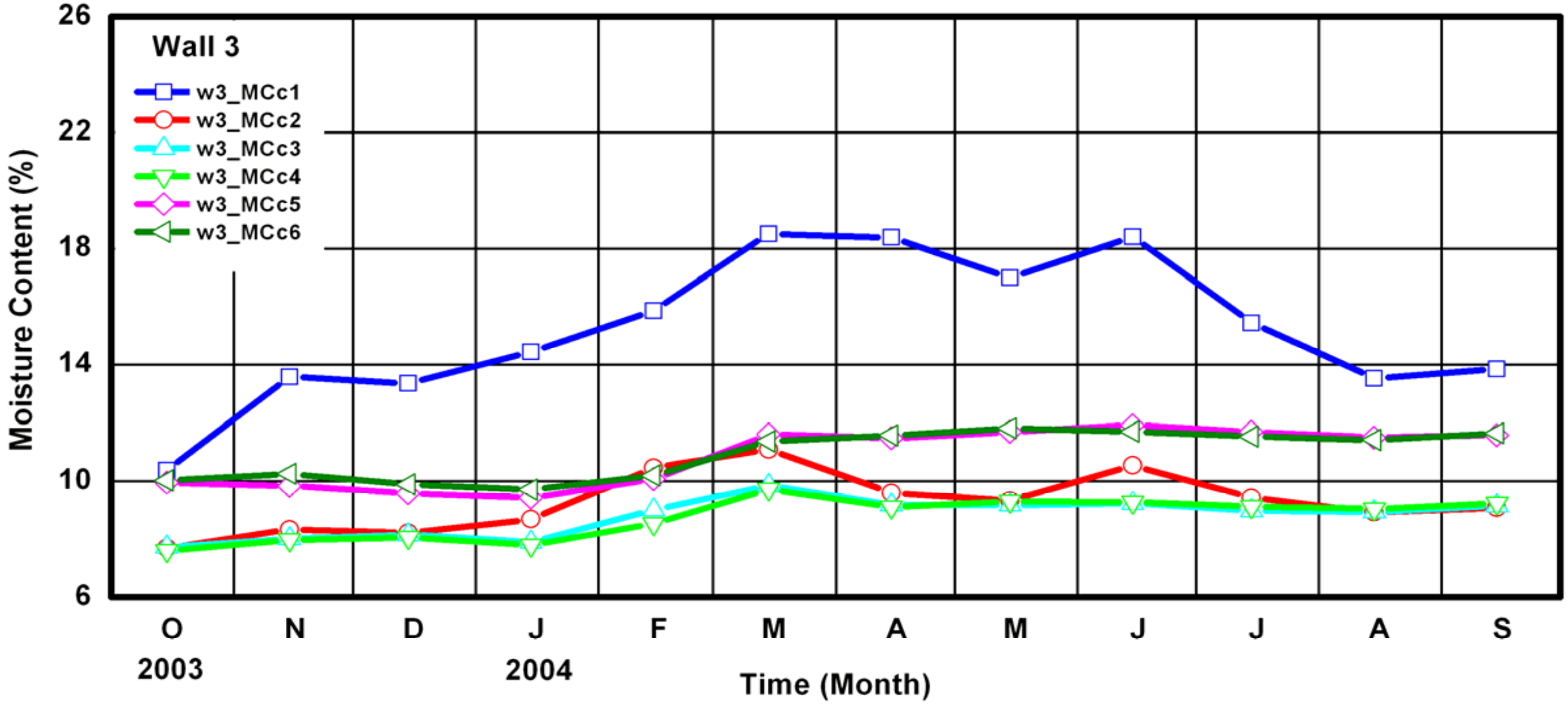
Wall 1: Stucco, Poly, Unvented, OSB

1-top pl, 2-OSB, 3-OSB_out, 4-OSB, 5-Stud, 6-bot pl



Wall 3: Stucco, Poly, Vented, OSB

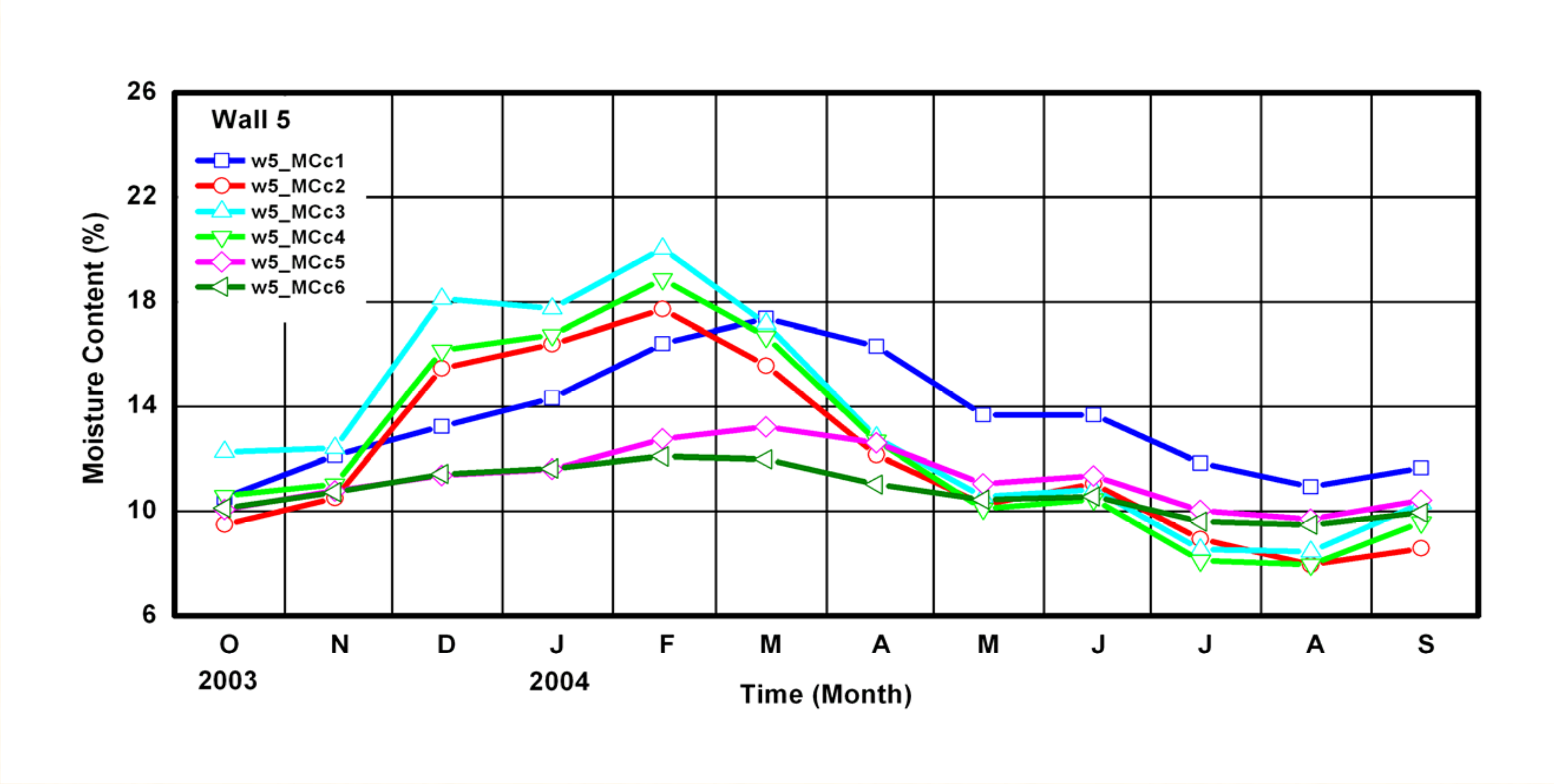
1-top pl, 2-OSB, 3-OSB_out, 4-OSB, 5-Stud, 6-bot pl



UT-BATTELLE

Wall 5: Stucco,Kraft,Unvented, Plywood, R-11(2x4), Oil Paint

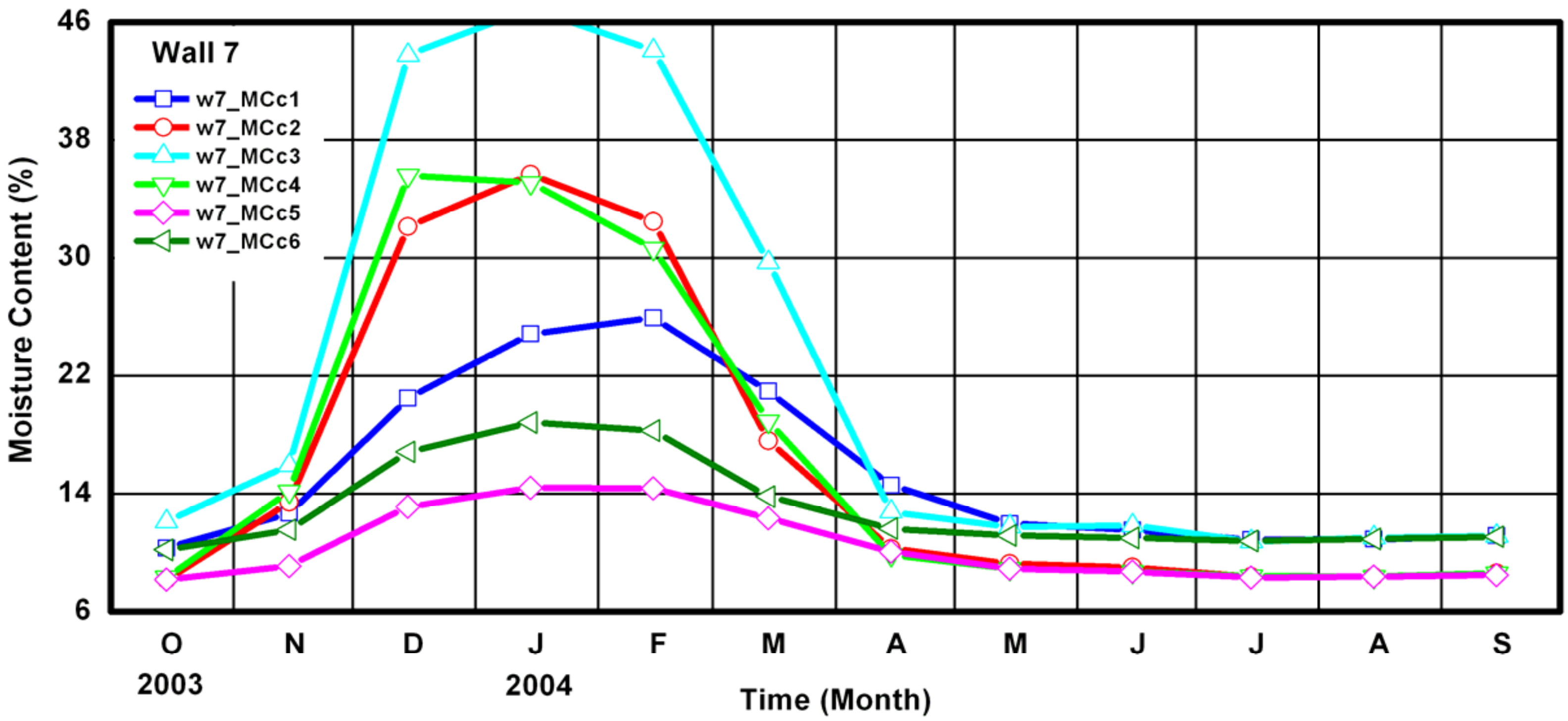
1-top pl, 2-Ply, 3-Ply_out, 4-Ply, 5-Stud, 6-bot pl



UT-BATTELLE

Wall 7: Stucco,No VR,Unvented,OSB

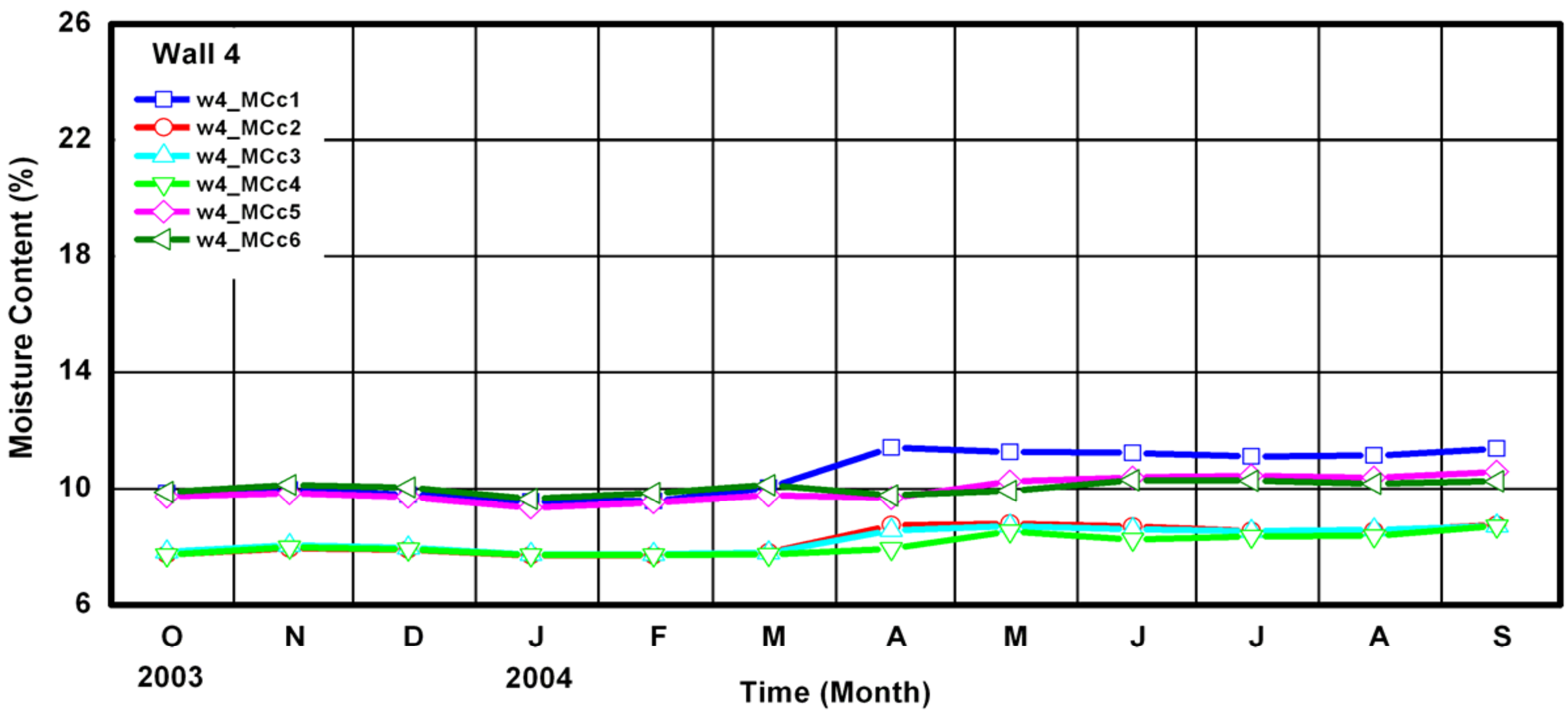
1-top pl, 2-OSB, 3-OSB_out, 4-OSB, 5-Stud, 6-bot pl



UT-BATTELLE

Wall 4: Stucco, Poly, Ventilated, OSB

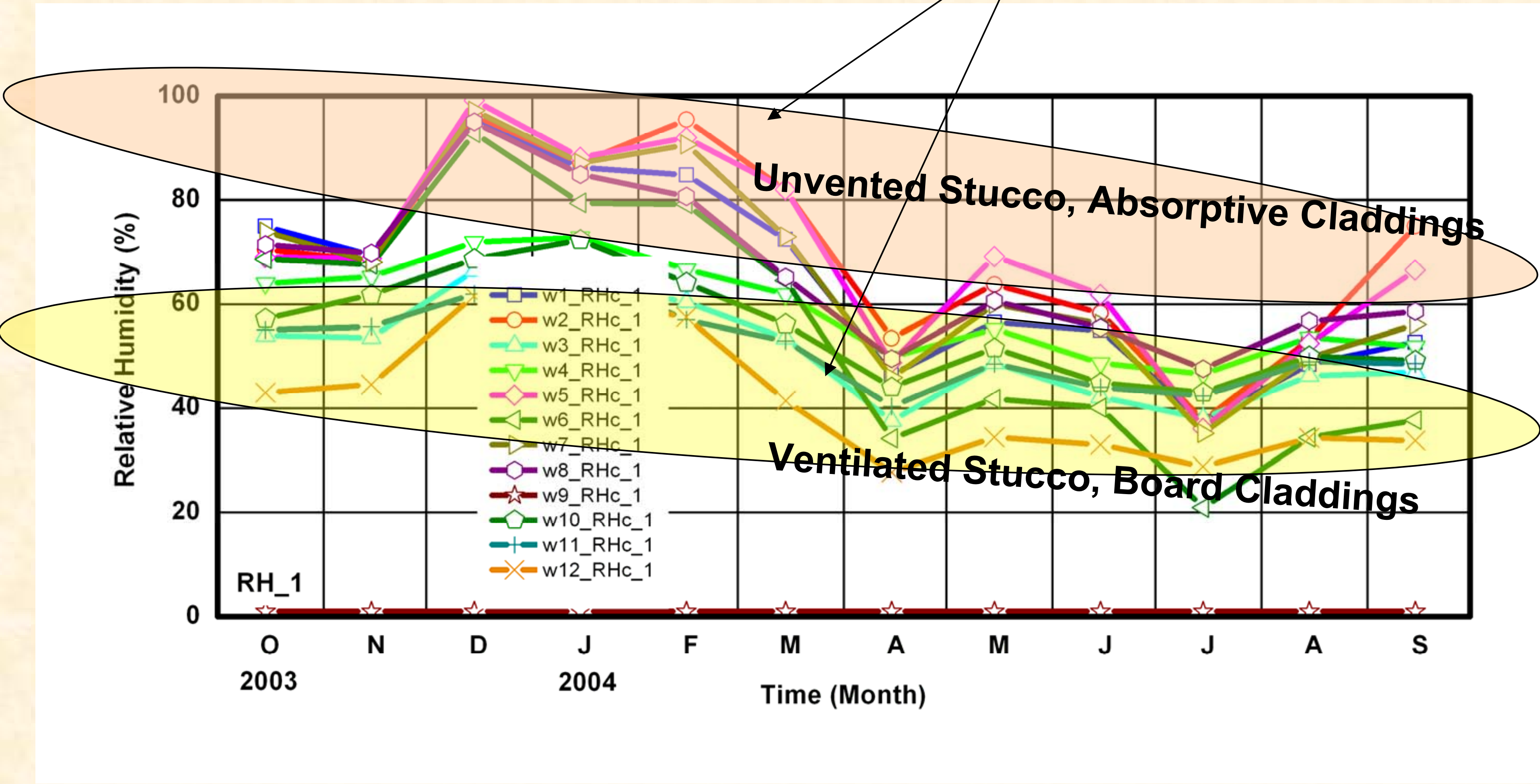
1-top pl, 2-OSB, 3-OSB_out, 4-OSB, 5-Stud, 6-bot pl



UT-BATTELLE

More investigations…

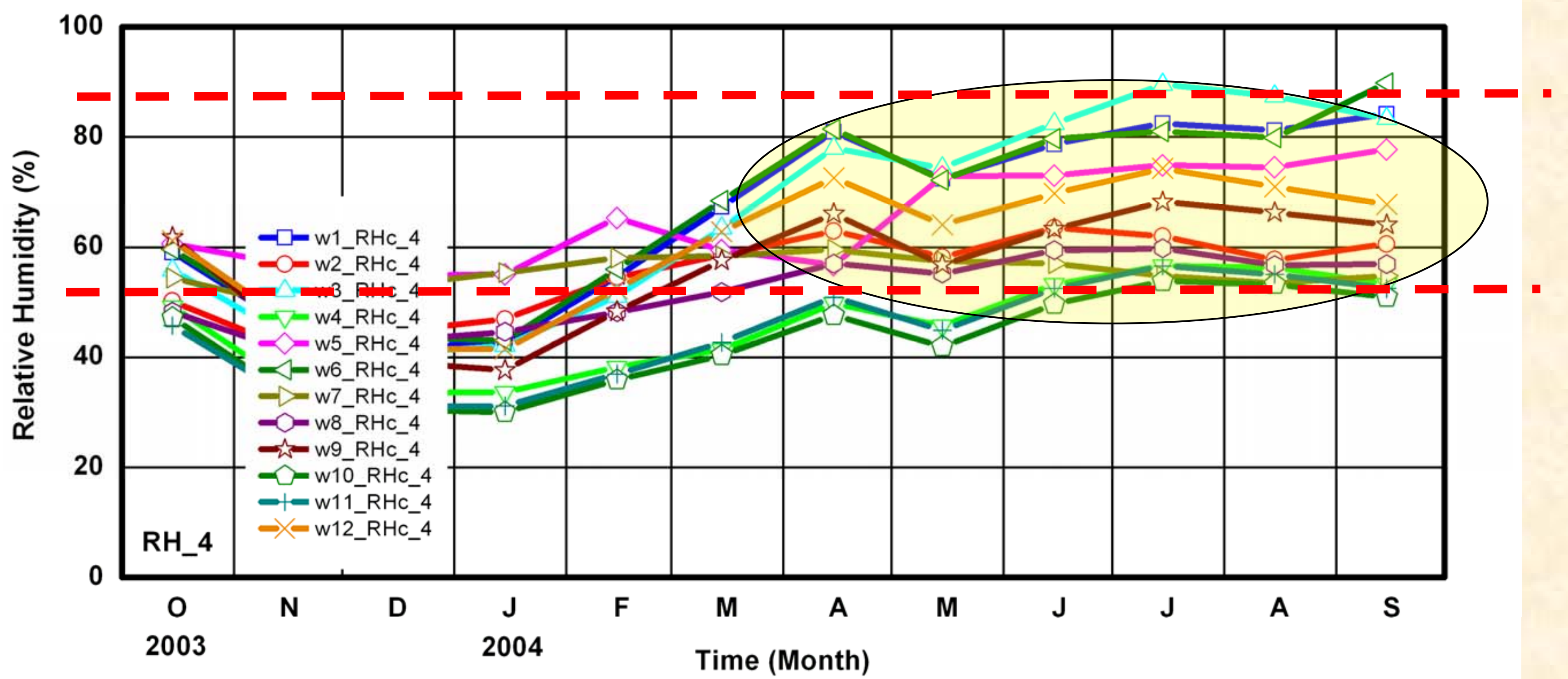
Two classes of Claddings



UT-BATTELLE

RH... interior

Notice- High RH at inner surface of insulation 55 % to 85 % (5 months/year May to Oct)



UT-BATTELLE

Conclusion- 1 Year Results

- Ventilation increases drying potential by a factor of 3 (drying rate using stucco loading in Seattle)
- Venting increases drying performance by 33 %
- Foam insulation keeps wall warm and increases drying performance
- Seattle requires an interior vapor retarder (at least kraft coating unless cladding ventilated), Membrain outperforms poly and no vapor retarder
- Old constructions also prone to moisture problems if use similar stucco
- No Vapor Retarder (60-perms or 10 as thought of when built)

UT-BATTELLE

Conclusion- 1 Year Results

- **Membrain outperforms poly and n…**
- **No Vapor Retarder (60… …ought of when built)**
- **Fiel… …t be used together to d… …changes**

Do not use ONLY models but field and models to produce code changes that are needed

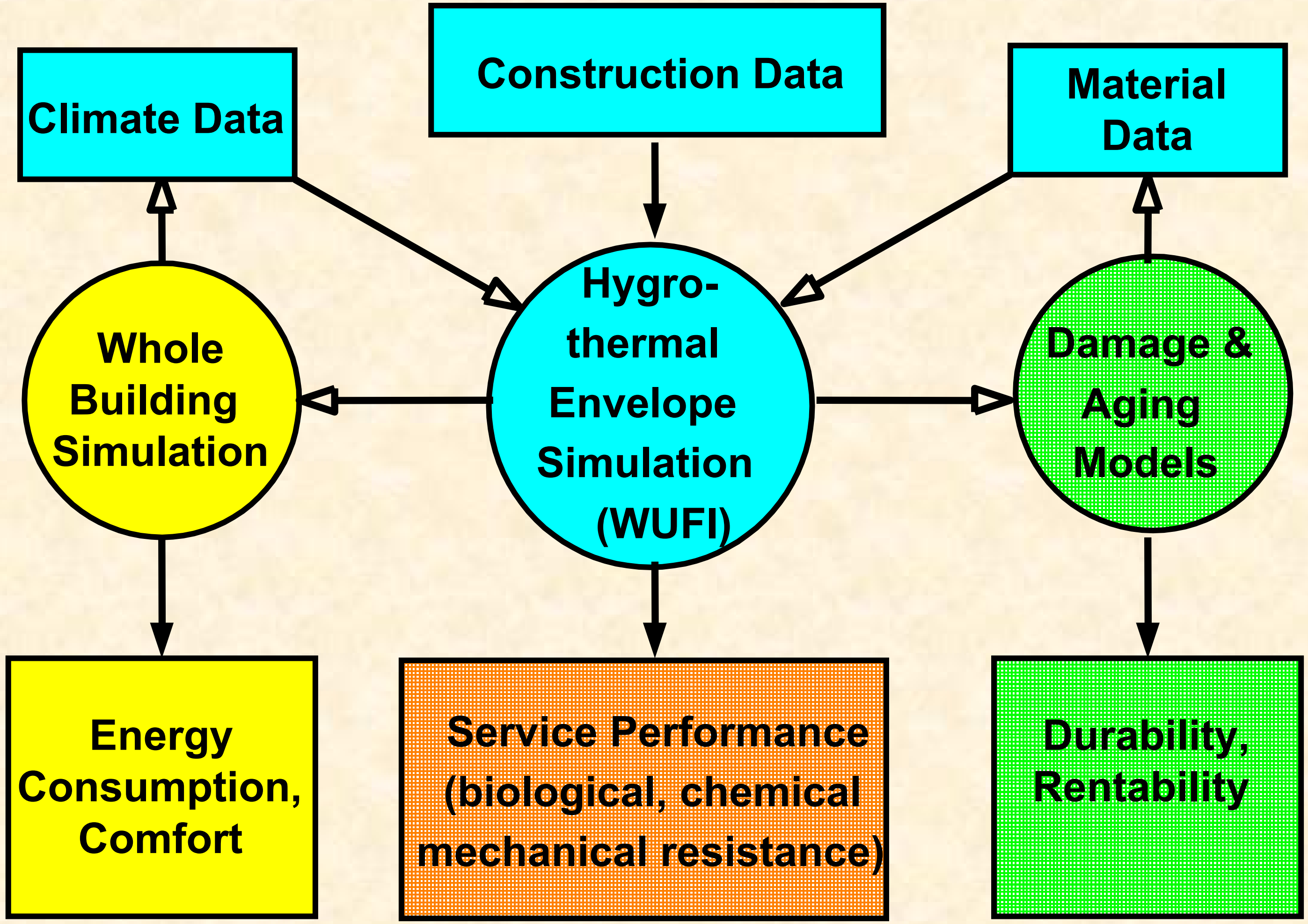
UT-BATTELLE

Future

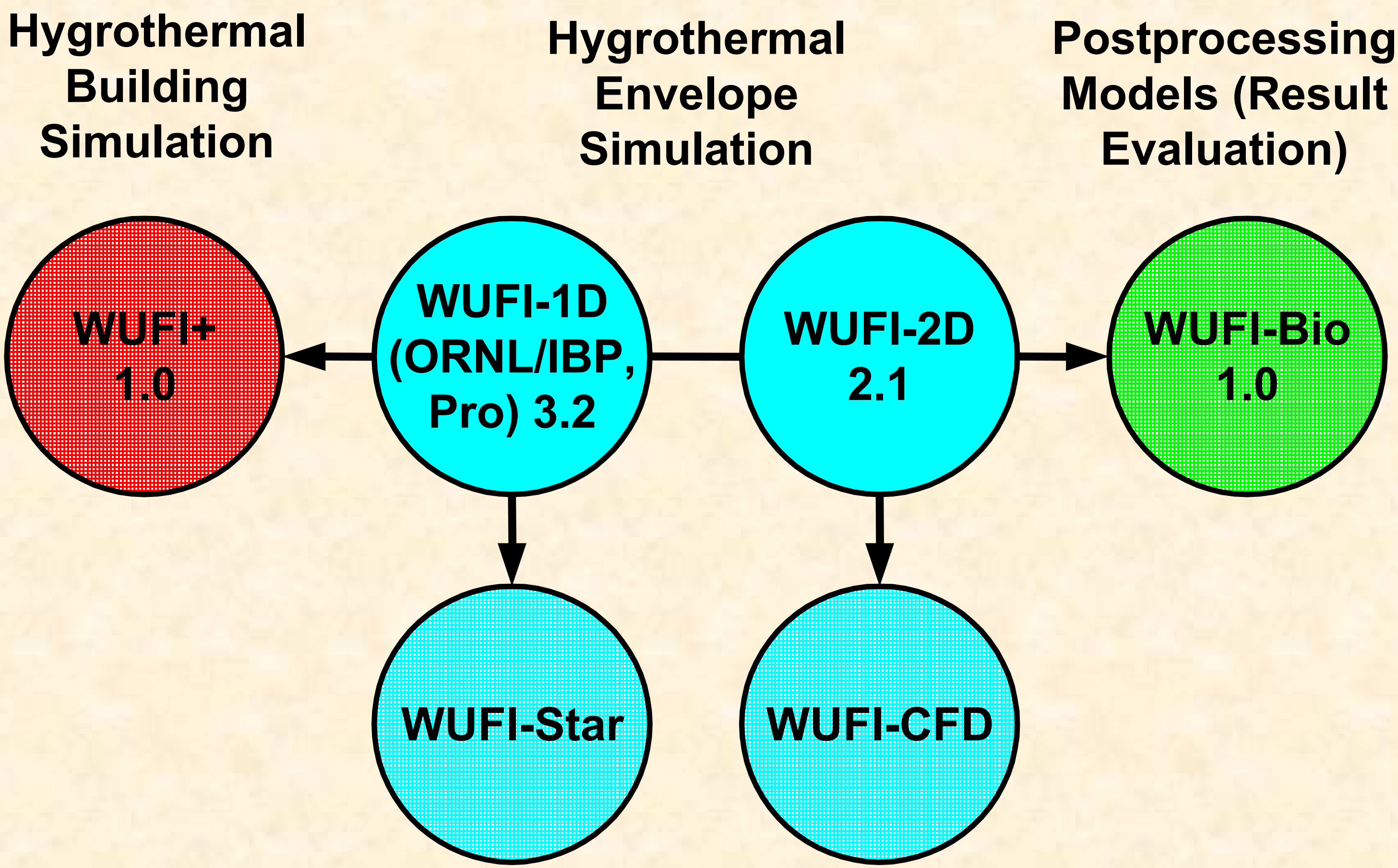
WUFI-plus

Whole Simulation Model

What is next?

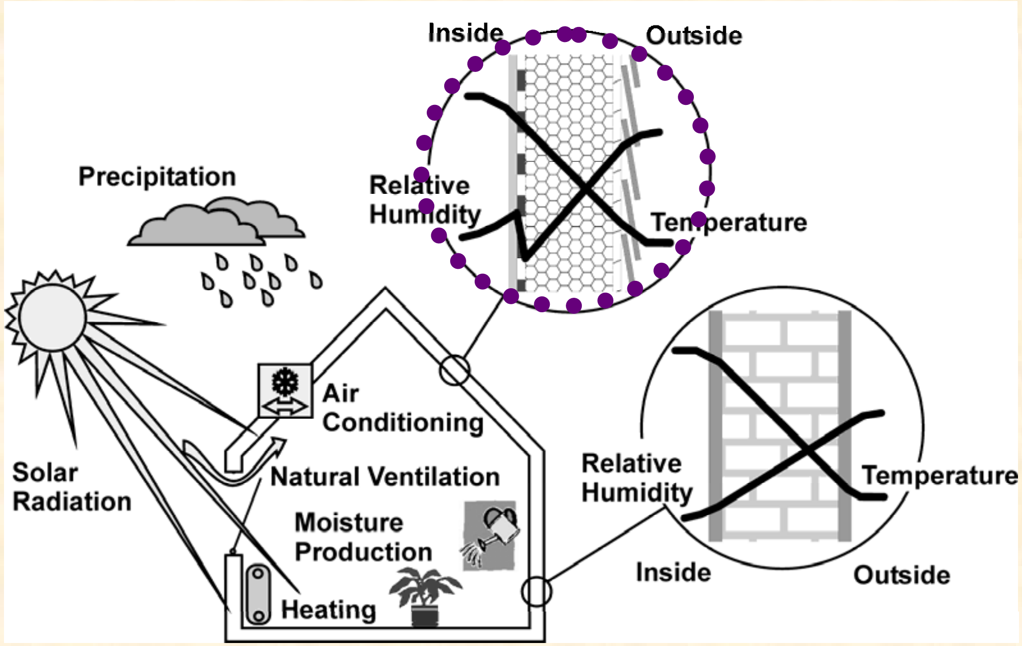

Climate Data
Construction Data
Material Data
Whole Building Simulation
Hygro-thermal Envelope Simulation (WUFI)
Damage & Aging Models
Energy Consumption, Comfort
Service Performance (biological, chemical mechanical resistance)
Durability, Rentability

WUFI-Family 2006



COMBINING THERMAL BUILDING SIMULATION AND HYGROTHERMAL ENVELOPE CALCULATION

Envelope

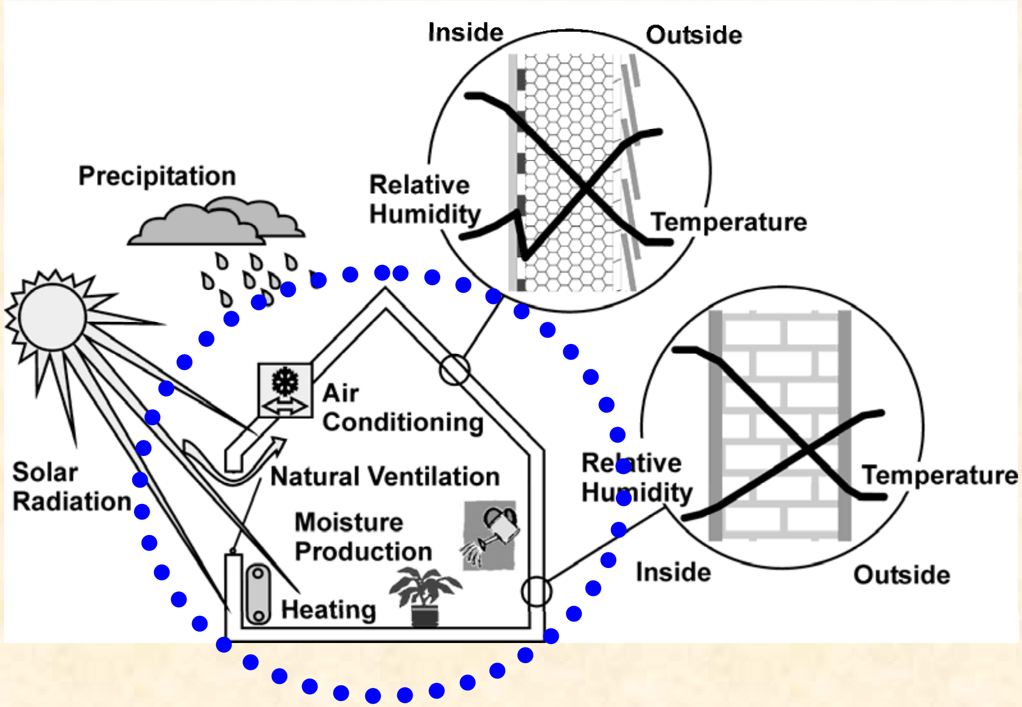


- **Heat**

$$\frac{\partial w}{\partial \phi} \cdot \frac{\partial \phi}{\partial t} = div\left(D_\phi grad(\phi) + \delta_p grad(\phi\, p_{sat})\right)$$

UT-BATTELLE

COMBINING THERMAL BUILDING SIMULATION AND HYGROTHERMAL ENVELOPE CALCULATION



Whole Building

- **Heat**

$$\rho \cdot c \cdot V \cdot \frac{d\theta_i}{dt} = \sum_j A_j \alpha_j (\theta_j - \theta_i) + \dot{Q}_{Sol} + \dot{Q}_{il} + n \cdot V \cdot \rho \cdot c \cdot (\theta_a - \theta_i) + \dot{Q}_{vent}$$

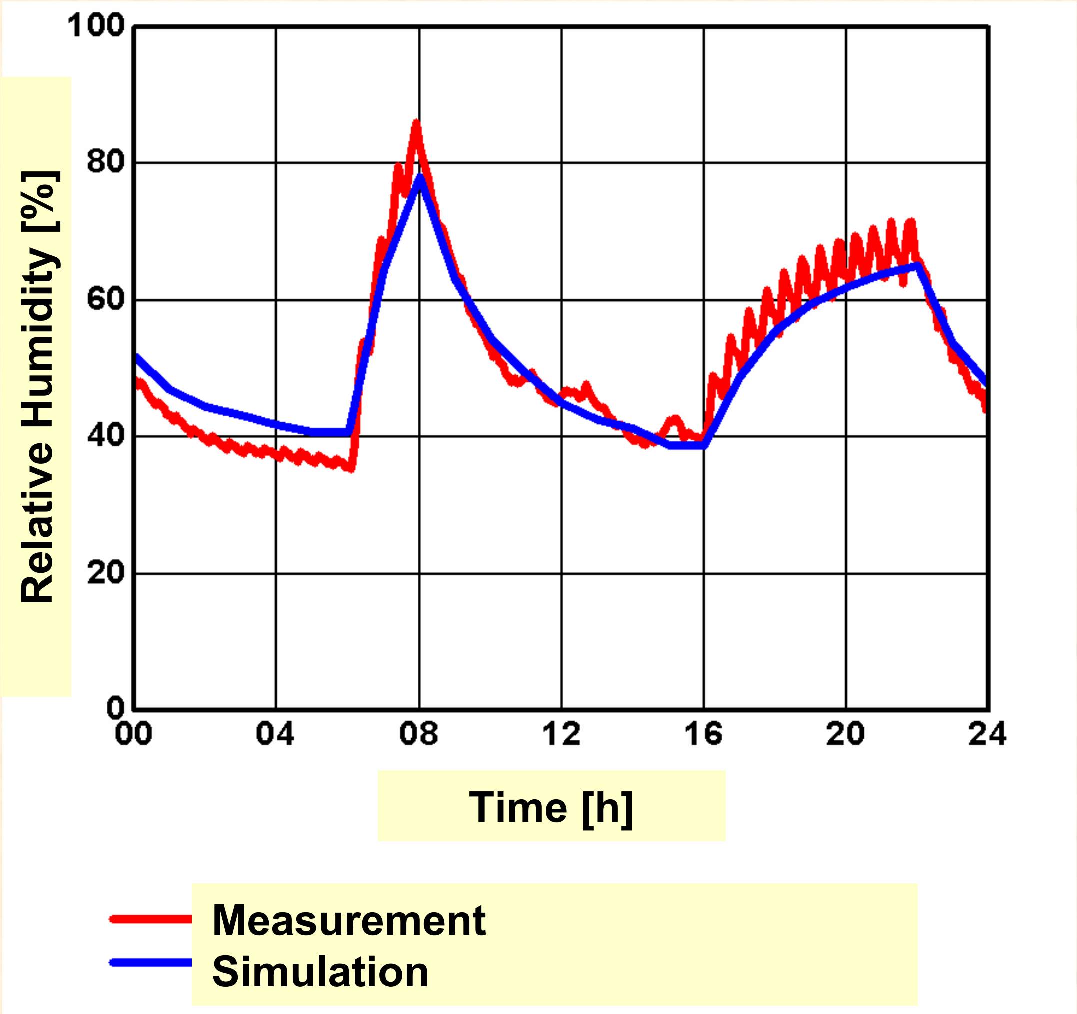
MODEL VALIDATION

foil faced test room

reference room

UT-BATTELLE

MODEL VALIDATION



UT-BATTELLE

Future Modeling

- It was always considered: indoor humidity is of small importance for a successful design because temperature is easier to sense, quantify and comprehend.
- Indoor relative humidity (RH) is important and has significantly impact.
- New model for : Transient behavior for the whole building, its indoor climate AND the envelope
- With the model it is possible to make more and more accurate predictions of the indoor humidity variations

UT-BATTELLE

Conclusions

- **Models are as experienced as the operator who uses them (Training is necessary)**
- **There are many limitations to models**
- **There are even more limitations for testing**
- **Field and Modeling should be used for CODES**
- **In the near future WUFI-PLUS will assist in Whole Building Design**
- **Work is proceeding with a 3-D CFD WUFI model with CAD interfaces**

UT-BATTELLE