CAE 463/524
Building Enclosure Design
Spring 2016

Week 7: February 23, 2016
Moisture flows in enclosures

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Review from last time

- Finished complex conduction in building enclosures
  - Multiple layers
  - Heat transfer in parallel
  - More complex thermal networks (isothermal and parallel path)
  - Numerical solvers (THERM)
  - Below- and on-grade heat transfer

- HW 2 (THERM) due today

Campus enclosure assessment projects

- Need to do thermal assessments by early/mid March
  - Don't wait too long!
  - All teams have now been formed

Team #	Members	Building
1	Naveen, Julia, Xu, Luanzhizi, Steve	Alumni
2	Bianca, Al, Taylor, David	SSV
3	Nina, Dina, Lindsey, Salvatore, JiWan	Vandercook
4	Andrea, Ben, Keonho, Kevin	Crown
5	Afshin, Ali, Mehdi, Jose, Kamal	Siegel

- Email me (brent@iit.edu) and our TA Akram (aali21@hawk.iit.edu) when you're ready to check out the IR camera, IR thermometer, and air T/RH sensor

MOISTURE FLOWS IN ENCLOSURES

Water vapor transport

- Moisture in air is one of the most important sources of wetting in buildings
  - We need to know to how to design and construct buildings that are safe from damage caused by water vapor and liquid water
  - Thus we need to understand the physics of water vapor, including:
    - Transport by diffusion and air movement (bulk convection)
    - Deposition by condensation
    - Removal by evaporation

- Most of notes today come from the Straube textbook
  - Some also come from *Moisture Control Handbook: Principles and Practices for Residential and Small Commercial Buildings*, Listiburek and Carmody, Wiley, 1996, ISBN 0471318639.
  - Reduced version of this text is available as a DOE report:
    - http://www.ornl.gov/sci/roofs+walls/facts/moisture/Moisturehandbook2.pdf

Moisture management basics

- Moisture is involved in the majority of performance problems or deterioration process that affect building enclosures
  - Leakage of water into the building
  - Freeze-thaw deterioration of concrete, stone, or masonry
  - Corrosion of metal components
  - Biological growth
    - Occupant health, structural integrity, and visual appearance
  - Chemical deterioration/dissolution of materials
  - Volume changes
    - Structural failure, cracking, degradation of appearance
  - Discoloration
    - Staining, dusting, irregular wetting

Moisture management basics

- For a moisture-related problem to occur, at least four conditions must be met
  - A moisture **source** must be available
  - There must be a **route** for moisture to travel
  - Three must be a **driving force** to cause moisture movement
  - The material(s) involved must be **susceptible** to moisture damage

- Address at least one of these can usually solve (or avoid) most problems

- More on moisture management next lecture
  - For now, we will identify moisture problems and causes
  - Then learn the fundamental physics of moisture transport

Types of moisture failure

We use the term failure typically to include some level of:

(a) material deformation or

(b) degradation of physical performance that stems from physical changes, chemical processes, and/or biological processes

Moisture can cause several types of failure:

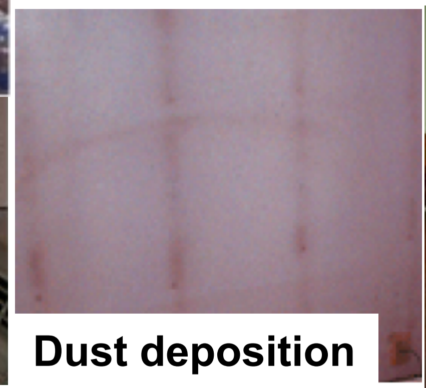
- Structural failures from rot damage and freeze-thaw cycles
- Biological growth (mold)
  - Emission of microbial volatile organic compounds (mVOCs)
- Increased heat loss caused by moisture content in materials and airflow through moisture enhanced gaps
- Insect problems
- Flooding

Examples of moisture problems

Freeze-thaw damage

Mold growth

Wood deformation: Shrinking, swelling



Dust deposition

Insects

Efflorescence

Rot

Corrosion

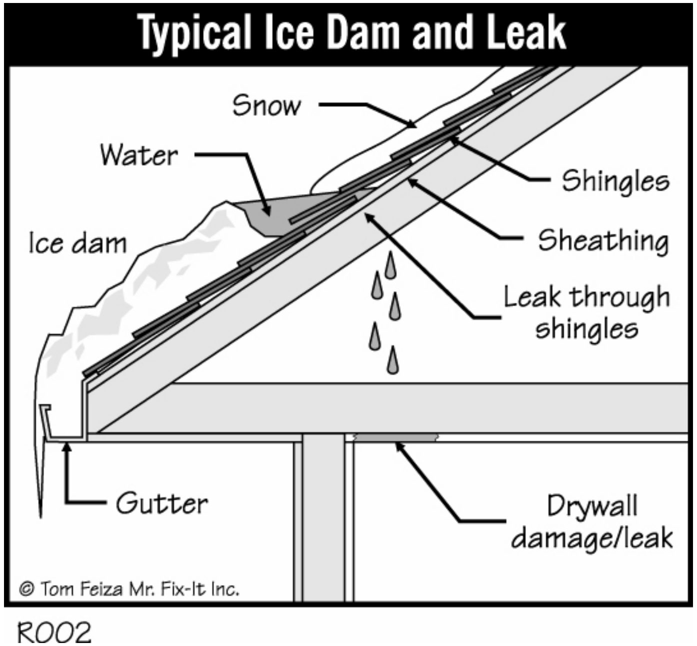
Examples of moisture problems

Frost formation on interior surfaces

http://www.bobvila.com/articles/how-to-avoid-frost-on-windows/#.Vsyn3rSxMeM
http://www.energyvanguard.com/blog-building-science-HERS-BPI/bid/74172/Frost-on-Indoor-Walls-A-Dramatic-Insulation-Failure

Examples of moisture problems

Ice dams



https://d12m281ylf13f0.cloudfront.net/images10/ice-dam2.jpg

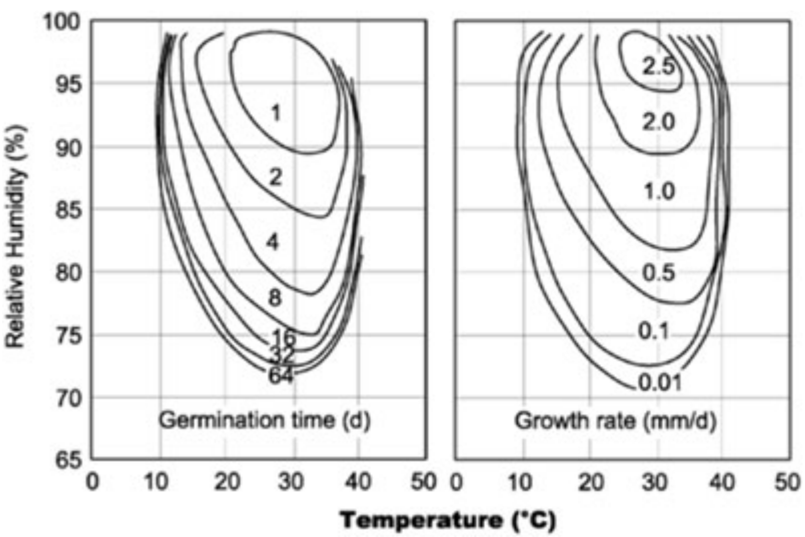
http://meltsnow.com/wp-content/uploads/2010/01/icedam-lg-1.jpg

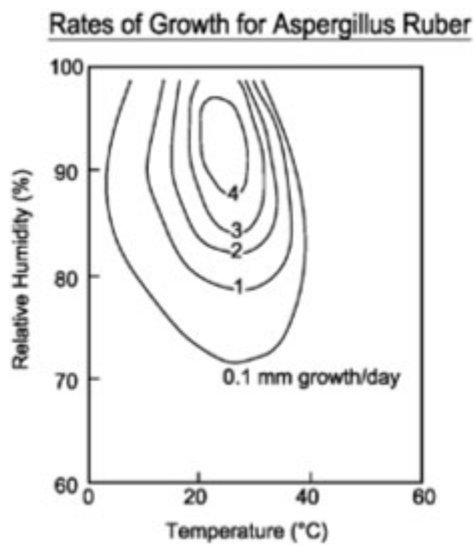
http://www.tpstry.com/images/awesome-roof-ice-dam-solutions-5-ice-dams-on-roofs-and-gutters-539-x-501.jpg

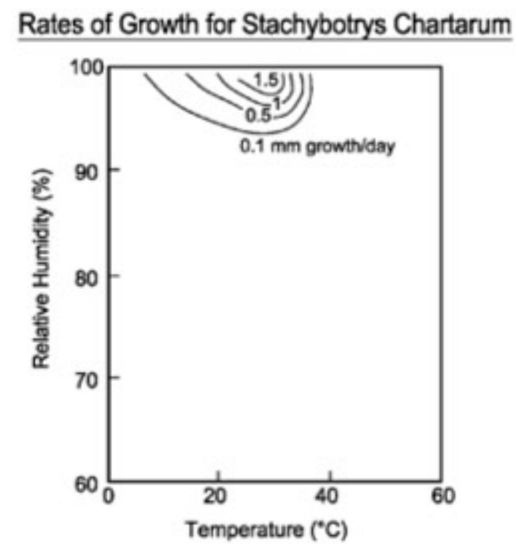

Mold growth requirements

- Typical room temperatures are often ideal for mold growth
  - Temperatures: 20-25°C
  - Particularly if humidity is high (e.g., > 80%)

Growth rates at different T and RH:



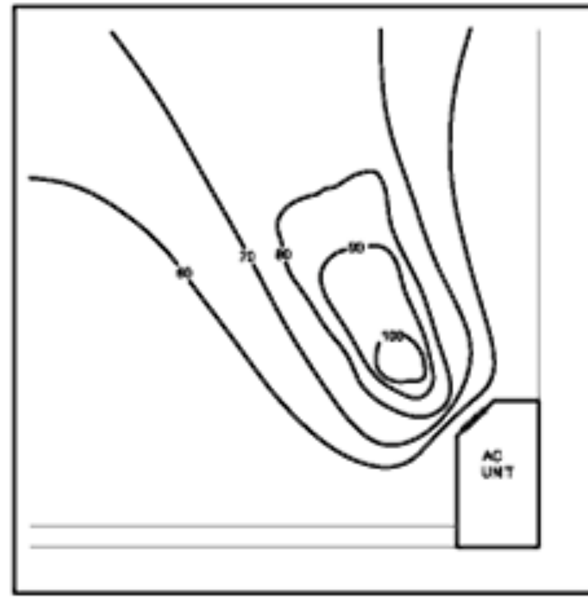




Detecting moisture damage: Moisture mapping

Condensation near an AC unit

- A surface moisture meter was used to map out the condensation pattern on a wall



- When the wall paper was pulled back we see mold growth that matches the condensation pattern

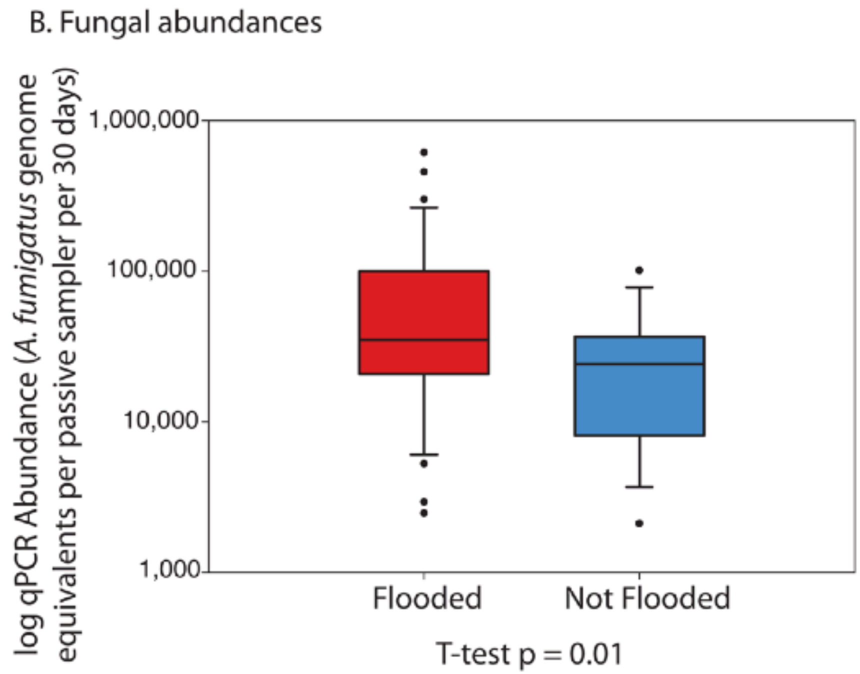
Moisture problems can last after the source is removed

Samples from the basements of 50 homes in Boulder, CO after 2013 flooding event

- 36 flood-damaged, 14 non-flooded

Impacts of Flood Damage on Airborne Bacteria and Fungi in Homes after the 2013 Colorado Front Range Flood

Joanne B. Emerson,[†] Patricia B. Keady,[‡] Tess E. Brewer,[§] Nicholas Clements,[‡] Emily E. Morgan,[§] Jonathan Awerbuch,[‡] Shelly L. Miller,[‡] and Noah Fierer*[†,||]



"Fungal abundances were estimated to be three times higher in flooded, relative to non-flooded homes"

"Fungal communities continue to be affected by flooding, even after relative humidity has returned to baseline levels and remediation has removed any visible evidence of flood damage."

Emerson et al. **2015** *Environ. Sci. Technol.*

Indoor dampness and health

Respiratory and Allergic Health Effects of Dampness, Mold, and Dampness-Related Agents: A Review of the Epidemiologic Evidence

Mark J. Mendell,[1,2] Anna G. Mirer,[3] Kerry Cheung,[4] My Tong,[1] and Jeroen Douwes[4]

[1]Indoor Air Quality Section, Environmental Health Laboratory Branch, California Department of Public Health, Richmond, California, USA; [2]Indoor Environment Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA; [3]Department of Population Health Sciences, University of Wisconsin School of Medicine and Public Health, Madison, Wisconsin, USA; [4]Centre for Public Health Research, Massey University, Wellington, New Zealand

Conclusions: Evident dampness or mold had consistent positive associations with multiple allergic and respiratory effects. Measured microbiologic agents in dust had limited suggestive associations, including both positive and negative associations for some agents. Thus, prevention and remediation of indoor dampness and mold are likely to reduce health risks, but current evidence does not support measuring specific indoor microbiologic factors to guide health-protective actions.

Mendell et al., **2011** *Environ Health Perspect*

Association of residential dampness and mold with respiratory tract infections and bronchitis: a meta-analysis

William J Fisk*†, Ekaterina A Eliseeva†, Mark J Mendell†

Conclusions: Residential dampness and mold are associated with substantial and statistically significant increases in both respiratory infections and bronchitis. If these associations were confirmed as causal, effective control of dampness and mold in buildings would prevent a substantial proportion of respiratory infections.

Fisk et al., **2010** *Environ Health*

How do we define moisture failure?

Some criteria:

- Total water content (WC) of assembly
  - Does it increase over time?
- Moisture content (%) in each component
  - Particularly critical wood components (should be less than 20%)
- Condensation potential
  - Are surface temperatures lower than indoor air dewpoint?
    - If so, any air leak could cause condensation
  - No good guidelines on critical values
- Potential for mold growth
  - ASHRAE Standard 160: 30 day running average surface RH>80% when temperature is between ~40°F and ~100°F

Why wasn't moisture a problem before?

- In the past, enclosure materials could store a lot more moisture in their denser, more porous construction and thus dry slowly
  - e.g. brick and stone
- Enclosures used to lack moisture barriers
  - Few materials were good vapor barriers
  - So any moisture that did get to an internal wall surface could dry by diffusion and air motion to either the inside or outside
- Larger air leaks in older, leaker enclosures also allowed moisture in internal surfaces to dry to either the inside or the outside

Why moisture is a problem now

Besides basic changes in wall construction from masonry to stud walls, there have been other changes in construction as well:

- Construction is more airtight
  - So any moisture that does get in cannot dry as easily
- Construction includes more materials that act as vapor barriers or at least have high vapor resistances
  - If vapor barrier is in the wrong spot it can cause condensation and limit drying
    - Latex paints
    - Foil coated insulation
    - Insulation in encapsulated in polyethelyne bags

Sources of moisture

- Water leakage
- Water penetration through joints and seams
- Bulk convection of moist air through cracks (and then condensation on surfaces below the dew point)
- Diffusion through the assembly materials
- Rising from damp ground

Moisture transport

Moisture enters a building in two forms:

- Liquid
- Vapor

We can break transport into three main categories:

- Condensed water infiltration (bulk liquid)
  - Infiltration of water in liquid form
- Moist air infiltration
  - Infiltration of water vapor in air that leaks into building
- Vapor diffusion
  - Infiltration of water vapor from high to low vapor pressure

Controlling Mode 1 (bulk liquid) differs from controlling Modes 2 and 3 (which involved water vapor)

- We will focus on water vapor first and bulk liquid water later

Water vapor transport

- Water vapor moves through the building enclosure in two primary modes
  1. Diffusion
  2. Bulk convection

- Combined transport of mass by diffusion and convection is called ***advection***

Water vapor transport: Diffusion

- Diffusion, like conduction, is mass/energy transport through a solid material, driven by a gradient

- Fick's Law:
  - Mass flow of water vapor dm_v/dt under a gradient in vapor pressure ∇p_w

$$\frac{dm_v}{dt} = -D\nabla p_w$$

where

$D =$ diffusivity

$p_w =$ vapor pressure (concentration)

$\nabla =$ divergent operator ($\partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$)

Water vapor diffusion

- In one dimension, the difference in vapor pressure, dp_w, over a thickness x drives the rate of water vapor mass flow:

$$\frac{dm_v}{dt} = -\mu A \frac{dp_w}{dx}$$

where

$\frac{dm_v}{dt} =$ rate of water vapor mass flow [ng/s]

$A =$ area perpendicular to flow [m^2]

$\mu =$ average vapor permeability [ng/(m Pa s)]

$\frac{dp_w}{dx} =$ vapor pressure gradient [Pa/m]

Water vapor diffusion

- Assuming that vapor permeance (μ) does NOT vary with T/RH (it actually does), Fick's law can be written as:

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,1} - p_{w,2}\right)$$

where

$\dot{M}_v =$ rate of water vapor mass flow [ng/s]

$A =$ area perpendicular to flow [m^2]

$\mu =$ average vapor permeability [ng/(m Pa s)]

$L =$ length of material [m]

$p_{w,i} =$ vapor pressure on either side of material [Pa]

$$\dot{m}_v = \frac{Q_v}{A} = \frac{\mu}{L}\left(p_{w,1} - p_{w,2}\right)$$

$\dot{m}_v =$ rate of water vapor mass flow per unit area [ng/s per m^2]

Water vapor diffusion

- We can rearrange terms just like in heat transfer:

$$\dot{m}_v = \frac{\dot{m}_v}{A} = \frac{\mu}{L}\left(p_{w,1} - p_{w,2}\right) = M\left(p_{w,1} - p_{w,2}\right) = \frac{1}{R_v}\left(p_{w,1} - p_{w,2}\right)$$

$$M = \frac{\mu}{L} \qquad \text{and} \qquad R_v = \frac{1}{M}$$

M = vapor permeance [ng/(s m^2 Pa)]

R_v = vapor resistance [(s m^2 Pa)/ng]

- *M* is analogous to *U*
- R_v is analogous to *R*

Water vapor diffusion: look familiar?

- Fick's law for diffusive vapor flow is the same as Fourier's Law for conductive heat flow

Table 6.1: Comparison of conductive heat flow and diffusive vapor flow

	Heat		Vapor	
Driving Potential	Temperature	t,T	Vapor Pressure	P_W
Measures	Conductivity	k, λ	Permeability	μ
	Conductance	C	Permeance	M
	Overall Transmittance	U	Overall Vapor Transmittance	V
	Resistance	R	Resistance	R_V
Flow	Heat flow	Q	Vapor Flow	Q_v
	Heat flux	q	Vapor flux	q_v
Single Layer	$\frac{\lambda}{l} \cdot \Delta t$ $= C \cdot \Delta t$ $= \Delta t / R$	q	$\frac{\mu}{l} \cdot \Delta P$ $= M \cdot \Delta P$ $= \Delta P / R_V$	i
Multi-Layer	$U \cdot \Delta t$		$V \cdot \Delta P$	

I prefer using:
$\dot{M}$
$\dot{m}$

Water vapor transport: Bulk convection

- The bulk convective flow of air can transport significant quantities of water vapor with it
  - Simple function of the flow rate of air
  - Remember the humidity ratio, $W = m_v/m_a$
  - If the rate of air movement is known:

$$\frac{dm_v}{dt} = \frac{dm_a}{dt}W$$

where

$\frac{dm_v}{dt}$ = rate of water vapor mass flow [kg_v/s]

$\frac{dm_a}{dt}$ = rate of air mass flow [kg_a/s]

W = humidity ratio [kg_v/kg_a]

Water vapor transport: convection

- Mass flow rate of convective water vapor movement

$$\dot{M}_{v,conv} = \rho_{air}\dot{V}_{air}W$$

  - Again, very similar to bulk convective heat transfer
  - Mass flow rate of water vapor equals mass flow rate of air times humidity ratio

Key terms for moisture performance

Water vapor diffusion: movement under a pressure gradient of water vapor

Term	Symbol	Definition	SI Units	IP Units
Vapor flow	$\dot{M}_v$	Time rate at which water vapor moves	[ng/s]	[grains/hr]
Vapor permeability	μ	Rate of vapor flow through a unit thickness of material under a unit vapor pressure difference	[ng/(s m Pa)]	perm-inch [grain/(hr in Hg in)]
Vapor permeance	M	Permeability of a material for a given thickness	[ng/(s m^2 Pa)]	perm [grains/(hr ft^2 inHg)]
Vapor resistance	R_v	Resistance of a material for a given thickness	[(s m^2 Pa)/ng]	rep = 1/perm [(hr ft^2 inHg)/grain]

A note on the unit **perm**:
Materials in the US (IP units) are referred to by **perm** values
1 perm = 1 grain/(hr ft^2 inHg) → similar to a unit R value
1 perm = 57.2 ng/(s m^2 Pa)

Material moisture resistance properties

Table 7A Typical Water Vapor Permeance and Permeability Values for Common Building Materials[a]

Material	Thickness, mm	Permeance, ng/(s·m²·Pa)	Resistance[h], (TPa·m²·s)/kg	Permeability, ng/(s·m·Pa)	Resistance/m[h], (TPa·m·s)/kg
Construction Materials					
Concrete (1:2:4 mix)				4.7	0.21
Brick masonry	100	46[f]	0.022		
Concrete block (cored, limestone aggregate)	200	137[f]	0.0073		
Tile masonry, glazed	100	6.9[f]	0.14		
Asbestos cement board	3	220-458[d]	0.0017-0.0035		
With oil-base finishes		17-29[d]	0.0035-0.052		
Plaster on metal lath	19	860[f]	0.0012		
Plaster on wood lath		630[e]	0.0016		
Plaster on plain gypsum lath (with studs)		1140[f]	0.00088		
Gypsum wall board (plain)	9.5	2860[f]	0.00035		
Gypsum sheathing (asphalt impregnated)	13		29[f]	0.038	
Structural insulating board (sheathing quality)				29-73[f]	0.038-0.014
Structural insulating board (interior, uncoated)	13	2860-5150[f]	0.00035-0.00019		
Hardboard (standard)	3.2	630[f]	0.0016		
Hardboard (tempered)	3.2	290[f]	0.0034		
Built-up roofing (hot mopped)		0.0	∞		
Wood, sugar pine				0.58-7.8[f,b]	172.0-131
Plywood (douglas fir, exterior glue)	6.4	40[f]	0.025		
Plywood (douglas fir, interior glue)	6.4	109[f]	0.0092		
Acrylic, glass fiber reinforced sheet	1.4	6.9[f*]	0.145		
Polyester, glass fiber reinforced sheet	1.2	2.9[f]	0.345		
	L	M	R_v (strange units)	μ	

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,1} - p_{w,2}\right)$$

2013 ASHRAE Handbook Chapter 26

Material moisture resistance properties

Table 7A Typical Water Vapor Permeance and Permeability Values for Common Building Materials[a]

Material	Thickness, mm	Permeance, ng/(s·m²·Pa)	Resistance[h], (TPa·m²·s)/kg	Permeability, ng/(s·m·Pa)	Resistance/m[h], (TPa·m·s)/kg
Thermal Insulations					
Air (still)				174[f]	0.0057
Cellular glass				0.0[d]*	∞
Corkboard				3.0-3.8[d]	0.33-0.26
				14[e]	0.076
Mineral wool (unprotected)				245[e]	0.0059
Expanded polyurethane [R = 1.94 W/(m²·K)] board stock				0.58-2.3[d]	1.72-0.43
Expanded polystyrene—extruded				1.7[d]	0.57
Expanded polystyrene—bead				2.9-8.4[d]*	0.34-0.12
Phenolic foam (covering removed)				38	0.026
Unicellular synthetic flexible rubber foam				0.029[d]	34-4.61
Plastic and Metal Foils and Films[c]					
Aluminum foil	0.025	0.0[d]	∞		
Aluminum foil	0.009	2.9[d]	0.345		
Polyethylene	0.051	9.1[d]	0.110		2133
Polyethylene	0.1	4.6[d]	0.217		2133
Polyethylene	0.15	3.4[d]*	0.294		2133
Polyethylene	0.2	2.3[d]*	0.435		2133
Polyethylene	0.25	1.7[d]	0.588		2133
Polyvinylchloride, unplasticized	0.051	39[d]*	0.026		
Polyvinylchloride, plasticized	0.1	46-80[d]*	0.032		
Polyester	0.025	42[d]	0.042		
Polyester	0.09	13[d]	0.075		
Polyester	0.19	4.6[d]	0.22		
Cellulose acetate	0.25	263[d]	0.0035		
Cellulose acetate	3.2	18[d]	0.054		
	L	M	R_v (strange units)	μ	

Materials: Vapor barriers and vapor retarders

- Vapor retarders slow the rate of vapor diffusion
  - But do not prevent it
- General rules for vapor permeance are as follows:

Type	Perms (IP units) [grains/(hr ft^2 inHg)]	SI units [ng/(s m^2 Pa)]	Example
Class I vapor retarder Vapor barrier Vapor impermeable	0.1 or less	5.7	Foil Polyethylene
Class II vapor retarder Vapor semi-impermeable	0.1-1	5.7-57	Brick XPS
Class III vapor retarder Vapor semi-permeable	1-10	57-570	Poly-iso EPS
Vapor permeable NOT a vapor retarder	10+	570+	Gypsum board

Materials: Vapor barriers and vapor retarders

- Vapor retarders also need to satisfy some other requirements:
  - Mechanically strong
  - Adhesive
  - Elastic
  - Thermally stable
  - Fire resistant
  - Resistant to UV degradation
  - Easily applied and installed

- Very small punctures can lead to moist air leakage
  - Significantly increases overall permeance

Calculating steady state 1-D vapor flow

- Calculating 1-D vapor flow follows same general principles as calculating 1-D heat flow by conduction

- However, results of calculations tend to be **much less accurate**, for several reasons:
  - Values for vapor permeability (*μ*) are not always accurate
    - They also vary widely with moisture content and temperature
      - Variations of an order of magnitude are common for some materials
    - Extrapolating for different thicknesses also introduces inaccuracy
  - Moisture storage capacity for most building materials is large
    - Steady state conditions almost never occur in practice
    - Evaporation and desorption act as moisture sources and sinks

- It is still important to understand basic vapor diffusion calculations
  - Helps identify potential condensation problems and understand how design decisions can impact potential moisture problems

Calculating steady state 1-D vapor flow

- **Example problem:** A 2 m wide, 3 m high, and 50 mm thick sheet of extruded polystyrene insulation material stands between indoor conditions of 24°C and 50% RH and exterior conditions of 35°C and 40% RH

- Calculate the following:
  - Water vapor permeance, M
  - Water vapor resistance, R_v
  - Water vapor flow rate, M_v
  - Water vapor flux, m_v

Example: Calculating steady state 1-D vapor flow

- First get p_{ws} for inside and outside conditions

Table 3 Thermodynamic Properties of Water at Saturation (*Continued*)

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m^3/kg_w Sat. Liquid v_f	Evap. v_{fg}	Sat. Vapor v_g	Specific Enthalpy, kJ/kg_w Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Specific Entropy, $kJ/(kg_w \cdot K)$ Sat. Liquid s_f	Evap. s_{fg}	Sat. Vapor s_g	Temp., °C t
0	0.6112	0.001 000	206.141	206.143	−0.04	2500.81	2500.77	−0.0002	9.1555	9.1553	0
1	0.6571	0.001 000	192.455	192.456	4.18	2498.43	2502.61	0.0153	9.1134	9.1286	1
2	0.7060	0.001 000	179.769	179.770	8.39	2496.05	2504.45	0.0306	9.0716	9.1022	2
3	0.7580	0.001 000	168.026	168.027	12.60	2493.68	2506.28	0.0459	9.0302	9.0761	3
4	0.8135	0.001 000	157.137	157.138	16.81	2491.31	2508.12	0.0611	8.9890	9.0501	4
5	0.8725	0.001 000	147.032	147.033	21.02	2488.94	2509.96	0.0763	8.9482	9.0244	5
6	0.9373	0.001 000	137.653	137.654	25.22	2486.57	2511.79	0.0913	8.9077	8.9990	6
7	1.0020	0.001 000	128.947	128.948	29.42	2484.20	2513.62	0.1064	8.8674	8.9738	7
8	1.0728	0.001 000	120.850	120.851	33.62	2481.84	2515.46	0.1213	8.8273	8.9488	8
9	1.1481	0.001 000	113.326	113.327	37.82	2479.47	2517.29	0.1362	8.7878	8.9240	9
10	1.2280	0.001 000	106.328	106.329	42.01	2477.11	2519.12	0.1511	8.7484	8.8995	10
11	1.3127	0.001 000	99.812	99.813	46.21	2474.74	2520.95	0.1659	8.7093	8.8752	11
12	1.4026	0.001 001	93.743	93.744	50.40	2472.38	2522.78	0.1806	8.6705	8.8511	12
13	1.4978	0.001 001	88.088	88.089	54.59	2470.02	2524.61	0.1953	8.6319	8.8272	13
14	1.5987	0.001 001	82.815	82.816	58.78	2467.66	2526.44	0.2099	8.5936	8.8035	14
15	1.7055	0.001 001	77.897	77.898	62.97	2465.30	2528.26	0.2244	8.5556	8.7801	15
16	1.8184	0.001 001	73.307	73.308	67.16	2462.93	2530.09	0.2389	8.5178	8.7568	16
17	1.9380	0.001 001	69.021	69.022	71.34	2460.57	2531.92	0.2534	8.4804	8.7338	17
18	2.0643	0.001 002	65.017	65.018	75.53	2458.21	2533.74	0.2678	8.4431	8.7109	18
19	2.1978	0.001 002	61.272	61.273	79.72	2455.85	2535.56	0.2821	8.4061	8.6883	19
20	2.3388	0.001 002	57.774	57.773	83.90	2453.48	2537.38	0.2964	8.3694	8.6658	20
21	2.4877	0.001 002	54.499	54.500	88.08	2451.12	2539.20	0.3107	8.3329	8.6436	21
22	2.6448	0.001 002	51.433	51.434	92.27	2448.75	2541.02	0.3249	8.2967	8.6215	22
23	2.8104	0.001 003	48.562	48.563	96.45	2446.39	2542.84	0.3390	8.2607	8.5996	23
24	2.9851	0.001 003	45.872	45.873	100.63	2444.02	2544.65	0.3531	8.2249	8.5780	24
25	3.1692	0.001 003	43.350	43.351	104.81	2441.66	2546.47	0.3672	8.1894	8.5565	25
26	3.3631	0.001 003	40.985	40.986	108.99	2439.29	2548.28	0.3812	8.1541	8.5352	26
27	3.5673	0.001 004	38.766	38.767	113.18	2436.92	2550.09	0.3951	8.1190	8.5141	27
28	3.7822	0.001 004	36.682	36.683	117.36	2434.55	2551.90	0.4090	8.0842	8.4932	28
29	4.0083	0.001 004	34.726	34.727	121.54	2432.17	2553.71	0.4229	8.0496	8.4724	29
30	4.2460	0.001 004	32.889	32.889	125.72	2429.80	2555.52	0.4367	8.0152	8.4519	30
31	4.4959	0.001 005	31.160	31.161	129.90	2427.43	2557.32	0.4505	7.9810	8.4315	31
32	4.7585	0.001 005	29.535	29.536	134.08	2425.05	2559.13	0.4642	7.9471	8.4112	32
33	5.0343	0.001 005	28.006	28.007	138.26	2422.67	2560.93	0.4779	7.9133	8.3912	33
34	5.3239	0.001 006	26.567	26.568	142.44	2420.29	2562.73	0.4915	7.8790	8.3713	34
35	5.6278	0.001 006	25.212	25.213	146.62	2417.91	2564.53	0.5051	7.8465	8.3516	35

Example: Calculating steady state 1-D vapor flow

- Then get p_w for indoor and outdoor conditions
  - Gives us the driving force

- Indoor @ 24°C and 50% RH:

$$p_{w,in} = \phi p_{ws,in} = 0.5(2985.3) = 1492.6 \text{ Pa}$$

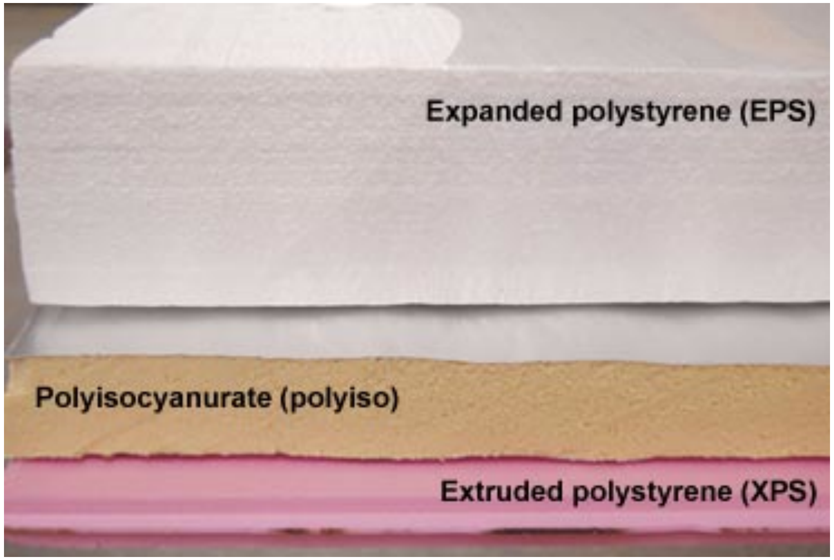
- Outdoor @ 35°C and 40% RH:

$$p_{w,out} = \phi p_{ws,out} = 0.4(5627.8) = 2251.1 \text{ Pa}$$

Example: Calculating steady state 1-D vapor flow

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,out} - p_{w,in}\right) = MA\left(p_{w,out} - p_{w,in}\right)$$

Need μ or M or extruded polystryene (XPS) foam



Example: Calculating steady state 1-D vapor flow

Table 7A Typical Water Vapor Permeance and Permeability Values for Common Building Materials[a]

Material	Thickness, mm	Permeance, $ng/(s \cdot m^2 \cdot Pa)$	Resistance[h], $(TPa \cdot m^2 \cdot s)/kg$	Permeability, $ng/(s \cdot m \cdot Pa)$	Resistance/m[h], $(TPa \cdot m \cdot s)/kg$
Thermal Insulations					
Air (still)				174[f]	0.0057
Cellular glass				0.0[d]*	∞
Corkboard				3.0-3.8[d]	0.33-0.26
				14[e]	0.076
Mineral wool (unprotected)				245[e]	0.0059
Expanded polyurethane [$R = 1.94$ W/($m^2 \cdot K$)] board stock				0.58-2.3[d]	1.72-0.43
Expanded polystyrene—extruded				1.7[d]	0.57
Expanded polystyrene—bead				2.9-8.4[d]*	0.34-0.12
Phenolic foam (covering removed)				38	0.026
Unicellular synthetic flexible rubber foam				0.029[d]	34-4.61
Plastic and Metal Foils and Films[c]					
Aluminum foil	0.025	0.0[d]	∞		
Aluminum foil	0.009	2.9[d]	0.345		
Polyethylene	0.051	9.1[d]	0.110		2133
Polyethylene	0.1	4.6[d]	0.217		2133
Polyethylene	0.15	3.4[d]*	0.294		2133
Polyethylene	0.2	2.3[d]*	0.435		2133
Polyethylene	0.25	1.7[d]	0.588		2133
Polyvinylchloride, unplasticized	0.051	39[d]*	0.026		
Polyvinylchloride, plasticized	0.1	46-80[d]*	0.032		
Polyester	0.025	42[d]	0.042		
Polyester	0.09	13[d]	0.075		
Polyester	0.19	4.6[d]	0.22		
Cellulose acetate	0.25	263[d]	0.0035		
Cellulose acetate	3.2	18[d]	0.054		

L   M R_v (strange units)   μ

Example: Calculating steady state 1-D vapor flow

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,out} - p_{w,in}\right) = MA\left(p_{w,out} - p_{w,in}\right)$$

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,out} - p_{w,in}\right)$$

$$\dot{M}_v = \frac{1.7 \dfrac{\text{ng}}{\text{s} \cdot \text{m} \cdot \text{Pa}}}{0.05 \text{ m}} (2 \text{ m})(3 \text{ m})(2251.1 - 1492.6 \text{ Pa})$$

$$\dot{M}_v = 157768 \frac{\text{ng}}{\text{s}} = 157.768 \frac{\mu\text{g}}{\text{s}} = 0.157 \frac{\text{mg}}{\text{s}}$$

Is that a lot of water?

Example: Calculating steady state 1-D vapor flow

Is that a lot of water?

$$\dot{M}_v = 157768 \ \frac{\text{ng}}{\text{s}} = 157.768 \ \frac{\mu\text{g}}{\text{s}} = 0.157 \ \frac{\text{mg}}{\text{s}}$$

- In 1 hour, or 3600 seconds, that would mean ~565 mg of water vapor would be driven inward
- Density of water vapor is ~0.622(1.2 kg/m^3) = ~0.746 kg/m^3

$$(565 \text{ mg})\left(\frac{\text{m}^3}{0.746 \text{ kg}}\right)\left(\frac{1 \text{ kg}}{1000 \text{ g}}\right)\left(\frac{1 \text{ g}}{1000 \text{ mg}}\right) = 0.000757 \text{ m}^3 \approx 0.8 \text{ L}$$

Example: Calculating steady state 1-D vapor flow

- Assume the insulation was adjacent to a 2 m x 3 m x 3 m space
  - Volume = 18 m^3 = 18,000 L

- Adding 0.8 L to 18,000 L would raise the water content of the room by about 0.005%

Is that a lot of water?

No.

Vapor diffusion through multiple layers

- Simplest estimation method is called Glaser's method
  - Used since the 1930s

- Analogous to heat flow through multiple layers

- Two things to remember:
  - Vapor flux across the entire assembly must also pass through each layer (conservation of mass)
  - Sum of the **resistances** of each layer gives the total resistance
    - Do not add permeances
    - *Does that sound familiar?*

Vapor diffusion through multiple layers

- For any layer j:

$$\dot{M}_v = M_j A \Delta p_{w,j} = \frac{1}{R_{v,j}} A \Delta p_{w,j}$$

- For an assembly of n layers:

$$\dot{M}_v = A \frac{p_{w,interior} - p_{w,exterior}}{\sum_{j=0}^{n} R_{v,j}}$$

- Vapor transmittance of a system of n layers

$$M_{v,total} = \frac{1}{\sum_{j=0}^{n} R_{v,j}}$$

Vapor diffusion through multiple layers

- Vapor pressure drop across layer j:

$$\Delta p_{w,j} = \dot{M}_v R_{v,j}$$

- Combining equations:

$$\Delta p_{w,j} = \frac{p_{w,interior} - p_{w,exterior}}{\sum_{j=0}^{n} R_{v,j}} R_{v,j}$$

- Again: *Doesn't this look familiar?*

Vapor diffusion through multiple layers

- A note on surface transfer coefficients:
- Remember that for heat transfer analysis we have to incorporate combined convective/radiative heat transfer coefficients into a “film” resistance
- For vapor transport, the convective mass transfer at exterior and interior surfaces is so high relative to vapor resistance that it can be ignored
  - There is no need for a “film resistance”
  - Equivalent permeance values (M)
    - Interior surfaces: 15000 ng/(Pa s m^2)
    - Still air spaces: 18000 ng/(Pa s m^2)
    - Exterior surfaces: 75000 ng/(Pa s m^2)
    - Compared to most building materials having 0-1000 ng/(Pa s m^2)

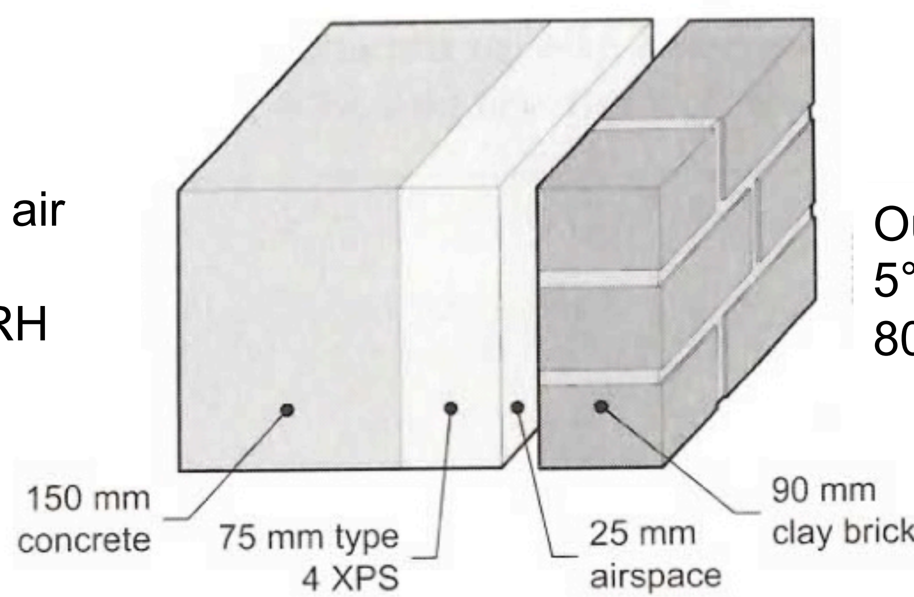
Glaser Method procedure

1. Break assembly into parallel paths
2. Find the temperature on all surfaces, T_j, of each path
3. Calculate saturation vapor pressure on all surfaces at the surface temp ($p_{ws,j}$ @ T_j)
4. Calculate interior and exterior vapor pressure from interior and exterior conditions
5. Estimate the vapor pressure, $p_{w,j}$, through the assembly assuming no condensation
6. Check if $p_{w,j} > p_{ws,j}$ at any location
   - If so, then condensation occurs on that surface
7. If condensation occurs, set $p_{w,j} = p_{ws,j}$ and reanalyze

Example: Vapor diffusion through multiple layers

- Calculate vapor distribution through the wall assembly shown
  - Is condensation expected to occur anywhere in the assembly under the given conditions?

Inside air
21°C
50% RH



Outside air
5°C
80% RH

Example: Vapor diffusion through multiple layers

- Start by finding material properties

	Permeability	Thickness	Permeance	Resistance
	μ	L	M_j	$R_{v,j}$
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m^2)**	**(Pa-s-m^2)/ng**
Indoors				
Interior film			15000	0.000067
Concrete	2.6	0.15	17.3	0.058
XPS	2.0	0.075	26.7	0.0375
Air space		0.025	7200	0.00014
Brick	10	0.09	111	0.009
Exterior film			75000	0.000013
Outdoors				

Example: Vapor diffusion through multiple layers

- Calculate total vapor resistance (R_v)
  - R_v = sum of all R_j
- Calculate vapor pressure difference across each element

$$\Delta p_{w,j} = \frac{p_{w,interior} - p_{w,exterior}}{\sum_{j=0}^{n} R_{v,j}} R_{v,j}$$

- Calculate vapor pressure at each interface

$$p_{w,2} = p_{w,1} - \Delta p_{w,2-1}$$

Example: Vapor diffusion through multiple layers

- Need to determine vapor pressure and temperature at each interface in the assembly
  - p_{ws} at boundaries:
  - Indoor (21°C, 50%RH) → p_{ws} = 2488 Pa
    - p_w = 0.5(2488) = 1244 Pa

  - Outdoor (5°C, 80% RH) → p_{ws} = 873 Pa
    - p_w = 0.8(873) = 698 Pa

Example: Vapor diffusion through multiple layers

	Permeability	Thickness	Permeance	Resistance		
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m^2)**	**(Pa-s-m^2)/ng**	**Pa**	**Pa**
Indoors						1244
Interior film			15000	0.000067	0.3	
						1243.7
Concrete	2.6	0.15	17.3	0.058	301.7	
						942.0
XPS	2.0	0.075	26.7	0.0375	196.1	
						745.9
Air space		0.025	7200	0.00014	0.7	
						745.1
Brick	10	0.09	111	0.009	47.1	
						698.1
Exterior film			75000	0.000013	0.1	
Outdoors						698
			$R_{v,total}$	0.104		

Now we have the vapor pressure at each surface interface

Great! But not that helpful yet…

Example: Vapor diffusion through multiple layers

- Now estimate temperature distribution throughout assembly
  - We learned how to do this last week

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**
Indoors						21
Interior film			8.0	0.125		
					0.7	20.3
Concrete	1.8	0.15	12	0.083		
					0.4	19.9
XPS	0.029	0.075	0.39	2.564		
					13.5	6.4
Air space		0.025	n/a	0.17		
					0.9	5.5
Brick	1.3	0.09	14.4	0.069		
					0.4	5.2
Exterior film			34	0.029		
Outdoors					0.2	5.0
			R_{total} (m^2K/W)	3.04		
			U_{total} (W/m^2K)	0.33		

Example: Vapor diffusion through multiple layers

- Now, calculate saturation vapor pressure at each interface ($p_{w,s}$)
  - Remember: p_{ws} it's a function of temperature only

$$\ln p_{ws} = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T$$

where

C_8 = –5.800 220 6 E+03
C_9 = 1.391 499 3 E+00
C_{10} = –4.864 023 9 E–02
C_{11} = 4.176 476 8 E–05
C_{12} = –1.445 209 3 E–08
C_{13} = 6.545 967 3 E+00

Example: Vapor diffusion through multiple layers

- Saturation vapor pressure at each interface ($p_{w,s}$)

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					0.7	20.3	293.5	2388.9
Concrete	1.8	0.15	12	0.083				
					0.4	19.9	293.1	2324.9
XPS	0.029	0.075	0.39	2.564				
					13.5	6.4	279.6	962.4
Air space		0.025	n/a	0.17				
					0.9	5.5	278.7	904.6
Brick	1.3	0.09	14.4	0.069				
					0.4	5.2	278.3	881.9
Exterior film			34	0.029				
Outdoors					0.2	5.0	278.2	872.5
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

Example: Vapor diffusion through multiple layers

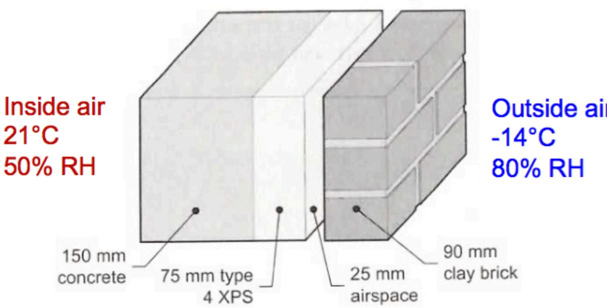
- Will we have condensation?
  - Compare actual vapor pressure to saturation vapor pressure at each layer interface (p_w vs. $p_{w,s}$)

	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m^2)**	**(Pa-s-m^2)/ng**	**Pa**	**Pa**	**Pa**	**%**
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	0.3			
						1243.7	2388.9	52%
Concrete	2.6	0.15	17.3	0.058	301.7			
						942.0	2324.9	41%
XPS	2.0	0.075	26.7	0.0375	196.1			
						745.9	962.4	77%
Air space		0.025	7200	0.00014	0.7			
						745.1	904.6	82%
Brick	10	0.09	111	0.009	47.1			
						698.1	881.9	79%
Exterior film			75000	0.000013	0.1			
Outdoors						698	872.5	80%
			$R_{v,total}$	0.104				

No condensation predicted under these conditions

Example: Vapor diffusion through multiple layers

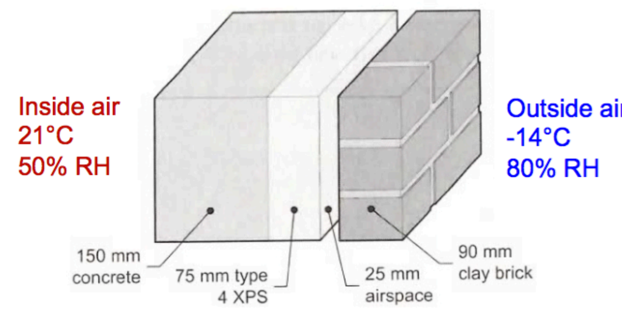
- What happens if conditions change?
  - Interior stays same (21°C and 50% RH)
  - Exterior drops to -14°C and 80% RH



	Permeability	Thickness	Permeance	Resistance		
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng	Pa	Pa
Indoors						1244
Interior film			15000	0.000067	0.7	
						1243.3
Concrete	2.6	0.15	17.3	0.058	595.6	
						647.7
XPS	2.0	0.075	26.7	0.0375	387.2	
						260.5
Air space		0.025	7200	0.00014	1.4	
						259.1
Brick	10	0.09	111	0.009	92.9	
						166.1
Exterior film			75000	0.000013	0.1	
Outdoors						166
			$R_{v,total}$	0.104		

Example: Vapor diffusion through multiple layers

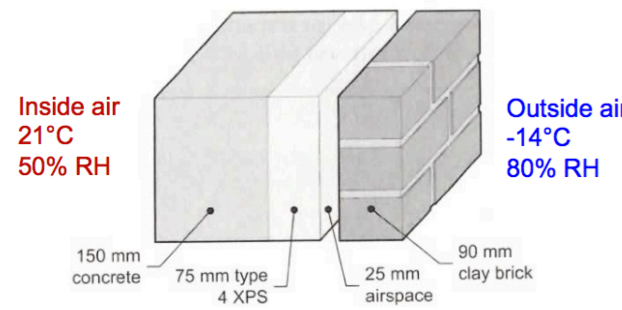
- What happens if conditions change?
  - Interior stays same (21°C and 50% RH)
  - Exterior drops to -14°C and 80% RH



	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					1.4	19.6	292.7	2276.0
Concrete	1.8	0.15	12	0.083				
					1.0	18.6	291.8	2143.8
XPS	0.029	0.075	0.39	2.564				
					29.5	-10.9	262.2	266.7
Air space		0.025	n/a	0.17				
					2.0	-12.9	260.3	228.0
Brick	1.3	0.09	14.4	0.069				
					0.8	-13.7	259.5	213.6
Exterior film			34	0.029				
Outdoors					0.3	-14.0	259.2	207.8
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

Example: Vapor diffusion through multiple layers

- What happens if conditions change?
  - Interior stays same (21°C and 50% RH)
  - Exterior drops to -14°C and 80% RH



	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng	Pa	Pa	Pa	%
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	0.7			
						1243.3	2276.0	55%
Concrete	2.6	0.15	17.3	0.058	595.6			
						647.7	2143.8	30%
XPS	2.0	0.075	26.7	0.0375	387.2			
						260.5	266.7	98%
Air space		0.025	7200	0.00014	1.4			
						259.1	228.0	114%
Brick	10	0.09	111	0.009	92.9			
						166.1	213.6	78%
Exterior film			75000	0.000013	0.1			
Outdoors						166	207.8	80%
			$R_{v,total}$	0.104				

Condensation will occur between air and brick
(RH > 100%)

Example: Vapor diffusion through multiple layers

- Now, RH can't actually be greater than 100%

- To continue the analysis, we would divide the wall into 2 sections and analyze them independently
  - If condensation occurs on a surface, some amount of moisture is removed at that interface
    - Assumption that mass flow in = mass flow out would be **false**
    - Some vapor is removed (by conversion to condensate)

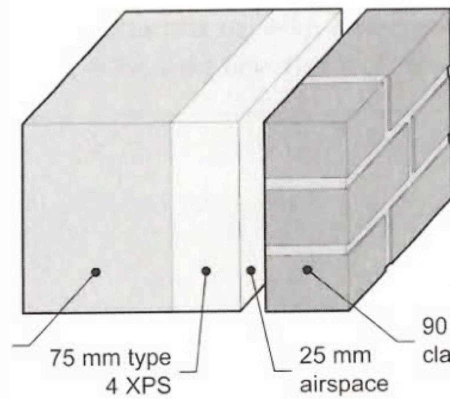
Example: Vapor diffusion through multiple layers

Procedure:

- Divide wall into two separate portions at the condensation plane
- Set the vapor pressure at the condensation plane equal to the saturation vapor pressure (RH = 100%)
  - This is more realistic and makes all calculations more accurate
- Analyze each portion of the divided wall separately using methods from previous example, but using the temperature and vapor pressure at the condensation plane as a boundary condition
  - For example: the interior portion of the divided assembly uses the vapor pressure at the condensation plane as the “exterior” vapor pressure

Example: Vapor diffusion through multiple layers

Layer Material	M_i (ng/Pa·s·m²)	$R_{v,i}$ (Pa·s·m²/ ng)	T (°C)	$P_{w,sat}$ (Pa)	P_w (Pa)	RH (%)
Interior			*21.0*	*2497.*	*1249.*	*50.*
Interior film [note]	15000.	0.000067				
			19.6	2287.	1248.	55.
Concrete	17.3	0.058				
			18.6	2155.	631.	29.
Type 4 XPS	26.7	0.038				
			-10.9	268.	230.	86.
Air space	7200.	0.00014				
			-12.9	229.	229.	100.
	ΣR_v	**0.0954**		$\Sigma \Delta P_w$	**1020.**	
		Flow to:	$\Delta P/\Sigma R_v$	10689.	ng/·s·m²	
			-12.9	229.	229.	100.
Brick	111.1	0.0090				
			-13.7	215.	167.	78.
Exterior film	*75000.*	0.000013				
Exterior			*-14.0*	*209.*	*167.*	*80.*
	ΣR_v	**0.0090**		$\Sigma \Delta P_w$	**62.**	
		Flow away:	$\Delta P/\Sigma R_v$	6862.	ng/·s·m²	
		Net Accumulation:		3827.	ng/·s·m²	



RH set to 100%

RH set to 100%

Example: Vapor diffusion through multiple layers

- What happened to the condensate?

ΣR_v	0.0954		$\Sigma \Delta P_w$	1020.
	Flow to:	$\Delta P / \Sigma R_v$	10689.	$ng/\cdot s \cdot m^2$

The vapor pressure difference from interior to edge of brick divided by the sum of the vapor resistances on this side of the wall division tells us the rate of inflow or outflow of vapor (inflow from interior to brick surface in this case)

- Similarly, on the other wall division:

ΣR_v	0.0090		$\Sigma \Delta P_w$	62.
	Flow away:	$\Delta P / \Sigma R_v$	6862.	$ng/\cdot s \cdot m^2$
	Net Accumulation:		3827.	$ng/\cdot s \cdot m^2$

Rate of outflow from brick surface to exterior

Example: Vapor diffusion through multiple layers

- The difference between the rate of vapor flow into the condensation plane and the rate of vapor flow away from the plane yields the net accumulation

ΣR_v	0.0090		$\Sigma \Delta P_w$	62.
	Flow away:	$\Delta P / \Sigma R_v$	6862.	$ng/\cdot s \cdot m^2$
	Net Accumulation:		3827.	$ng/\cdot s \cdot m^2$

- Net accumulation = rate of condensate formation
  - From water vapor to liquid water
  - Net accumulation = 3827 ng/(s m^2) or 0.0137 grams per hr per m^2
    - This is not a lot of condensation
  - If conditions stayed the same for 24 hours, condensation due to vapor diffusion would make a layer of water ~1 μm thick (1 millionth of a meter)

Example: Vapor diffusion through multiple layers

- Even though vapor diffusion was low…
  - What to do to prevent condensation under these conditions?
  - Look back at the table of materials
    - Brick, XPS, and concrete have the lowest permeance
    - What if we just add some <u>ventilation to the brick cladding</u>?

	Permeability	Thickness	Permeance	Resistance
	μ	L	M_j	$R_{v,j}$
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m^2)**	**(Pa-s-m^2)/ng**
Indoors				
Interior film			15000	0.000067
Concrete	2.6	0.15	17.3	0.058
XPS	2.0	0.075	26.7	0.0375
Air space		0.025	7200	0.00014
Brick	10	0.09	111	0.009
Exterior film			75000	0.000013
Outdoors				

Adding "weep holes" can increase permeance of brick cladding to **1000** ng/(Pa s m^2)

Example: Vapor diffusion through multiple layers

- Even though vapor diffusion was low…
  - What to do to prevent condensation under these conditions?
  - Look back at the table of materials
    - Brick, XPS, and concrete have the lowest permeance
    - What if we just add some ventilation to the brick cladding?

	Permeability	Thickness	Permeance	Resistance
	μ	L	M_j	$R_{v,j}$
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng
Indoors				
Interior film			15000	0.000067
Concrete	2.6	0.15	17.3	0.058
XPS	2.0	0.075	26.7	0.0375
Air space		0.025	7200	0.00014
Brick	10	0.09	1000	0.001
Exterior film			75000	0.000013
Outdoors				

Adding “weep holes” can increase permeance of brick cladding to **1000** ng/(Pa s m^2)

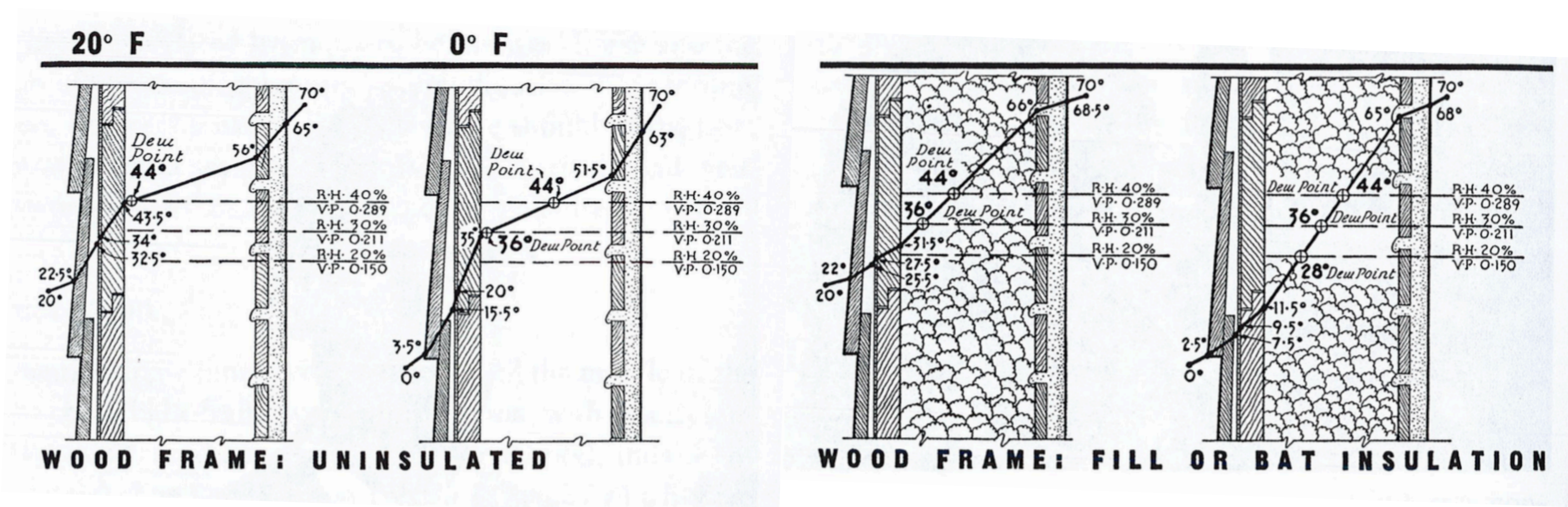
Example: Vapor diffusion through multiple layers

- Ventilated brick cladding eliminates condensation potential under these conditions

	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng	Pa	Pa	Pa	%
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	0.7			
						1243.3	2276.0	55%
Concrete	2.6	0.15	17.3	0.058	645.1			
						598.2	2143.8	28%
XPS	2.0	0.075	26.7	0.0375	419.3			
						178.9	266.7	67%
Air space		0.025	7200	0.00014	1.6			
						177.3	228.0	78%
Brick	10	0.09	1000	0.001	11.2			
						166.1	213.6	78%
Exterior film			75000	0.000013	0.1			
Outdoors						166	207.8	80%
			$R_{v,total}$	0.096				

Vapor pressure diagrams

- We can plot the saturation vapor pressures and predicted vapor pressures on charts as a function of distance from the wall interior
  - Offers a way to interpret previous calculations graphically
  - If the predicted pressure is above the saturation vapor pressure we will have condensation



Vapor pressure diagrams

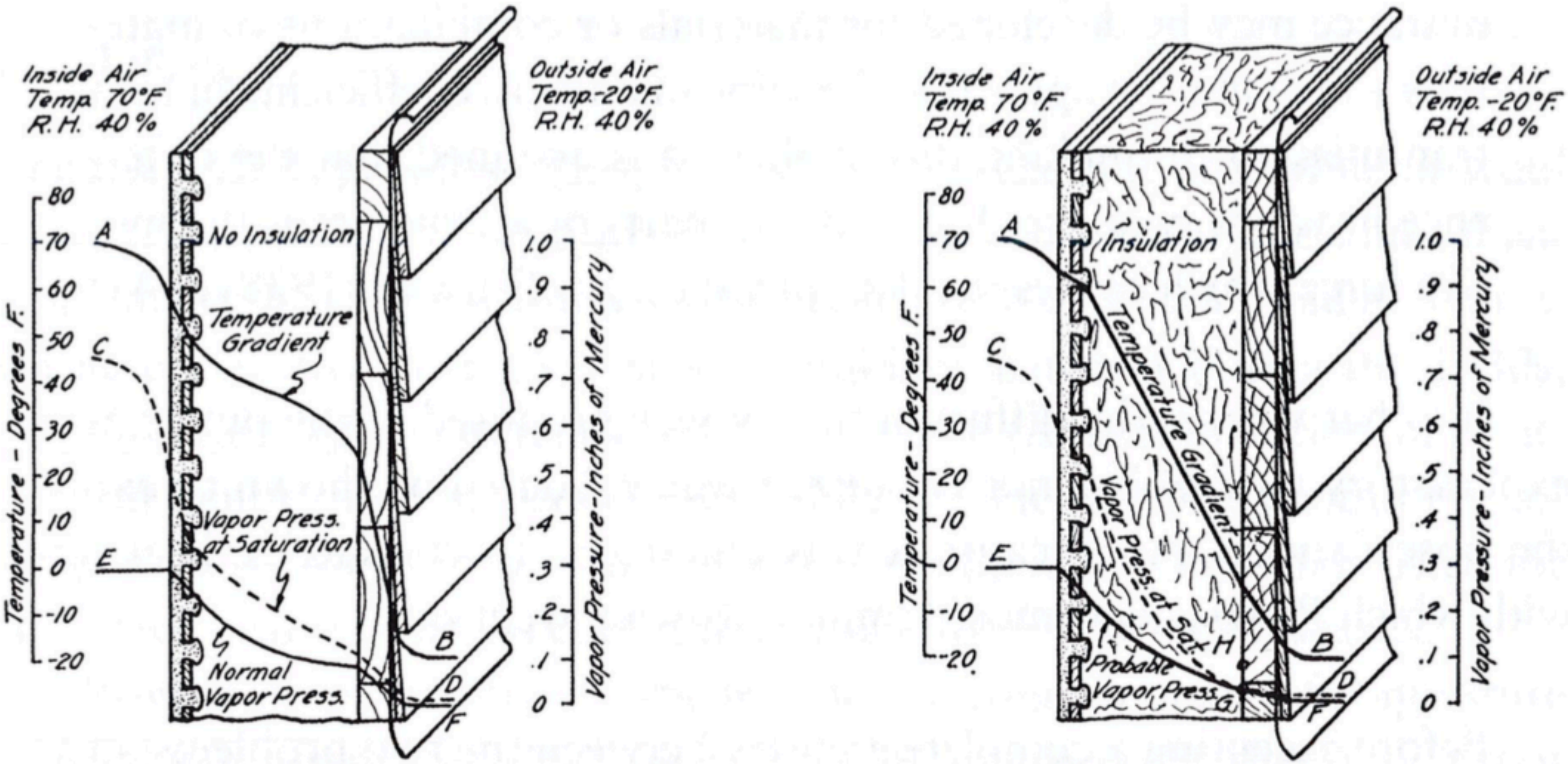
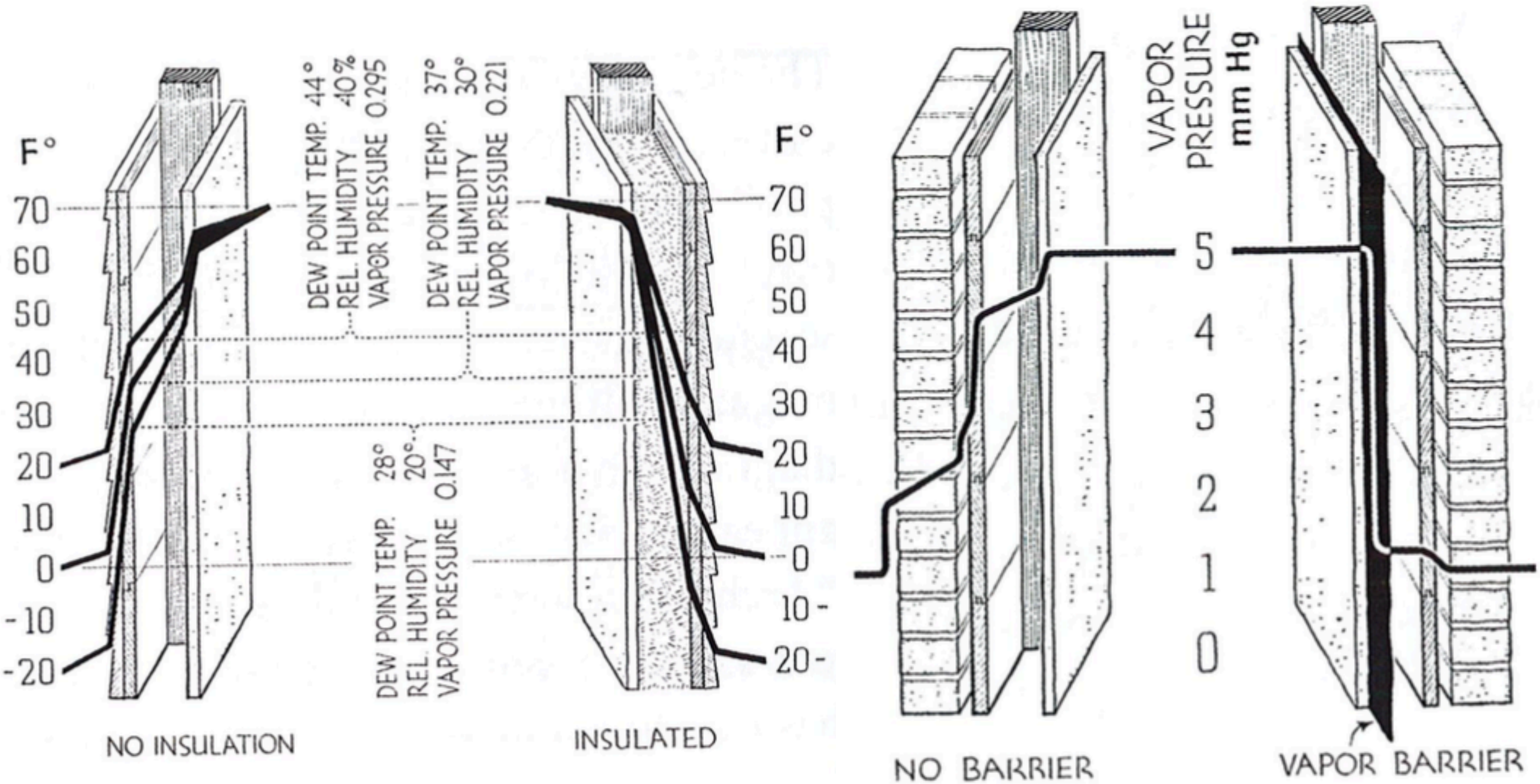


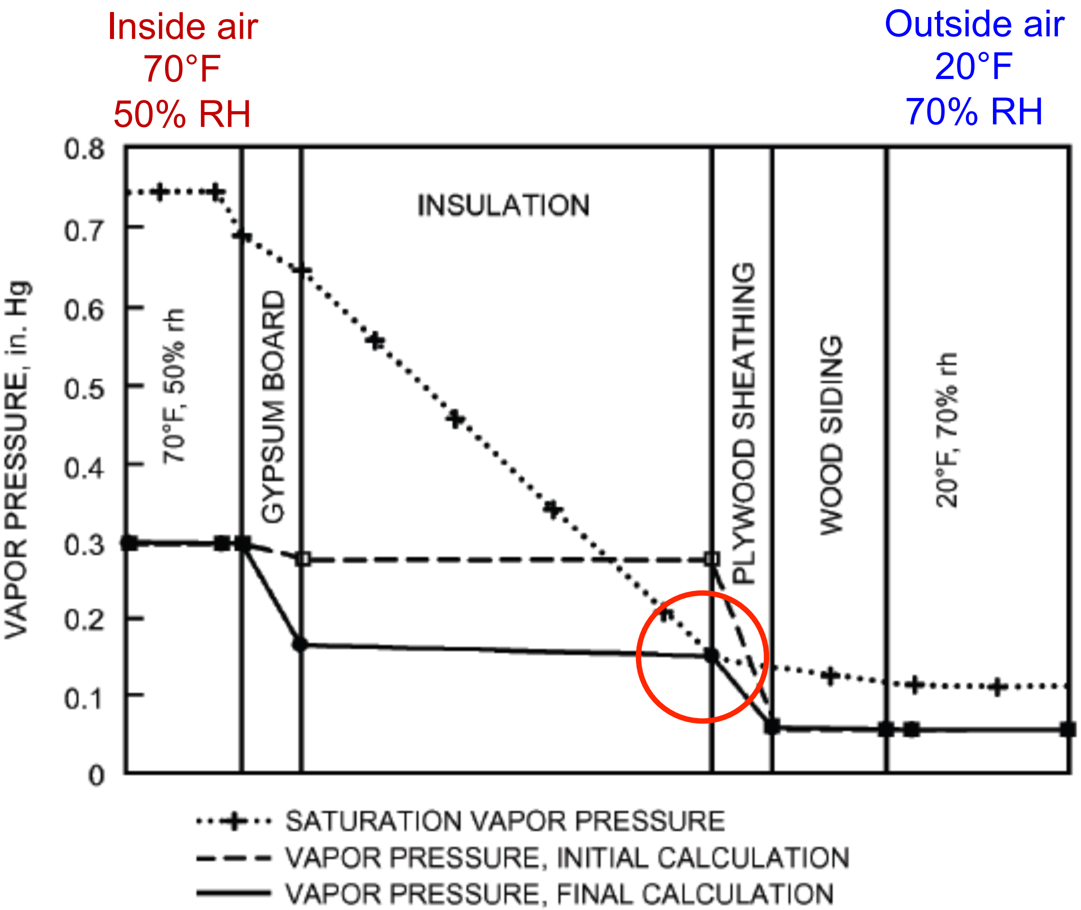
Figure 3-5

Saturation vapor pressure and vapor pressure curves on the same section. (From Rowley, 1938.)ASHRAE Transactions 1938. © American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., www.ashrae.org.

Vapor pressure **diagrams**



Vapor pressure **diagrams**

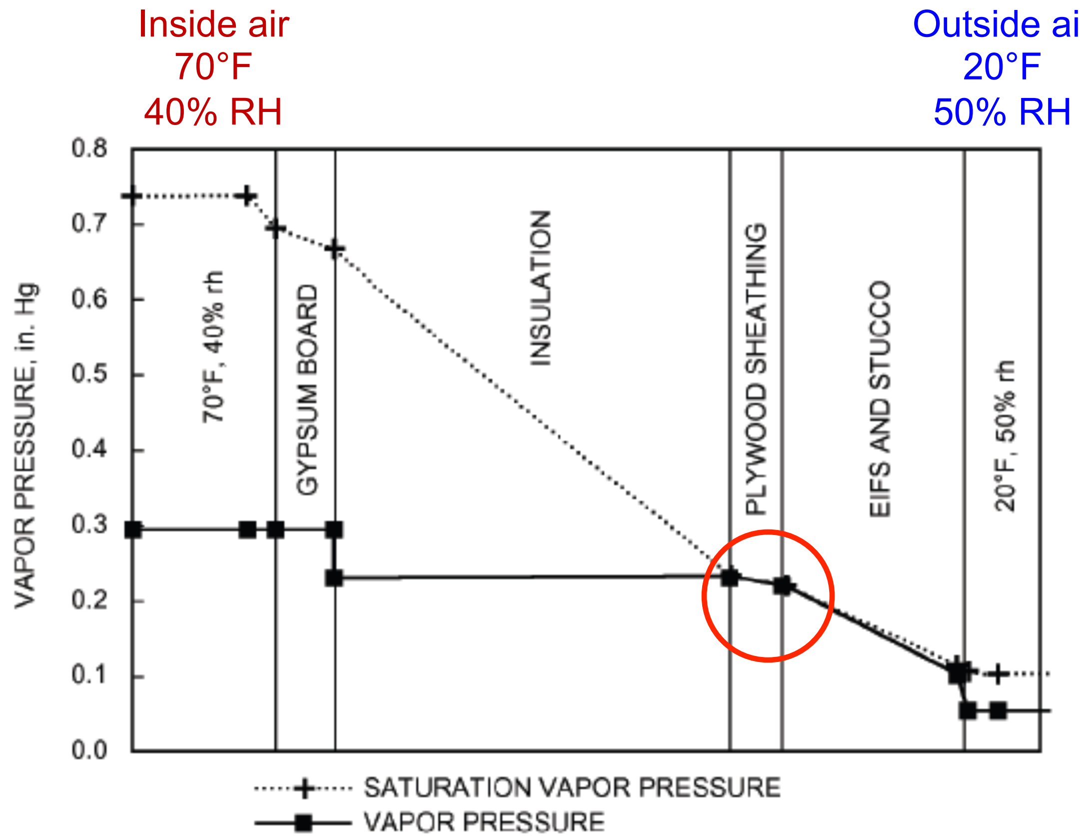


- Condensation is occurring between the insulation and the plywood
- Drying occurs to outside since it is lowest p_w

Vapor pressure diagrams

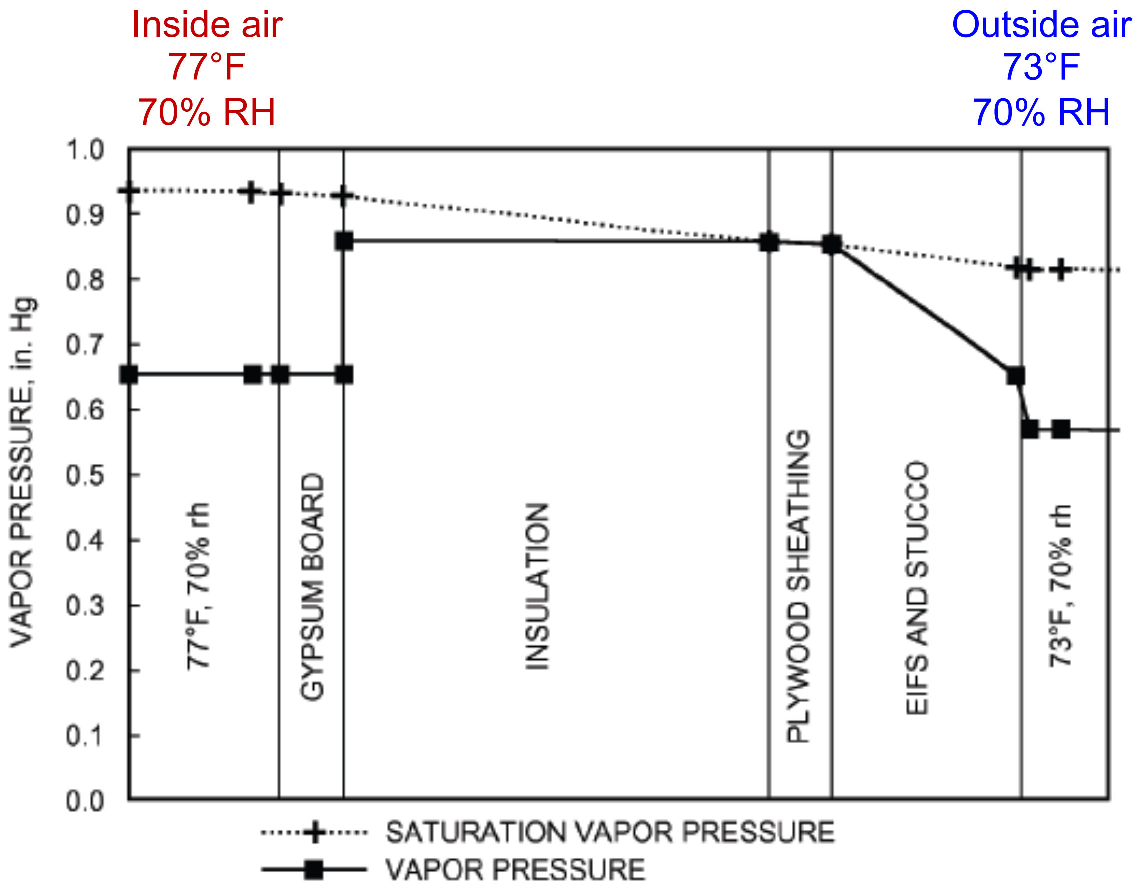
- Condensation between insulation and sheathing and possibly between sheathing and EIFS

- Drying occurs to the outside



Vapor pressure diagrams

- Condensation on this sheathing can dry to either outside or inside



Bulk air movement and vapor transport

- Vapor diffusion is often a **relatively small** contributor to vapor transport
  - Bulk movement of air usually transports far more water vapor than diffusion

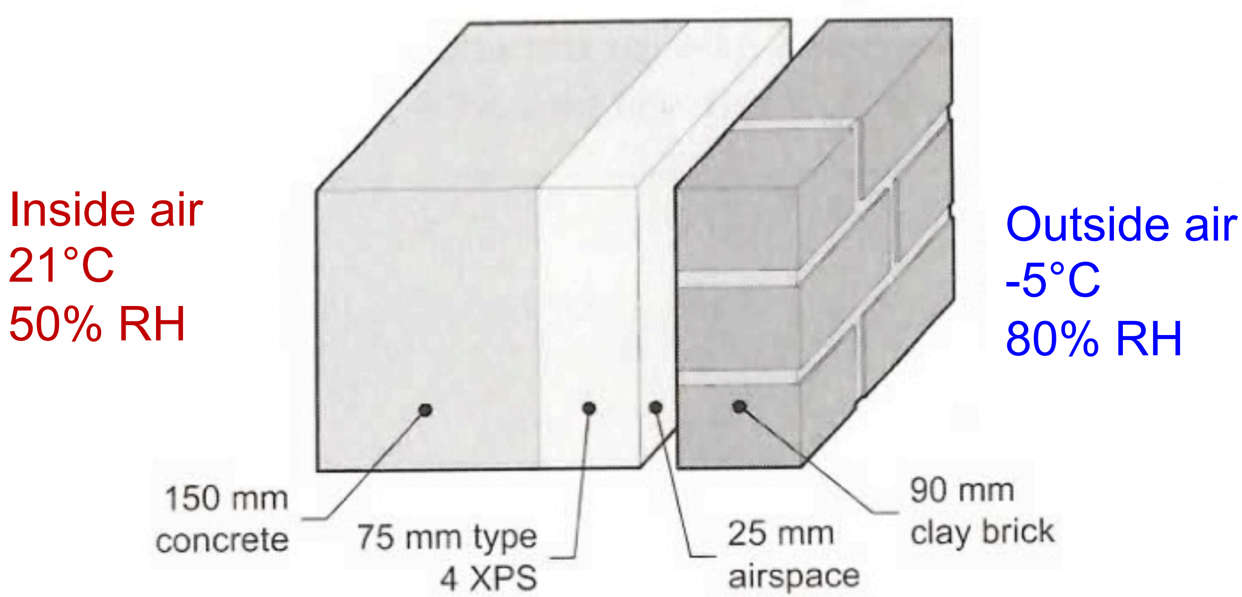
- The capacity of air to hold water vapor is high enough that bulk air movement can transport a significant amount of moisture
  - When air comes in contact with enclosure surfaces, condensation will occur at those surfaces below the air's dew point temperature

Bulk air movement and vapor transport

- Calculating the quantity of air leakage condensation in enclosures is difficult to do accurately
  - But given a flow rate, we can find the maximum amount of condensation that could occur

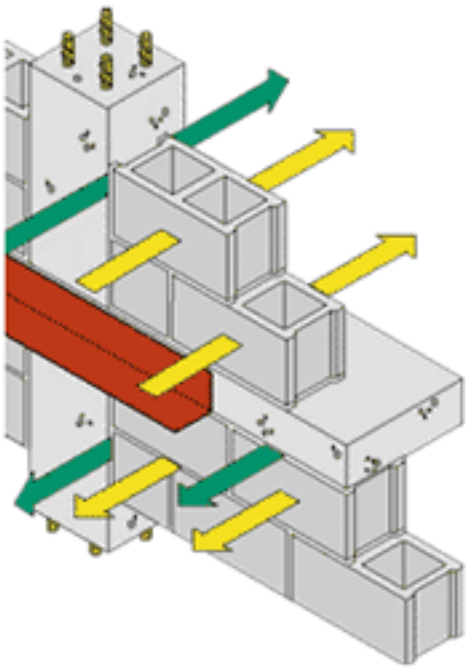
Example: Bulk air movement and vapor transport

- Let's calculate the volume of condensation that would form if we had bulk air leakage through the same assembly from before
  - Air leakage rate of **0.5 L per second per m²** of exfiltration
    - Air moving from interior to exterior



Air leakage and water vapor transport

- 0.5 L/s per m^2 of wall



Imagine a 20m x 10m building:

0.5	Leakage, L/s/m^2
10	Width, m
20	Length, m
2.4	Height, m
144	Surface area of walls, m^2
72	Flow rate, L/s
259.2	Flow rate, m^3/hr
480	Volume, m^3
0.54	ACH, 1/hr

Example: Bulk air movement and vapor transport

- Method:
  1. Calculate temperature at every layer
  2. Calculate moisture content (i.e., humidity ratio) and dew point temperature of the interior or exterior air (direction of air movement)
  3. Calculate saturation vapor pressure of the first **upstream-facing** surface in the enclosure that is below the dew point temperature of the stream of air
  4. The maximum amount of condensate transported by bulk convection (and thus deposited on the condensation plane) is the moisture content of the indoor air minus the saturation moisture content of air at this particular layer

Example: Bulk air movement and vapor transport

1. Calculate temperature at every layer

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					1.1	19.9	293.1	2328.9
Concrete	1.8	0.15	12	0.083				
					0.7	19.2	292.4	2228.0
XPS	0.029	0.075	0.39	2.564				
					21.9	-2.7	270.4	501.2
Air space		0.025	n/a	0.17				
					1.5	-4.2	269.0	449.6
Brick	1.3	0.09	14.4	0.069				
					0.6	-4.7	268.4	429.9
Exterior film			34	0.029				
Outdoors					0.3	-5.0	268.2	421.8
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

Example: Bulk air movement and vapor transport

2. Calculate humidity ratio and dew point temperature of the interior or exterior air

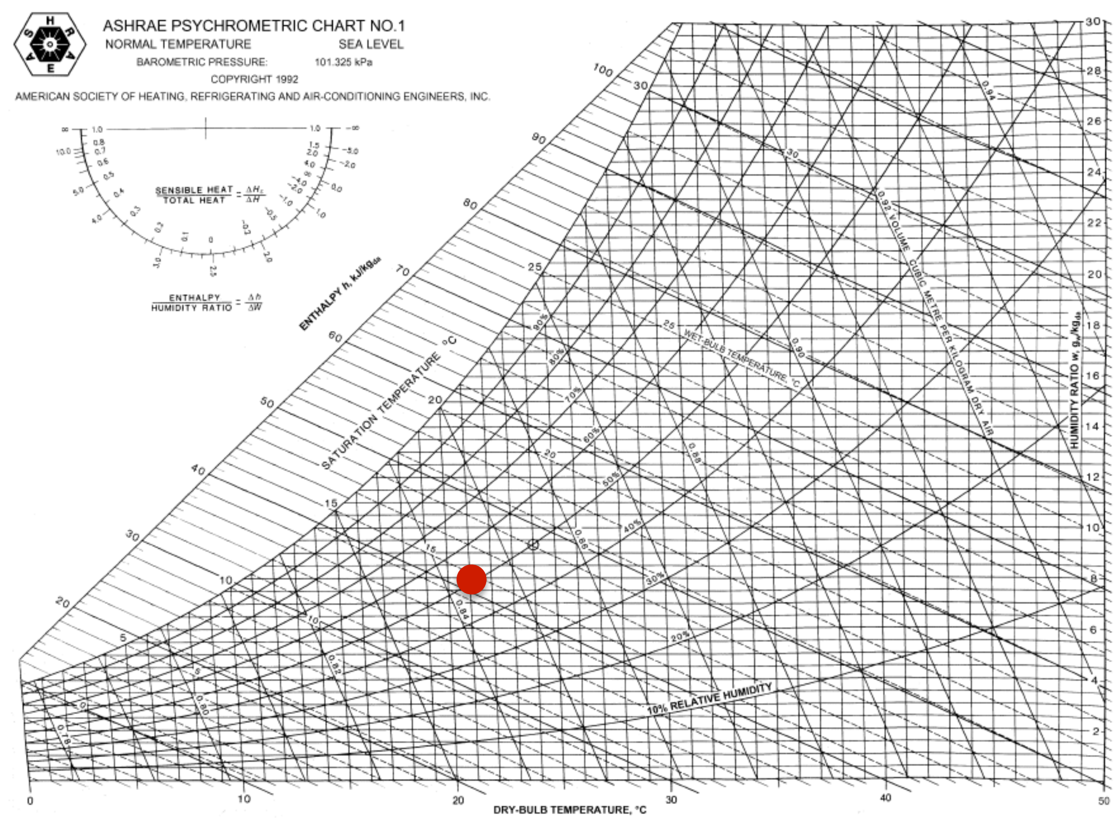
p_{ws} at boundaries:

Indoor (21°C, 50%RH) → p_{ws} = 2488 Pa

$p_w = 0.5(2488) = 1244$ Pa → $W_{surf} = 0.622 p_w / (p_{total} - p_w)$

$W_{surf} = 0.622(1244)/(101325 - 1244) = 0.00773\ kg_w/kg_{da}$

$T_{dew\ point} = \sim 10.2°C$



Example: Bulk air movement and vapor transport

3. Calculate saturation vapor pressure of the first surface in the enclosure that is below the dewpoint of the stream of air (T_{dew} = 10.2°C)

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					1.1	19.9	293.1	2328.9
Concrete	1.8	0.15	12	0.083				
					0.7	19.2	292.4	2228.0
XPS	0.029	0.075	0.39	2.564				
					21.9	-2.7	270.4	501.2
Air space		0.025	n/a	0.17				
					1.5	-4.2	269.0	449.6
Brick	1.3	0.09	14.4	0.069				
					0.6	-4.7	268.4	429.9
Exterior film			34	0.029				
Outdoors					0.3	-5.0	268.2	421.8
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

The exterior side of the XPS insulation is the first surface below dew point of air stream

BUT, remember our rule for the first "upstream-facing" solid surface

Upstream = inside ($p_{w,in} > p_{w,out}$) & XPS side faces out

Choose upstream-facing <u>brick surface</u> (T = -4.2 °C)

$p_{w,sat}$ = 450 Pa → W_{sat} = 0.622(450)/(101325 – 450) = 0.00279 kg_w/kg_{da}

Example: Bulk air movement and vapor transport

4. Maximum amount of condensate transported by bulk convection and deposited on the condensation plane

Mass flow rate of vapor at 0.5 L/s per m^2, assuming density of air is ~1.2 kg/m^3:

$\dot{m}$ = 1.2 kg/m^3 * (0.5 L/s) (1 m^3 / 1000 L) per m^2

$\dot{m}$ = 0.0006 kg/s per m^2

Under ideal conditions, moisture will condense on the back of the brick at the following rate:

$(W_{in} – W_{sat,condensation\ plane}) * \dot{m}$ = (7.73 g/kg – 2.79 g/kg)*(0.0006 kg/s) per m^2

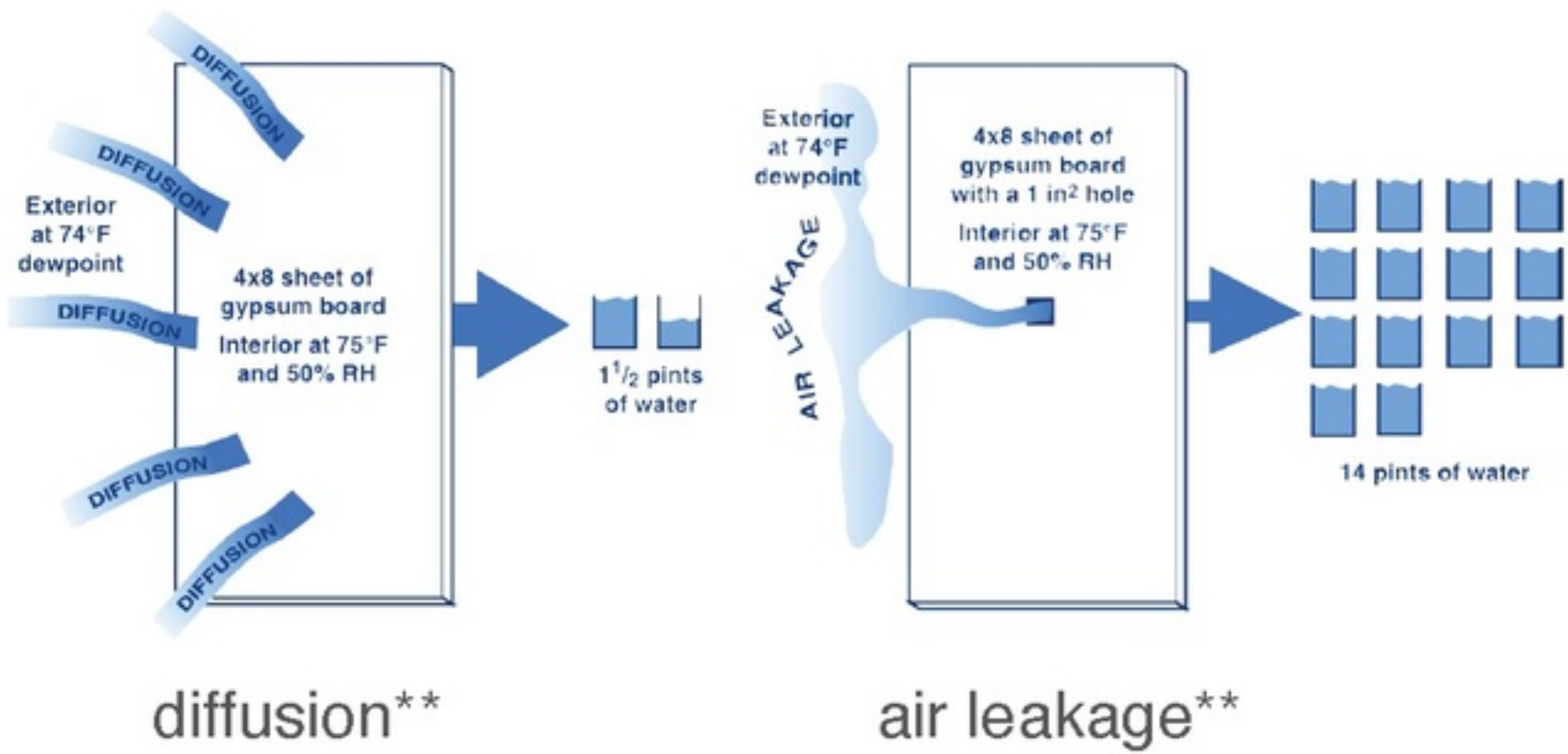
Condensation rate = 4.97 x 10^{-3} g/s per m^2

or Condensation rate = 17.9 g/hour per m^2

Remember: condensation rate due to **diffusion** in last example was: 0.0137 g/hr per m^2

Over 1000 times more condensation by bulk convection than by diffusion

Bulk vapor transport vs. vapor diffusion



Bulk air movement and vapor transport

- Equivalent vapor permeance for various airflow rates:

Airflow rate (L/s per m^2)	Equiv. vapor permeance ng/(s m^2 Pa)
0.05	375
0.10	750
0.25	1875
0.50	3750
1.00	7500
3.00	22600

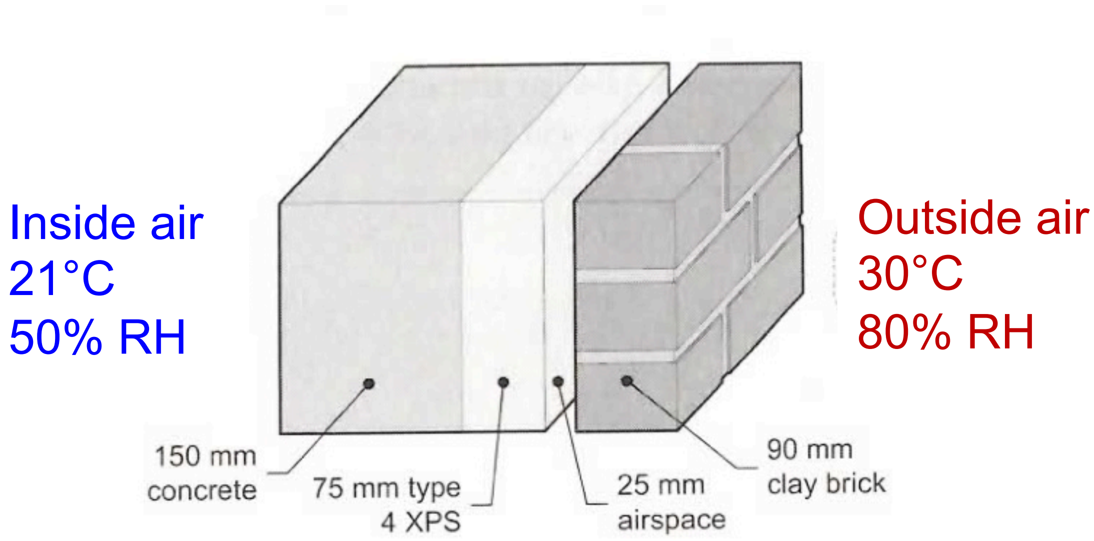
  - For comparison: vapor permeance of brickwork and wood siding is approximately 50 ng /(s m^2 Pa)
  - We will learn more about airflows in a couple of weeks

Bulk air movement and vapor transport

- This value should be considered the **maximum amount** of condensation because several issues prevent accurate calculations:
  - Method assumes steady state diffuse (1-D) convection flow
  - Large flows of air will tend to alter temperatures near the actual flow path (i.e., if warm air entering an envelope actually warms the surface it's passing over, less condensation than we predict will occur)
  - Some moist air will pass through the assembly without actually contacting the surface that we're assuming condensation may be occurring
  - Flow through some enclosures is incredibly complex (think: flow through mineral fiber insulations – our 1-D steady state assumptions lead to inaccuracies)

Vapor diffusion: Summer example

- Determine the vapor and temperature distribution through the wall assembly from last time for a hot, humid, summer day with exterior conditions of 30 C and 80% RH



  – This time, water vapor is driven inward
    - **Exterior** is the high vapor pressure side

Summer conditions

	Permeability	Thickness	Permeance	Resistance
	μ	L	M_j	$R_{v,j}$
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m²)**	**(Pa-s-m²)/ng**
Indoors				
Interior film			15000	0.000067
Concrete	2.6	0.15	17.3	0.058
XPS	2.0	0.075	26.7	0.0375
Air space		0.025	7200	0.00014
Brick	10	0.09	1000	0.001
Exterior film			75000	0.000013
Outdoors				
			$R_{v,total}$	0.096

Summer conditions

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					-0.4	21.4	294.5	2544.8
Concrete	1.8	0.15	12	0.083				
					-0.2	21.6	294.8	2583.5
XPS	0.029	0.075	0.39	2.564				
					-7.6	29.2	302.4	4055.9
Air space		0.025	n/a	0.17				
					-0.5	29.7	302.9	4175.2
Brick	1.3	0.09	14.4	0.069				
					-0.2	29.9	303.1	4224.9
Exterior film			34	0.029				
Outdoors					-0.1	30.0	303.2	4246.0
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

New outdoor temperature and saturation vapor pressures, $p_{w,sat}$

Summer conditions

	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng	Pa	Pa	Pa	%
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	-1.5			
						1245.5	2544.8	49%
Concrete	2.6	0.15	17.3	0.058	-1288.4			
						2533.8	2583.5	98%
XPS	2.0	0.075	26.7	0.0375	-837.4			
						3371.3	4055.9	83%
Air space		0.025	7200	0.00014	-3.1			
						3374.4	4175.2	81%
Brick	10	0.09	1000	0.001	-22.3			
						3396.7	4224.9	80%
Exterior film			75000	0.000013	-0.3			
Outdoors						3397	4246.0	80%
			$R_{v,total}$	0.096				

$$\Delta p_{w,j} = \frac{p_{w,interior} - p_{w,exterior}}{\sum_{j=0}^{n} R_{v,j}} R_{v,j}$$

Condensation potential --- very close!

Summer conditions (more realistic)

- But, this example ignores **solar radiation**
  - What if the same assembly is exposed to solar radiation?
  - Exterior surface temperature increases
    - We could estimate the surface temperature using surface energy balance
    - Or we could get a rough estimate using this table (*sol-air temperatures*):

Table 5.5: Approximate extreme radiation-induced surface temperatures (°C)

Situation	Thermally massive	Thermally lightweight
Roofs: direct sun	$t_a + 42\,\alpha$	$t_a + 55\,\alpha$
Roof: sun + reflected /emitted radiation	$t_a + 55\,\alpha$	$t_a + 72\,\alpha$
Roof exposed to night sky	$t_a - 5\,\varepsilon$	$t_a - 10\,\varepsilon$
Walls: winter sun	$t_a + 35\,\alpha$	$t_a + 48\,\alpha$
Walls: summer sun	$t_a + 28\,\alpha$	$t_a + 40\,\alpha$
Walls exposed to night sky	$t_a - 2\,\varepsilon$	$t_a - 4\,\varepsilon$

Notes: t_a refers to the ambient air temperature, ε is the surface emittance, and α is the solar absorptance.

Summer conditions (more realistic)

- Taking a hypothetical exterior surface temperature in direct sunlight where $T_{surface,exterior}$ = 45°C
  - Change distribution of T and $p_{w,sat}$
    - But p_w distribution does not change

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					-1.0	22.0	295.1	2642.6
Concrete	1.8	0.15	12	0.083				
					-0.7	22.6	295.8	2750.5
XPS	0.029	0.075	0.39	2.564				
					-20.2	42.9	316.0	8594.4
Air space		0.025	n/a	0.17				
					-1.3	44.2	317.4	9214.9
Brick	1.3	0.09	14.4	0.069				
					-0.5	44.8	317.9	9479.3
Exterior film			34	0.029				
Outdoors					-0.2	45.0	318.2	9593.2
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

Summer conditions (more realistic)

- Taking a hypothetical exterior surface temperature in direct sunlight where $T_{surface,exterior} = 45°C$
  - Change distribution of T and $p_{w,sat}$
    - But p_w distribution does not change

	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng	Pa	Pa	Pa	%
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	-1.5			
						1245.5	2642.6	47%
Concrete	2.6	0.15	17.3	0.058	-1288.4			
						2533.8	2750.5	92%
XPS	2.0	0.075	26.7	0.0375	-837.4			
						3371.3	8594.4	39%
Air space		0.025	7200	0.00014	-3.1			
						3374.4	9214.9	37%
Brick	10	0.09	1000	0.001	-22.3			
						3396.7	9479.3	36%
Exterior film			75000	0.000013	-0.3			
Outdoors						3397	9593.2	35%
			$R_{v,total}$	0.096				

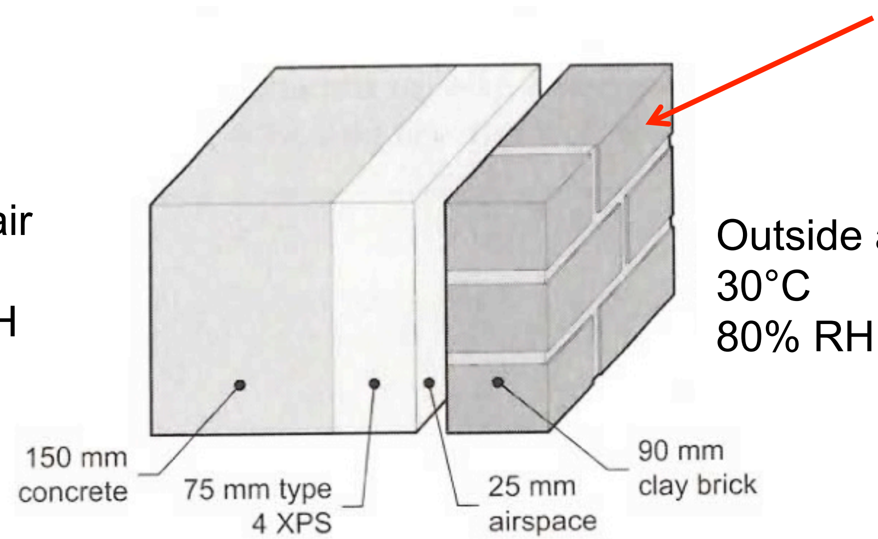
- Reduced chance of condensation because of warmer surface T

Water vapor transport: Wet cladding

- **What happens if the brick cladding was already wet?**
  - From either previous rains, condensation, or built-in moisture (i.e., construction occurred with wet materials)
  - Let's assume the same sun-heated wall assembly and summer conditions, but the brick cladding is wet (already saturated)

Brick saturated
w/ water vapor

Inside air
21°C
50% RH



Outside air
30°C
80% RH

Water vapor transport: Wet cladding

- Same solution procedure, but the front of the brickwork is assumed to be at RH 100%
  - That becomes the exterior boundary condition
    - Meaning we don't use the outdoor humidity in this calculation

	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng	Pa	Pa	Pa	%
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	-5.7			
						1249.7	2642.6	47%
Concrete	2.6	0.15	17.3	0.058	-4928.7			
						6178.4	2750.5	225%
XPS	2.0	0.075	26.7	0.0375	-3203.6			
						9382.0	8594.4	109%
Air space		0.025	7200	0.00014	-11.9			
						9393.9	9214.9	102%
Brick	10	0.09	1000	0.001	-85.4			
						9479.3	9479.3	100%
Exterior film								
Outdoors								
			$R_{v,total}$	0.096				

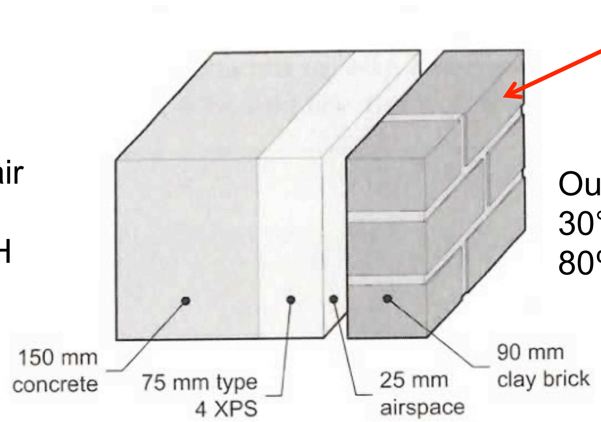
Brick set to 100% RH
Becomes new boundary condition

Condensation would occur at two interior surfaces

- Inward-driven water vapor can also condense in the interior wall assembly, given the right conditions

Water vapor transport: Wet cladding

- Big question: Does the condensation even matter?

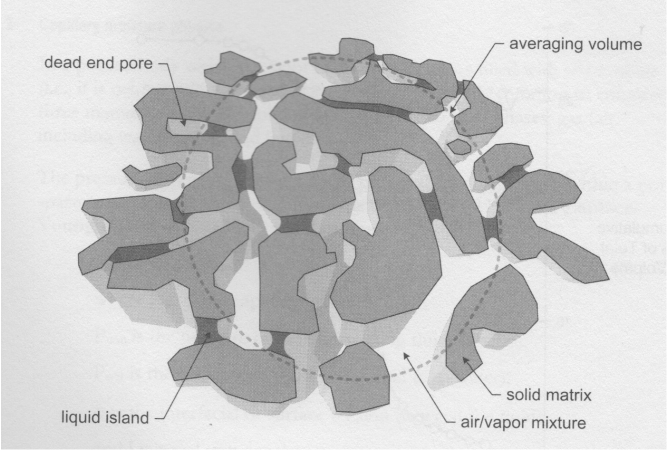


- Condensation would occur between air space and XPS, as well as between the concrete and XPS
  - Largest accumulation occurs at the XPS-air interface
  - What happens to the condensation?
    - **Concrete:** can store a lot of moisture; as long as it's dry by the time freeze-thaw could occur, moisture shouldn't be an issue
    - **XPS-air interface:** condensation can be harmlessly drained away
      - Or drain into the foundation and cause issues (which could be a problem)

MORE COMPLEX MOISTURE MOVEMENT

Moisture storage and transport in porous media

- Our textbook, Straube and Burnett, has an in depth chapter on moisture and porous materials
  - Focus is on the micro-scale physics of moisture storage, wetting, and drying
  - We will not go into this level of detail; just a summary
- Most materials appear completely solid to the eye
  - But many natural building materials are very porous
  - Large fractions of the material are actually air volumes
    - Wood, brick, gypsum, stone, and concrete
  - Concrete and brick can be 50% air by volume
    - Metals and hard plastics have almost no porosity



Moisture content and porosity of common materials

- Because of porosity and density effects, building materials can hold moisture in widely varying amounts

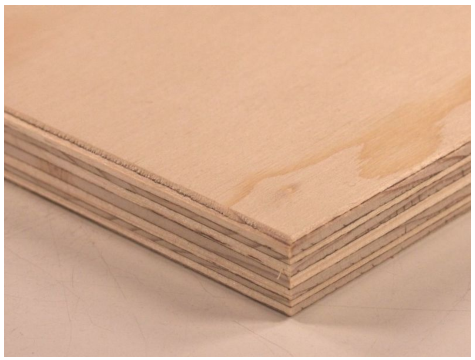
Table 8.1: Moisture contents of some common building materials

Material	Density (dry) kg/m^3	Open porosity (%)	MC @ ≅ 95%RH (M%)	w_{cap} (M%)
Concrete	2200	15-18	4-5	6-8
Brick	1600-2100	11-40	3-8	6-20
Cement mortar	1800-1900	20-30	5-7	14-20
Softwood	400-600	50-80	20-30	100-200
Fibreboard	240-380	60-80	20-25	100-200
Wood chipboard	700	50-70	15-20	100-150
Expanded polystyrene	32	95	5	> 300
Gypsum (exterior)	1000	70	10	50-100

Note: these values are approximate and from a variety of sources [e.g., Whitley *et al* 1977, Kumaran 1996, Lohmeyer 1996, Pel 1996, Kuenzel 1994]

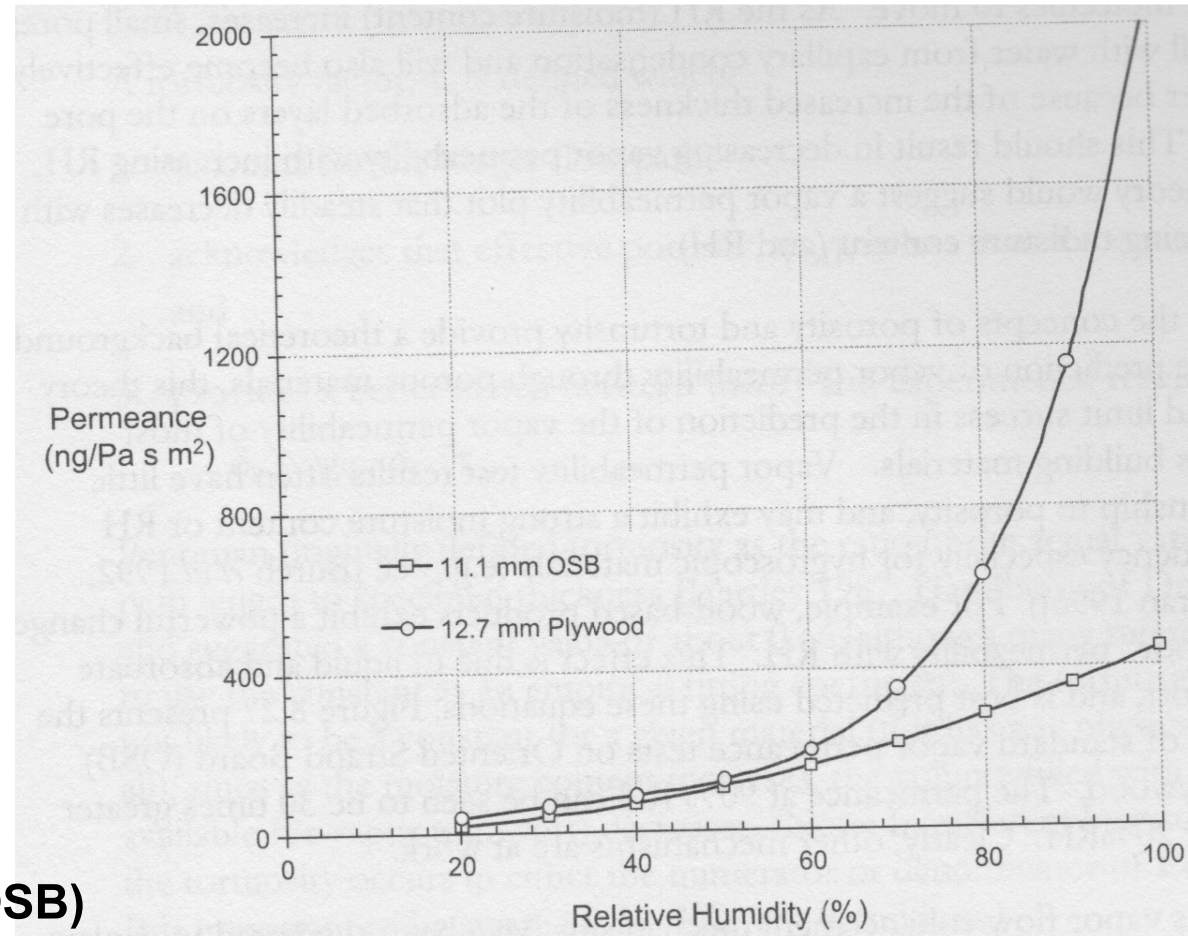
Moisture content influences vapor permeance

- Increasing RH increases capillary transport in small pores
  - Makes mass flow of water vapor easier (creates a "water canal" effect)



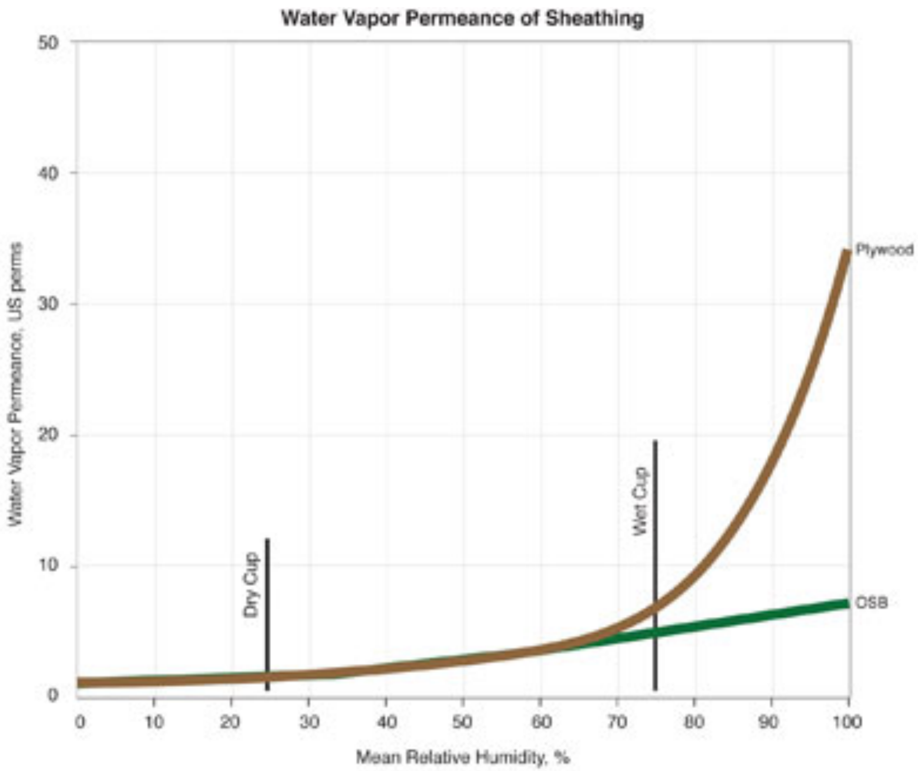
Plywood

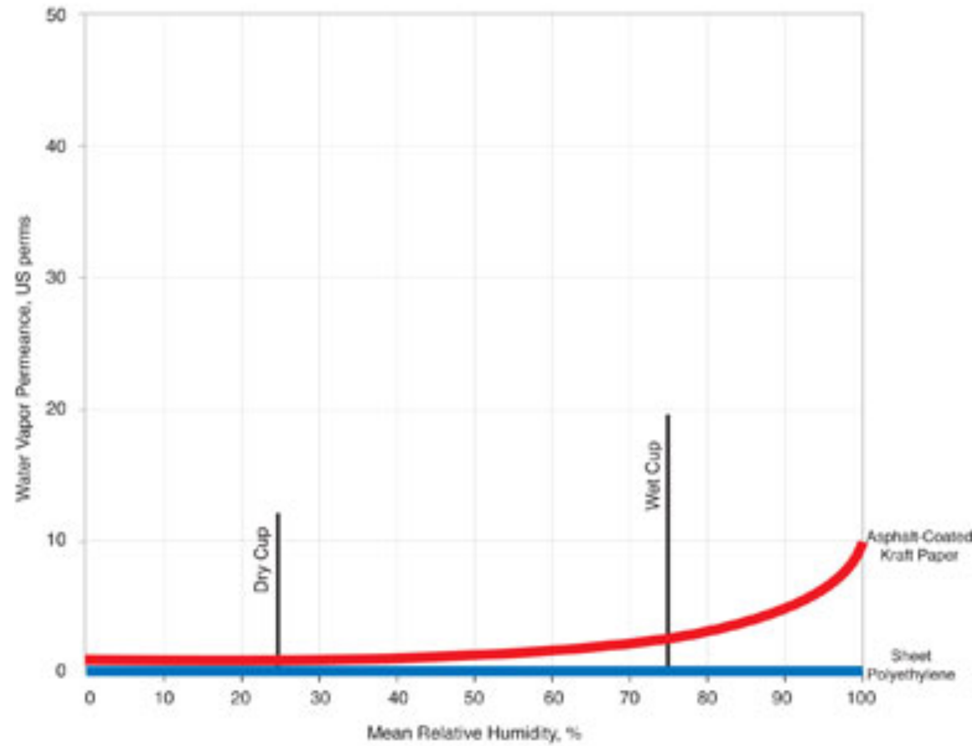
Oriented strand board (OSB)



Moisture content influences vapor permeance

"Wet cup" vs. "Dry cup"





http://buildingscience.com/documents/insights/bsi-038-mind-the-gap-eh

Limitations of the Glaser method of vapor diffusion

- Steady state calculations
  - Temperature and humidity are actually always changing
- Static material properties
  - We cannot easily vary material properties (which vary with RH) without recalculating
- Does not take moisture storage into account
  - Porous materials like wood and masonry can hold very large amounts of water

- These are pretty **huge limitations**

The real way to perform moisture analysis

- A more complete analysis will find temperature, heat flow, moisture flow and moisture diffusion with changing interior and exterior conditions
  - Including changing material properties
  - Including thermal and moisture storage

- We call this **hygrothermal analysis**
  - There are free software packages available to do this
  - The most popular is WUFI
  - http://www.wufi-pro.com/

WUFI

- WUFI applies a limited finite element analysis to walls and roofs
  - **WUFI** stands for **W**ärme- **U**nd **F**euchtetransport **I**nstationär (Transient heat and moisture transport)
  - Assumes homogenous layers and only 1-D heat transfer

- Thermal and vapor diffusion are calculated
  - Includes solar radiation and real time-varying weather data

- Moisture transport by air infiltration can be added

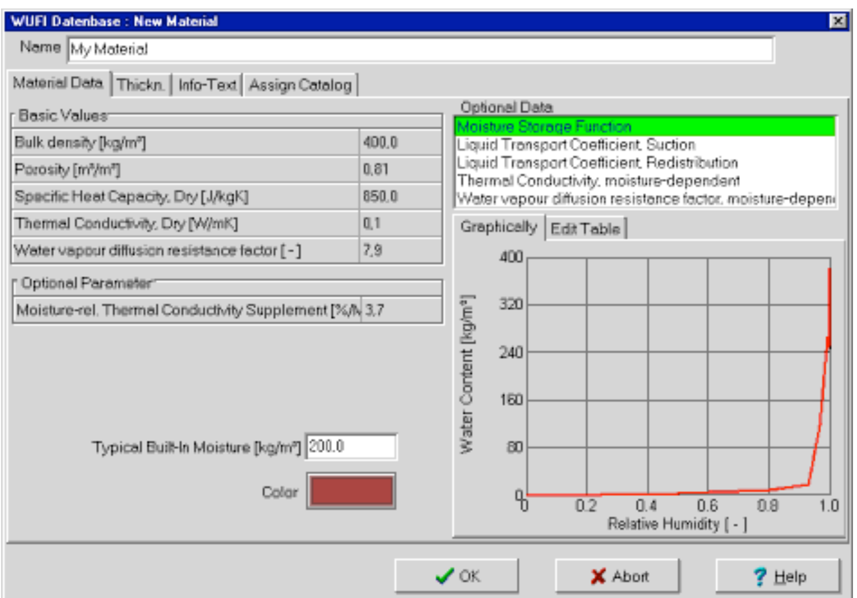
- Liquid transport and by capillary suction is also included

Moisture storage in WUFI

- Sorption isotherms are used to inform how much moisture materials can or will store at various environmental conditions

Notice the different regimes:

- Hygroscopic/absorbent regime
- Saturated/supersaturated regime



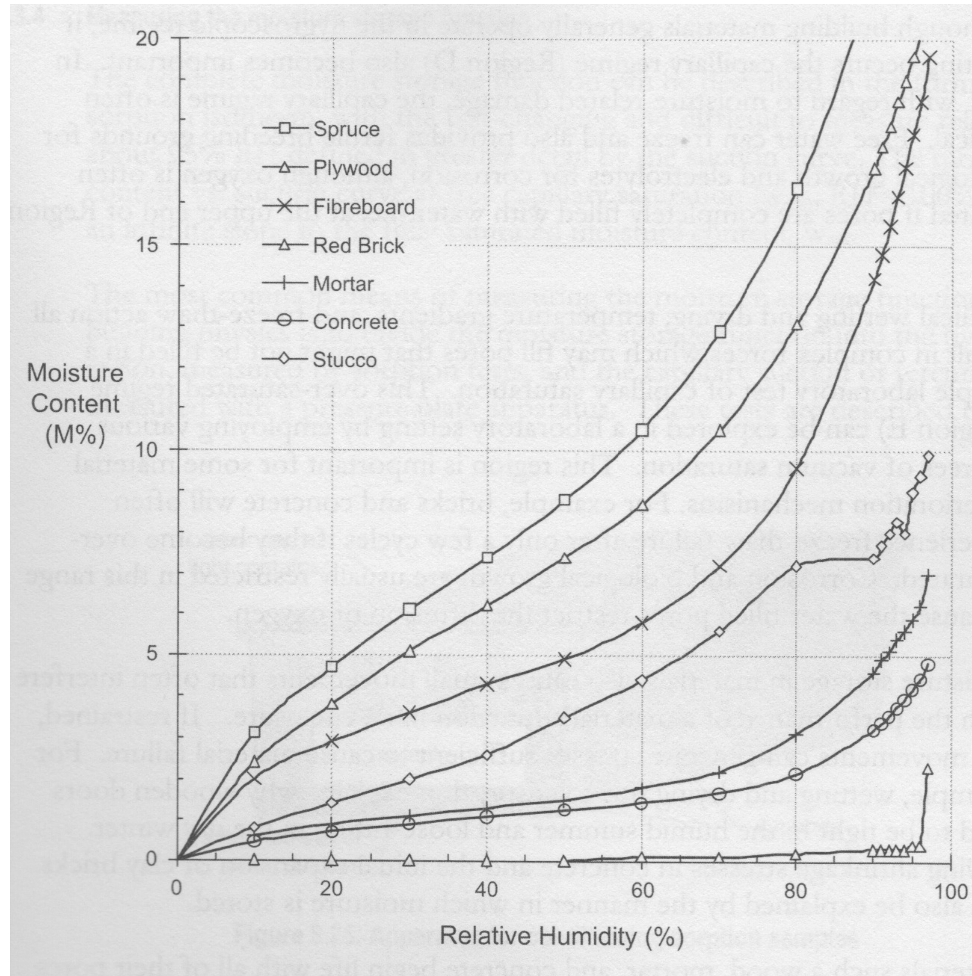


Figure 8.24: Sorption isotherm for several building materials [Kumaran 2002]

WUFI

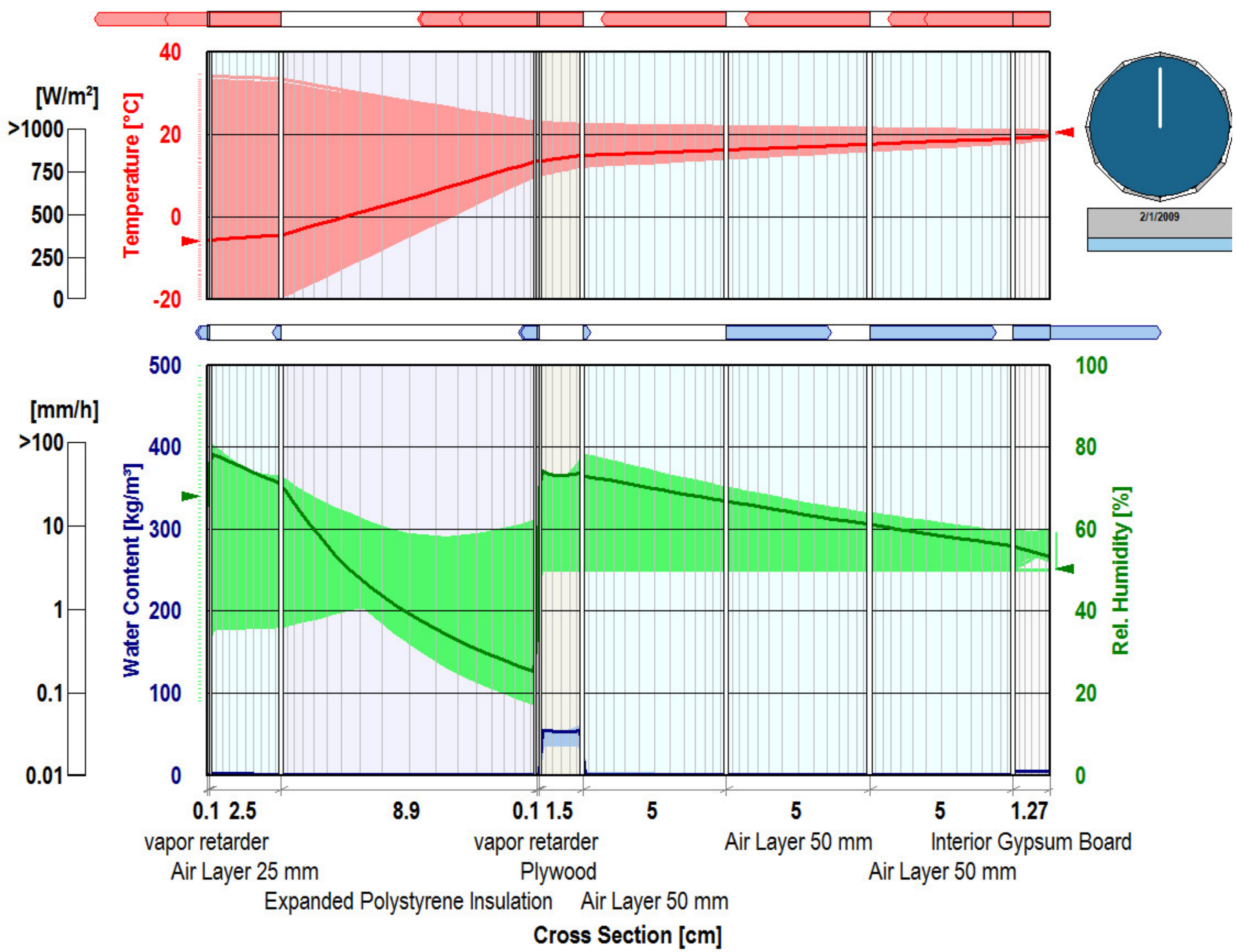
- The commercial version of WUFI is available at http://www.wufi-pro.com/ at a cost of €1950 ≈ $2600

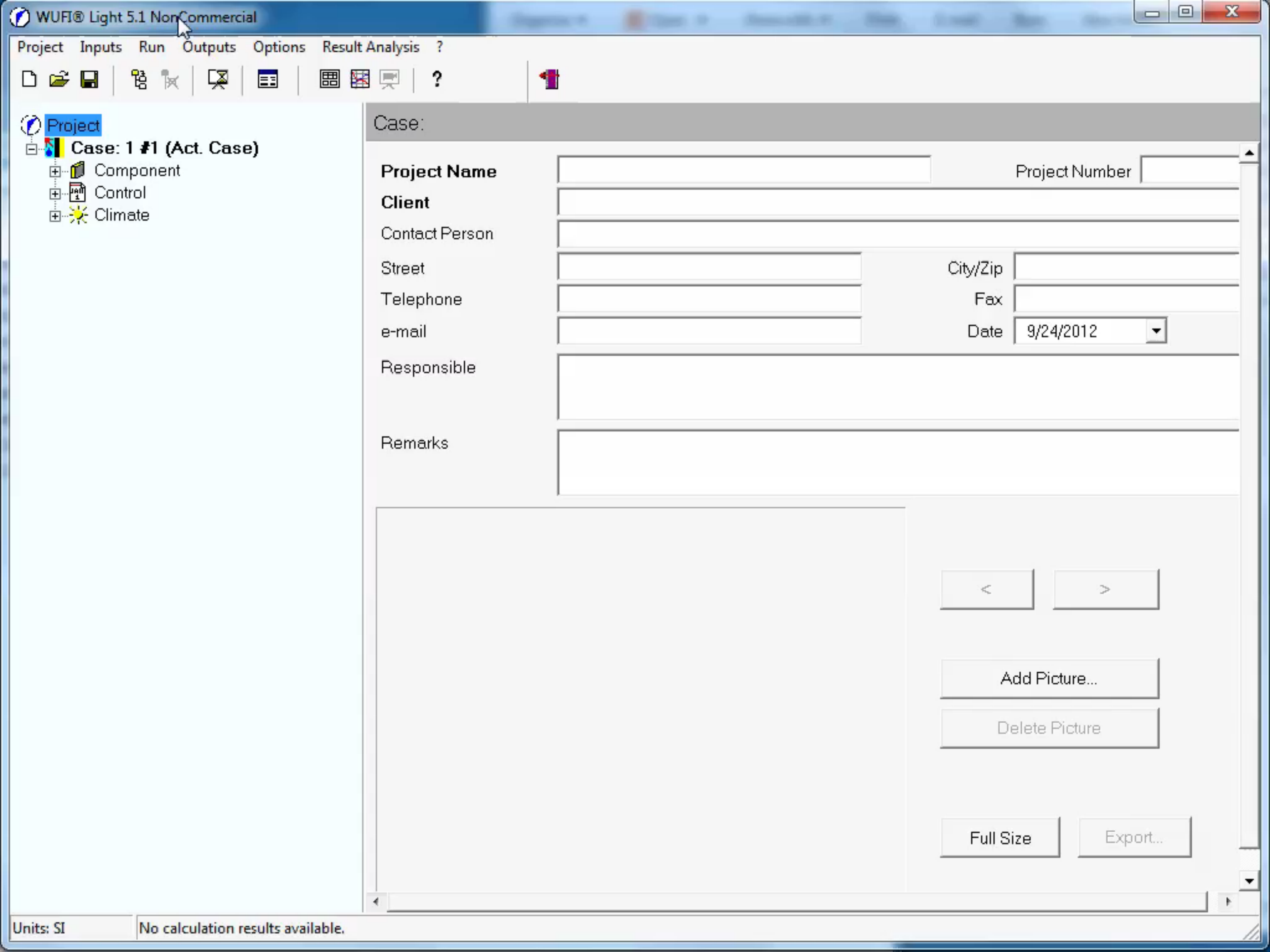
- A free limited version is available as well
  - It is installed in the Alumni 217 computer lab
    - You can have OTS setup a VCL image if necessary (for remote students)
  - You can also get a free copy online but you have to register
    - https://wufi.de/en/
    - Go to “Online shop” and “Apply” to download WUFI Light or WUFI ORNL

  - **Demo film:** http://www.hoki.ibp.fhg.de/wufi/Movie/Movie_Pro_E/Movie_Pro_E.htm

WUFI

- You will use both WUFI and hand-calculation methods in **HW 3**
  - Assigned today, due in 2 weeks (March 8, 2016)




WUFI® Light 5.1 NonCommercial
Project
Inputs
Run
Outputs
Options
Result Analysis
?
Project
Case: 1 #1 (Act. Case)
Component
Control
Climate
Case:
Project Name
Project Number
Client
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Street
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