CAE 463/524
Building Enclosure Design

Fall 2012

Lecture 5: Moisture flows in building enclosures

Dr. Brent Stephens, Ph.D.
Department of Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu
Built Environment Research Group
www.built-envi.com

Housekeeping

- HW 1 solutions finally posted
  - Everyone did quite well
  - Will use some of these concepts again today
- HW 2 officially due today (extended)
  - Will grade and post grades online to Blackboard ASAP
- HW 3 (THERM) due next Monday
  - October 1, 2012
  - 1 week from today
  - Any issues?
- Career fair
  - Anybody have a good experience?

Housekeeping

- Assigned campus project teams last week
  - Any issues?
- Still waiting to hear from facilities on availability of blueprints/drawings
- For building inspections
  - I will loan out IR camera and IR thermometer for ~24 hours per group when you are ready to inspect
    - One group will check out equipment from me during the day
    - Take photos and measurement
    - Return to me the following day

Housekeeping

- Final project
  - High performance/advanced building enclosures
    - 10 teams of 2; 1 team of 1
    - Outcomes will include report and presentation (~10-12 minutes)
- Topic justification moved back one week
  - October 8 (was October 1)
  - October 8 is fall break day
    - No class, plus I'm at a conference anyway
  - Email me topic justification as soon as you have it
- I have sorted through your previous requests for teams and/or topics, and randomly assigned others

Housekeeping

- Tentative final project topics and groups
  - Still have 1-2 weeks to finalize

Team	Member	Member	Topic
1	Russo, Lynda	Foley, Patrick	Green roofs
2	Vagner, Inna	Diaz, Giovanni	Electrochromic windows
3	Espinoza, Juan	Wright, Mike	TBD
4	Angulo, Melissa	Huo, Yechen	Double skin facades
5	Sebastian, Daniel	Morris, Frank	Phase change materials
6	Kayo, Luciana	Gonzalez, Alvaro	Building integrated photovoltaics
7	Zwang, Stuart	Gomez Soriano, Maria	Exterior insulated finish systems
8	El Orch, Zeineb	Gonzalez, Arturo	Strawbale construction
9	Mcgreal, Thomas	Diaz, Nestor	Conventional construction
10	Daras Ballester, Alejandro	Zylstra, Robert	High performance glass
11	Mejia, Jennifer	n/a	TBD

Other potential topics include (two teams T.B.D. right now):

- Sun shading
- Vegetative walls
- Life cycle of enclosure materials
- Thermally massive walls
- Cool roofs

Last lecture

- Finished heat transfer
  - More complex conduction
  - Thermal bridges
  - Multi-dimensional heat transfer (using software)
    - Finite elemental analysis

This time

- Moisture flows in building enclosures

Water vapor transport

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

- Most of notes today come from our textbook
  - Some also come from *Moisture Control Handbook: Princples 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 almost all 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 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 later
  - For now, we will identify moisture problems and causes
  - Then learn the fundamentals/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 from stem physical changes, chemical processes, and/or biological processes

Moisture can cause several types of failure:

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

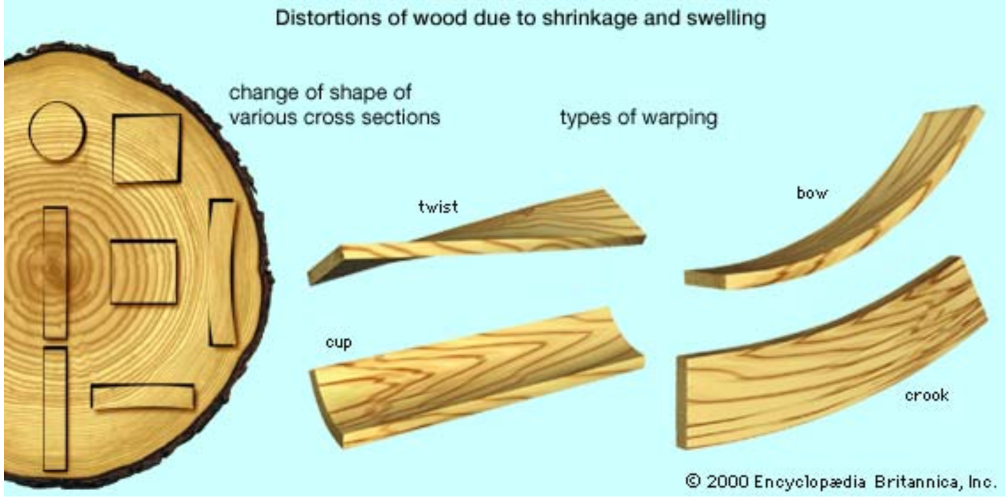
Examples of direct moisture problems

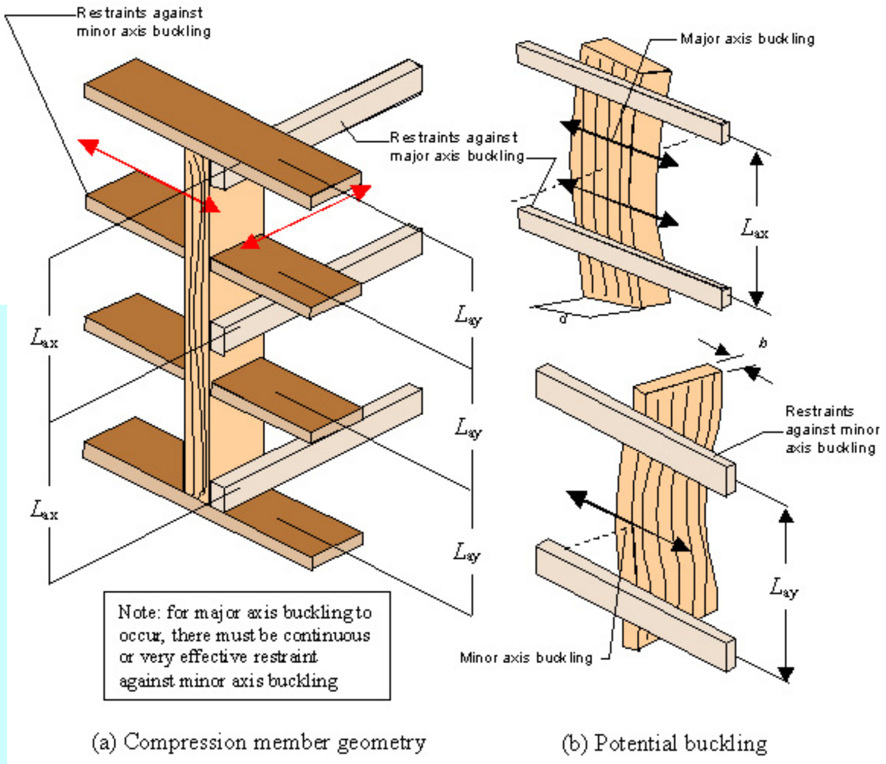
- Wood Deformation
- Freeze Thaw
- Corrosion
- Efflorescence
- Reduction in heat insulation

Rainwater drained from the roof onto the wall was absorbed into the brickwork, allowing freeze-thaw damage to occur.

Wood deformation and delamination

Wood swelling and shrinkage causes distortions, buckling and delamination





Critical dimensions for buckling restraint

Freeze-Thaw detachment

Water gets in cracks and expands when it freezes. This can cause detachment and delamination

Rainwater drained from the roof onto the wall was absorbed into the brickwork, allowing freeze-thaw damage to occur.

Corrosion

- Corrosion is a degradation of metals from oxidation
- Corrosion can occur from moisture with RH as low as 80% (i.e. no standing water)
  - Rusting occurs from water
- Chemical incompatibility can also cause corrosion
  - Dissimilar metal contact
  - Chloride diffusion
- The density of corroded metal is lower than non-corroded
  - So, corroded metal expands and can cause cracking of surrounding masonry

Efflorescence

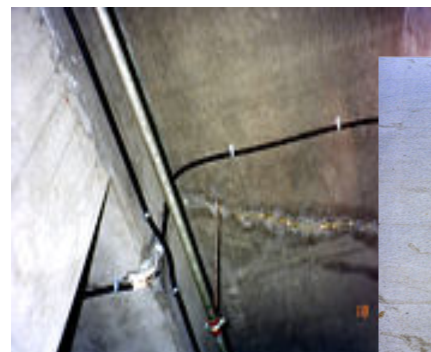
Primary Efflorescence

Occurs when moisture traveling through the masonry pulls salts along, resulting in a white fluffy deposit


- Occurs during construction
- Usually on aesthetic issue

Secondary Efflorescence

Occurs when moisture transports chlorides to the masonry which can reduce structural integrity of the masonry



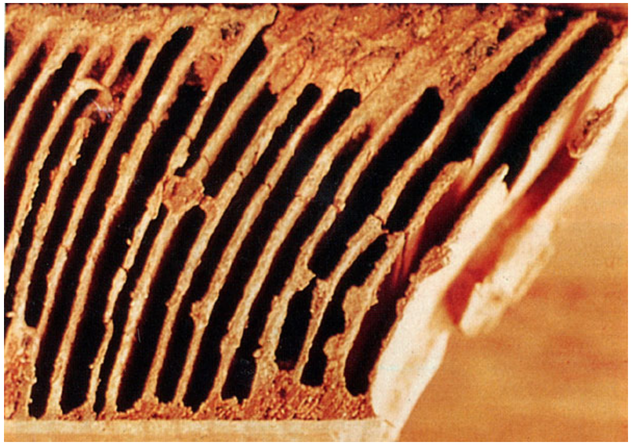

- Occurs after structure is in place
- Both structural and aesthetic issue

Indirect moisture effects

- Insect Damage
- Wood Rot
- Mold growth
- Dust accumulation from condensation resulting from temperature drop that comes from reduced insulating capabilities

Insects

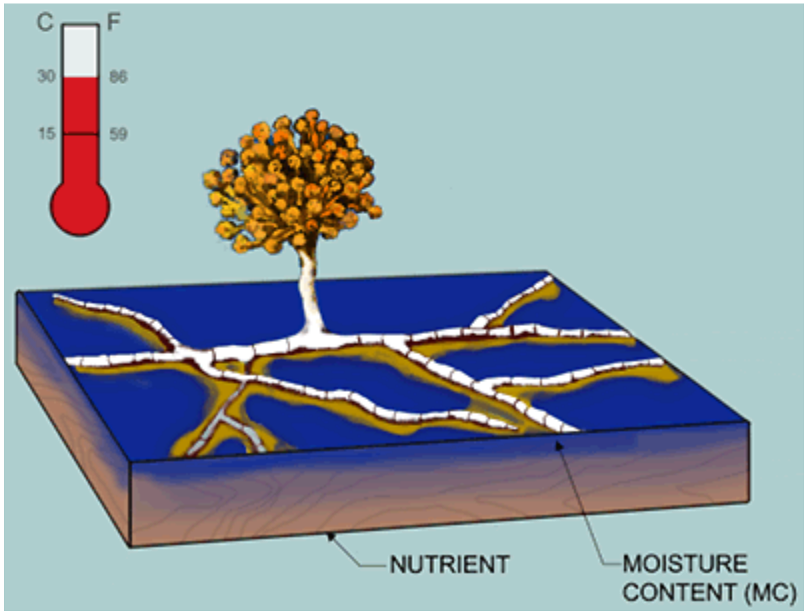
- Insects require moisture to live
  - Presence of moisture makes materials susceptible to insect damage
- Insects damage wood by boring holes in it or eating it
- Serious problems are with termites and beetles
- Insect problems are usually treated with insecticides



Wood rot

- Rot is the result of a fungal infection of wood
  - Brown rot attacks cellulose and destroys the structure reducing the strength
  - White rot attacks the lignin with less damage
  - Soft rot causes cavities in the cell wall reducing the strength with little color change

Mold

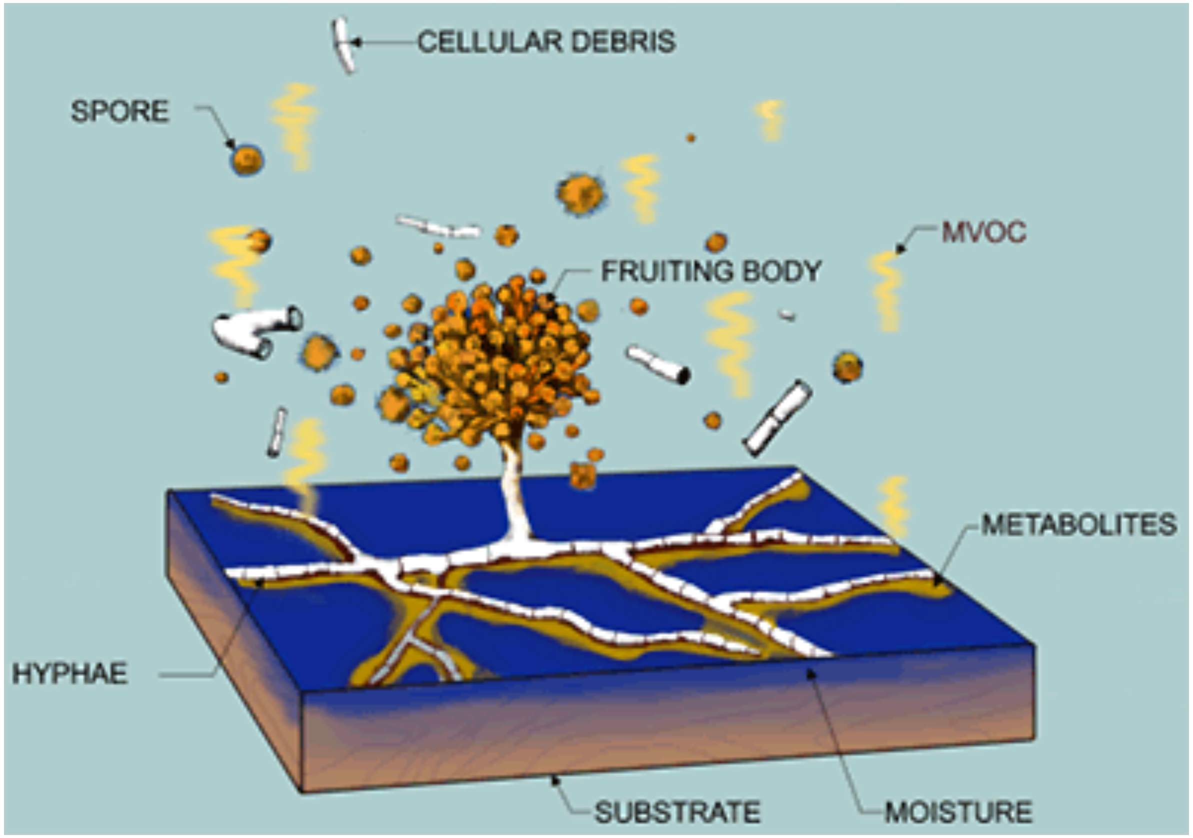


Mold growth on vinyl wall covering.

- Mold is a fungi that grows where there are moisture and nutrients (organic material)
  - Organic material can be carried into a building through air leaks
- Mold can destroy material structure
  - Also can cause air quality problems

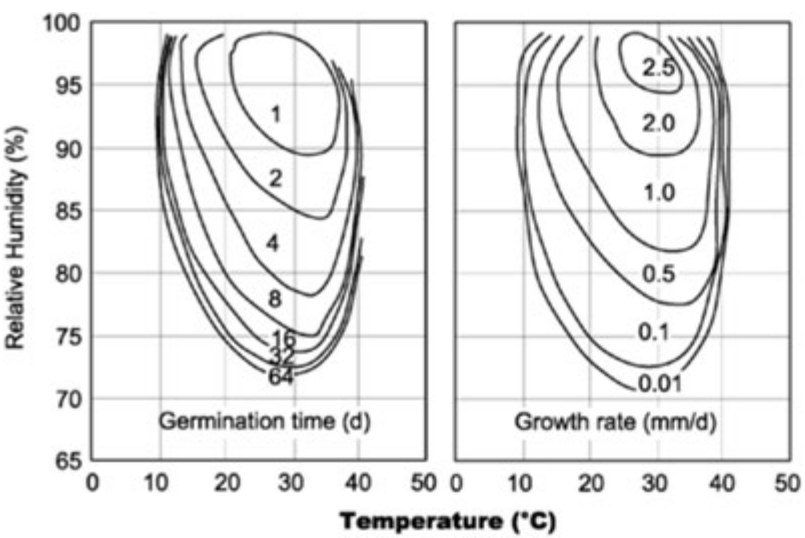
Mold byproducts

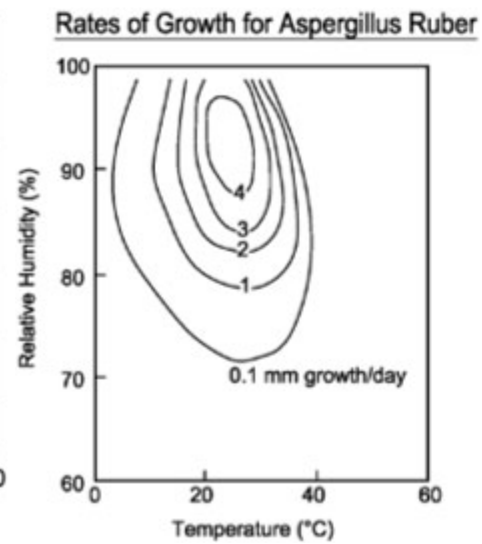
- Molds produce spores, debris, toxins, and MVOCs
  - Microbial volatile organic compounds

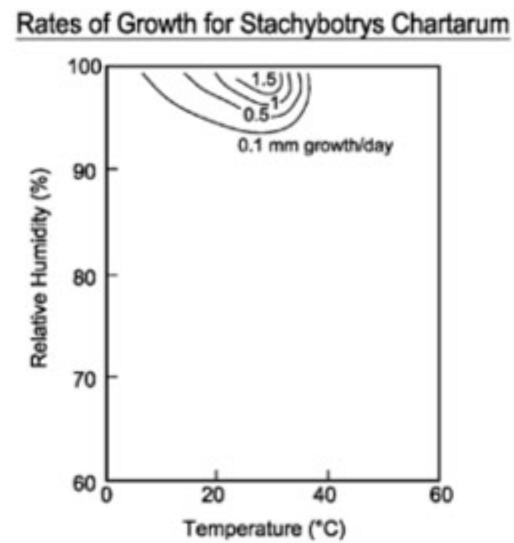


Mold growth requirements

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

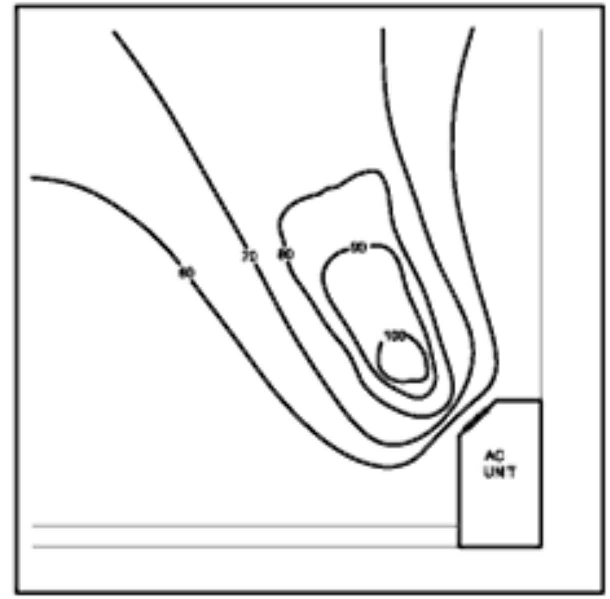




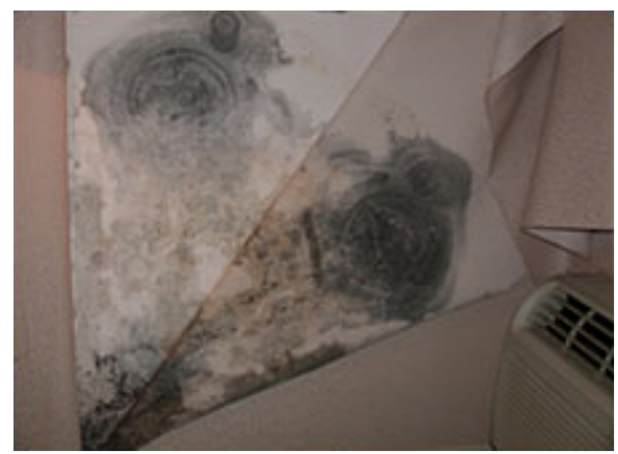


Moisture mapping

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

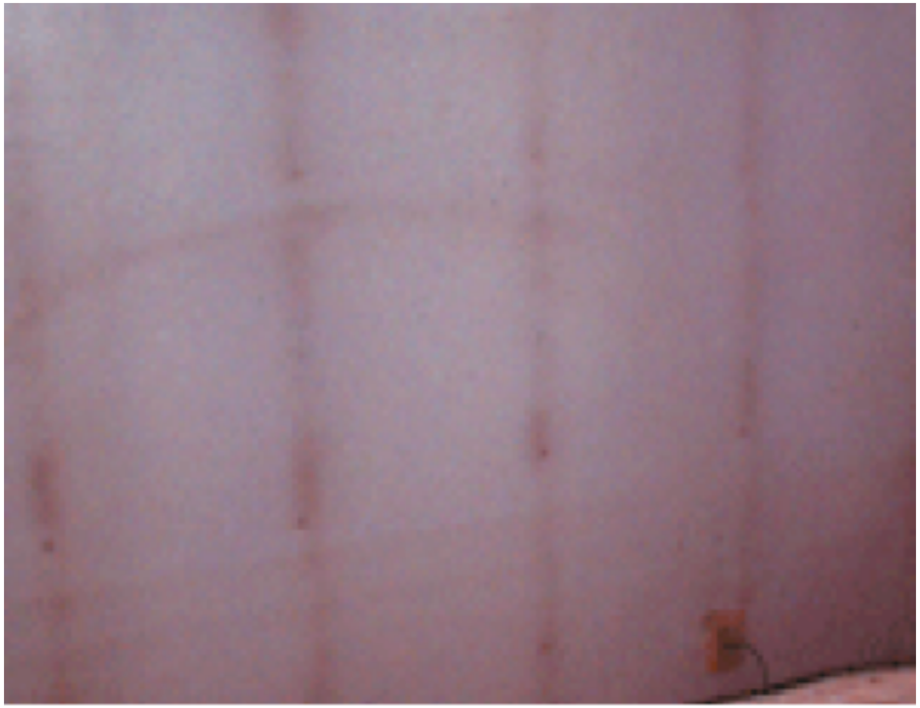


- When the wall paper was pulled back we see the mold growth that matches the condensation pattern



Dust condensation

- Dust particles are attracted to cold regions with condensed water and will settle there, resulting in dark lines and spots on interior walls
  - Thermophoresis



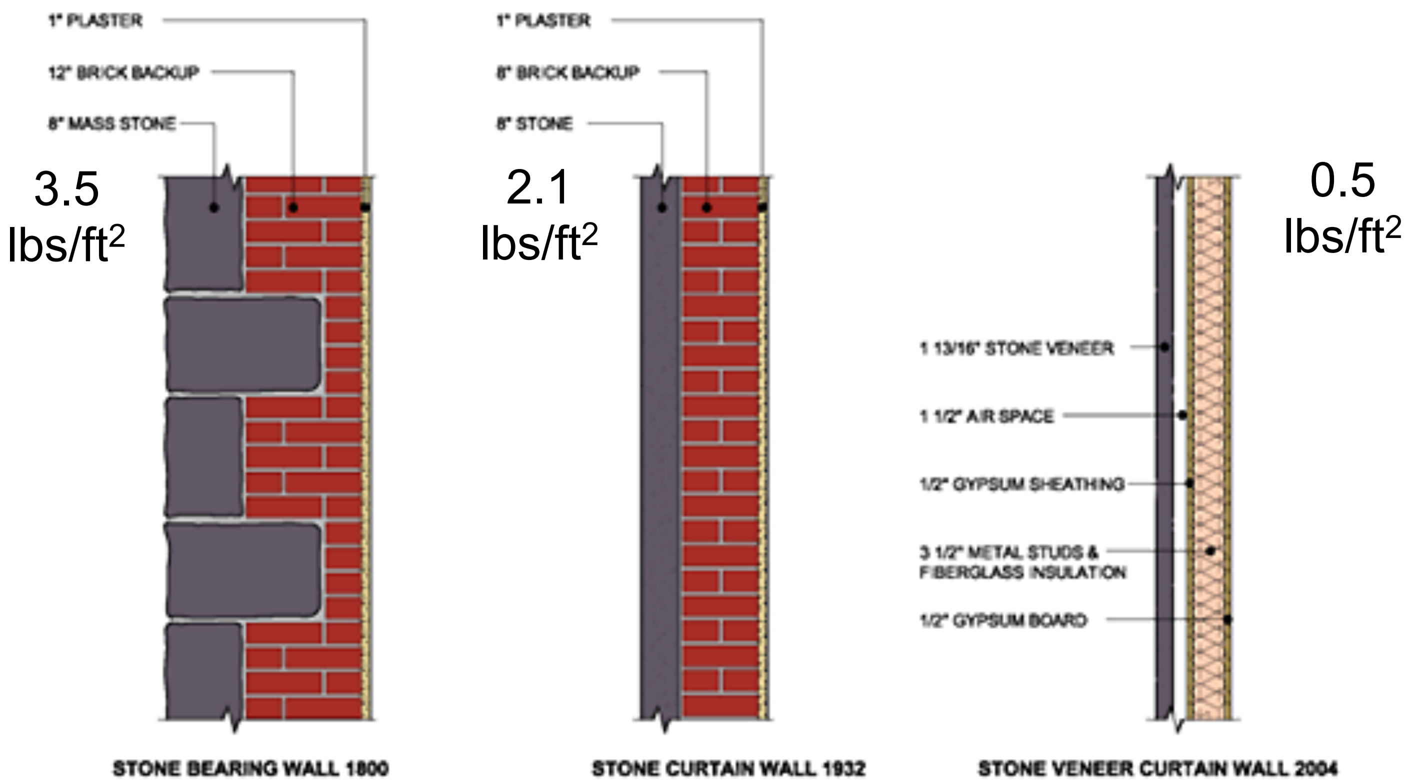
$$V_{\mathrm{th}} = -\frac{K_{\mathrm{th}}\nu}{T}\nabla T.$$

Sources of moisture

- Water leakage
- Penetration through joints and seams
- Convection of damp air through cracks
- Diffusion through structure
- Rising from damp ground

Why wasn't moisture a problem before?

- In the past, enclosure materials could hold a lot of moisture in their porous construction and thus dry slowly



Maximum moisture storage before achieving 70%RH on surface occurs

Why wasn't moisture a problem before?

- Another reason why moisture was not a problem in the past was the lack of a moisture barrier
  - 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 also allow moisture in internal surfaces to dry to either inside or 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 resistance
  - 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

Critical RH levels for failure

Material	Mold Growth	Decay
Pine	> 80%-95%	>95%
Particle Board	> 80%-95%	>95%
Gypsum Board	> 80%-95%	>90%
Fiber Board	> 80%-95%	>95%
Wallpapers	>75%-95%	
Putties	>90%-95%	
Concrete	>95%-98%	

Moisture transport

- Moisture enters a building in two forms:
  - Liquid
  - Vapor
    - We can break transport into three main categories:

1. Condensed water infiltration (bulk liquid)
   - Infiltration of water in liquid form
2. Moist air infiltration
   - Infiltration of water vapor in air that leaks into building
3. 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, bulk liquid water later

Water vapor transport

- Water vapor moves through the building enclosure in two primary modes
  - Diffusion
  - Convection

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

Water vapor transport

- 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

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

where

$D =$ diffusivity

$C =$ concentration (e.g., vapor pressure)

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

Water vapor diffusion

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

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

where

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

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

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

$\dfrac{dp_w}{dx} =$ 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:

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

where

$Q_v =$ 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]

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

$q_v =$ 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:

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

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

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	$U \cdot \Delta t$		$V \cdot \Delta P$	

Water vapor transport: 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

$$\dot{m}_v = \rho_{air} \dot{V}_{air} W$$

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

Key terms reference

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

Term	Symbol	Definition	SI Units	IP Units
Vapor flow	Q_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	perm [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)]	[grains/(hr ft inHg)]
Vapor resistance	R_v	Resistance of a material for a given thickness	[(s m^2 Pa)/ng]	[(hr ft^2 inHg)/grain]

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	

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	

Calculating steady state 1-D vapor flow

- Calculating vapor flow follows same general principles as calculating 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
    - 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
- Still important to understand 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

- Basic example 5.1

- 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:
    - Vapor flow rate,
    - Vapor flux,
    - Vapor permeance, and
    - Vapor resistance

Example 5.1: 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 5.1: 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·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	

Example 5.1: Calculating steady state 1-D vapor flow

- See board calculations

Vapor diffusion through multiple layers

- Analogous to heat flow through multiple layers
- Method is called Glaser's method
  - Used since the 1930s
- 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
    - *Sound familiar?*

Vapor diffusion through multiple layers

- For any layer j

$$q_v = \frac{Q_v}{A} = M_j \Delta p_{w,j} = \frac{1}{R_{v,j}} \Delta p_{w,j}$$

- For an assembly of n layers

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

  – 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

$$\Delta p_{w,j} = q_v R_{v,j}$$

- Combining equations:

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

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
    - No need for “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 0-100 ng/(Pa s m^2)

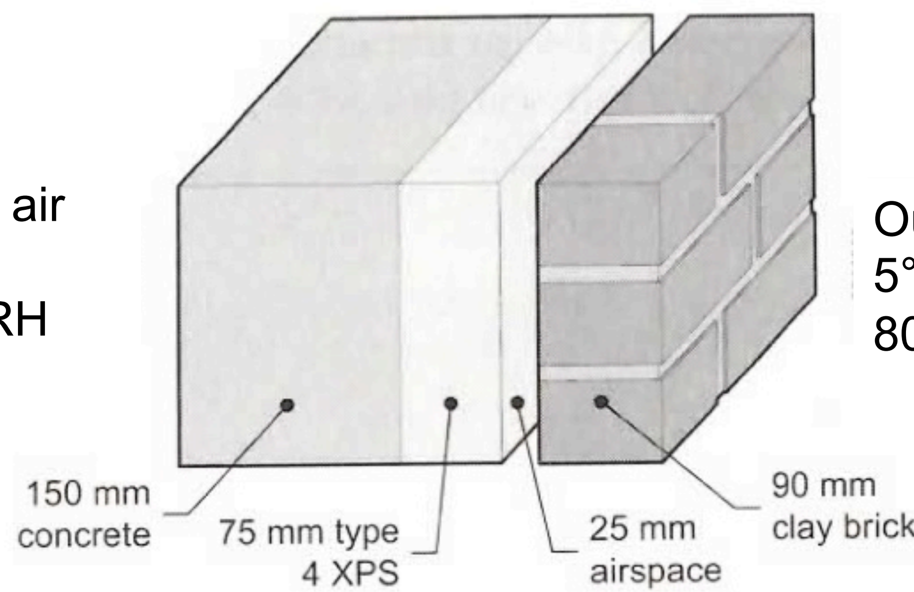
Glaser Method procedure

1. Break assembly into parallel paths
2. Find temp 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 5.2: 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 5.2: Vapor diffusion through multiple layers

- Start by finding material properties

	Permeability	**Thickness**	**Permeance**	**Resistance**
	μ	**L**	$\mathbf{M_j}$	$\mathbf{R_{v,j}}$
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 5.2: 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 5.2: 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 5.2: 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 5.2: Vapor diffusion through multiple layers

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

	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 5.2: Vapor diffusion through multiple layers

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

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

where

$$\begin{aligned} C_8 &= -5.800\,220\,6 \text{ E+03} \\ C_9 &= 1.391\,499\,3 \text{ E+00} \\ C_{10} &= -4.864\,023\,9 \text{ E-02} \\ C_{11} &= 4.176\,476\,8 \text{ E-05} \\ C_{12} &= -1.445\,209\,3 \text{ E-08} \\ C_{13} &= 6.545\,967\,3 \text{ E+00} \end{aligned}$$

Example 5.2: Vapor diffusion through multiple layers

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

	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 5.2: 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 under these conditions!

Example 5.2: 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 5.2: 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/m²K**	**m²K/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} (m²K/W)	3.04				
			U_{total} (W/m²K)	0.33				

Example 5.2: 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 5.2: Vapor diffusion through multiple layers

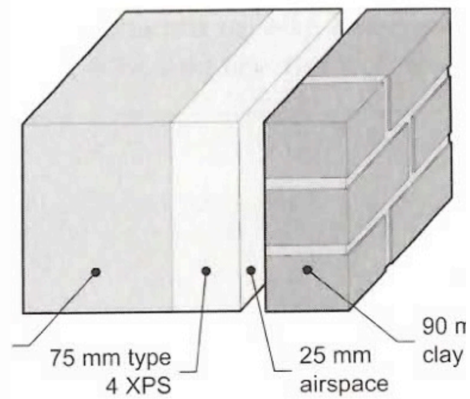
- Now, RH can’t technically be greater than 100%
- To continue the analysis, we would divide the wall into two sections
  - Analyze the sections independently
  - The reason is that if condensation occurs on a surface, some amount of moisture is removed at that interface
    - Assumption that mass flow in = mass flow out is false
    - Some vapor is removed (by conversion to condensate)
- Reality check:
  - Condensation plane will seldom be inside a highly porous material (i.e., not brick, stone, wood, or batt insulation)
  - As a general rule, the **condensation plane will usually be the next upstream-facing solid surface on the cold side of the dewpoint**
  - The condensation plane we pick will determine how we device the wall into two portions and continue

Example 5.2: Vapor diffusion through multiple layers

- Dividing a wall at the condensation plane
- Steps:
  - 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
    - 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 5.2: 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 5.2: 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 5.2: 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 accounts for the rate of condensate formation
  - From 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 5.2: 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	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 5.2: 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 5.2: 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				

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
  - Forced or natural convection
  - When air comes in contact with enclosure surfaces, condensation will occur at those surfaces below the air's dew point temperature
    - We can attempt to calculate the quantity of condensation at surfaces

Bulk air movement and vapor transport

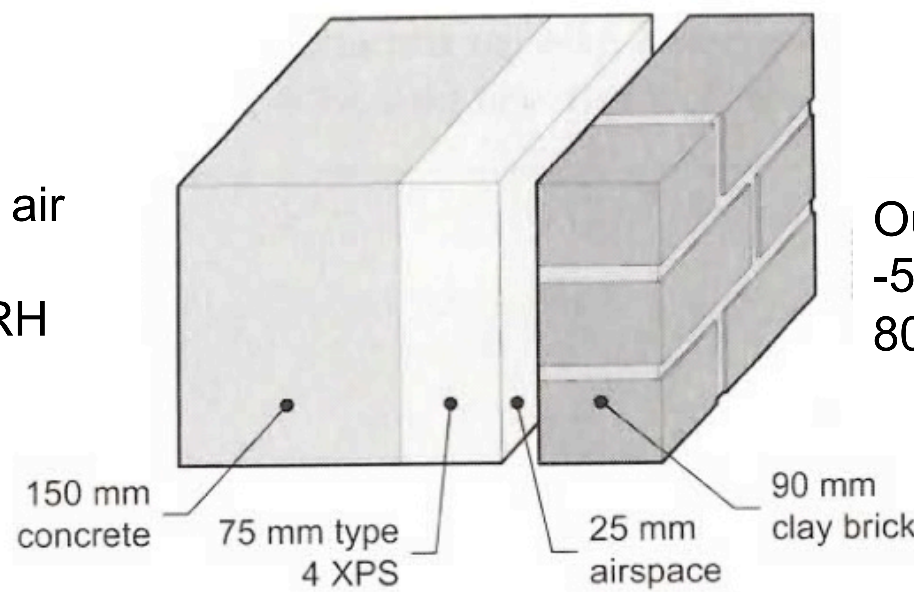
- Calculating the quantity of air leakage condensation in enclosures is difficult to do accurately
  - But given a flow rate, we can find the maximum amount of condensation that could occur

  - We say “maximum amount” because several issues prevent easy and accurate calculation
    - 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)

Example 5.3: Bulk air movement and vapor transport

- Let's calculate the volume of condensation that would form if we had bulk air leakage through this assembly
  - Air leakage rate of 0.5 L per second per m^2 of exfiltration
    - Air moving from interior to exterior

Inside air
21°C
50% RH



Outside air
-5°C
80% RH

Example 5.3: Bulk air movement and vapor transport

- Method:
  1. Calculate temperature at every layer
  2. Calculate moisture content (i.e., humidity ratio) and dewpoint temperature of the interior or exterior air
  3. Calculate saturation vapor pressure of the first **upstream-facing** surface in the enclosure that is below the dewpoint 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 5.3: 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 5.3: Bulk air movement and vapor transport

2. Calculate moisture content and dewpoint temperature of the interior and exterior air

p_{ws} at boundaries:

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

$p_w = 0.5(2488) = 1244$ Pa

$W_{surf} = 0.622 p_w / (p_{total} – p_w)$

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

$T_{dew\ point}$ = ~10.2°C (psych chart or equation)

Example 5.3: 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 brick surface (T = -4.2 °C)

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

Example 5.3: 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 = 4.97×10^{-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 grams per hr per m^2

Over 1000 times more condensation by bulk convection than by diffusion!

Bulk air movement and vapor transport

- Equivalent vapor permeance for various airflow rates:

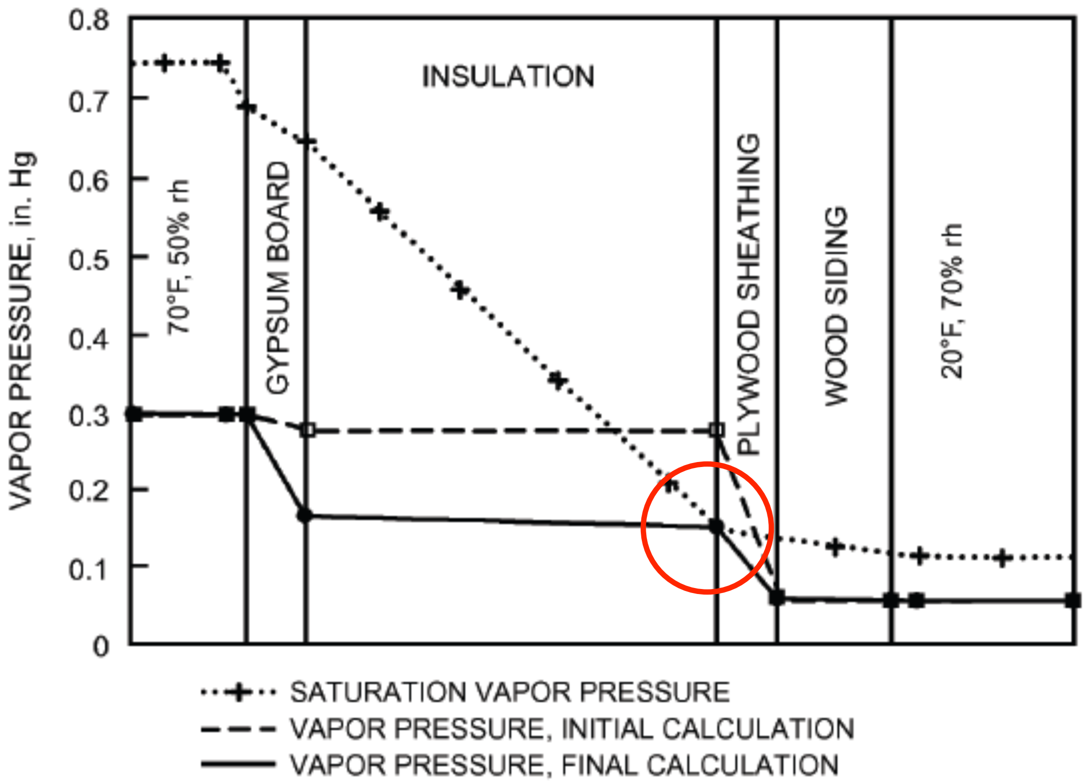
Airflow rate (L/s per m^2)	**Equiv. vapor permeance ng/(s m^2 Pa)**
0.05	375
0.10	750
0.25	1875
0.50	3750
1.00	7500
3.00	22600

  – For comparison: vapor permeance of brickwork and wood siding is approximately 50 ng /(s m^2 Pa)

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
- The ASHRAE handbook shows several examples of these charts

Vapor pressure diagrams

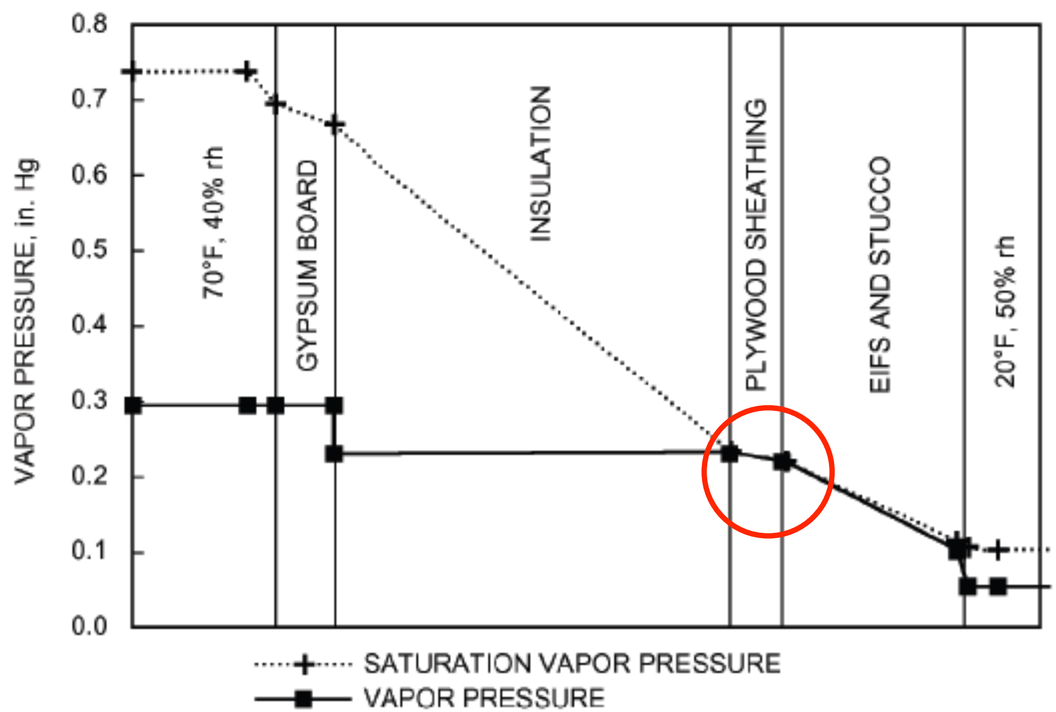


- Condensation is occurring between the insulation and the plywood
- Drying occurs to outside since it is lowest p_w

Vapor pressure diagrams

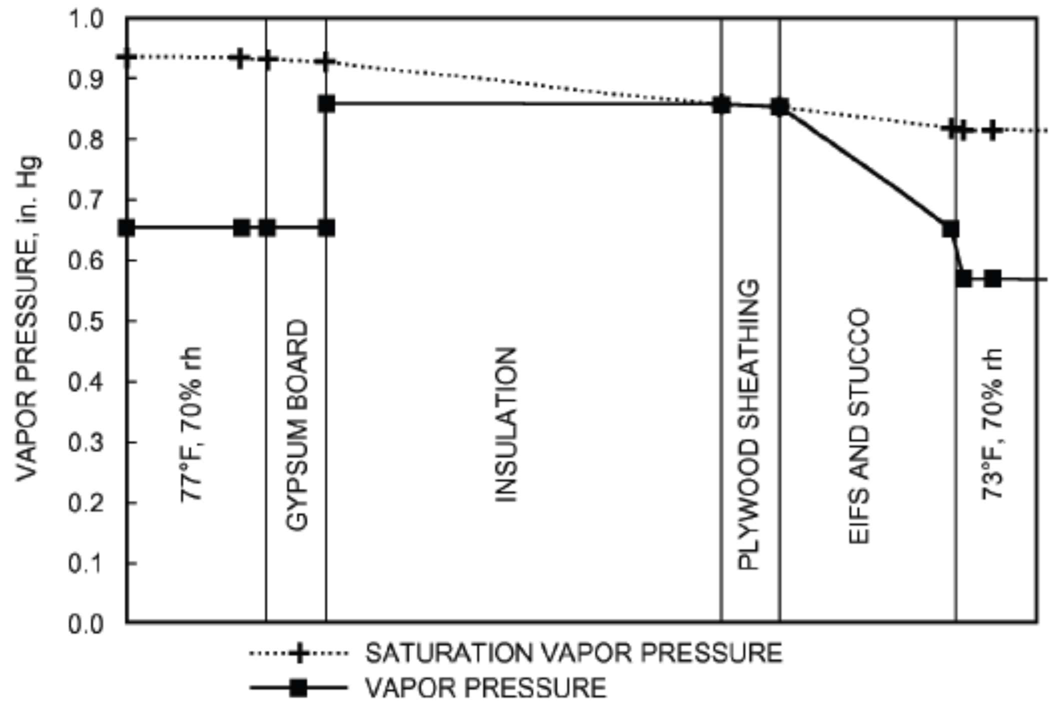
- Condensation between insulation and sheathing and possibly between sheathing and EIFS

- Drying occurs to outside



Vapor pressure diagrams

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



Limitations of Glaser Method

- Static calculation
  - 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

Advanced “hygro-thermal” 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 hygro-thermal 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
- Moisture transport by air infiltration can be added
- Liquid transport and by capillary suction can be included as well

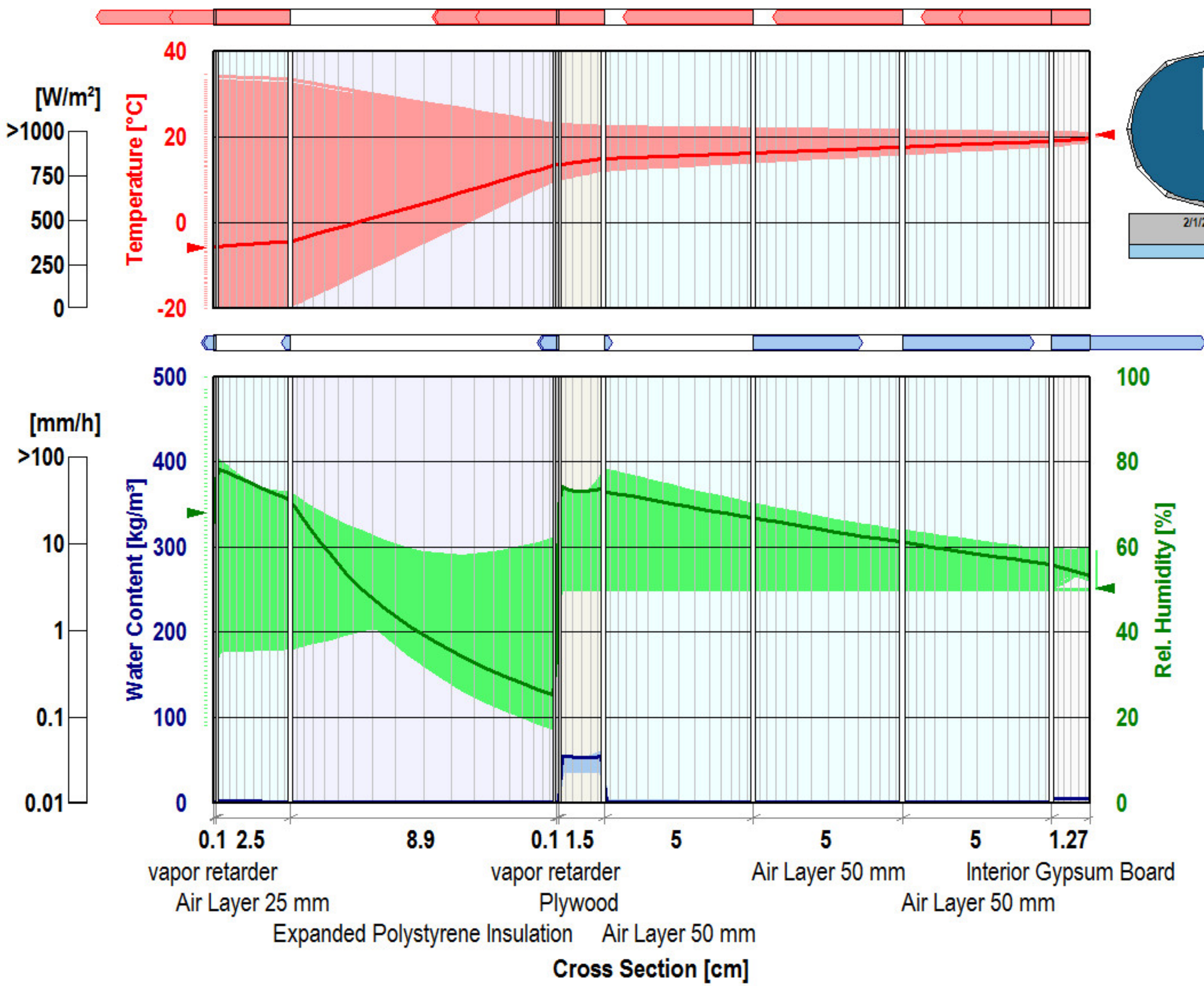
WUFI

- 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 from Oak Ridge National Lab (ORNL) who helped support development
  - WUFI Light or WUFI ORNL
  - http://www.ornl.gov/sci/ees/etsd/btric/wufi/

  - You can get a free copy but you have to register (free)
    - Only WUFI Light seems to work
  - Demo film: http://www.hoki.ibp.fhg.de/wufi/Movie/Movie_Pro_E/Movie_Pro_E.htm

WUFI



[W/m²]
>1000
750
500
250
0
Temperature [°C]
40
20
0
-20
2/1/2009
[mm/h]
>100
10
1
0.1
0.01
Water Content [kg/m³]
500
400
300
200
100
0
Rel. Humidity [%]
100
80
60
40
20
0
0.1 2.5
8.9
0.1 1.5
5
5
5
1.27
vapor retarder
Air Layer 25 mm
Expanded Polystyrene Insulation
vapor retarder
Plywood
Air Layer 50 mm
Air Layer 50 mm
Air Layer 50 mm
Interior Gypsum Board
Cross Section [cm]