CAE 463/524
Building Enclosure Design
Spring 2015

Lecture 6: February 24, 2015
Finish moisture flow calculations
Moisture management and control

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Campus projects

- Need to do thermal assessments by early March
  - 20 students in this class: 5 teams of 4

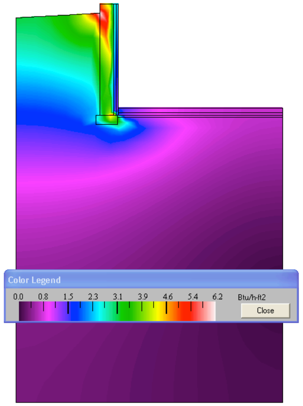
Building	Team members
Alumni	Maria, Yin Ling, Whitney, Liz
Crown	Henry, Yun Joon, Jose, Oleg
E1 - Rettaliata	Jinzhe, Julie, Roger, Rebecca
Hermann	Dilip, Allan, Dhaval
SSV	Thomas, Kim, Larry, Michelle

Do I need to move the due date?

- From March 10 to March 24?

Last time

- Finished complex conduction in enclosures
  - Slab and below grade heat transfer models



- Began moisture flows and movements in enclosures

Today's objectives

- Finish moisture flows
- Introduce WUFI
- Moisture management and control
  - Practical focus

Review from last time

Moisture flows in building enclosures

Water vapor diffusion:

Permeability and permeance

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

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

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

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

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

A = area perpendicular to flow [m^2]

μ = average vapor permeability [ng/(m Pa s)]

L = length of material [m]

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

Bulk convection of moist air:

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

Vapor pressure through assembly:

(Condensation potential)

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

Units for M:

1 perm = 1 grain/(hr ft^2 inHg)

1 perm = 57.2 ng/(s m^2 Pa)

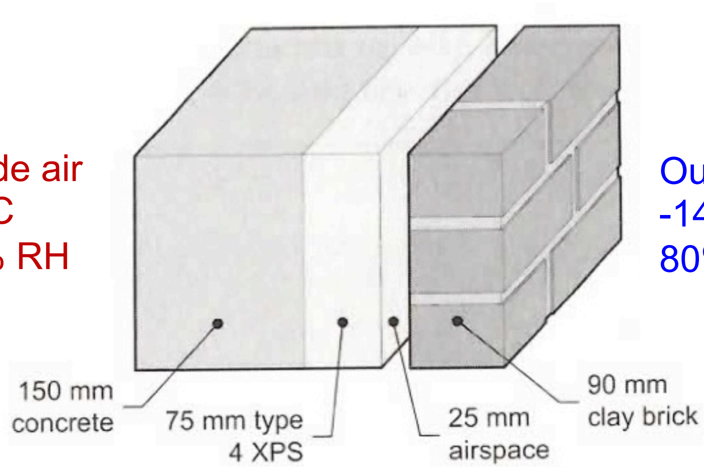
Materials: Vapor barriers and vapor retarders

- 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

Glaser method review: Winter example

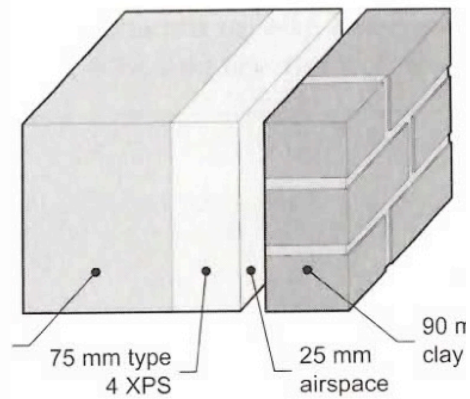


Condensation will occur between air and brick (RH > 100%)

	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				

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 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: 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

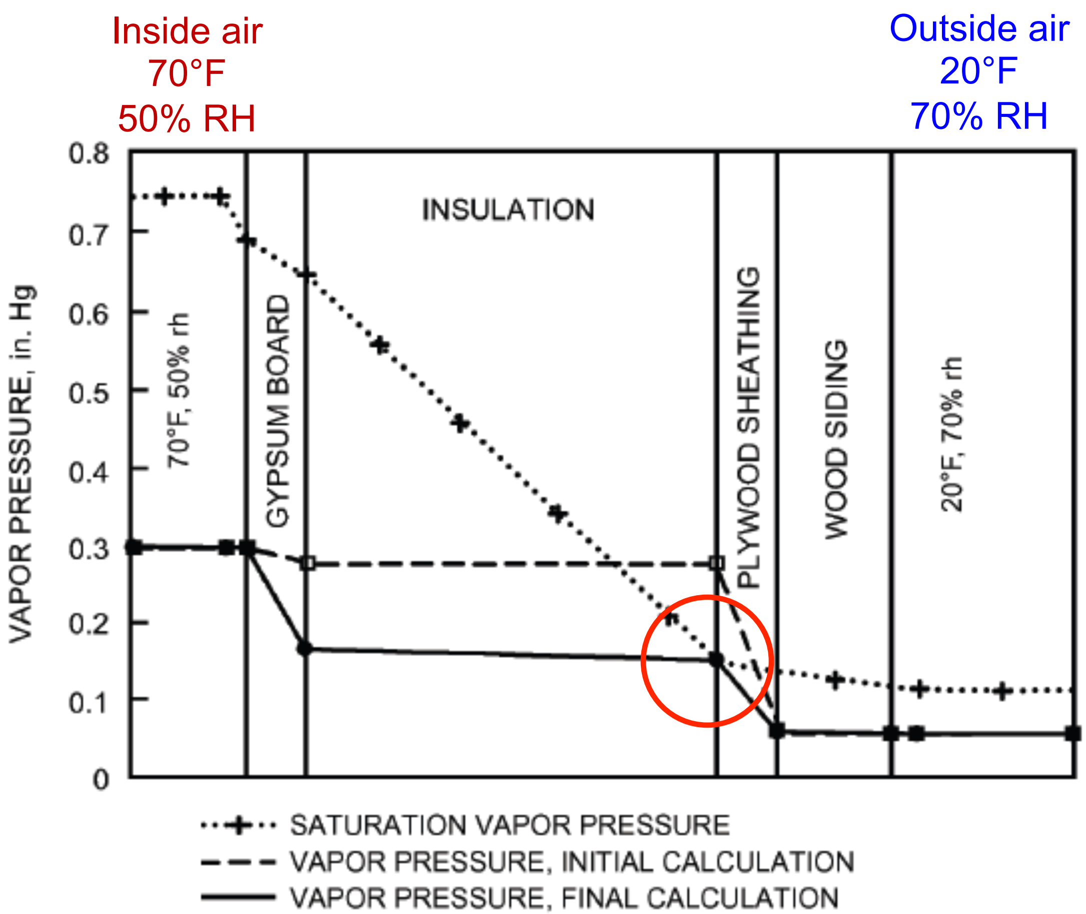
- Ventilated brick cladding eliminates condensation potential under these conditions

	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
- The ASHRAE handbook shows several examples of these charts

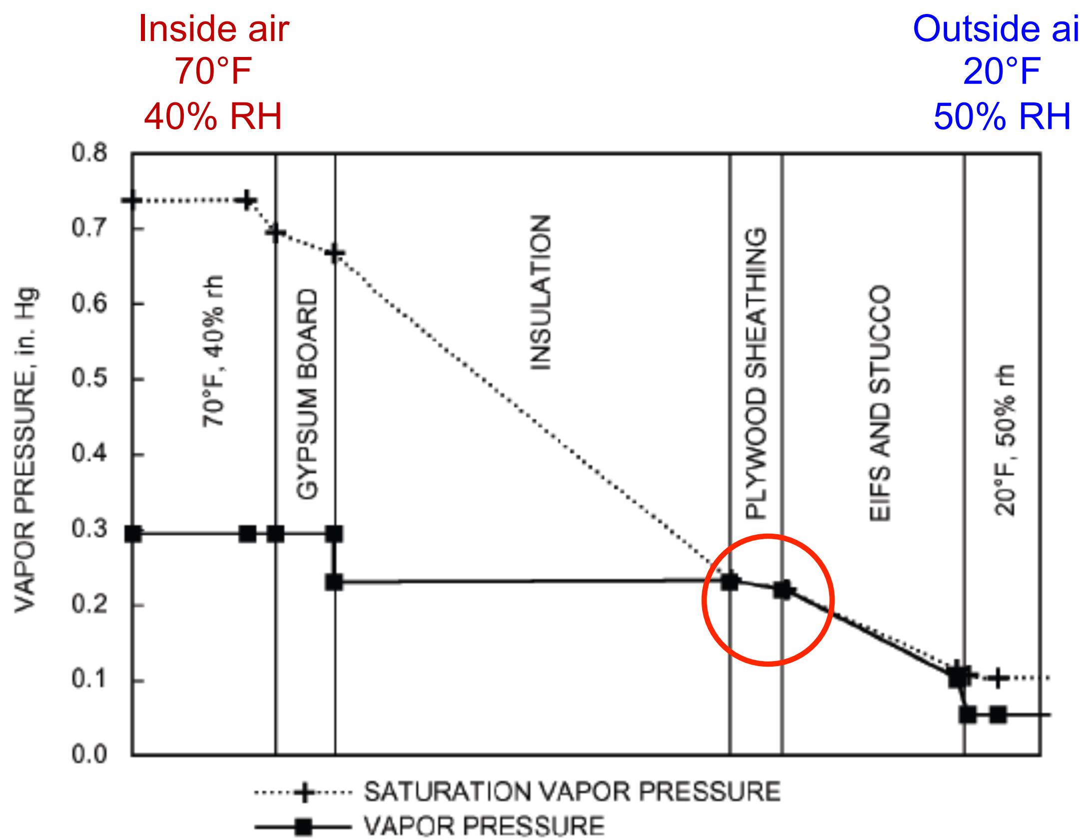
Vapor pressure diagrams



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

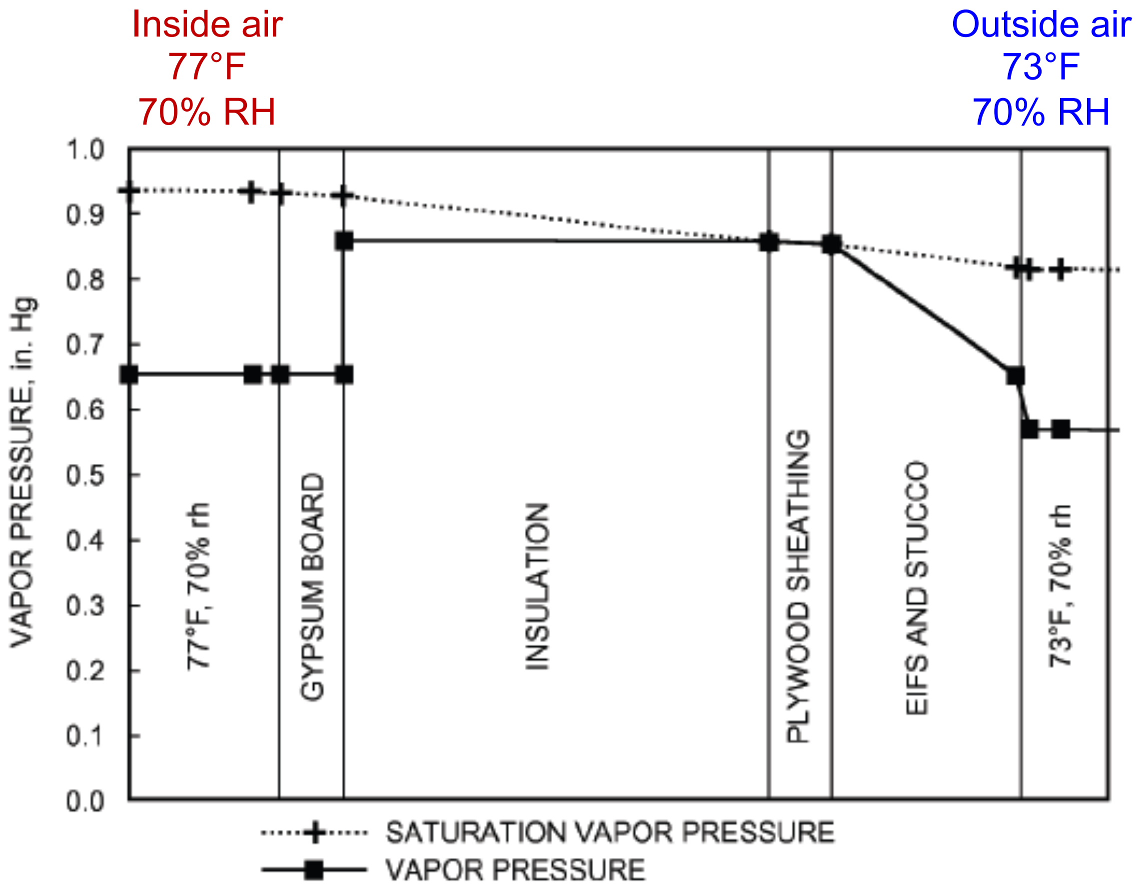
Vapor pressure **diagrams**

- Condensation between insulation and sheathing and possibly between sheathing and EIFS
- Drying occurs to the outside



Vapor pressure diagrams

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



Bulk air movement and vapor transport

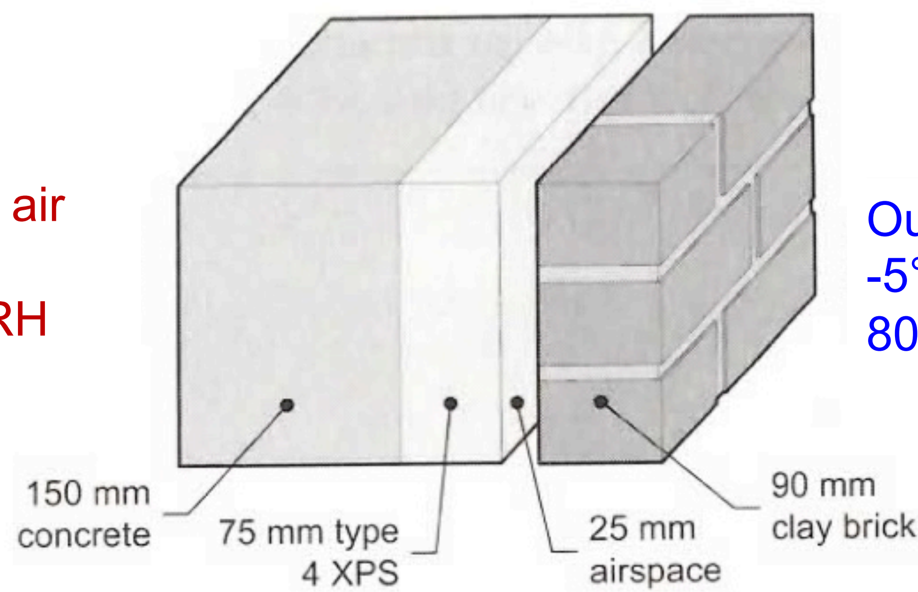
- Vapor diffusion is often a **relatively small** contributor to vapor transport
  - Bulk movement of air usually transports far more water vapor than diffusion

- 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

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

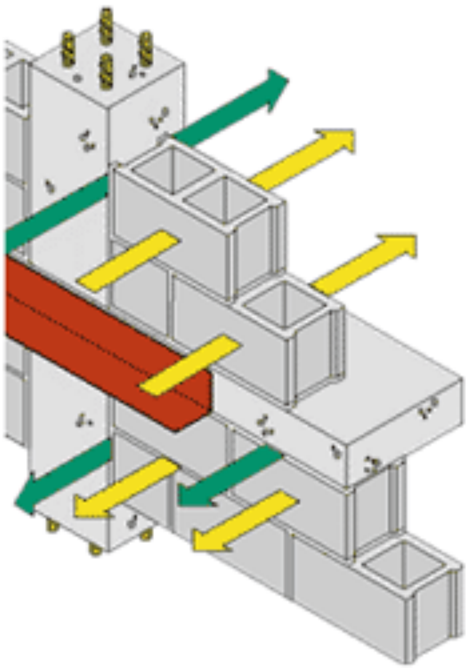
Inside air
21°C
50% RH



Outside air
-5°C
80% RH

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
  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 and exterior air

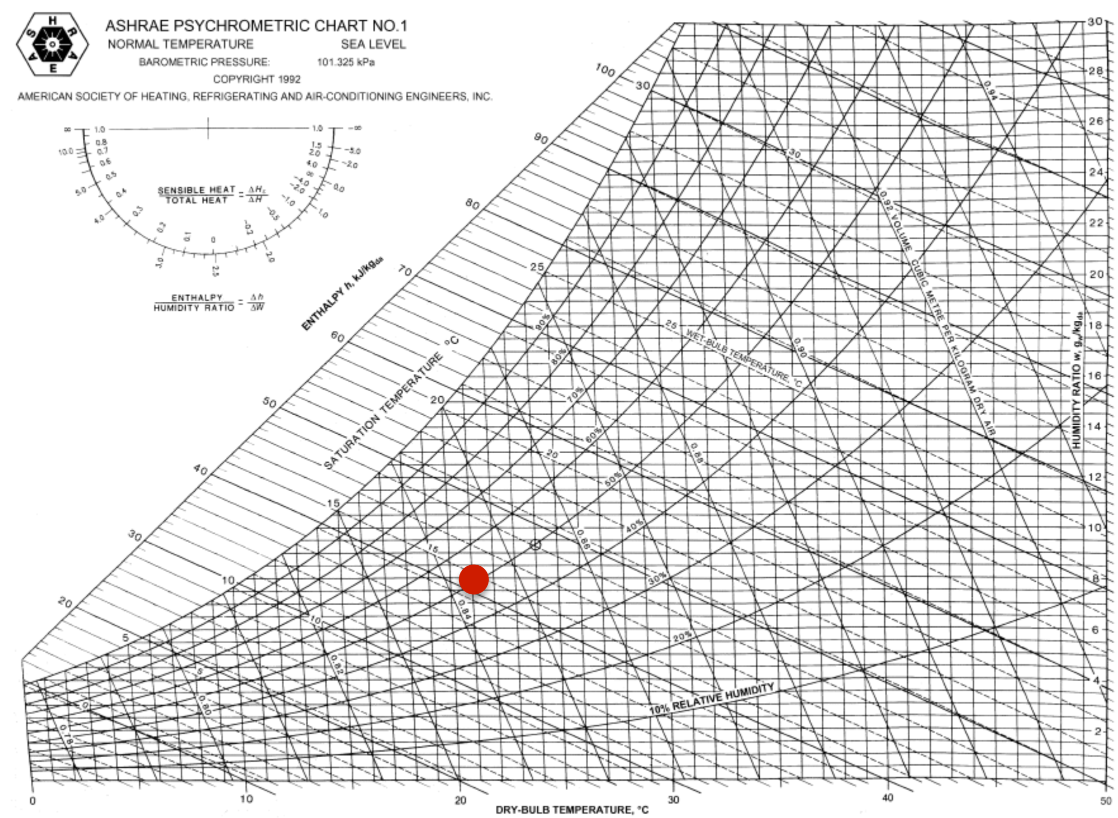
p_{ws} at boundaries:

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



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

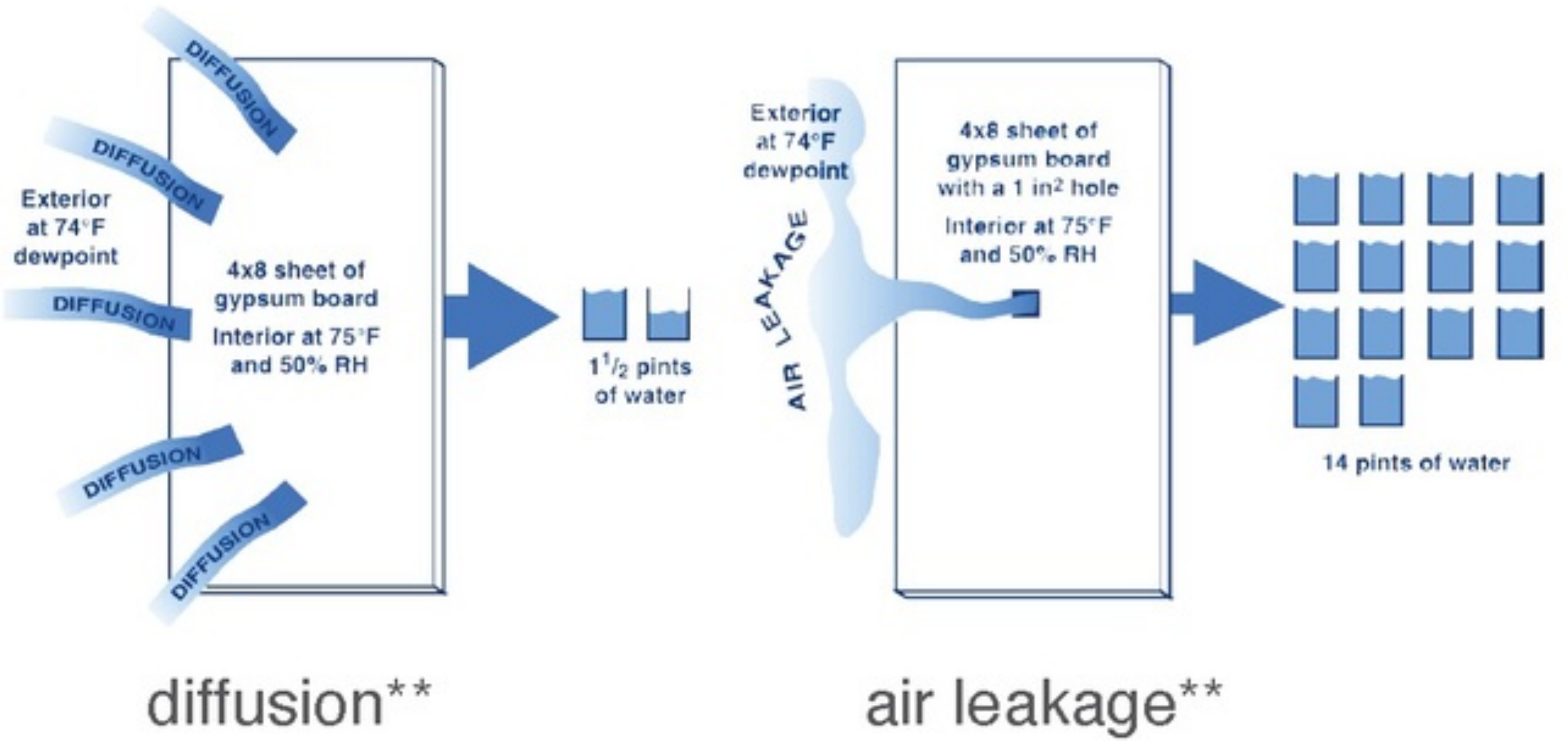
Condensation rate = 4.97 x 10^{-3} g/s per m^2

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

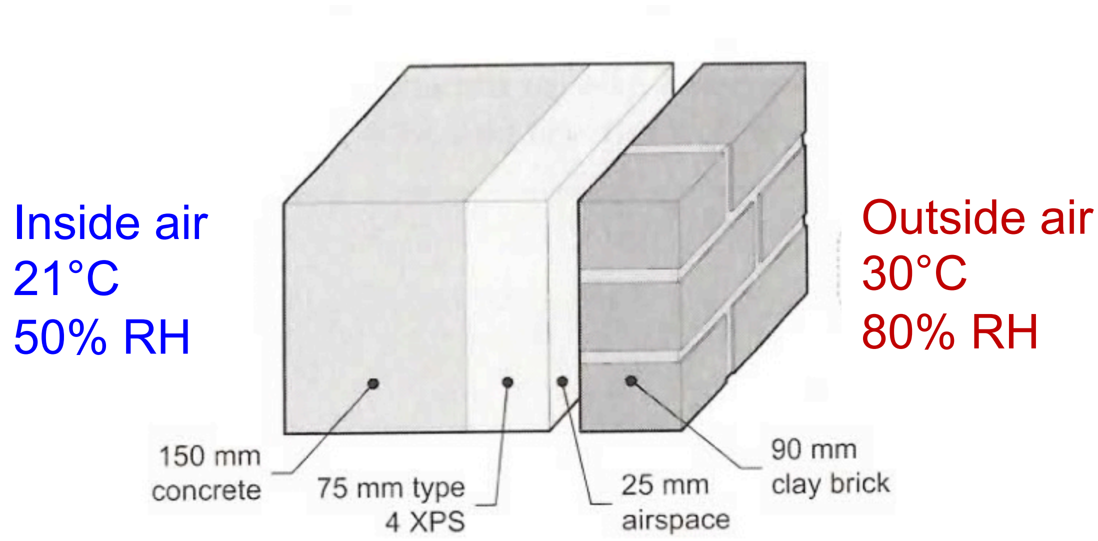
  - For comparison: vapor permeance of brickwork and wood siding is approximately 50 ng /(s m^2 Pa)
  - We will learn more about airflows in enclosures in a future lecture

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-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				
			$R_{v,total}$	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/m²K	m²K/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} (m²K/W)	3.04				
			U_{total} (W/m²K)	0.33				

Summer conditions (more realistic)

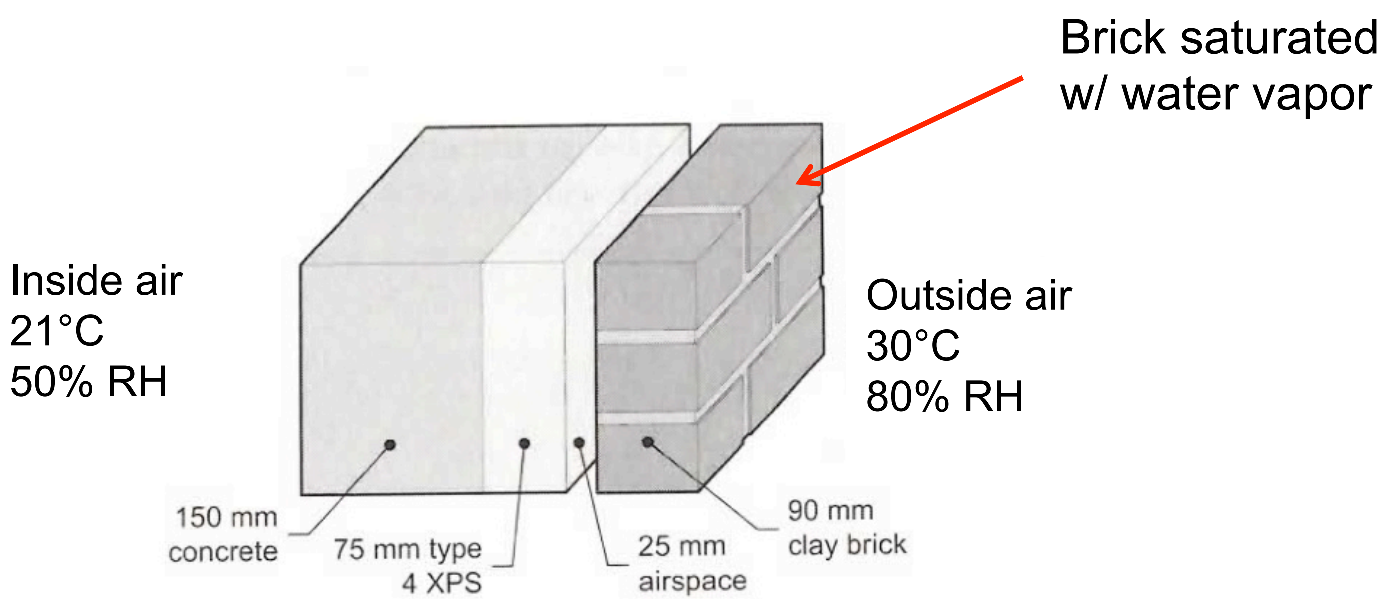
- Taking a hypothetical exterior surface temperature in direct sunlight where $T_{surface,exterior}$ = 45°C
  - Change distribution of T and $p_{w,sat}$
    - But pw distribution does not change

	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)



Water vapor transport: wet brick

- 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				

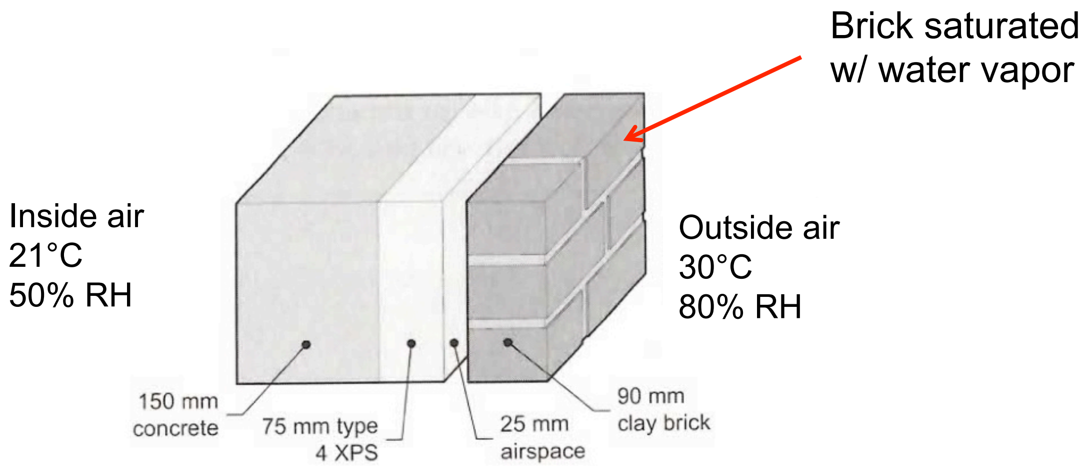
Brick set to 100% RH
Becomes new boundary condition

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 brick

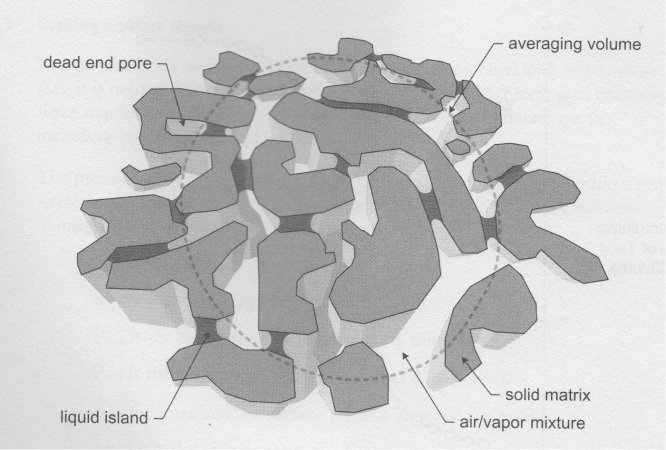
- Big question: Does the condensation even matter?



- 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 (BAD)

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 this porosity, building materials can hold moisture
  - In widely varying amounts

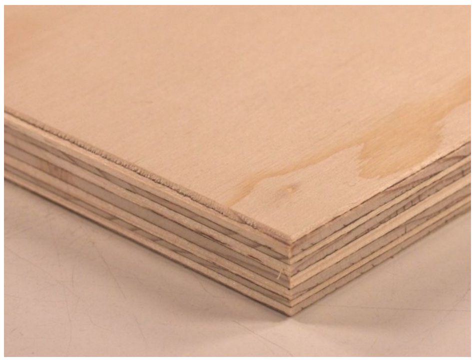
Table 8.1: Moisture contents of some common building materials

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]

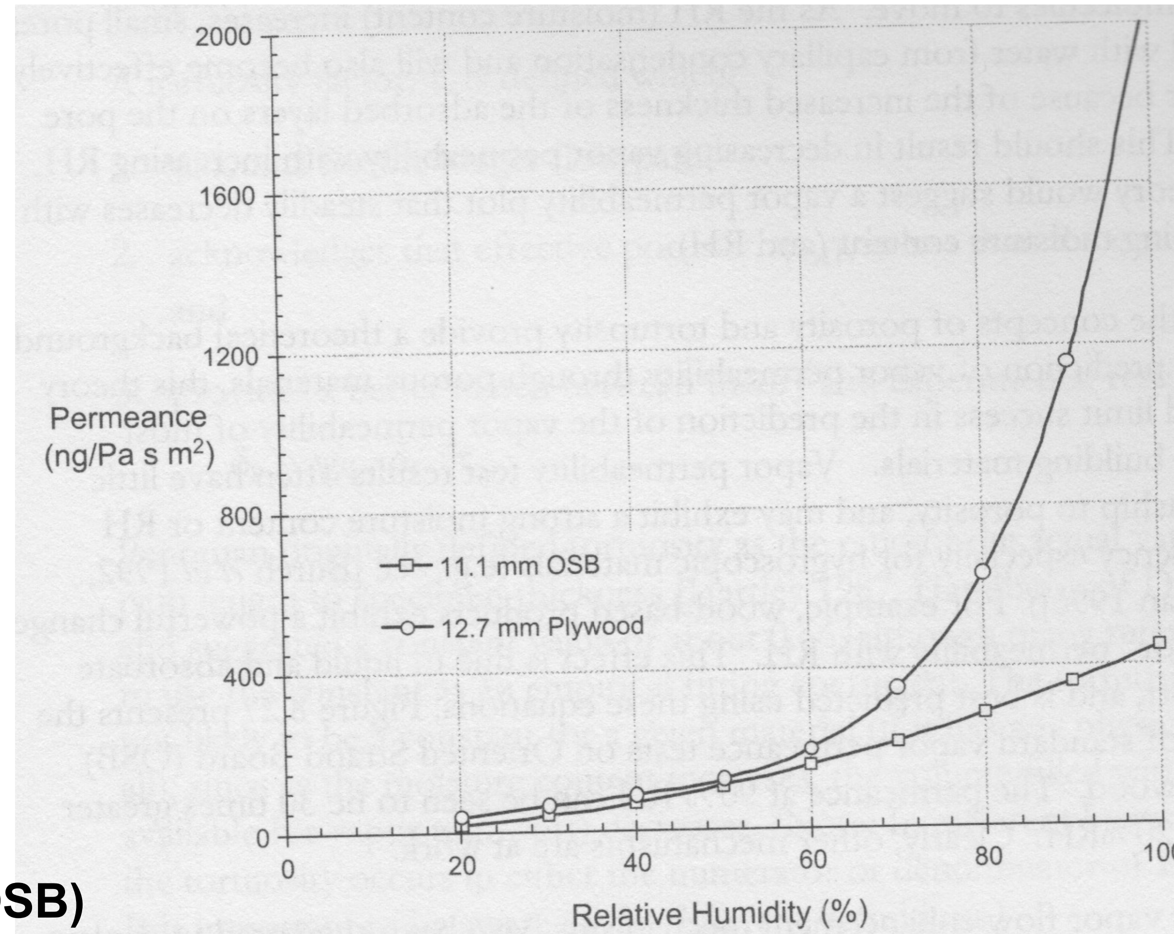
Moisture content influences vapor permeance

- 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)



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

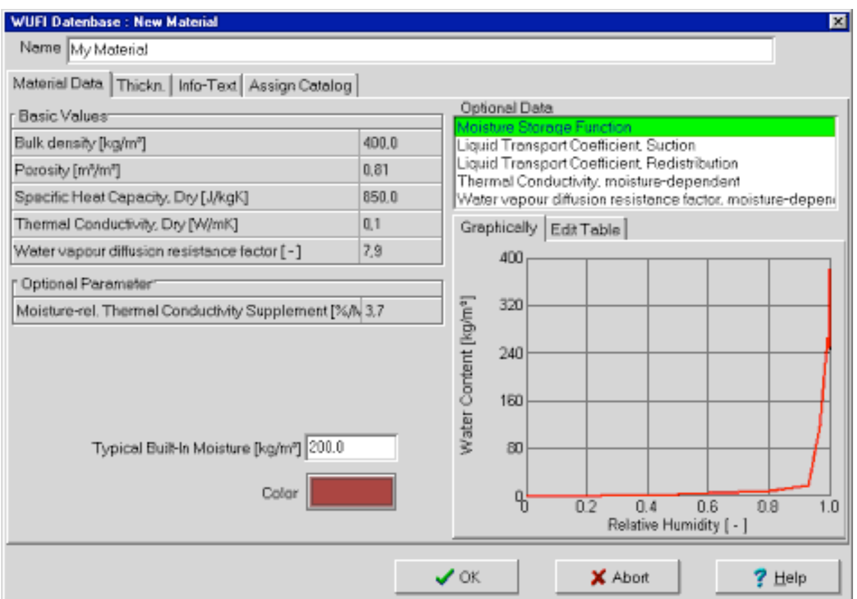
- Liquid transport and by capillary suction is also included

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



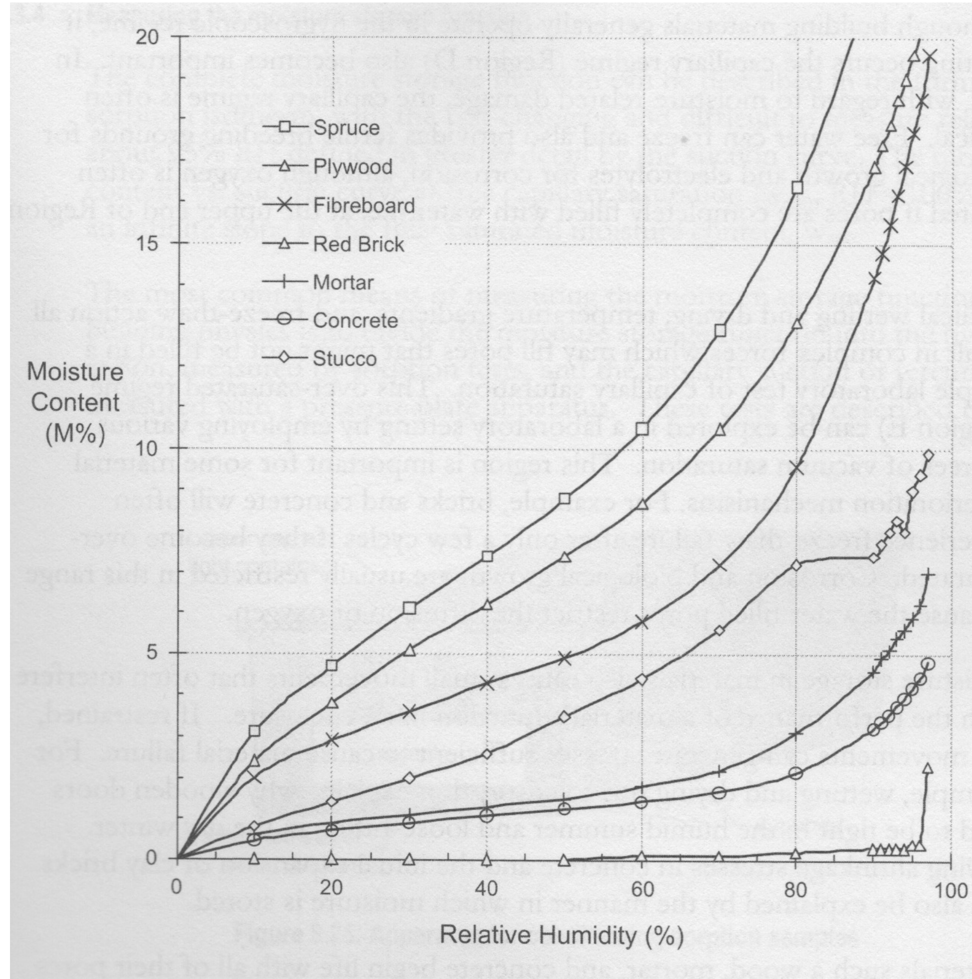


Figure 8.24: Sorption isotherm for several building materials [Kumaran 2002]

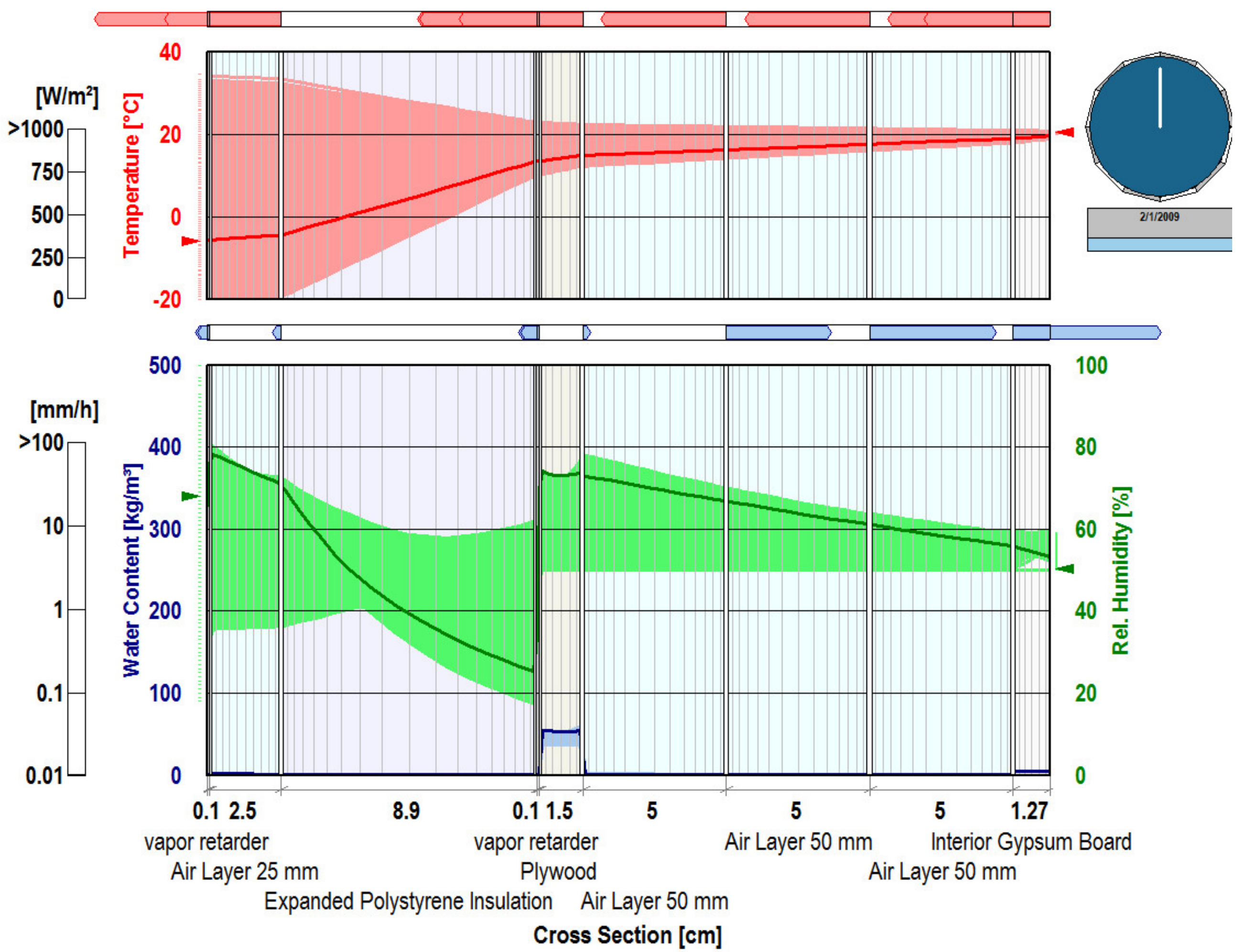
WUFI

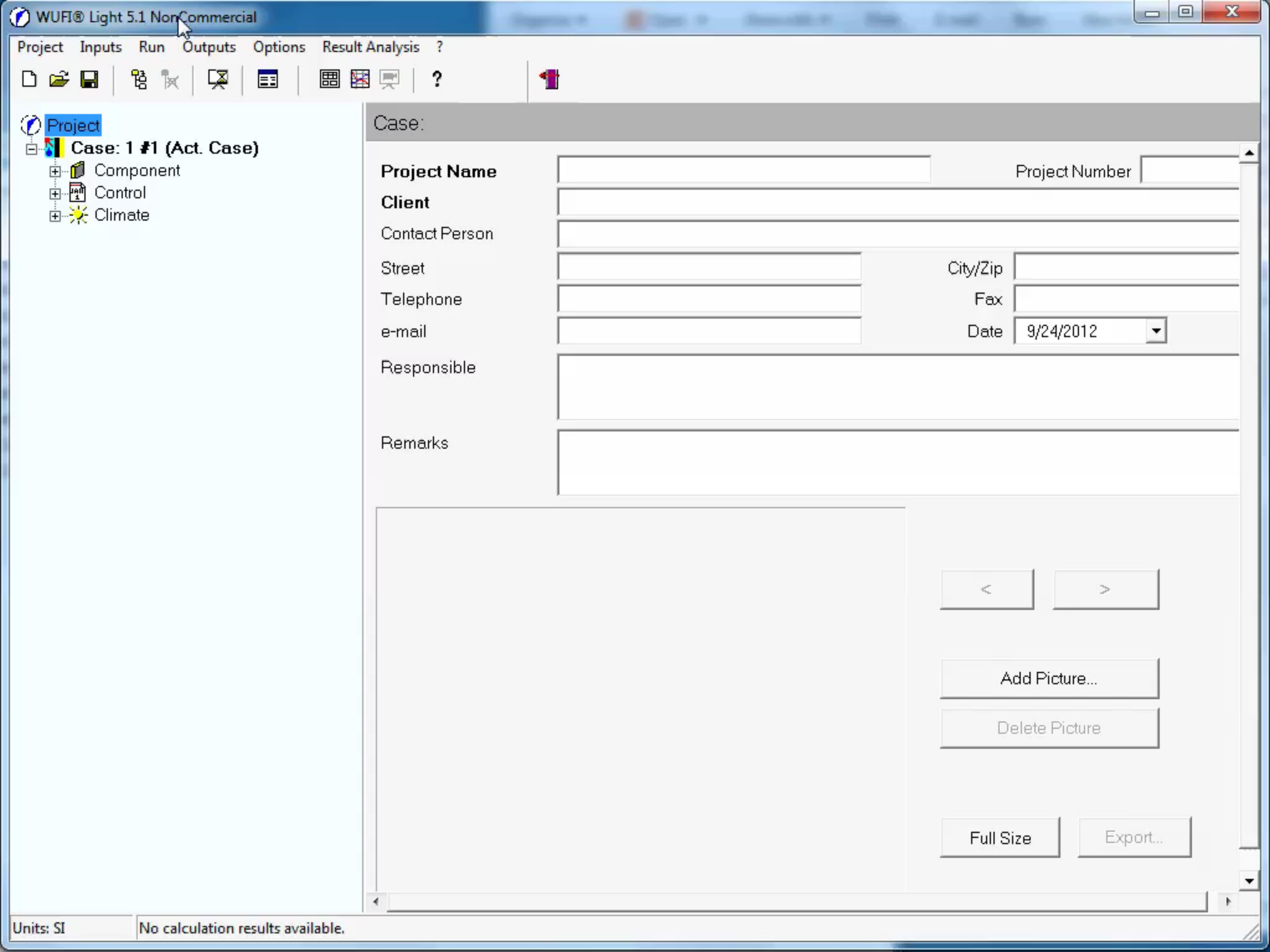
- The commercial version of WUFI is available at http://www.wufi-pro.com/ at a cost of €1950 ≈ $2600

- A free limited version is available 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

You will use both WUFI and hand-calculation methods in HW 3 (assigned today)




WUFI® Light 5.1 NonCommercial
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VAPOR BARRIERS

Applications

Materials: Vapor barriers and vapor retarders

- Vapor barriers are used in certain climates when condensation would be a regular occurrence
  - Hot-humid climates and very cold climates
- Vapor retarders are useful in many more climates
  - Cold and mixed climates
  - Sealing is not as important with a pure vapor barrier

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

Vapor barriers: Good or bad?

- While vapor barriers/retarders can reduce vapor diffusion regardless of where they are placed
  - They must be placed carefully in order to ensure that the potential for condensation is minimized
- In hot and humid climates
  - Vapor barriers go toward the outside of the enclosure
- In very cold climates
  - Vapor barriers go toward the inside of the enclosure
- In mixed or cold environments
  - V*apor retarders* should be used (not barriers), or you may have problems in the opposite seasons
- Largely depends on climate and order of material installation

Interior vapor barriers

- Insulation with Kraft Paper
  - Kraft paper is a barrier at low humidity and a retarder at high humidity
  - Kraft paper also holds some moisture so light condensation is not a problem
  - Not an air barrier as commonly installed (stapled)

- Polyethylene sheet (discouraged)
  - This is a vapor barrier installed after insulation
  - Polyethylene holds no moisture so condensation results in standing water
  - Not an air barrier as commonly installed

Paints as vapor barriers/retarders

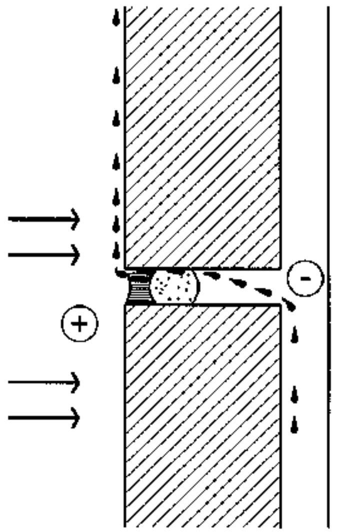
- Latex paints and primers are available in permeable, semi-permeable, or nearly impermeable forms
  - Typical latex paint has $5 < M < 10$ perm
  - Benjamin Moore Vapor Retardant Primer has $M \approx 0.43$ perm
  - These are especially useful when membrane vapor barriers cannot be installed

- Be careful to ensure that your paint is not acting as a vapor barrier or retarder unless you want it to act as a barrier or retarder

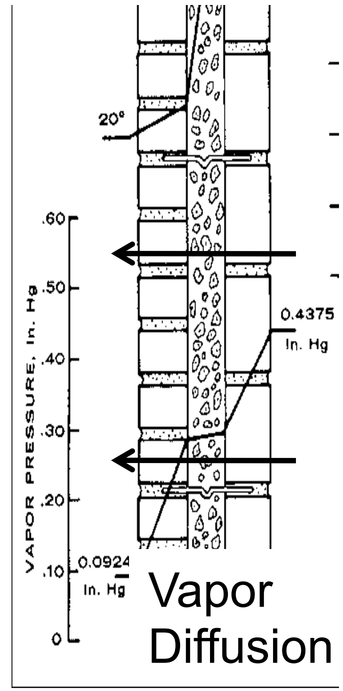
BULK LIQUID TRANSPORT

Moisture transport mechanisms

- So far, we've talked mostly about water **vapor**, either in terms of diffusion or water vapor associated with air leakage



Air Leakage

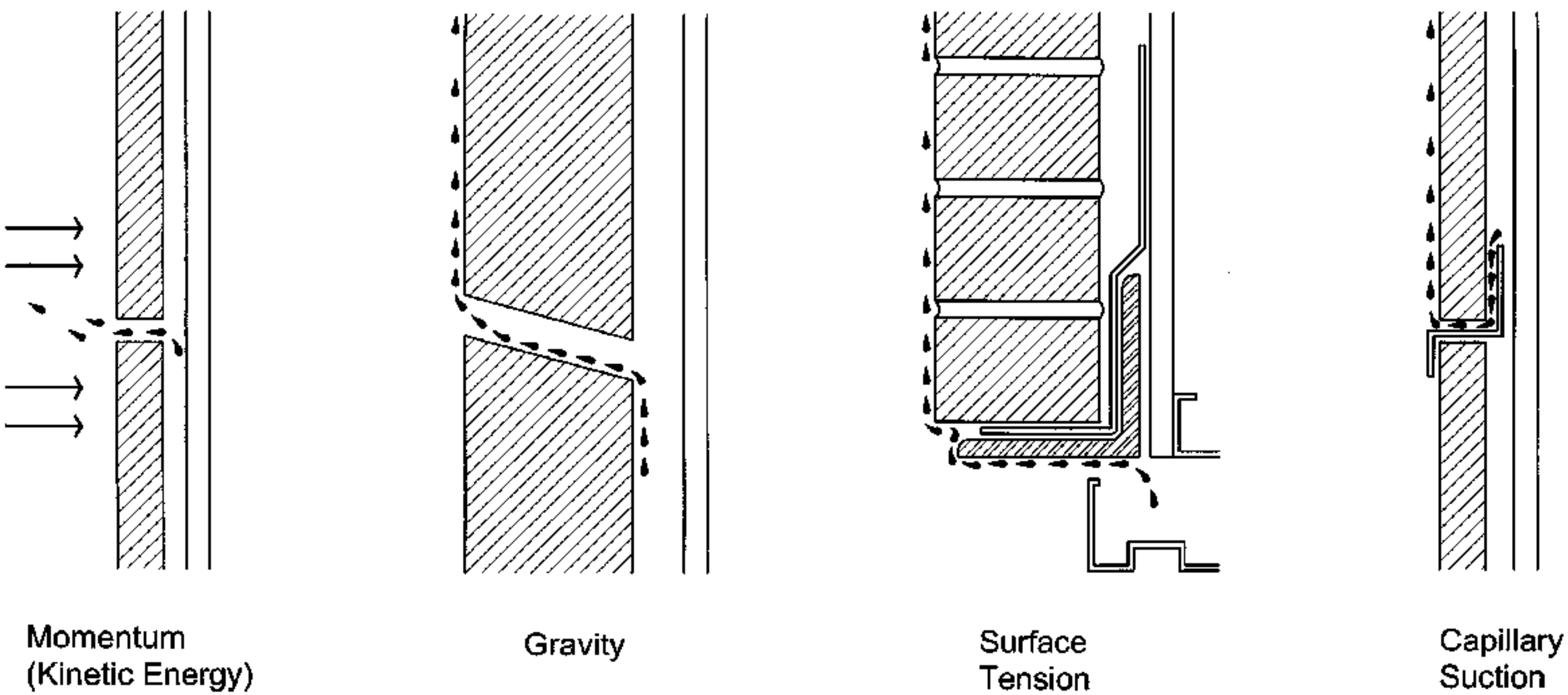


Vapor Diffusion

- We showed that water vapor due to air leakage is usually larger than that due to diffusion
  - It turns out that **liquid water** can be even more important
  - Liquid water can be very difficult to control

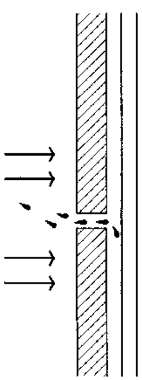
Condensed water (liquid) transport

- There are 4 main mechanisms for condensed moisture or rain to enter into wall cavities or directly inside buildings
  - These can be stopped fairly easily with simple design ideas



Momentum (kinetic) driven rain penetration

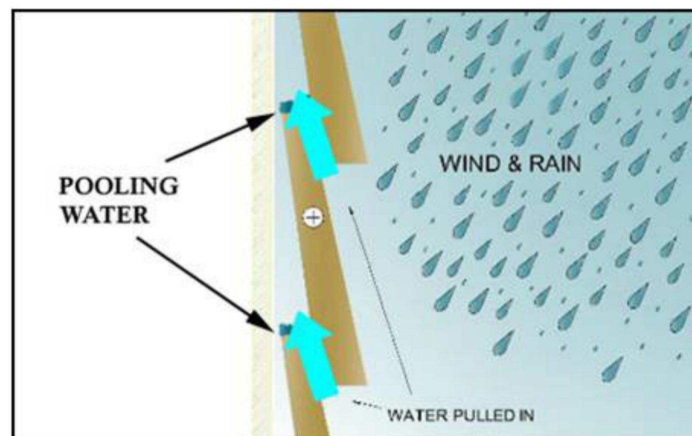
- Momentum of wind-driven raindrops
- Force will carry raindrops directly through openings of sufficient size
  - Recognize that rain doesn't fall straight down
  - Need to protect intentional openings from direct rain entry



Momentum
(Kinetic Energy)

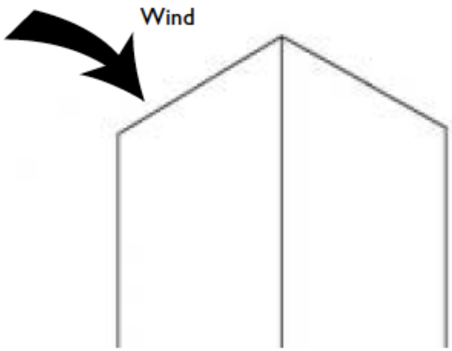
Pressure gradients (related to momentum driven rain)

- Air pressure differences across the building envelope can create suction
  - Draws water through available leakage paths
  - Air movement can also carry water droplets directly
- Pressure due to wind is a big concern for water penetration
  - In wall systems with impervious outer cladding, pressure differences can be the most significant source of driving rain into a building
    - e.g., curtain walls where outer walls are non-structural
- Pressure driven rain penetration can vary a lot within the same building

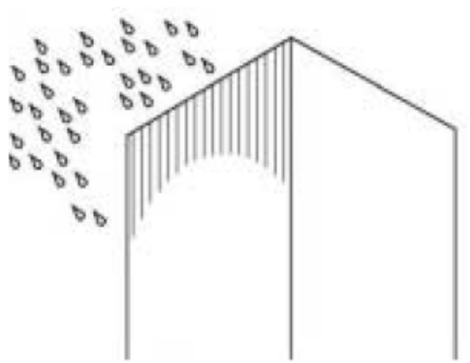


Pressure gradients acting on different parts of a building

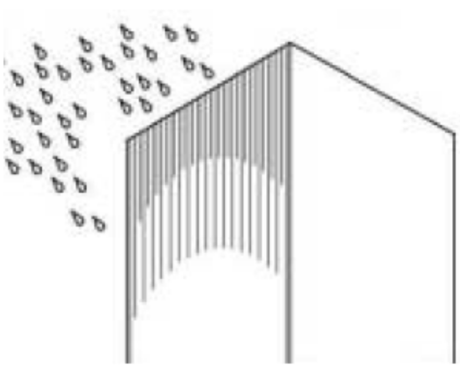
- Wetting of a section of a tall building



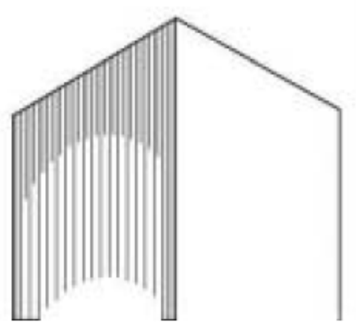
Dry building



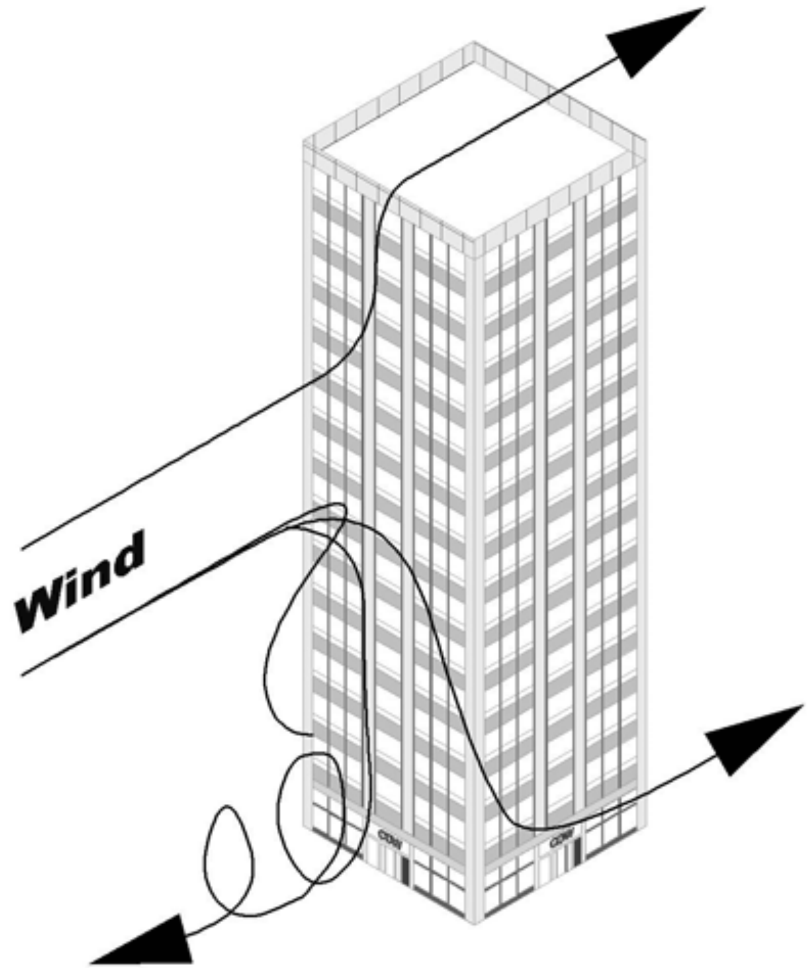
After 10 minutes: migration begins



After 20 minutes: development of characteristic rain-wetting pattern

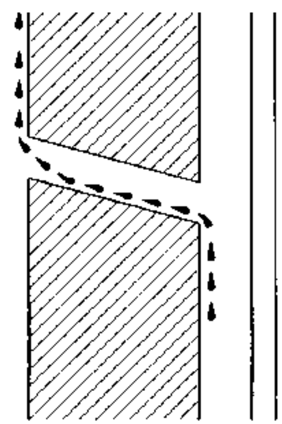


After 40 minutes: rain ends, wetting of windward faces by deposit and migration roughly proportional to directional exposure to driving rain



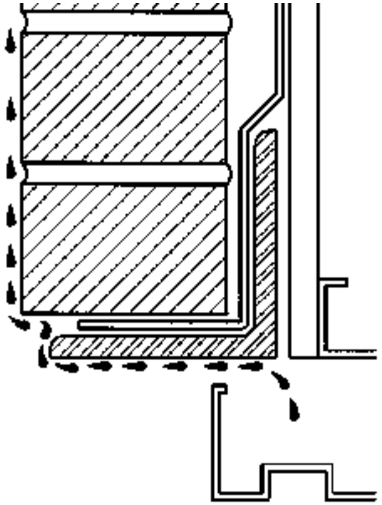
Gravity-driven water penetration

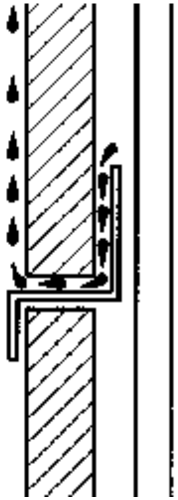
- Leakage due to gravity still occurs frequently in modern buildings
  - Particularly with near-horizontal or moderately sloped building elements
- Gravity-driven water movement seems elementary to prevent
  - Problems can usually be traced to errors in the design or construction of elements
    - Particularly flashings; restricted/clogged drainage paths after construction
  - Take care to avoid inward-sloping leakage paths and areas where water can pond

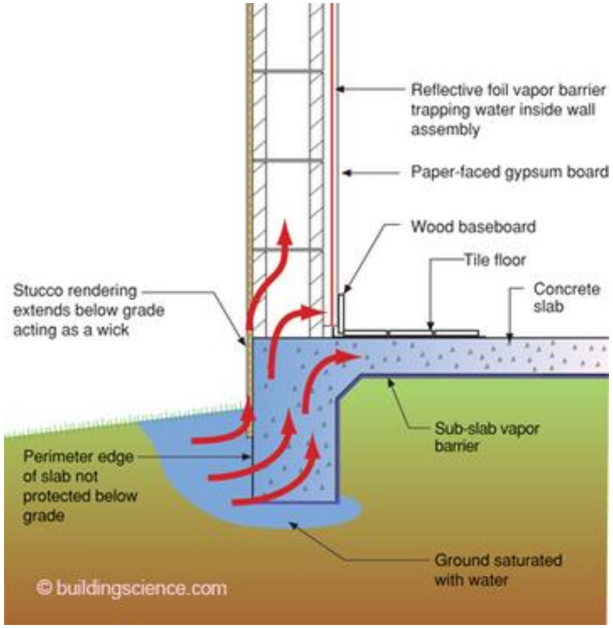


Capillary action and surface tension

- Cohesive forces allow water to cling and flow along horizontal surfaces
  - Can move against gravity
  - The force with which capillary action can work against gravity is inversely proportional to the size of openings
    - Small cracks allow more capillary action
  - Also depends on material affinity for water
  - More important in porous materials







Capillary action

- Capillary attraction
  - Occurs within porous bodies
  - Particularly when they are not saturated

- Capillary suction occurs in small pores under about 0.1 mm in diameter
  - Molecular attraction of water molecules and surfaces

$$s = \frac{2\sigma \cos\theta}{r}$$

s = capillary suction, Pa
σ = surface tension of H_2O, N/mm^2
r = equivalent radius, mm
θ = contact wetting angle, °

- A gradient in capillary suction will move liquid water
  - This could be from a variation in pore radius

$$m_l = -k_m \, \mathrm{grad}(s)$$

m_l = liquid flux, $g/(s\text{-} m^2)$
k_m = water permeability, $g/(m^2\ s\ Pa)$

Capillary action

- Capillary suction in a tube

Units on surface tension:

$$1\ \frac{\text{dyn}}{\text{cm}} = 1\ \frac{\text{erg}}{\text{cm}^2} = 1\ \frac{\text{mN}}{\text{m}} = 0.001\ \frac{\text{N}}{\text{m}} = 0.001\ \frac{\text{J}}{\text{m}^2}$$

$$s = \frac{2\sigma\cos\theta}{r}$$

s = capillary suction, Pa
σ = surface tension of H_2O, N/mm
r = equivalent radius, mm
θ = contact wetting angle, °

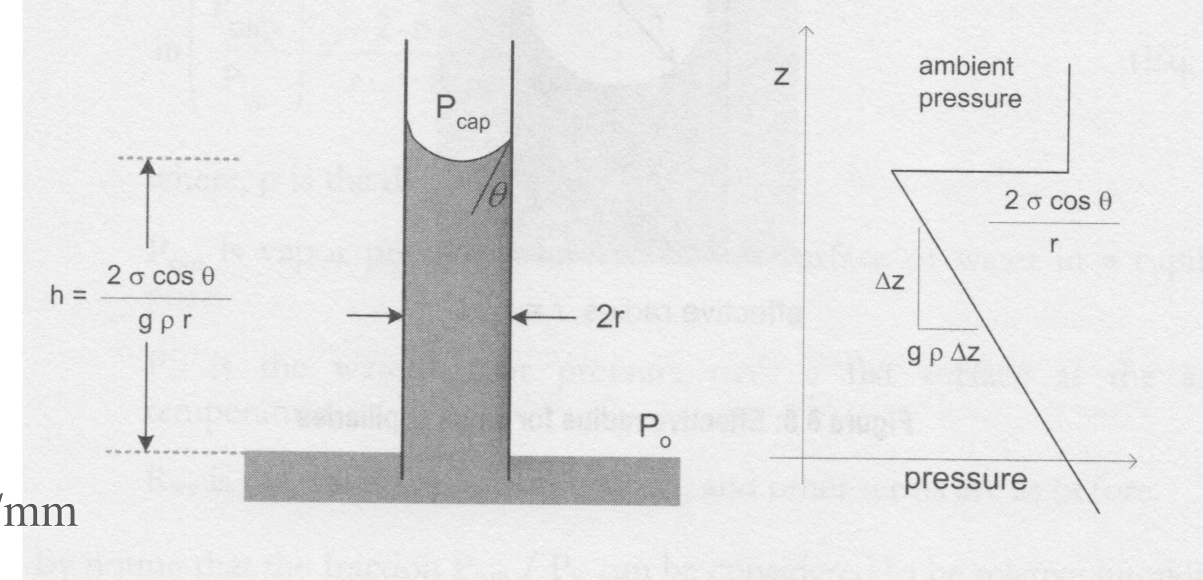
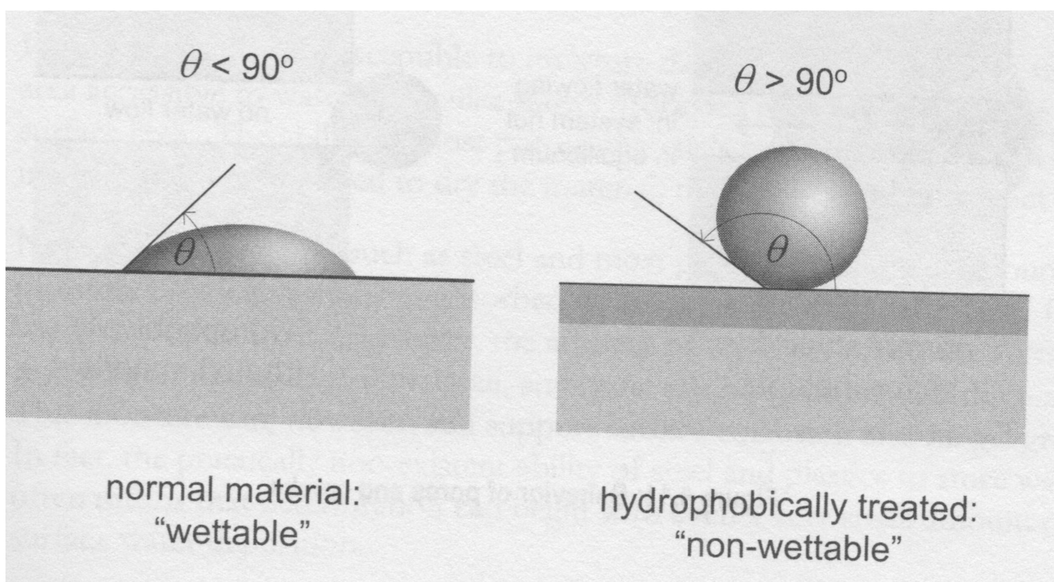


Figure 8.7: Capillary suction of water in a cylindrical tube

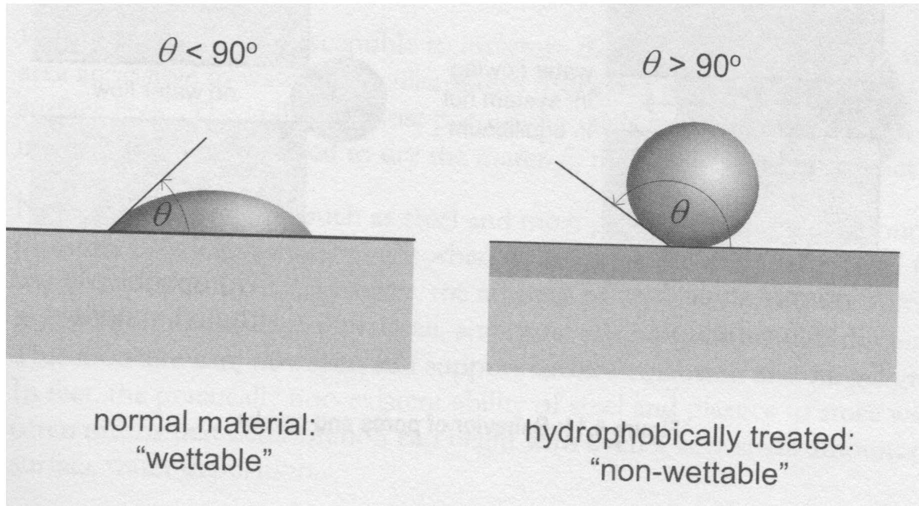
- The pressures involved with capillary suction in small pores (10-1000 nm) that make up a significant volume of concrete and wood generate large suction pressures (kPa to MPa)
  - Wicking water in small pores can be far greater than gravity forces or wind pressures

Wettable materials and hydrophobicity

- Capillary suction is driven in part by contact angle
  - Contact angle describes the angle of contact between water and a surface
  - **"Wettable"** materials have a surface structure that strongly attracts polar water molecules
    - Have a small contact angle (< 90 degrees)
  - **"Hydrophobic"** surfaces have a higher contact angle



Wettable materials and hydrophobicity



- Materials can be designed with pore radii and contact angles in mind to make them more or less water repellent
  - Waxes, oils, and silicone are all more hydrophobic than wood, brick, and stone (greater contact angles)
- Can apply treatments to surfaces of materials to change their wetting potential
  - Sometimes penetrating sealers for porous bodies
  - Sometimes just hydrophobic exterior coatings

DEALING WITH WATER

Conceptually

Liquid water problems

- When we have rain
  - Liquid water directly impacts our roofs and walls

- Without proper design, that water will get into the roof and wall assembly
  - Can lead to the problems we discussed in a previous lecture

- We need to divert that water away from our enclosure

Keeping moisture away

A proper gutter system diverts rain on building to sewer or away from foundation

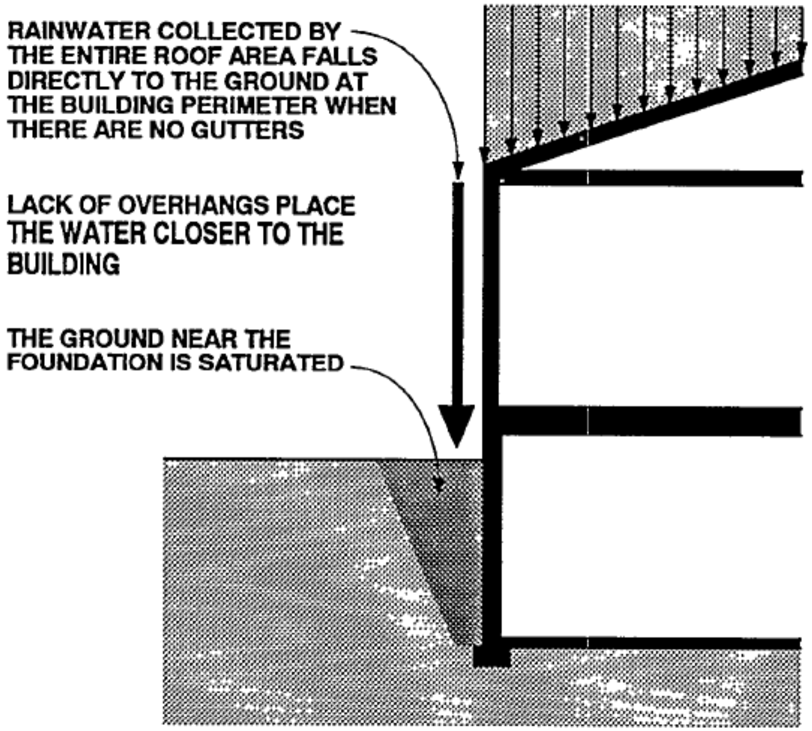


Figure 2-1A: Potential Surface Drainage Problems

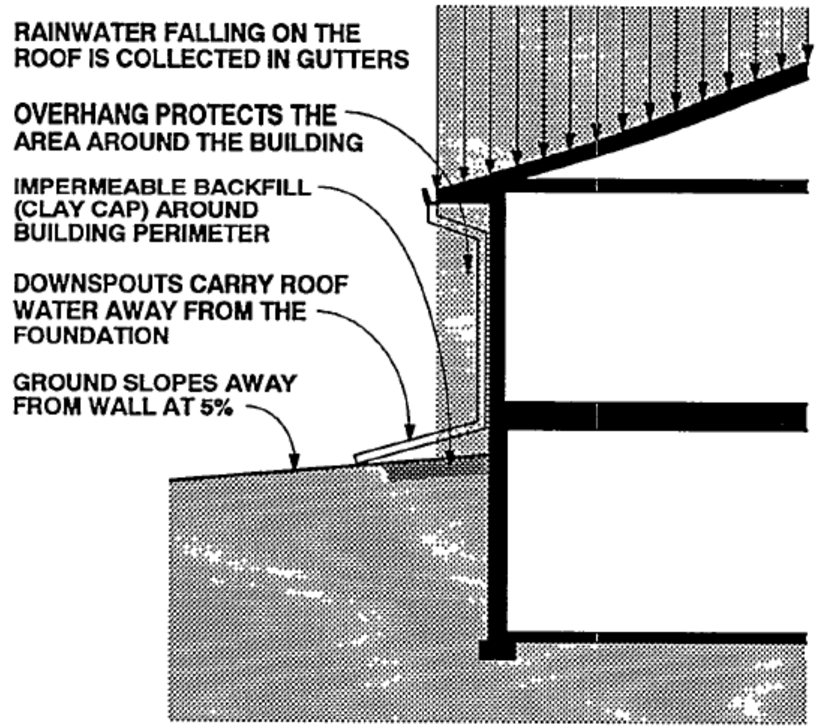


Figure 2-1B: Effective Surface Drainage Techniques

Good foundation design

Give water somewhere to go

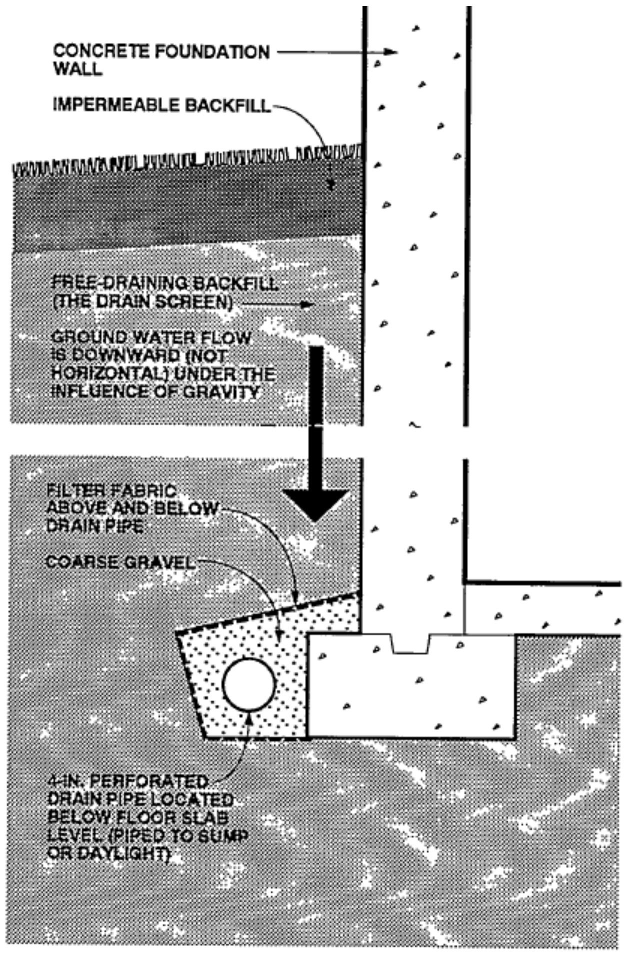


Figure 2-2: Drain Screen Concept Using Porous Backfill

Porous backfill

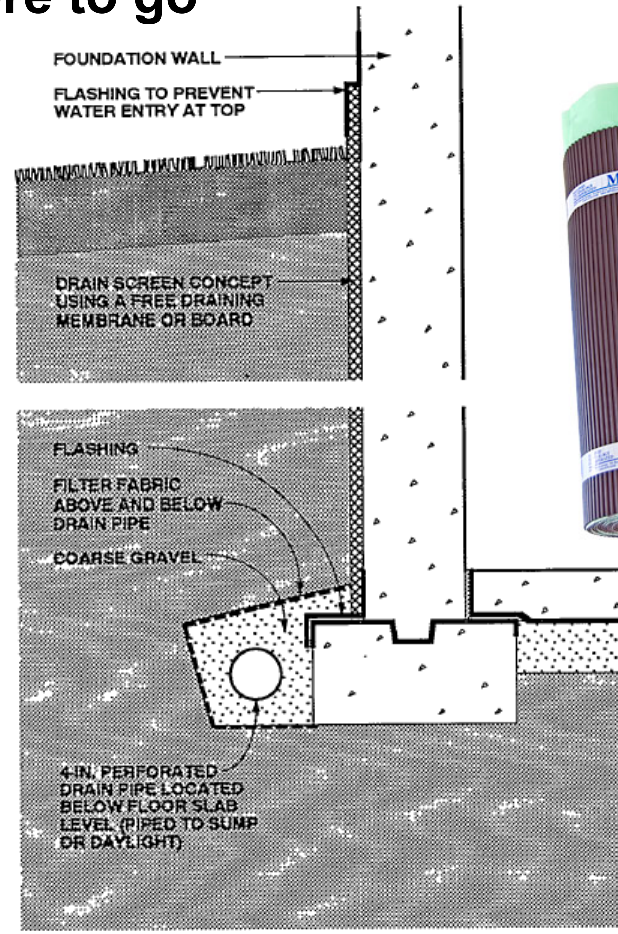
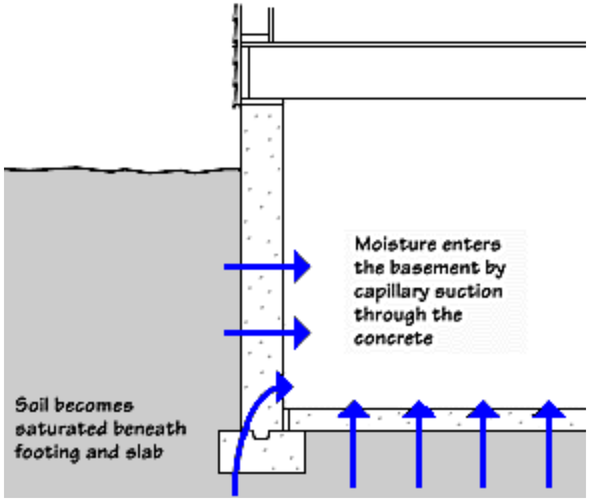


Figure 2-3: Drain Screen Concept Using a Free-Draining Board or Membrane

Add a drainage plane

Capillary suction: Foundations

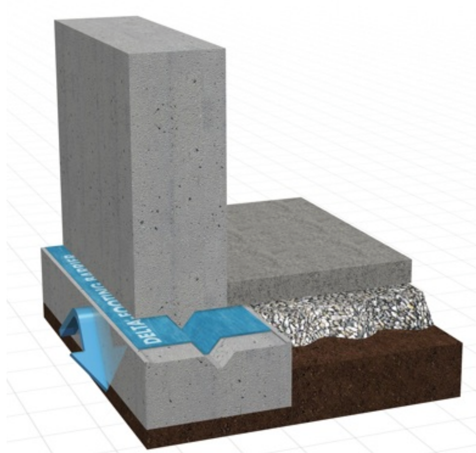
- Capillary suction draws water from saturated soil into the foundation and standing water through small cracks in brick, concrete and other materials
- To stop capillary suction we need to:
  - Keep moisture away from foundation
  - Seal pores or add barrier
  - Make pores larger or add separation plane
  - Provide a receptor for moisture



Soil Type	Capillary Rise
Gravel	Inches
Sand	1-8 ft
Silt	12-16 ft
Clay	12-20 ft

Stopping capillary suction in foundations

- Put concrete floor slab over large pore gravel
- Coat masonry block foundation with mortar and fluid applied sealant
- Capillary breaks (barriers) over concrete footing
  - Fluid applied sealant or Polyethylene sheet



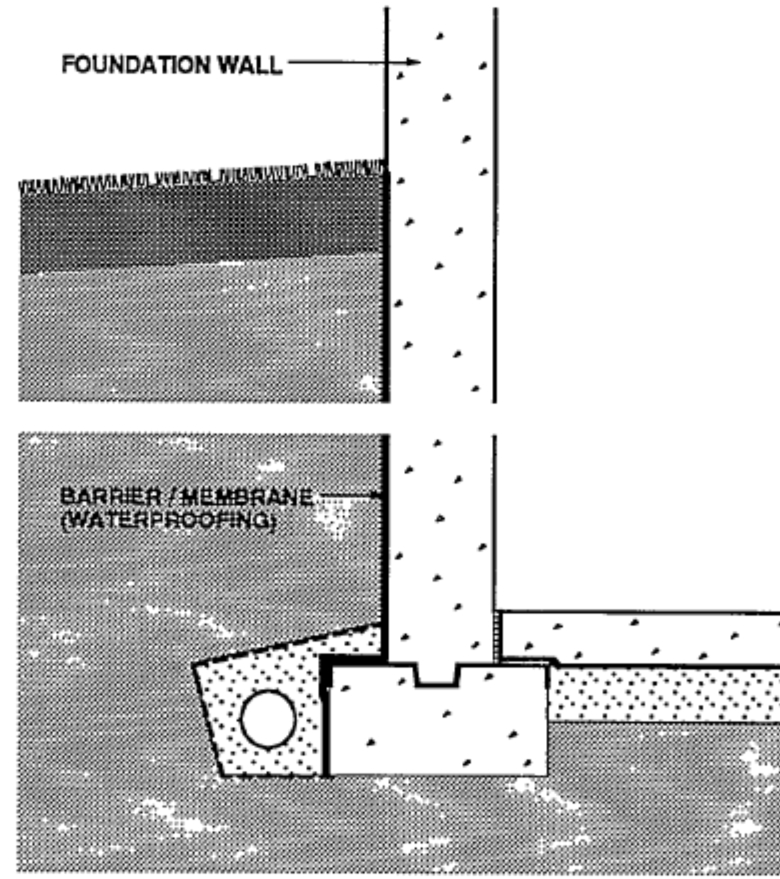
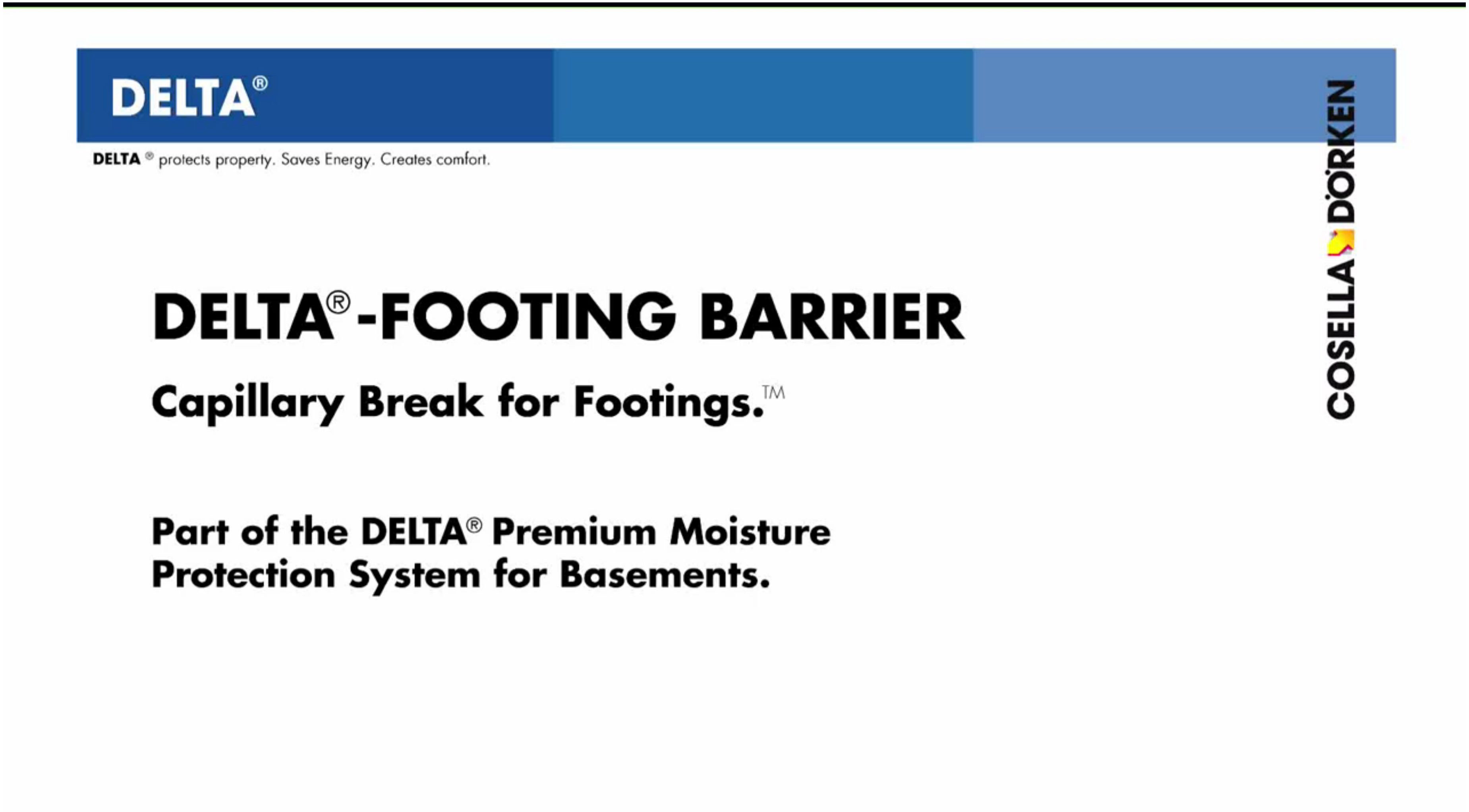


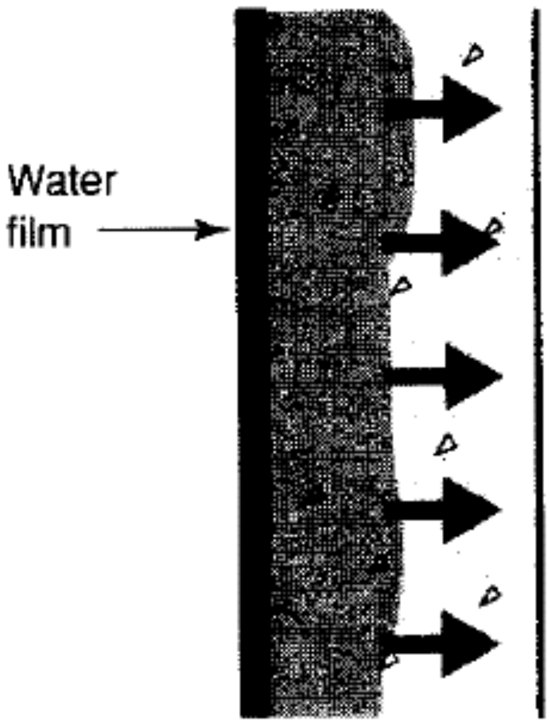
Figure 2-4: Barrier / Membrane Approach

Capillary break in foundation



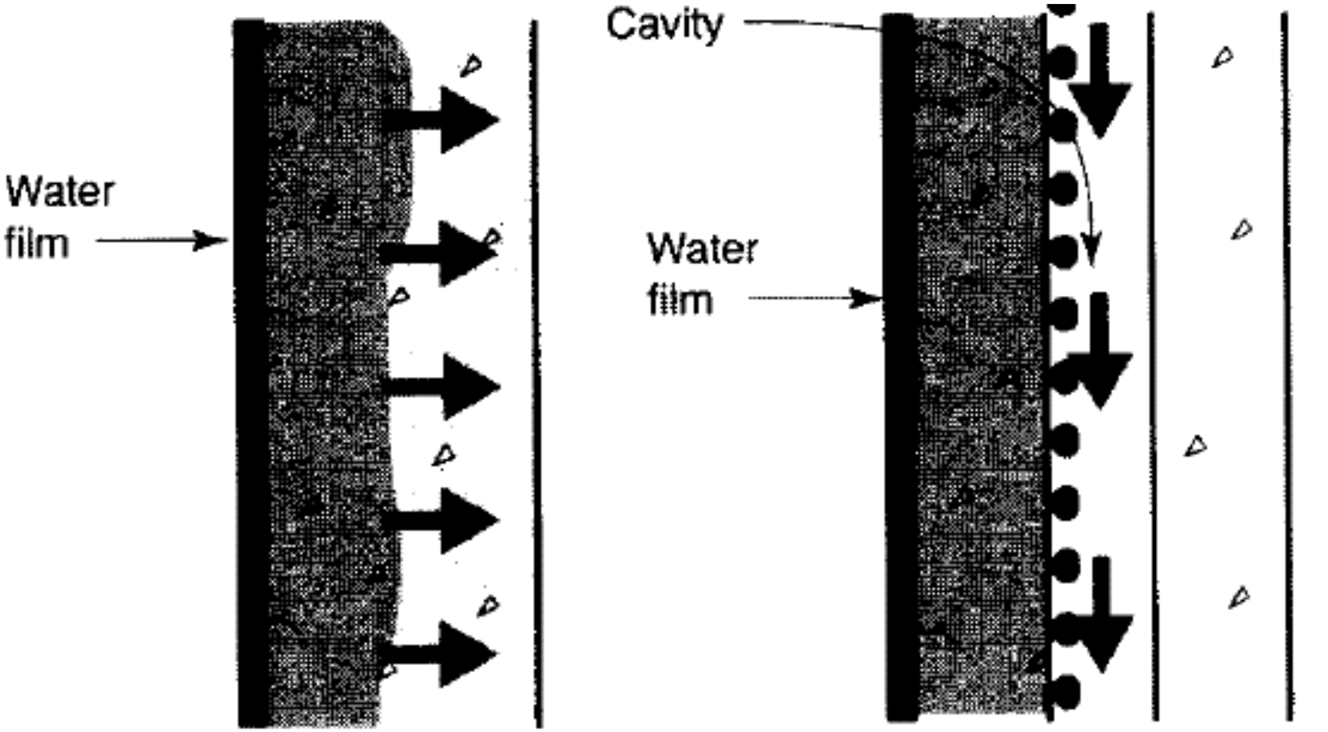
https://www.youtube.com/watch?v=wBhkI3sFfFA

Capillary suction (horizontal)



Capillary suction draws
water into porous material
and tiny cracks

Solution to capillary suction water movement

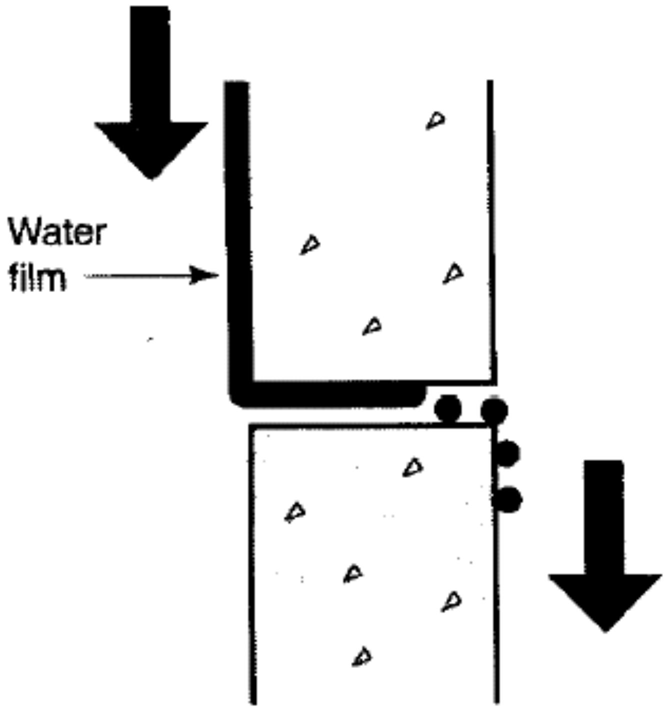


Capillary suction draws water into porous material and tiny cracks

Cavity acts as capillary break and receptor for capillary water interrupting flow

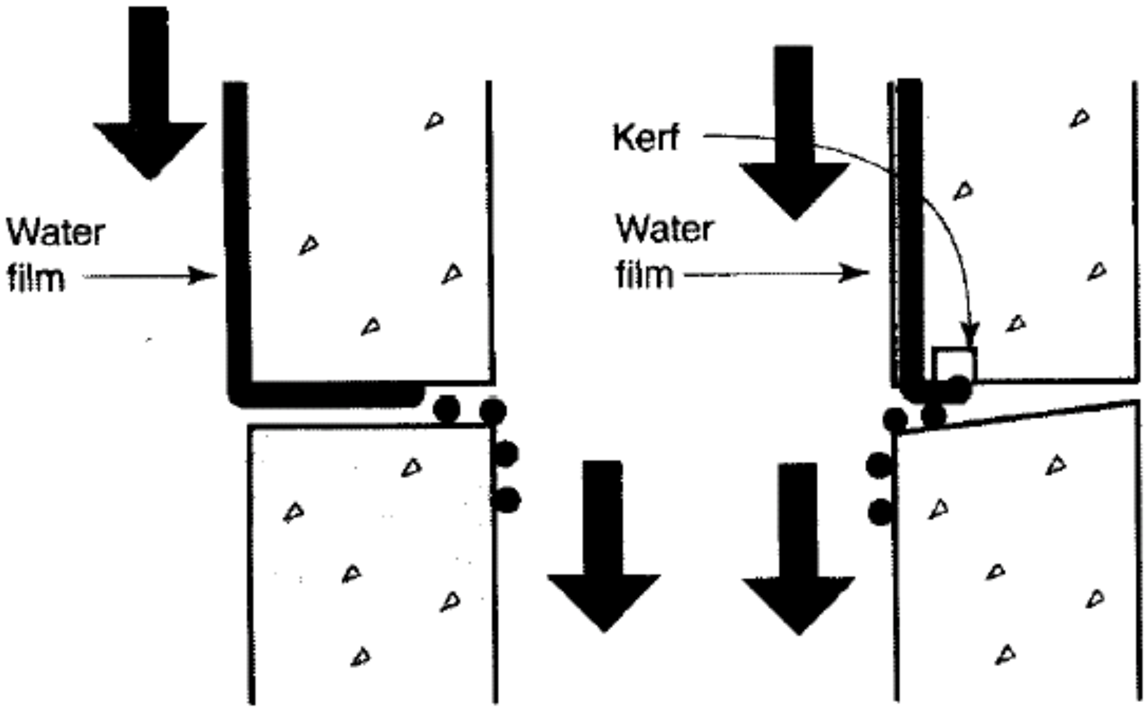
Add an air cavity

Surface tension



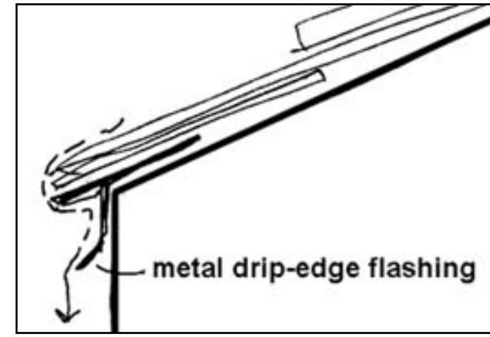
Rainwater can flow around a surface as a result of surface tension

Solution to surface tension water movement



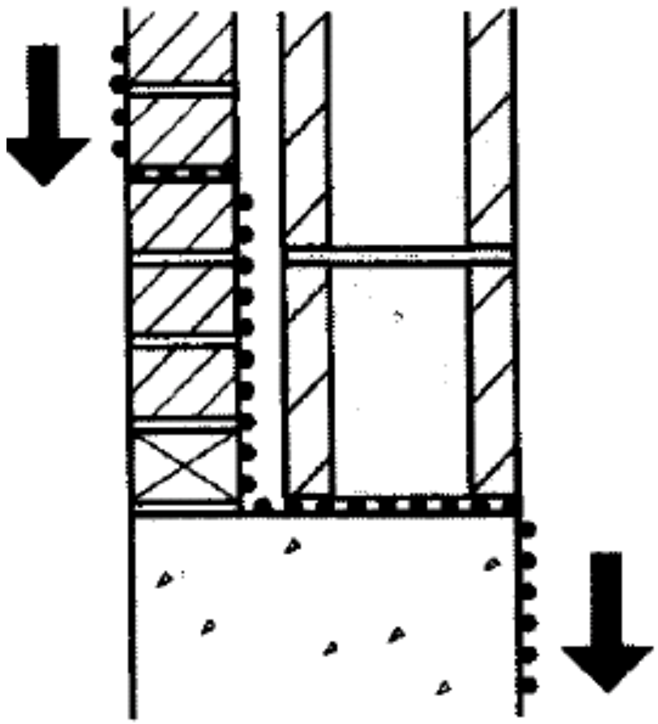
Rainwater can flow around a surface as a result of surface tension

Providing a kerf or drip edge will promote the formation of a water droplet and interrupt flow



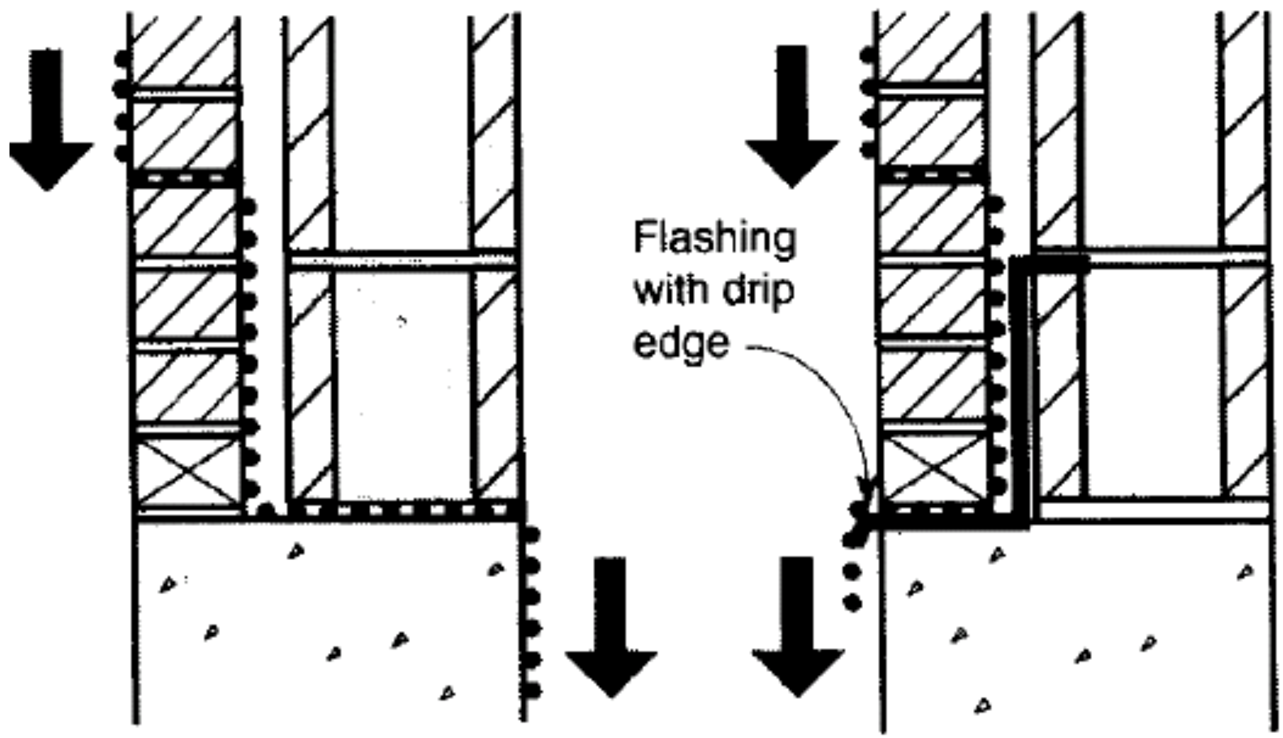
Provide a kerf or drip edge

Gravity



Rainwater can flow down surfaces and enter through openings and cavaties

Solution to gravity-driven water movement

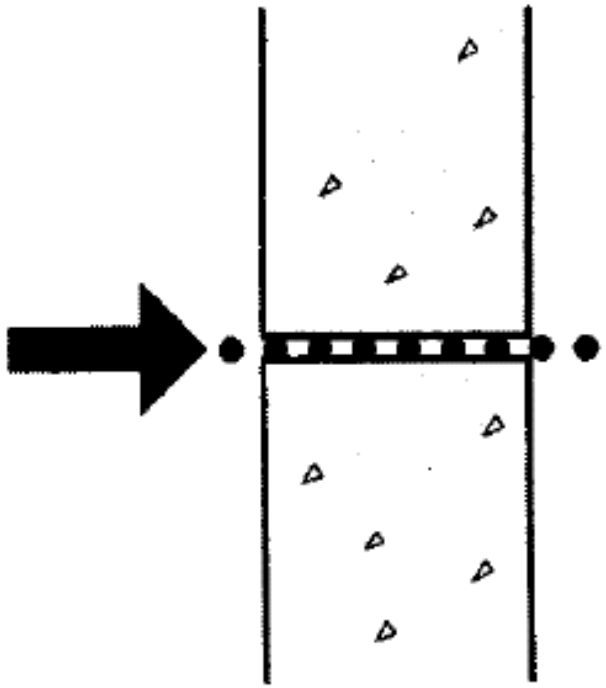


Rainwater can flow down surfaces and enter through openings and cavaties

Flashings direct gravity flow rainwater back toward the exterior

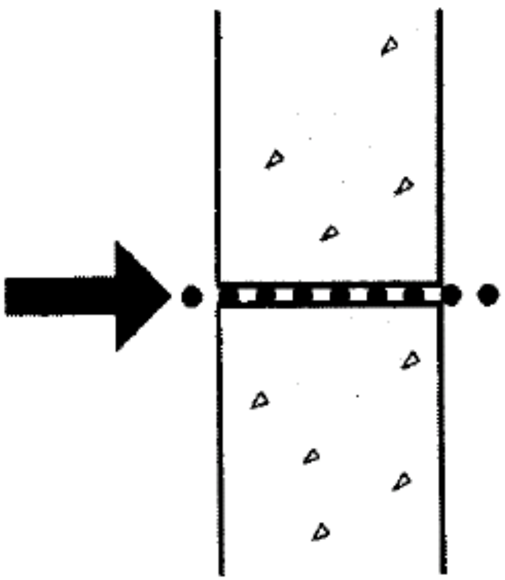
Flashing, flashing, flashing

Rain droplet momentum

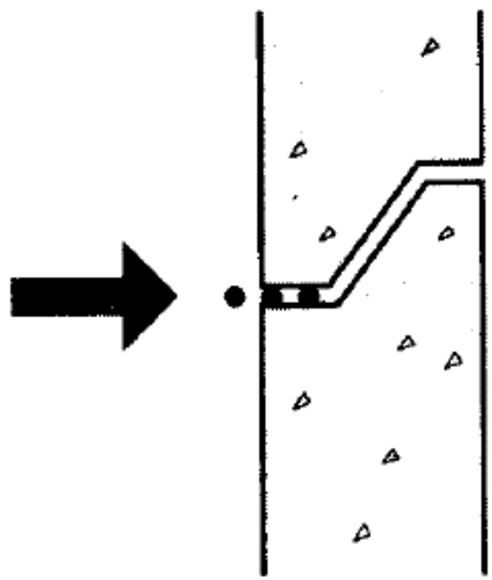


Rain droplets can be
carried through a wall
by their own momentum

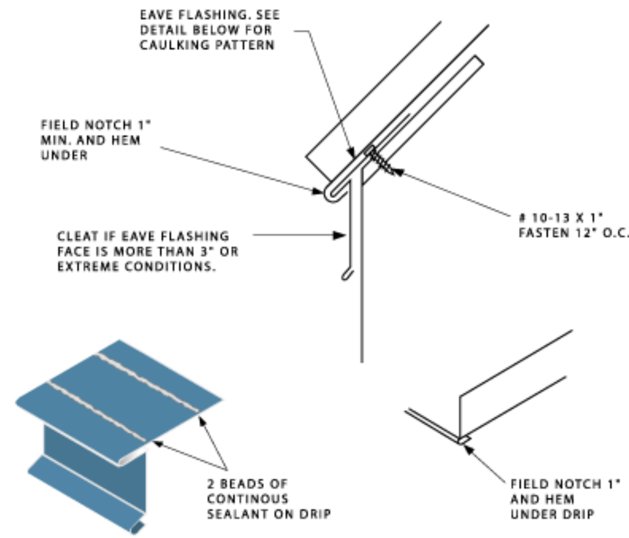
Solution to droplet momentum problems



Rain droplets can be carried through a wall by their own momentum



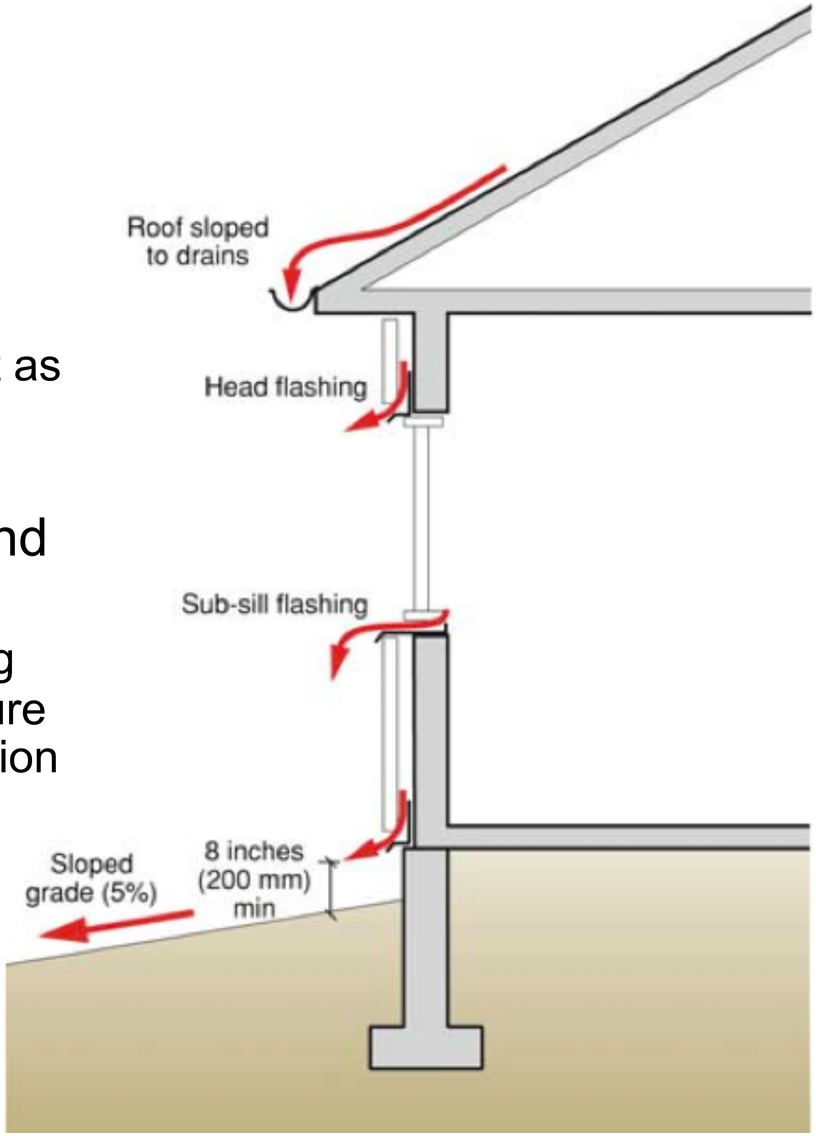
Rain entry by momentum can be prevented by designing wall systems with no straight through openings



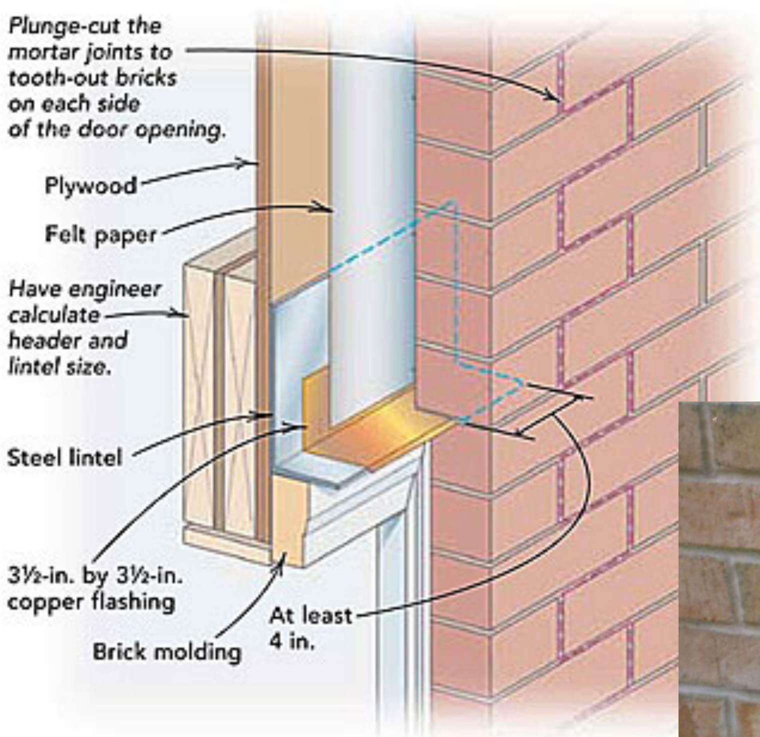
Also reduces gravity transport

Flashing: Extremely important architectural detail

- When we have liquid water, we must deal with it!
  - Major solution: **Flashing**
- Flashing design is not really science
  - The problem is ensuring that good detail construction documents are created and built as drawn
- ASTM E2112 Standard Practice for the Installation of Exterior Windows, Doors, and Skylights
  - Describes the proper flashing design, building wrap installation and sealing required to ensure watertight window, door, and skylight installation
- The architect is typically in charge of construction details
  - Then passed on to the contractor for construction
    - Sometimes no interaction with engineer
    - Many places to miss important flashing details



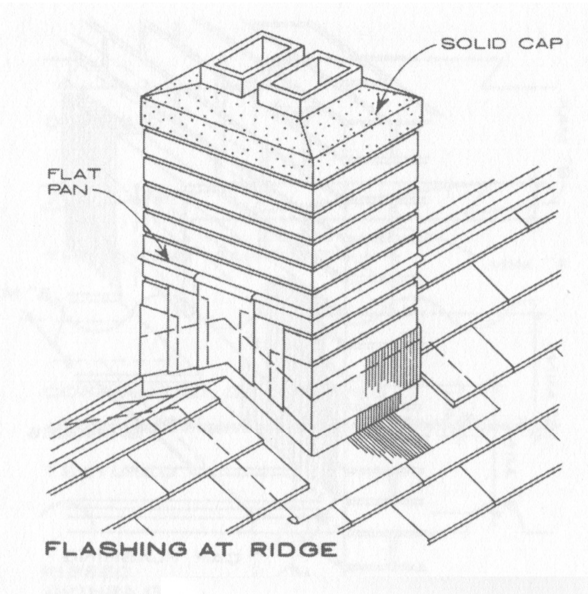
Flashing: Extremely important architectural detail

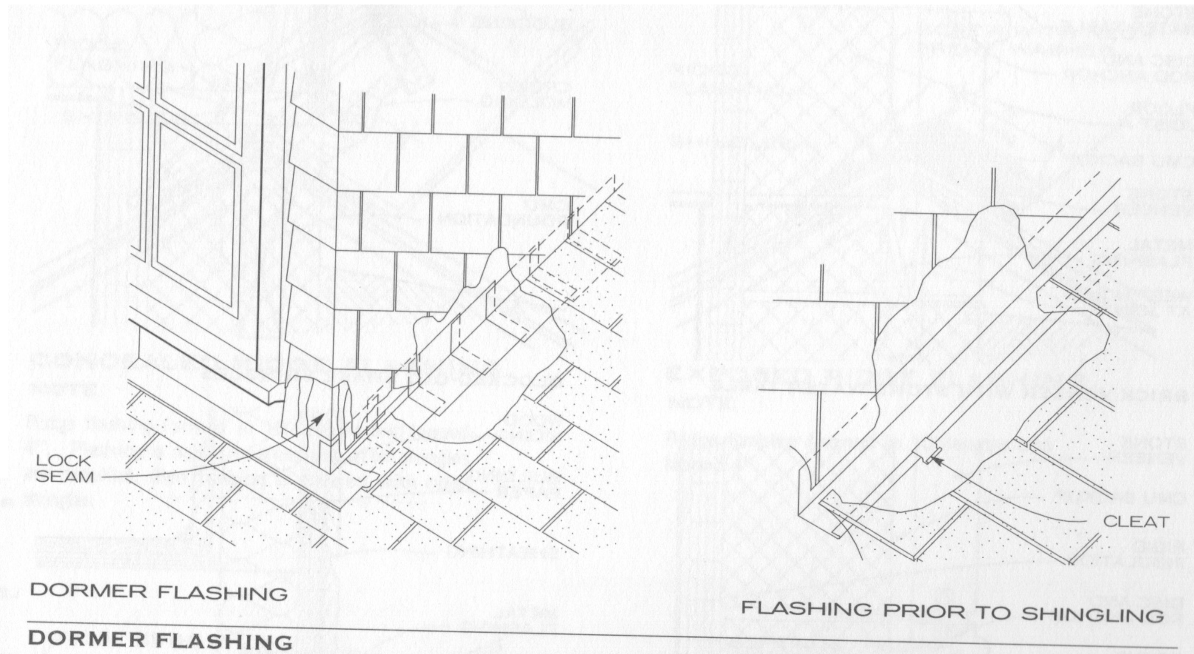


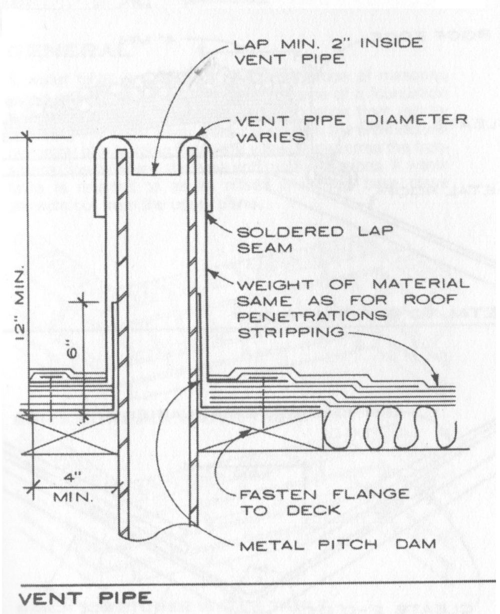
AIA provides good standard graphic details for flashing in residential construction

- Make sure your architect follows these!

Flashing details: roofs

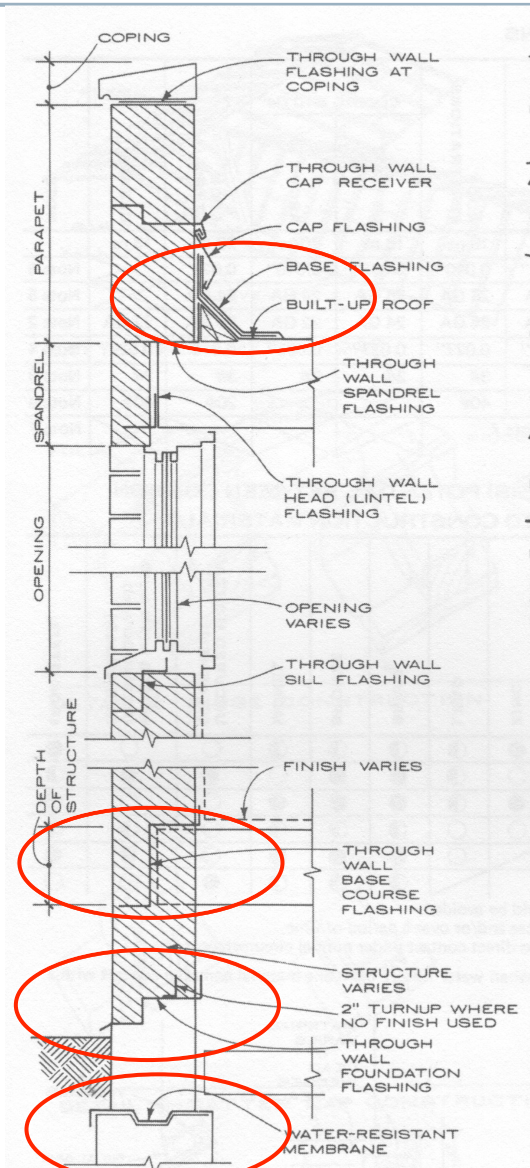




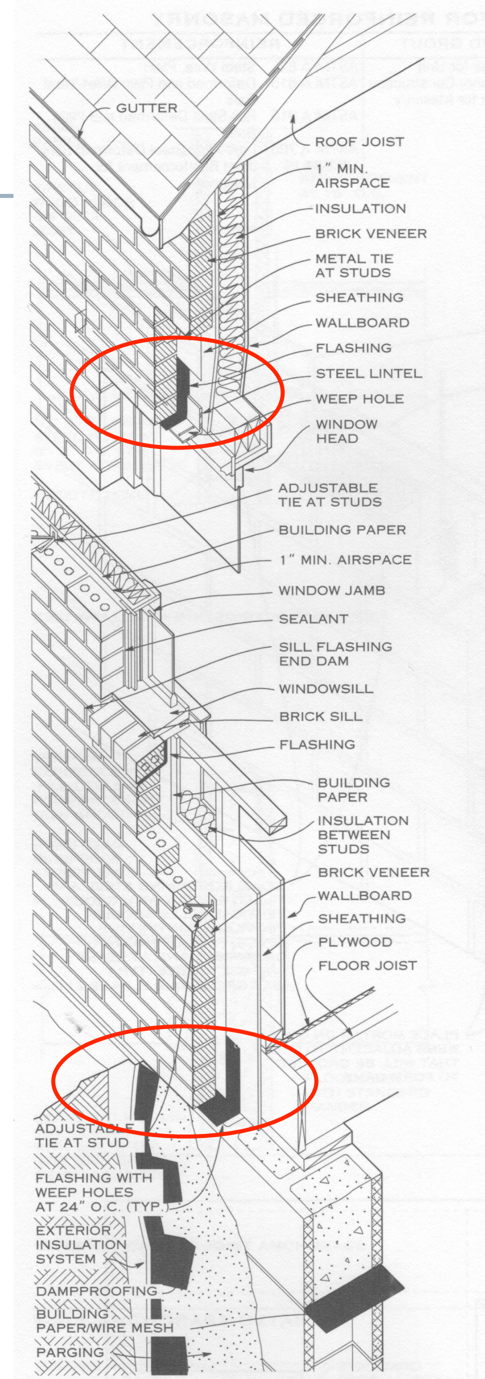


- Install prior to shingles
- Overlap in the correct direction for drainage

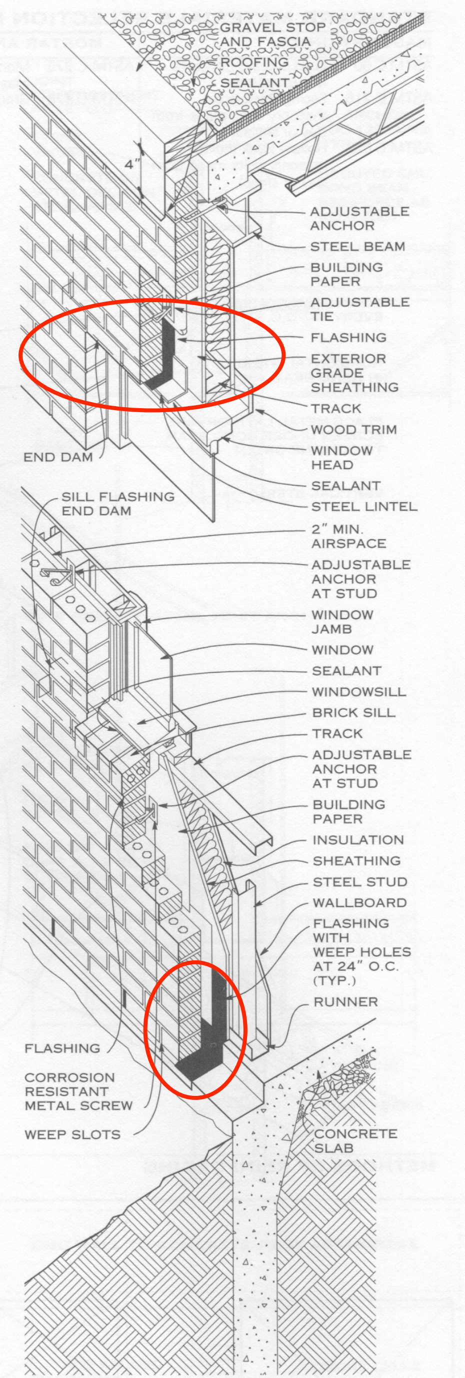
Flashing details: walls



TYPICAL THROUGH WALL FLASHING AT WALL SECTION



BRICK VENEER ON WOOD STUD BACKUP



BRICK VENEER ON STEEL STUD BACKUP

Flashing details: materials

Some flashing materials are more compatible with your building materials than others

MINIMUM THICKNESS (GAUGES OR WEIGHT) FOR COMMON FLASHING CONDITIONS

MATERIALS \ CONDITIONS	BASE COURSE	WALL OPENINGS HEAD AND SILL	THROUGH WALL AND SPANDREL	CAP AND BASE FLASHING	VERTICAL AND HORIZONTAL SURFACES	ROOF EDGE RIDGES AND HIPS	CRICKETS VALLEY OR GUTTER	CHIMNEY PAN	LEDGE FLASHING	ROOF PENETRATIONS	COPING WIDTH: UP TO 12"	COPING WIDTH: ABOVE 12"	EDGE STRIPS	CLEATS	NOTE
Copper	10 oz	10 oz	10 oz	16 oz	16 oz	16 oz	16 oz	16 oz	16 oz	16 oz	16 oz	20 oz	20 oz	16 oz	
Aluminum	0.019"	0.019"	0.019"	0.019"	0.019"	0.019"	0.019"	0.019"	0.019"	0.040"	0.032"	0.040"	0.024"	X	Note 6
Stainless steel	30 GA	30 GA	30 GA	26 GA	30 GA	26 GA	26 GA	30 GA	26 GA	26 GA	26 GA	24 GA	24 GA	X	Note 5
Galvanized steel	26 GA	26 GA	26 GA	26 GA	26 GA	24 GA	24 GA	26 GA	24 GA	24 GA	24 GA	22 GA	26 GA	22 GA	Note 2
Zinc alloy	0.027"	0.027"	0.027"	0.027"	0.027"	0.027"	0.027"	0.027"	0.027"	0.027"	0.027"	0.032"	0.040"	0.027"	Note 4
Lead	3#	2½#	2½#	2½#	3#	3#	3#	3#	3#	3#	3#	3#	3#	3#	Note 3
Painted terne	40#	40#	40#	20#	40#	20#	40#	20#	40#	40#	X	X	20#	40#	Note 8
elastomeric sheet; fabric-coated metal	See Note 7			X	X	X	X	X	See Note 7		X	X	X	X	Note 7

GENERAL NOTES

1. All sizes and weights of material given in chart are minimum. Actual conditions may require greater strength.
2. All galvanized steel must be painted.
3. With lead flashing use 16 oz copper cleats. If any part is exposed, use 3# lead cleats.
4. Coat zinc with asphaltum paint when in contact with redwood or cedar. High acid content (in these woods only) develops stains.
5. Type 302 stainless steel is an all purpose flashing type.
6. Use only aluminum manufactured for the purpose of flashing.
7. See manufacturer's literature for use and types of flashing.
8. In general, cleats will be of the same material as flashing, but heavier weight or thicker gauge.
9. In selecting metal flashing, precaution must be taken not to place flashing in direct contact with dissimilar metals that cause electrolysis.
10. Spaces marked [X] in the table are uses not recommended for that material.

GALVANIC CORROSION (ELECTROLYSIS) POTENTIAL BETWEEN COMMON FLASHING MATERIALS AND SELECTED CONSTRUCTION MATERIALS

FLASHING MATERIALS \ CONSTRUCTION MATERIALS	COPPER	ALUMINUM	STAINLESS STEEL	GALVANIZED STEEL	ZINC	LEAD	BRASS	BRONZE	MONEL	UNCURED MORTAR OR CEMENT	WOODS WITH ACID (REDWOOD AND RED CEDAR)	IRON/STEEL
Copper		●	●	◑	●	◑	◑	◑	◑	○	○	●
Aluminum			○	○	○	◑	●	●	○	●	●	◑
Stainless steel				◑	●	◑	●	●	●	○	○	◑
Galvanized steel					○	○	◑	◑	◑	○	◑	◑
Zinc alloy						○	●	●	●	○	●	●
Lead							◑	◑	◑	●	○	○

● Galvanic action will occur, hence direct contact should be avoided.
◑ Galvanic action may occur under certain circumstances and/or over a period of time.
○ Galvanic action is insignificant, metals may come into direct contact under normal circumstances.

GENERAL NOTE: Galvanic corrosion is apt to occur when water runoff from one material comes in contact with a potentially reactive material.

Flashing: An application of water barriers

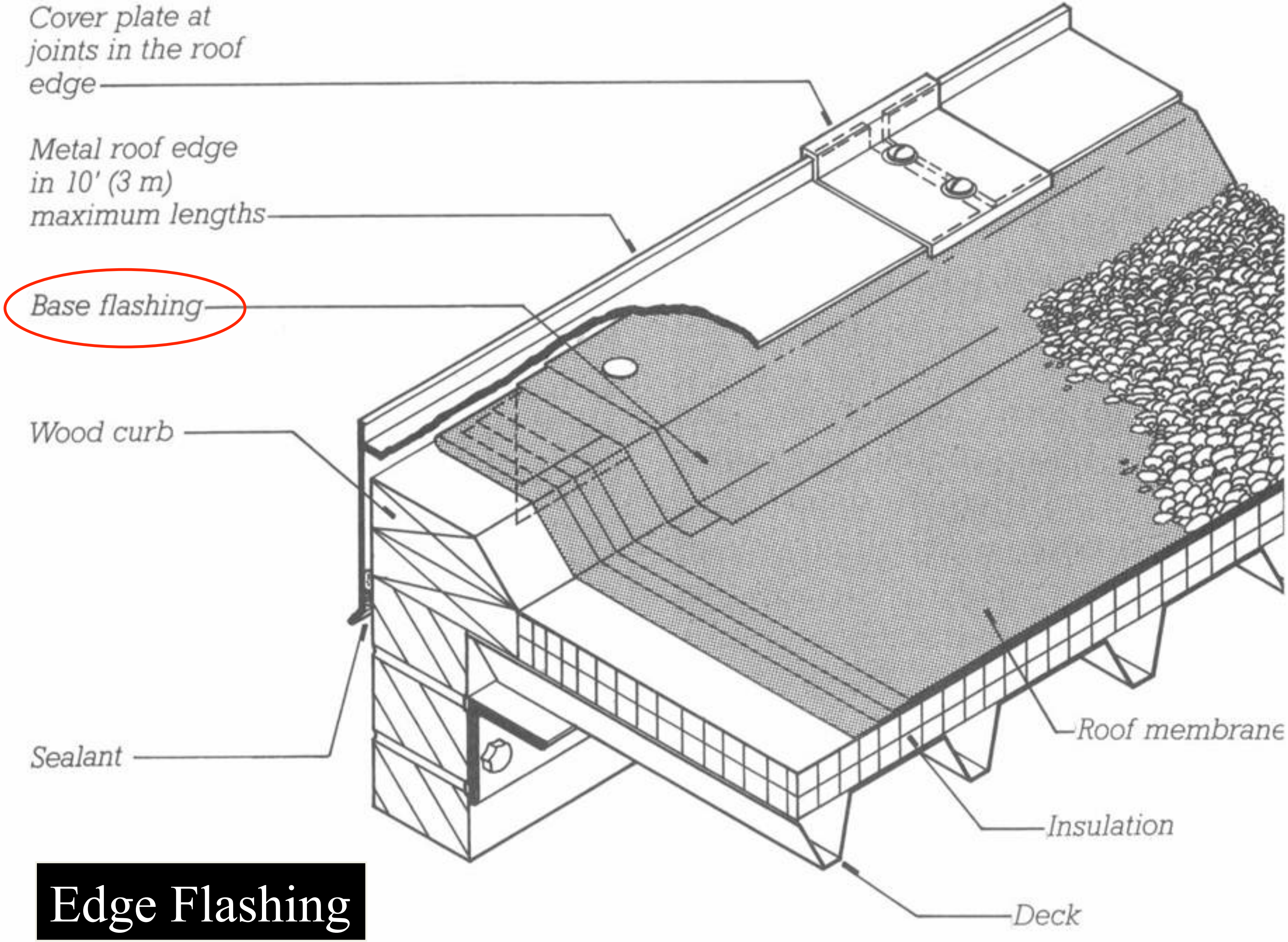
- A **water barrier** is a material that does not transport condensed water
  - It may allow air diffusion or vapor diffusion
  - It may not be completely sealed which allows direct and indirect air infiltration
- It is placed on the outside of a building to keep rainwater off the building wall components
- A water barrier need not be an air barrier or a vapor barrier
  - Shingles and building felt are good water barriers but poor air and vapor barriers

Flashing and joints on roofs

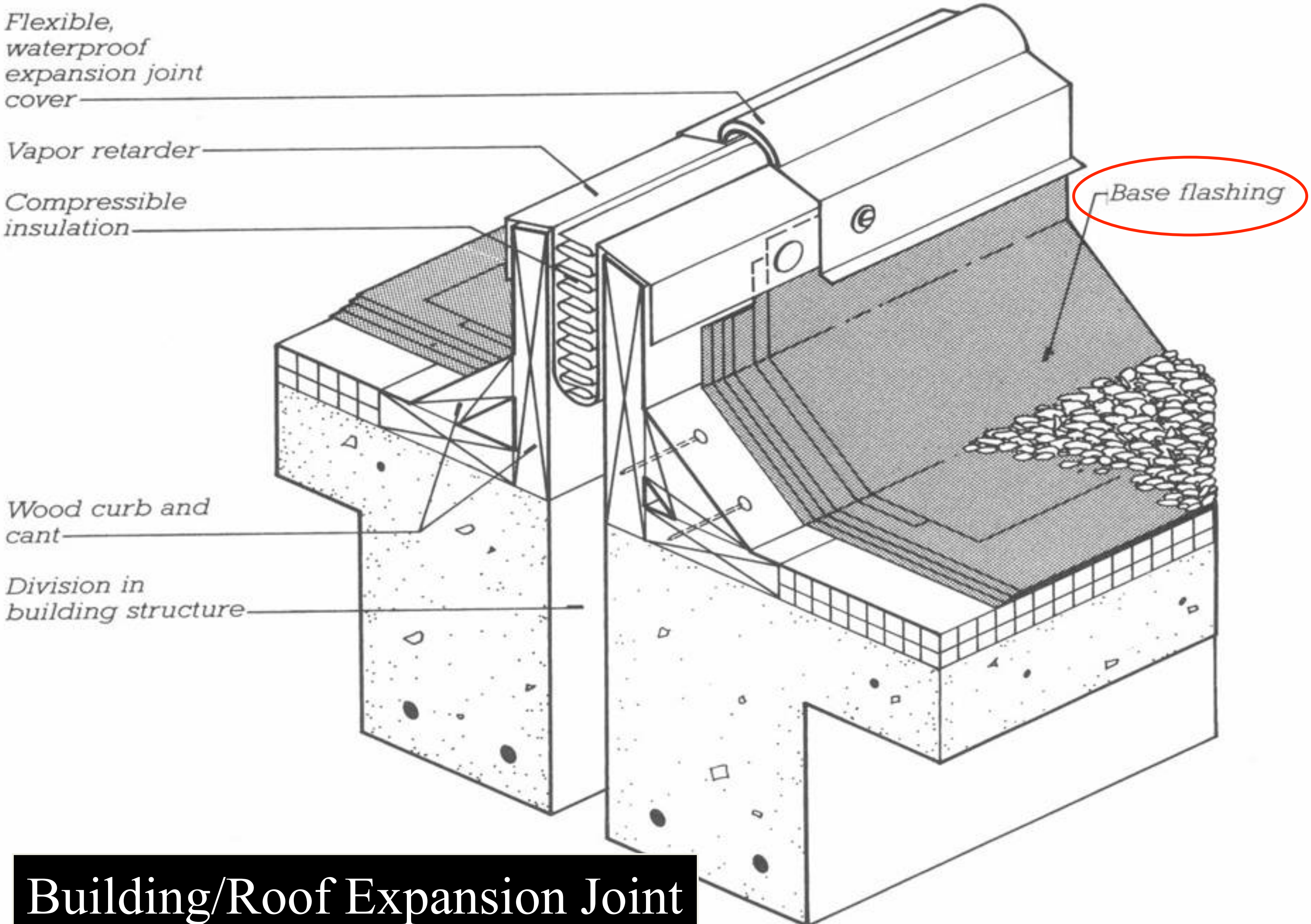
- Flashing needed to maintain seals
  - Building edges and parapets
  - Expansion joints
  - Over top of cavity walls
  - Around drains
  - Around vents

- Usually metals or plastics over which membrane is fastened

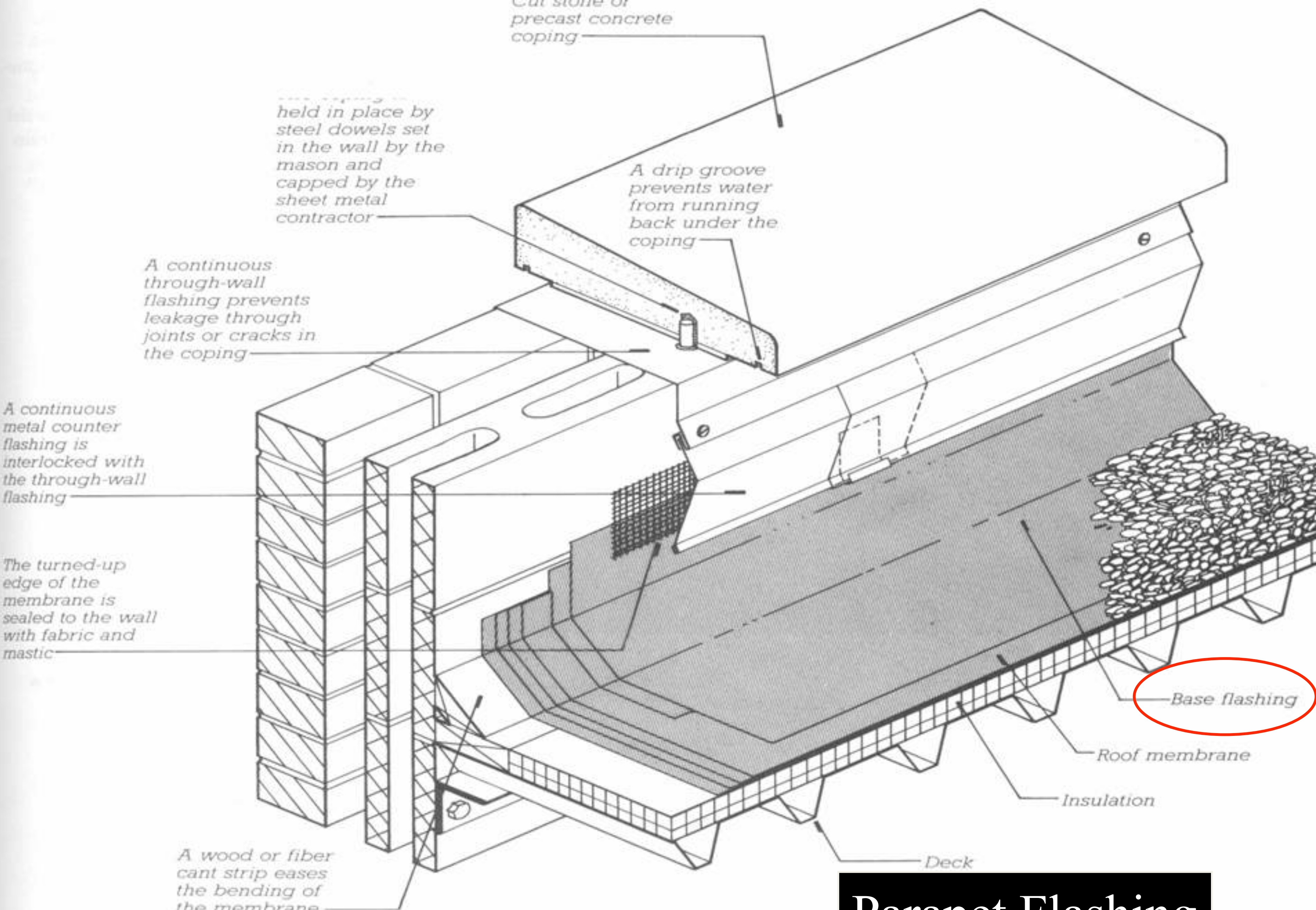
- Proper flashing is **absolutely essential** to avoid roof leaks



Edge Flashing



Building/Roof Expansion Joint



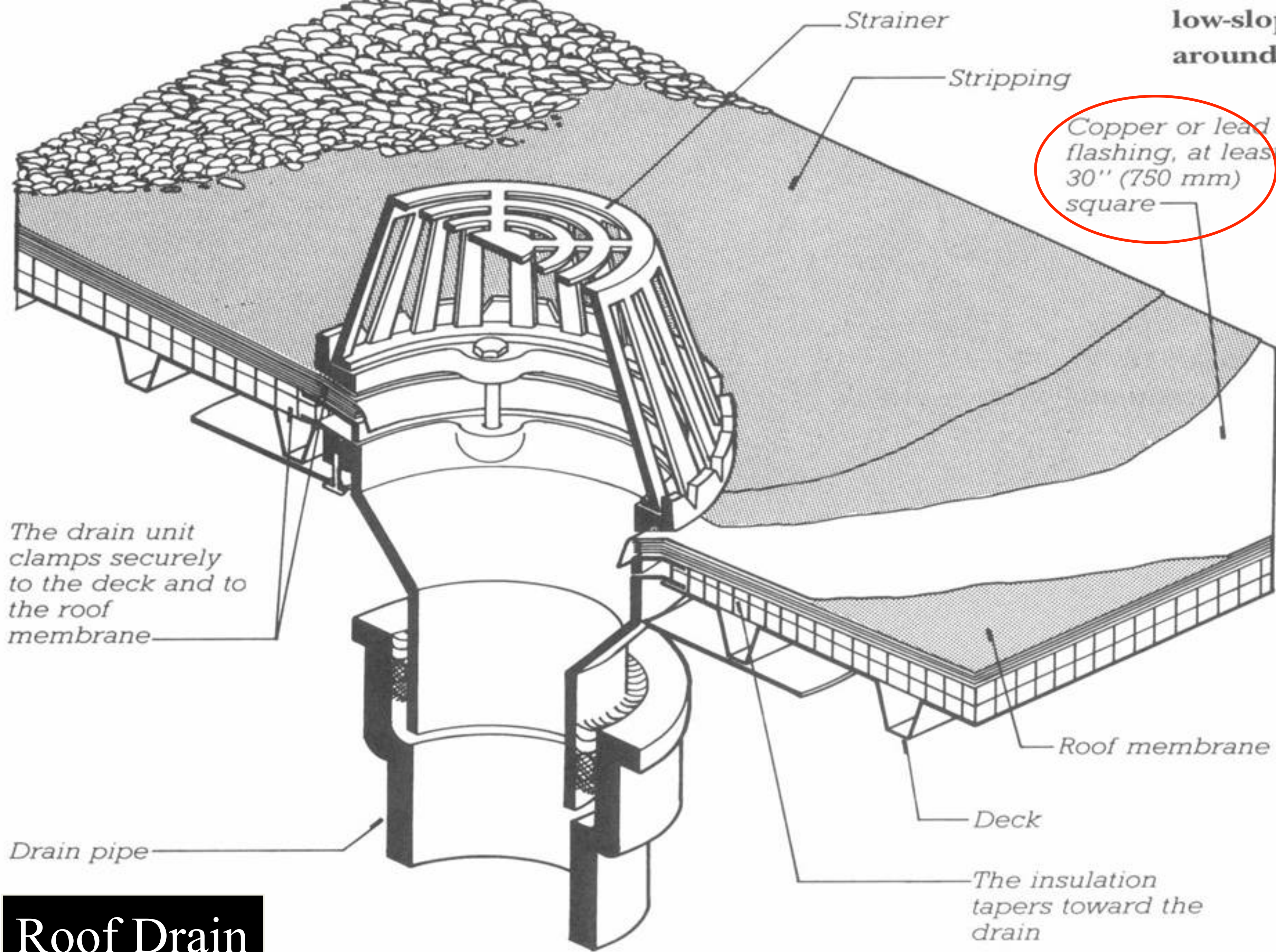
Parapet Flashing

FIGURE 16.30
A conventional parapet design.

Roof drainage

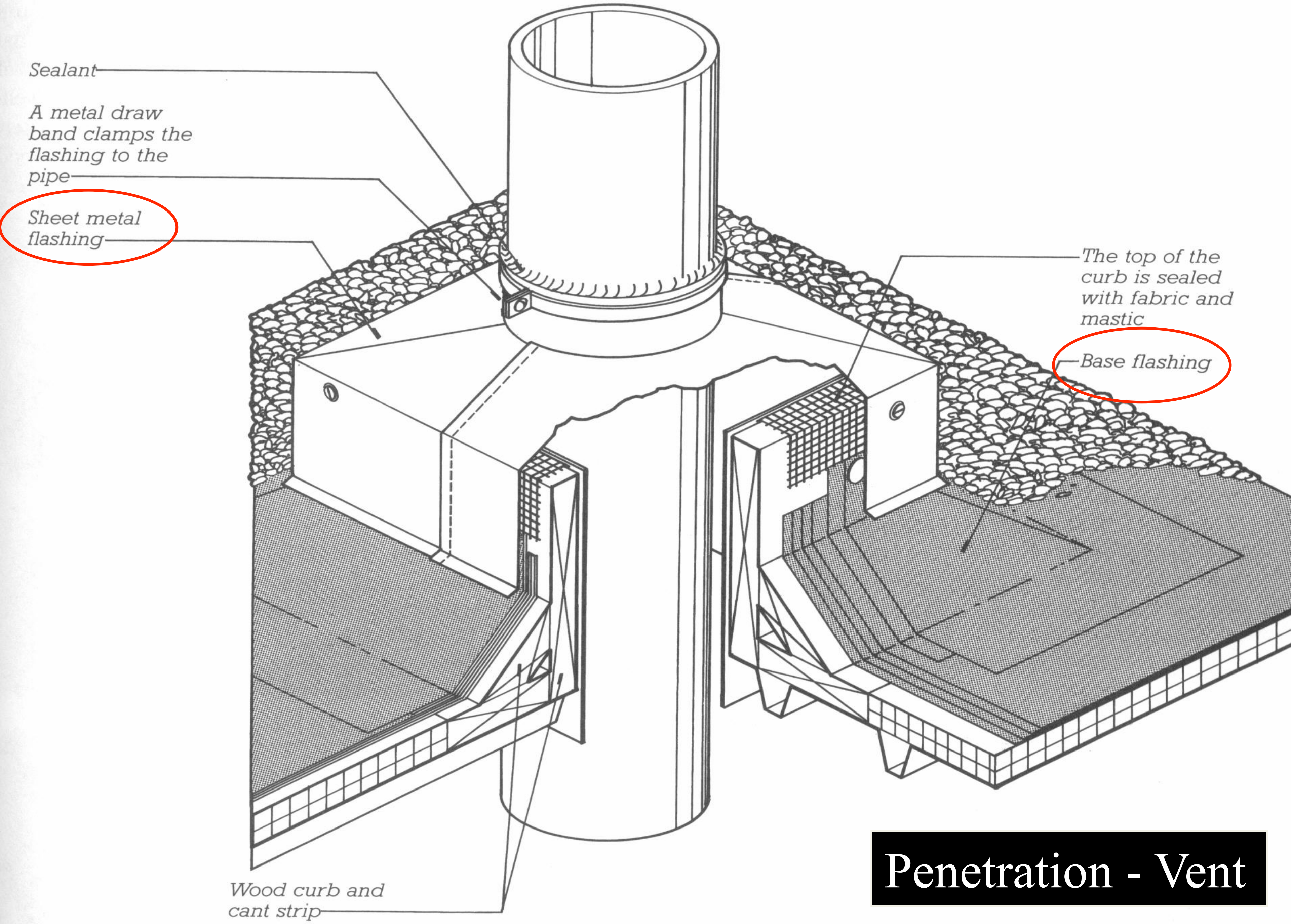
- Drains need to be at low points of roofs to avoid water ponding
  - Drains near columns are at high points since there is no deflection

- Smaller and closer spaced drains preferred to larger but fewer



low-slo
around

Roof Drain

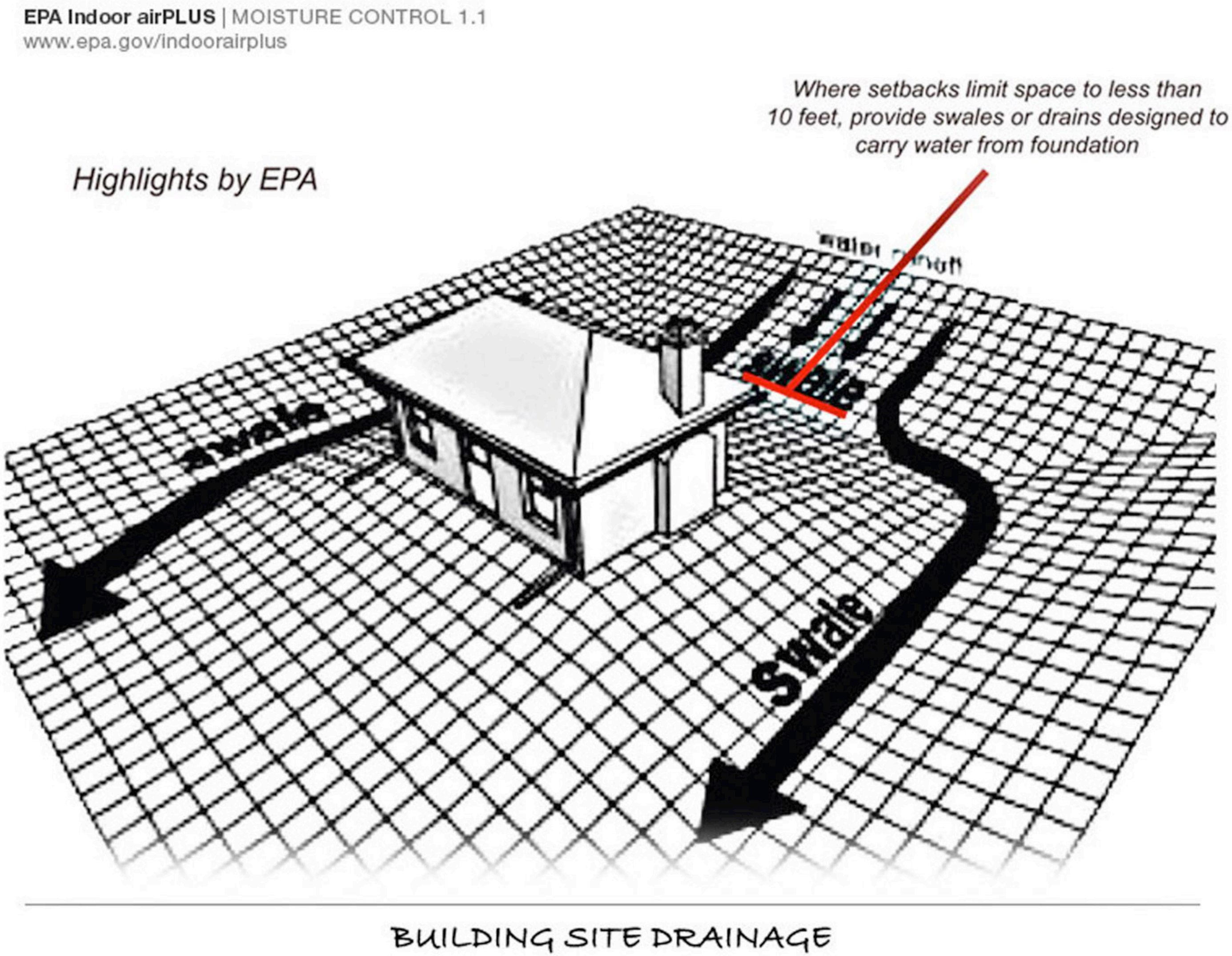


Penetration - Vent

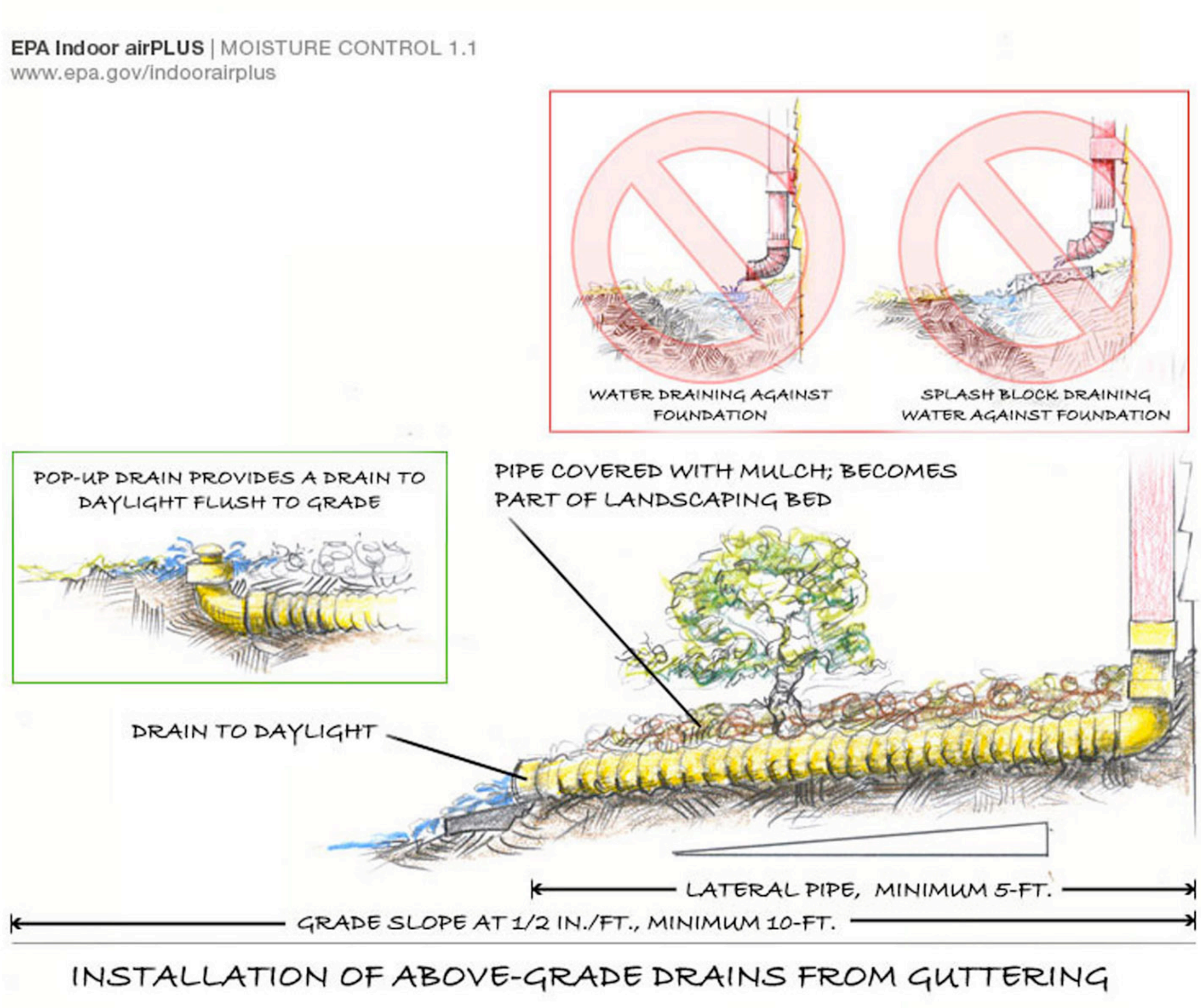
DEALING WITH WATER

Realistically w/ drawings

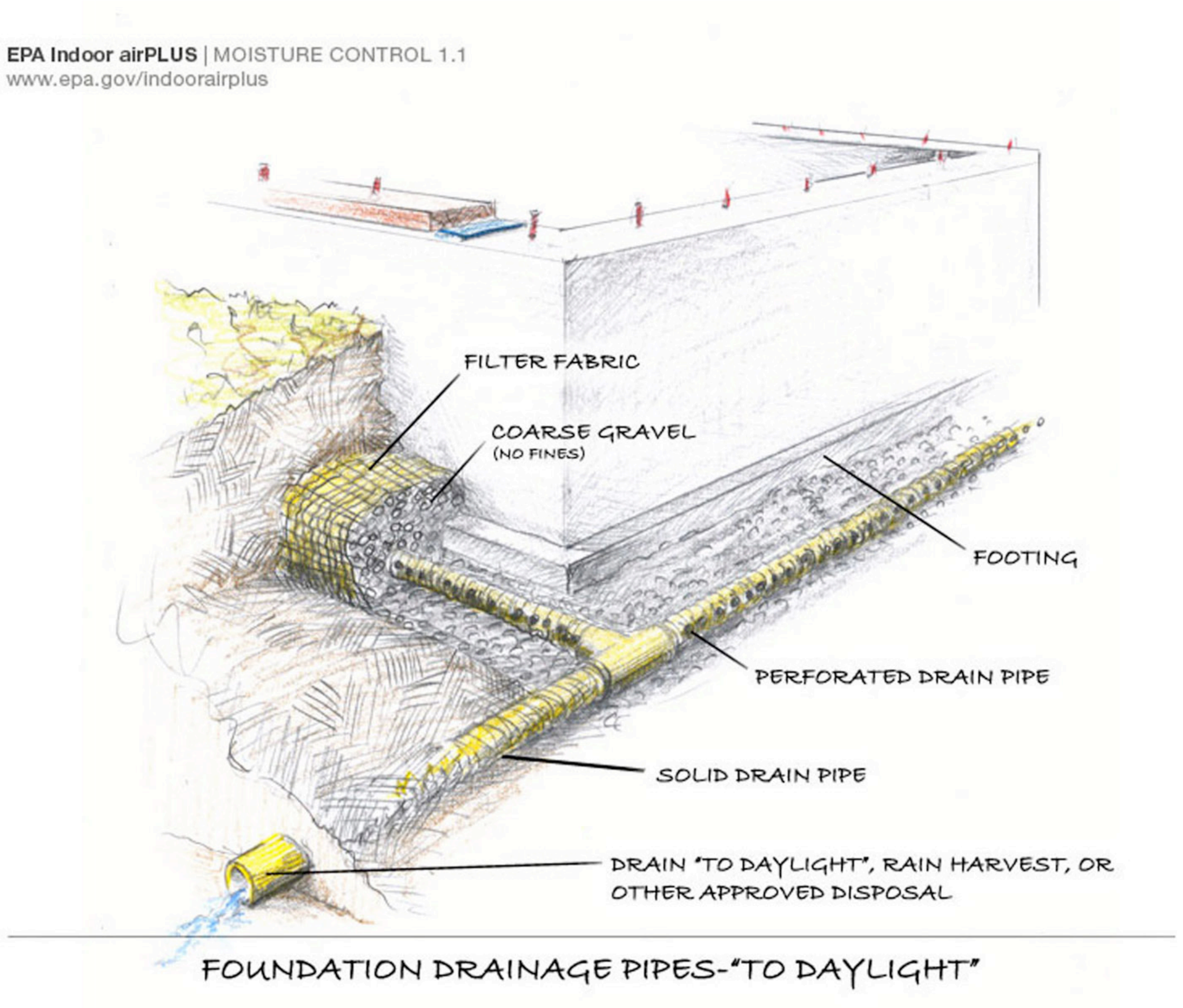
Site drainage



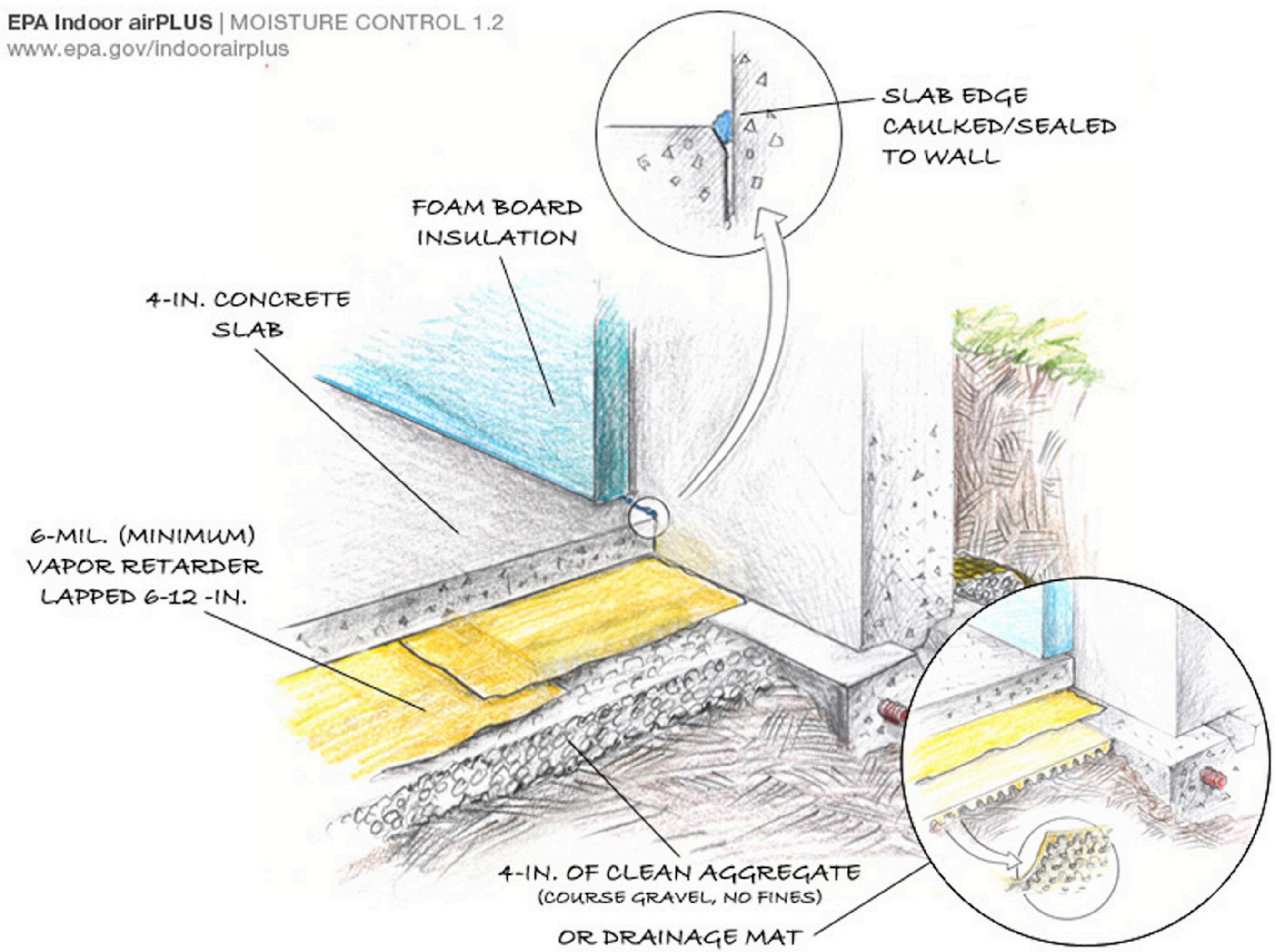
Site drainage



Good foundation design

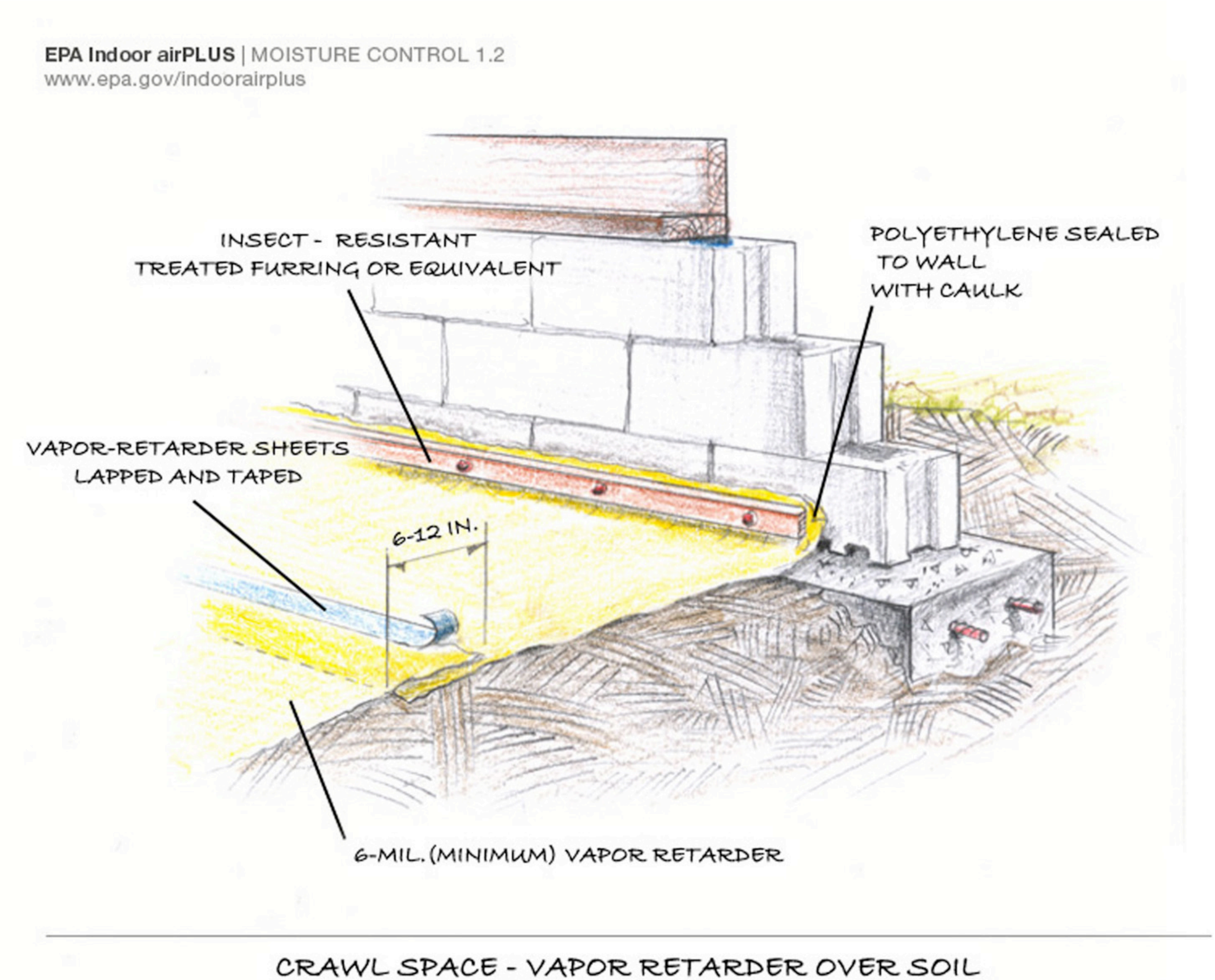


Basement slab with capillary break

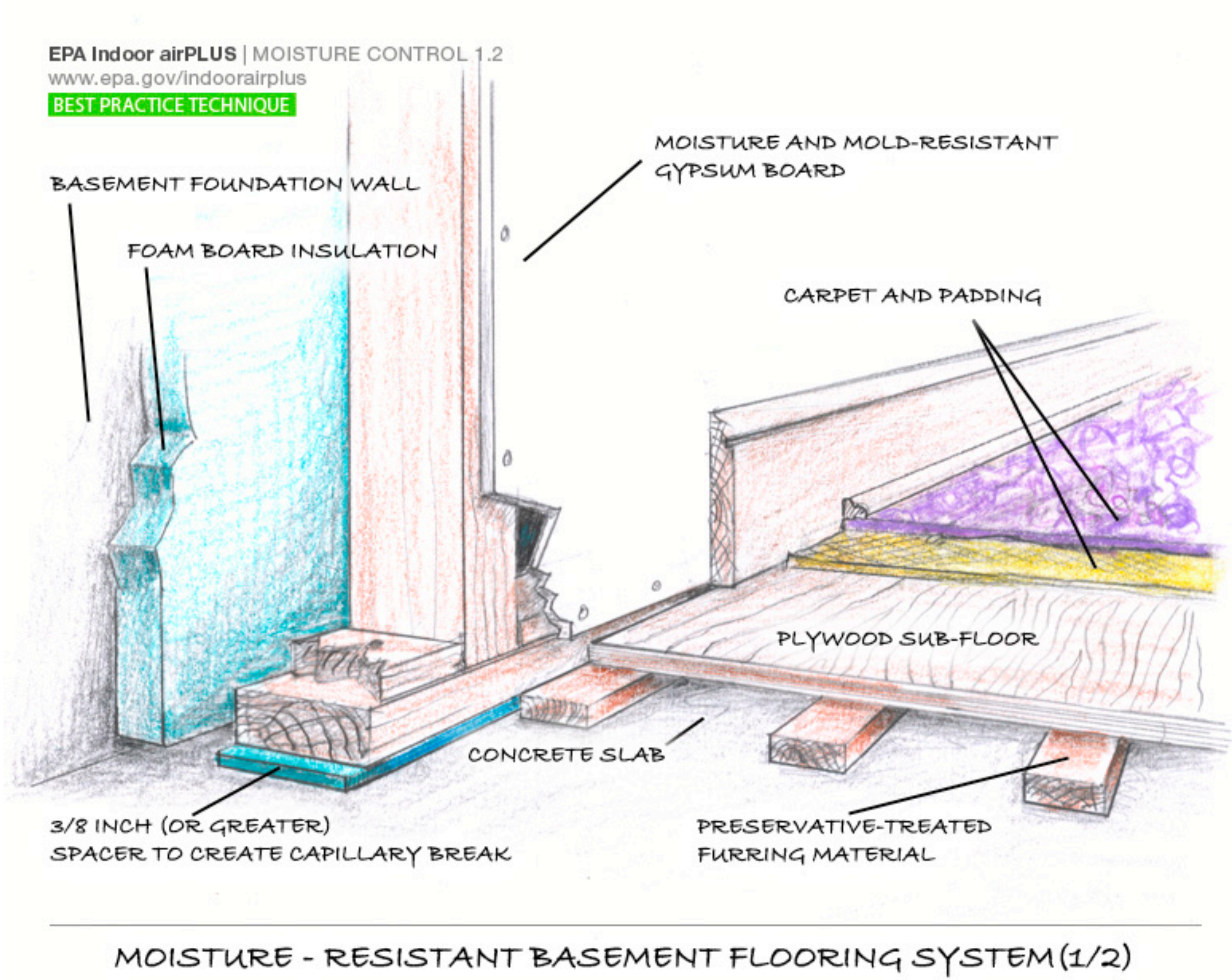


BASEMENT SLAB W/ CAPILLARY BREAK - GRAVEL AND GEOTEXTILE MAT (INSET)

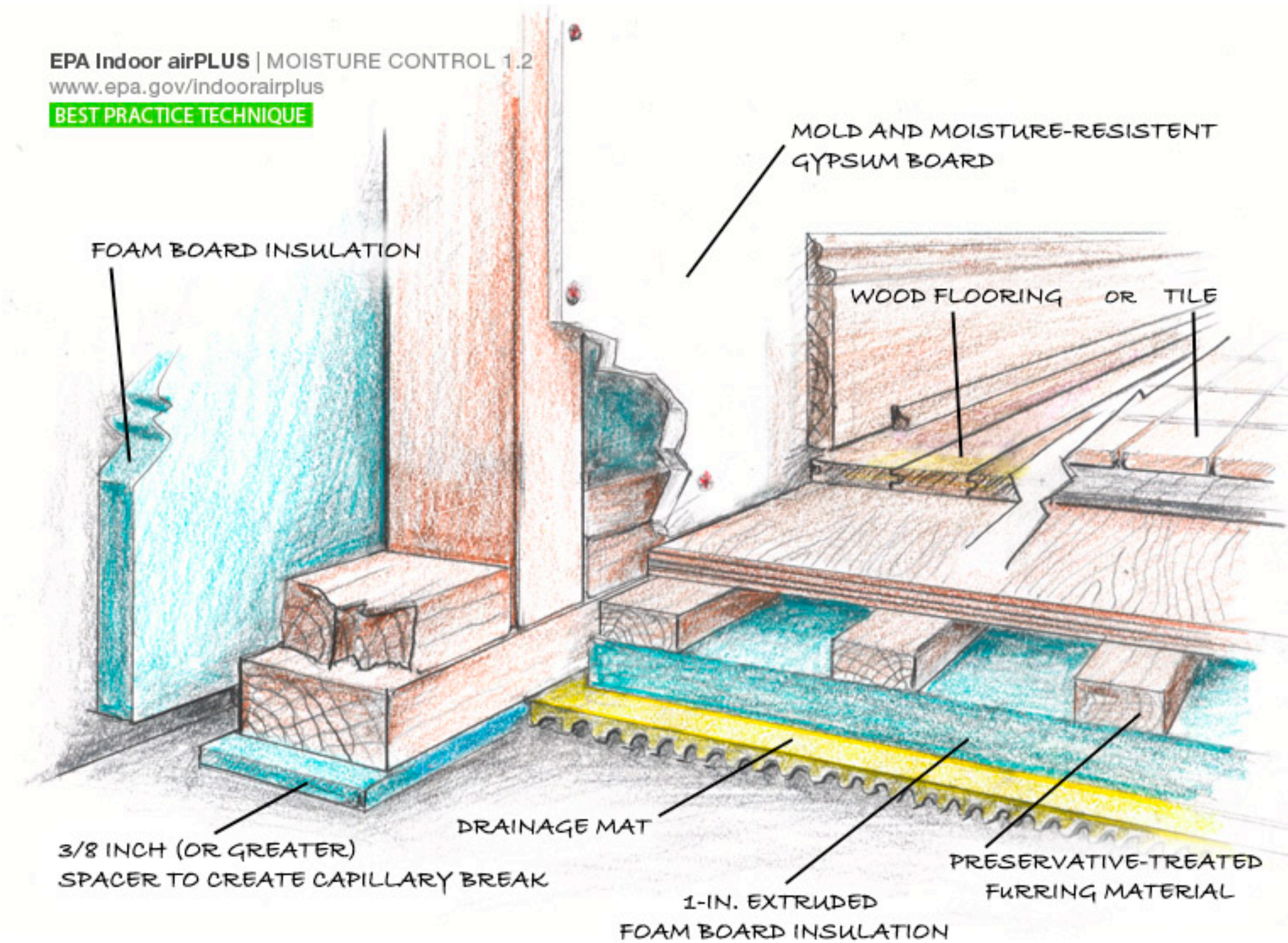
Crawl spaces and vapor retarders



Moisture resistant basement floors

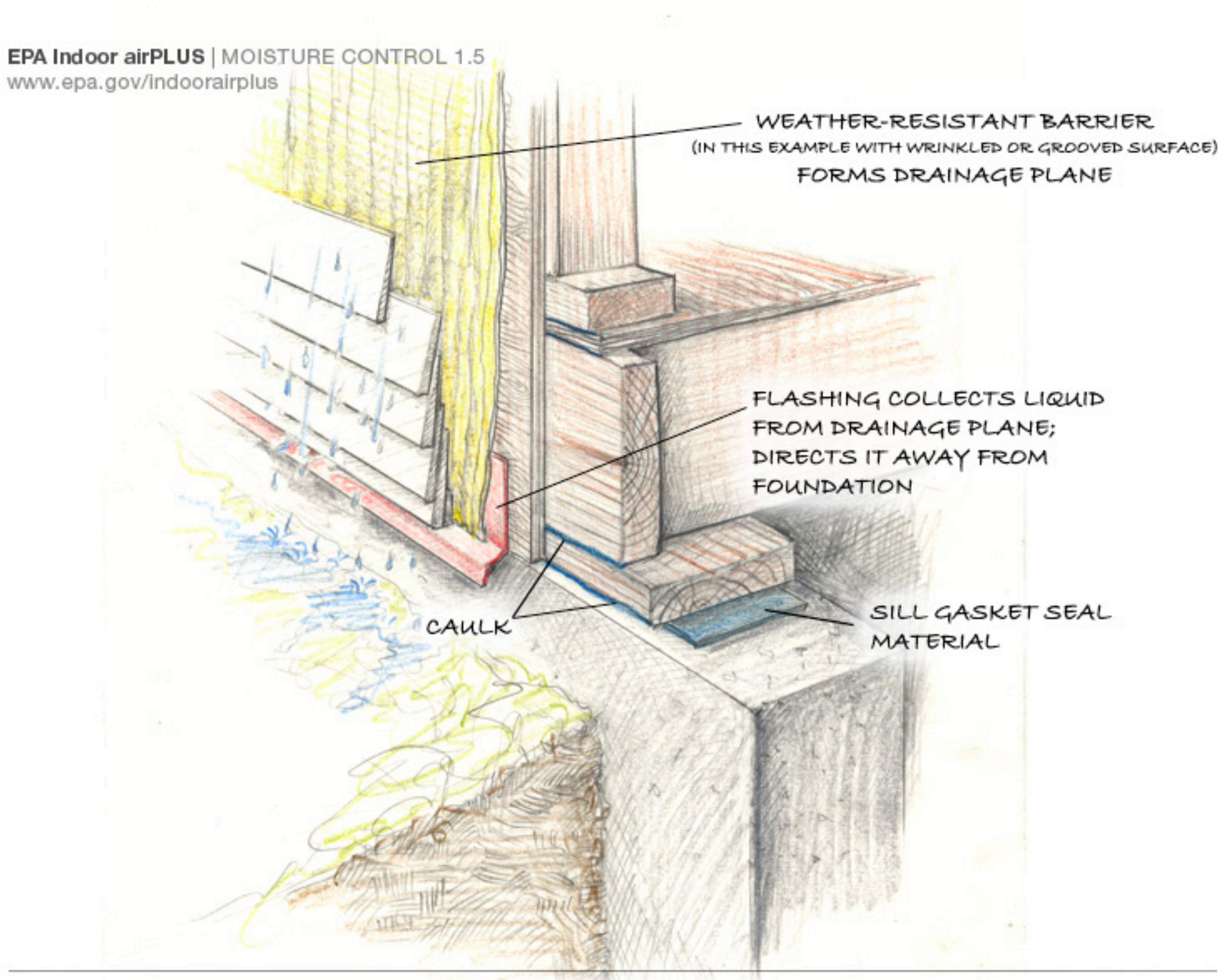


Moisture resistant basement floors



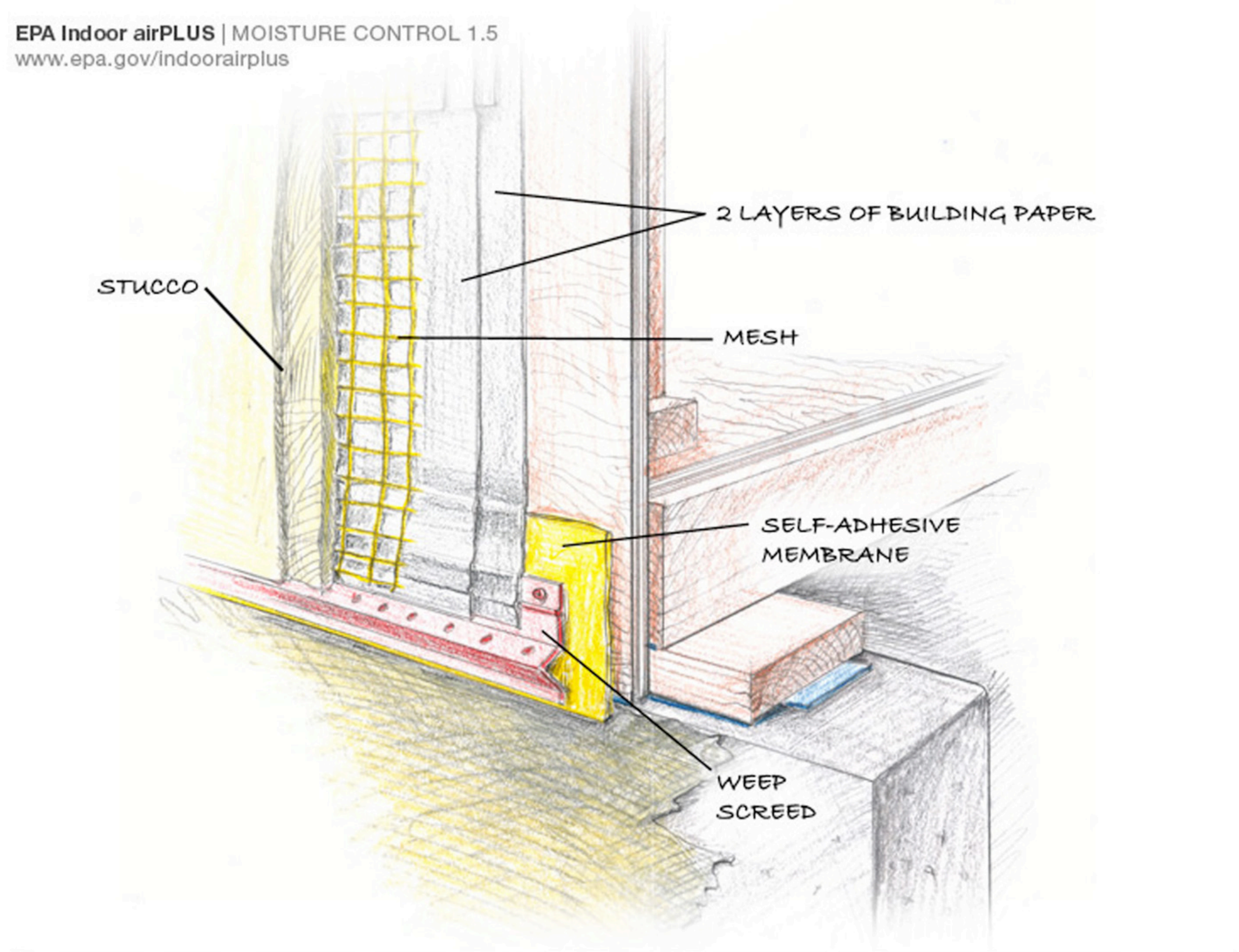
MOISTURE RESISTANT BASEMENT FLOORING SYSTEM (2/2)

Drainage planes and drip edges: Siding



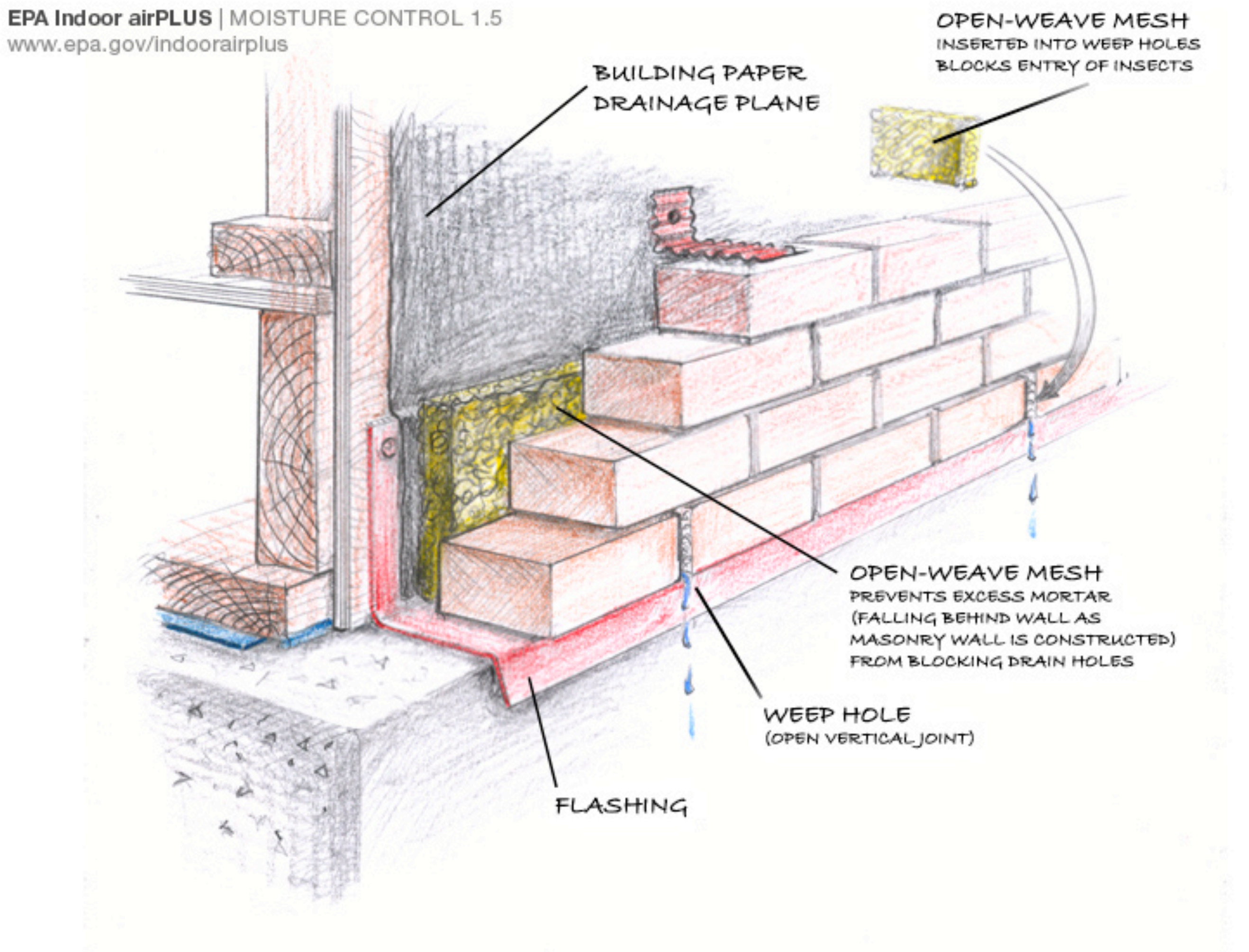
DRAINAGE PLANE AND DRIP-EDGE FLASHING WITH WOOD HORIZONTAL SIDING

Drainage planes and drip edges: Stucco



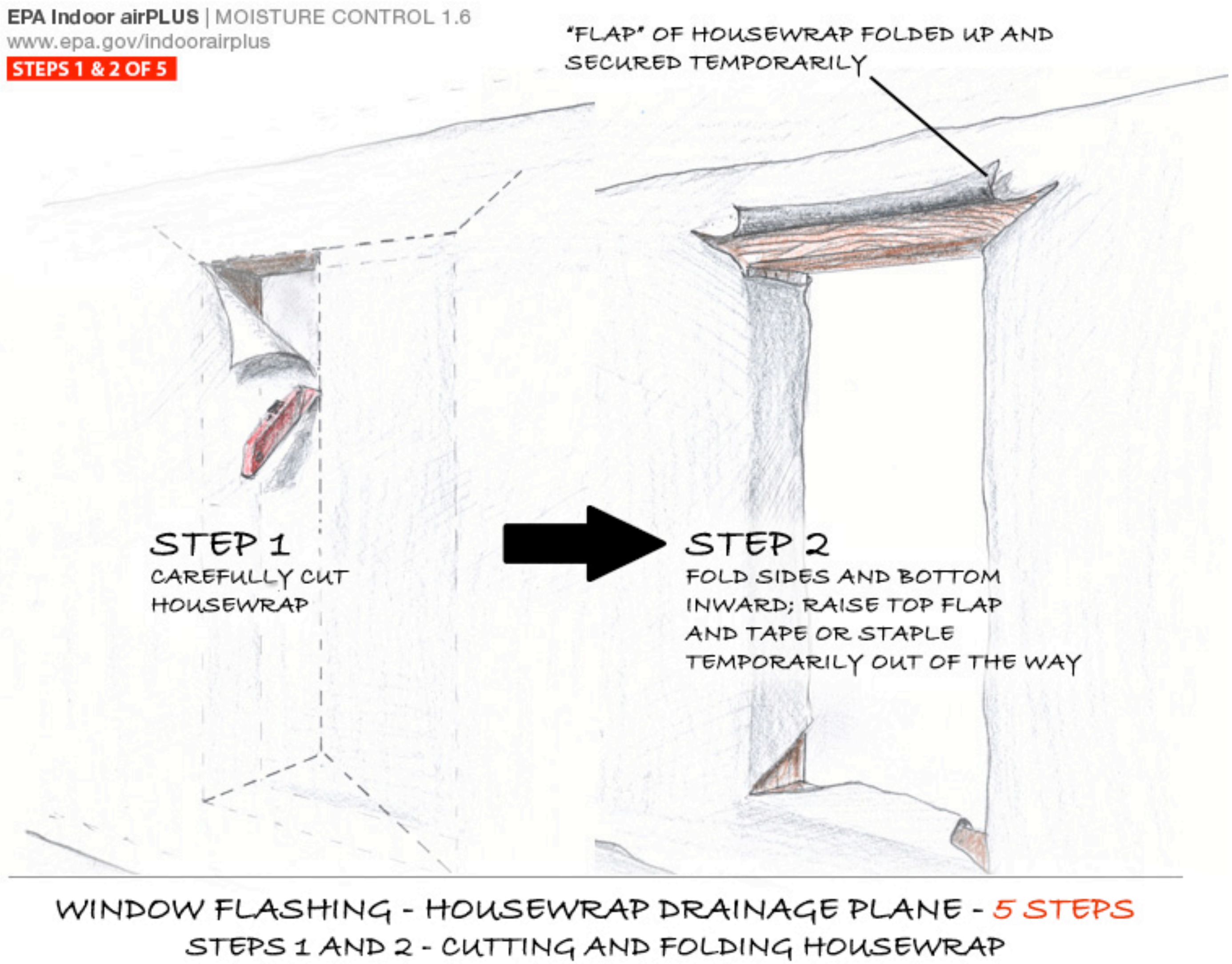
TWO LAYERS OF BUILDING PAPER FORM DRAINAGE PLANE BENEATH STUCCO

Drainage planes and drip edges: Masonry



MASONRY WALL WITH DRAINAGE PLANE, FLASHING, AND WEEP HOLES

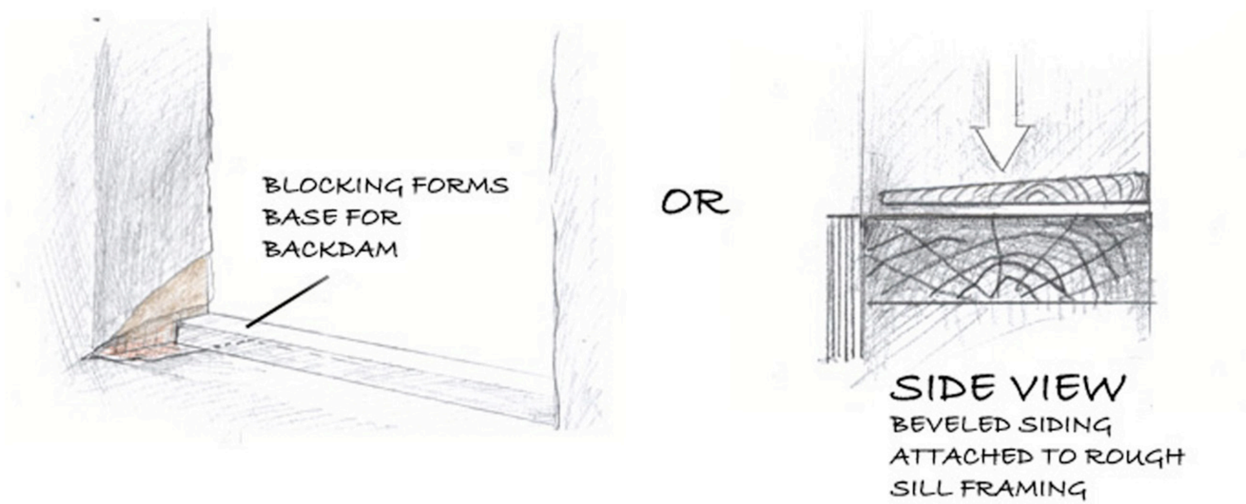
Window flashing: Housewrap



Window flashing: Housewrap + slope

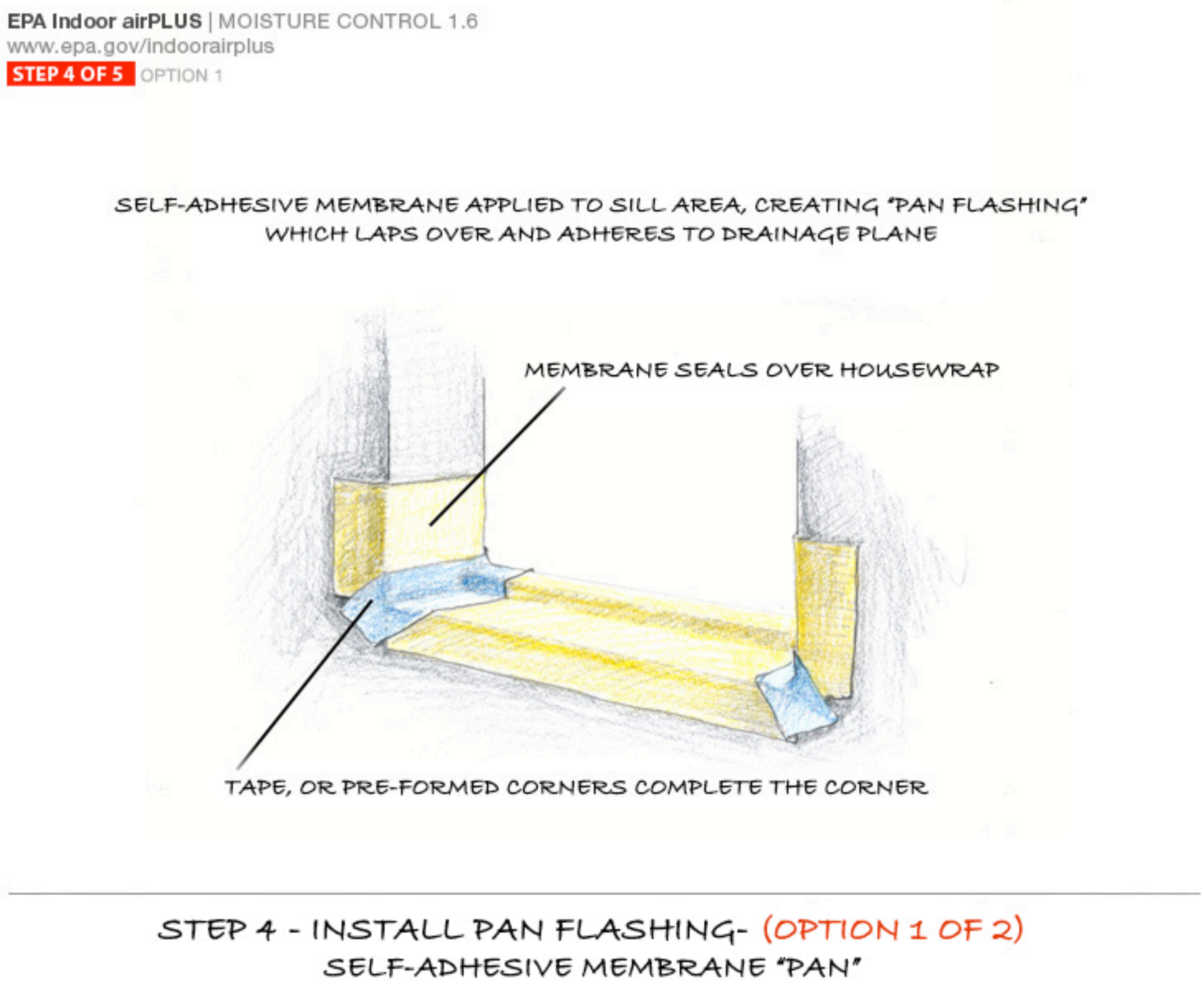
EPA Indoor airPLUS | MOISTURE CONTROL 1.6
www.epa.gov/indoorairplus
STEP 3 OF 5

CREATE BACK-DAM OR SLOPE TO DIRECT ANY WATER THAT DRAINS TO THE SILL AREA OUTWARD AND ONTO THE DRAINAGE PLANE (HOUSEWRAP)



STEP 3 - CREATE BACK DAM OR SLOPE

Window flashing: Housewrap + pan flashing



Window flashing: Housewrap + flashing

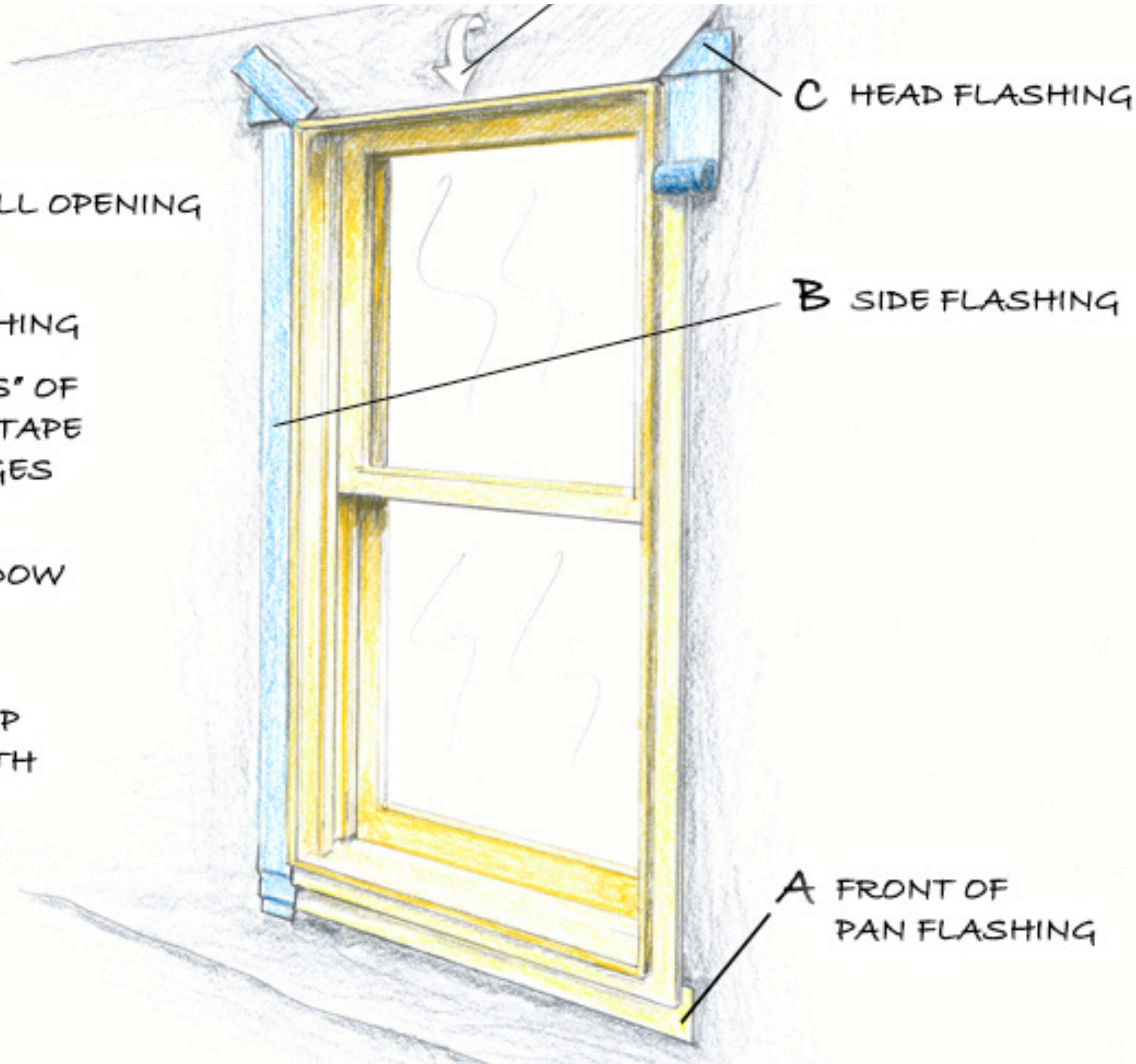
WINDOW PLACED IN WALL OPENING

A: WINDOW INSTALLED, RESTING ON PAN FLASHING

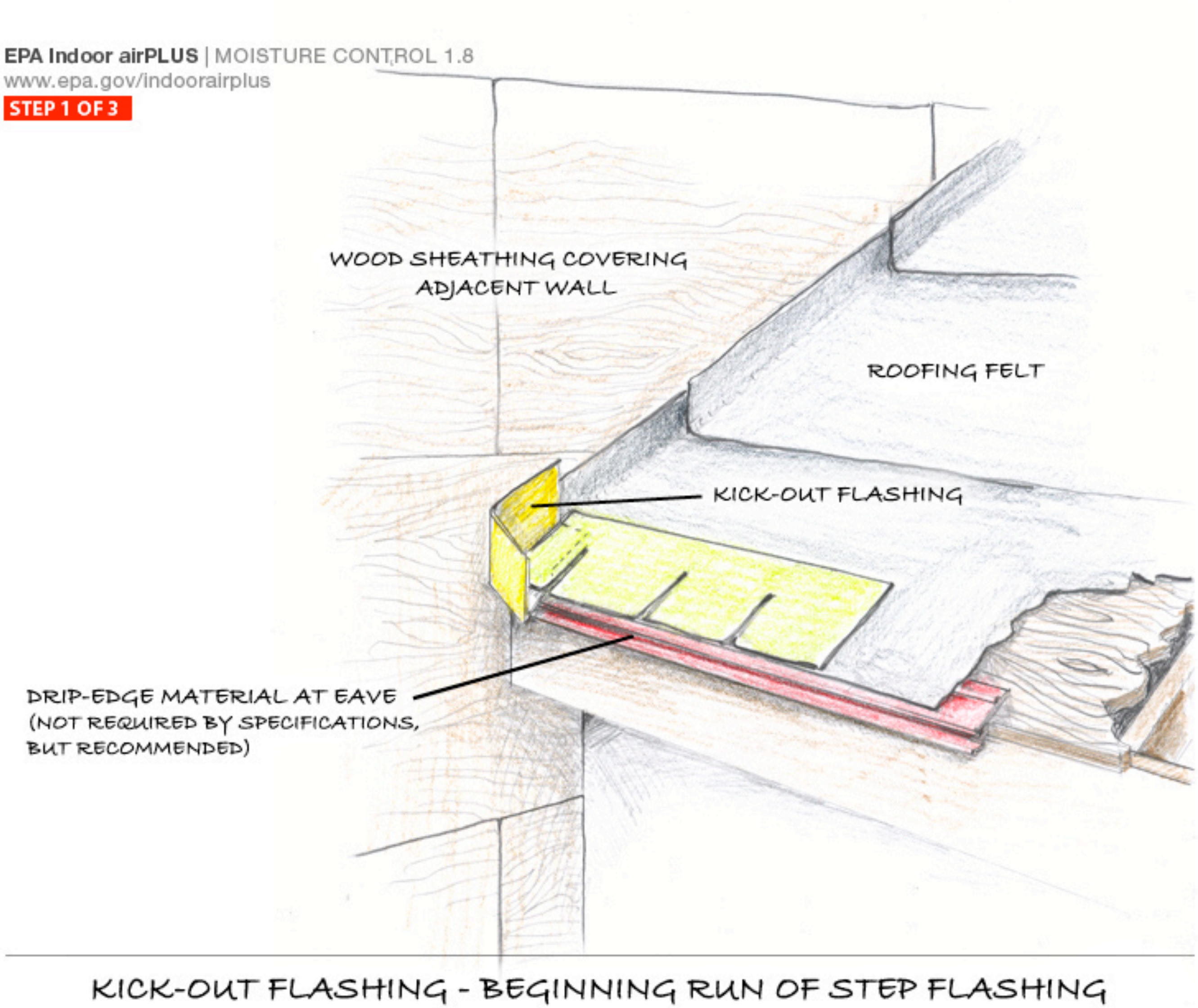
B: VERTICAL "SIDE-LEGS" OF MEMBRANE FLASHING TAPE SEAL OVER SIDE FLANGES OF WINDOW UNIT

C: TAPE AT TOP OF WINDOW COVERS SIDE-LEGS

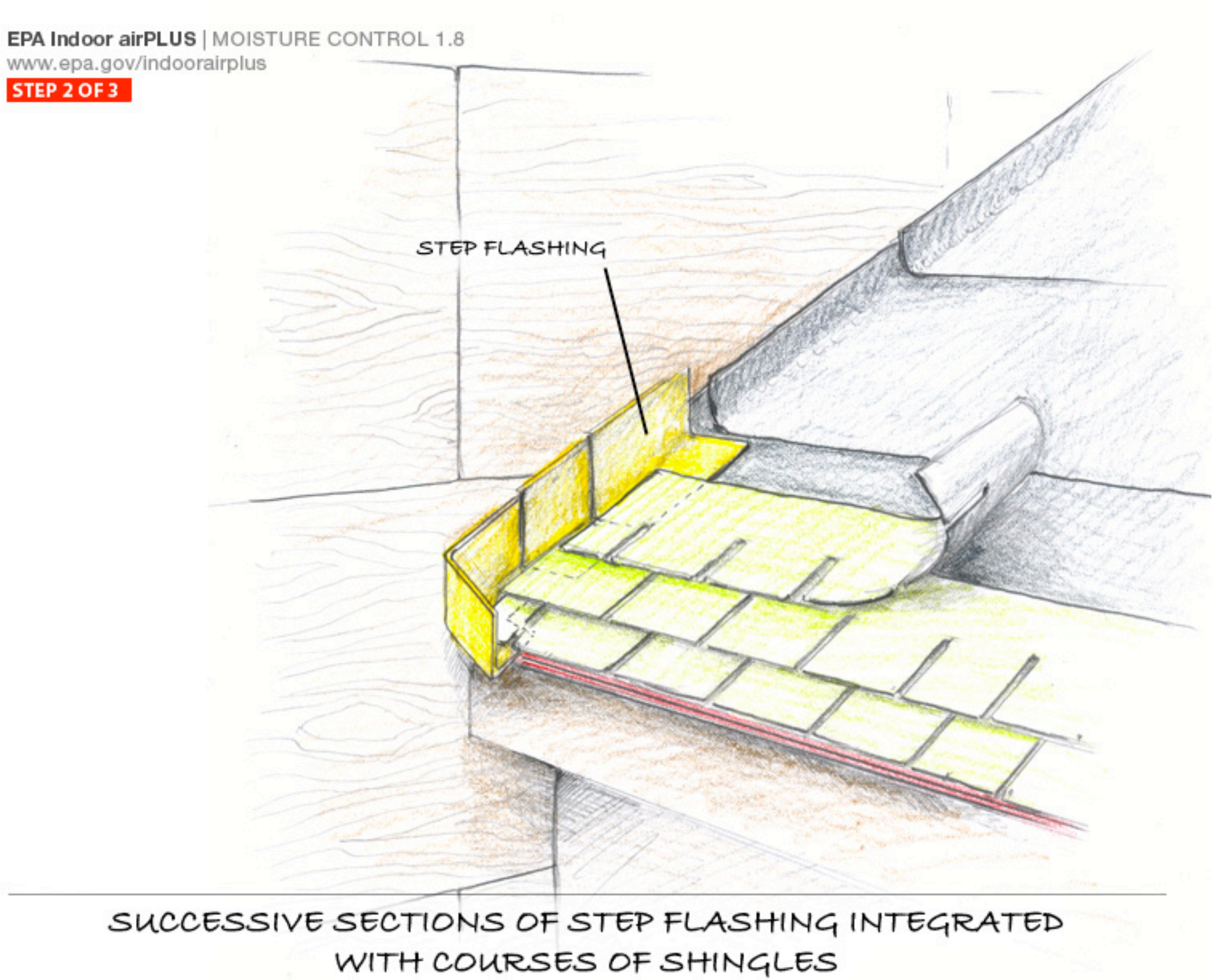
D: HOUSEWRAP "FLAP" LOWERED TO COVER TOP TAPE AND SECURED WITH TAPE AT CORNERS



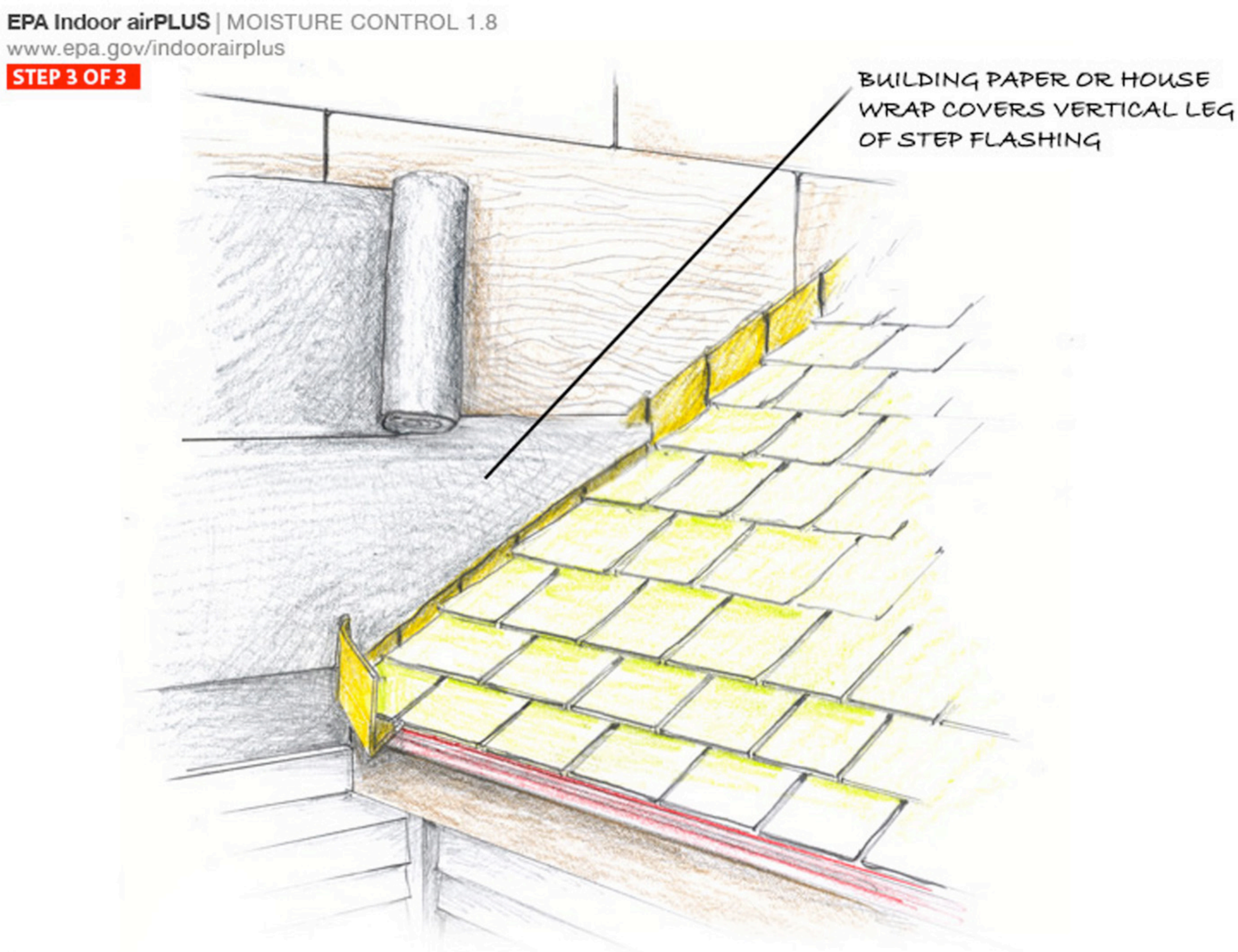
Roof flashing



Roof flashing

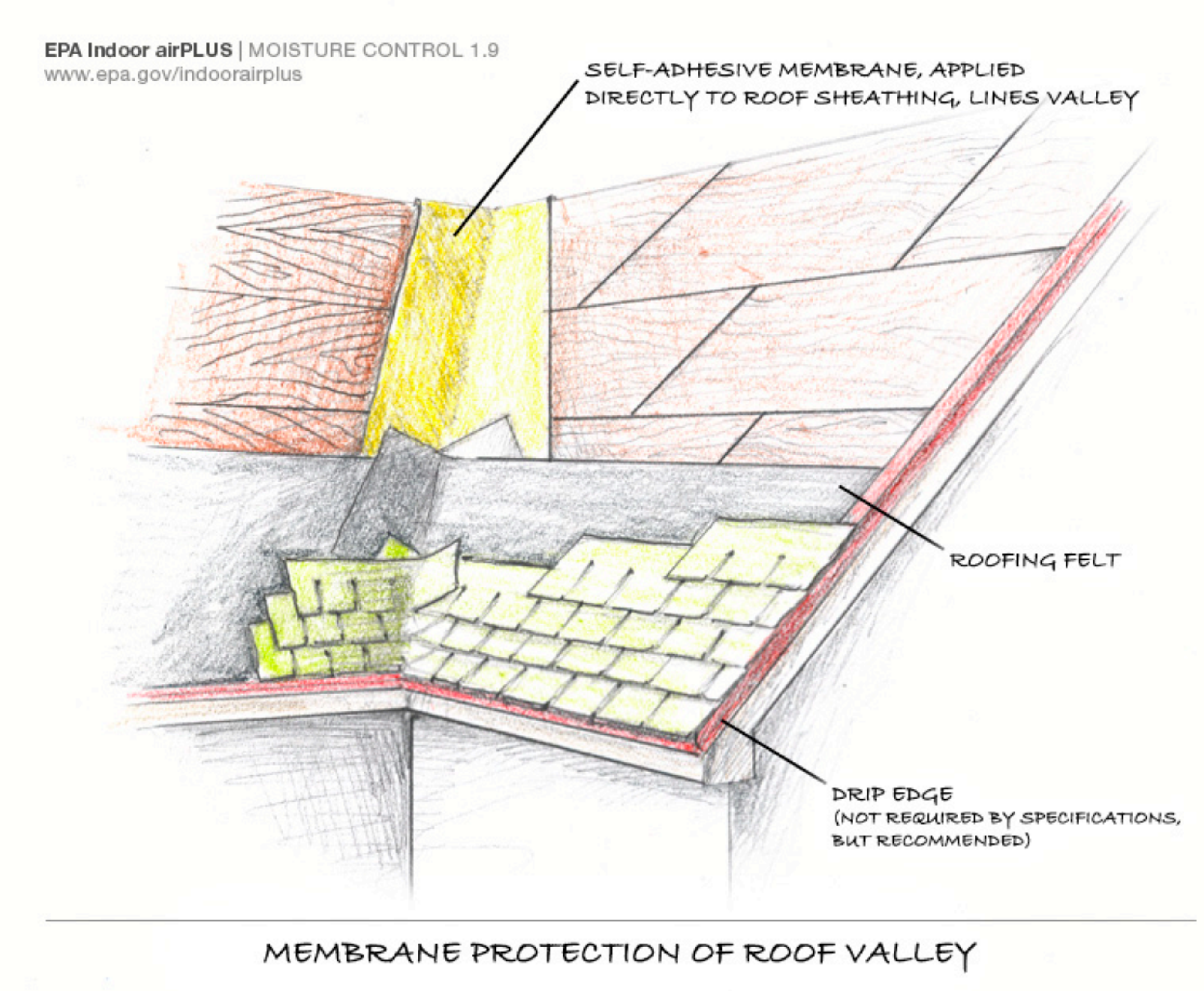


Roof flashing



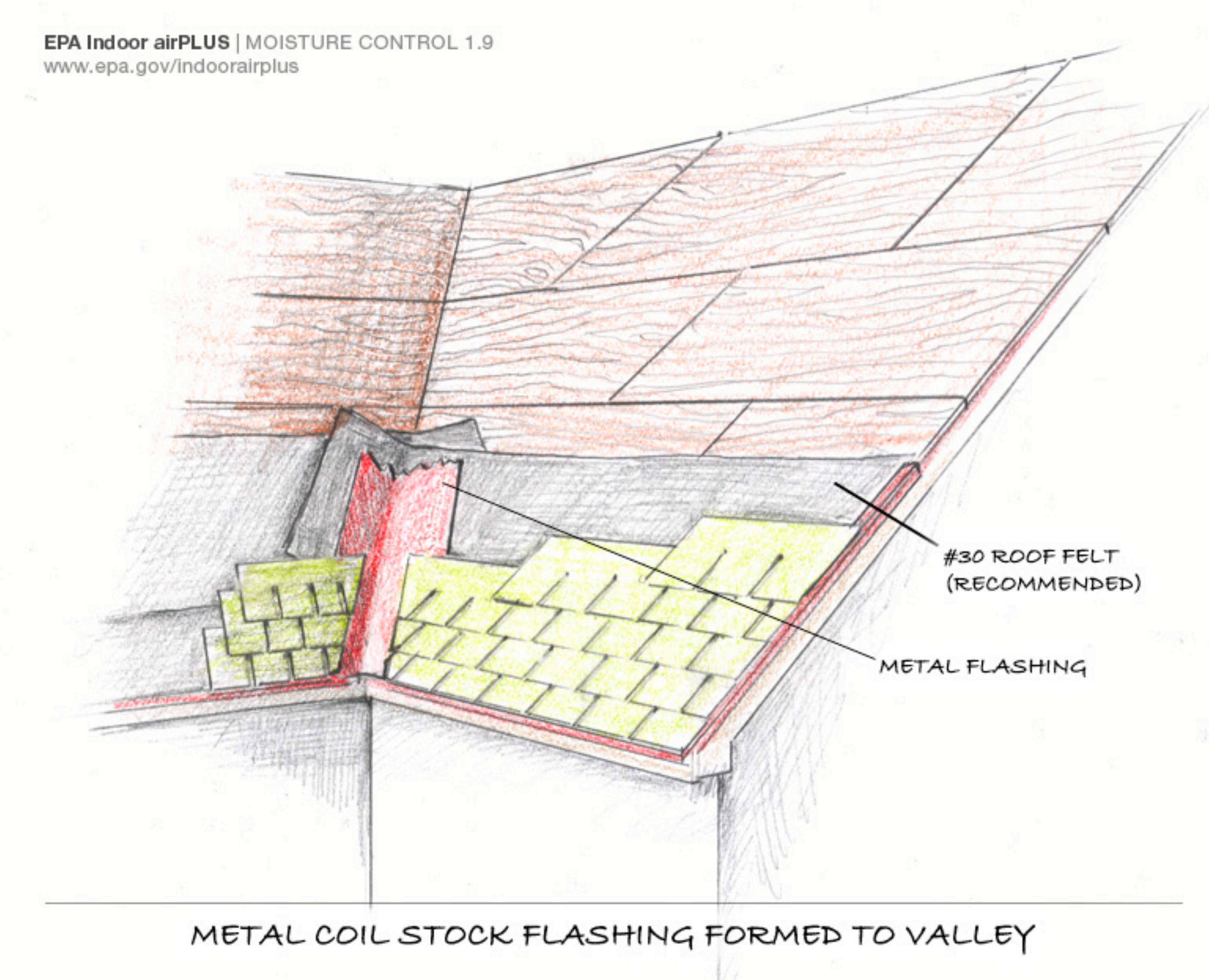
DRAINAGE PLANE MATERIAL COVERS STEP FLASHING

Membrane protection of roof valleys

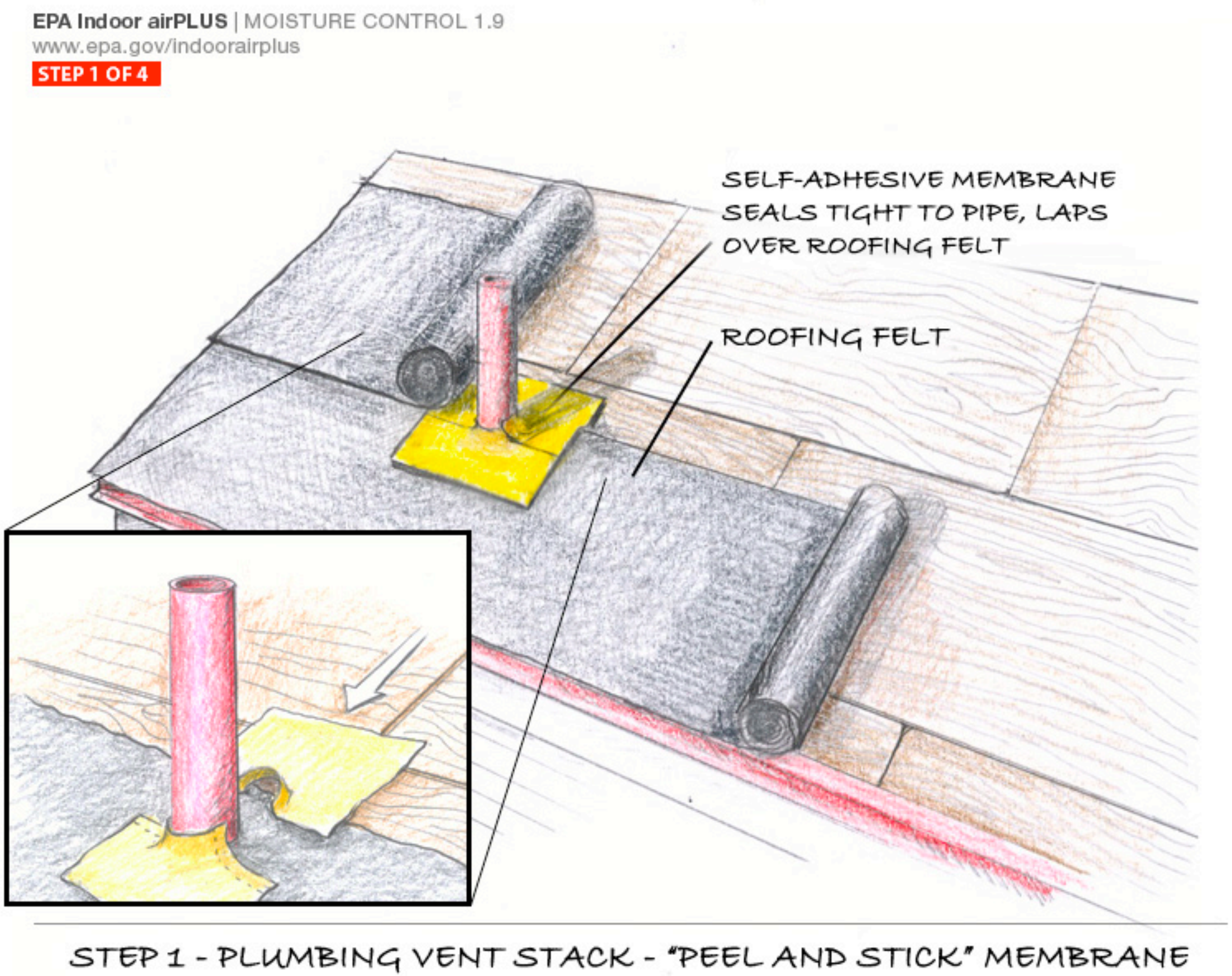


Membrane protection of roof valleys

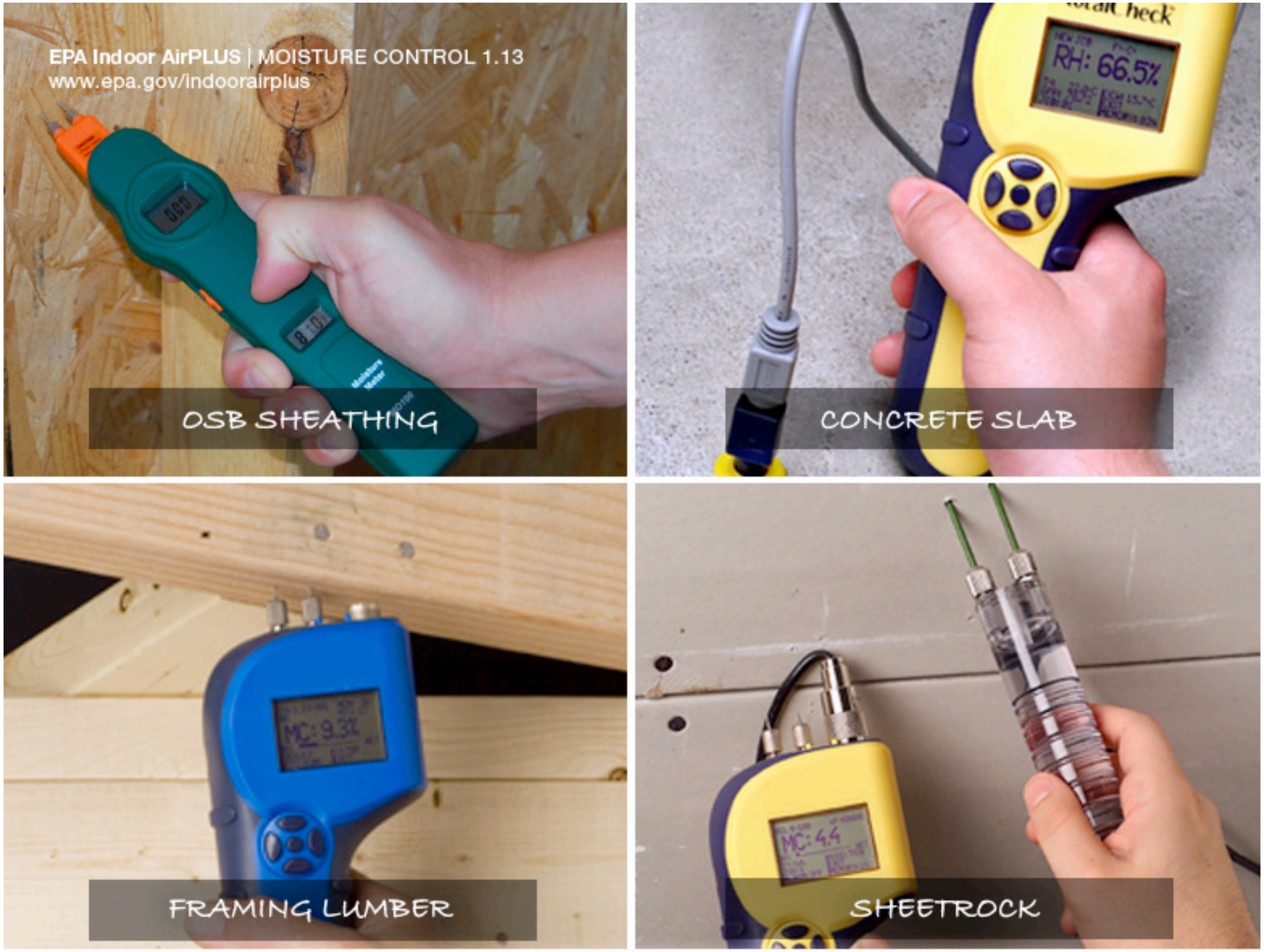
Metal flashing and roof valleys



Membranes and roof vents



Don’t install wet materials!



MEASURING MOISTURE IN VARIOUS BUILDING MATERIALS

What happens when you don't address these?

Photograph 2: Interior Frame Wall With Plastic Vapor Barrier

- Plastic vapor barrier prevents inward drying
- Common outcome are odor, mold, decay and corrosion problems

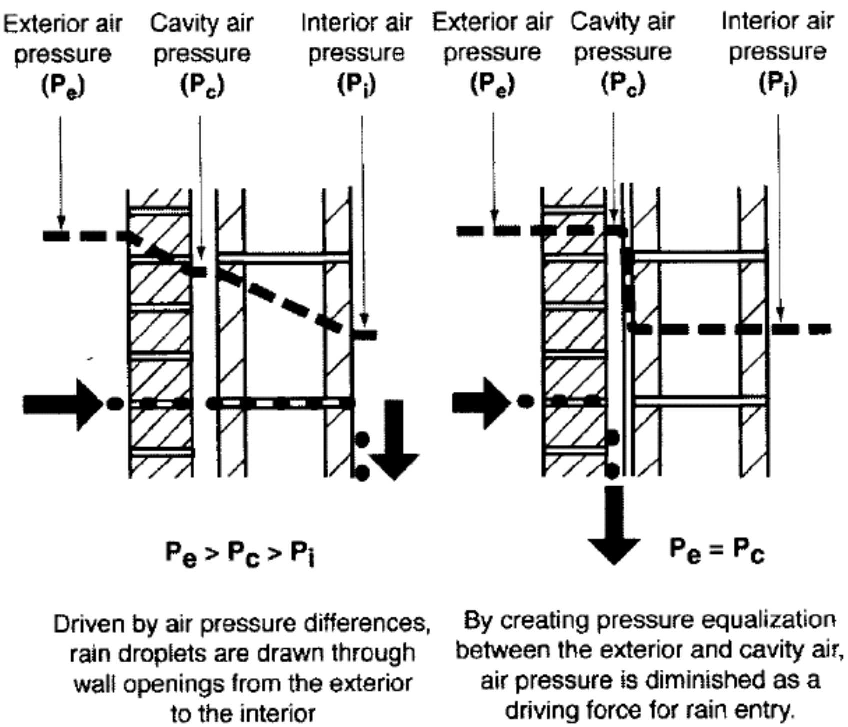
What happens when you don’t address these?

- Michaels Engineering report on construction defects and resultant water damage in a Wisconsin condominium
  - Confidential
  - Names have been changed/erased to protect the innocent (and I suppose the guilty as well)
  - Just show in class (can’t provide as a handout)

AIR CAVITIES FOR MOISTURE MANAGEMENT

Use of air cavities in moisture management

- Air cavities can provide beneficial breaks to:
  - Stop capillary suction
  - Allow flashings to direct gravity flow to exterior
  - Allow for pressure equalization to force rain back to exterior
- Intentional "**drain-screen**" walls and "**rain screen**" walls



Pressure equalization: Cavity ventilation

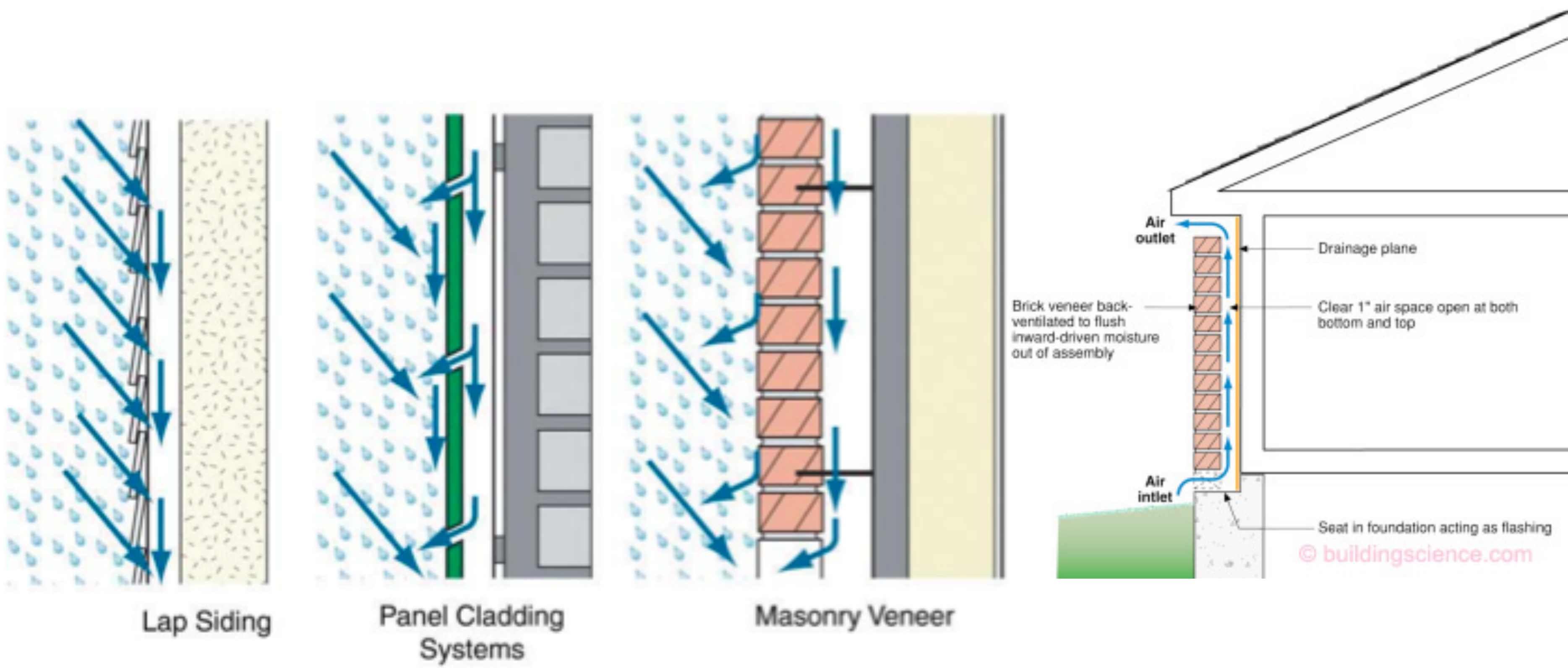
Drain-screen walls

- A **drain-screen** wall allows some water to penetrate the outer layer of a wall assembly
  - But uses the air cavity to break most water transport
  - *Uses that air space for drainage*
    - Air space should be at least 5 mm wide, although 10 mm is a better minimum to allow for normal construction tolerances

- The screen-drained wall then uses properly designed and installed flashing to redirect water from the drainage plane back outside the cavity

- Examples include cavity walls, brick and stone veneer, vinyl siding, and drained EIFS (synthetic stucco)
  - We've already seen these

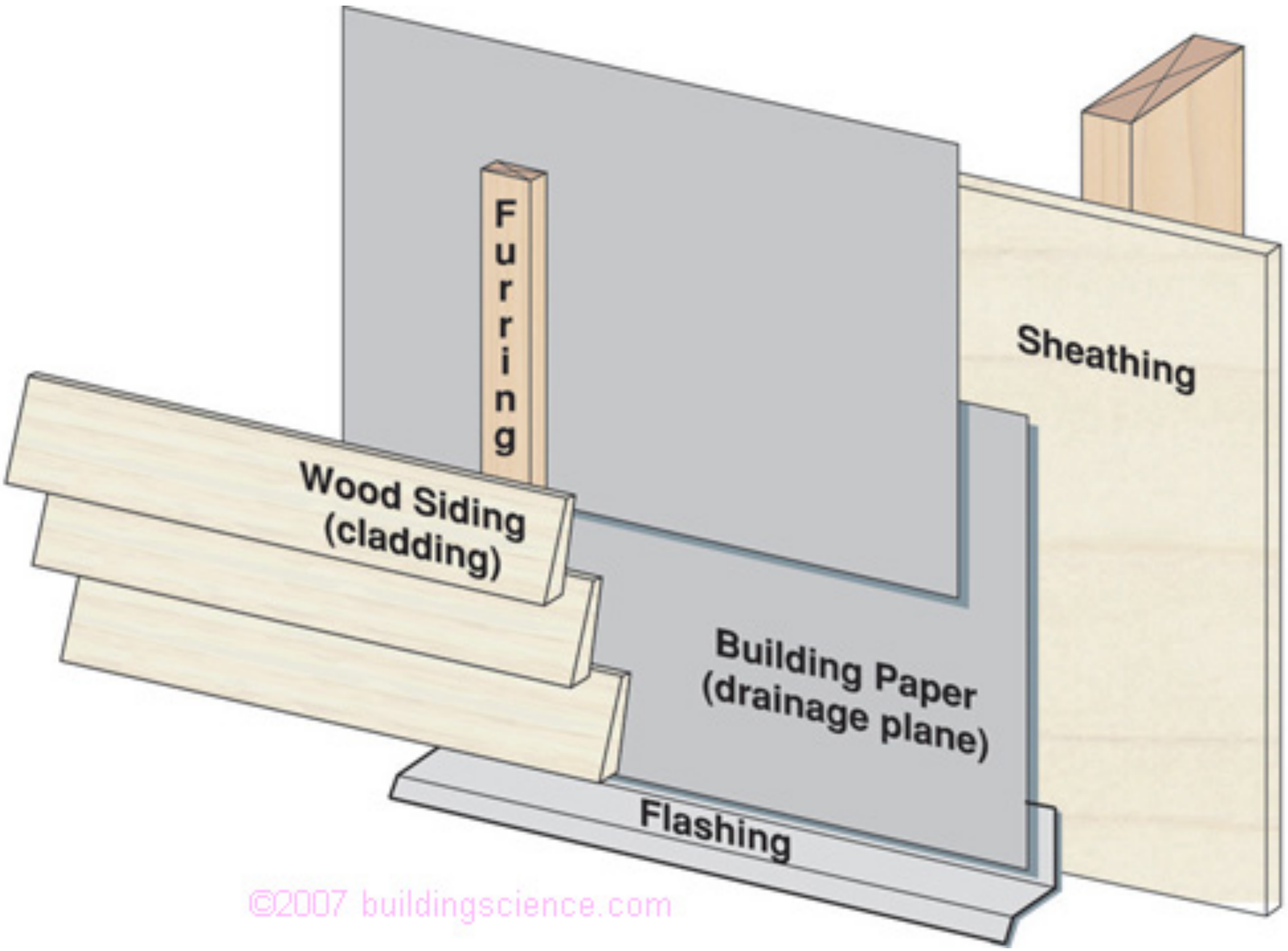
Drain-screen walls: Cavity ventilation



Each requires: (1) screen or cladding; (2) drainage gap; (3) drainage plane; (4) flashing at the base to direct water outwards; and (5) drain holes or weep holes to allow water out

Straube 2006

Drain-screen walls: Cavity ventilation



Straube 2006

Rain screen walls

- If we are a little more careful in the design of the air cavity between the outer layer and inner layers we can improve performance

- If the cavity has holes to the outside and the inside layer has an air barrier
  - The cavity will actually be pressurized to a pressure similar to outside
  - This will keep water from being driven into the cavity with by the pressure difference
  - We call this wall design a **rain screen** wall

Rain screen wall: Prevent momentum driven rain

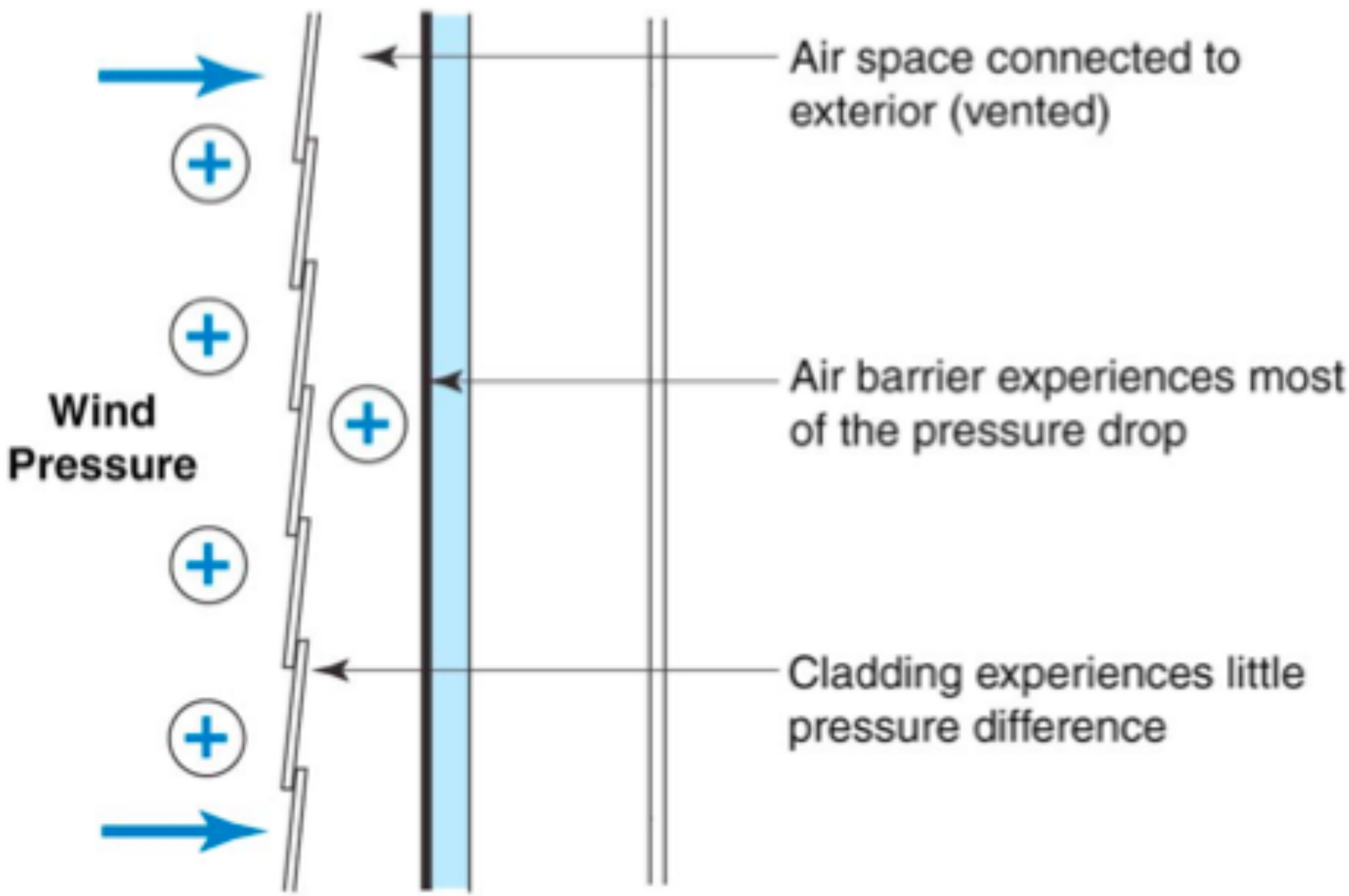
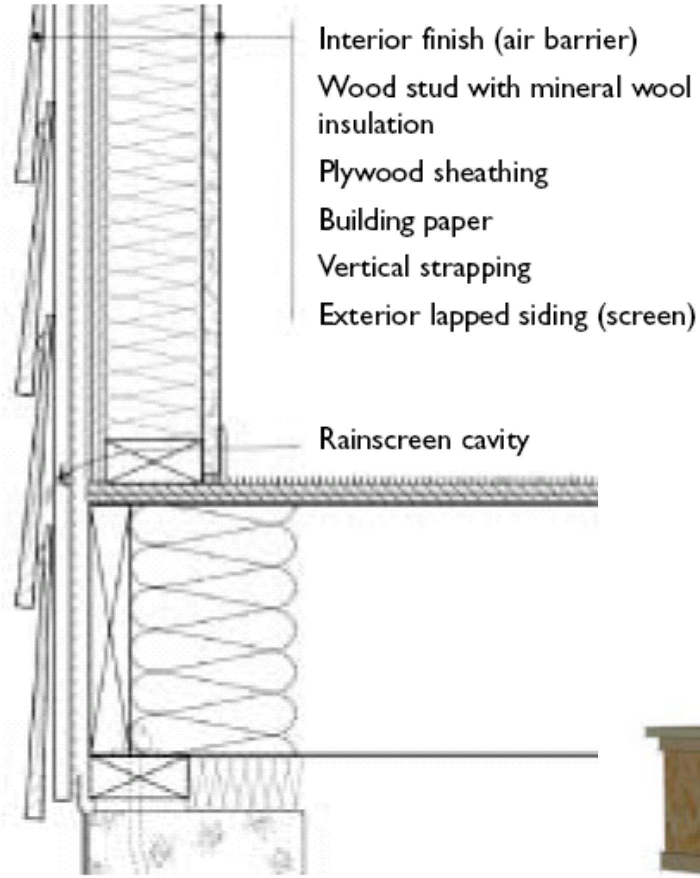


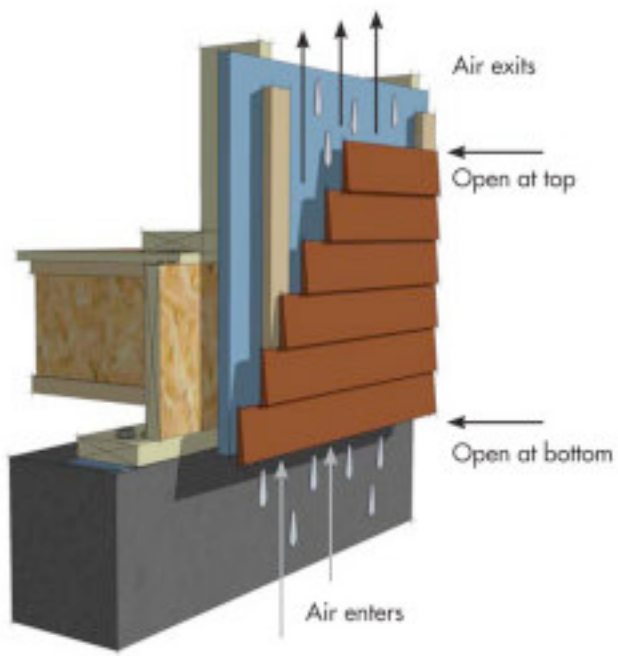
Figure 7: Pressure Moderated Air Space

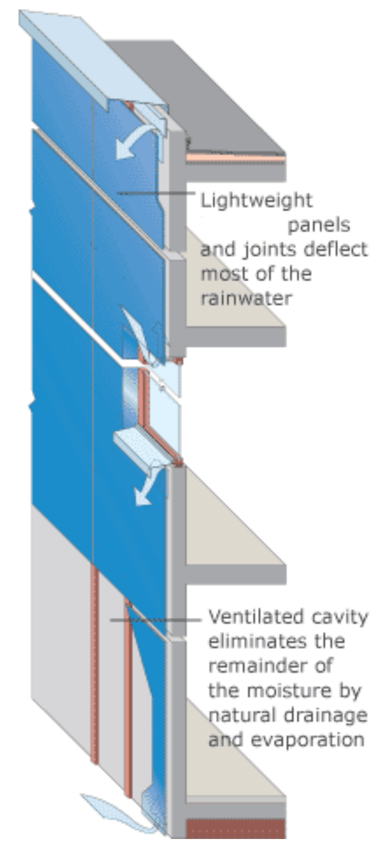
Straube 2006

Open (ventilated) rain screen



- A wall with siding will have natural air gaps
- Siding gaps act as a vent opening for drainage and drying
- Must have an air barrier somewhere on interior wall





Open rain screen video

https://www.youtube.com/watch?v=78KKx2Nx2m4

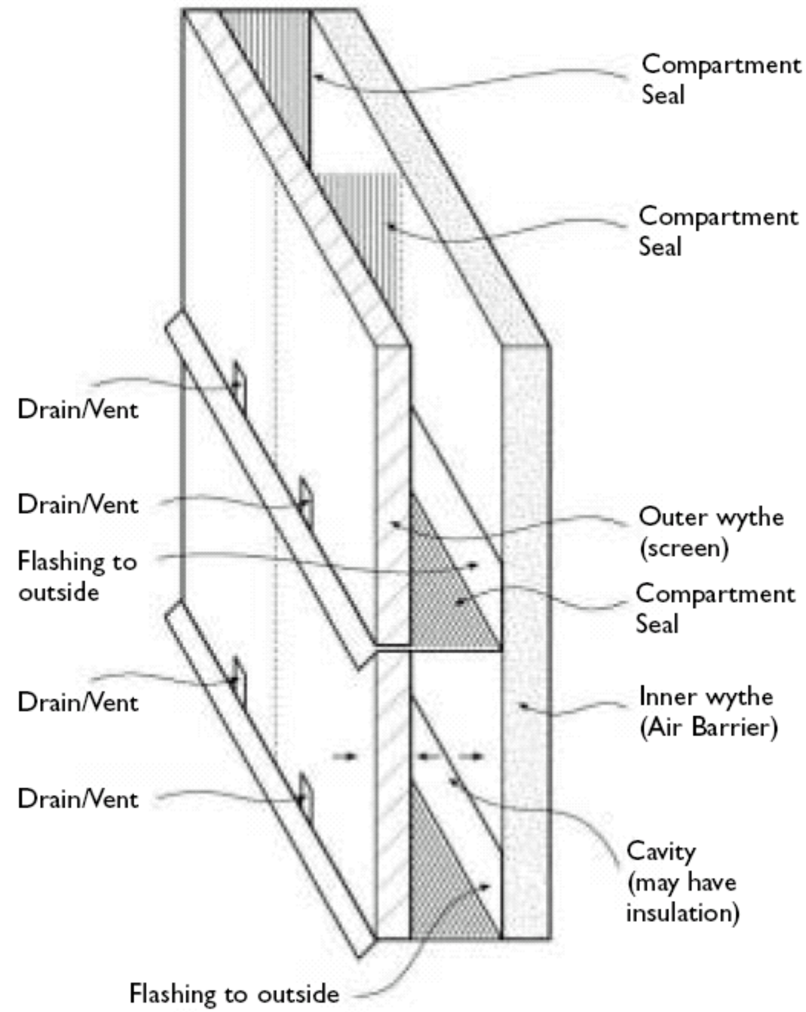
Pressure equalized rain screen (PER)

- Another type of rain screen is **pressure equalized**
  - Used more for tall buildings
- Allows compartmentalization of façade into chambers
  - Makes the pressure in the air cavity track outside air pressure
  - Stops the rain from even entering the cavity (if driven by pressure difference)

- PER screens are useful in high rain areas but are usually too expensive for general wall design

Basic PER design

- Flashing
  - Directs dripping water to the exterior drains
- Drain/Vents
  - Act as openings for pressure equalization
  - Allow rain that enters cavity to drain out
- Compartmental Seals
  - Breaks the interior cavity into smaller sections



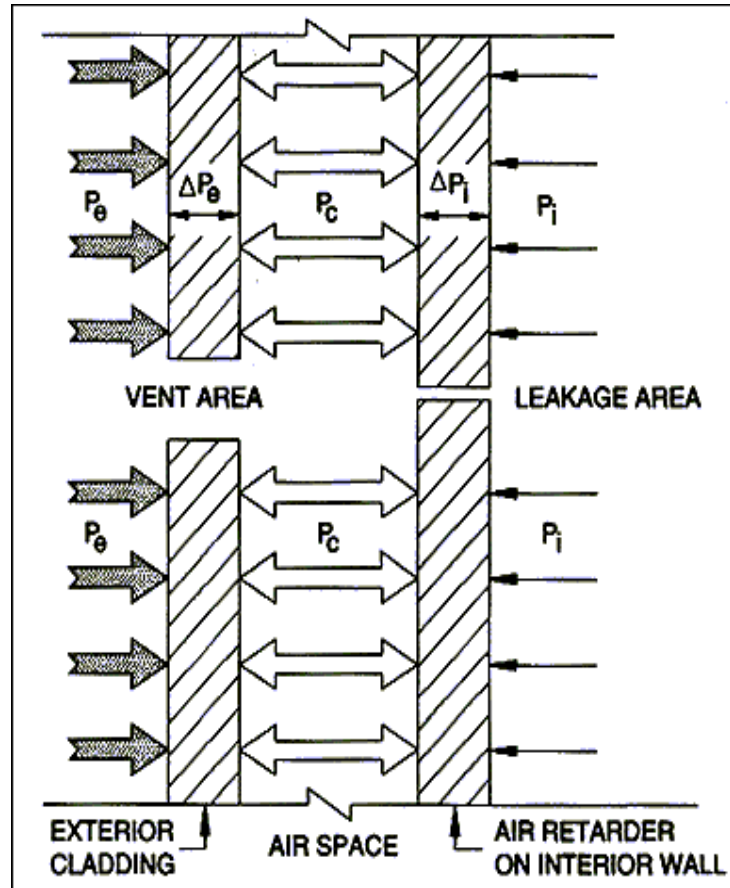
Pressure Equalized Rain Screen (PER)

- Large opening in exterior cladding increases cavity pressure equal to that of exterior so rain doesn't enter

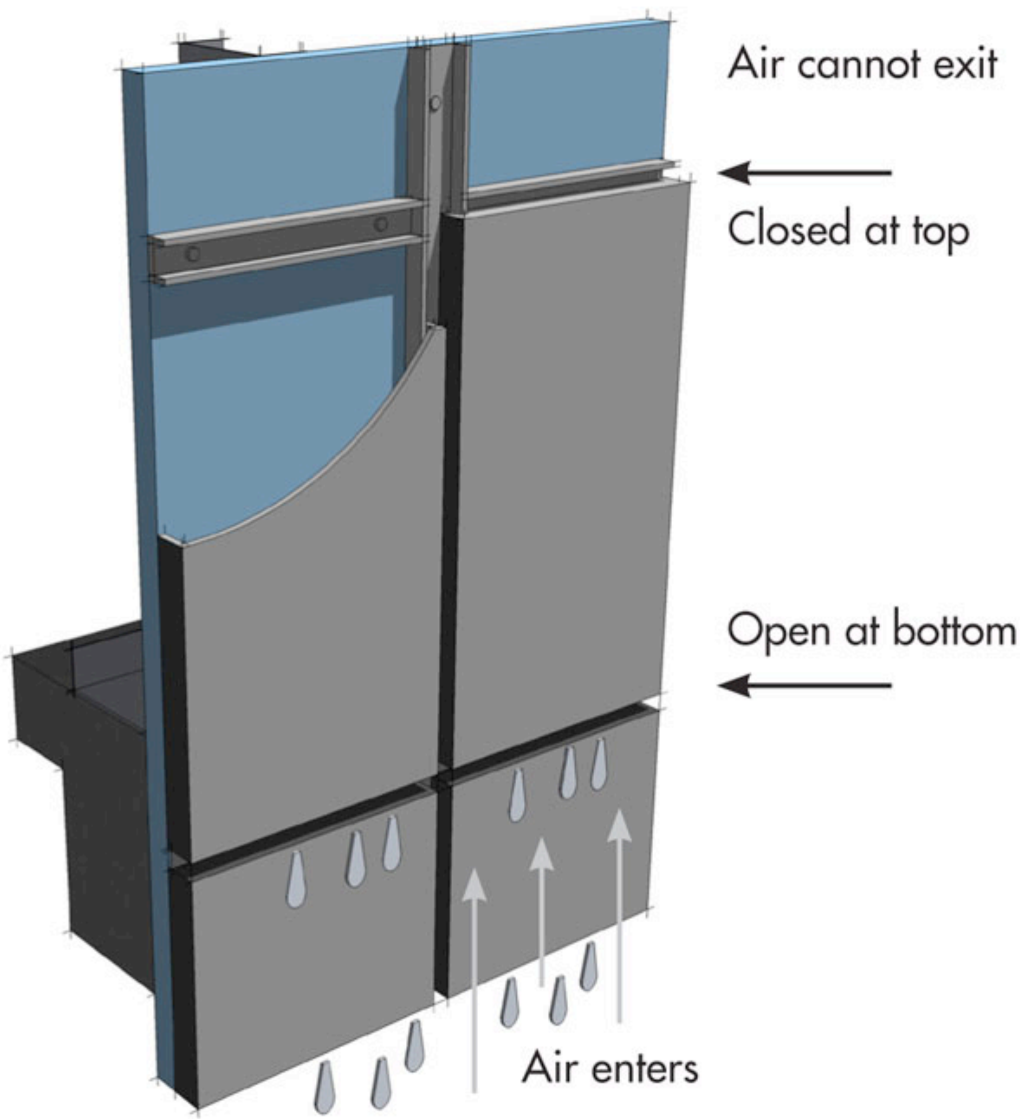
  $P_c \approx P_e$, $\Delta P_e \rightarrow 0$

- Interior wall must have an air barrier to ensure that high cavity pressure is maintained

  $P_c > P_i$, $\Delta P_i > 0$



PER detail



MOISTURE MANAGEMENT AND CONTROL: SUMMARY

Moisture management rules

- Remember:
  - For a moisture problem to occur
    - There must a source
    - There must be a route
    - There must be a driving force
    - The materials involved must be susceptible
  - Eliminate any one will avoid a problem, in theory
  - In practice, difficult to:
    - Remove all moisture sources
    - Build walls with no imperfections
    - Remove all driving forces for moisture movement
    - So, if you can address two of these
      - You will reduce the likelihood of having a problem

Susceptibility and vulnerability

- As we've seen, different materials and assemblies vary in their susceptibility to moisture-related damage
- Standards, codes, and industry criteria help assess susceptibility of materials
- Susceptible materials are susceptible only in a vulnerable environment
  - Responsibility of designers and builders to ensure that a material or assembly are used in appropriate manners
  - Location is a primary determinant of exposure
    - The location of the relevant portion of material on the wall
      - The wall on the building
        - The building on the site
          - And of the geographical region of the site

Moisture management

- "This is a durable, high-performance wall assembly"
  - Means nothing without context of climate and purpose
  - Is the enclosure expected to separate an operating room from the Antarctic winter?
    - Or a warehouse from the Saharan desert?
  - Using a material that is not supposedly susceptible to moisture damage in locations with high wetting potential often leads to a problem
    - Good quality face brick in window sills

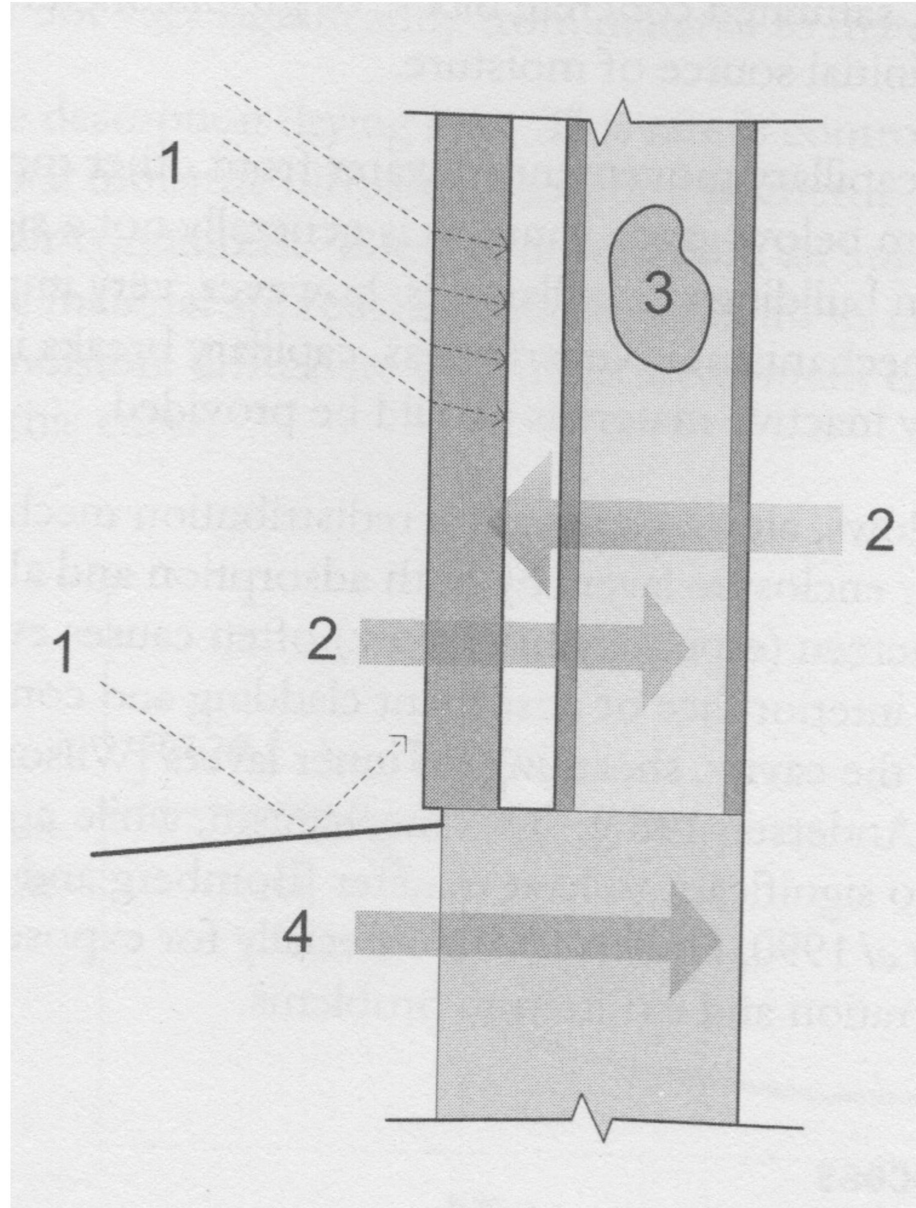
Moisture control

- If a balance between wetting and drying is maintained
  - Moisture will not accumulate over time
    - Moisture problems would then be unlikely

- Need to be cognizant of:
  - Moisture sources
  - Moisture removal mechanisms
  - Moisture storage

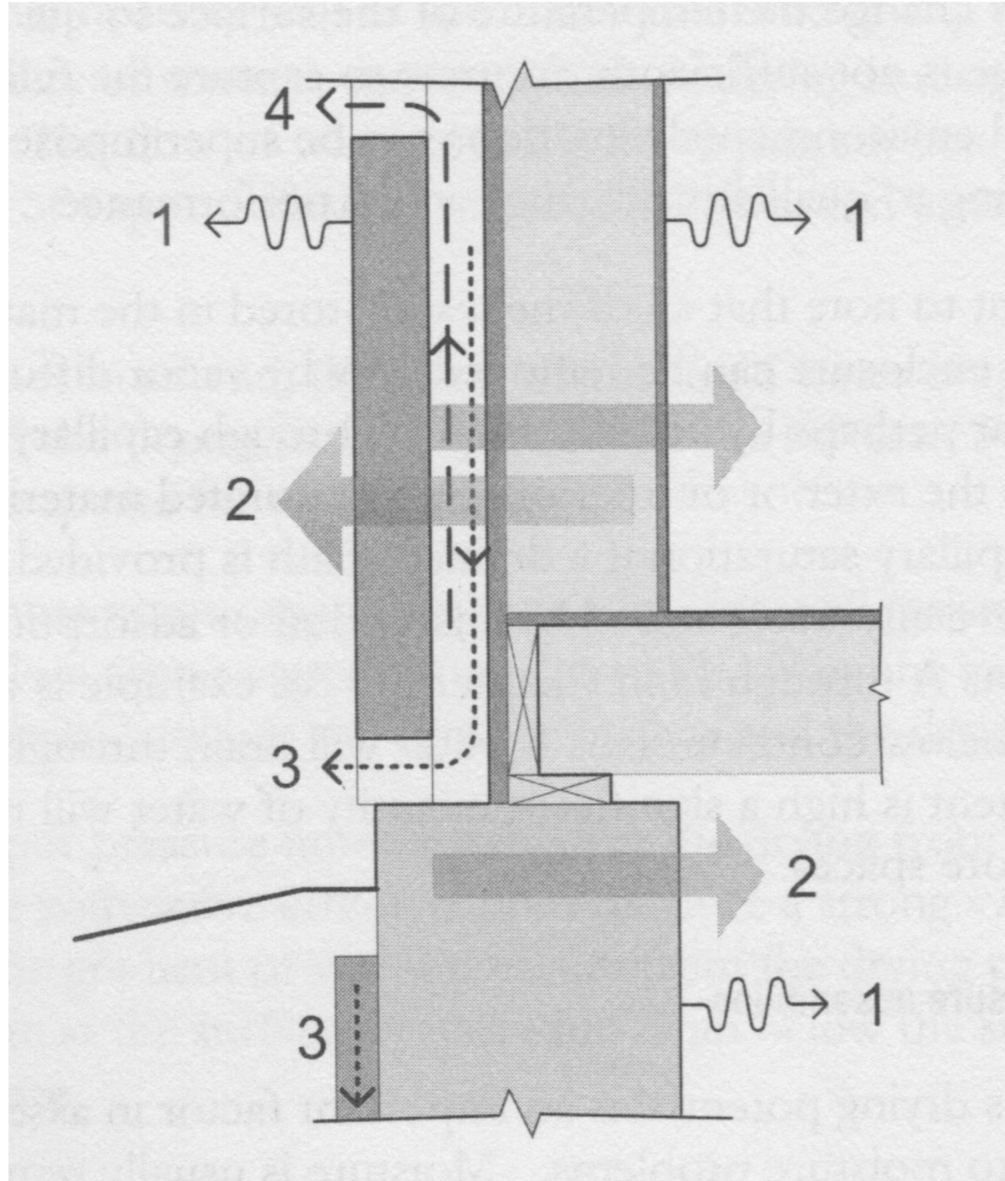
Wetting process (sources)

1. Precipitation
   – Driving rain
2. Water vapor transport
   – Diffusion
   – Air leakage
3. Built-in and stored moisture
   – During construction
4. Ground water



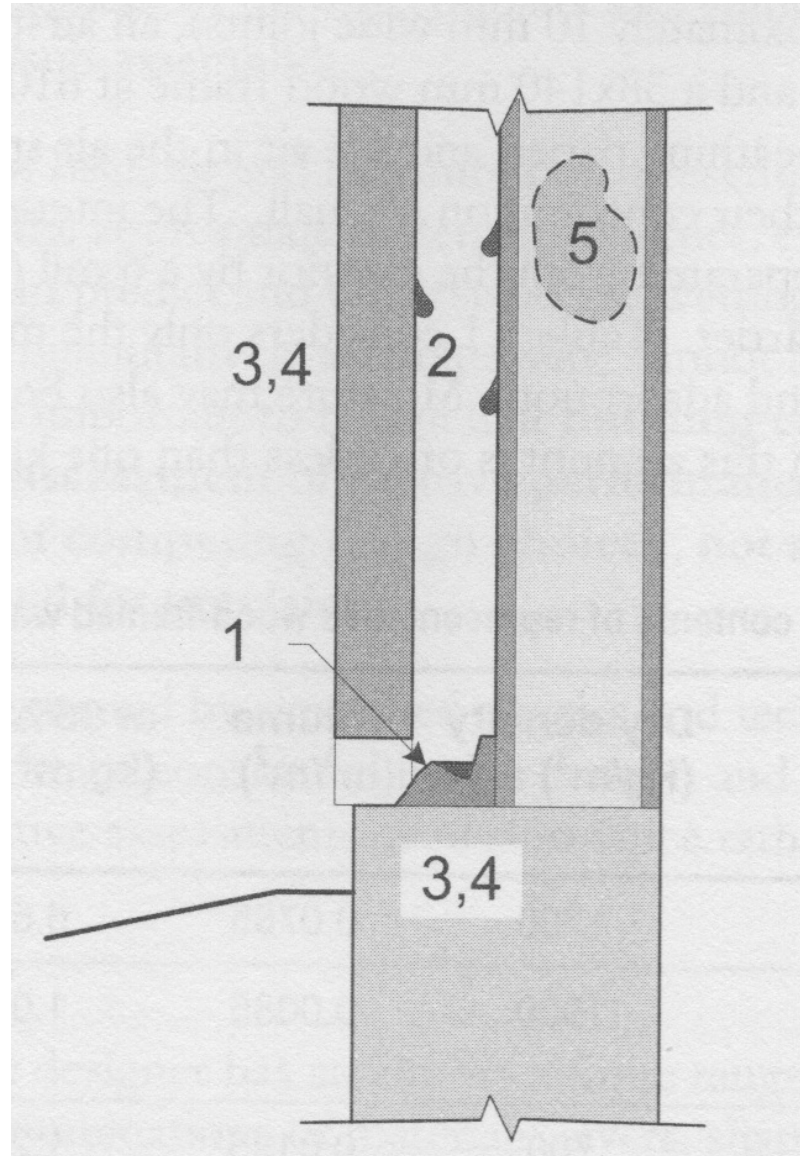
Drying mechanisms

1. Evaporation
2. Vapor transport
   - Diffusion
   - Air leakage
   - Outward or inward
3. Drainage
   - Driven by gravity
4. Ventilation drying



Moisture storage

1. Trapped in small depressions
   - Poorly drained portions of assemblies
2. Adhered by surface tension to materials
   - Droplets
   - Or even frost or ice
3. Adsorbed in or on hygroscopic building materials
   - Brick, wood, fibrous insulation, paper
4. Retained by capillarity (absorbed) in porous material
5. Stored in the air as vapor



Condensation control

- Two types that must be considered
  - Interior surface condensation
  - Interstitial (within enclosure) condensation
    - Just as important in hot-humid climates as in cold climates

- Like we've discussed, condensation on building surfaces is undesirable
  - On interior surfaces:
    - Moisture will damage moisture-sensitive finishes (wallpaper, paint, wood, gypsum wallboard)
    - Provides moisture for mold growth

Condensation control

- Surface condensation is often the result of dynamic/short-term variations in temperature or absolute humidity
  - Cold windy night
  - Cool morning
  - After a shower
  - During cooking

  - Need to consider these events

Condensation control

- Most modern enclosure walls and roofs are well insulated such that interior surface condensation in winter shouldn't be a problem
  - In winter, interior surface temperature is high enough to not be below indoor air dew point

- Surface condensation becomes a problem when:
  - Thermal resistance of the enclosure is low (i.e., at thermal bridges)
  - Surface film has an unusually high value
  - Interior humidity is very high

Designing enclosures for moisture control

- Building enclosure design usually involves the assessment of relative performance, pass-fail assessments, or the ranking of competing design choices
  - Not absolute values
  - Rarely a need for absolute precision

- Results generated by the simplified physics and solution techniques so far should be considered
  - Applied to arrive at reliable relative assessments
    - Rather than precise quantities

Designing enclosures for moisture control

- Material choices
  - You have an almost infinite range of choices considering possible combinations of
    - Materials
    - Layers
    - Shape
    - Orientation
  - There are no universally “good” materials

Refer to Building Science Corp's website for more info

- "Enclosures that work"
  - http://www.buildingscience.com/doctypes/enclosures-that-work
- "Designs that work"
  - http://www.buildingscience.com/doctypes/designs-that-work
- "Understanding vapor barriers"
  - http://www.buildingscience.com/documents/digests/bsd-106-understanding-vapor-barriers