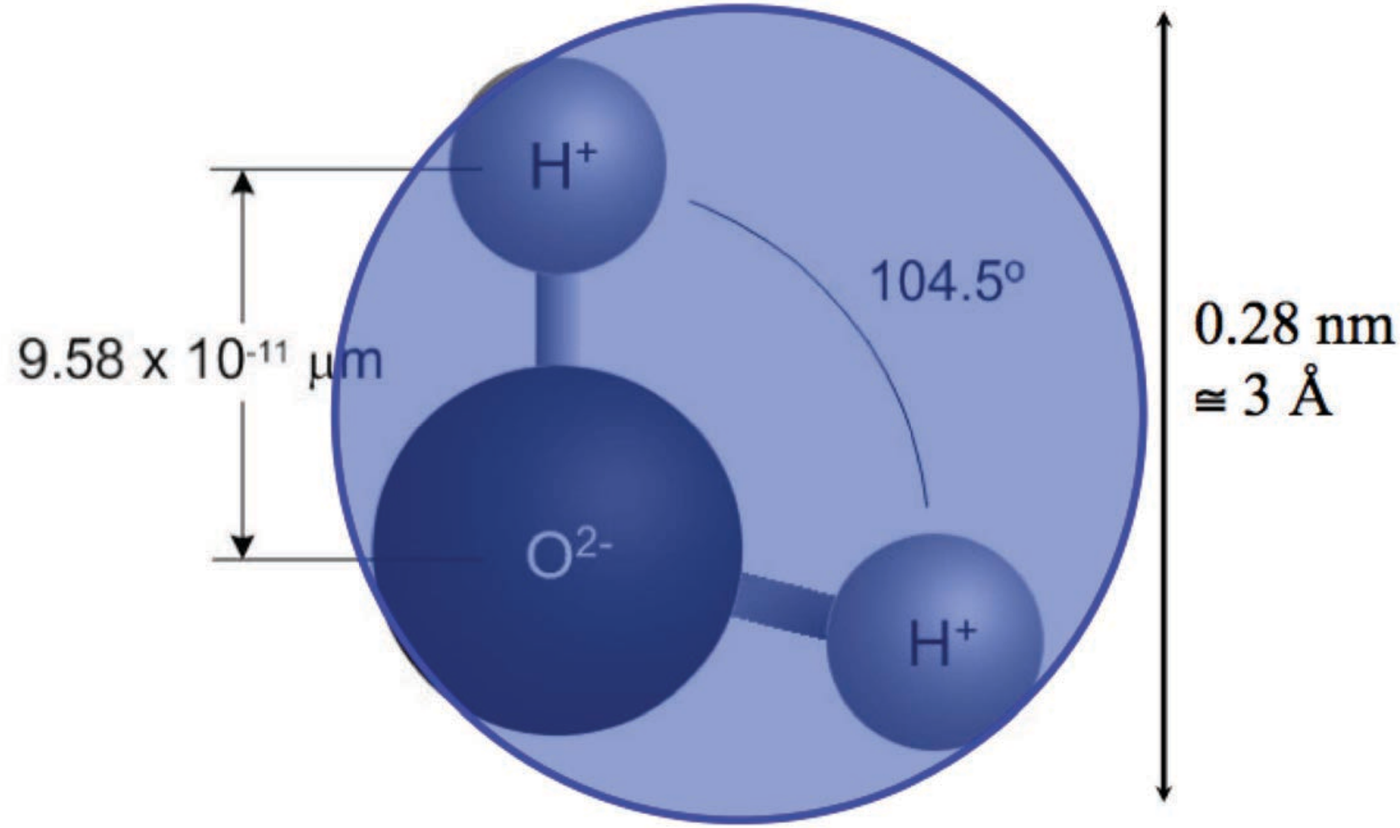
Joseph Lstiburek, Ph.D., P.Eng, ASHRAE Fellow

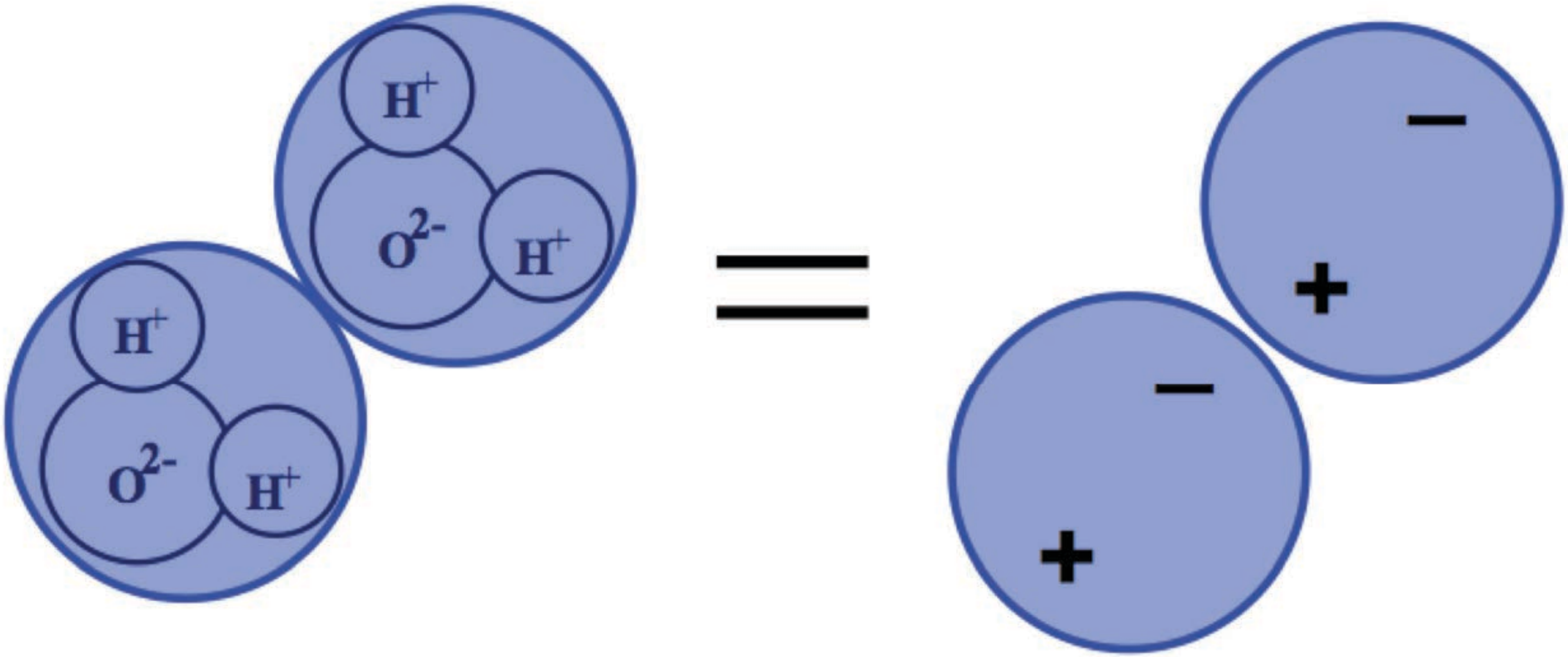
Building Science

The Water Molecule

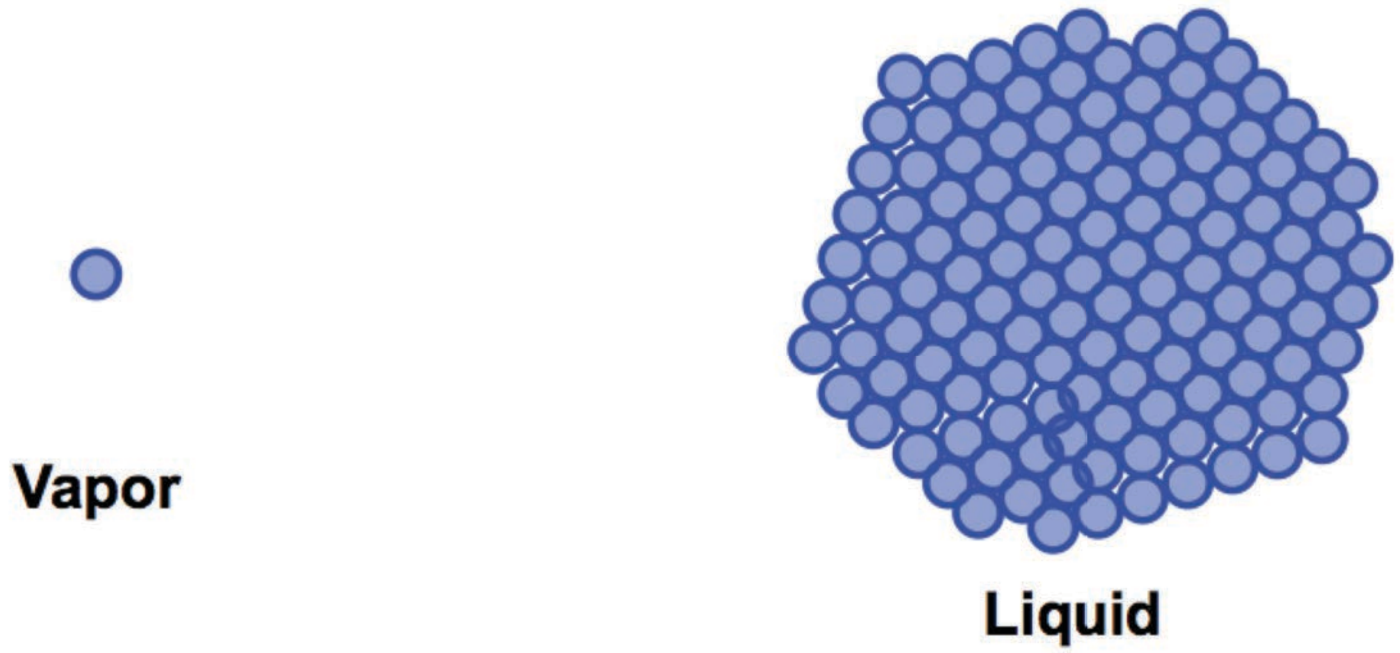
Water Molecules

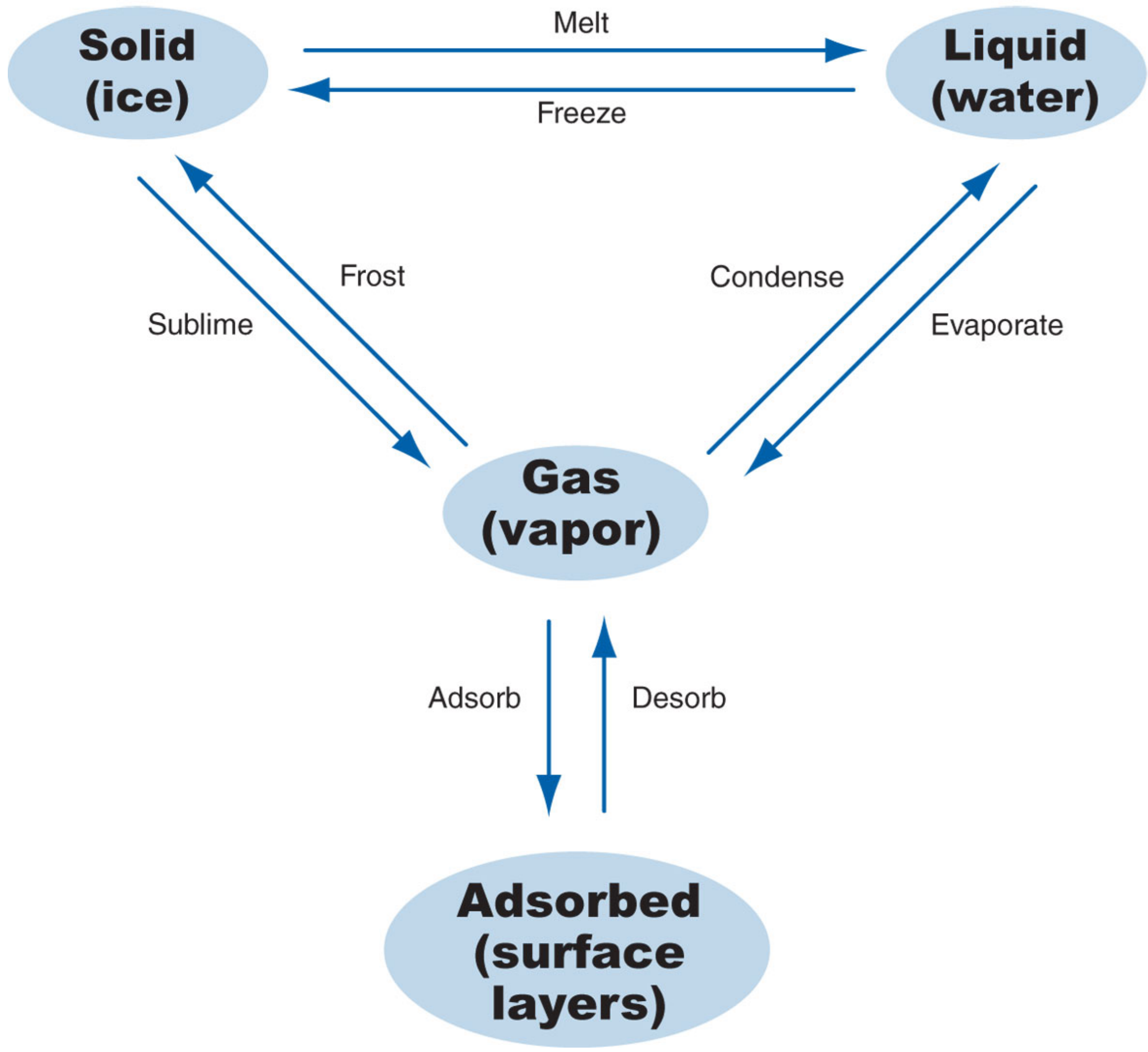

H+
104.5o
9.58 x 10-11 μm
0.28 nm
≅ 3 Å
O2-
H+

Polar Molecule


H+
O2-
H+
H+
O2-
H+
=
−
+
−
+

Size Matters


Vapor
Liquid


Solid
(ice)
Melt
Freeze
Liquid
(water)
Frost
Sublime
Condense
Evaporate
Gas
(vapor)
Adsorb
Desorb
Adsorbed
(surface
layers)

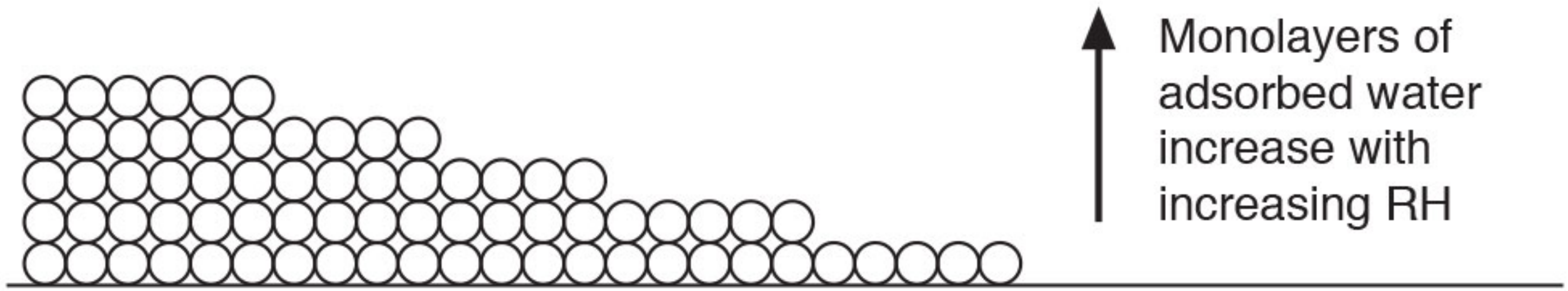
Moisture Transport in Porous Media

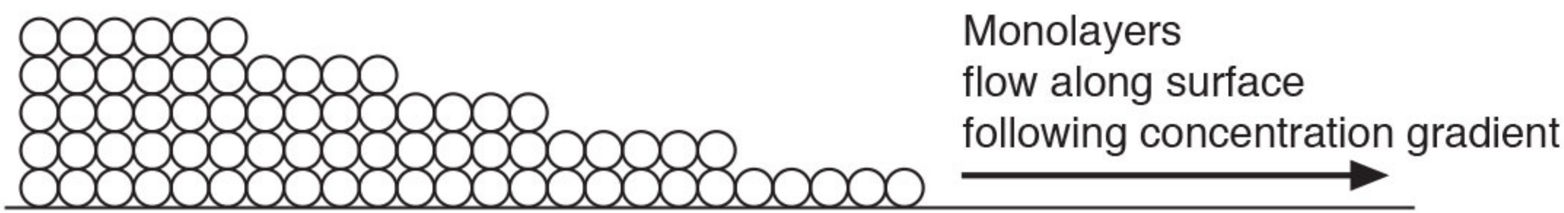
Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration

Moisture Transport in Assemblies

Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration
	Gravitational Flow	Height
	Surface Tension	Surface Energy
	Momentum	Kinetic Energy
	Convective Flow	Air Pressure

Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration


Monolayers of
adsorbed water
increase with
increasing RH


Monolayers
flow along surface
following concentration gradient

Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure

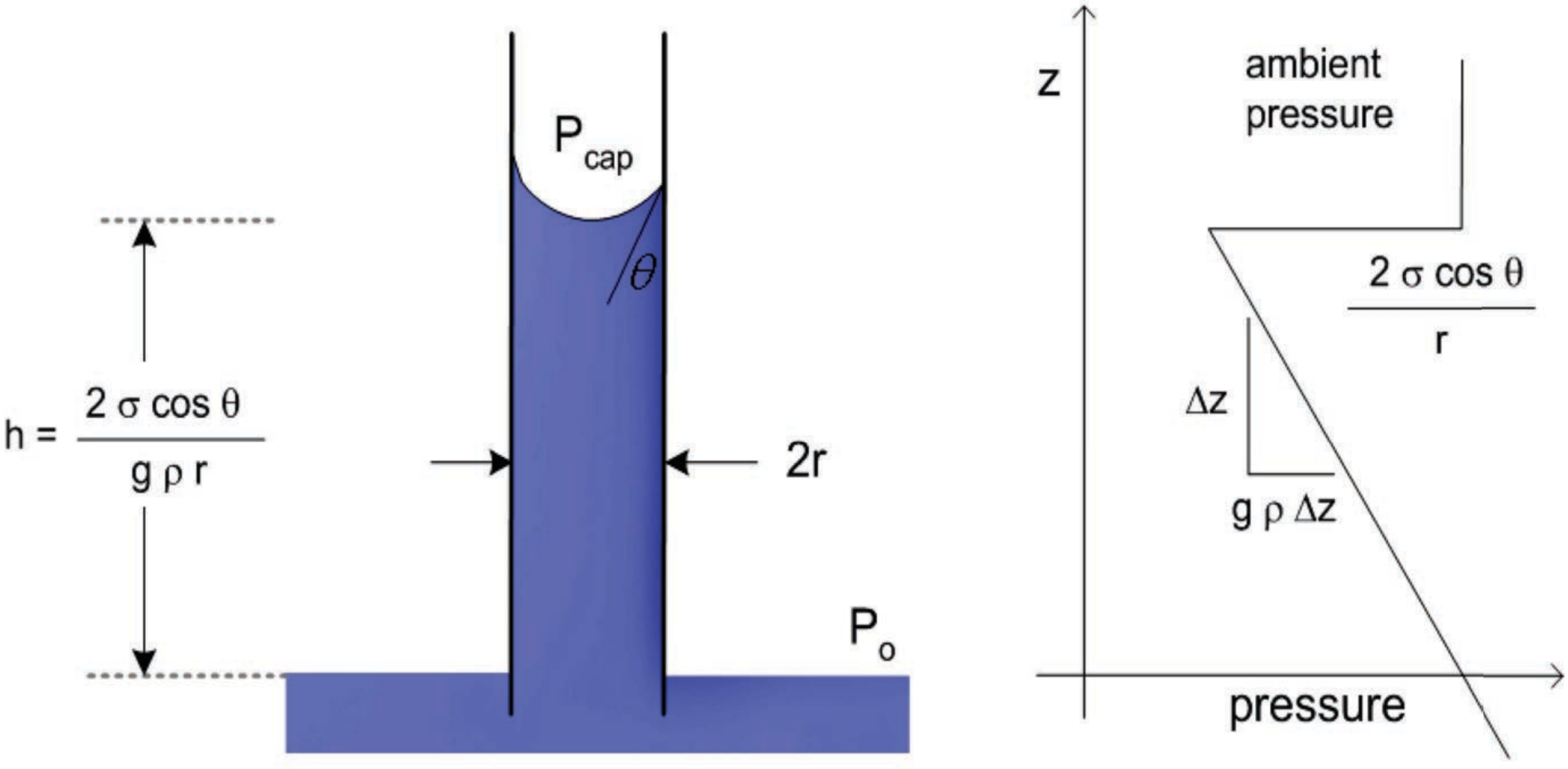
William Thomson

William Thomson – Lord Kelvin

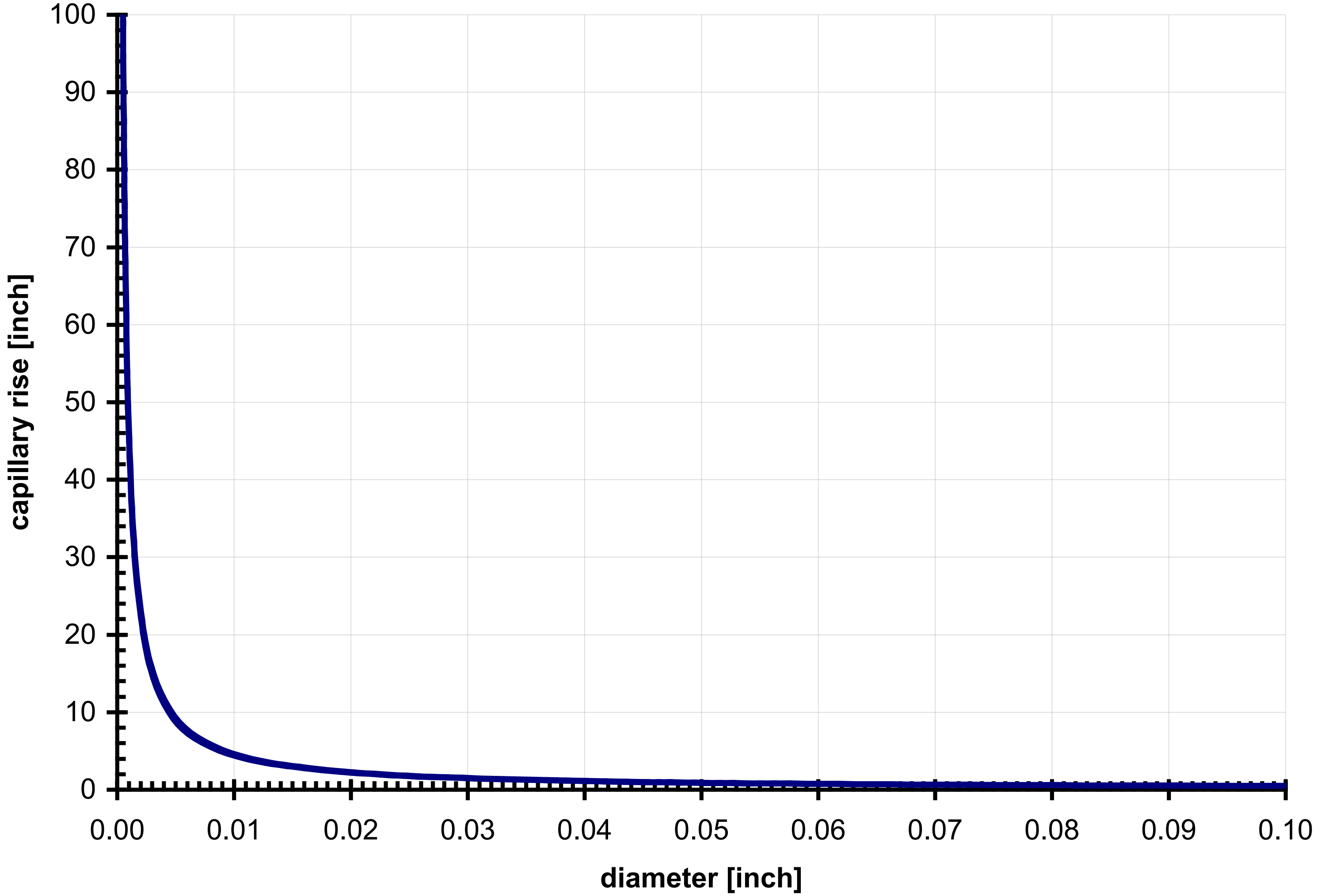
Kelvin Equation

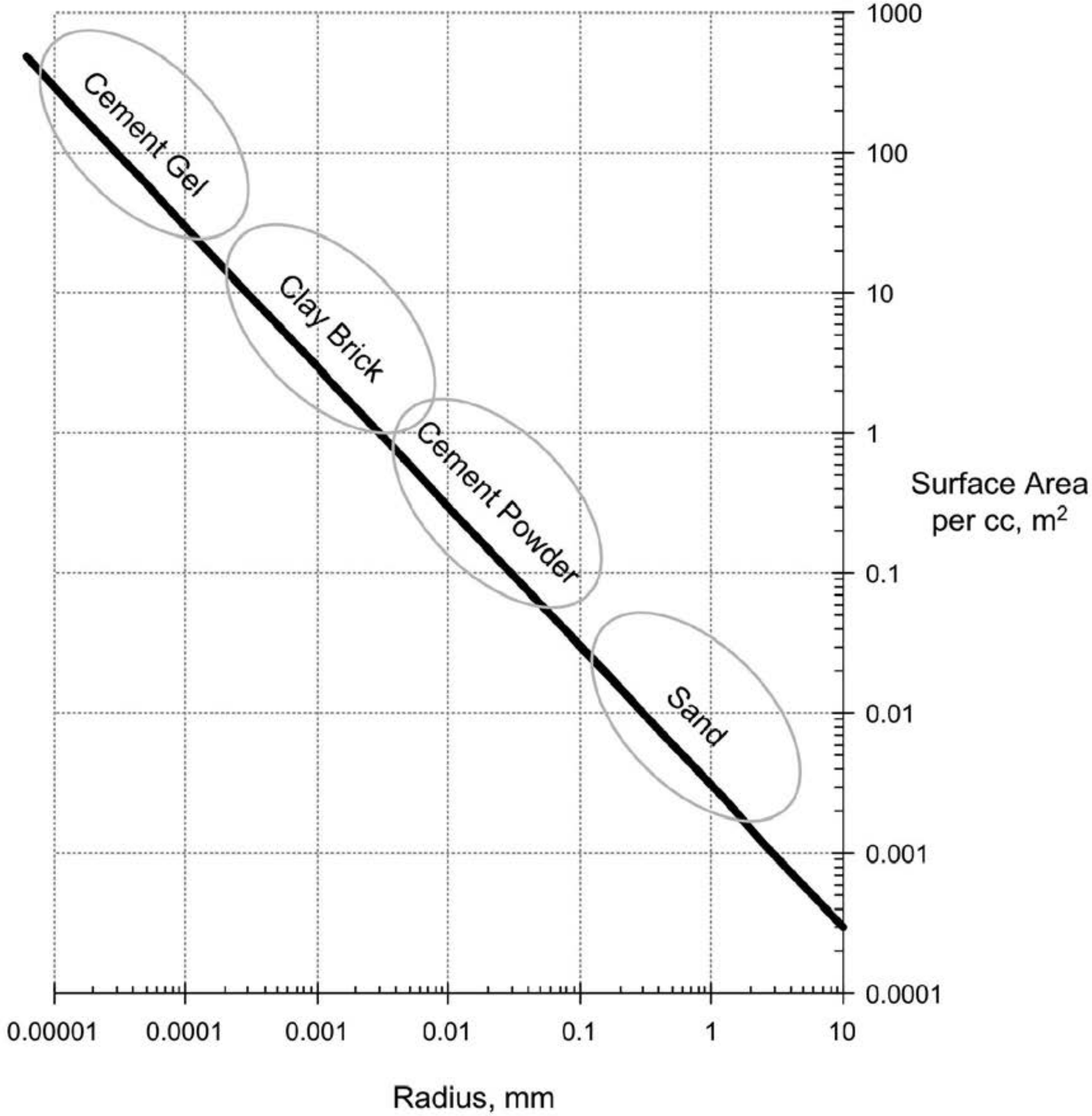
$$\ln \frac{p}{p_0} = \frac{2\gamma V_{\mathrm{m}}}{rRT}$$

Calculating capillary rise



Capillary rise versus diameter





Surface area vs. particle size
From Straube & Burnett, 2005

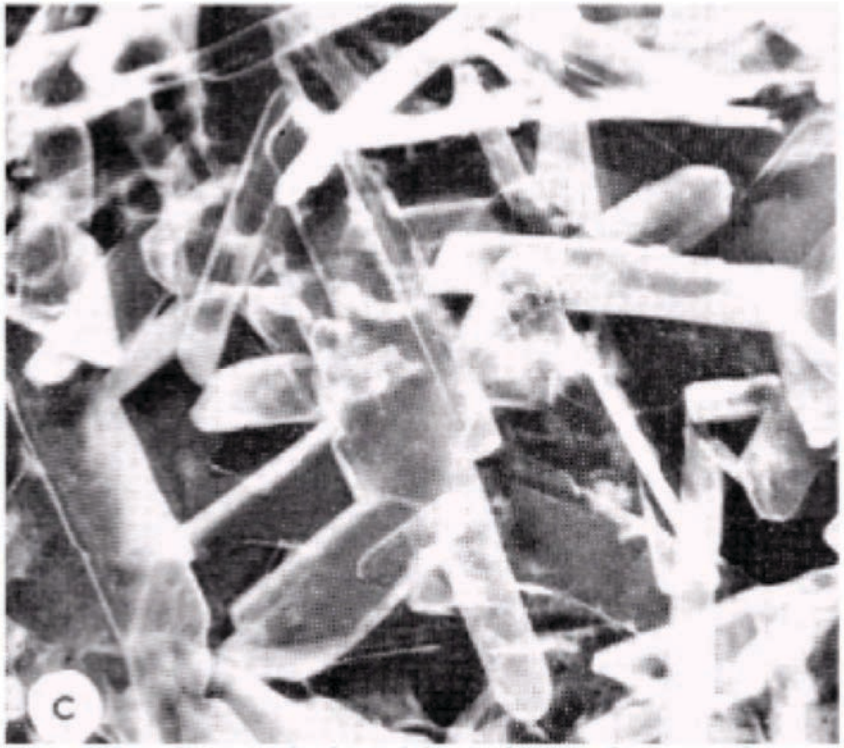


Figure 1c. Gypsum, hydrated from plaster of paris and water, porosity 30 per cent.

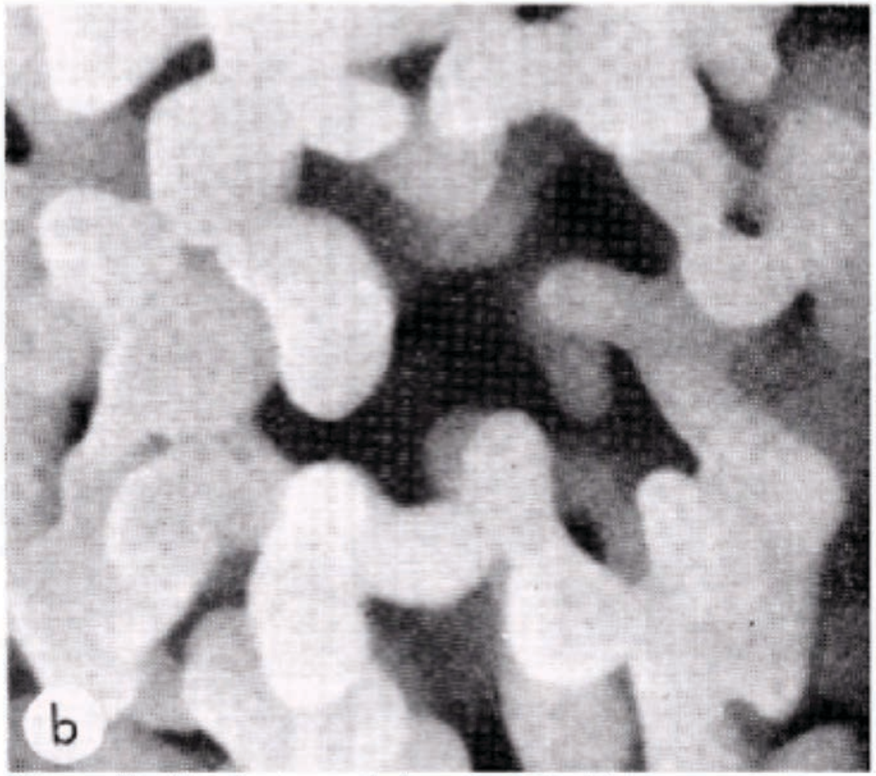
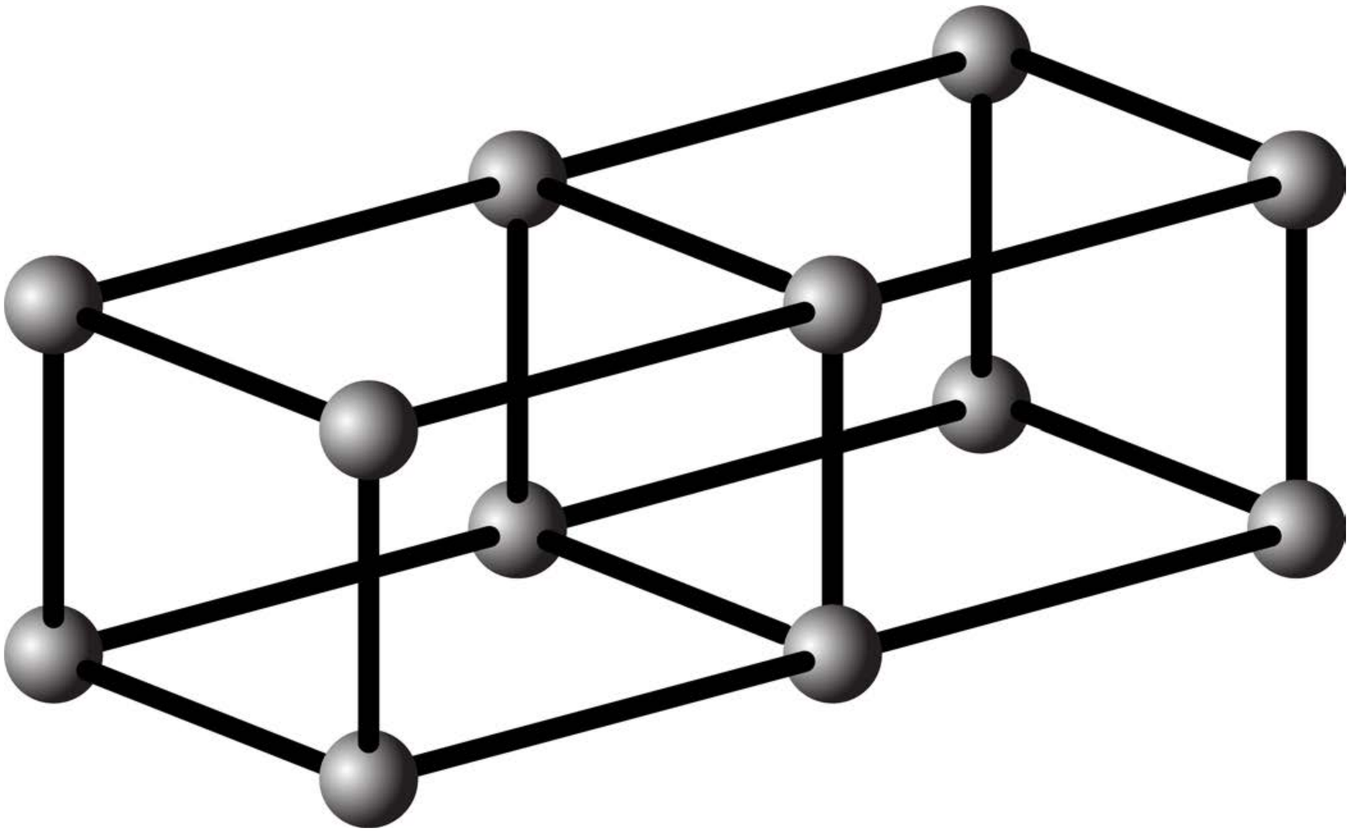
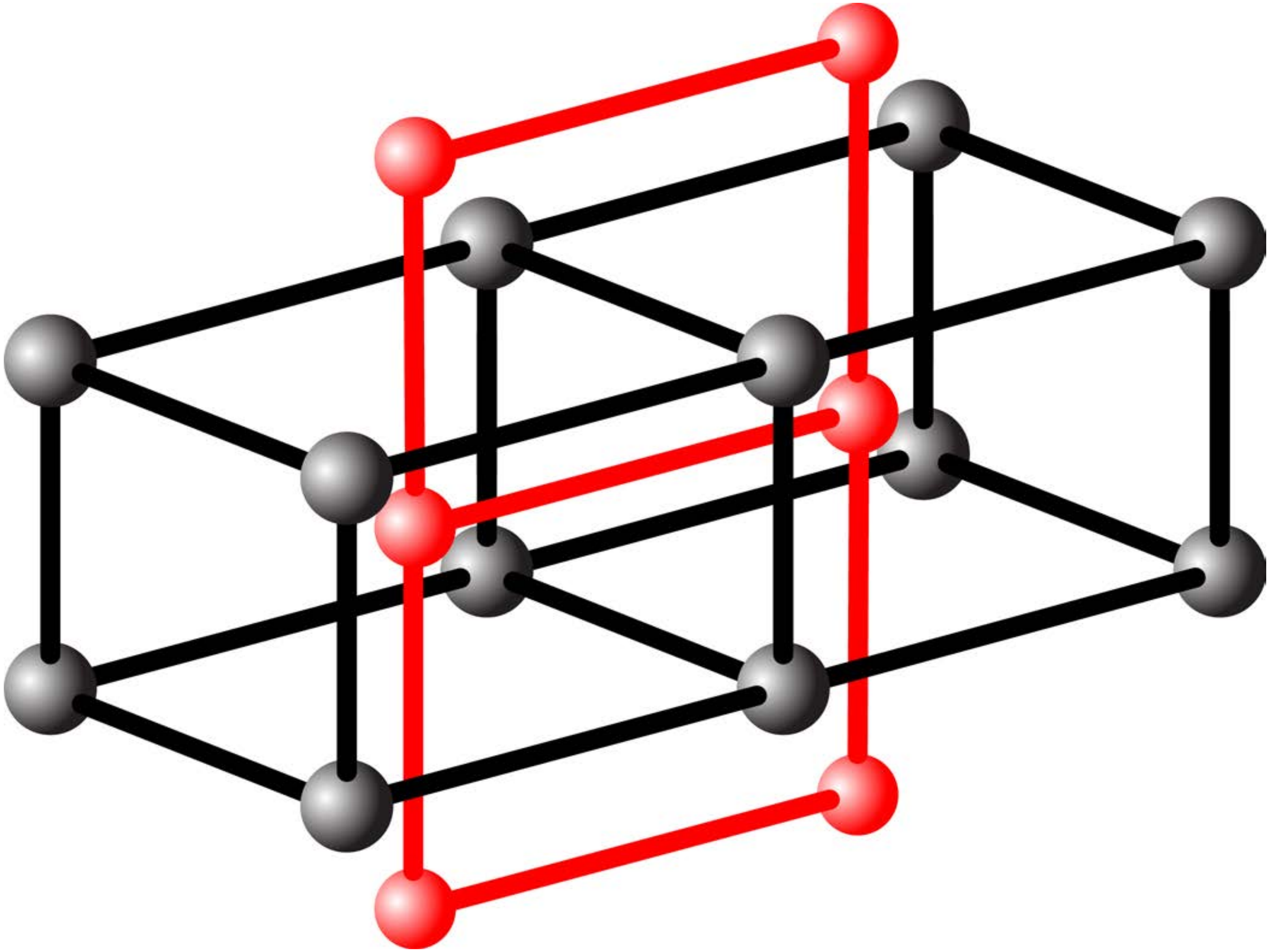
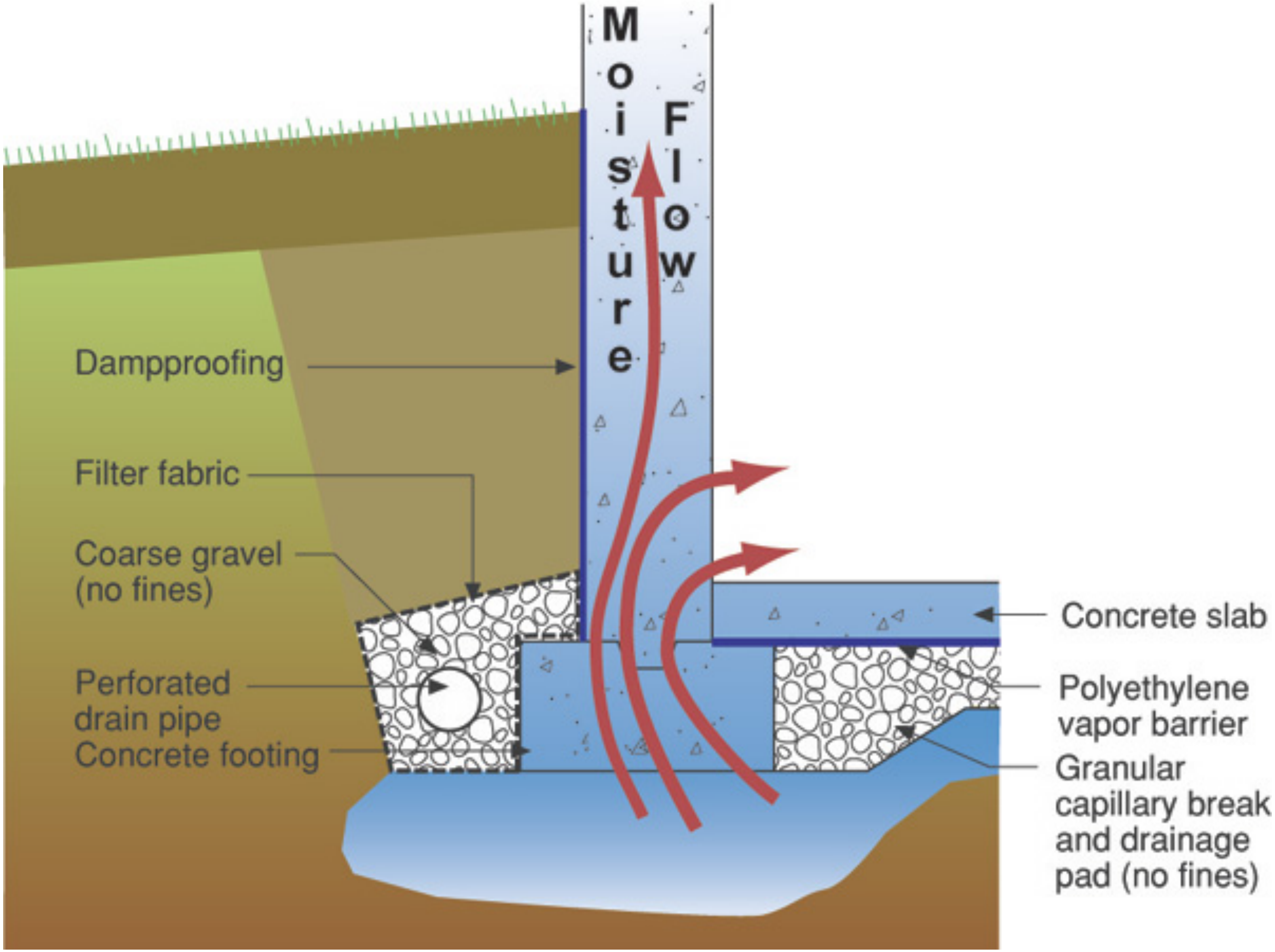
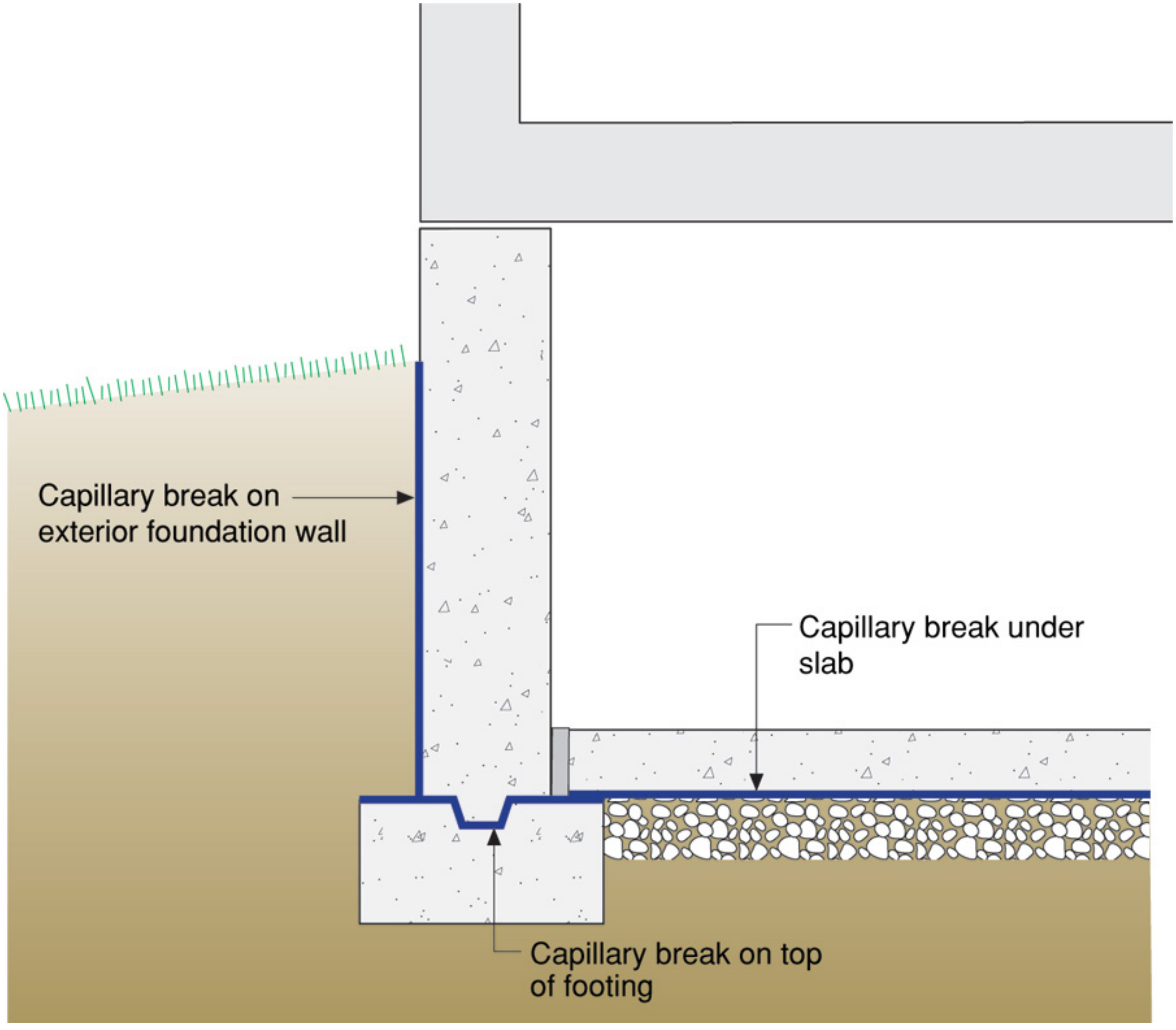


Figure 1b. Brick, sintered clay, porosity 40 per cent.

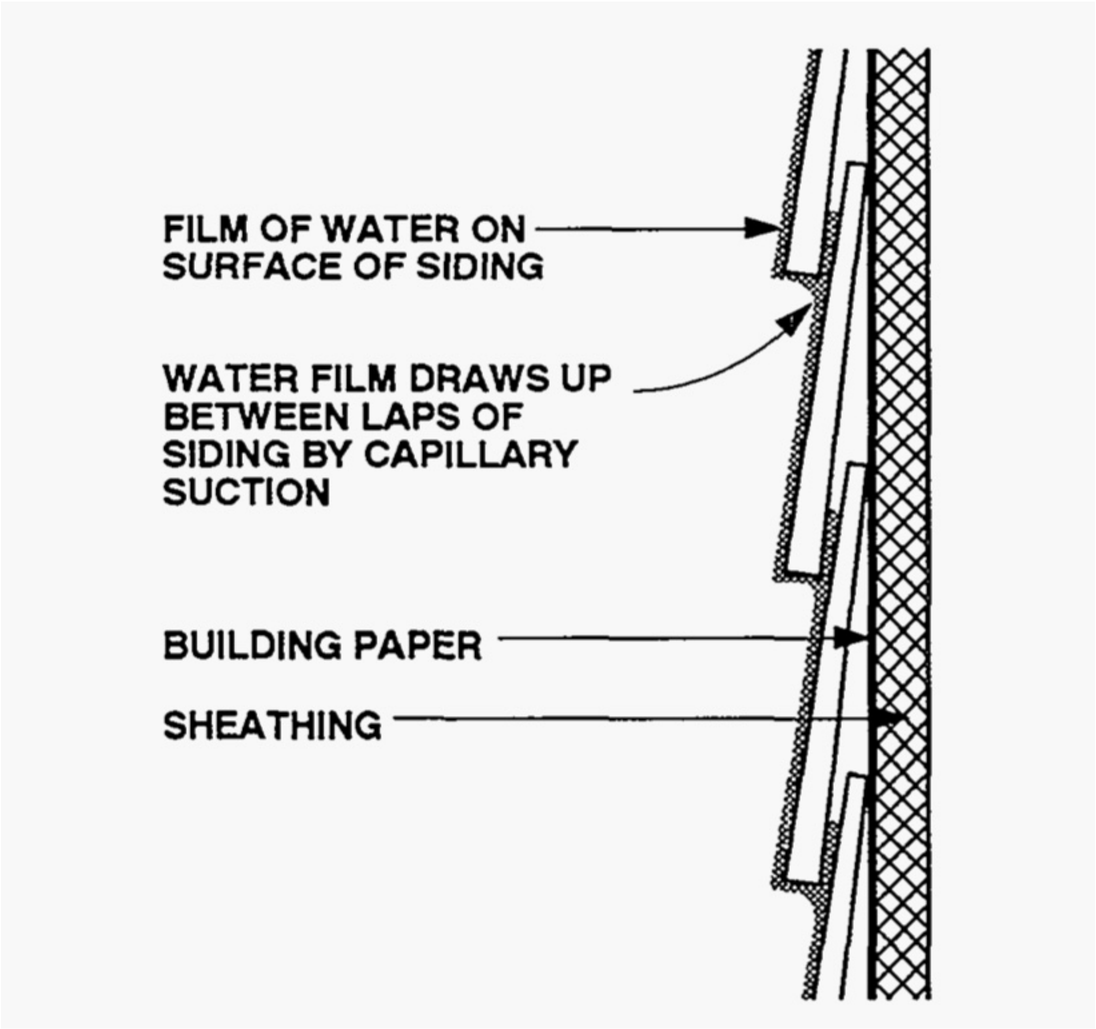


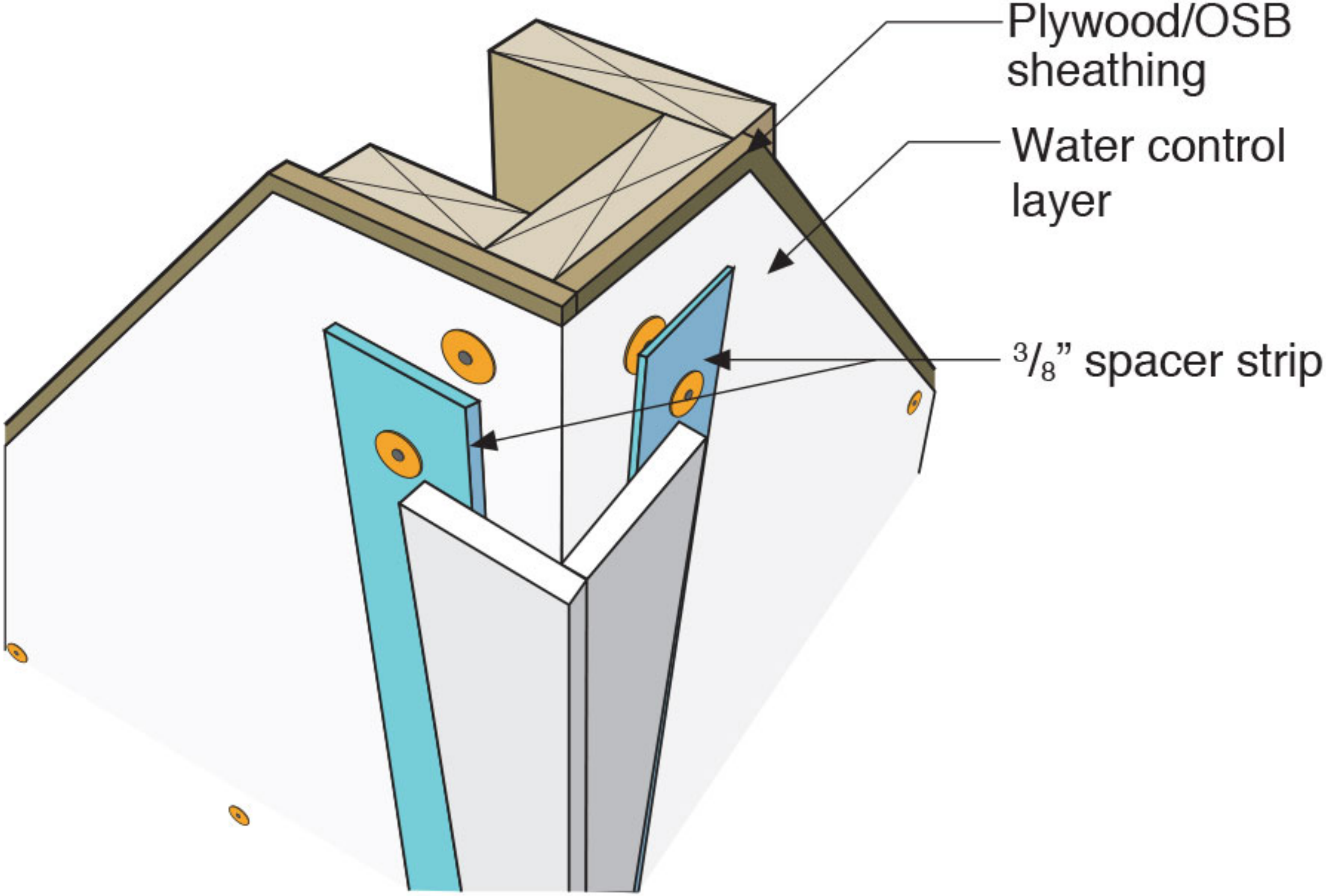


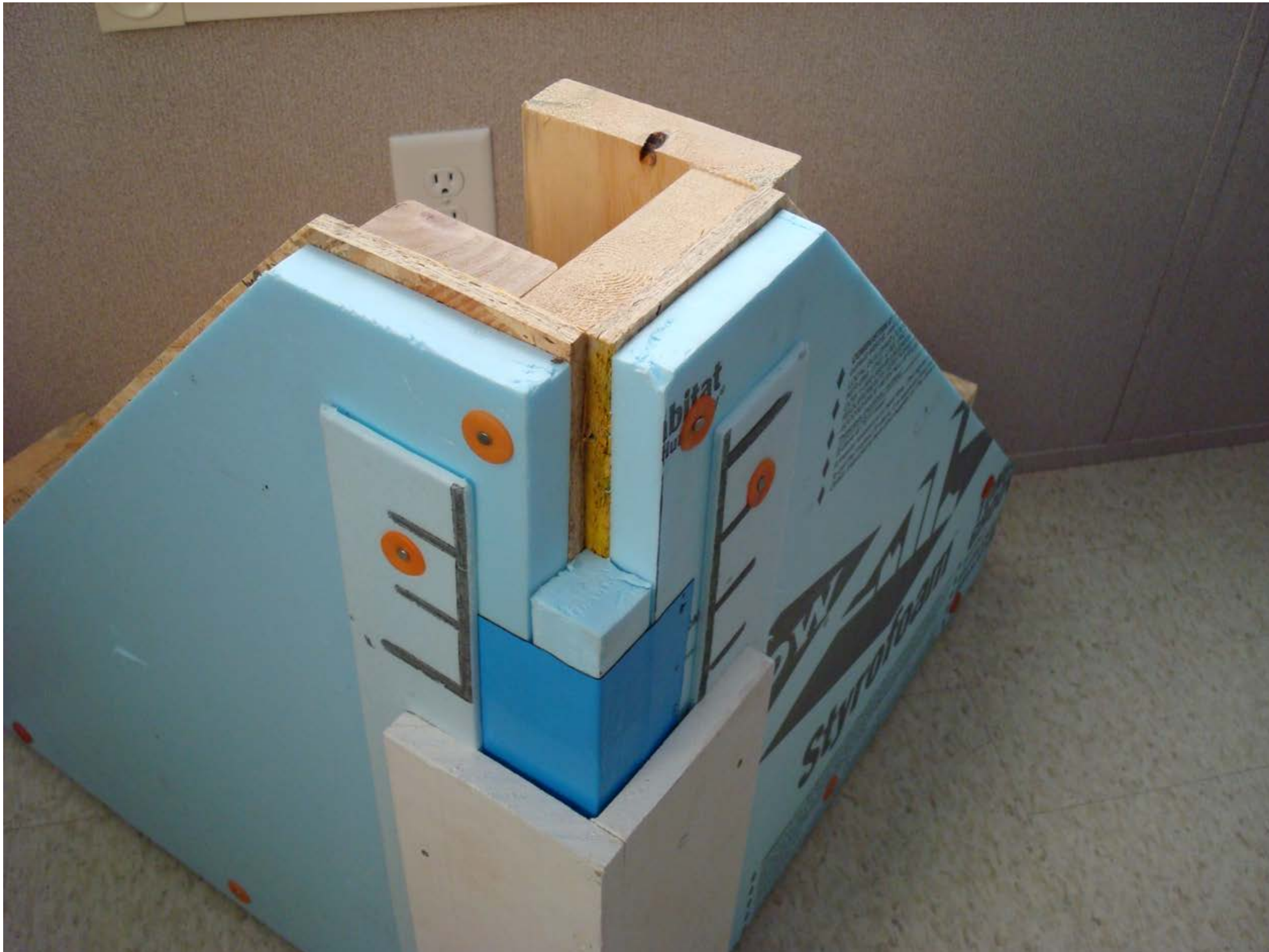

Moisture Flow
Dampproofing
Filter fabric
Coarse gravel (no fines)
Perforated drain pipe
Concrete footing
Concrete slab
Polyethylene vapor barrier
Granular capillary break and drainage pad (no fines)

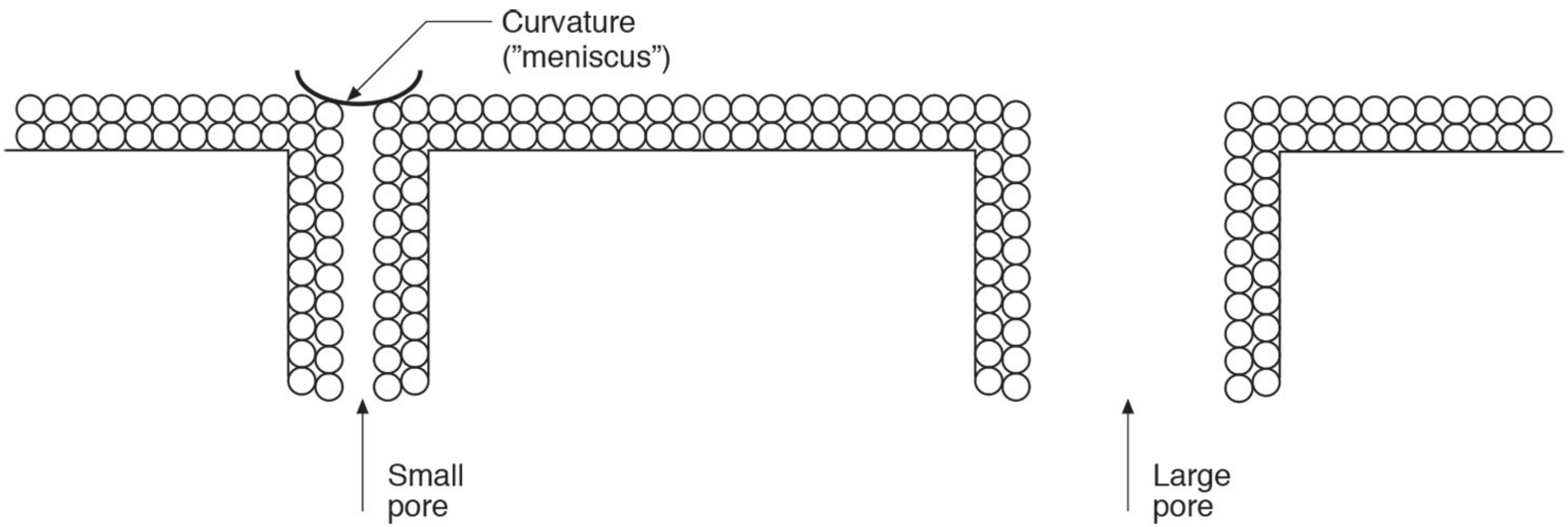

Capillary break on
exterior foundation wall
Capillary break under
slab
Capillary break on top
of footing

Siding Laps

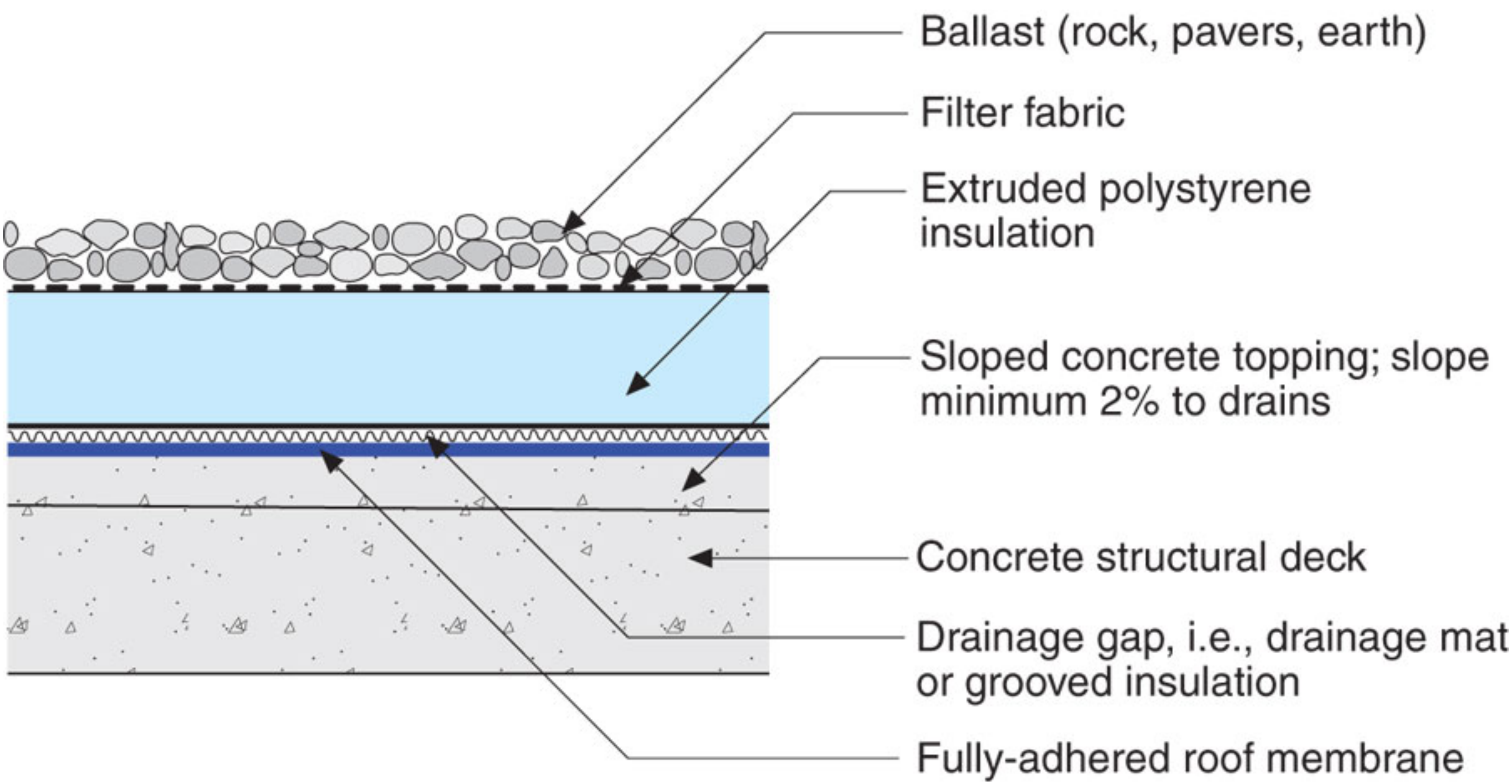

FILM OF WATER ON
SURFACE OF SIDING
WATER FILM DRAWS UP
BETWEEN LAPS OF
SIDING BY CAPILLARY
SUCTION
BUILDING PAPER
SHEATHING

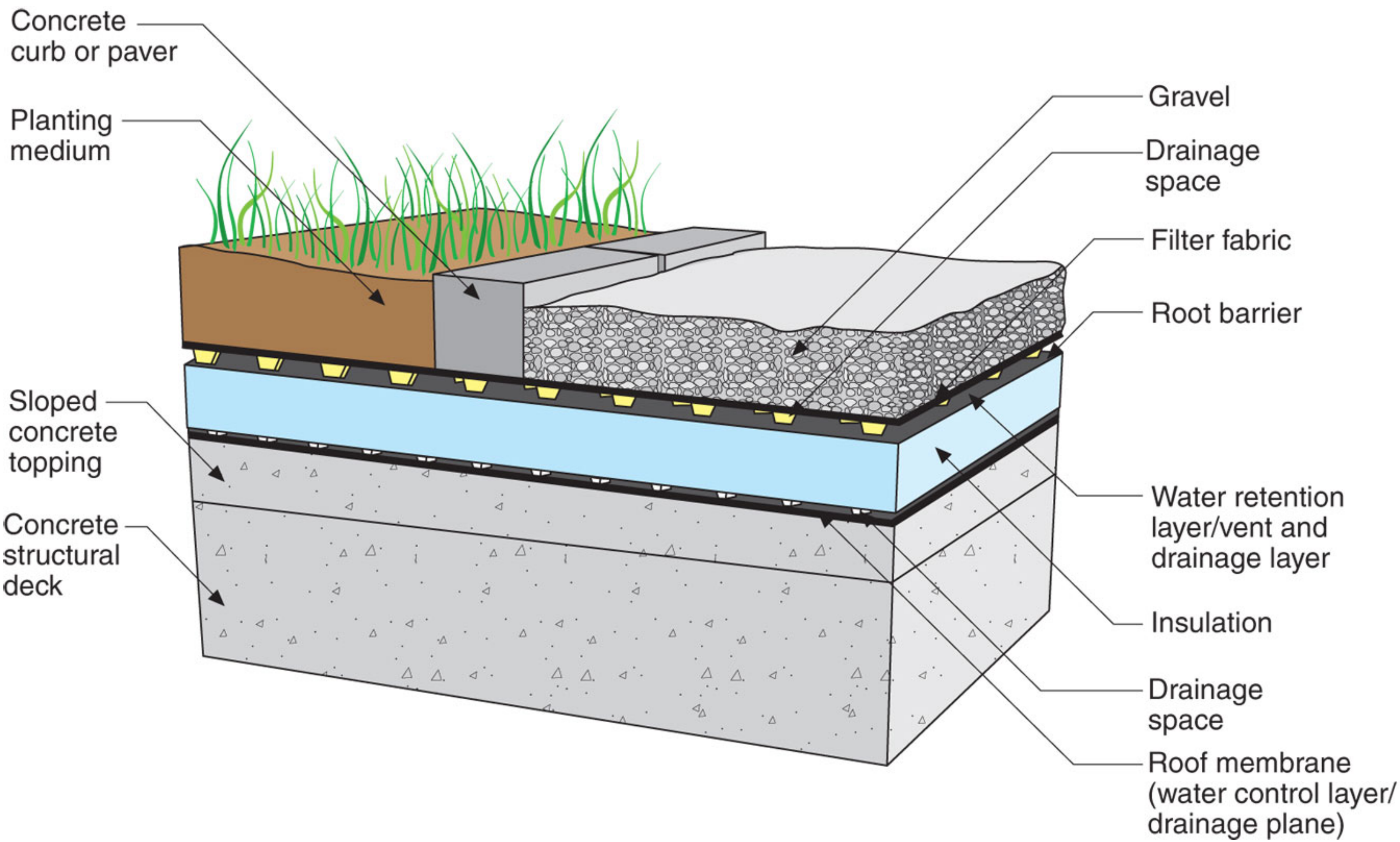

Plywood/OSB sheathing
Water control layer
3/8" spacer strip

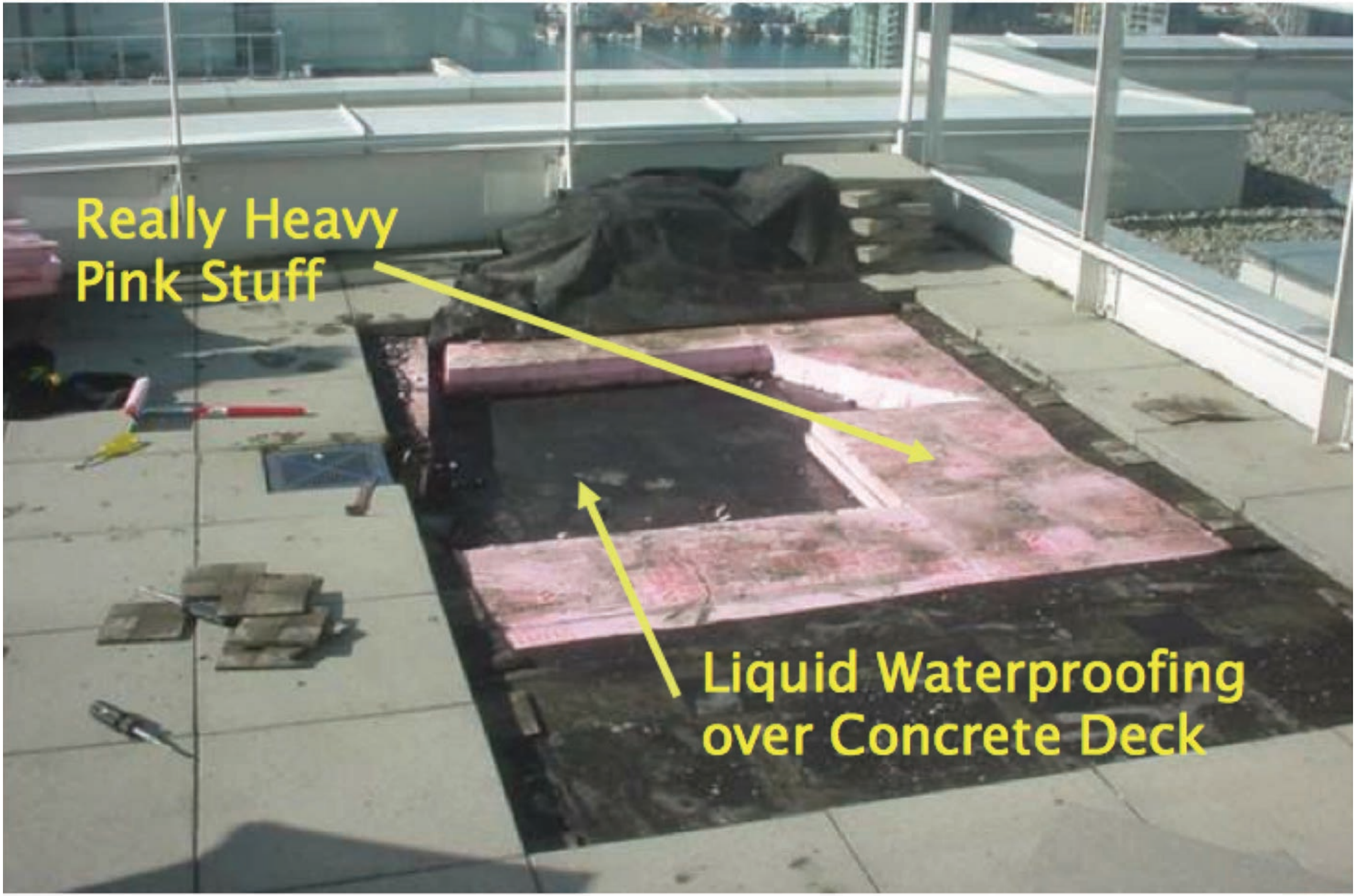

Styrofoam



Curvature
("meniscus")
Small
pore
Large
pore


Ballast (rock, pavers, earth)
Filter fabric
Extruded polystyrene insulation
Sloped concrete topping; slope minimum 2% to drains
Concrete structural deck
Drainage gap, i.e., drainage mat or grooved insulation
Fully-adhered roof membrane

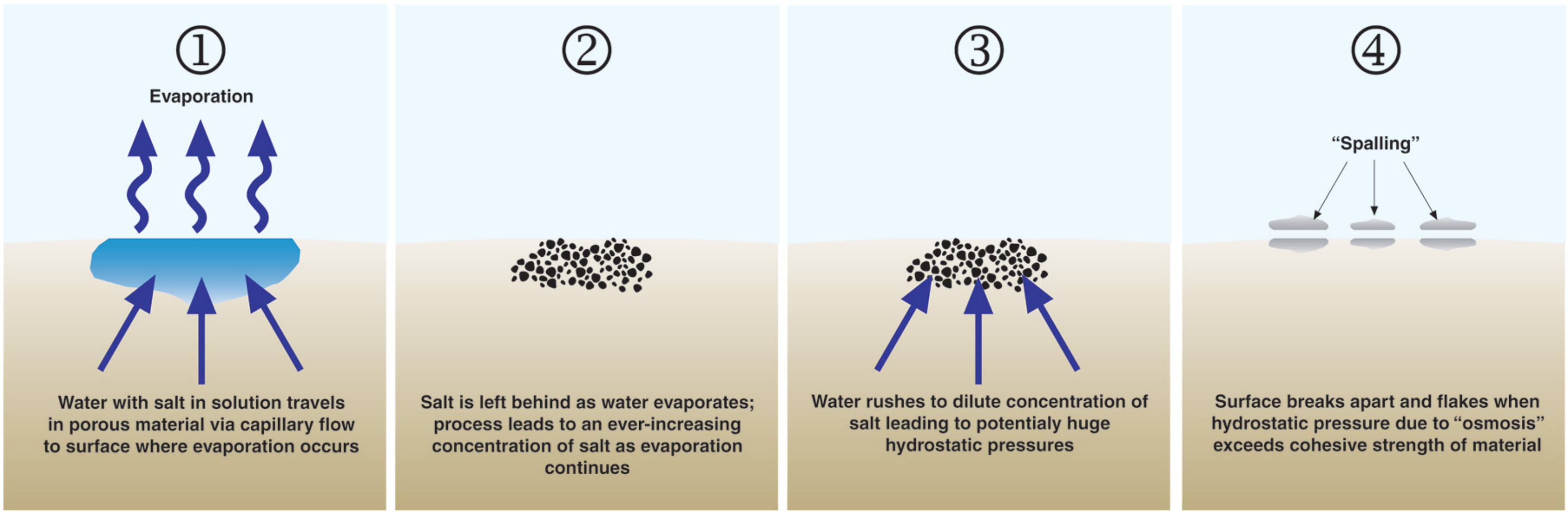

Concrete curb or paver
Planting medium
Sloped concrete topping
Concrete structural deck
Gravel
Drainage space
Filter fabric
Root barrier
Water retention layer/vent and drainage layer
Insulation
Drainage space
Roof membrane (water control layer/ drainage plane)


Really Heavy
Pink Stuff
Liquid Waterproofing
over Concrete Deck

Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration

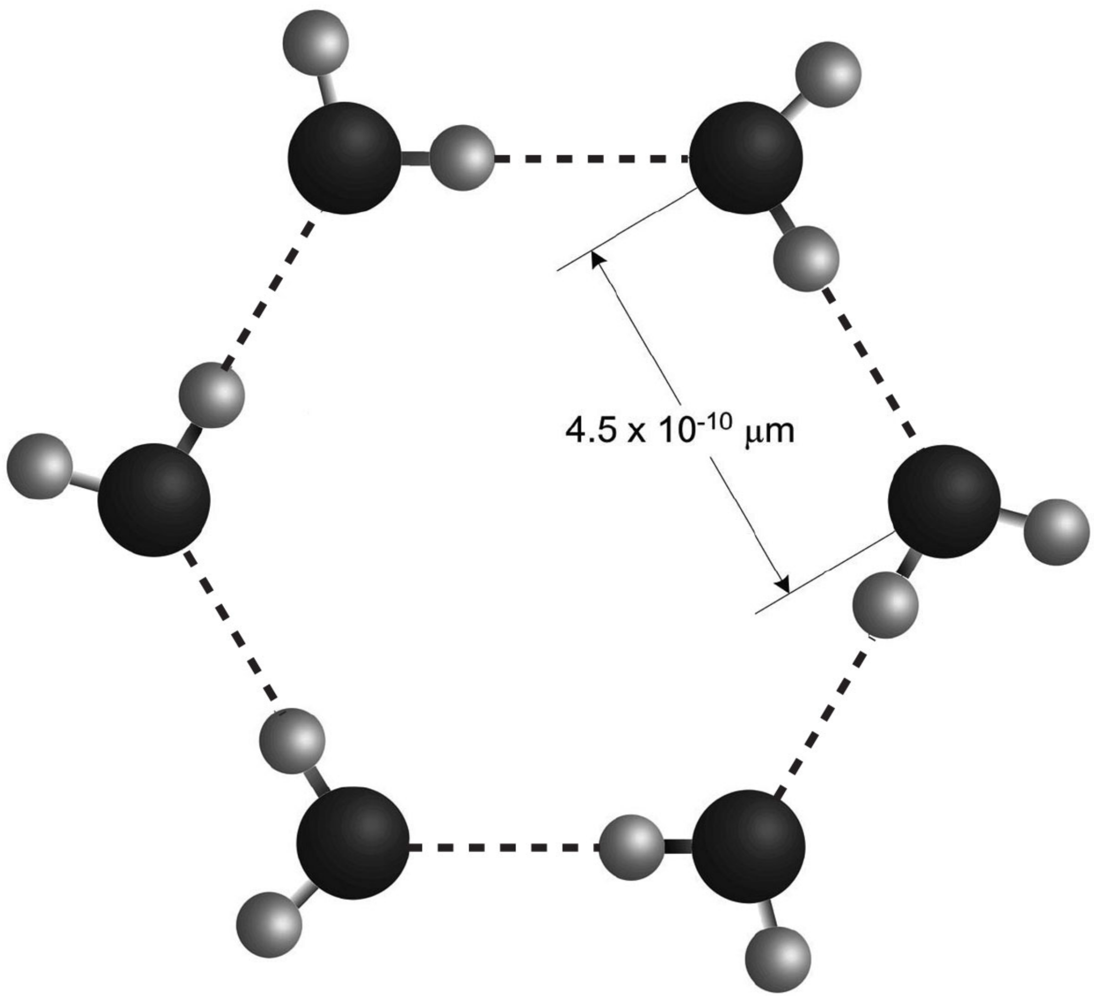
Capillarity + Salt = Osmosis

- Mineral salts carried in solution by capillary water
- When water evaporates from a surface the salts left behind form crystals in process called efflorescence
- When water evaporated beneath a surface the salts crystallize within the pore structure of the material in called sub-efflorescence
- The salt crystallization causes expansive forces that can exceed the cohesive strength of the material leading to spalling


①
Evaporation
Water with salt in solution travels in porous material via capillary flow to surface where evaporation occurs
②
Salt is left behind as water evaporates; process leads to an ever-increasing concentration of salt as evaporation continues
③
Water rushes to dilute concentration of salt leading to potentialy huge hydrostatic pressures
④
"Spalling"
Surface breaks apart and flakes when hydrostatic pressure due to "osmosis" exceeds cohesive strength of material

Pressures

• Diffusion Vapor Pressure	3 to 5 psi
• Capillary Pressure	300 to 500 psi
• Osmosis Pressure	3,000 to 5,000 psi


4.5 x 10-10 µm

Freeze-Thaw Damage

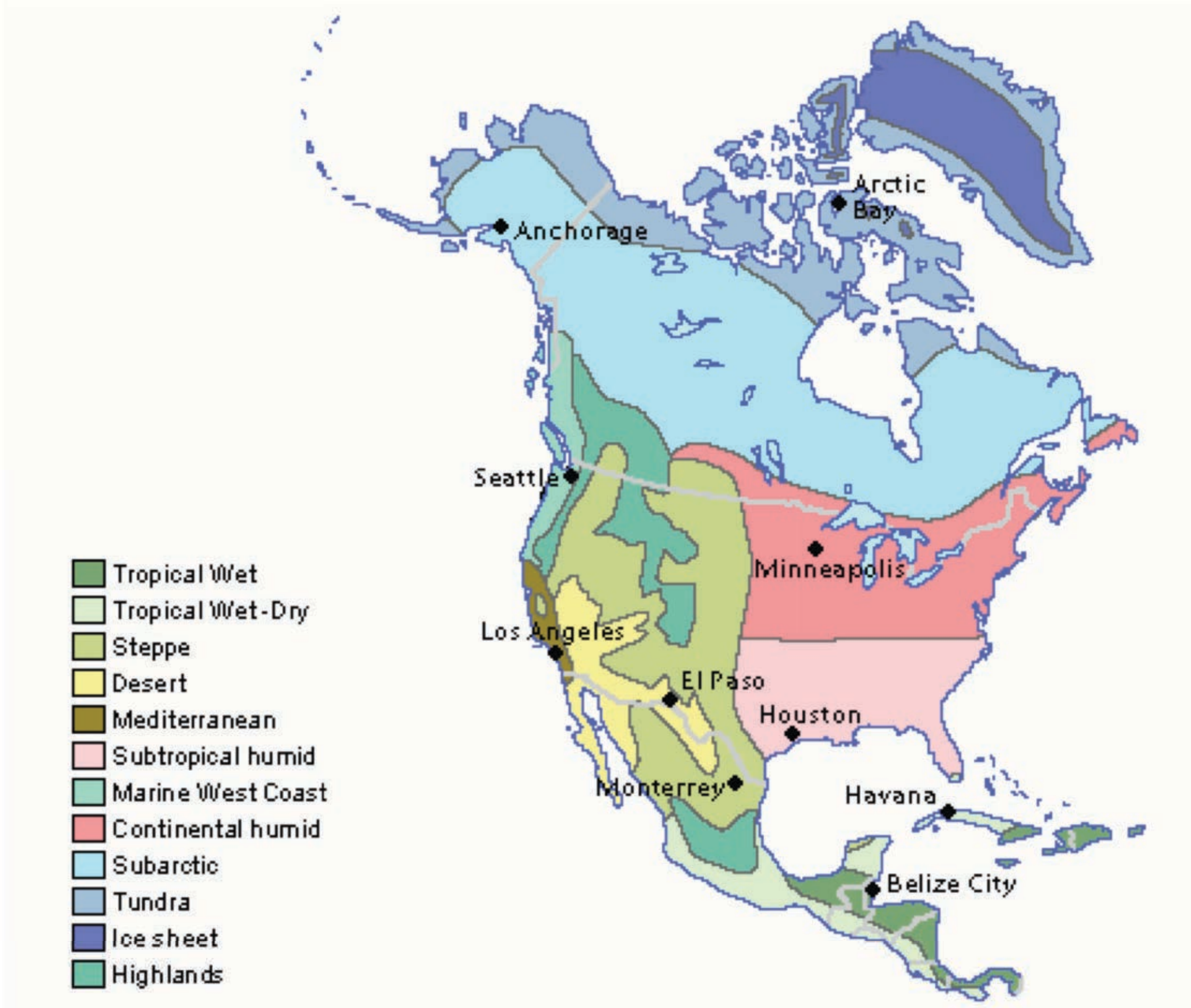
Freeze-Thaw Damage

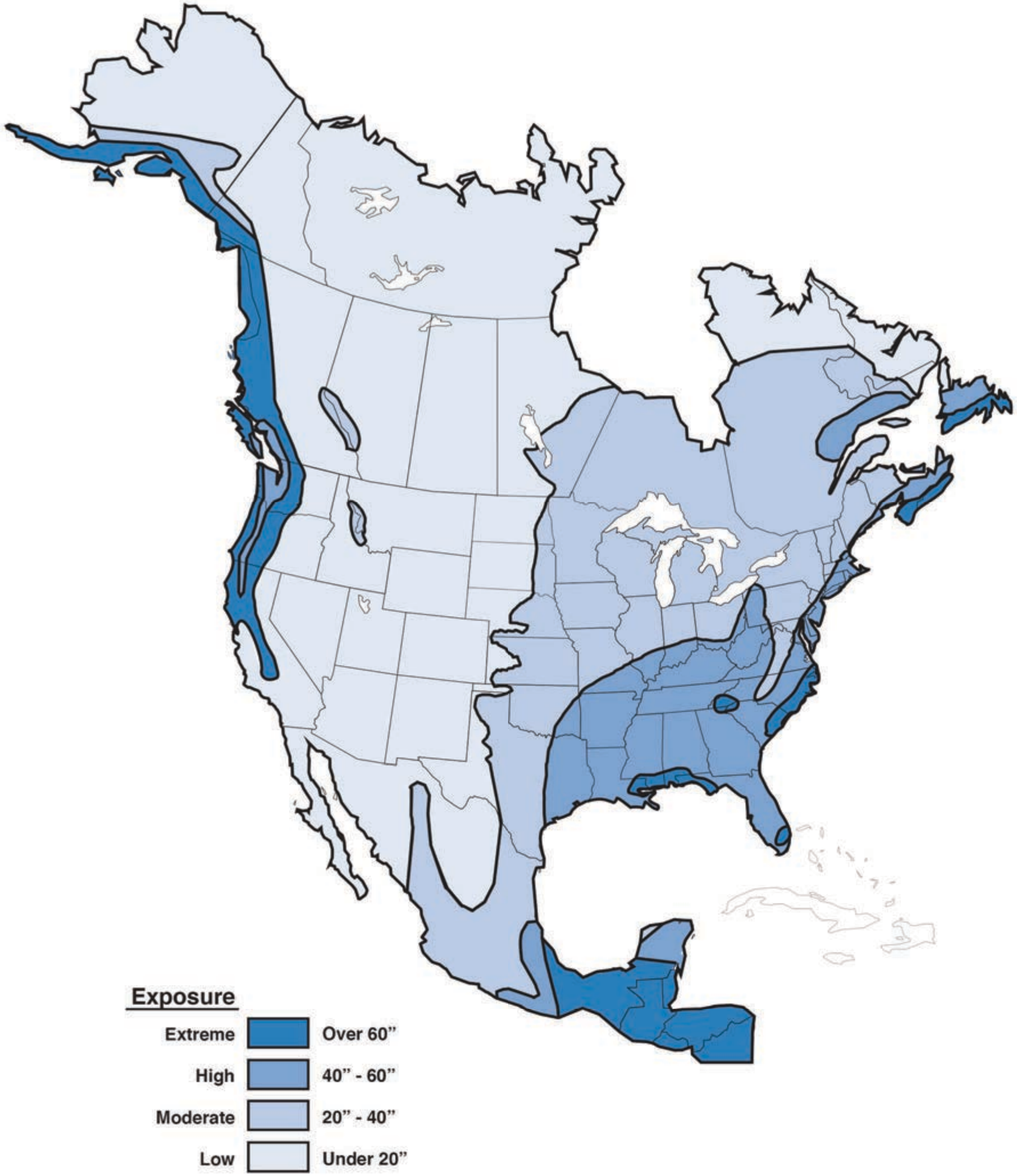
Freezing Temperatures

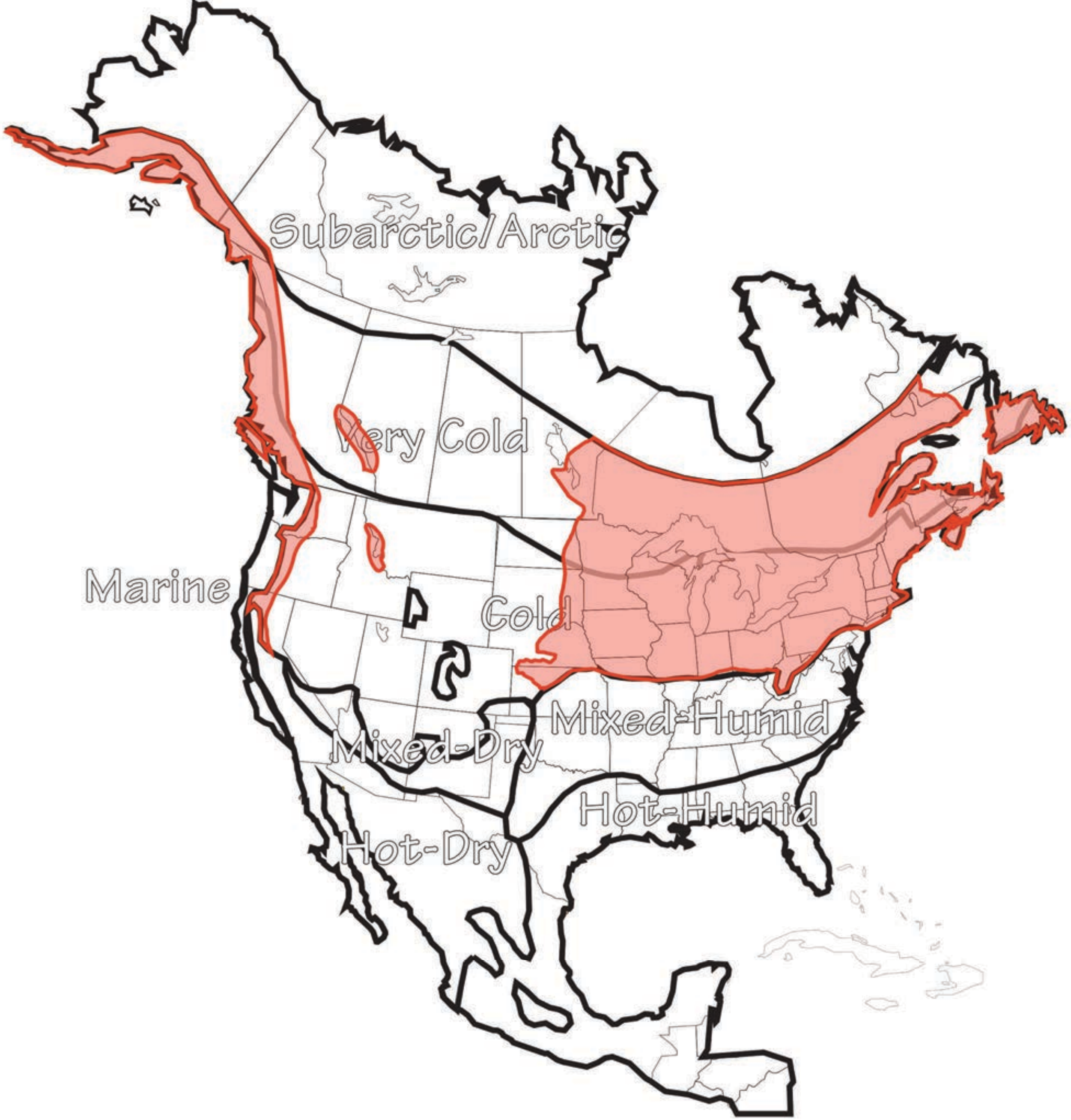
Water

Susceptible Brick


Subarctic/Arctic
Very Cold
Marine
Cold
Mixed-Humid
Mixed-Dry
Hot-Humid
Hot-Dry

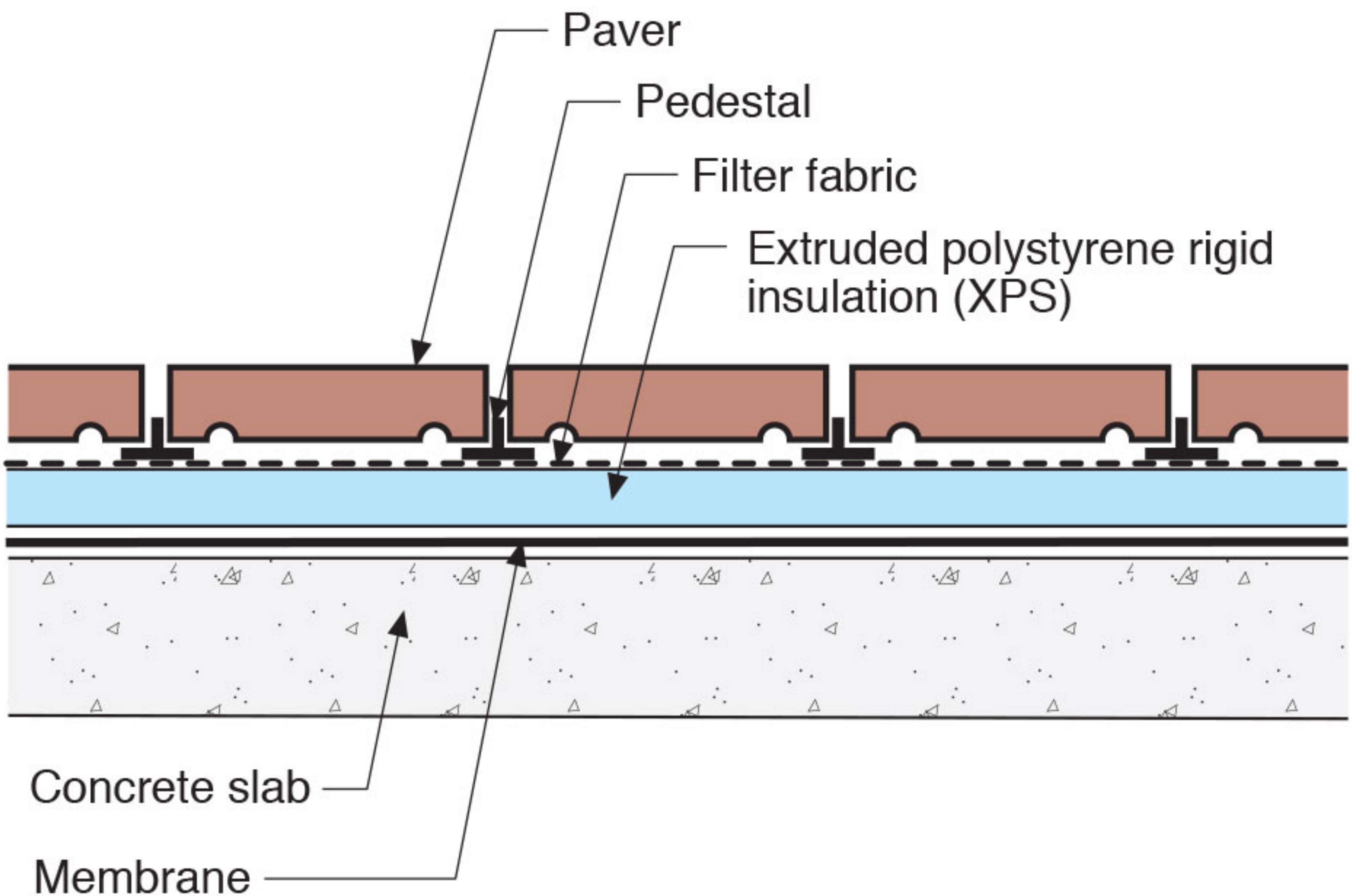

Arctic Bay
Anchorage
Seattle
Minneapolis
Los Angeles
El Paso
Houston
Monterrey
Havana
Belize City
Tropical Wet
Tropical Wet-Dry
Steppe
Desert
Mediterranean
Subtropical humid
Marine West Coast
Continental humid
Subarctic
Tundra
Ice sheet
Highlands

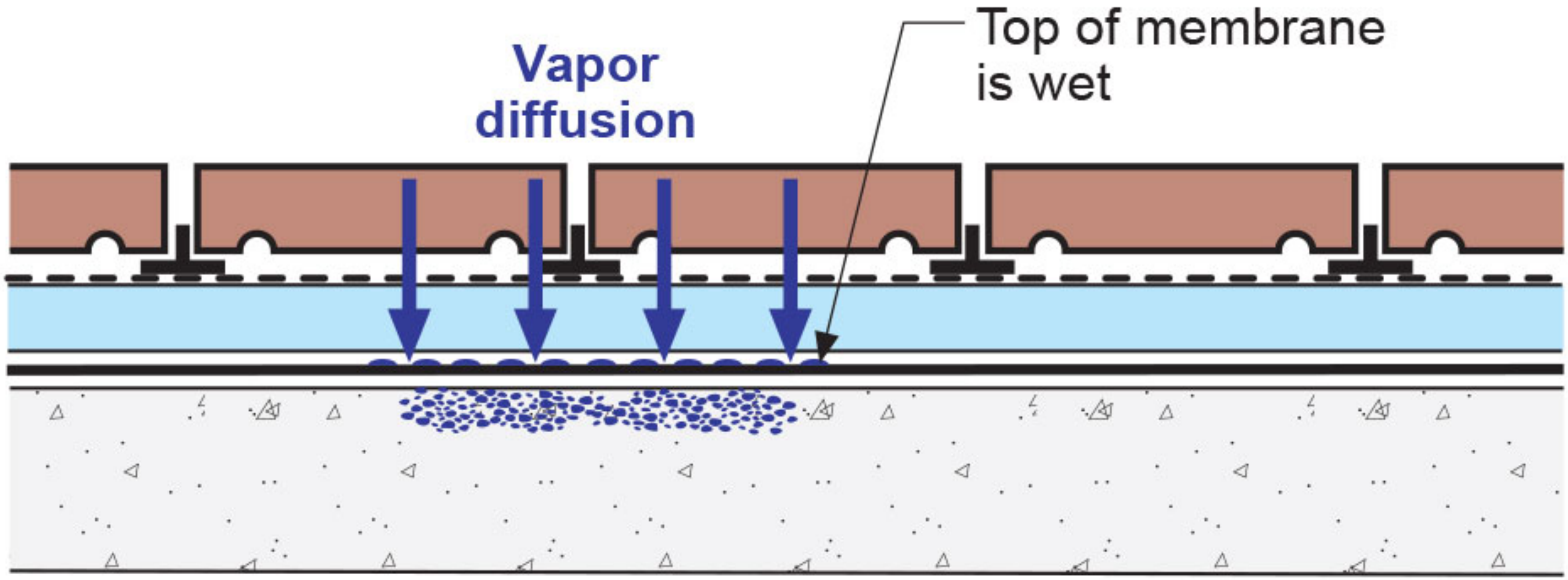

Exposure
Extreme
Over 60”
High
40” - 60”
Moderate
20” - 40”
Low
Under 20”

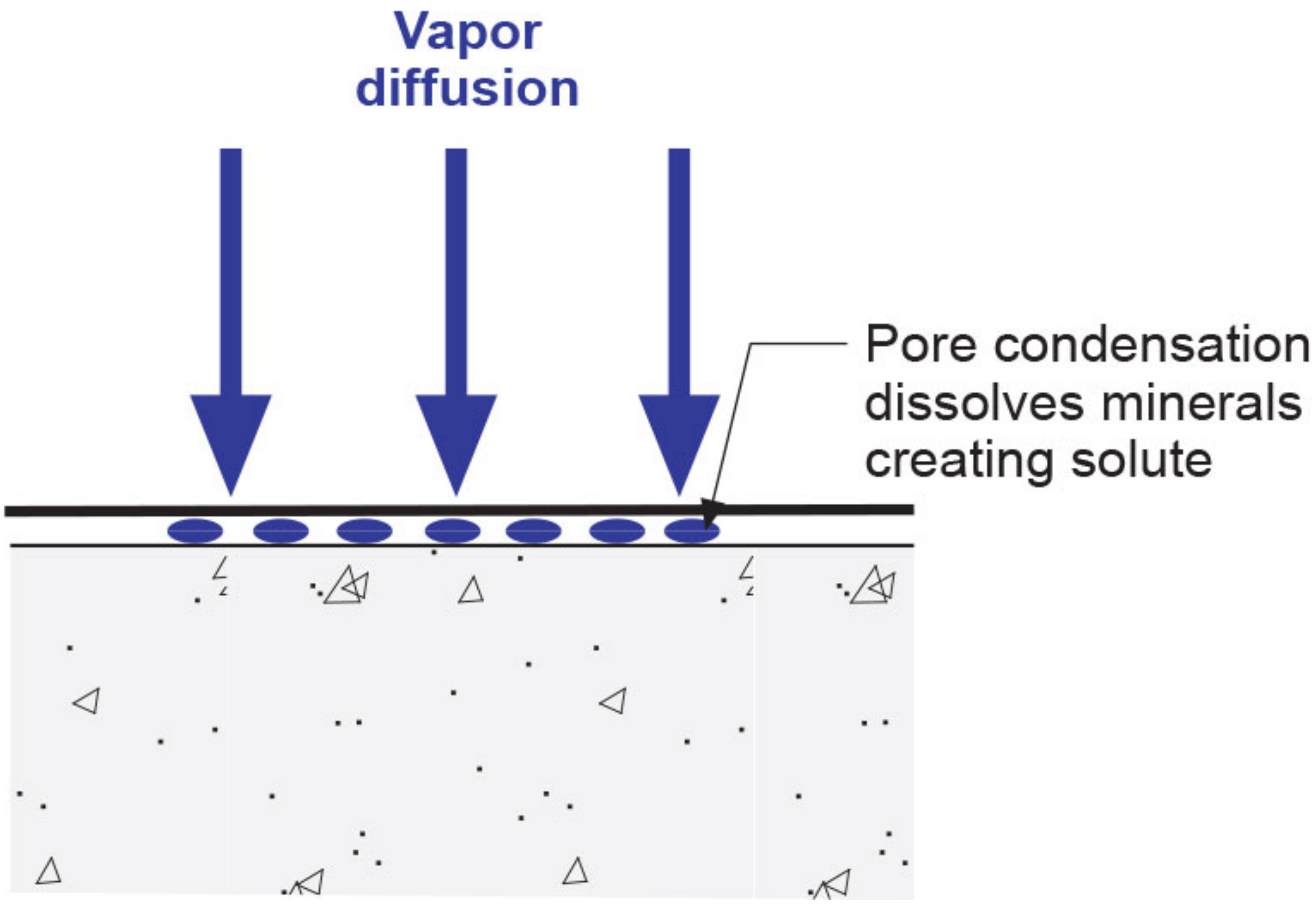


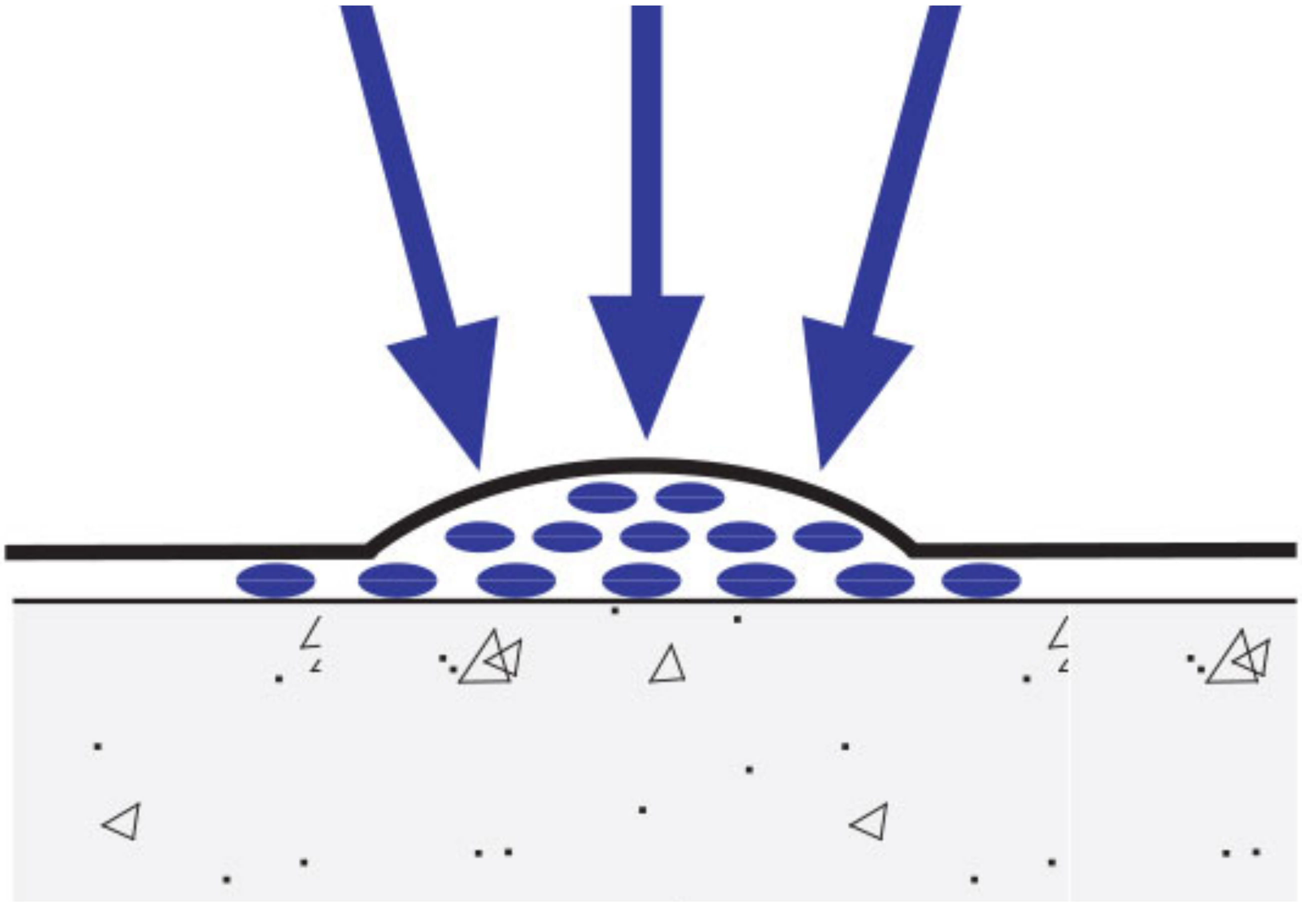
Subarctic/Arctic
Very Cold
Marine
Cold
Mixed-Humid
Mixed-Dry
Hot-Humid
Hot-Dry

More Osmosis

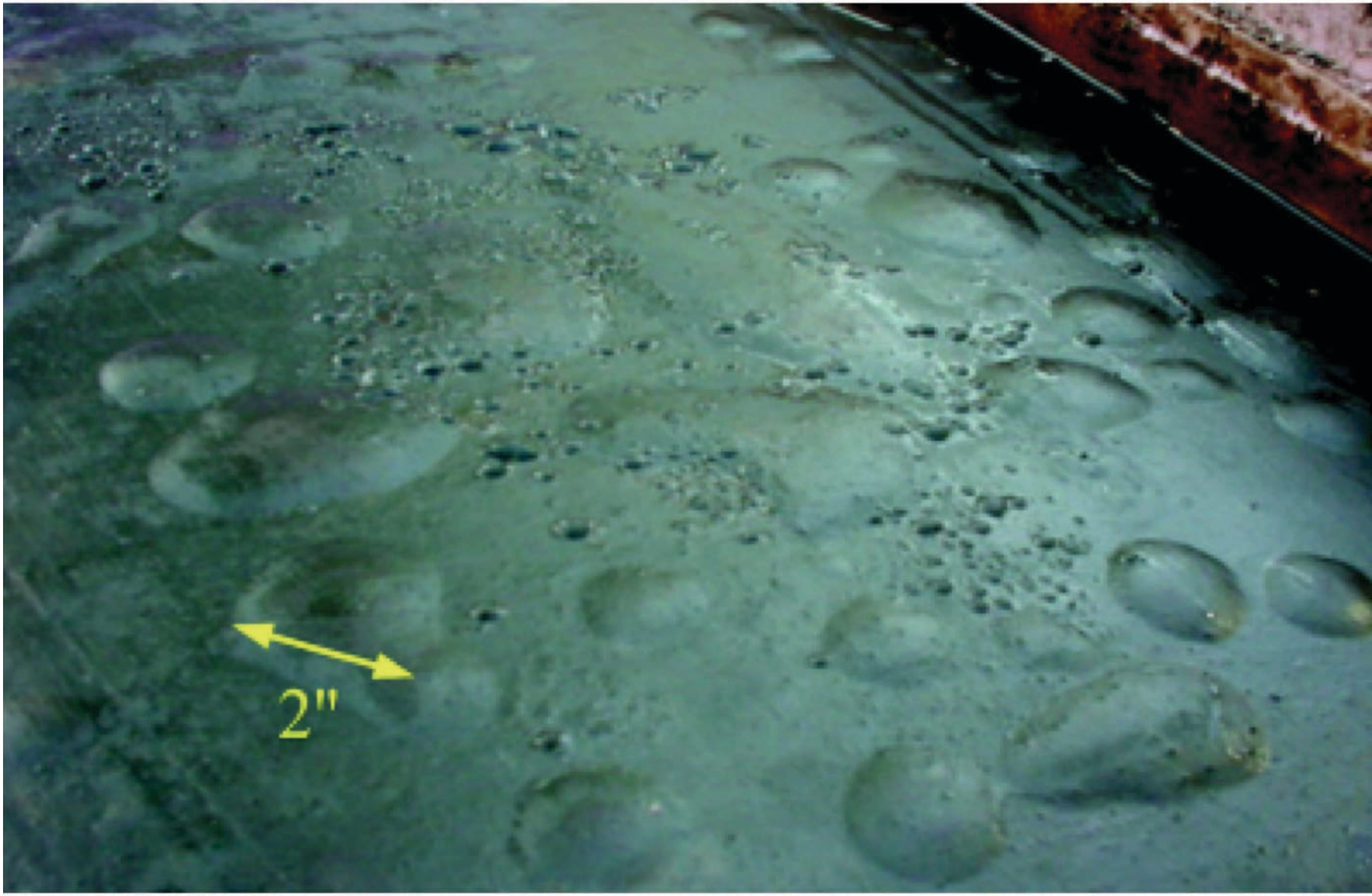

Paver
Pedestal
Filter fabric
Extruded polystyrene rigid insulation (XPS)
Concrete slab
Membrane


Vapor diffusion
Top of membrane is wet


Vapor
diffusion
Pore condensation
dissolves minerals
creating solute



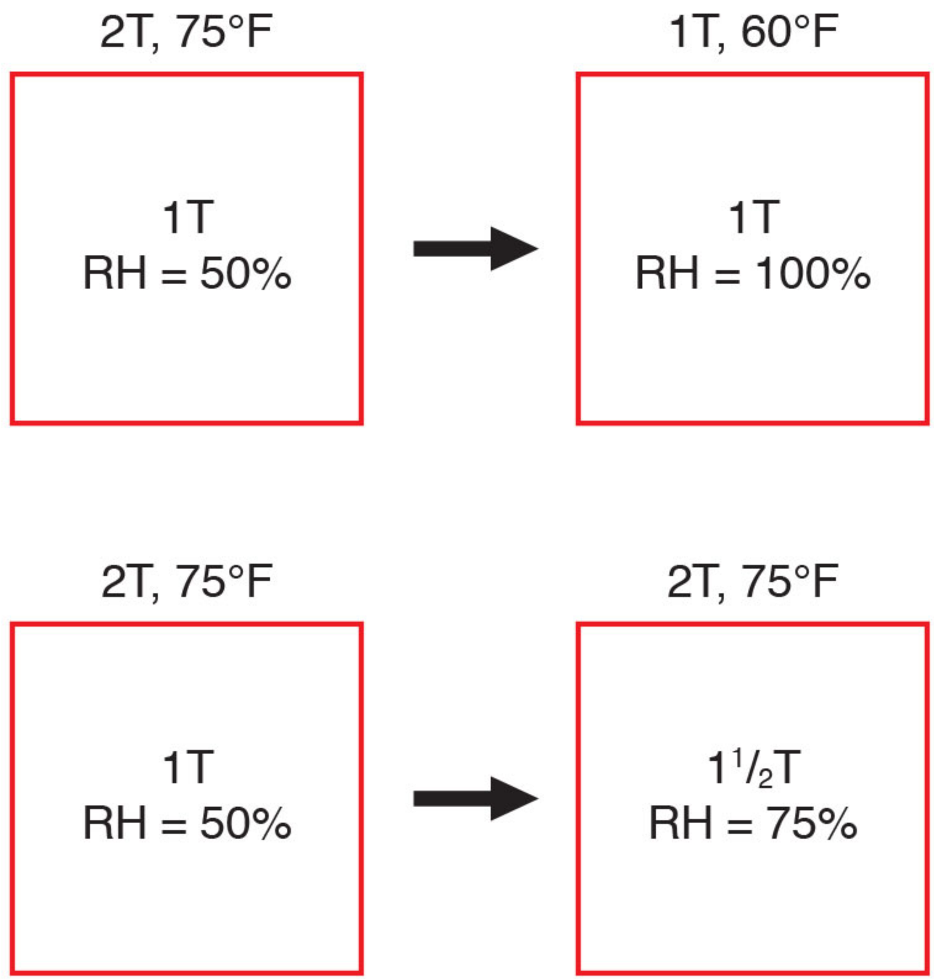

Paver Water Beds!

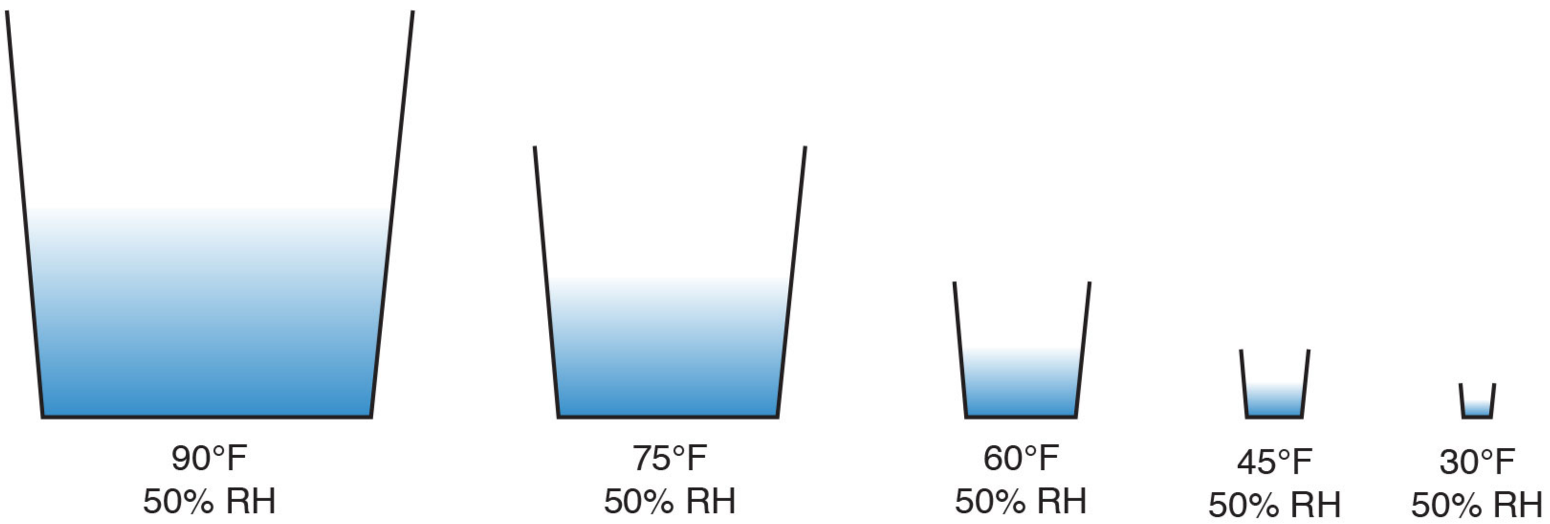

2"

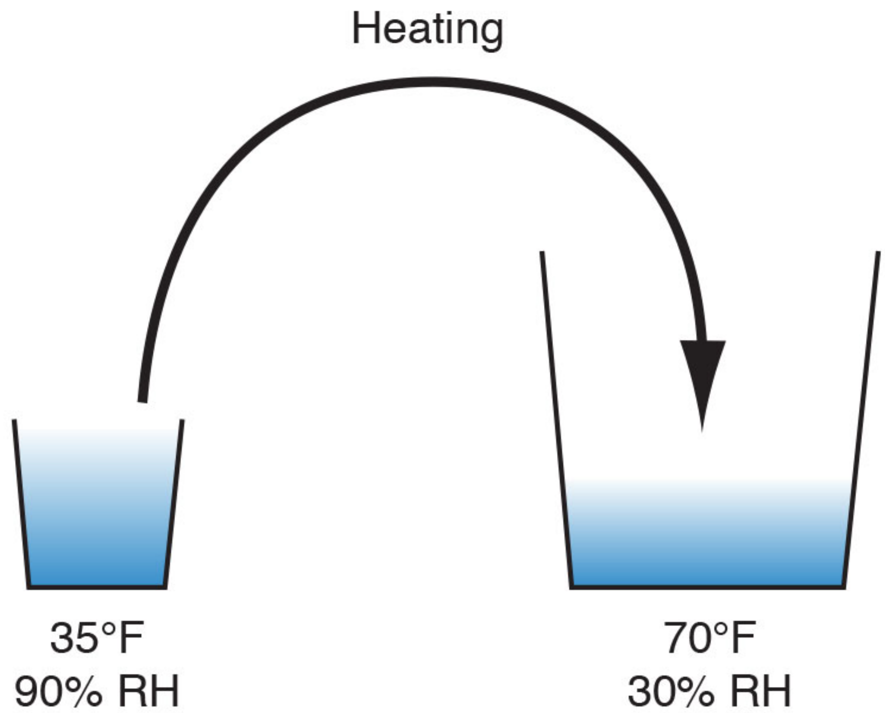
Need To Do An Aside…Necessary For A Segway

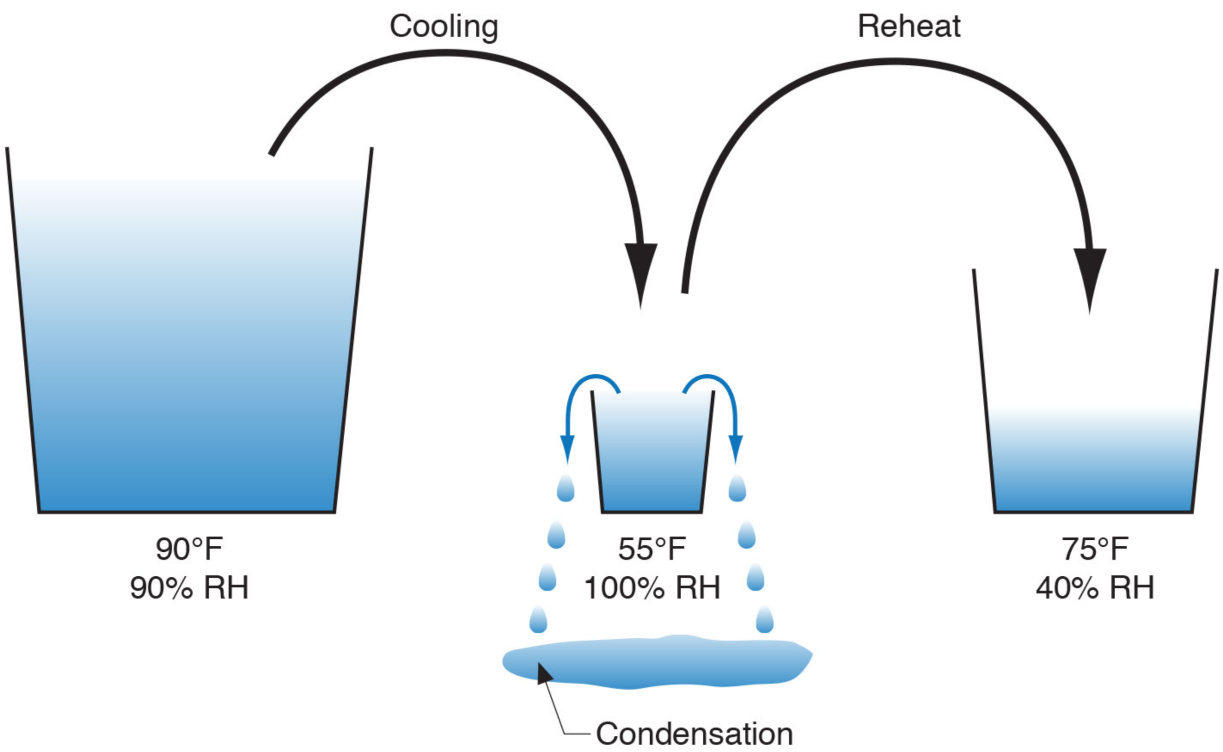
Relative Humidity

Vapor Pressure

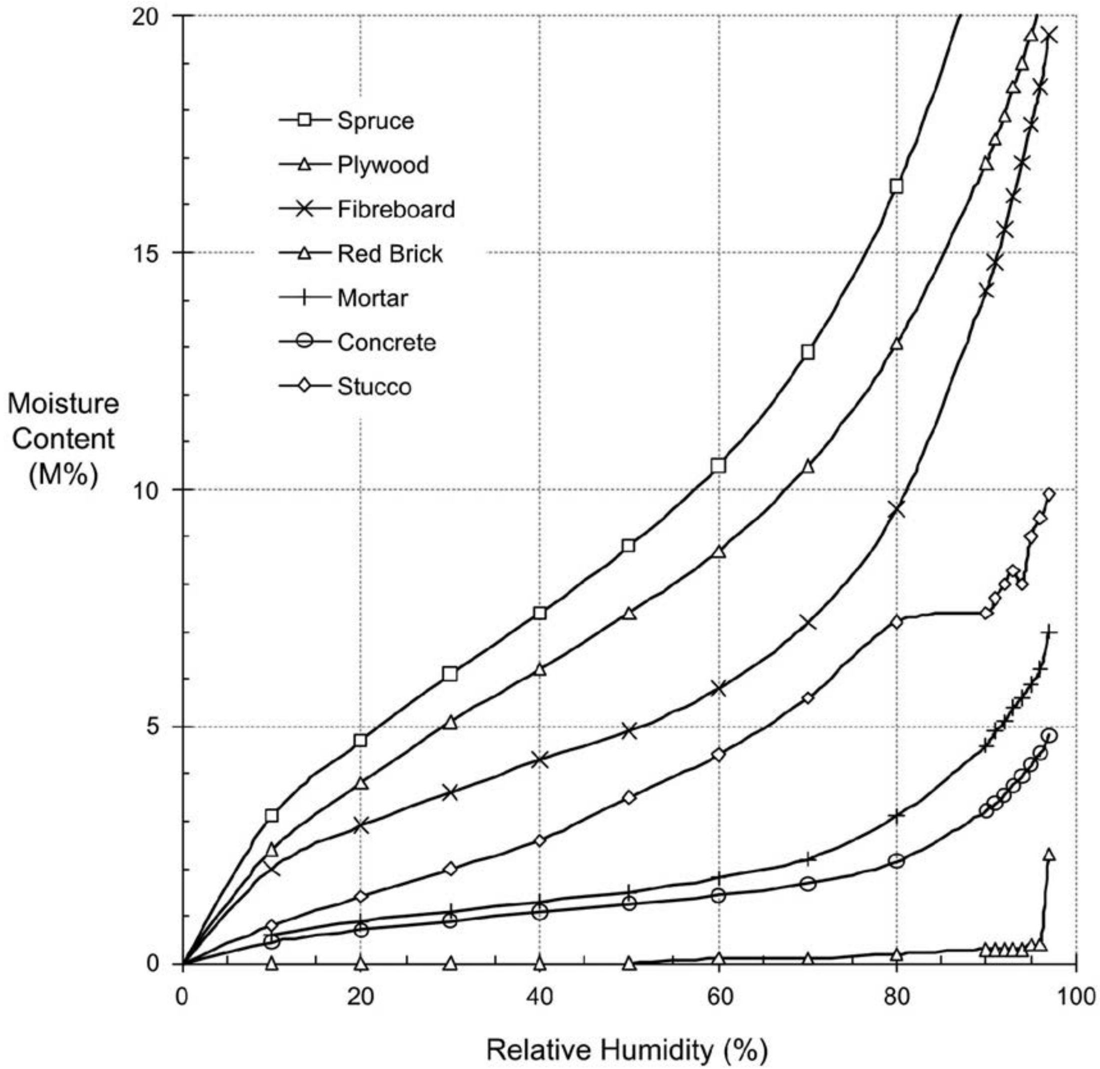

2T, 75°F
1T
RH = 50%
1T, 60°F
1T
RH = 100%
2T, 75°F
1T
RH = 50%
2T, 75°F
1 1/2T
RH = 75%


90°F
50% RH
75°F
50% RH
60°F
50% RH
45°F
50% RH
30°F
50% RH


Heating
35°F
90% RH
70°F
30% RH


Cooling
Reheat
90°F
90% RH
55°F
100% RH
75°F
40% RH
Condensation

Sorption



Sorption isotherm for several building materials [Kumaran 2002]
From Straube & Burnett, 2005

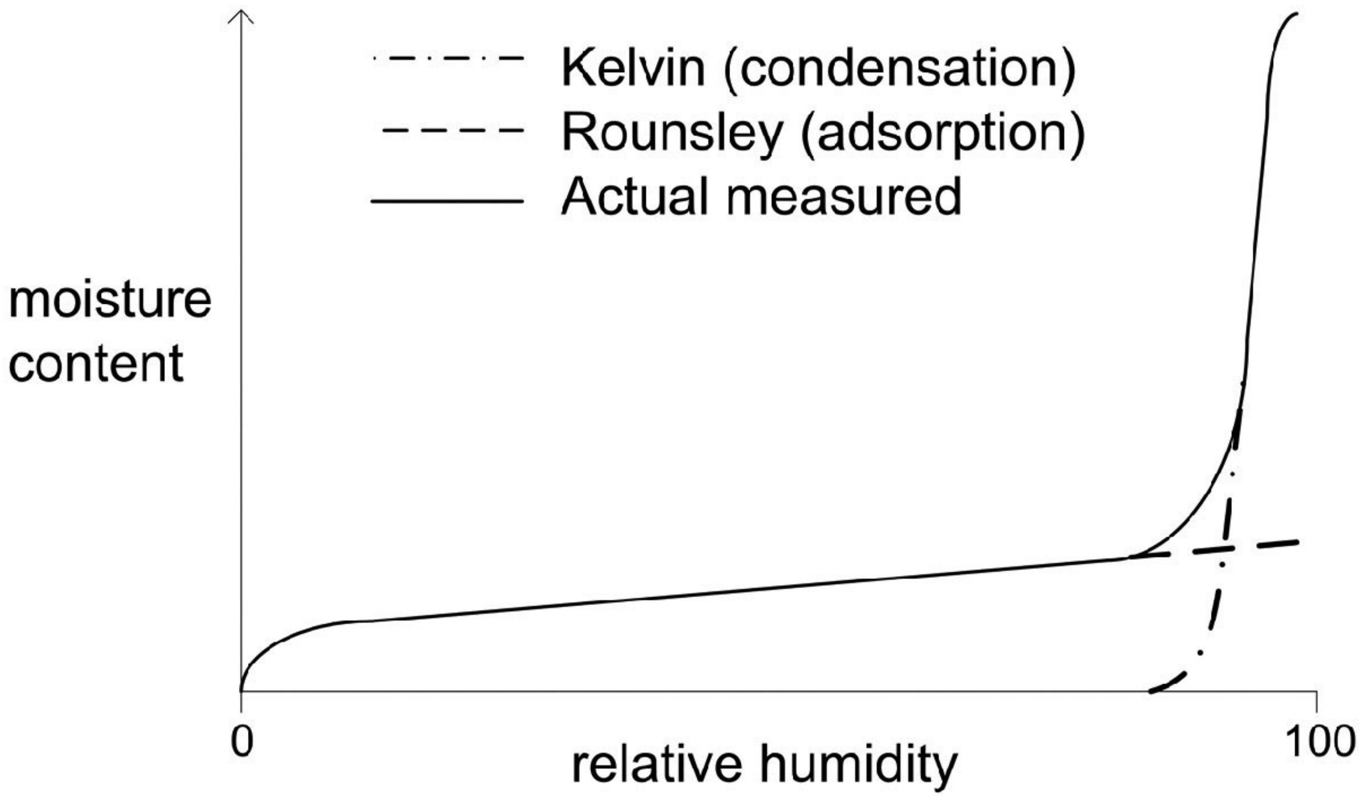
BET Theory

BET Theory

Stephen Brunauer

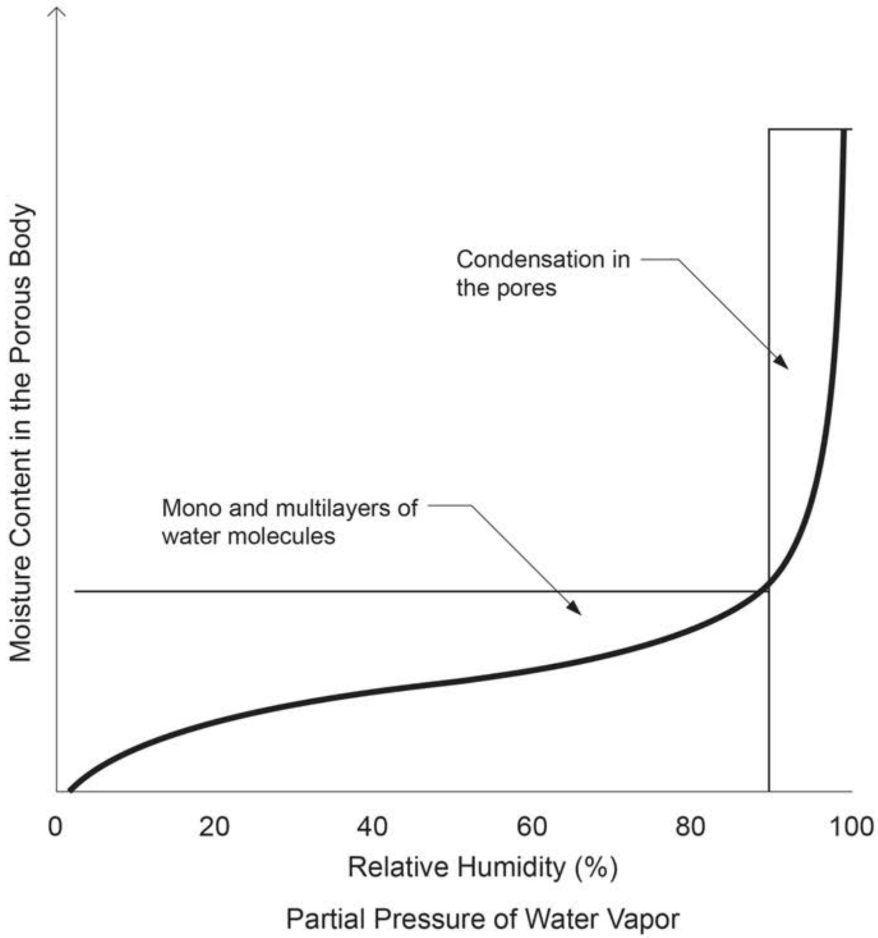
Paul Emmett

Edward Teller



Typical predicted sorption isotherm according to Kelvin equation and modified BET theory

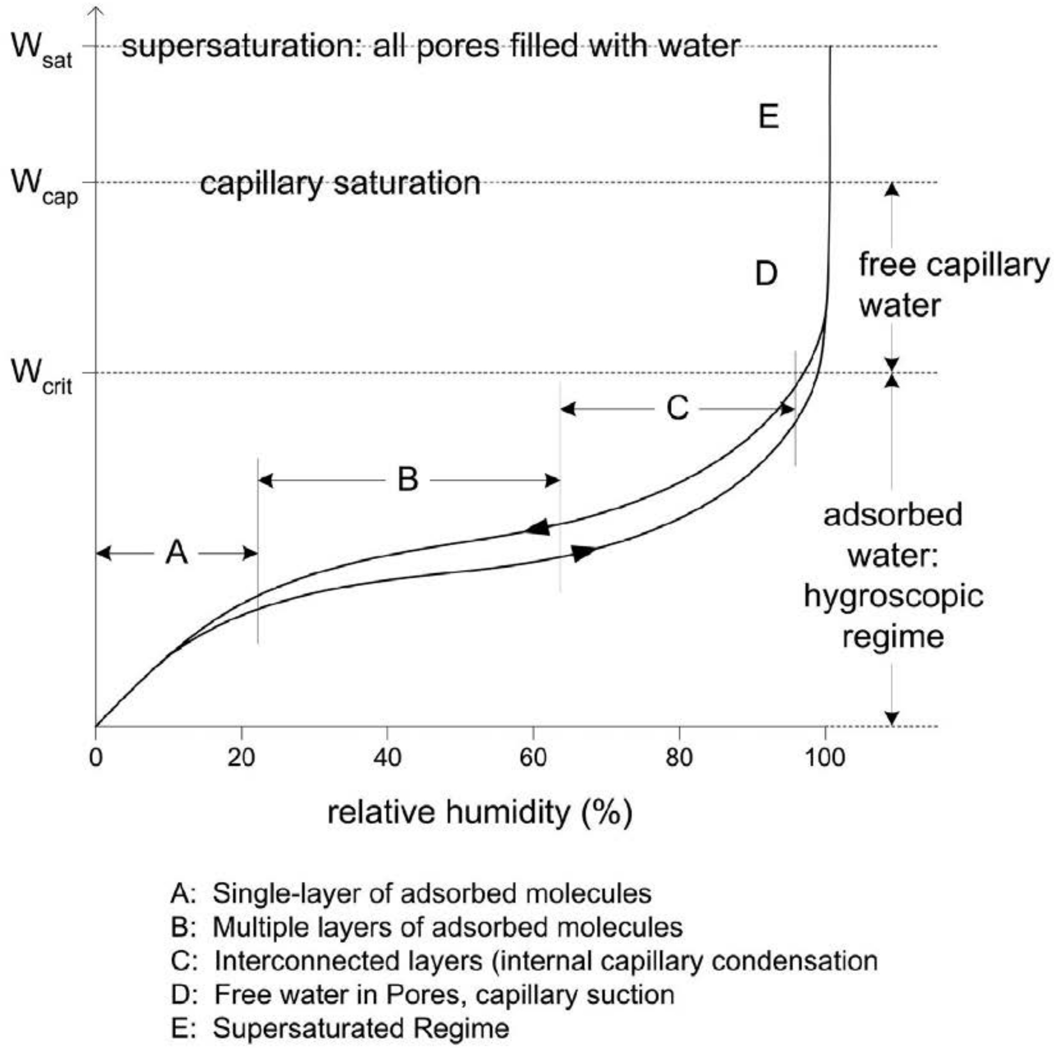
From Straube & Burnett, 2005



Change in the storage of moisture in a porous building material as the partial pressure of water vapor in the ambient air increases from zero to full saturation value at a given temperature.

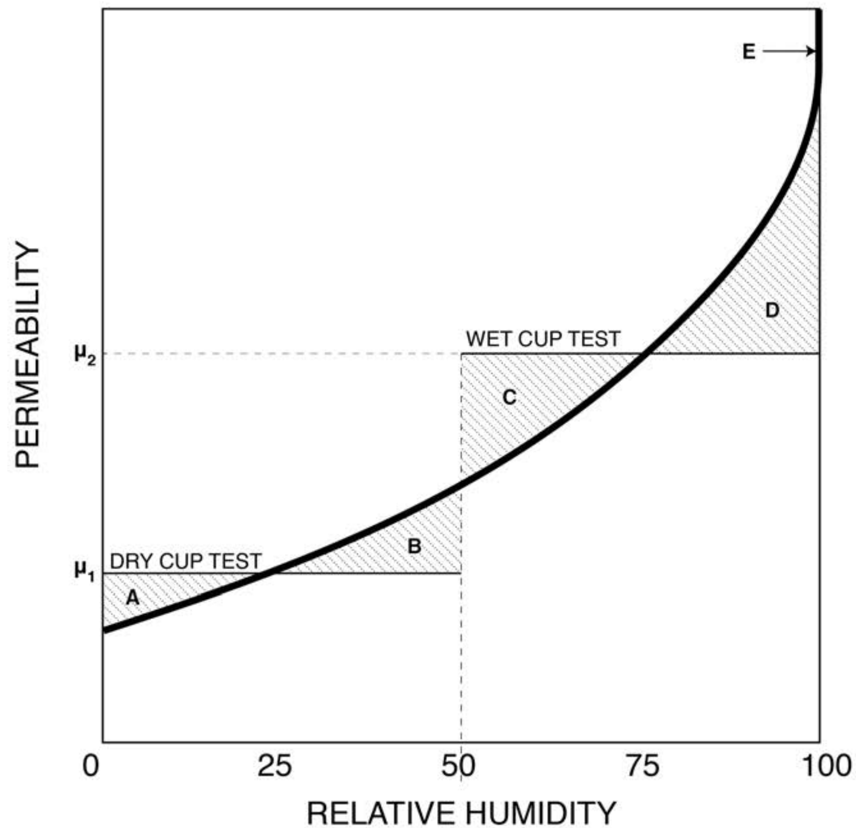
Sorption Curve

From M.K. Kumaran, ASTM MNL 18-2nd Edition, Moisture Control in Buildings, 2009



Regimes of moisture storage in a hygroscopic porous material

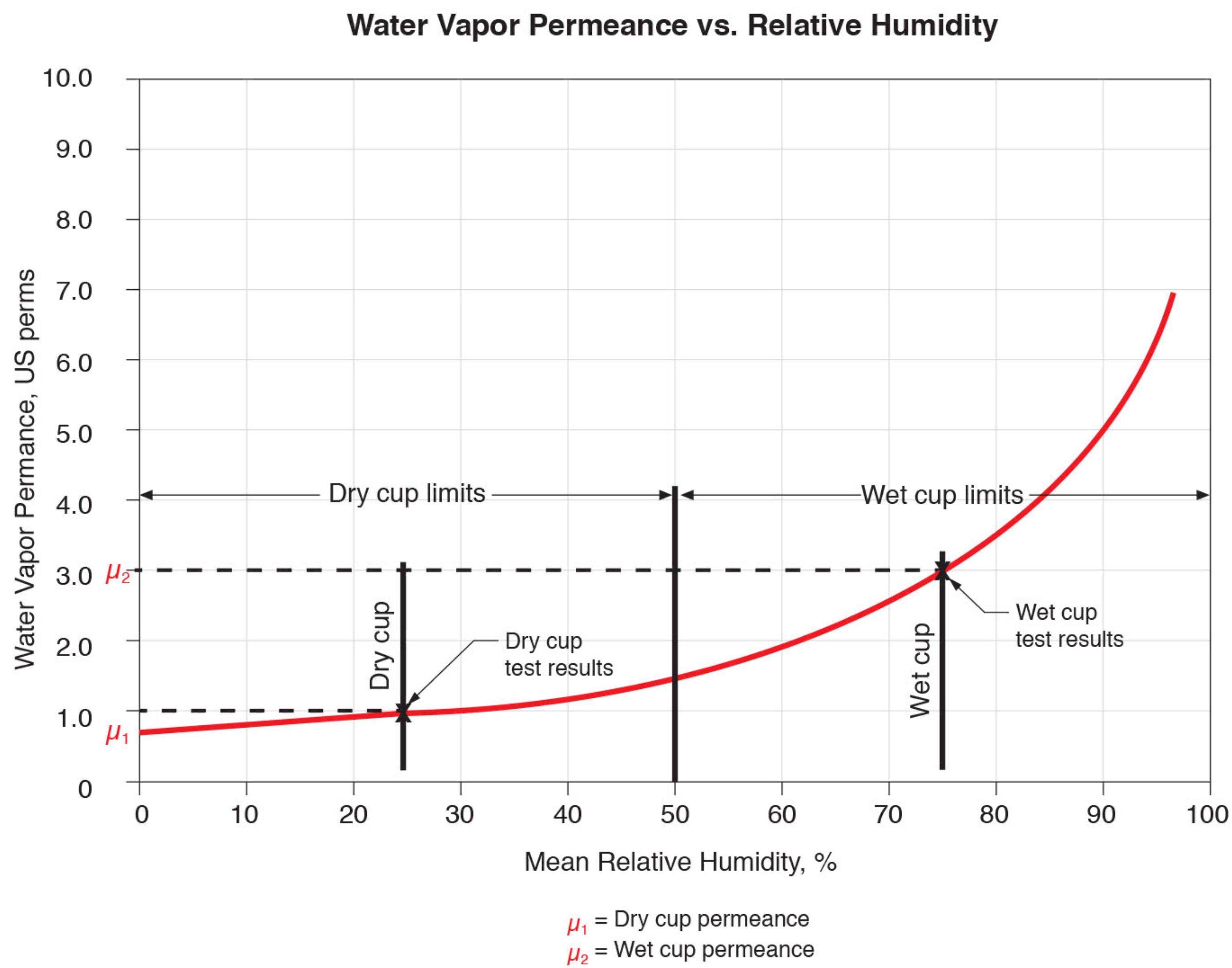
From Straube & Burnett, 2005

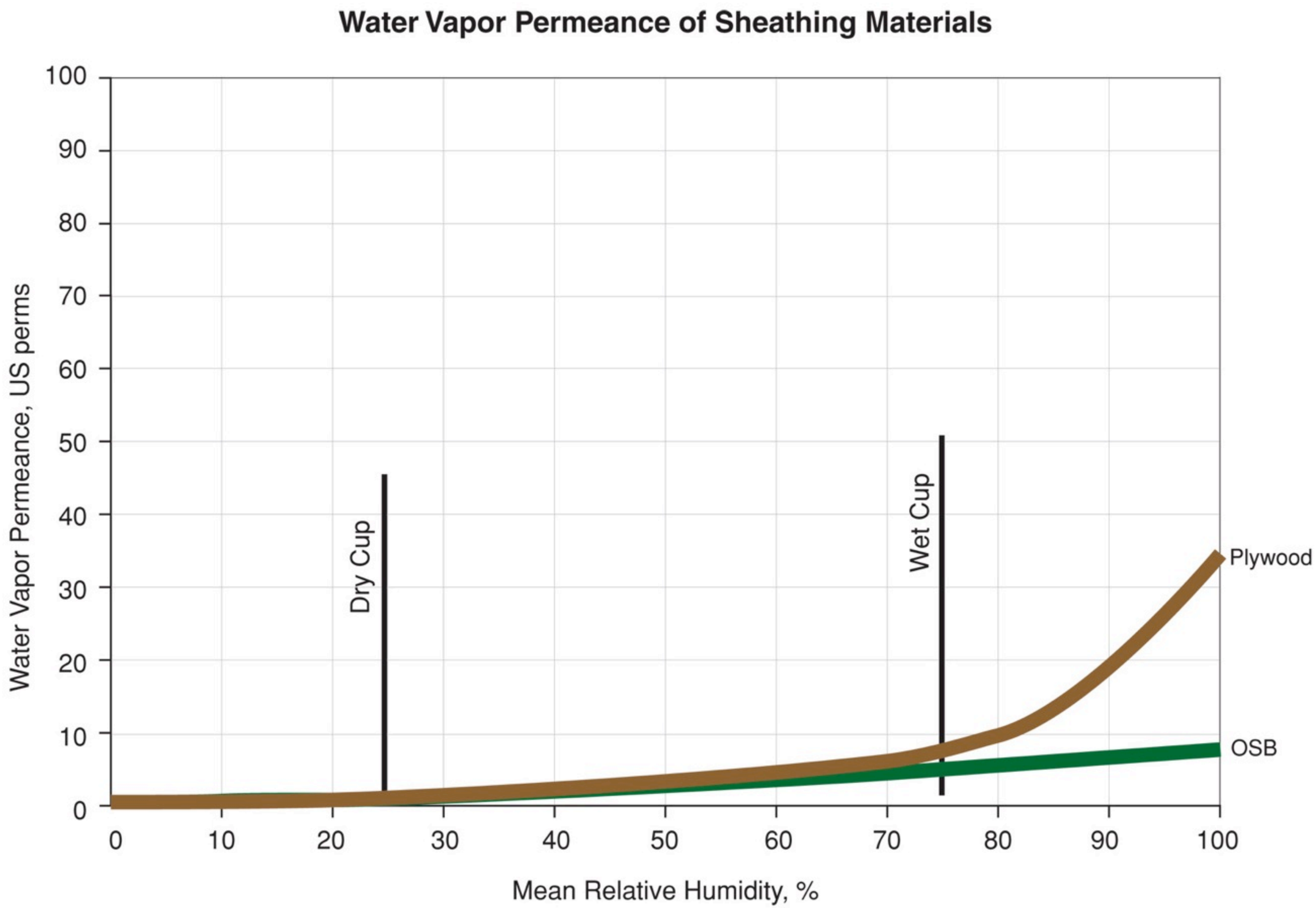


A - Single-layer of absorbed molecules
B - Multiple layers of absorbed molecules
C - Interconnected layers (internal capillary condensation)
D - Free water in pores, capillary suction
E - Supersaturated regime

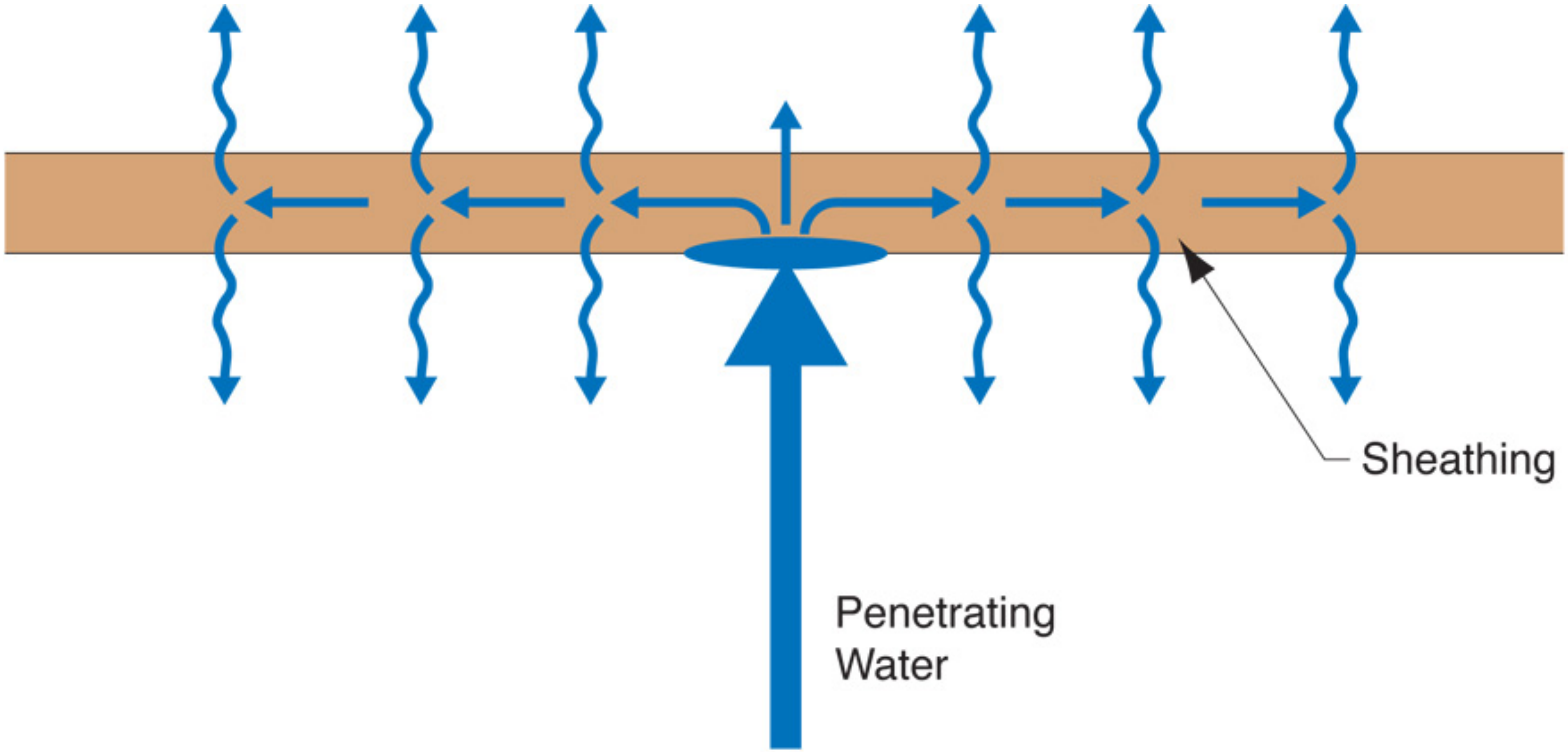
Relationship between Dry Cup and Wet Cup
Adapted from Joy & Wilson, 1963

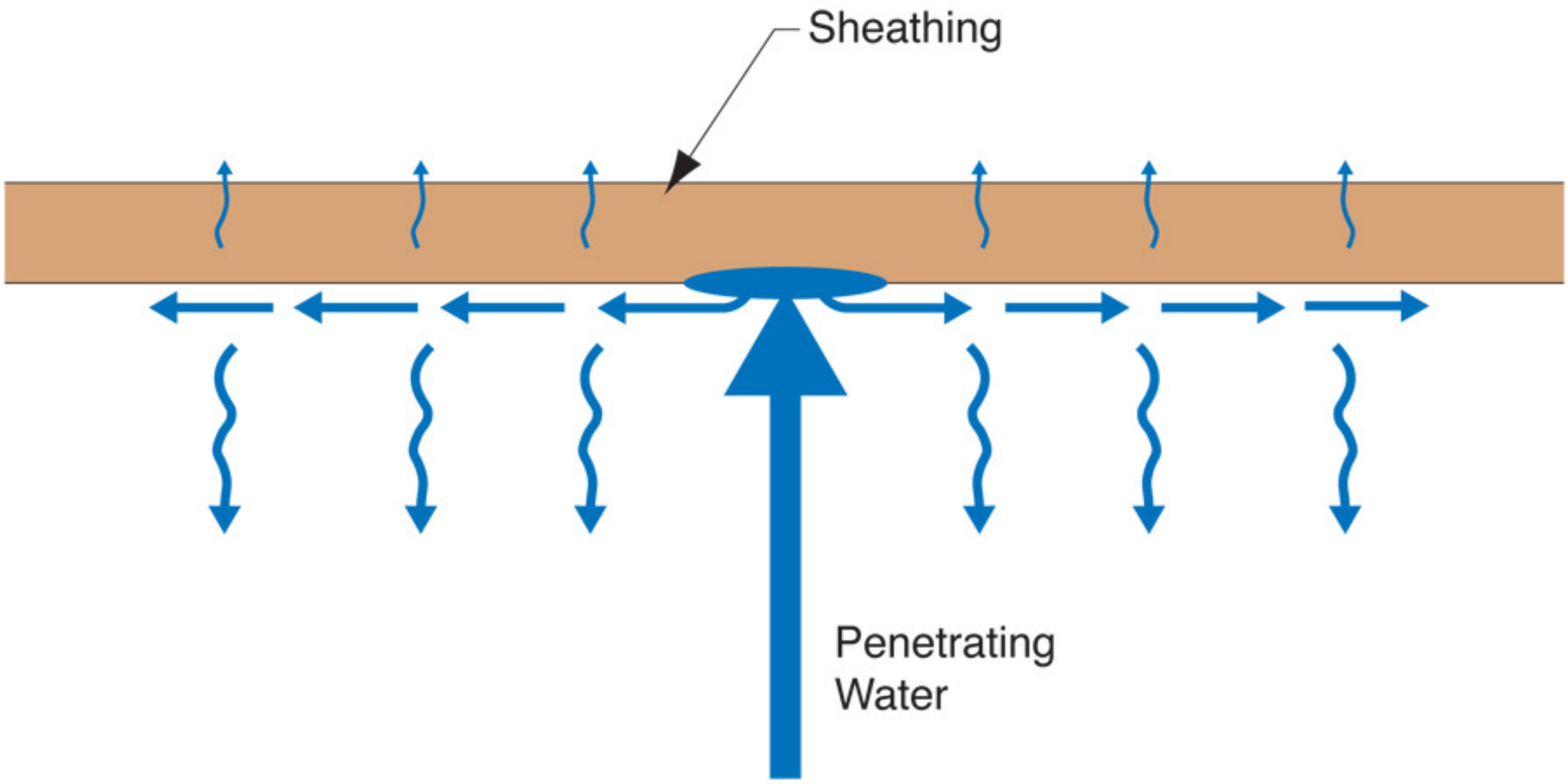

R-11 3½"
OWENS-CORNING
Fiberglas
Building
Insulation
FIBERGLAS
ASSURED THERMAL PERFORMANCE

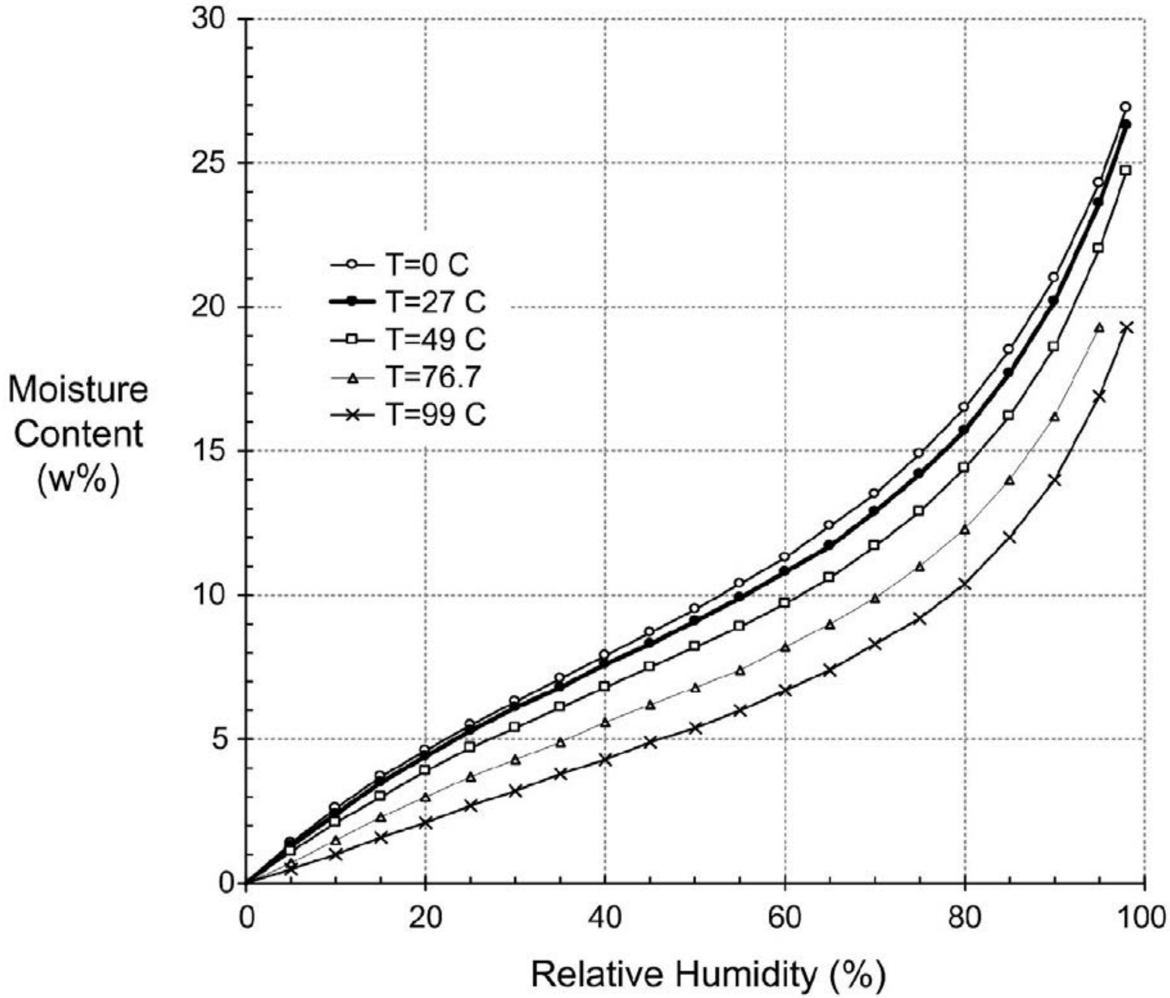

Water Vapor Permeance vs. Relative Humidity
Water Vapor Permance, US perms
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
μ2
μ1
Dry cup limits
Wet cup limits
Dry cup
Dry cup
test results
Wet cup
Wet cup
test results
0
10
20
30
40
50
60
70
80
90
100
Mean Relative Humidity, %
μ1 = Dry cup permeance
μ2 = Wet cup permeance



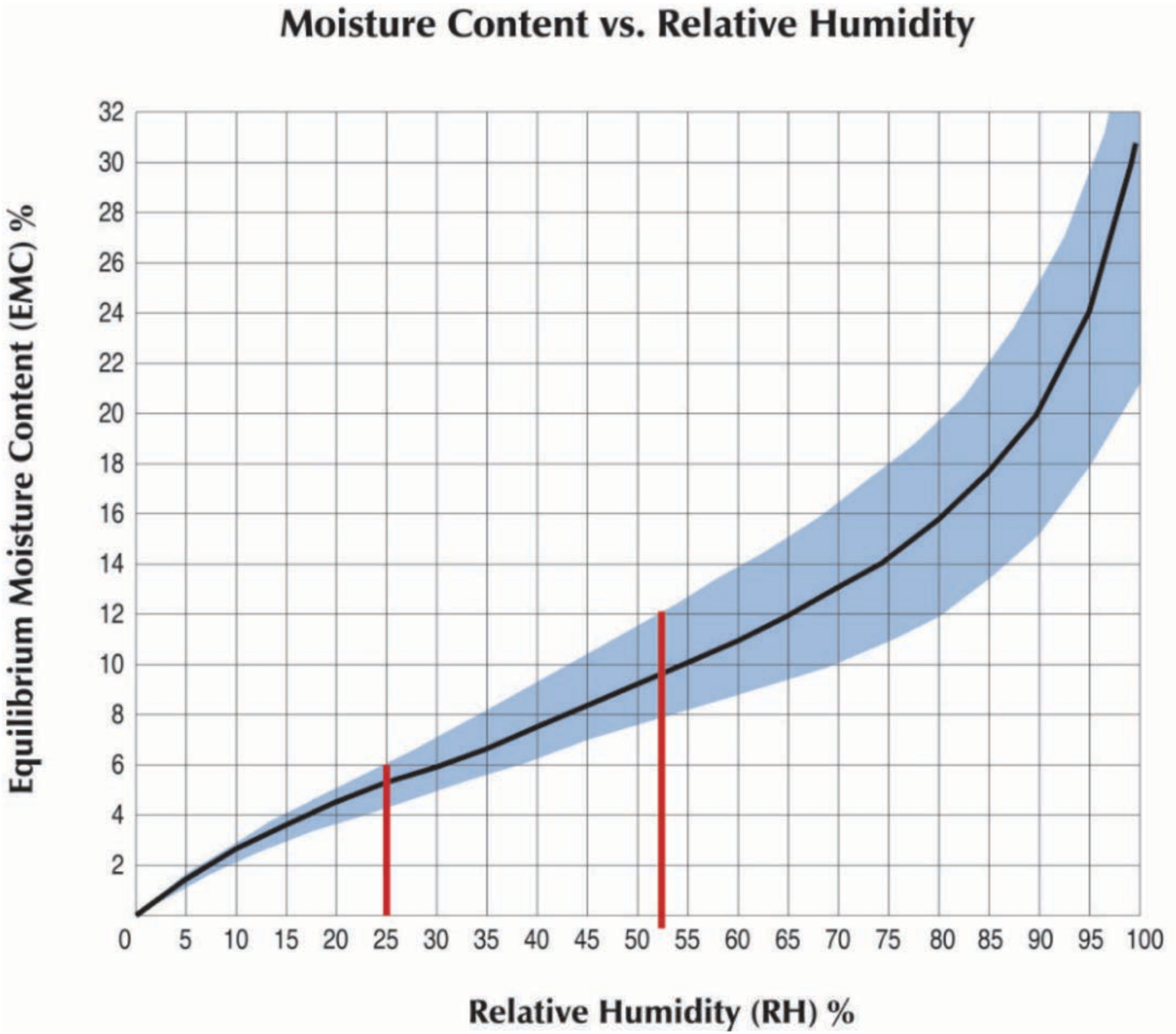
Water Vapor Permeance of Sheathing Materials
Water Vapor Permeance, US perms
Mean Relative Humidity, %
Dry Cup
Wet Cup
Plywood
OSB
0
10
20
30
40
50
60
70
80
90
100


Sheathing
Penetrating
Water

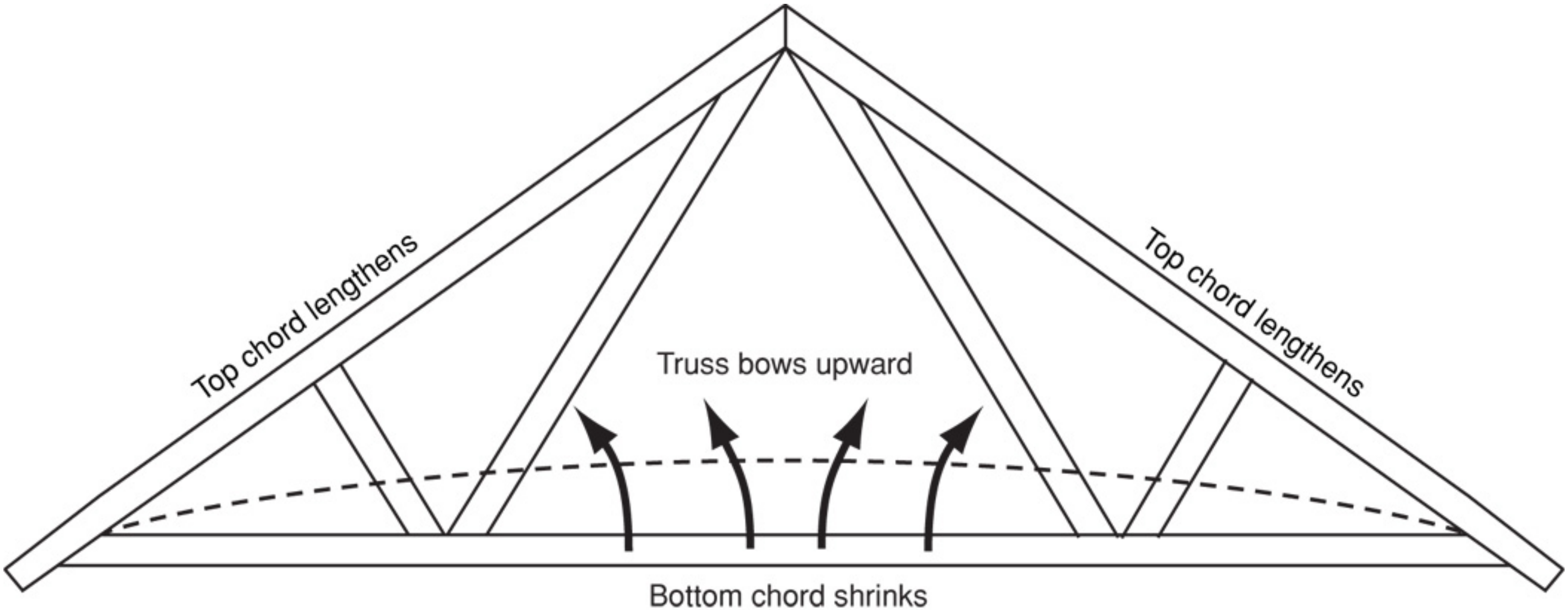

Sheathing
Penetrating
Water

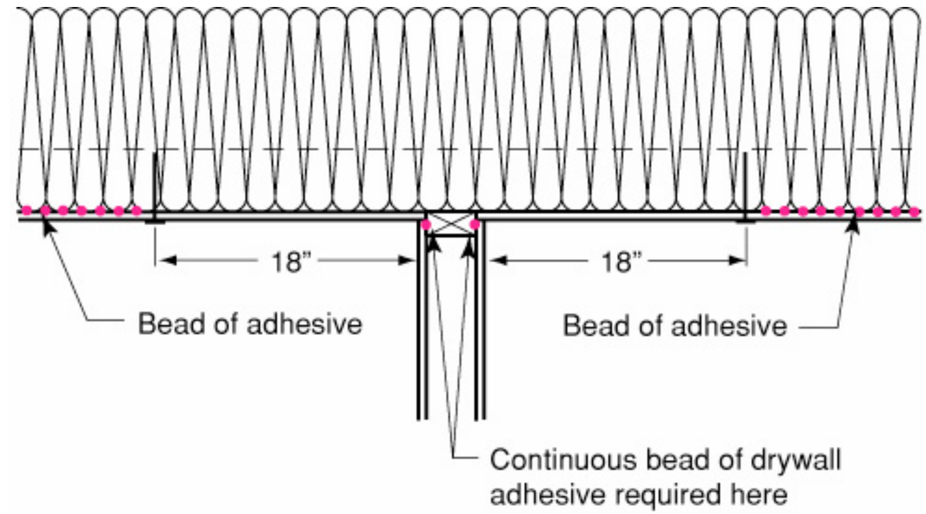


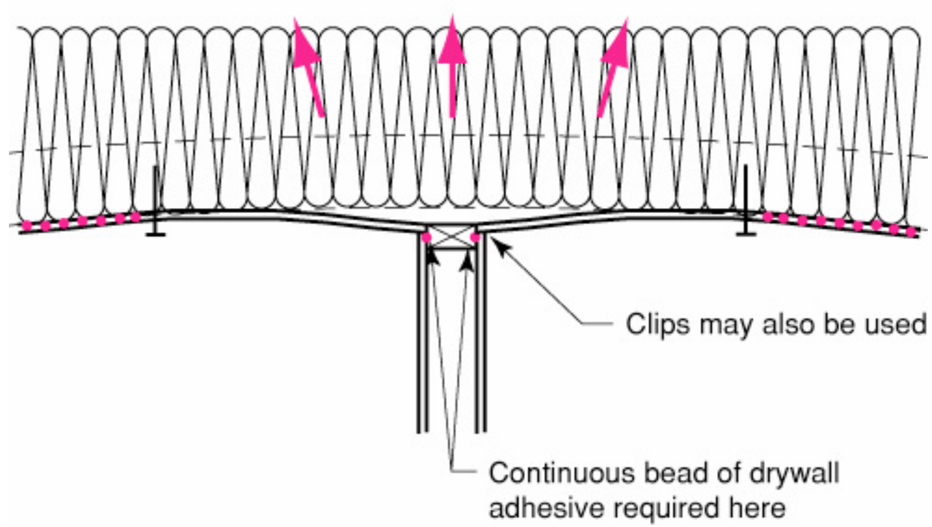
Average sorption isotherm for wood as a function of temperature
From Straube & Burnett, 2005

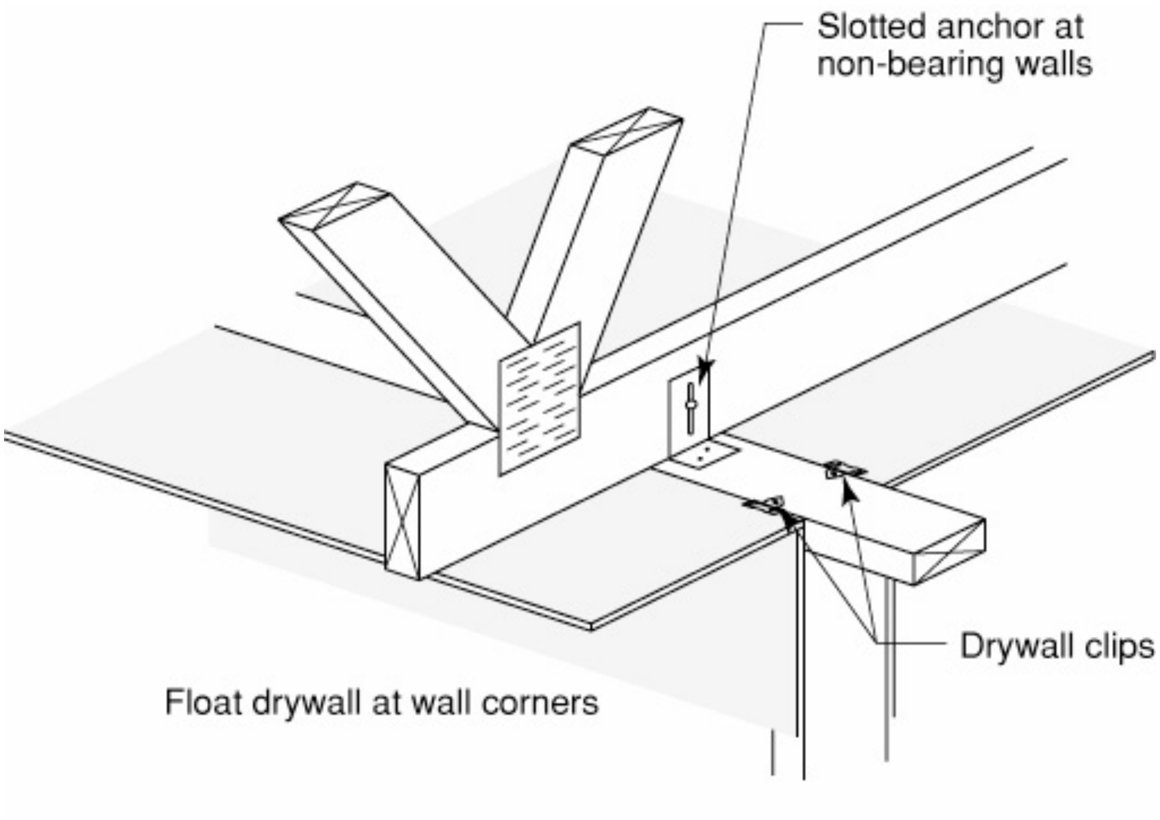

Moisture Content vs. Relative Humidity
Equilibrium Moisture Content (EMC) %
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
Relative Humidity (RH) %


6537

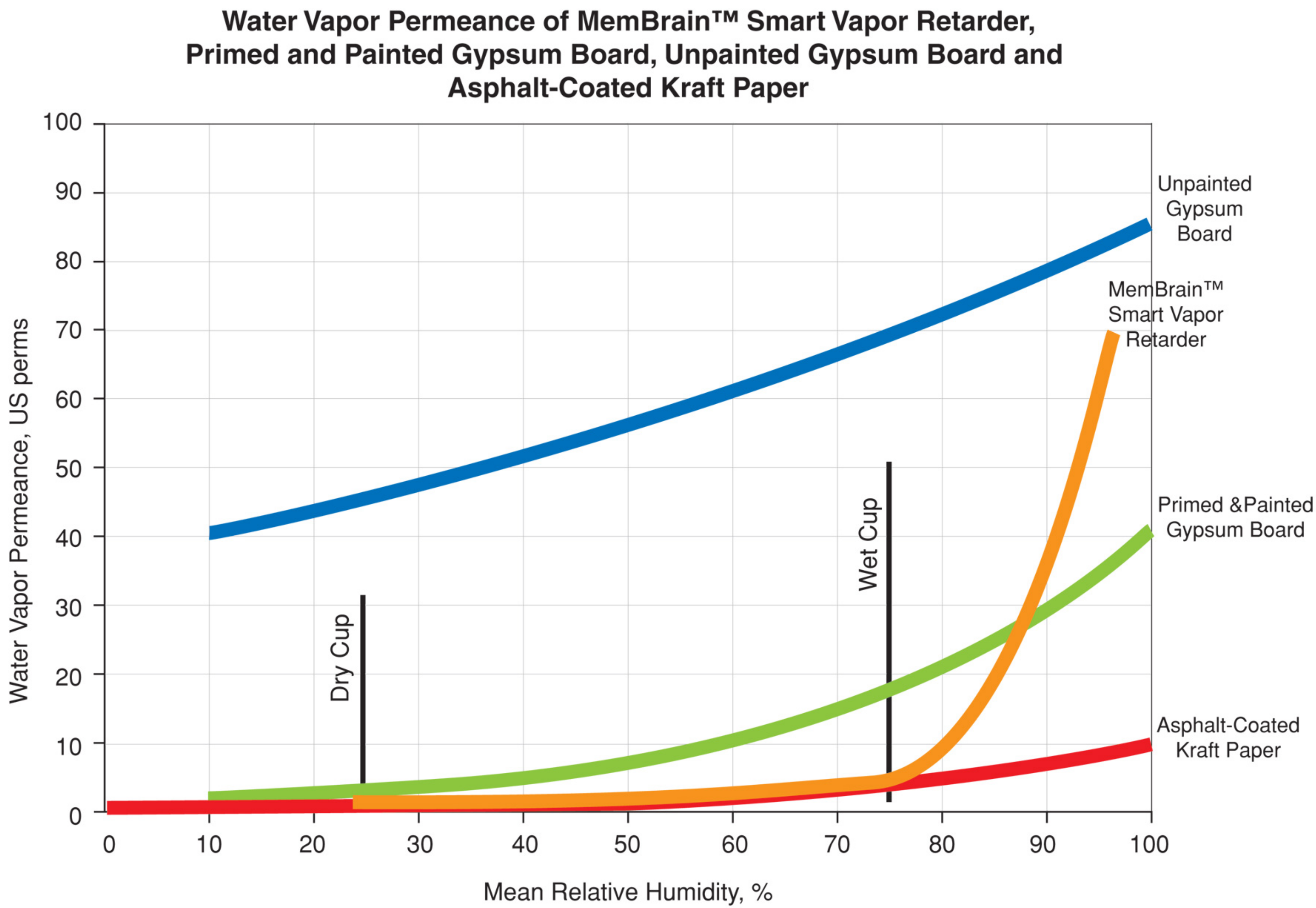

Top chord lengthens
Top chord lengthens
Truss bows upward
Bottom chord shrinks

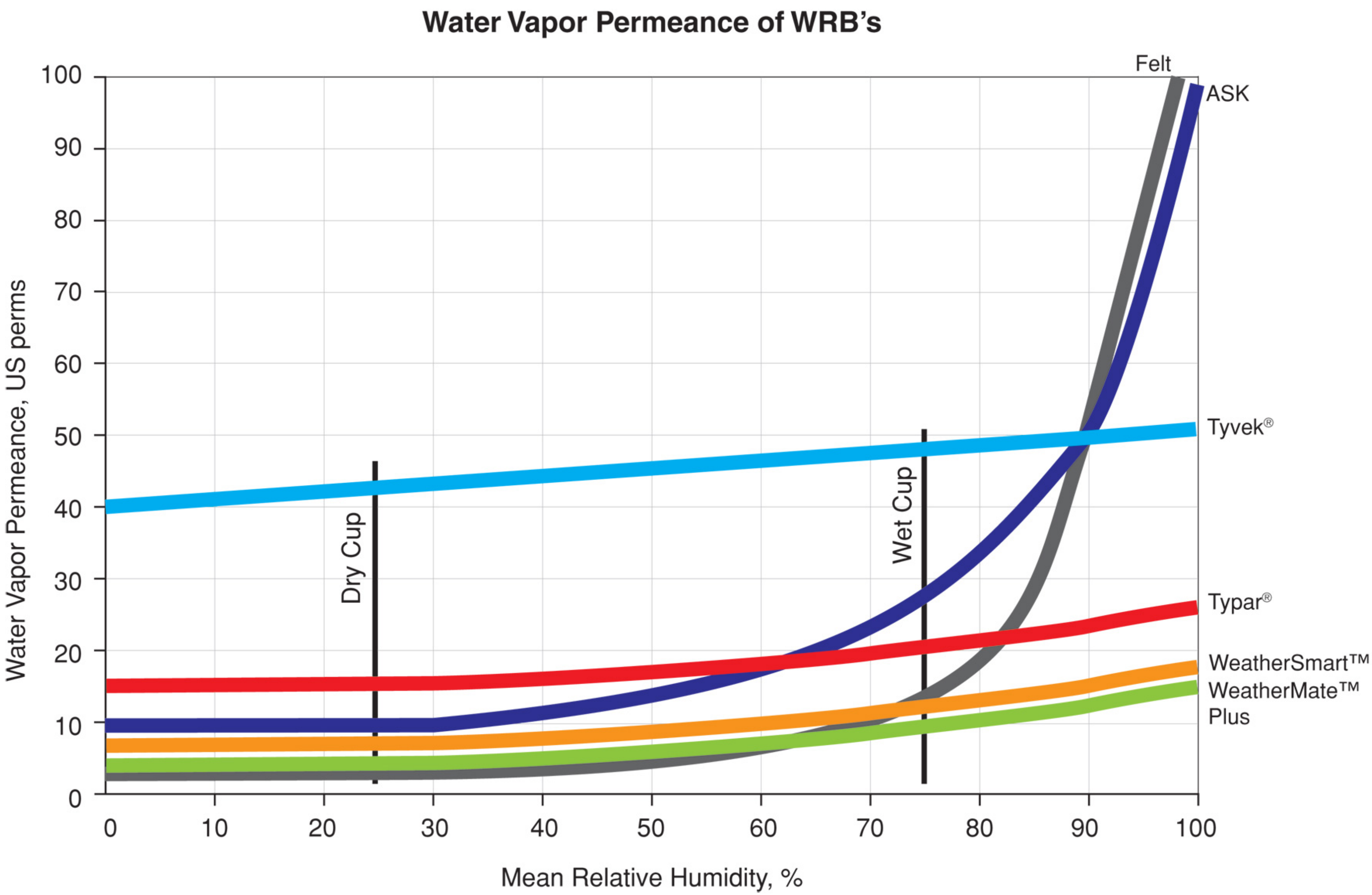

18"
18"
Bead of adhesive
Bead of adhesive
Continuous bead of drywall adhesive required here


Clips may also be used
Continuous bead of drywall adhesive required here


Slotted anchor at
non-bearing walls
Drywall clips
Float drywall at wall corners


10-4-8
STRUCTURAL GRADE
ermo-pl
INSULATIVE SHEATHING
FOR ADDED ENERGY
PERFORMANCE


Water Vapor Permeance of MemBrain™ Smart Vapor Retarder,
Primed and Painted Gypsum Board, Unpainted Gypsum Board and
Asphalt-Coated Kraft Paper
Water Vapor Permeance, US perms
Mean Relative Humidity, %
0
10
20
30
40
50
60
70
80
90
100
Unpainted Gypsum Board
MemBrain™ Smart Vapor Retarder
Primed &Painted Gypsum Board
Asphalt-Coated Kraft Paper
Dry Cup
Wet Cup



Water Vapor Permeance of WRB's
Water Vapor Permeance, US perms
Mean Relative Humidity, %
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Dry Cup
Wet Cup
Felt
ASK
Tyvek®
Typar®
WeatherSmart™
WeatherMate™
Plus

Laws of Thermodynamics

Zeroth Law – Equal Systems

First Law - Conservation of Energy

Second Law - Entropy

Third Law – Absolute Zero

2nd Law of Thermodynamics

In an isolated system, a process can occur only if it increases the total entropy of the system

Rudolf Clausius

Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

Thermal Gradient – Thermal Diffusion

Concentration Gradient – Molecular Diffusion

Moisture Flow Is From Warm To Cold

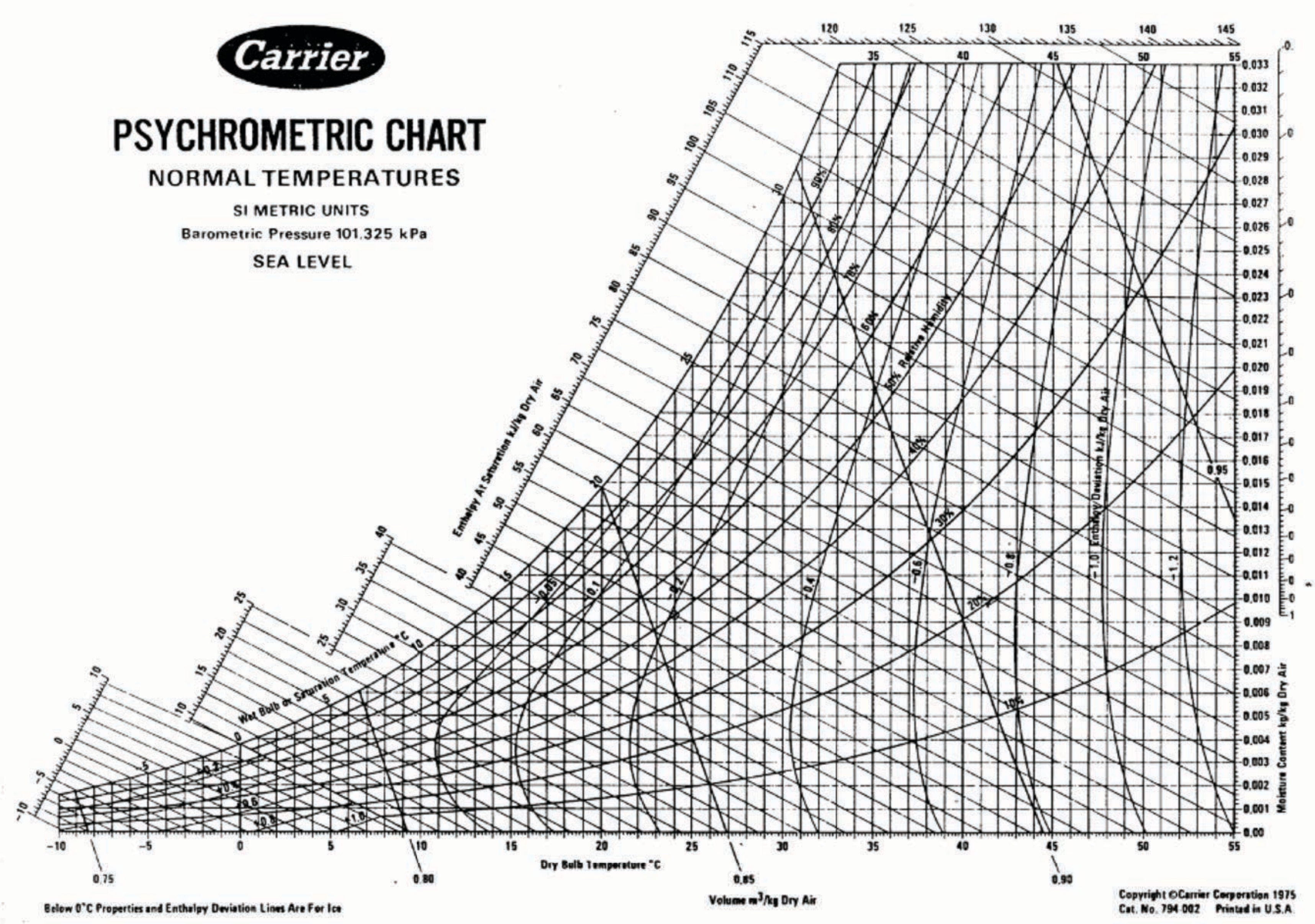
Moisture Flow Is From More To Less

Thermal Gradient – Thermal Diffusion

Concentration Gradient – Molecular Diffusion

Vapor Diffusion

Thermodynamic Potential


Carrier
PSYCHROMETRIC CHART
NORMAL TEMPERATURES
SI METRIC UNITS
Barometric Pressure 101.325 kPa
SEA LEVEL
Enthalpy At Saturation kJ/kg Dry Air
Wet Bulb or Saturation Temperature °C
Dry Bulb Temperature °C
Volume m³/kg Dry Air
Enthalpy Deviation kJ/kg Dry Air
Moisture Content kg/kg Dry Air
Relative Humidity
Below 0°C Properties and Enthalpy Deviation Lines Are For Ice
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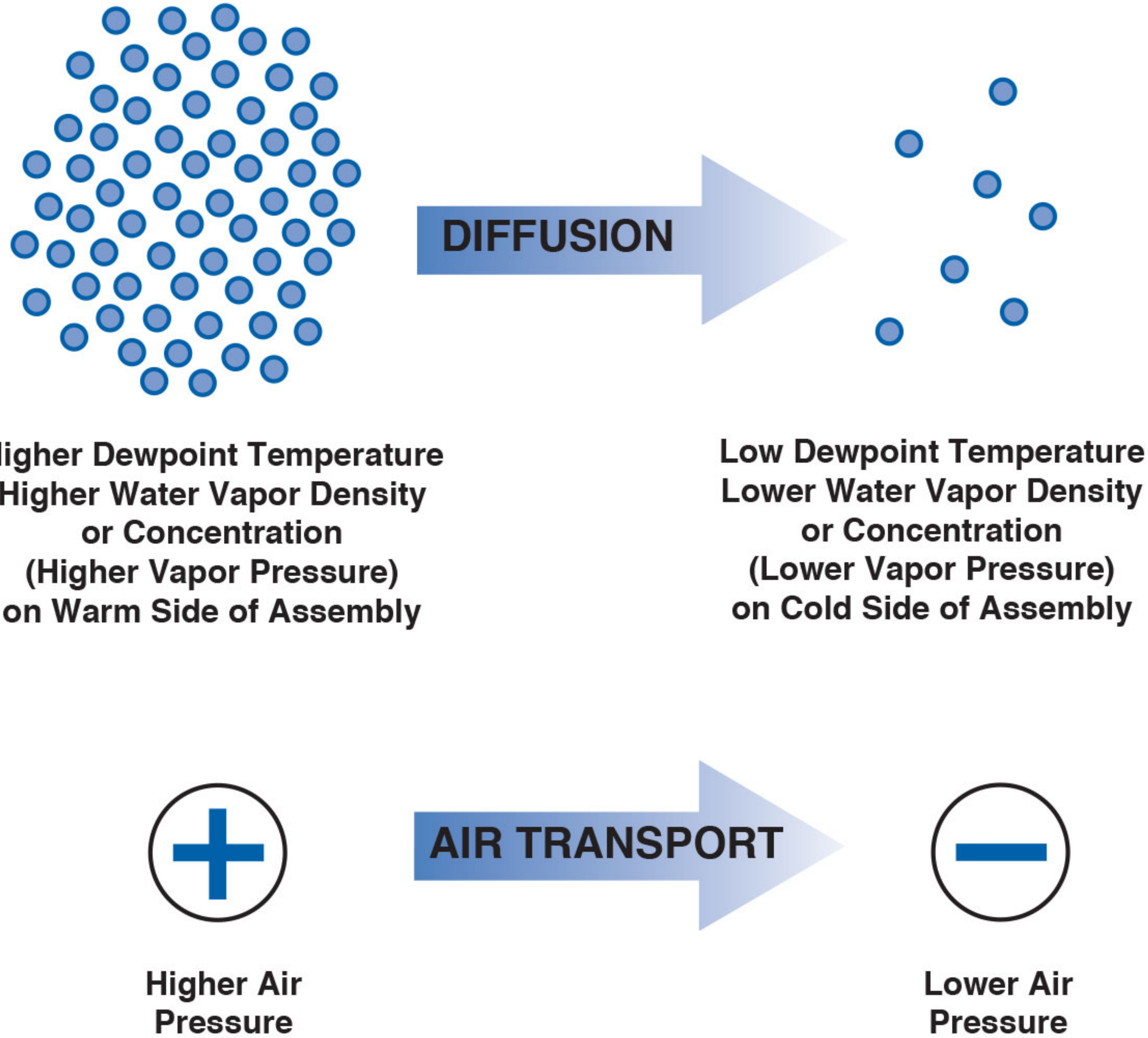
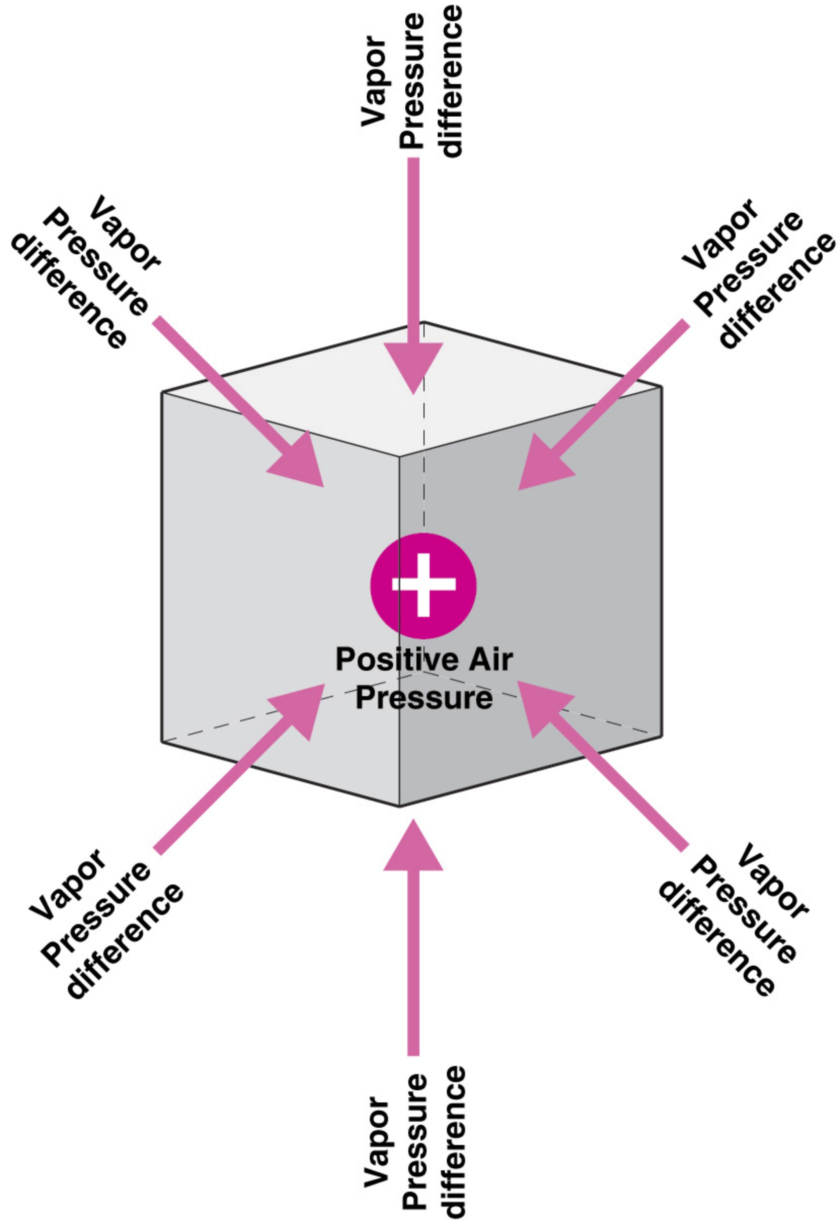
Cat. No. 794-002 Printed in U.S.A.

Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure

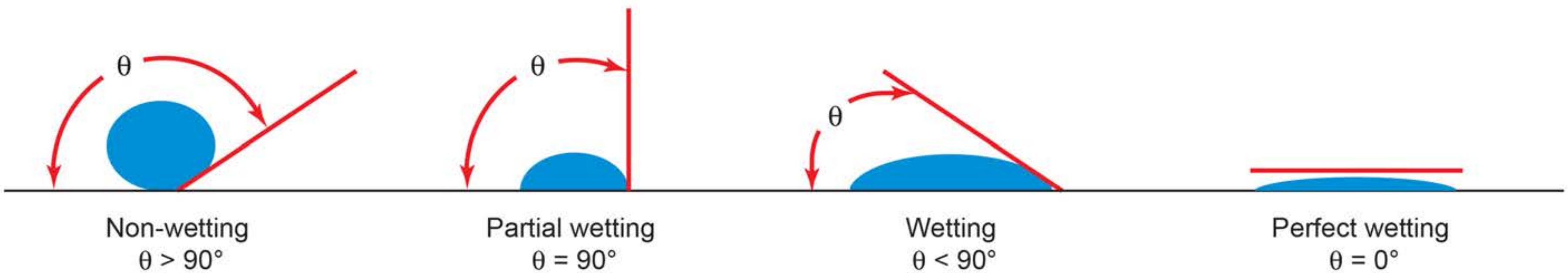

DIFFUSION
Higher Dewpoint Temperature
Higher Water Vapor Density
or Concentration
(Higher Vapor Pressure)
on Warm Side of Assembly
Low Dewpoint Temperature
Lower Water Vapor Density
or Concentration
(Lower Vapor Pressure)
on Cold Side of Assembly
AIR TRANSPORT
Higher Air
Pressure
Lower Air
Pressure

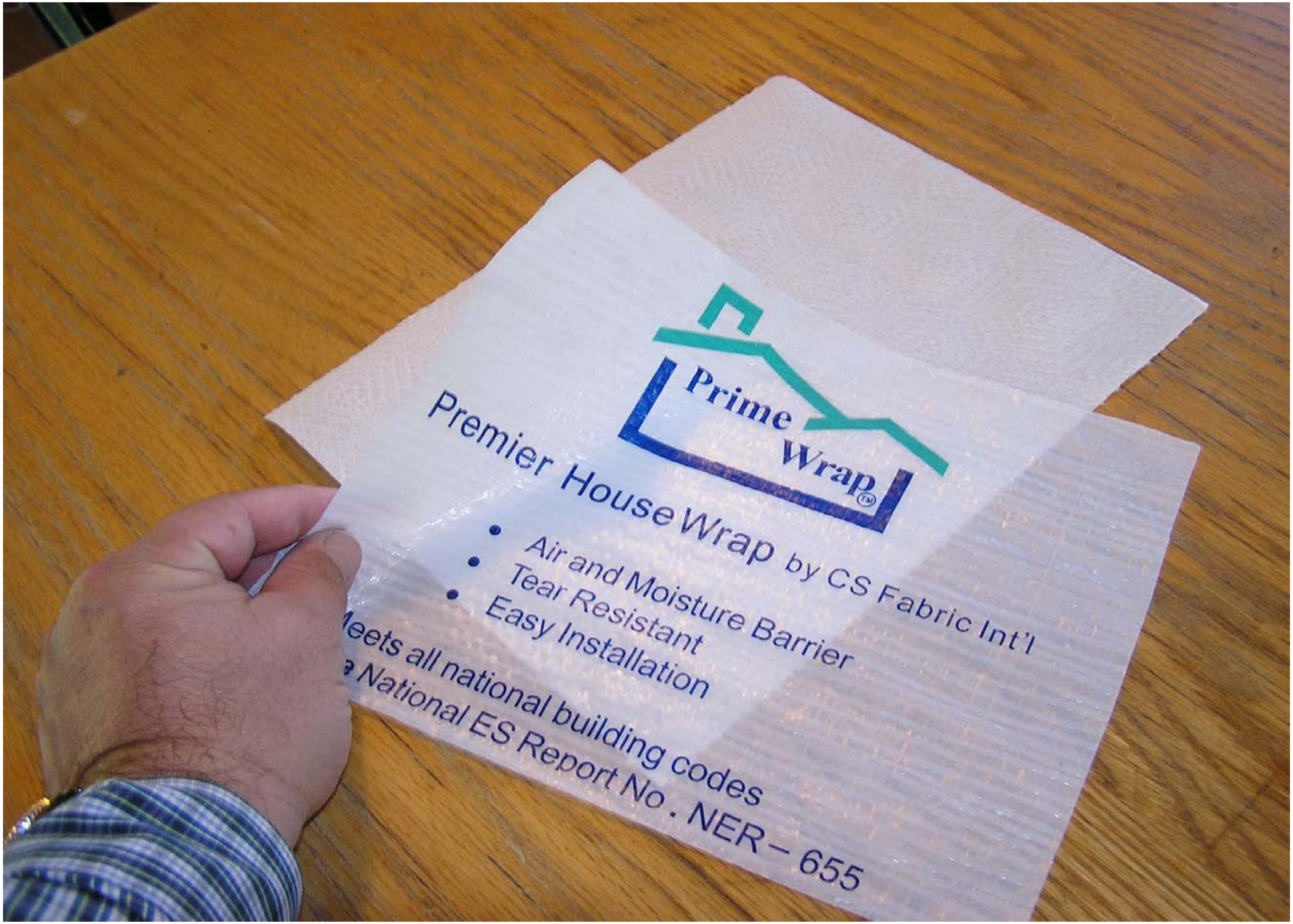

Vapor
Pressure
difference
Vapor
Pressure
difference
Vapor
Pressure
difference
Positive Air
Pressure
Vapor
Pressure
difference
Vapor
Pressure
difference
Vapor
Pressure
difference

How Does Wetting Occur?

- “non-wetable” surface
- water repellant surface
- hygrophobic surface
- water more attracted to itself than to surface
- surface energy of water greater than surface energy of surface
- water “beads up”
- “greasy” surface
- high contact angle “θ”

- “wetable” surface
- non-water repellant surface
- hygroscobic surface
- water more attracted to surface than itself
- surface energy of surface greater than surface energy of water
- water “spreads out”
- “non-greasy” surface
- low contact angle “θ”


θ
θ
θ
Non-wetting
θ > 90°
Partial wetting
θ = 90°
Wetting
θ < 90°
Perfect wetting
θ = 0°


Prime Wrap
Premier House Wrap by CS Fabric Int'l
• Air and Moisture Barrier
• Tear Resistant
• Easy Installation
Meets all national building codes
National ES Report No. NER – 655

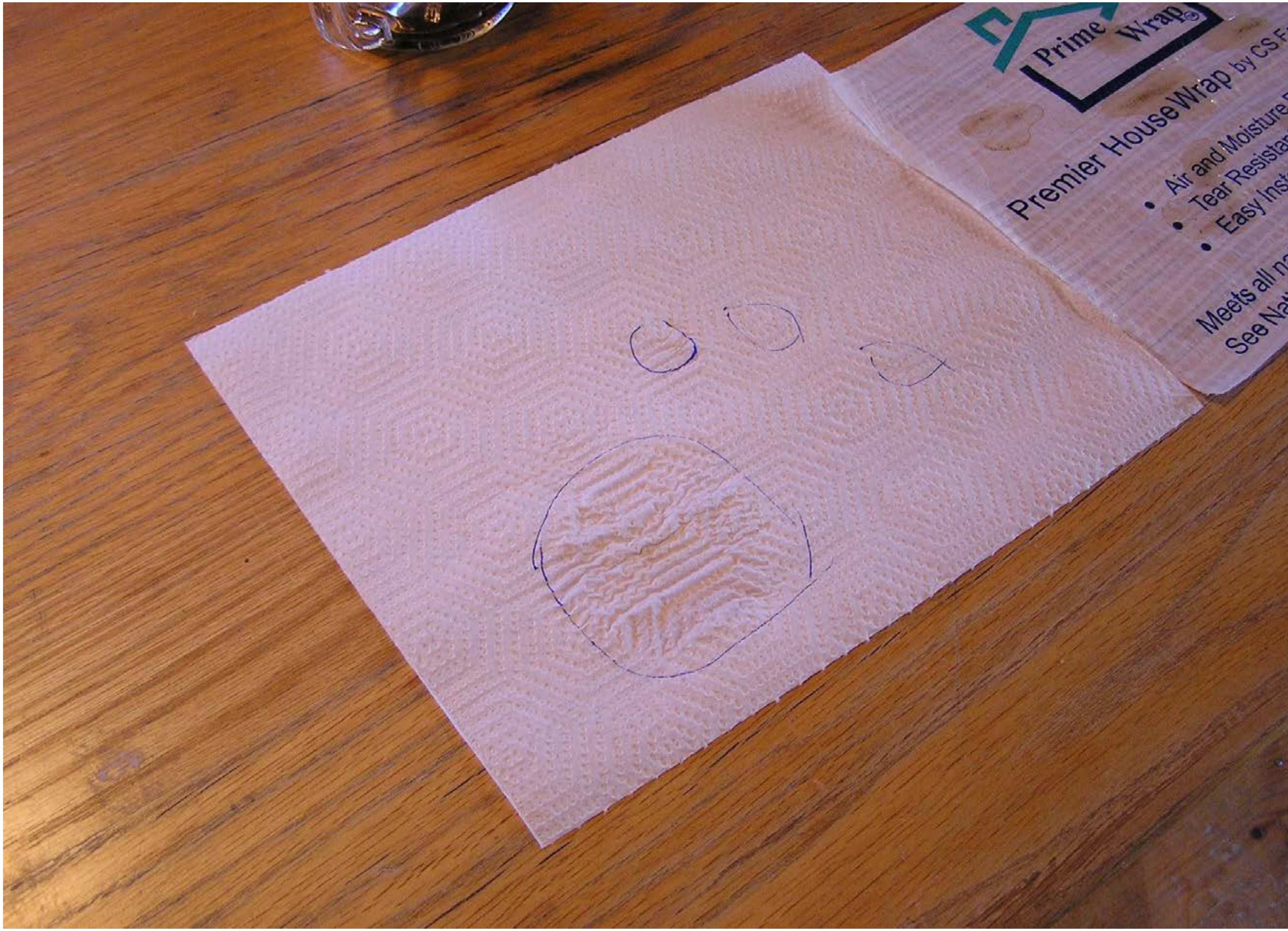

Prime
Wrap
Premier House Wrap by CS Fabric Int'l
• Air and Moisture Barrier
• Tear Resistant
• Easy Installation
Meets all national building codes
See National ES Report No . NER – 655


Prime
Wrap
emier House Wrap by CS Fabric
• Air and Moisture Barrier
• Tear Resistant
• Easy Installation


Fabric Int'l
nd Moisture Barrier
Resistant
codes
eport No. NER – 655


PYREX
2 CUPS
9:16
START


Prime Wrap
Premier House Wrap by CS Fabric Int'l
• Air and Moisture Barrier
• Tear Resistant
• Easy Installation
Meets all national building codes
See National ES Report No. NER – 655
PYREX

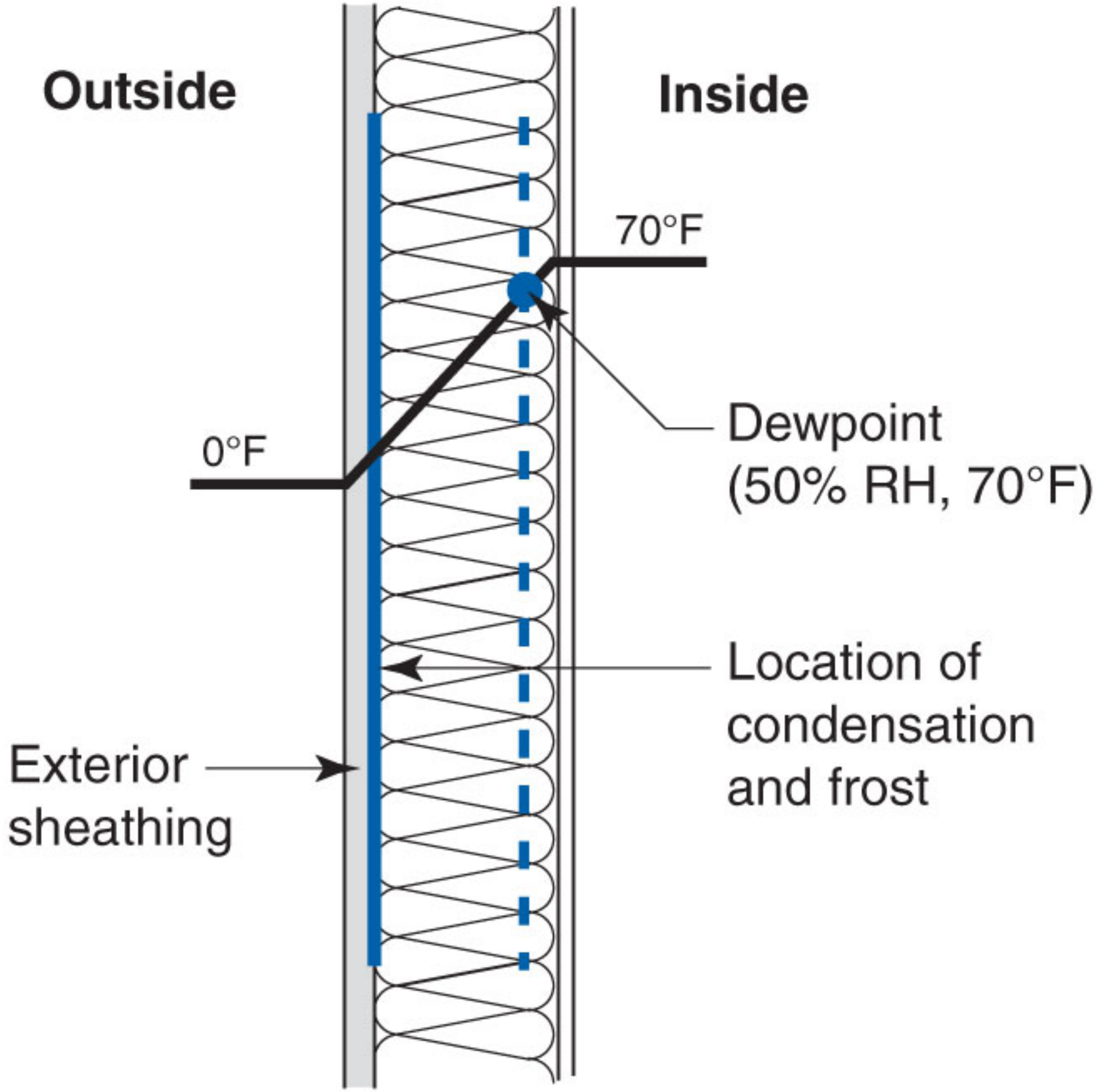

Prime Wrap
Premier HouseWrap by CS
Air and Moisture
Tear Resistant
Meets all

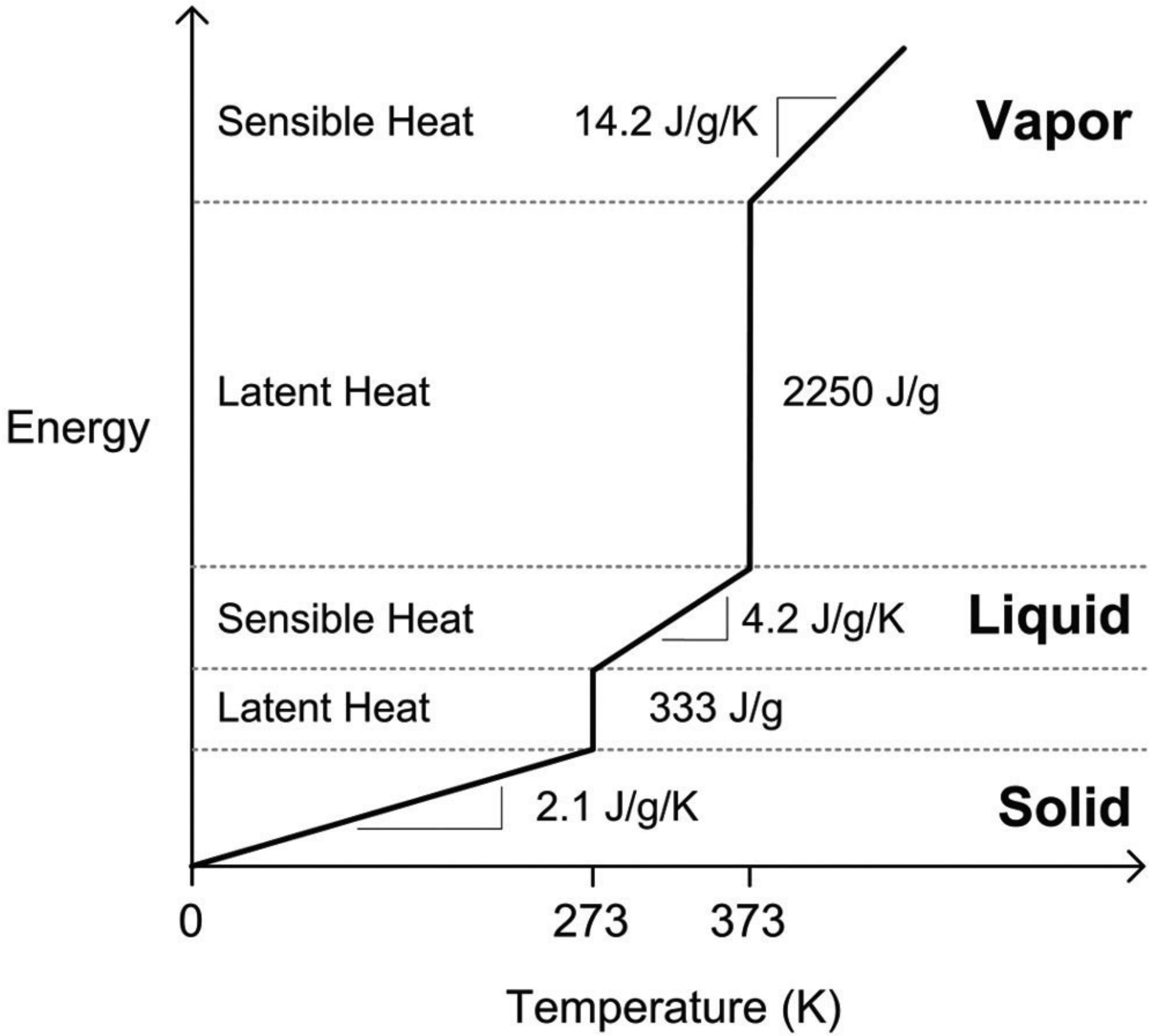

Cambridge
PINKWRAP


TYPAR
HouseWrap
TYPAR
HouseWrap

	Surface Energy
Water (20 C)	73 dynes/cm
Water (100 C)	59 dynes/cm
Epoxy	46 dynes/cm
Polyethylene	31 dynes/cm
Soapy water	30 dynes/cm
Paraffin wax	25 dynes/cm
Silicone	24 dynes/cm
Teflon	18 dynes/cm

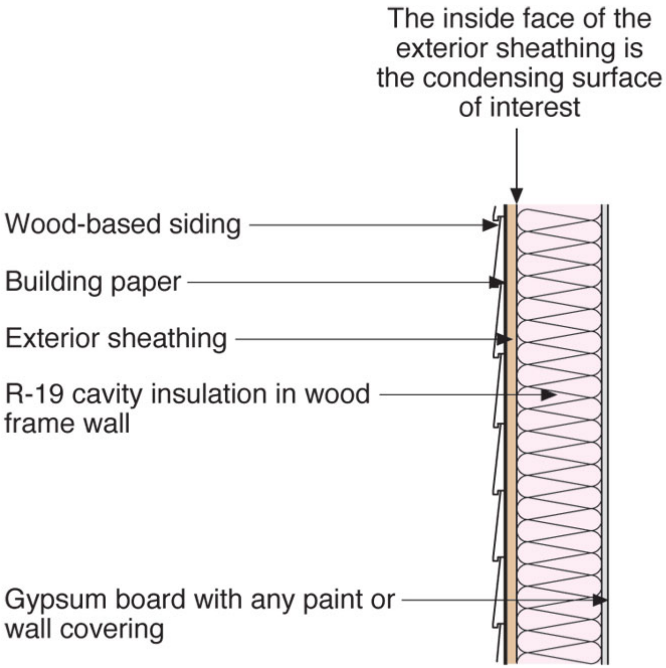
When Phases Change

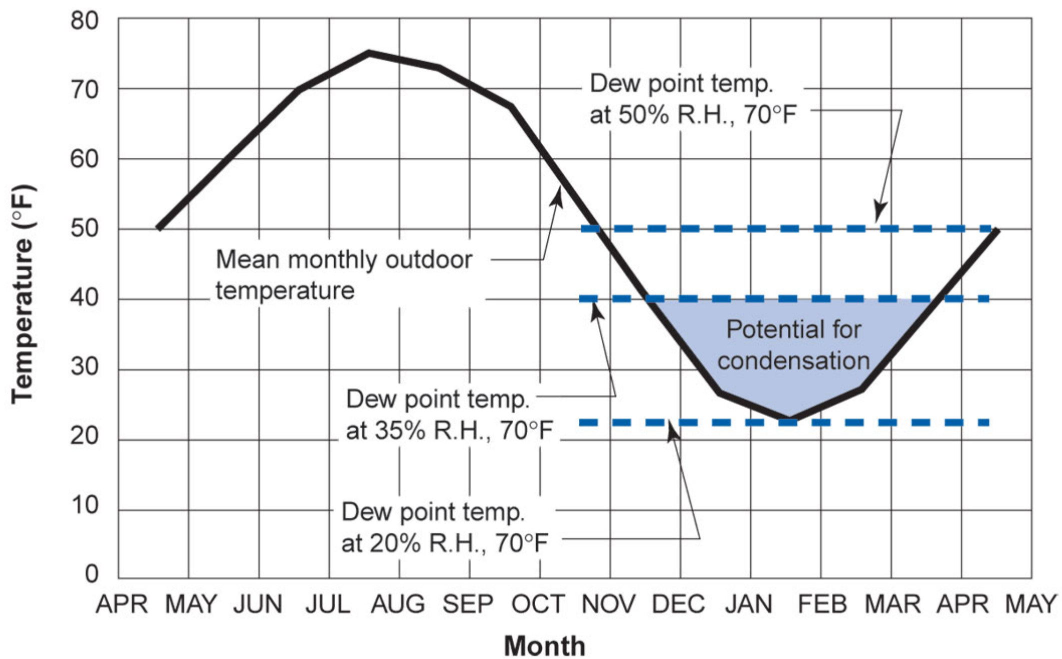

Outside
Inside
70°F
0°F
Dewpoint
(50% RH, 70°F)
Location of
condensation
and frost
Exterior
sheathing

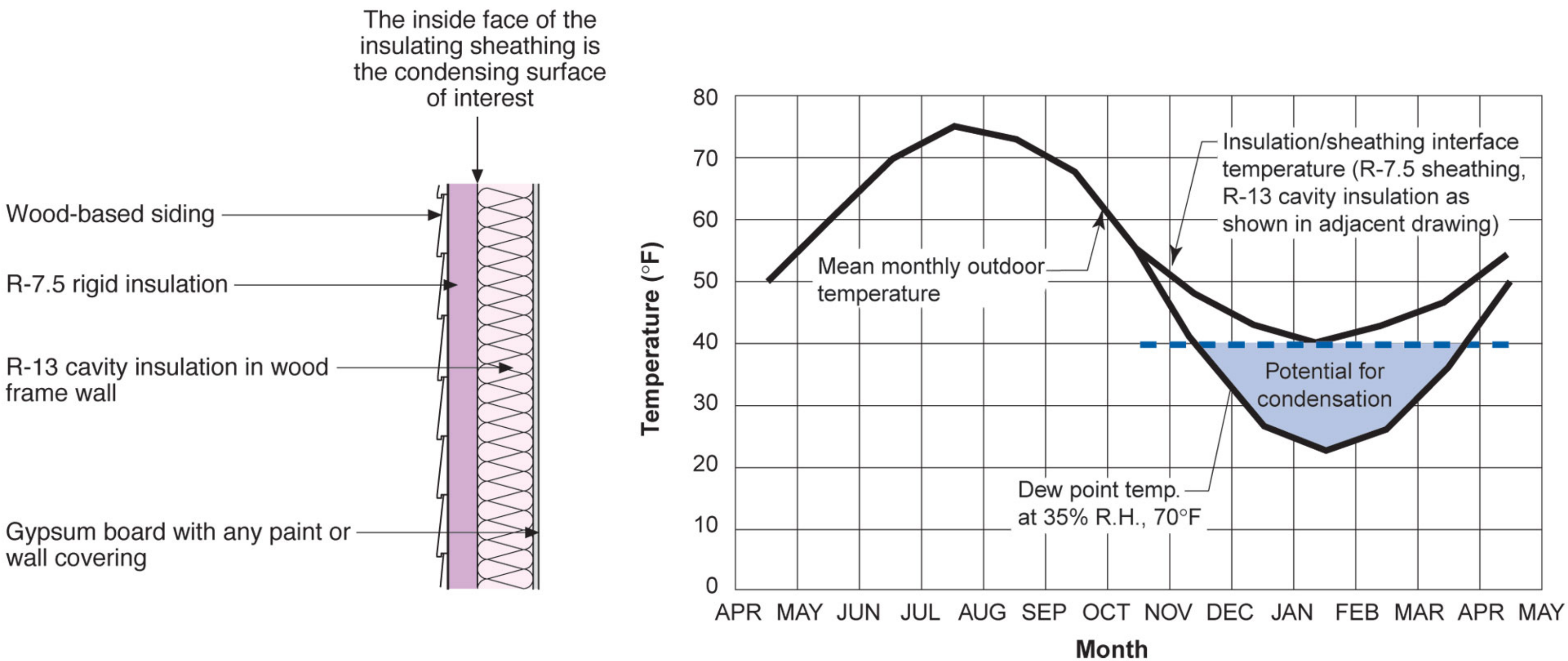


Simple linearized energy-temperature relation for water

From Straube & Burnett, 2005


The inside face of the exterior sheathing is the condensing surface of interest
Wood-based siding
Building paper
Exterior sheathing
R-19 cavity insulation in wood frame wall
Gypsum board with any paint or wall covering


80
70
60
50
40
30
20
10
0
Temperature (°F)
APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY
Month
Dew point temp. at 50% R.H., 70°F
Mean monthly outdoor temperature
Potential for condensation
Dew point temp. at 35% R.H., 70°F
Dew point temp. at 20% R.H., 70°F


The inside face of the insulating sheathing is the condensing surface of interest
Wood-based siding
R-7.5 rigid insulation
R-13 cavity insulation in wood frame wall
Gypsum board with any paint or wall covering
Insulation/sheathing interface temperature (R-7.5 sheathing, R-13 cavity insulation as shown in adjacent drawing)
Mean monthly outdoor temperature
Potential for condensation
Dew point temp. at 35% R.H., 70°F
Temperature (°F)
80
70
60
50
40
30
20
10
0
APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY
Month

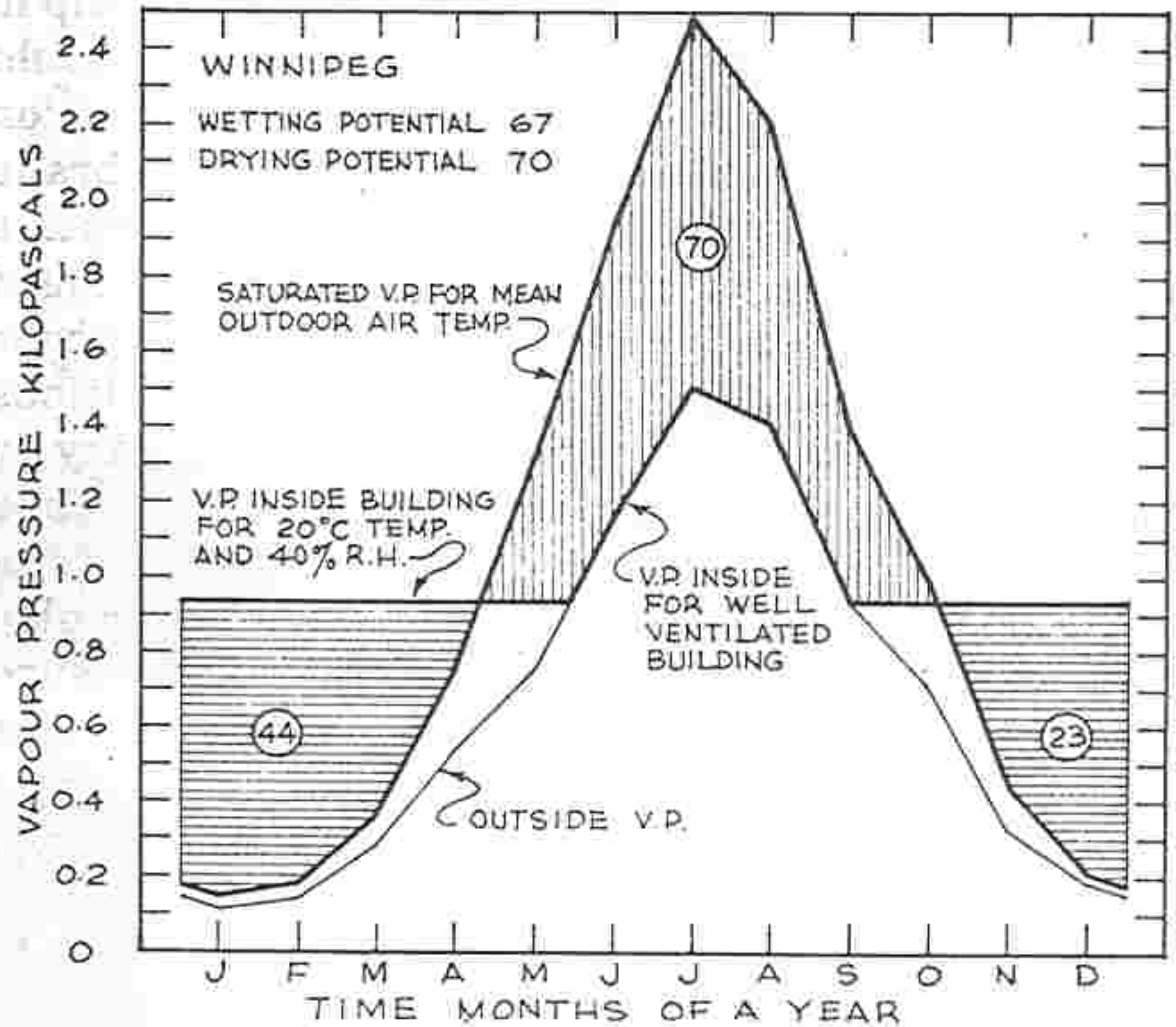
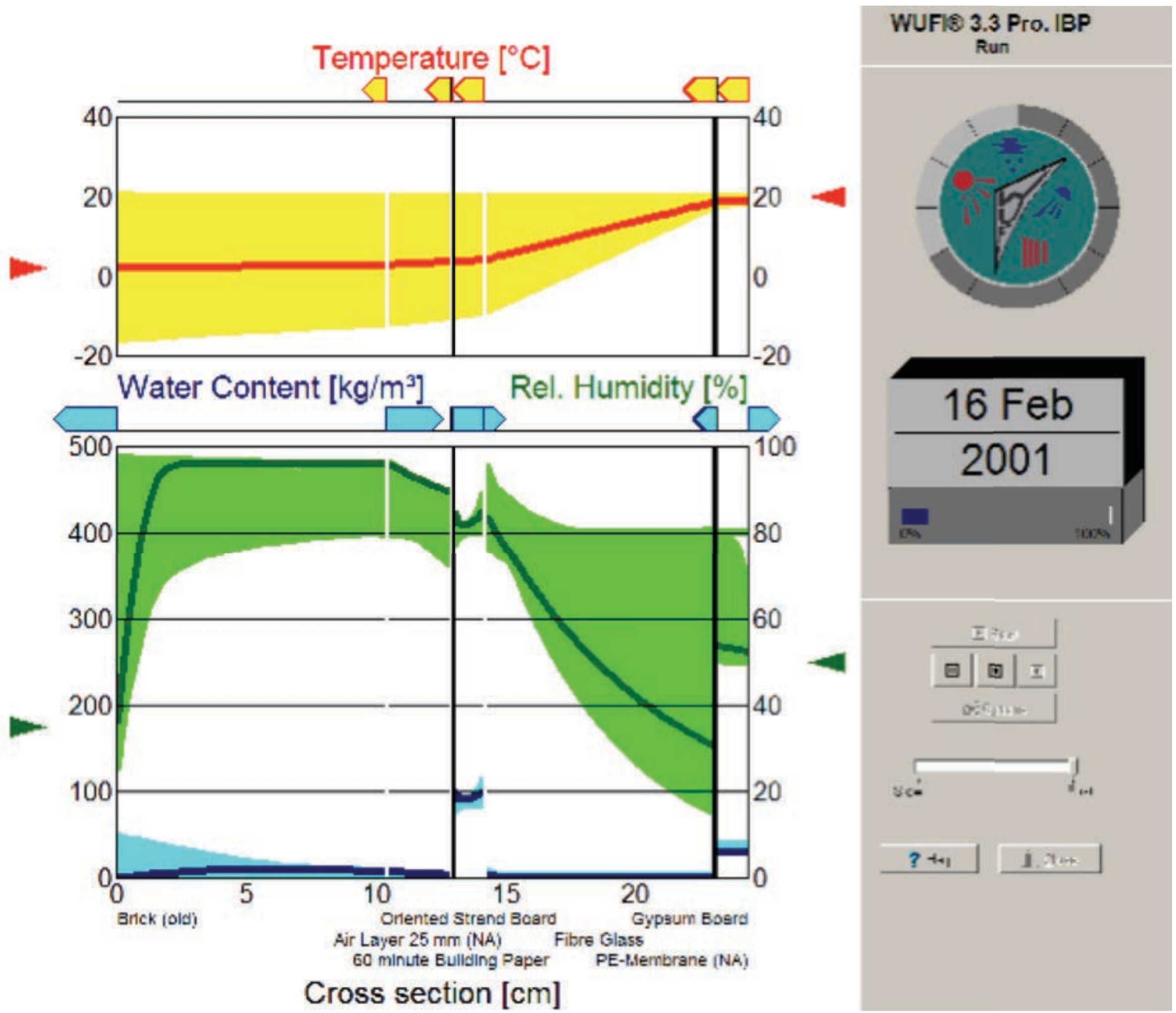
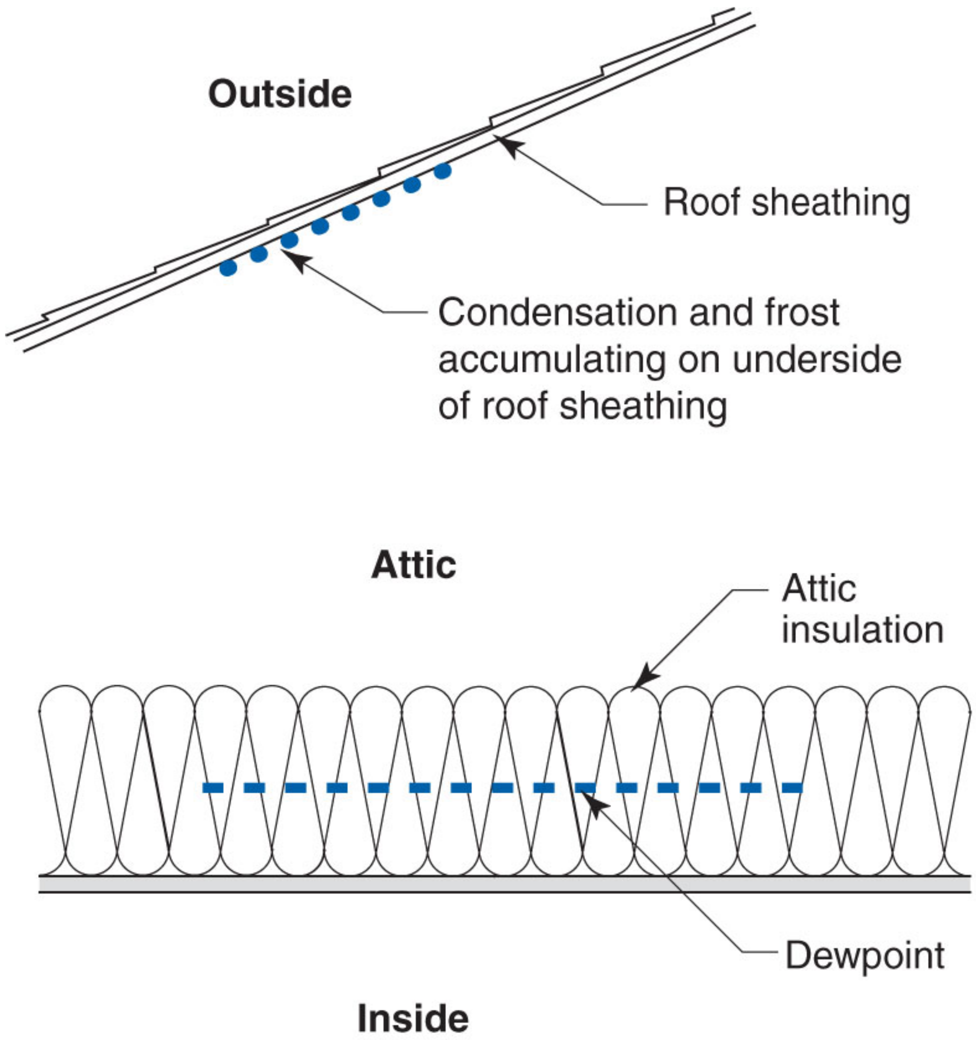
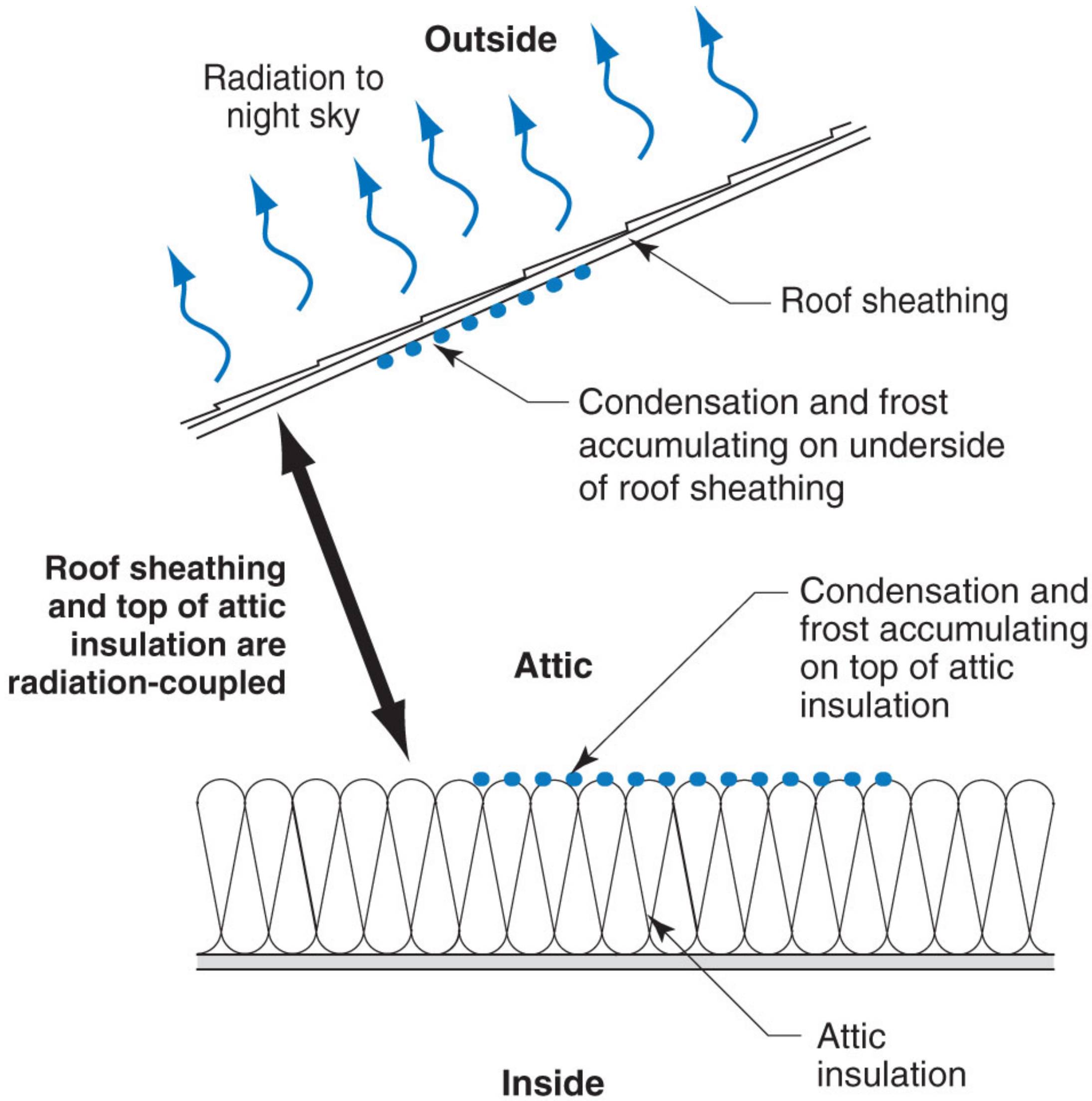


Figure 8-7. Outside vapour pressure, saturated vapour pressure and inside vapour pressure for Winnipeg.



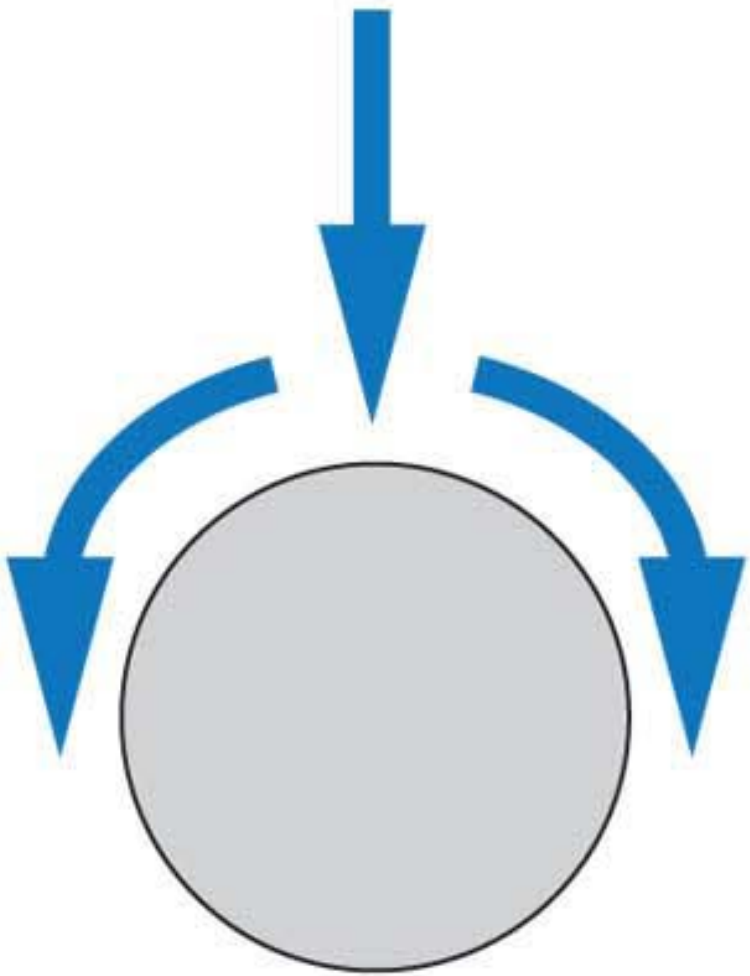
Temperature [°C]
40
20
0
-20
Water Content [kg/m³]
Rel. Humidity [%]
500
400
300
200
100
0
5
10
15
20
80
60
Brick (old)
Oriented Strand Board
Gypsum Board
Air Layer 25 mm (NA)
Fibre Glass
60 minute Building Paper
PE-Membrane (NA)
Cross section [cm]
WUFI® 3.3 Pro. IBP
Run
16 Feb
2001

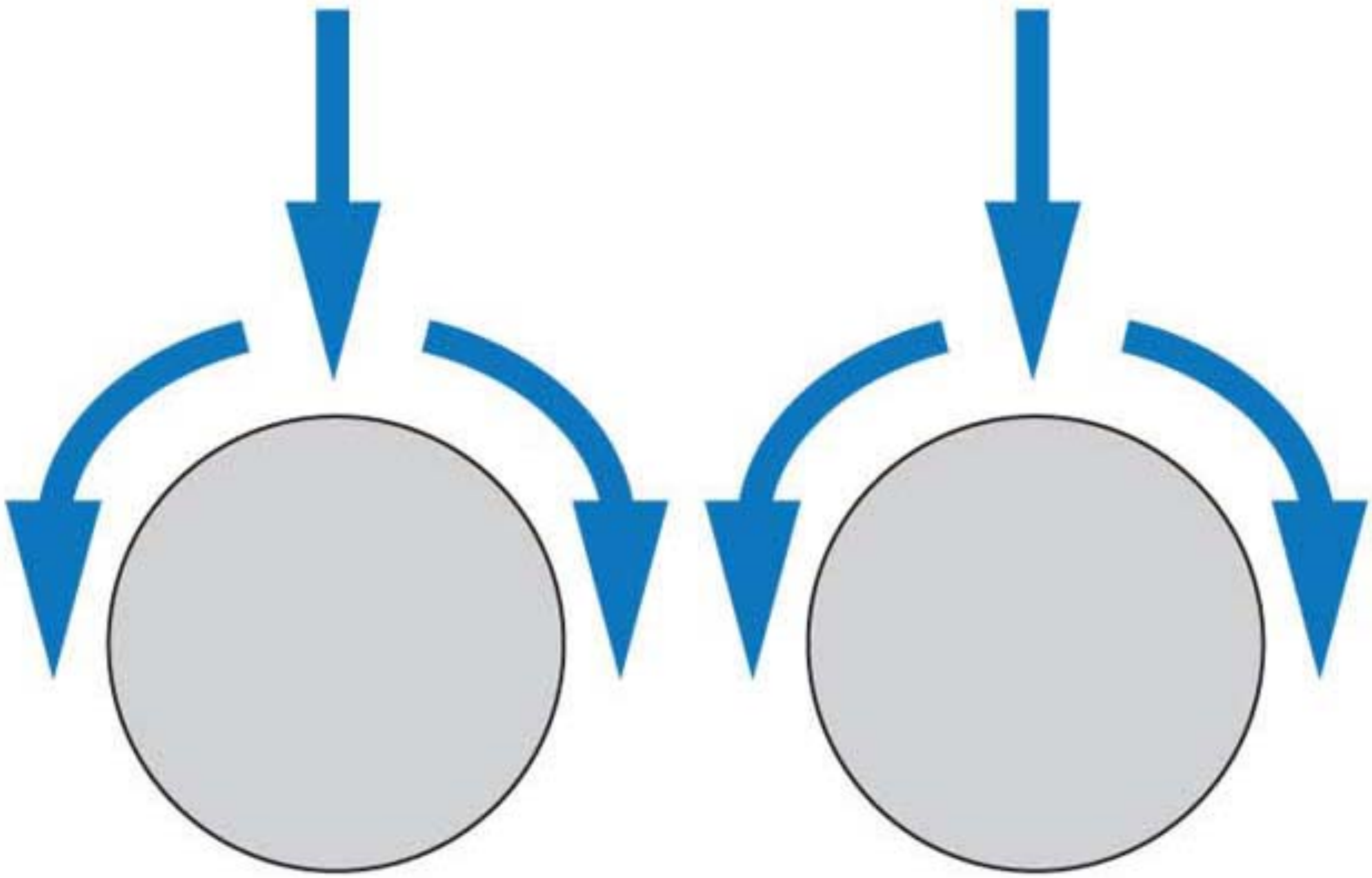

Outside
Roof sheathing
Condensation and frost accumulating on underside of roof sheathing
Attic
Attic insulation
Dewpoint
Inside

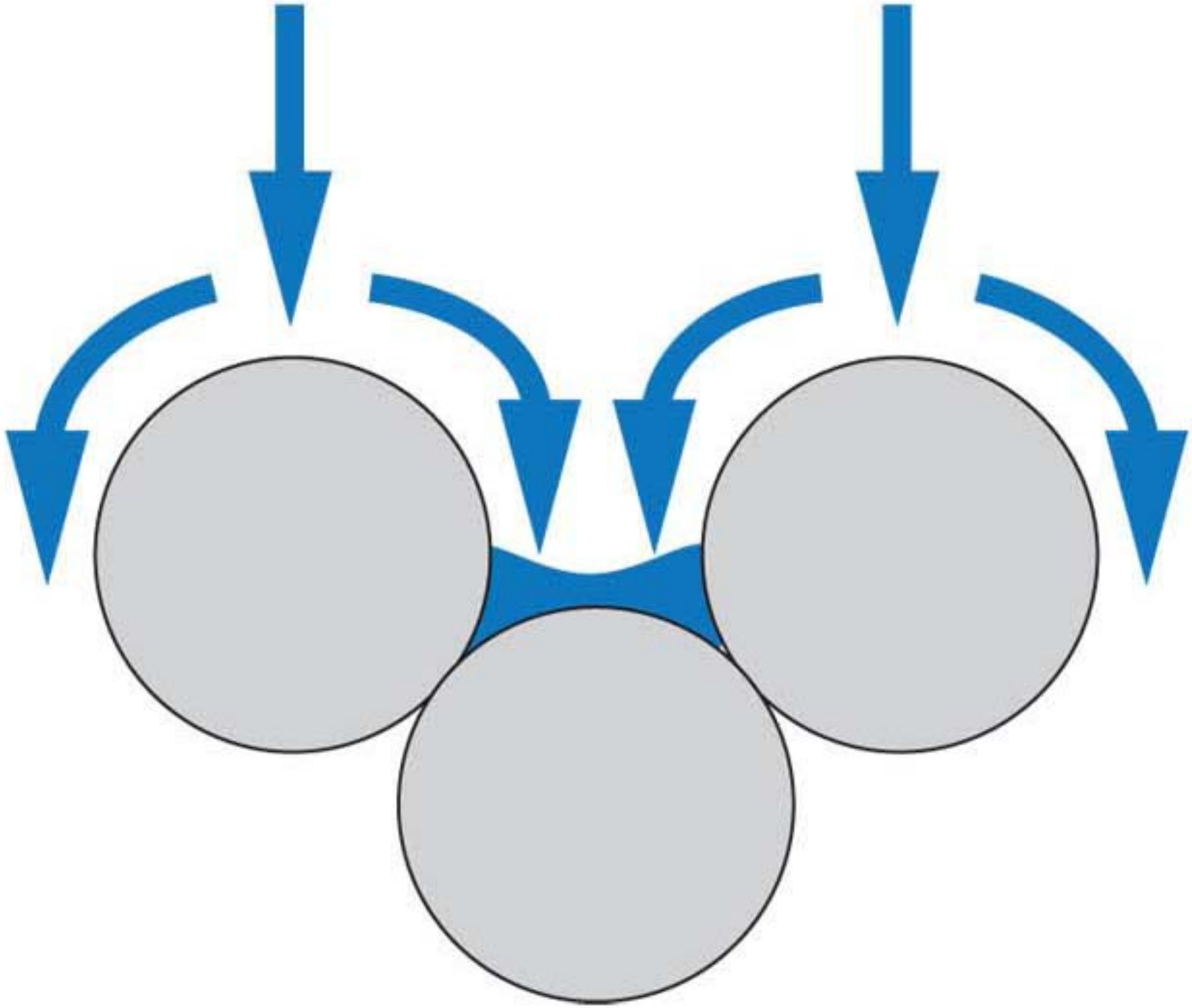

Outside
Radiation to night sky
Roof sheathing
Condensation and frost accumulating on underside of roof sheathing
Roof sheathing and top of attic insulation are radiation-coupled
Attic
Condensation and frost accumulating on top of attic insulation
Attic insulation
Inside

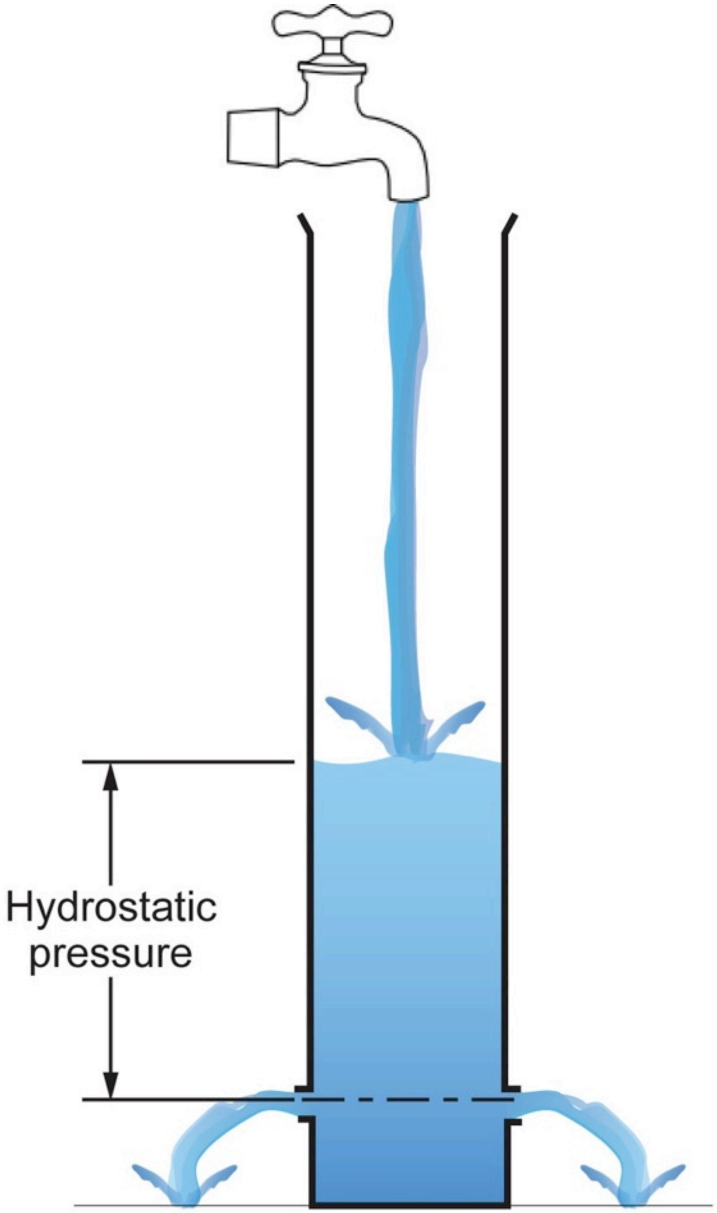
The Best For The Last….

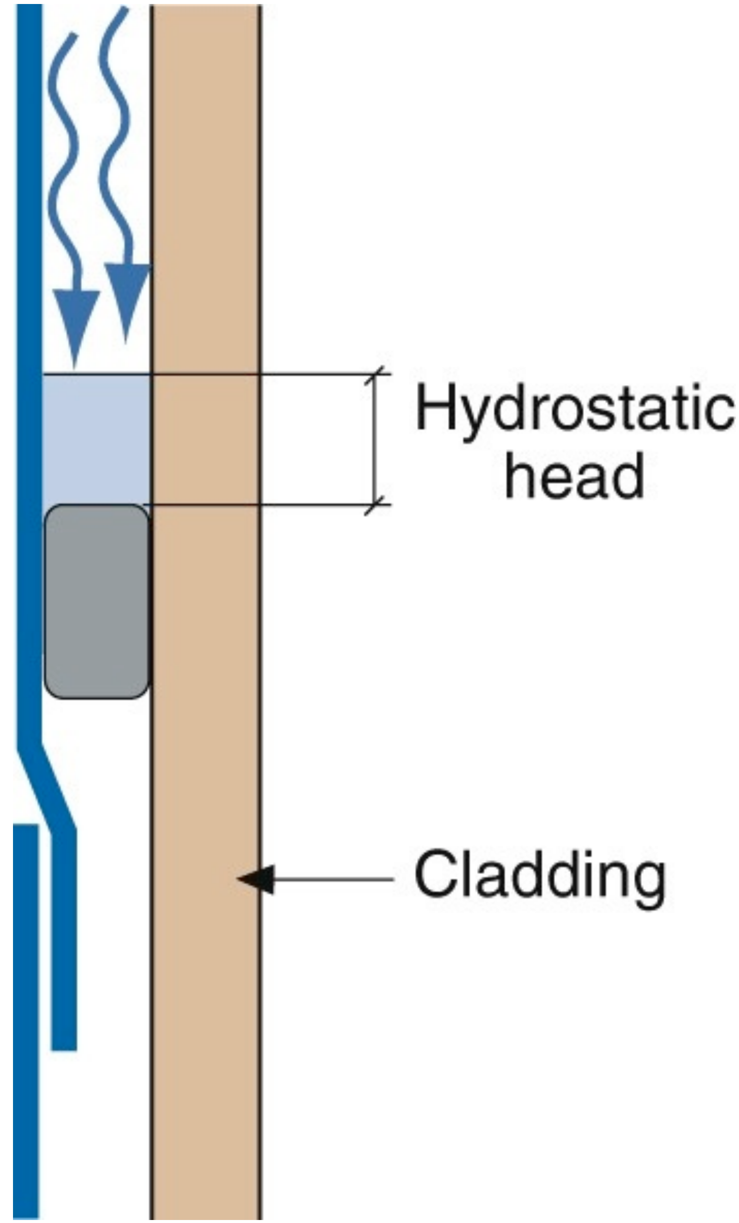

PUBLIC

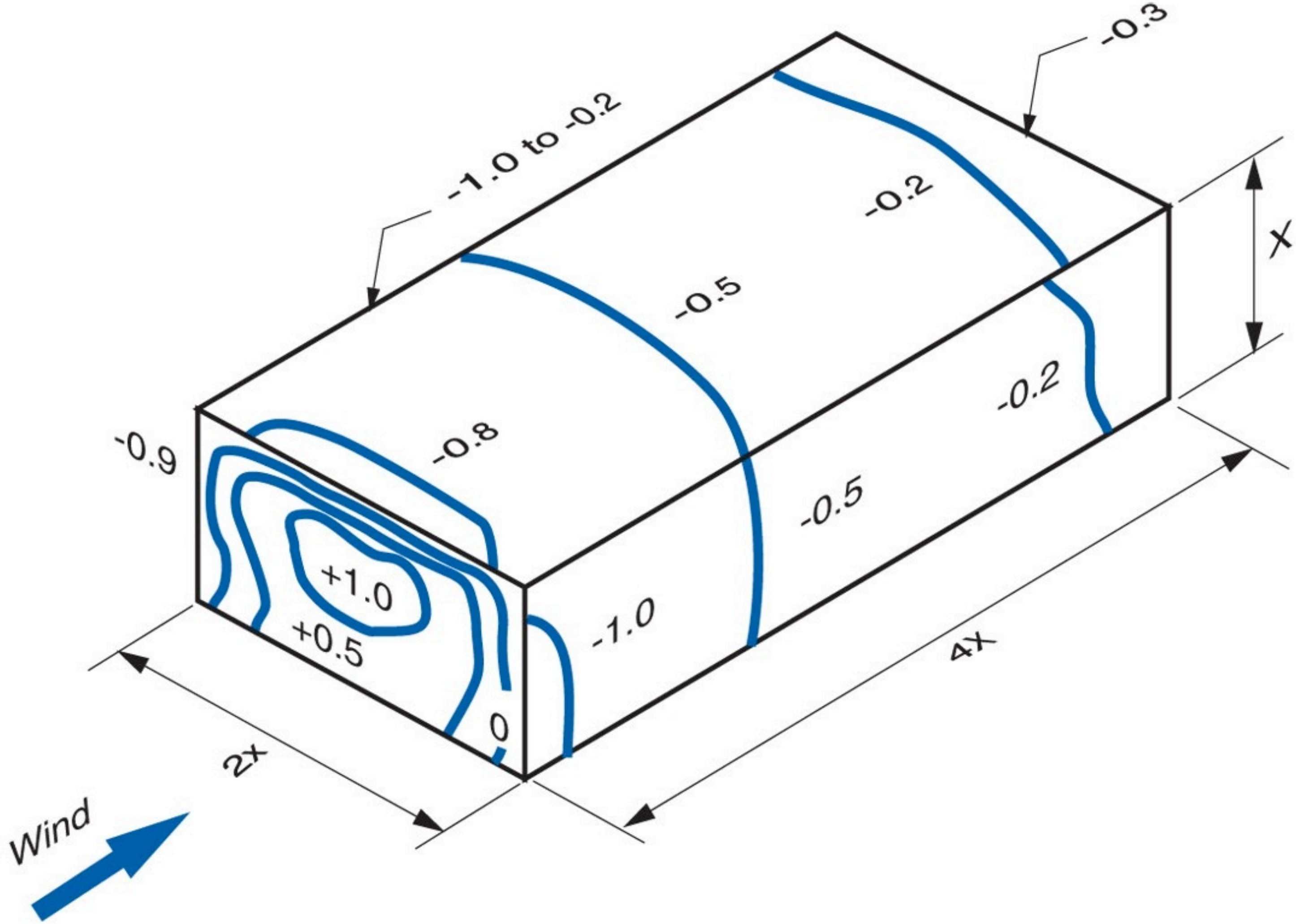




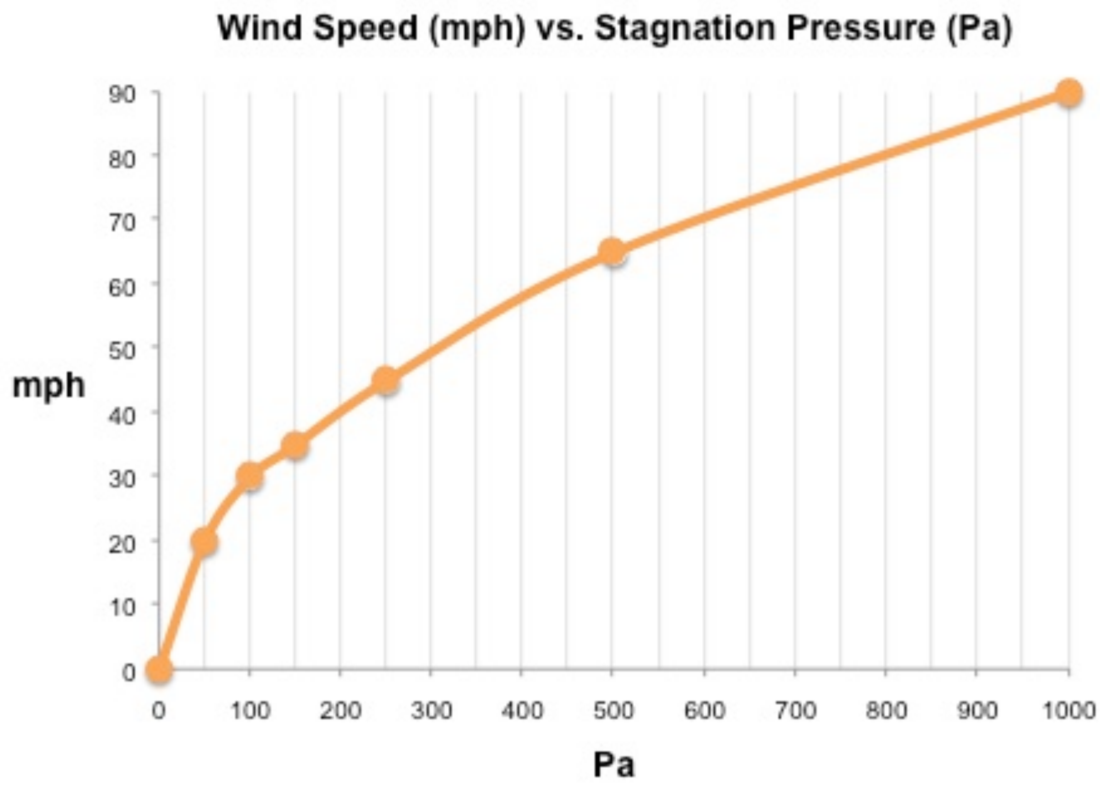



Hydrostatic
pressure
Hydrostatic
pressure


Hydrostatic head
Cladding


-0.3
-1.0 to -0.2
-0.2
X
-0.5
-0.2
-0.9
-0.8
-0.5
+1.0
-1.0
+0.5
4X
0
2X
Wind

Pascals		mph	
50	Pa =	20	mph
100	Pa =	30	mph
150	Pa =	35	mph
250	Pa =	45	mph
500	Pa =	65	mph
1,000	Pa =	90	mph

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HomeWrap
Tyvek
HomeWrap
DUPONT
Tyvek
HomeWrap


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DuPont
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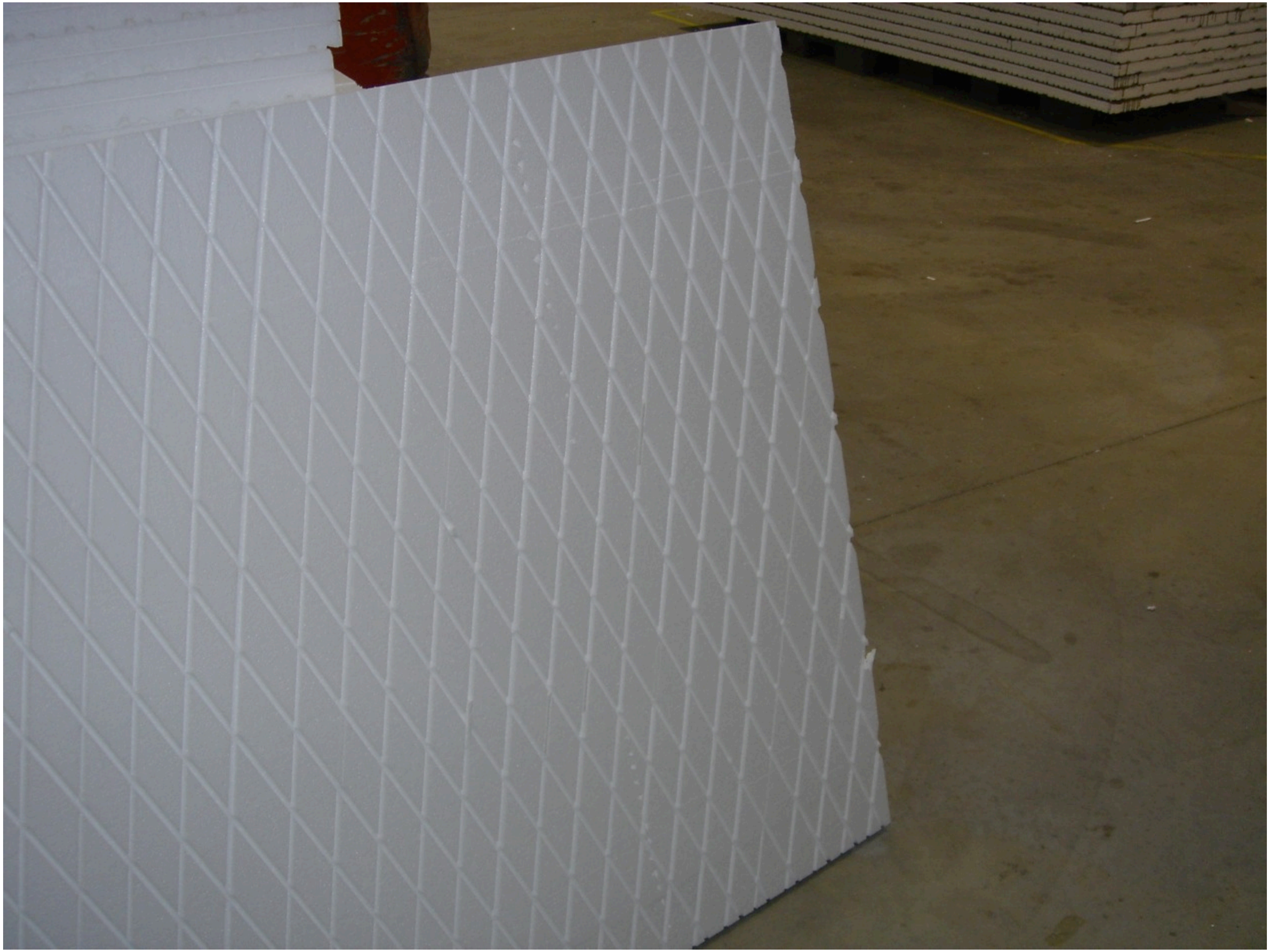
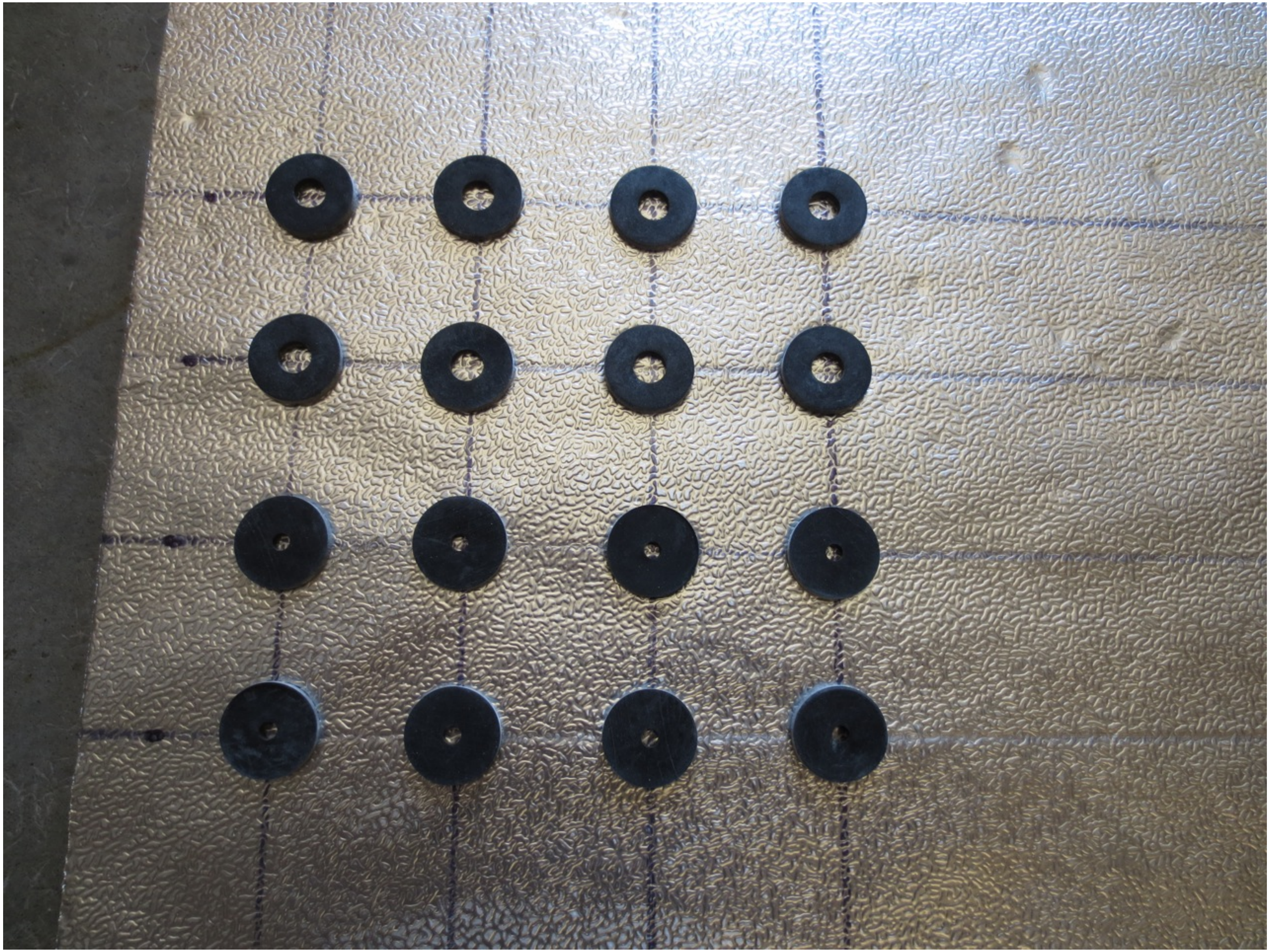
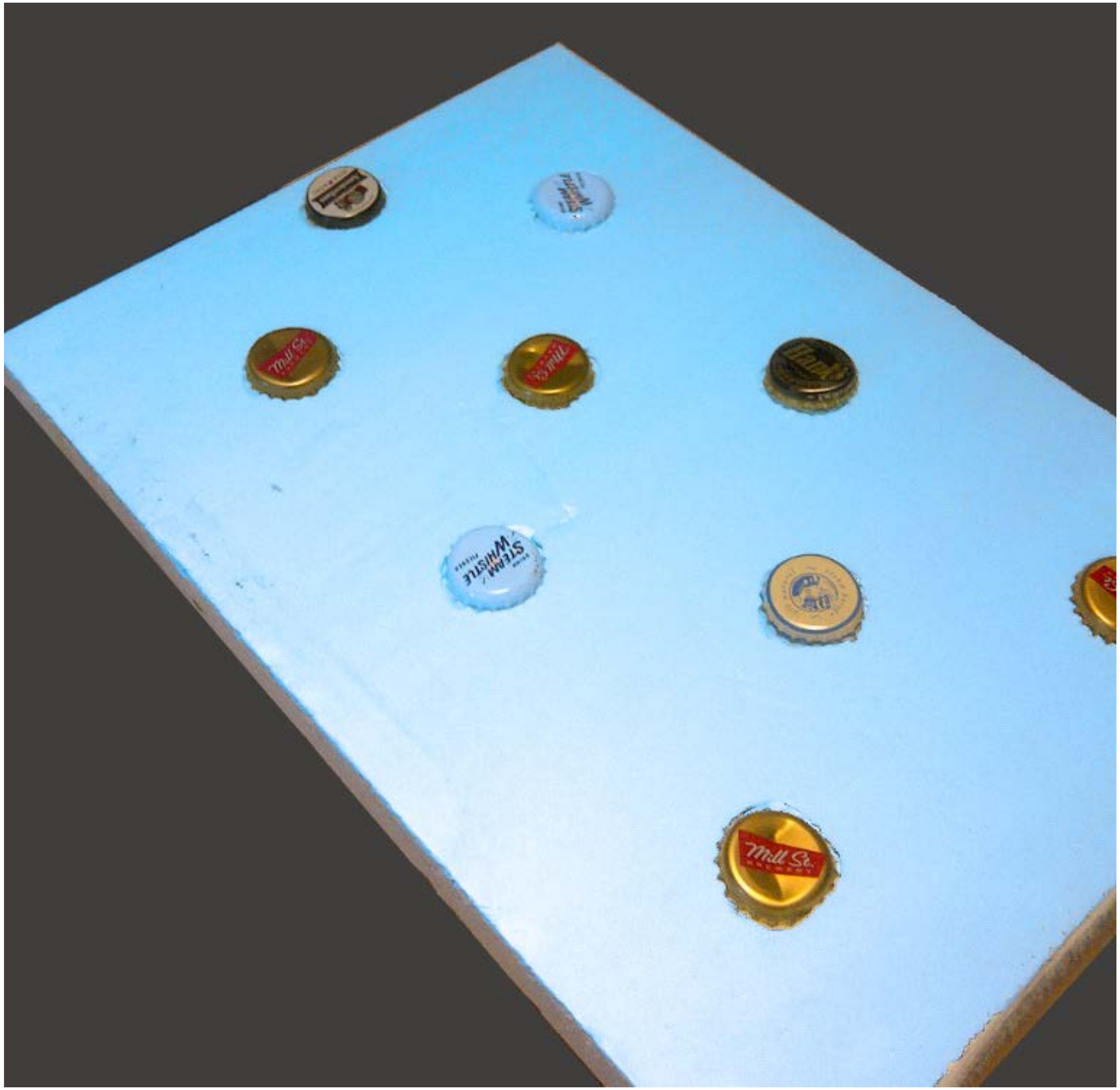
Tape
PONT



Rain Screen



Beer Screen?


Mill St.
STEAM WHISTLE