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

Building Science

Adventures In Building Science

"It isn't what we don't know that gives us trouble, it's what we know that ain't so"

Will Rogers

"There are known knowns. These are things we know. There are known unknowns. There are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

Donald Rumsfeld

Order of Magnitude

Order of Magnitude

1 to 10

10 to 100

100 to 1000

1000 to 10000

First Order Effects, Second Order Effects….

What is a Building?

A Building is an Environmental Separator

- Control heat flow
- Control airflow
- Control water vapor flow
- Control rain
- Control ground water
- Control light and solar radiation
- Control noise and vibrations
- Control contaminants, environmental hazards and odors
- Control insects, rodents and vermin
- Control fire
- Provide strength and rigidity
- Be durable
- Be aesthetically pleasing
- Be economical

Zeroth Law – Equal Systems

First Law - Conservation of Energy

Second Law - Entropy

Third Law – Absolute Zero

2^{nd} Law of Thermodynamics

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

Rudolf Clausius

Heat Flow Is From Warm To Cold

Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

Air Flow Is From A Higher Pressure to a Lower Pressure

Gravity Acts Down

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

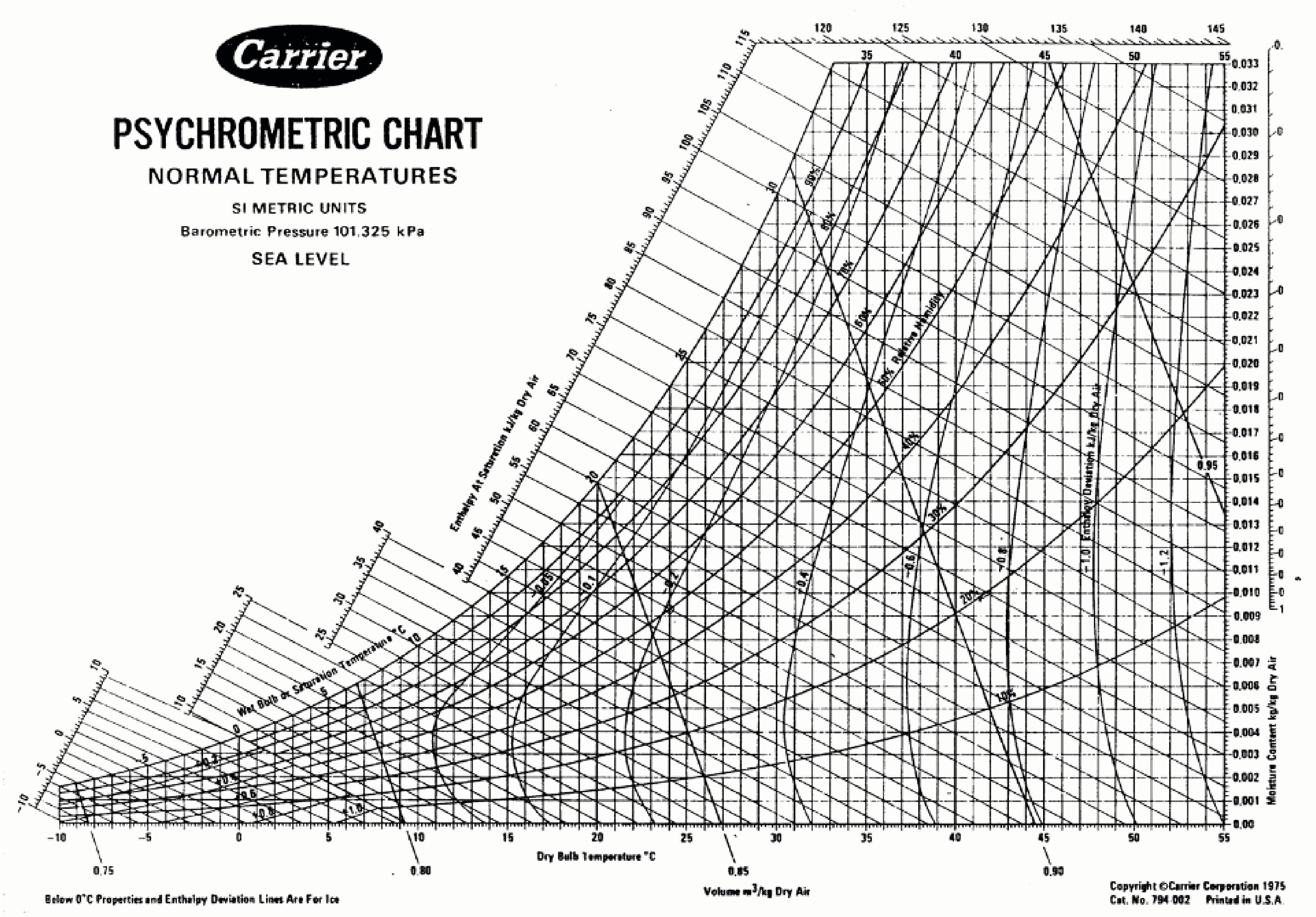
Moisture Flow Is From More To Less

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
Moisture Content kg/kg Dry Air
Relative Humidity
Enthalpy Deviation kJ/kg Dry Air
Below 0°C Properties and Enthalpy Deviation Lines Are For Ice
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Damage Functions

Damage Functions

Water

Heat

Ultra Violet Radiation

Damage Functions

Water

Heat

Ultra Violet Radiation

Oxidization (Ozone)

Fatigue (Creep)

The Three Biggest Problems In Buildings Are Water, Water and Water…

80 Percent of all Construction Problems are Related to Water

Heat

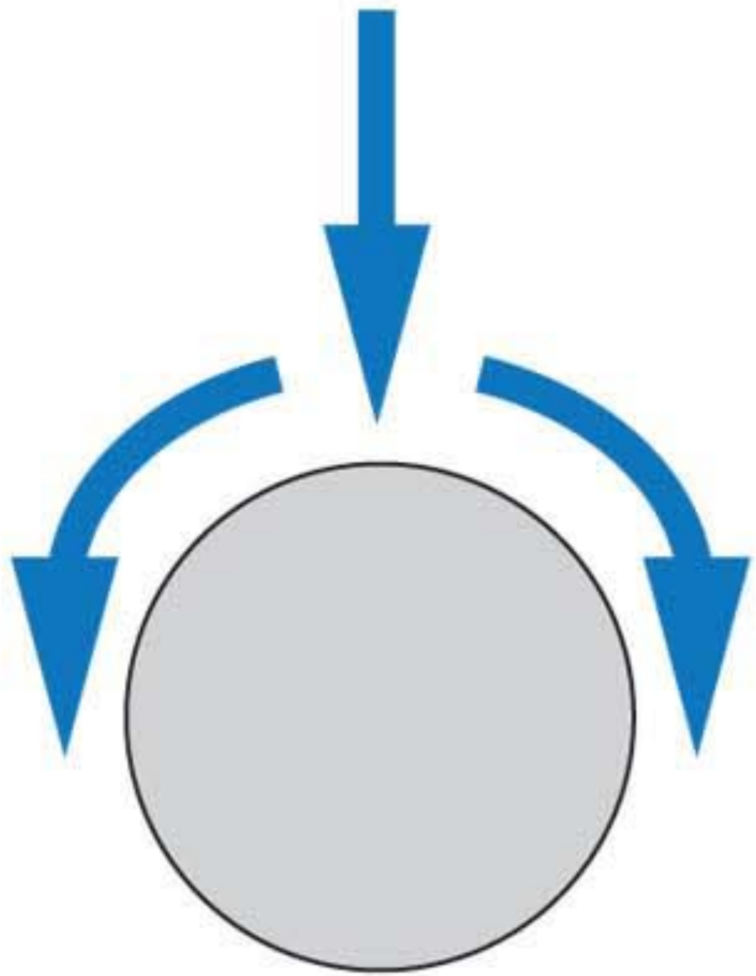
Air

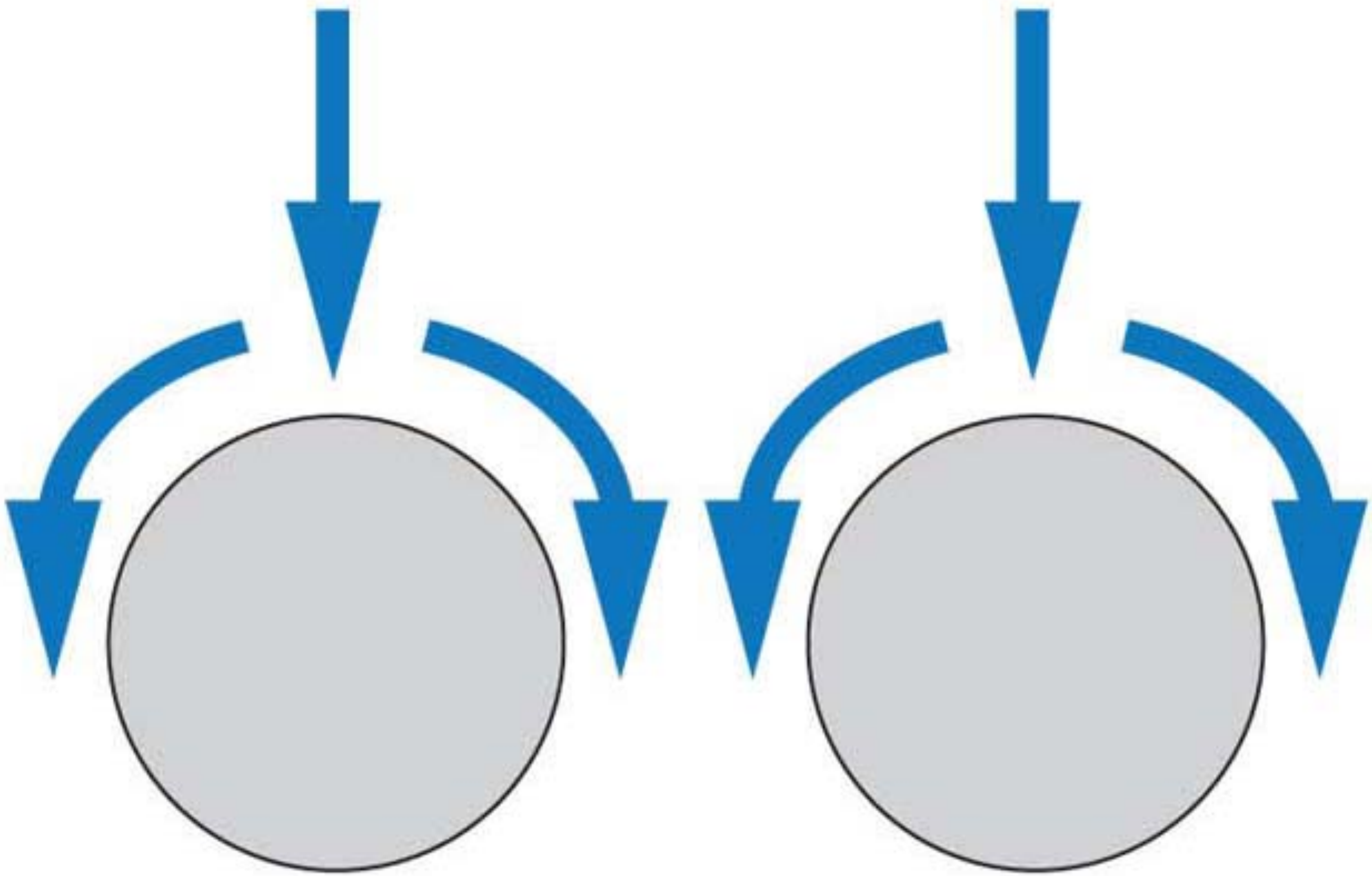
Moisture

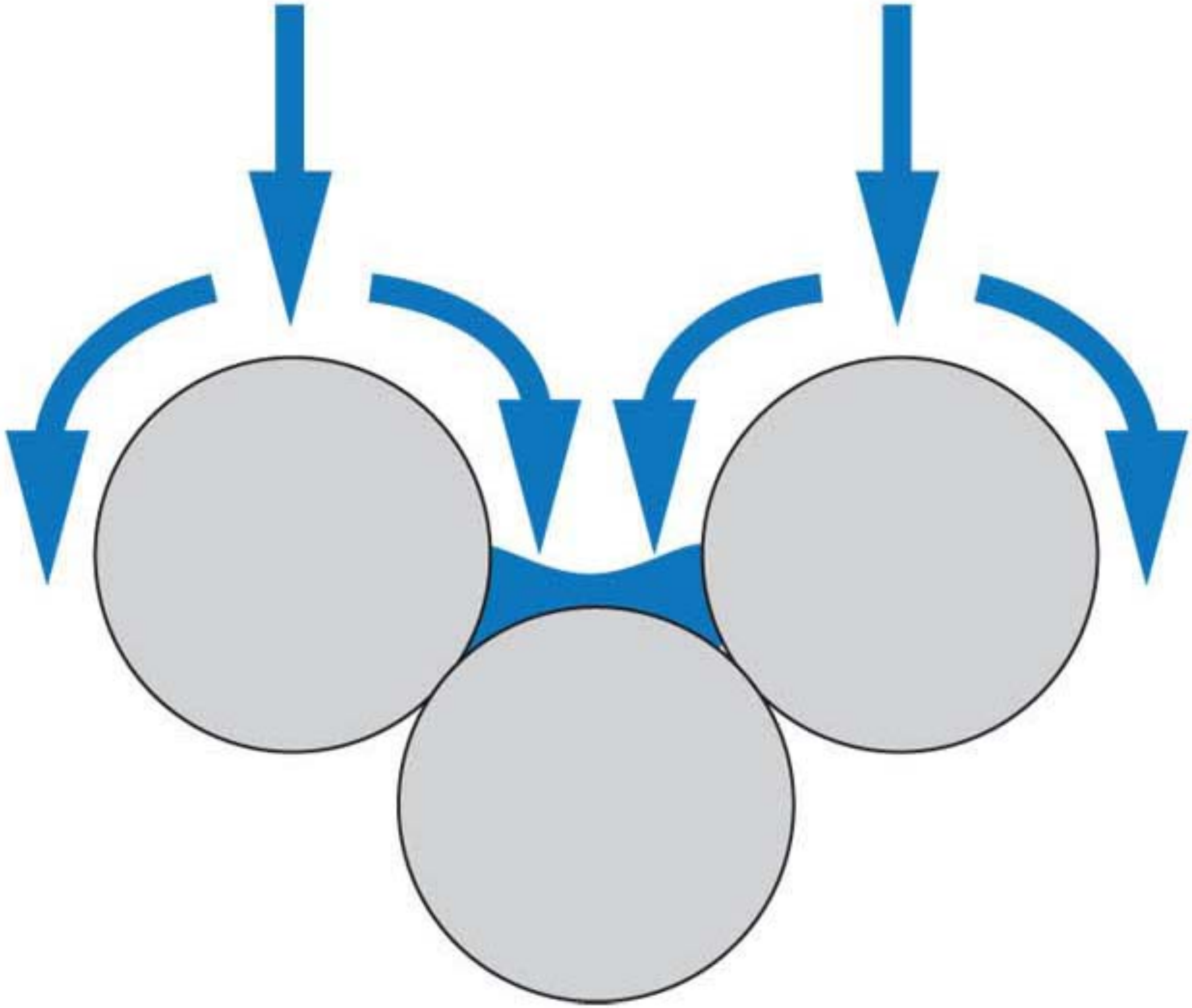
HAM

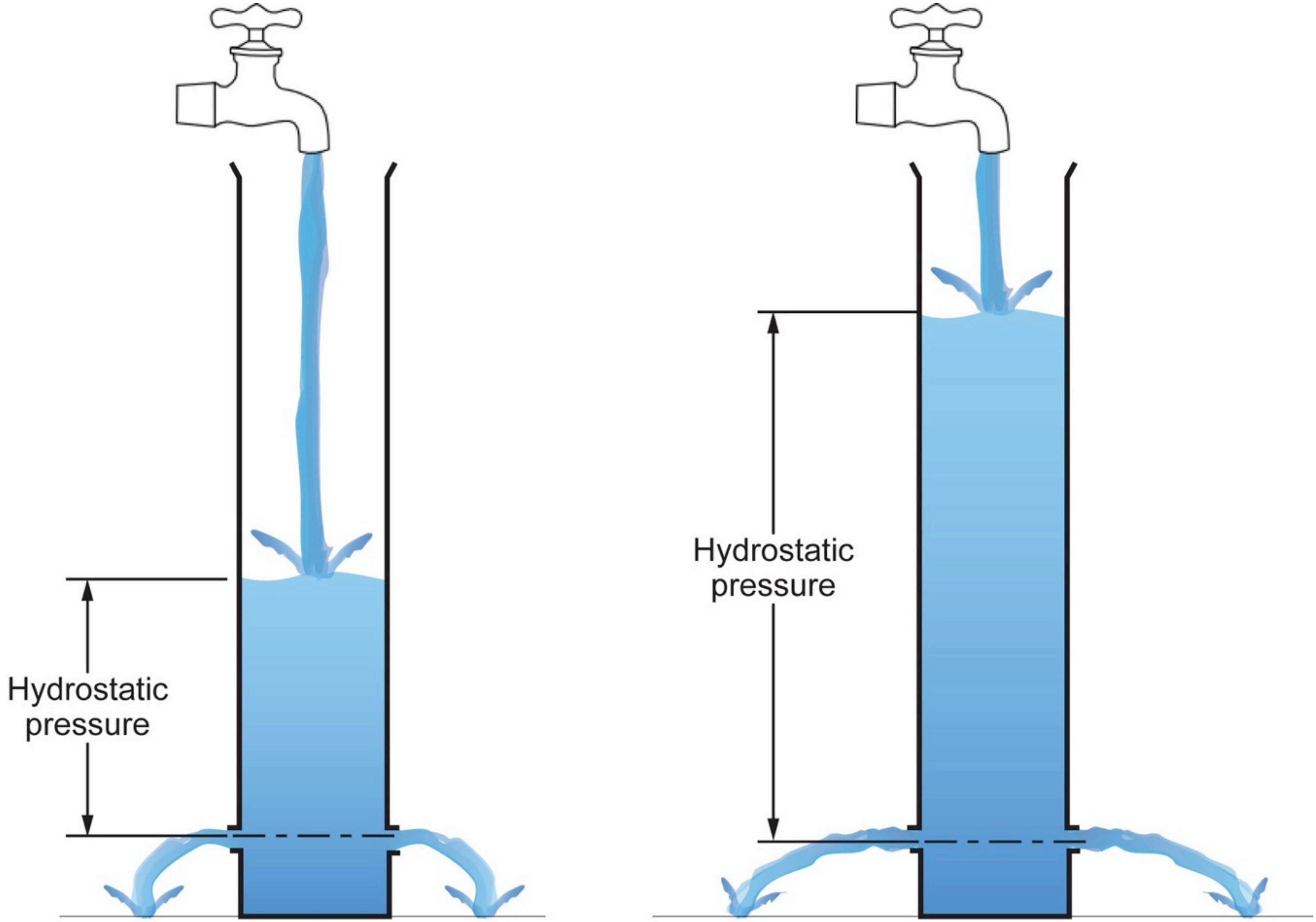
Hygrothermal Analysis

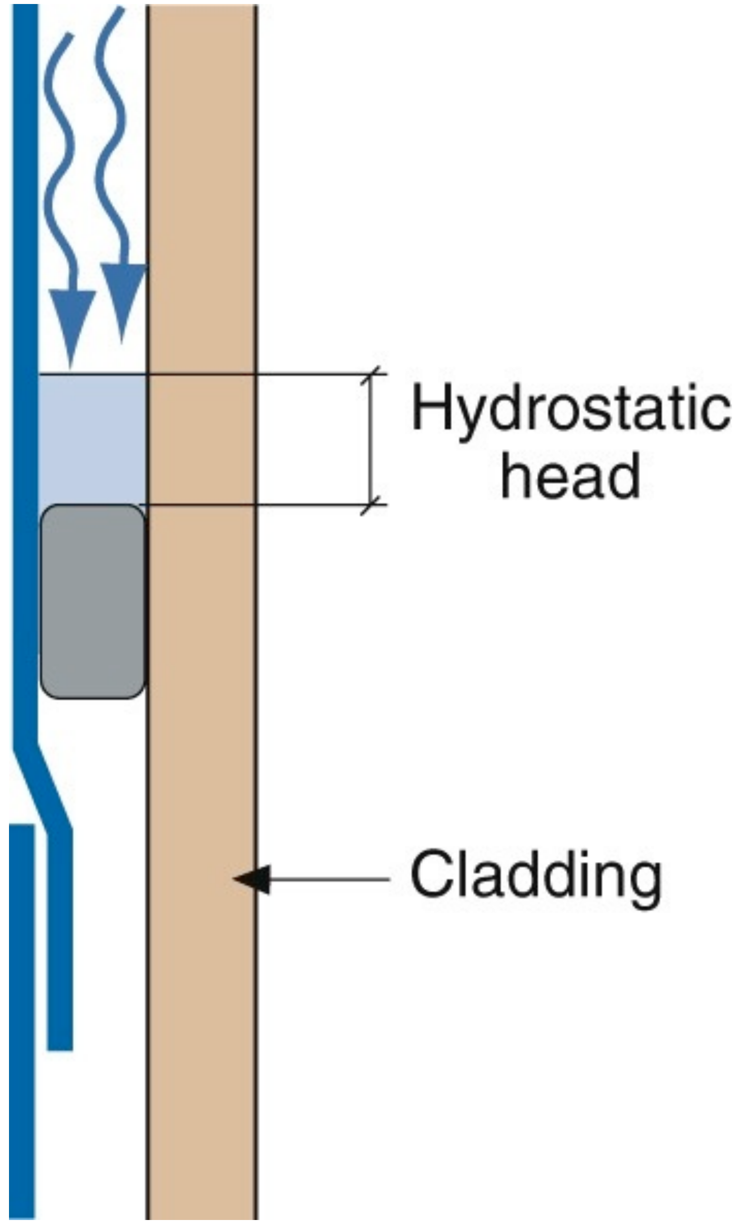

PUBLIC

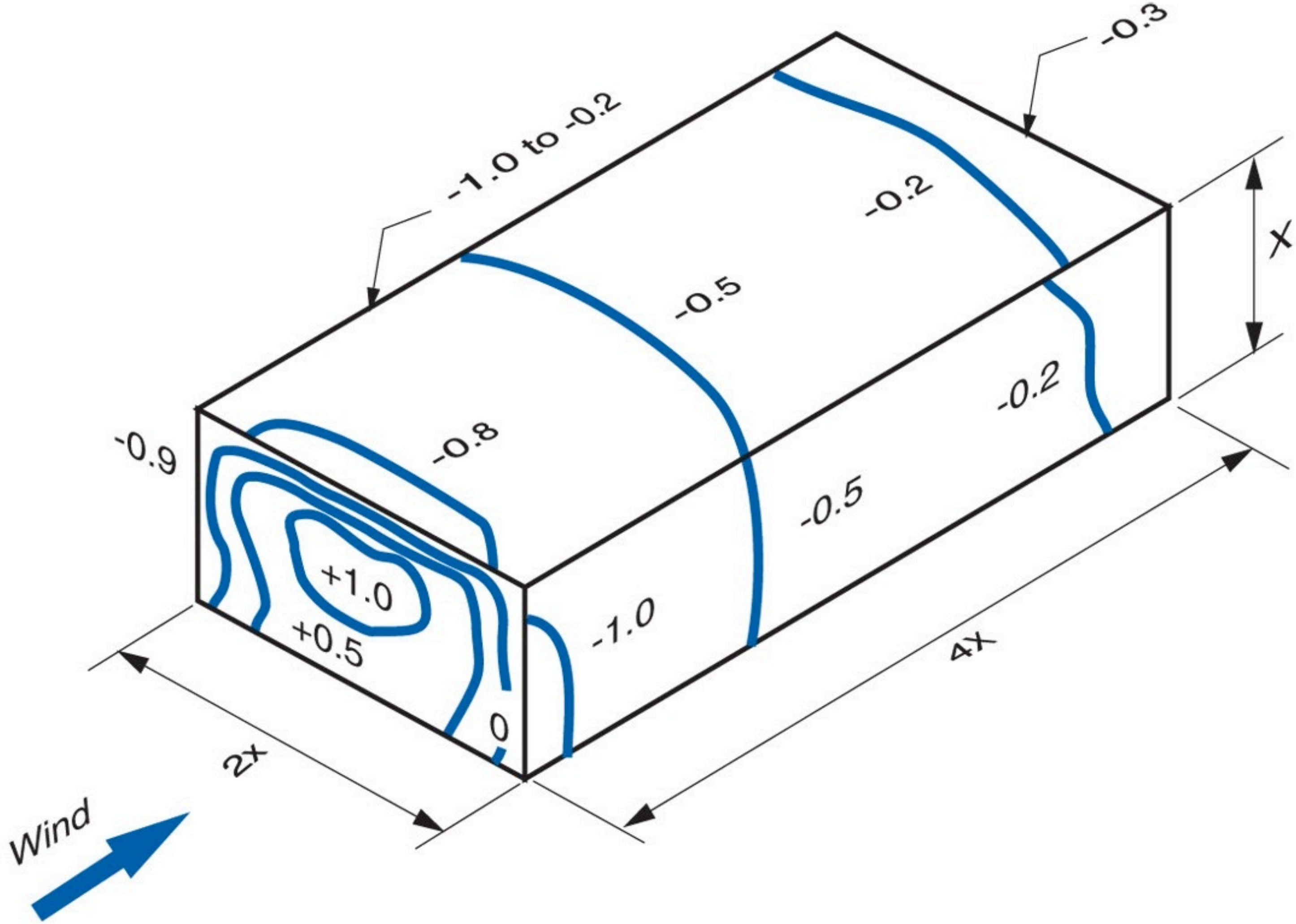




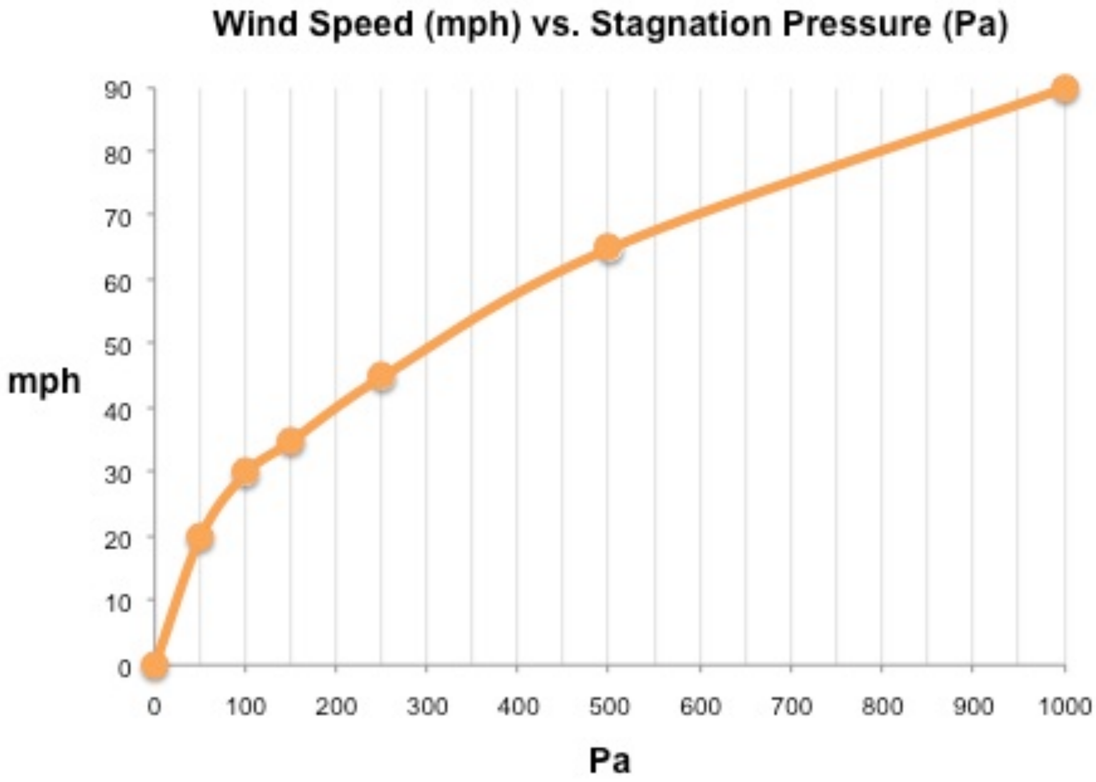


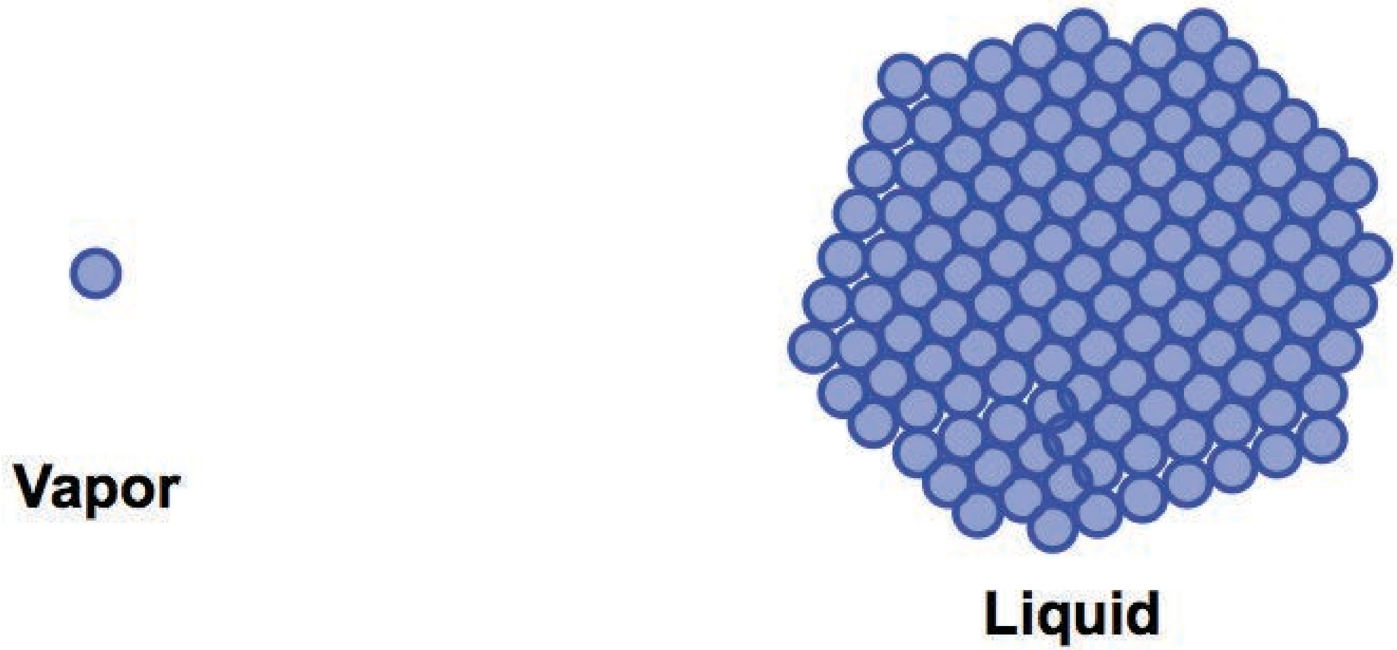

Hydrostatic
pressure
Hydrostatic
pressure

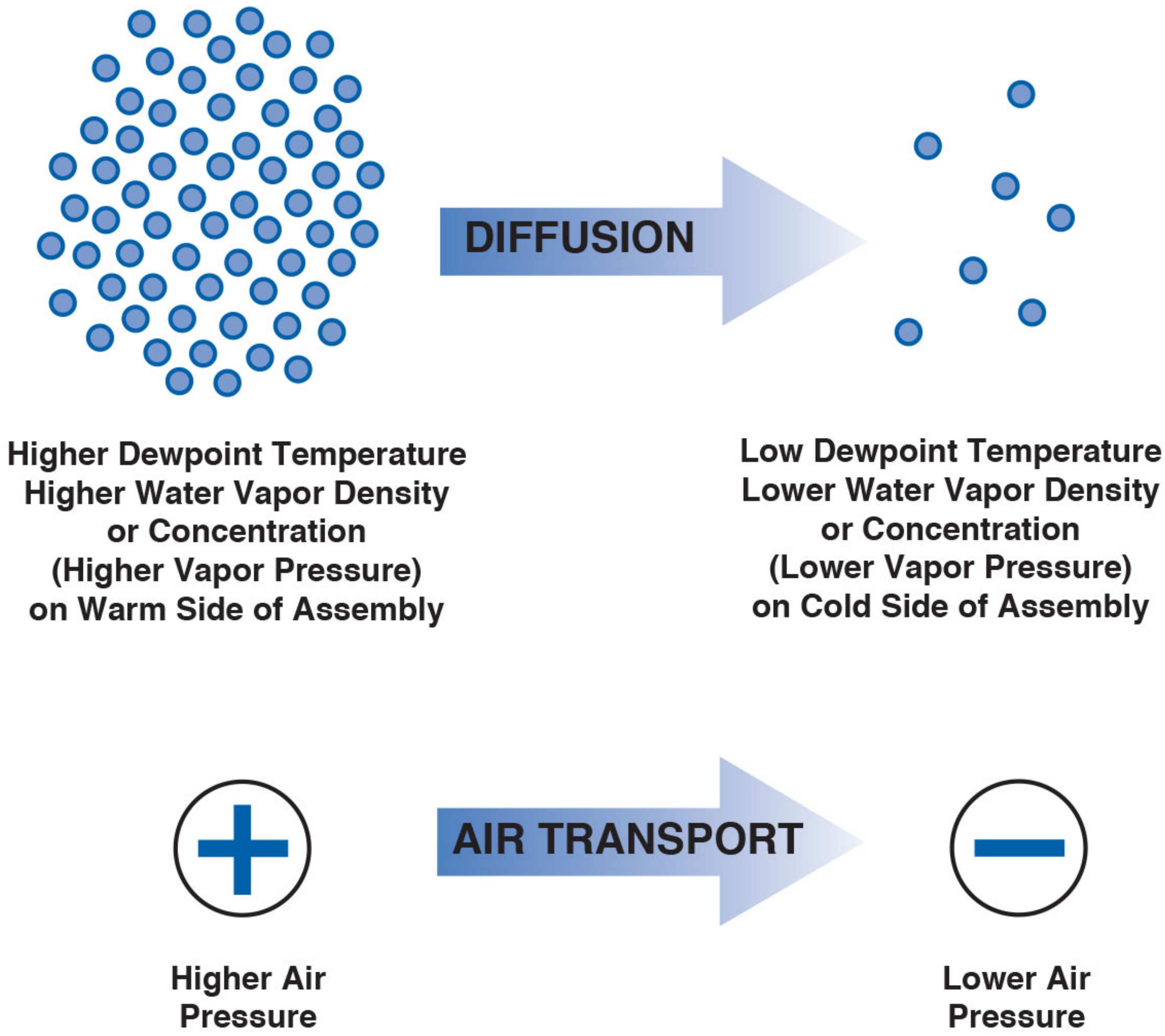

Hydrostatic
head
Cladding

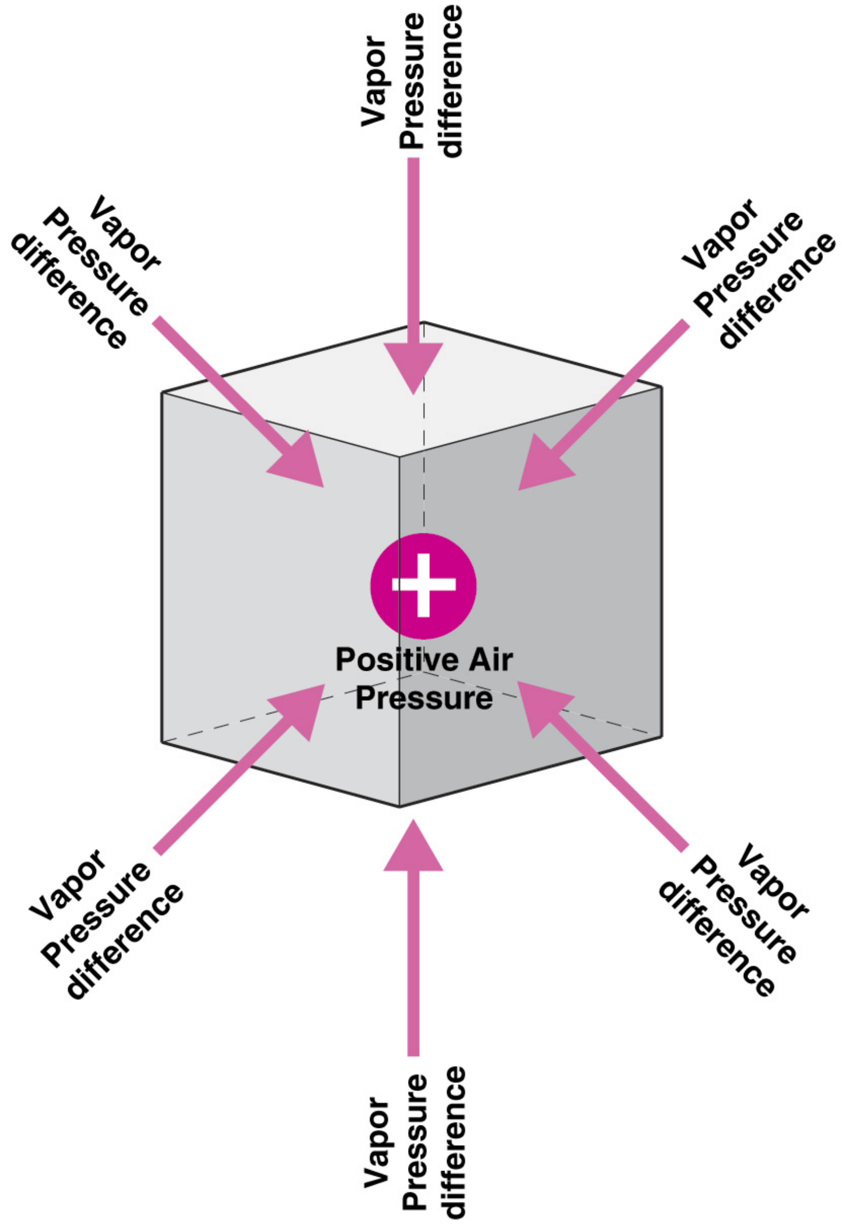

-0.3
-1.0 to -0.2
-0.2
X
-0.5
-0.2
-0.9
-0.8
-0.5
+1.0
-1.0
+0.5
4X
0
2X
Wind

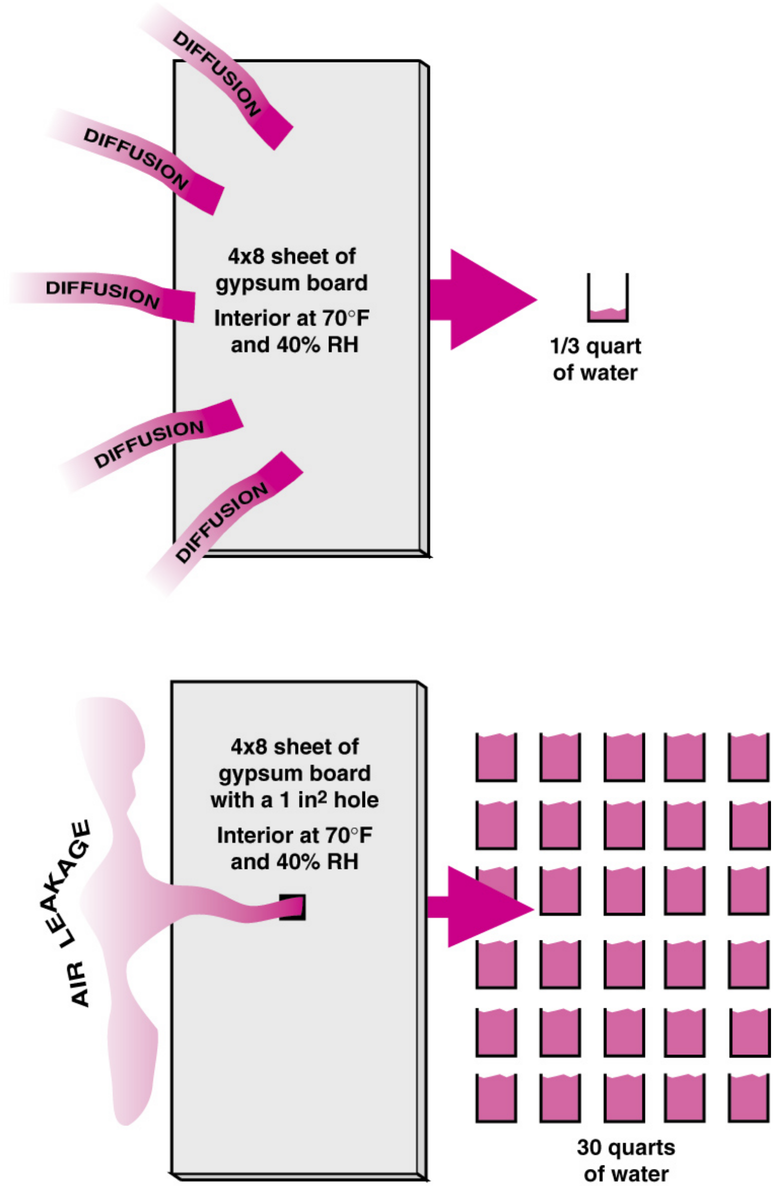
Pascals		mph	
50	Pa =	20	mph
100	Pa =	30	mph
150	Pa =	35	mph
250	Pa =	45	mph
500	Pa =	65	mph
1,000	Pa =	90	mph

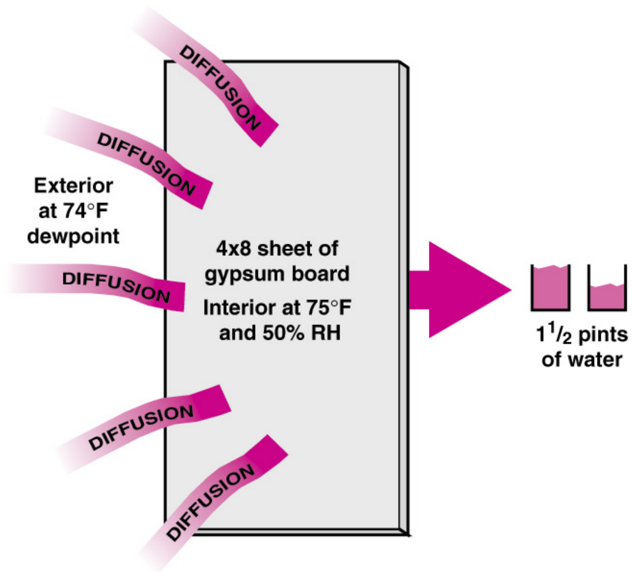


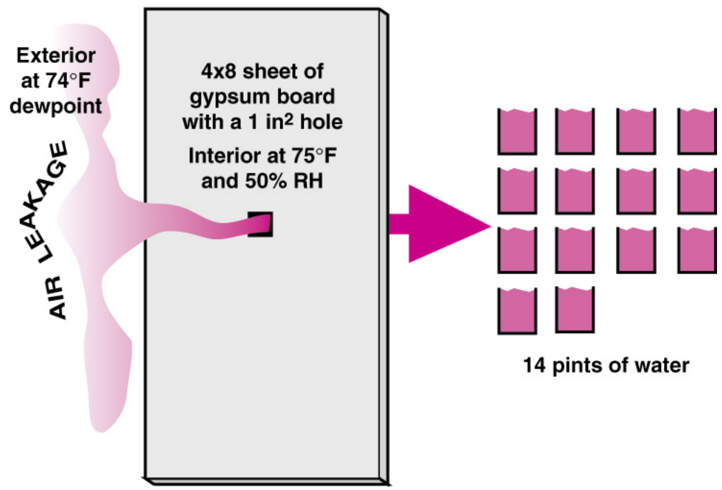

Vapor
Liquid

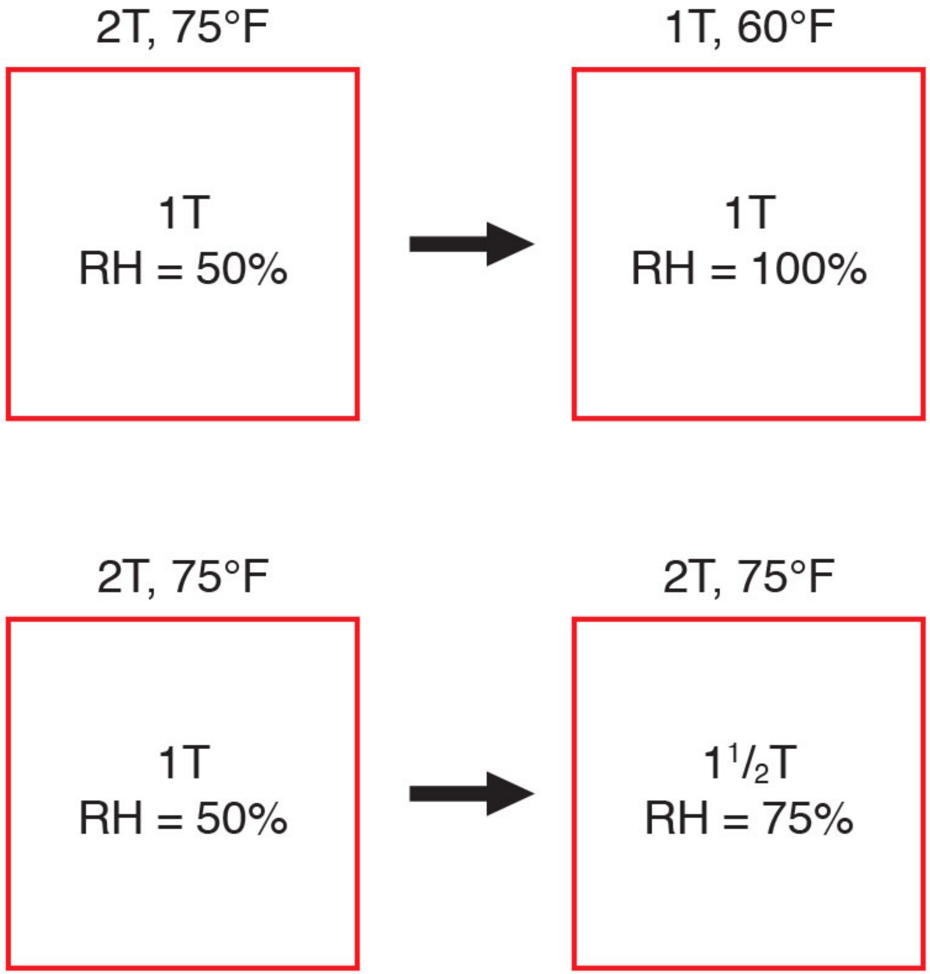

DIFFUSION
Higher Dewpoint Temperature
Higher Water Vapor Density
or Concentration
(Higher Vapor Pressure)
on Warm Side of Assembly
Low Dewpoint Temperature
Lower Water Vapor Density
or Concentration
(Lower Vapor Pressure)
on Cold Side of Assembly
AIR TRANSPORT
Higher Air
Pressure
Lower Air
Pressure

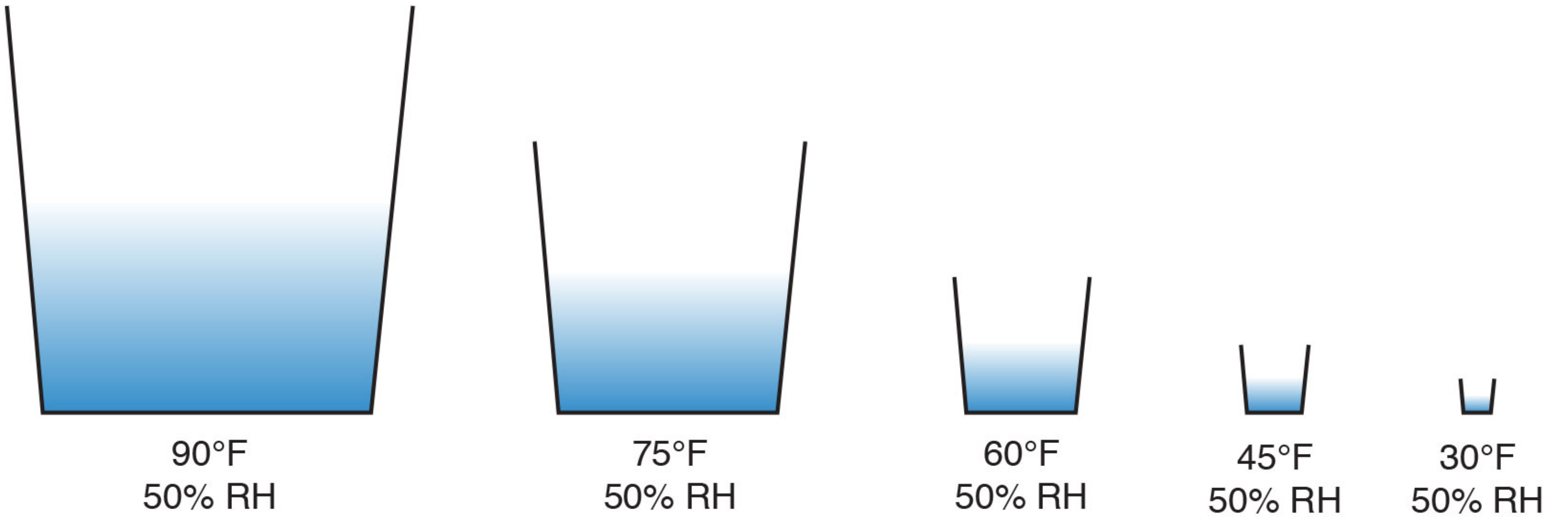

Vapor
Pressure
difference
Vapor
Pressure
difference
Vapor
Pressure
difference
Positive Air
Pressure
Vapor
Pressure
difference
Vapor
Pressure
difference
Vapor
Pressure
difference

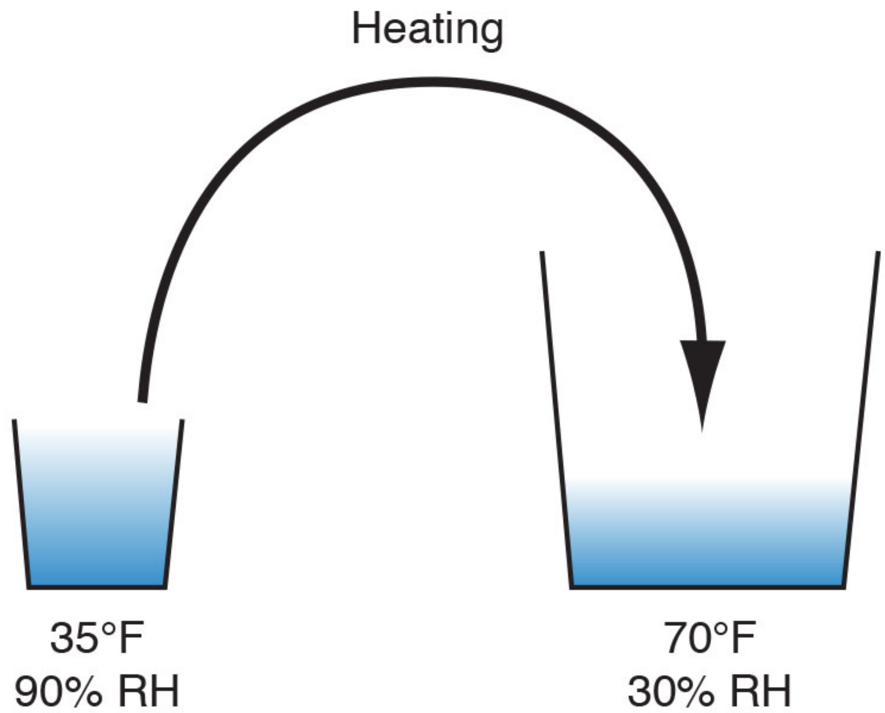

DIFFUSION
DIFFUSION
DIFFUSION
DIFFUSION
DIFFUSION
4x8 sheet of gypsum board
Interior at 70°F and 40% RH
1/3 quart of water
AIR LEAKAGE
4x8 sheet of gypsum board with a 1 in2 hole
Interior at 70°F and 40% RH
30 quarts of water

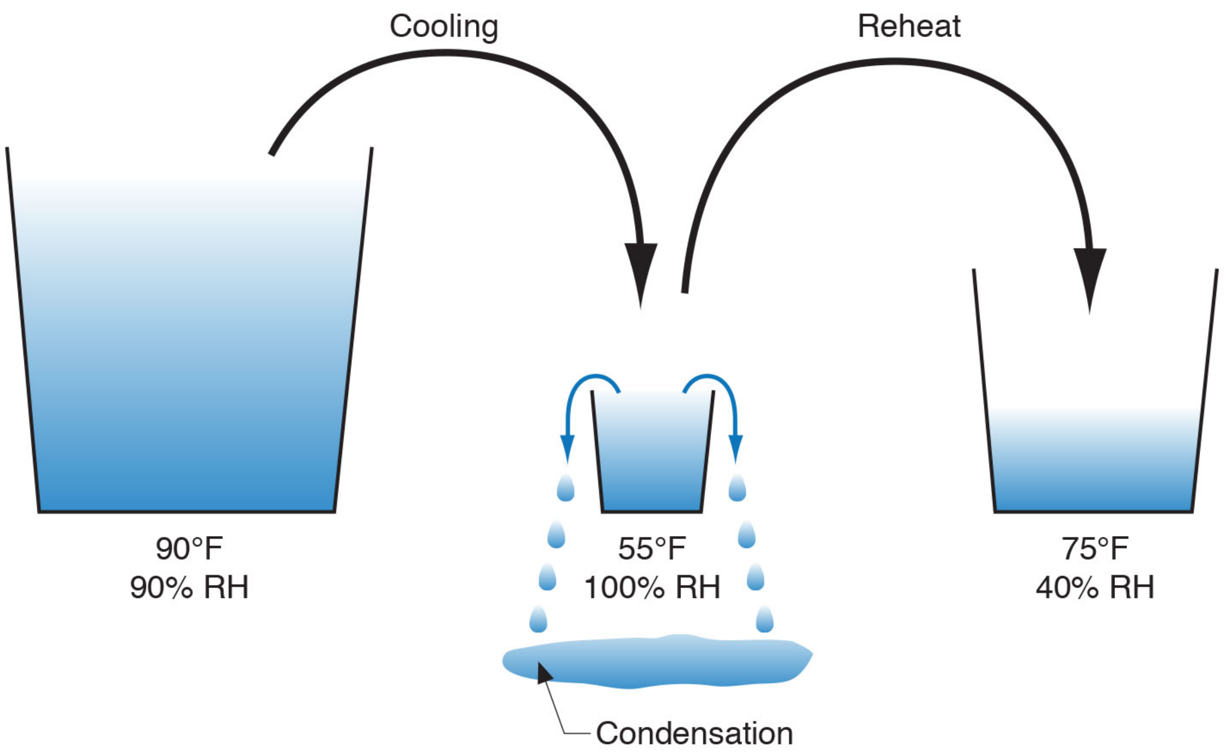

DIFFUSION
DIFFUSION
Exterior
at 74°F
dewpoint
DIFFUSION
4x8 sheet of
gypsum board
Interior at 75°F
and 50% RH
1 1/2 pints
of water
DIFFUSION
DIFFUSION

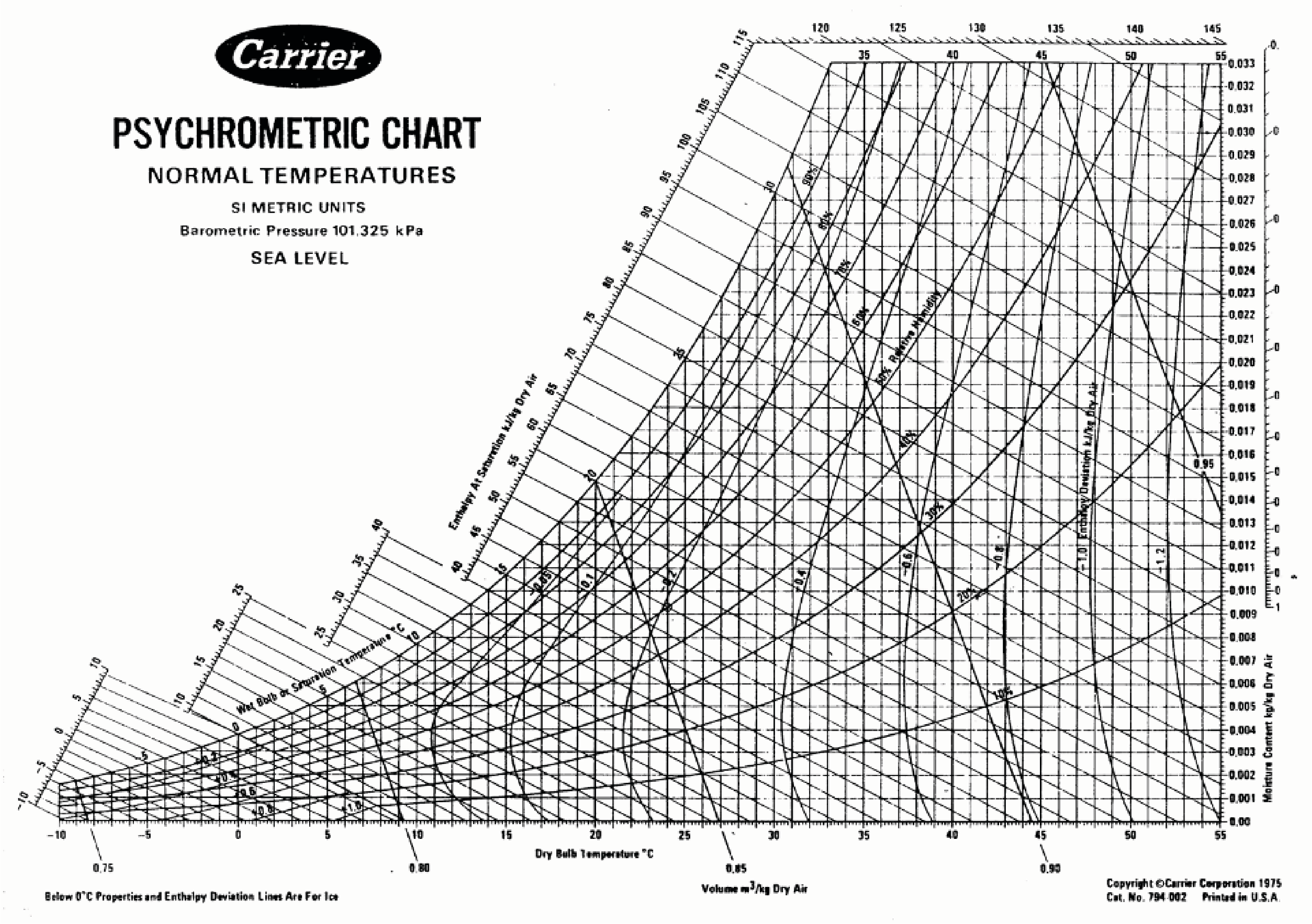

Exterior
at 74°F
dewpoint
AIR LEAKAGE
4x8 sheet of
gypsum board
with a 1 in2 hole
Interior at 75°F
and 50% RH
14 pints of water


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


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
Relative Humidity
Enthalpy Deviation kJ/kg Dry Air
Moisture Content kg/kg Dry Air
Dry Bulb Temperature °C
Volume m3/kg Dry Air
Below 0°C Properties and Enthalpy Deviation Lines Are For Ice
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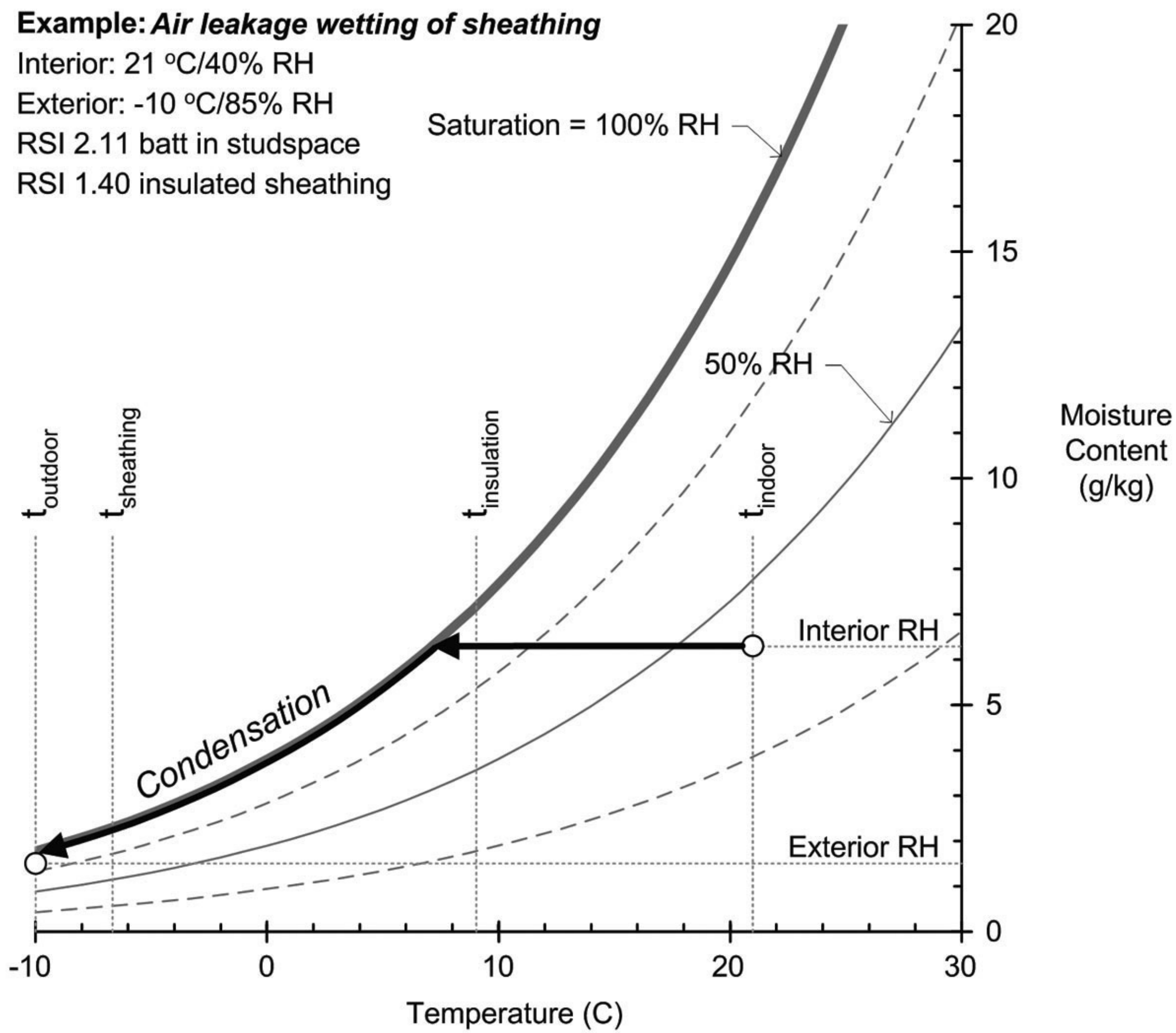
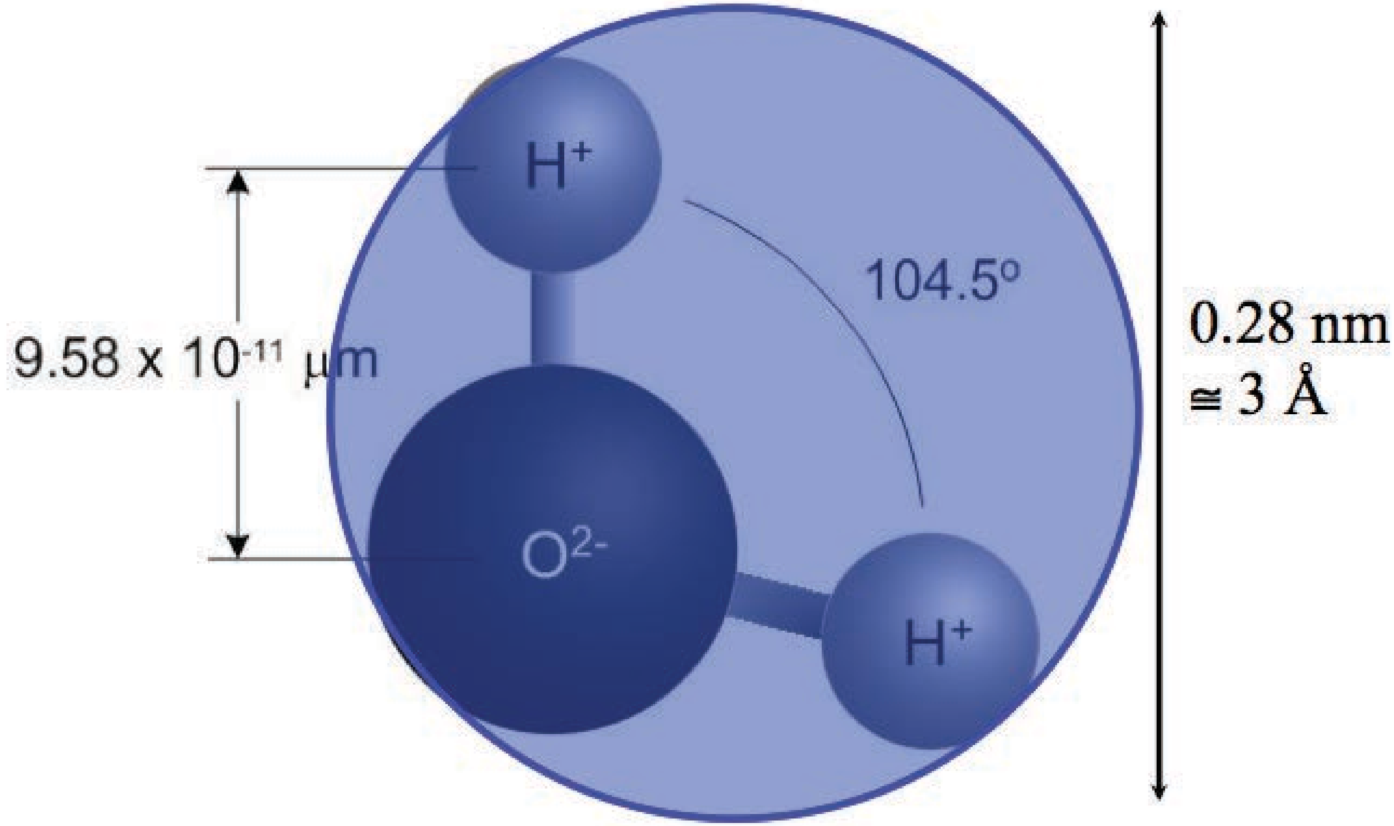
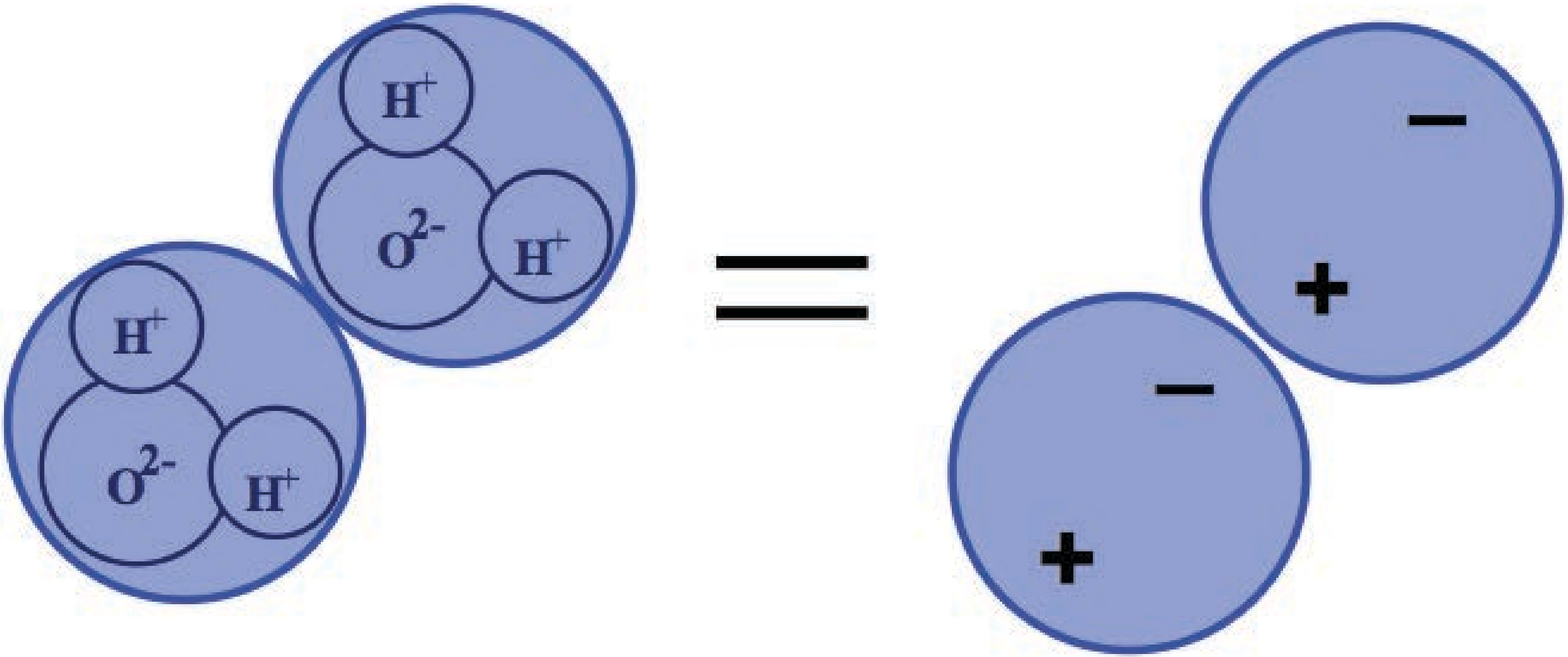
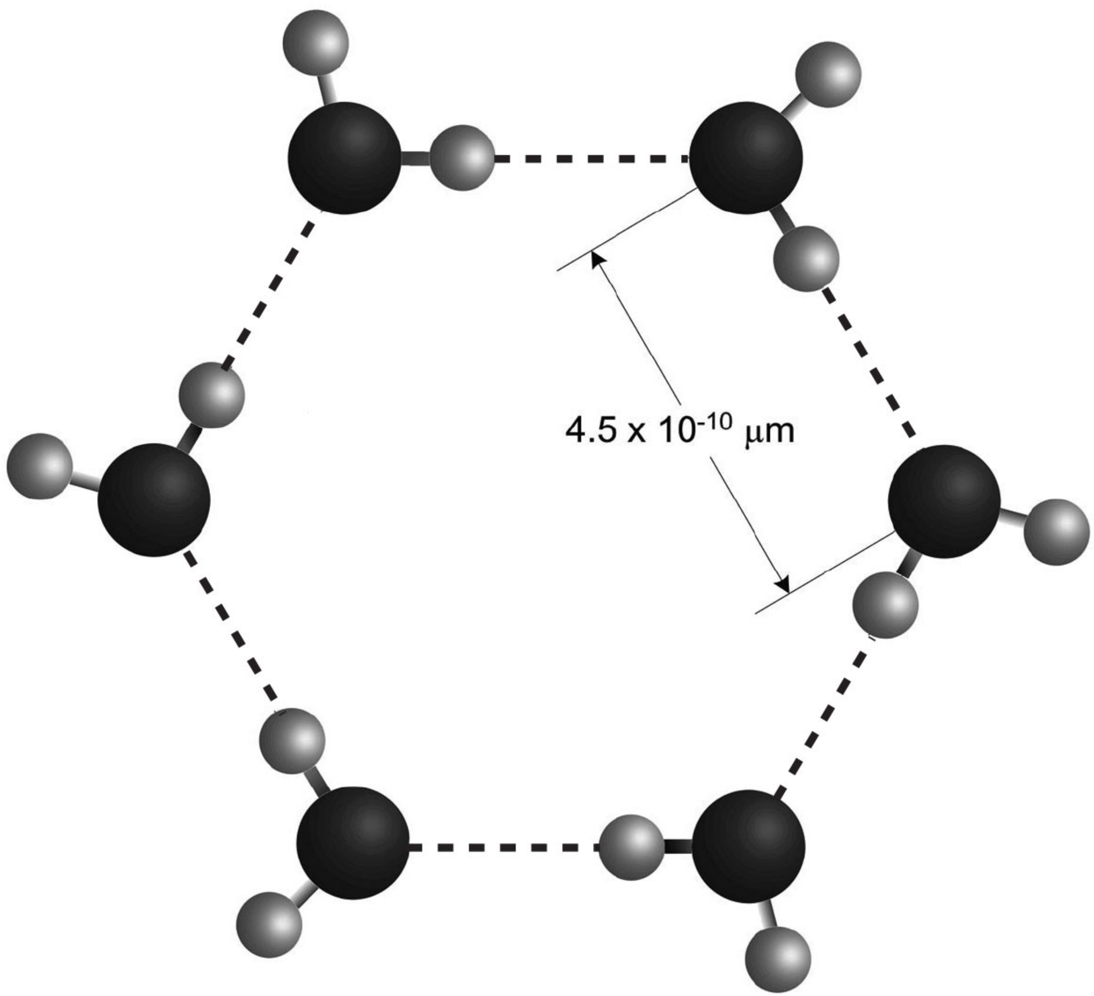
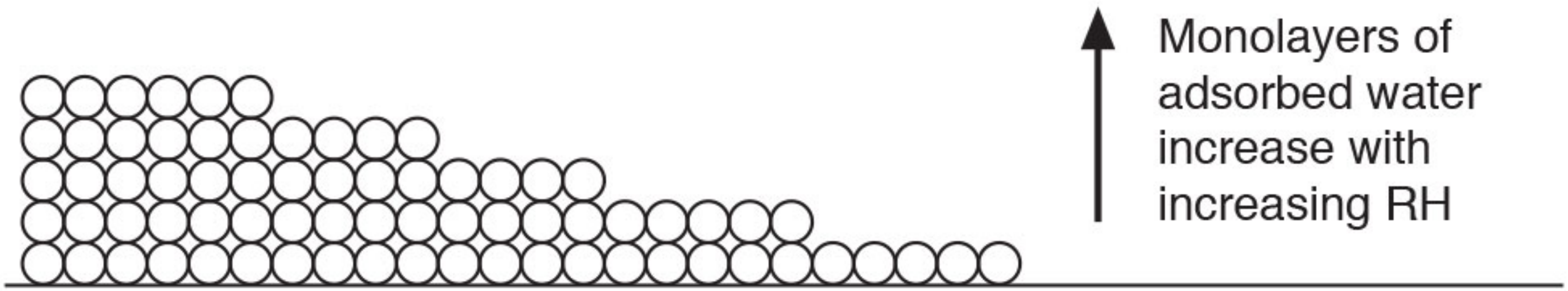


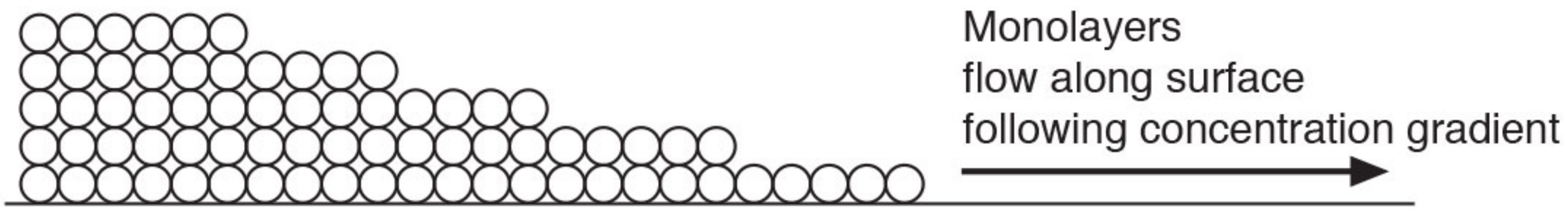
Cooling and condensation
From Straube & Burnett, 2005

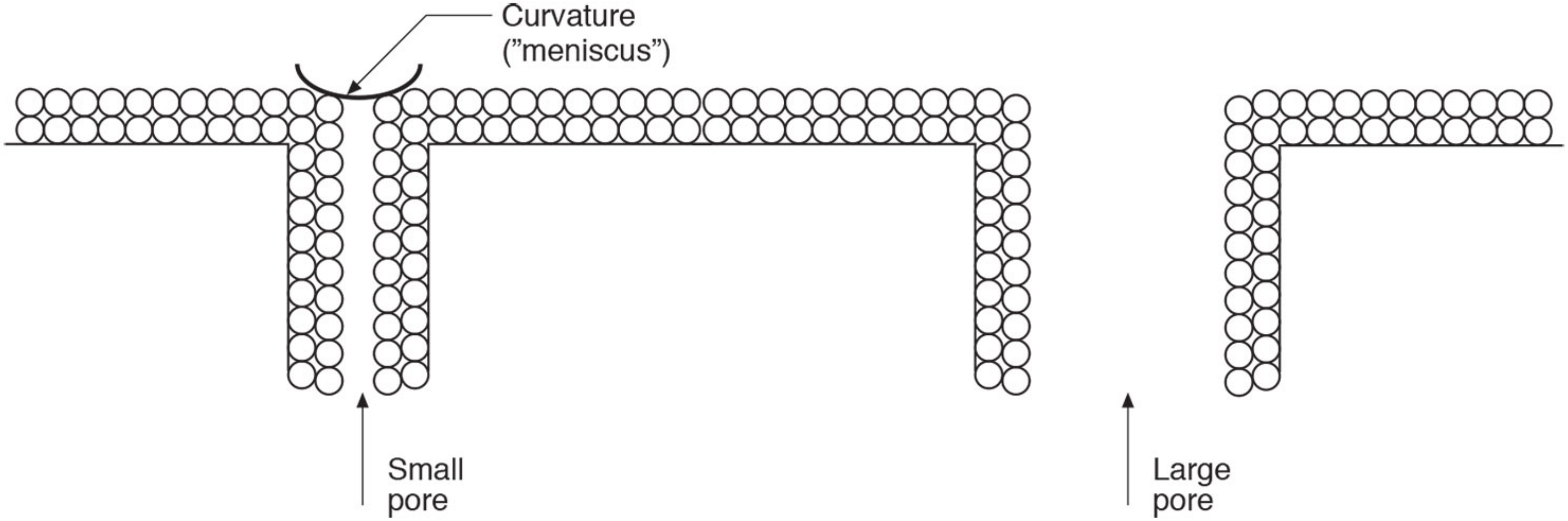

H+
104.5o
0.28 nm
≅ 3 Å
9.58 x 10-11 μm
O2-
H+


H+
O2-
H+
H+
O2-
H+
=
−
+
−
+


4.5 x 10-10 μm

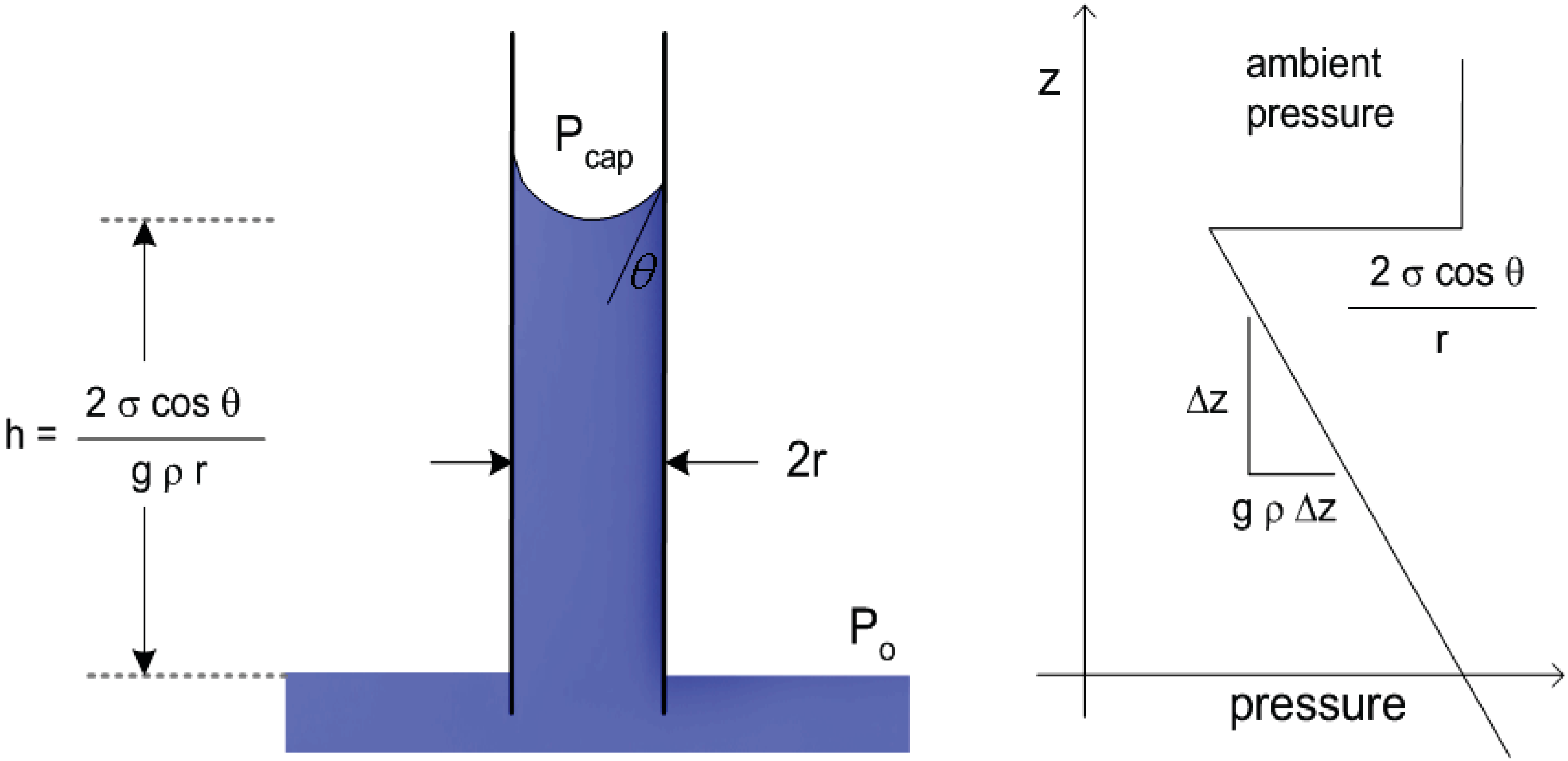

Monolayers of
adsorbed water
increase with
increasing RH


Monolayers
flow along surface
following concentration gradient

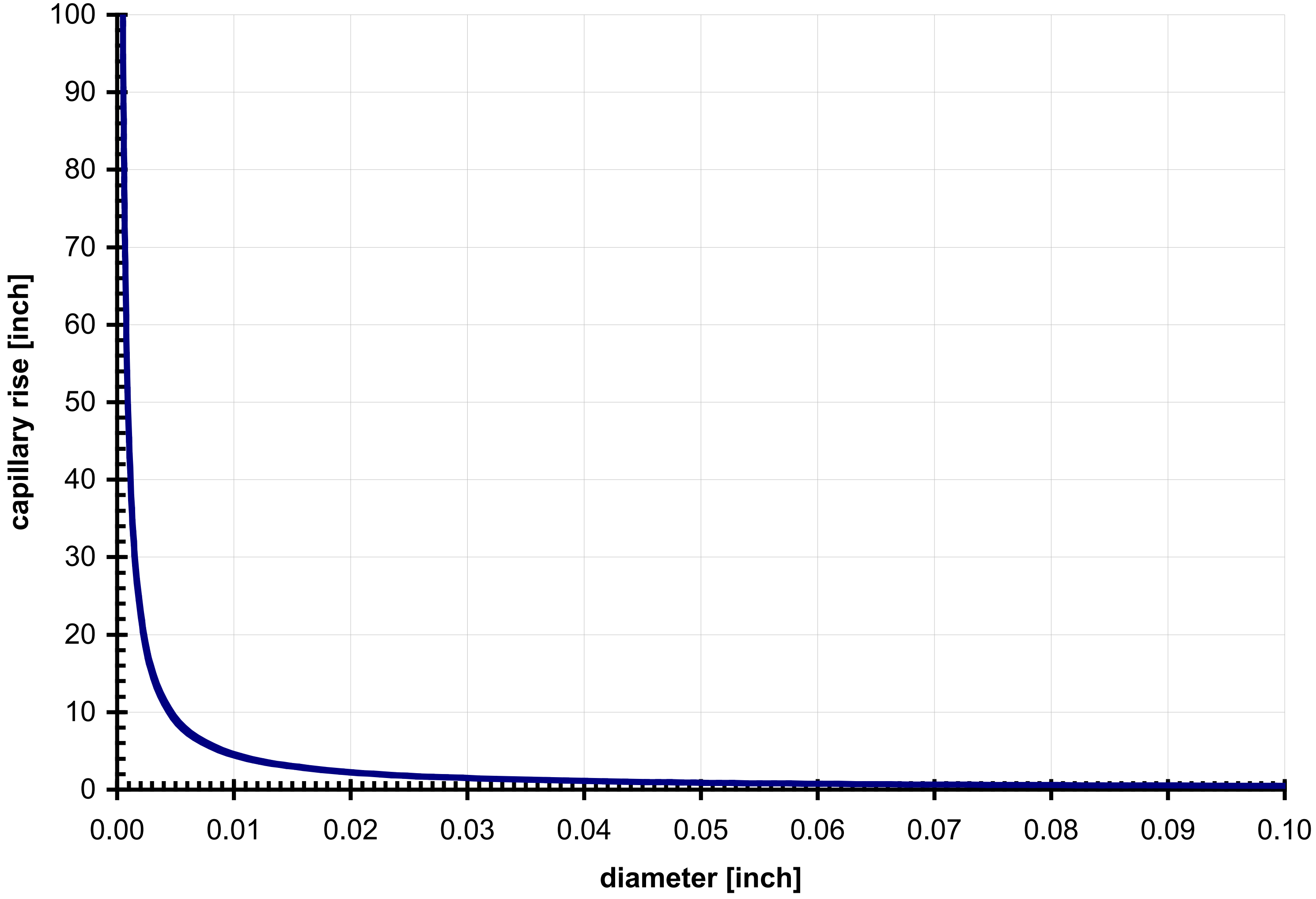


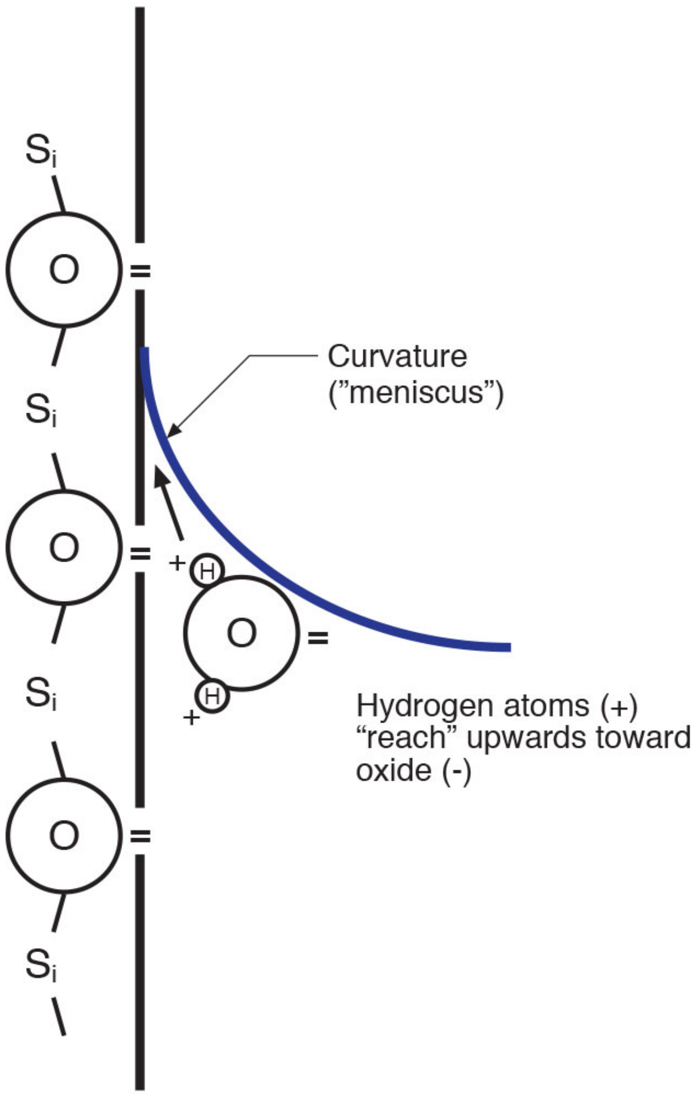
Curvature
("meniscus")
Small
pore
Large
pore

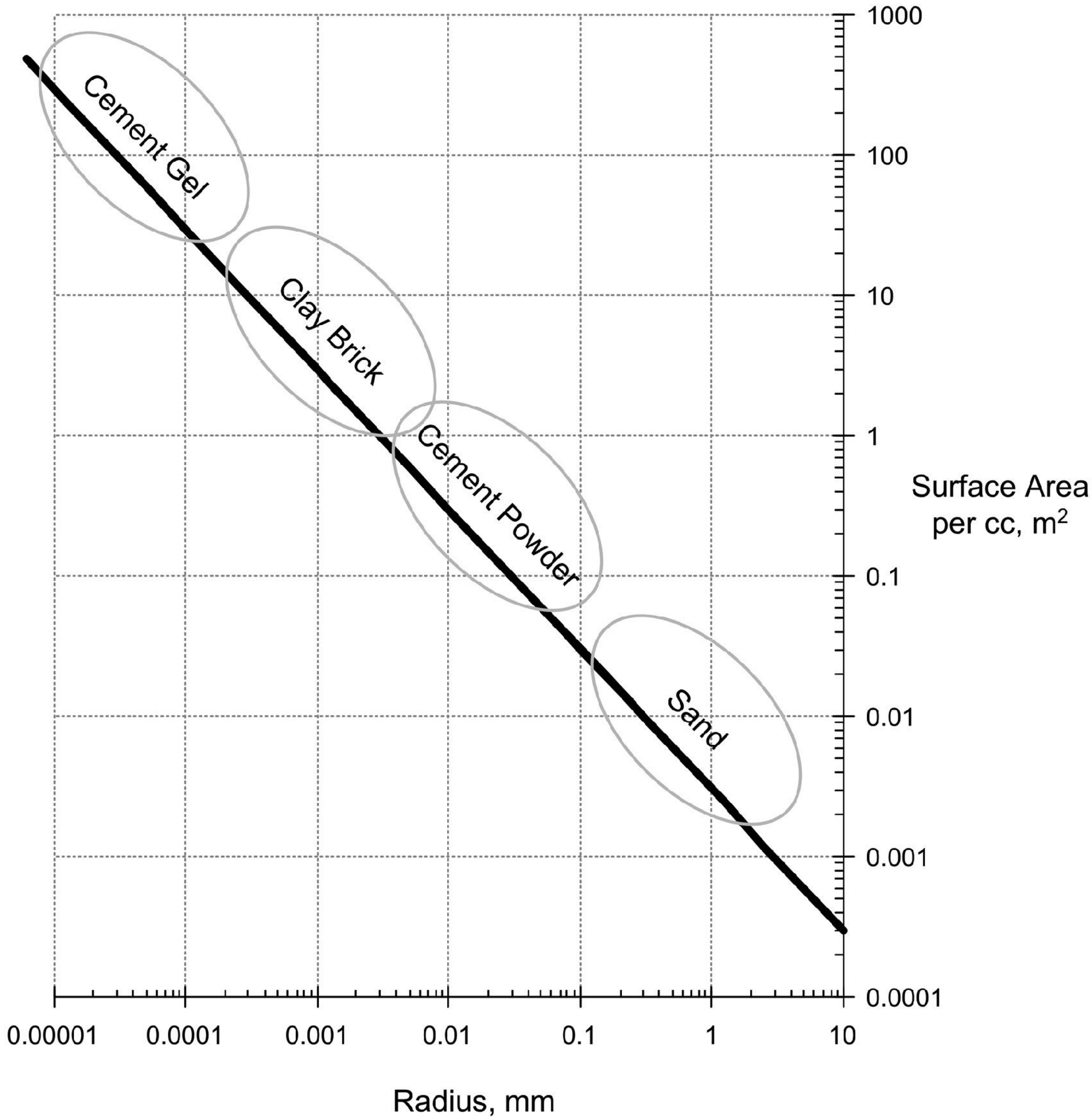
Calculating capillary rise



Capillary rise versus diameter




Si
O
=
Curvature
("meniscus")
Si
O
=
+ H
O
=
H
+
Si
Hydrogen atoms (+)
"reach" upwards toward
oxide (-)
O
=
Si



Surface area vs. particle size

From Straube & Burnett, 2005

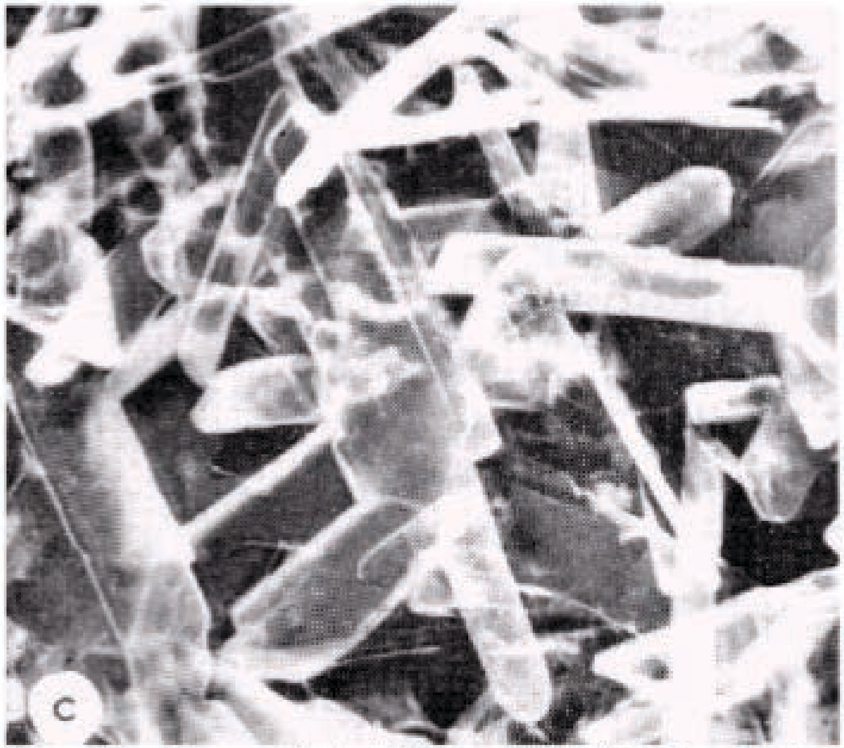


Figure 1c. Gypsum, hydrated from plaster of paris and water, porosity 30 per cent.

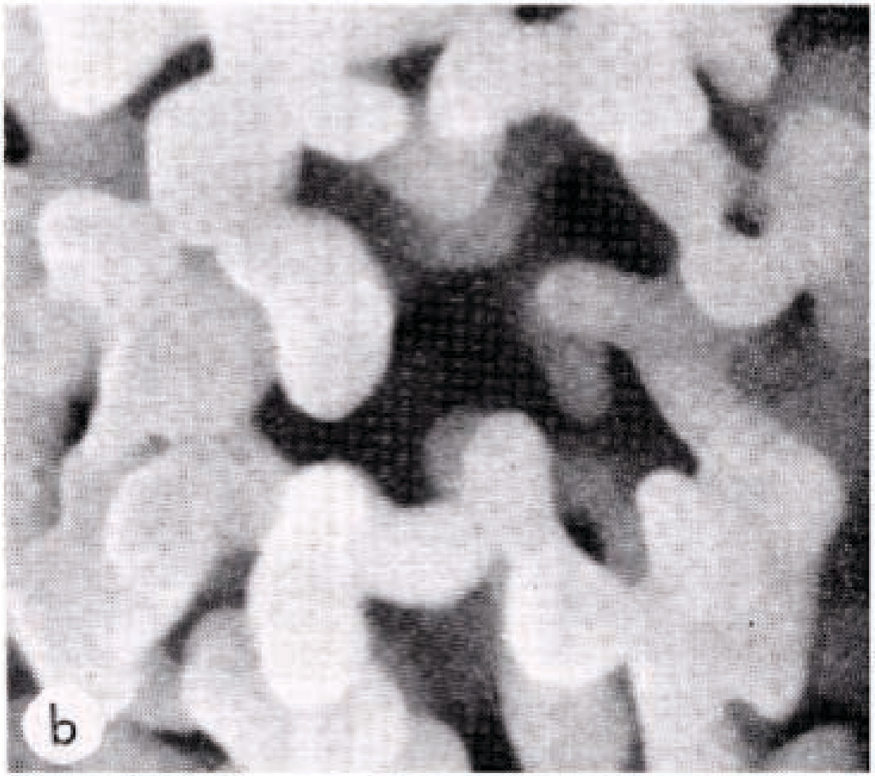
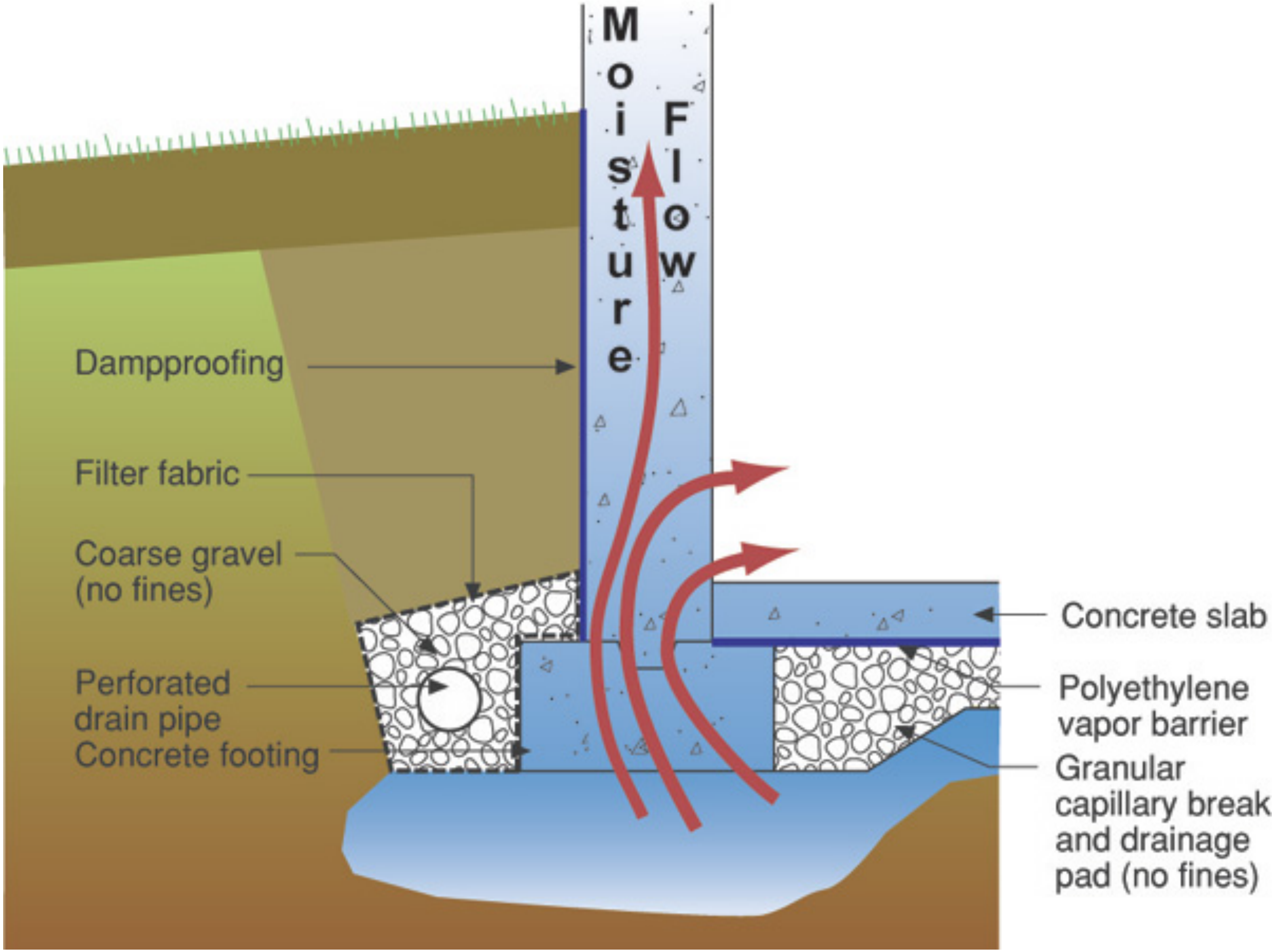
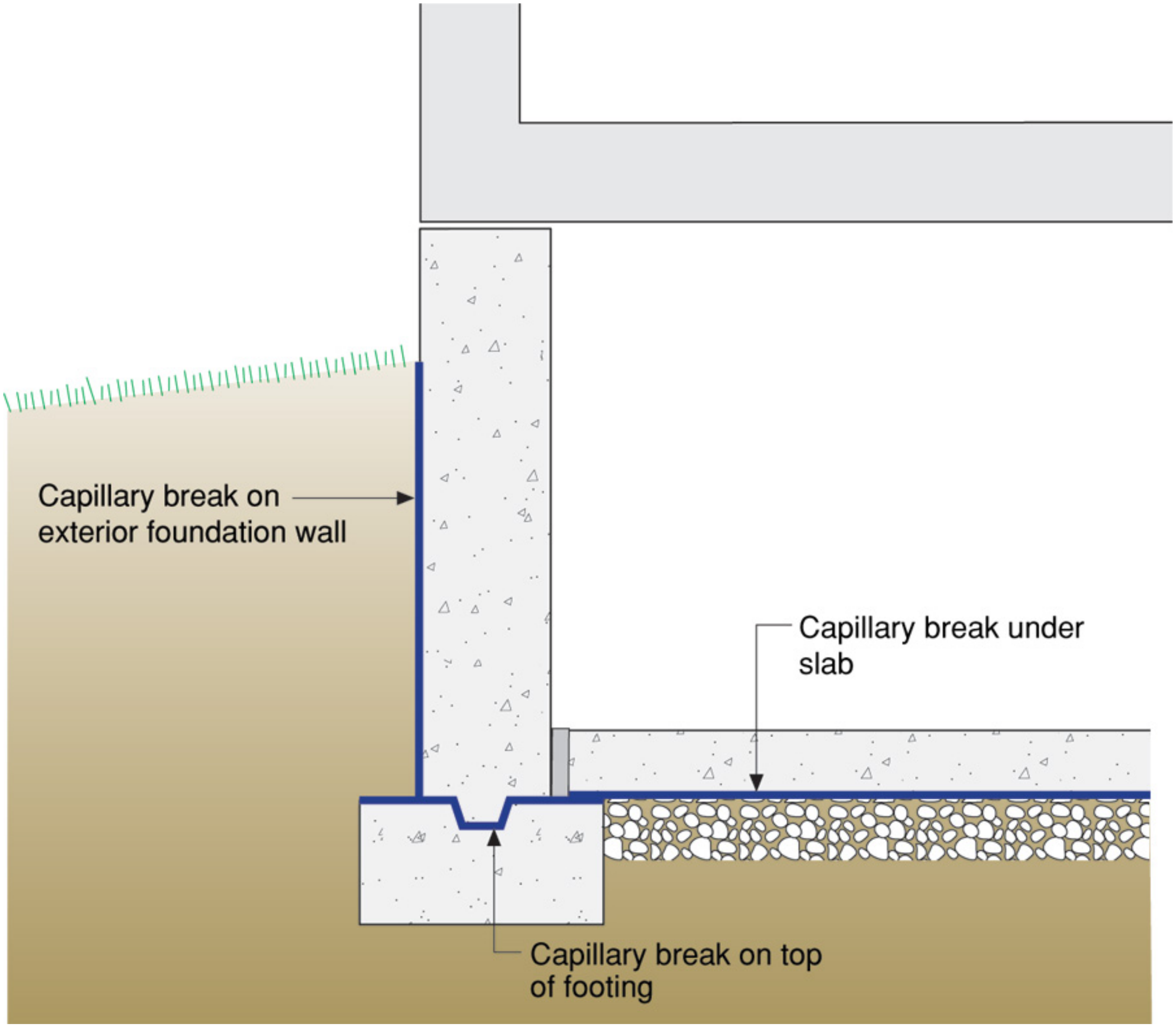
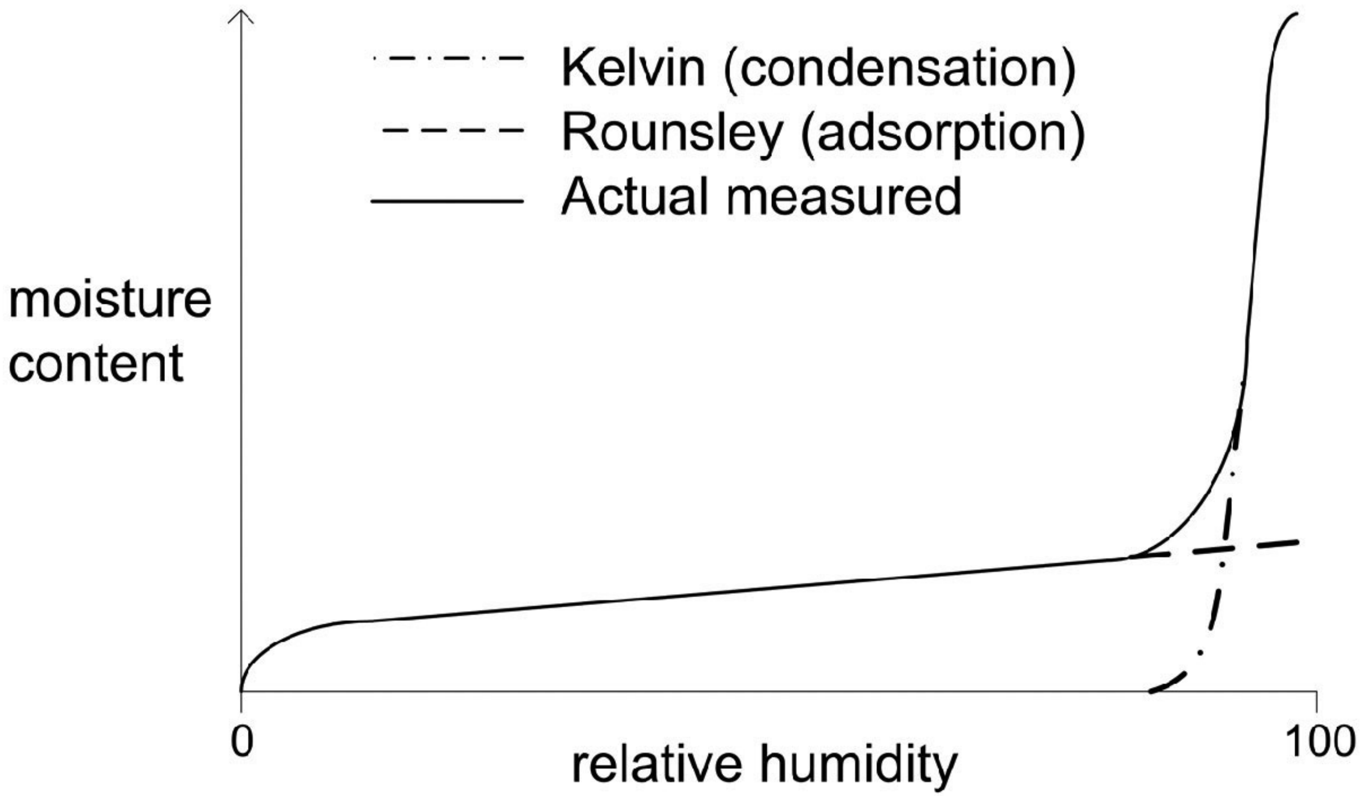


Figure 1b. Brick, sintered clay, porosity 40 per cent.

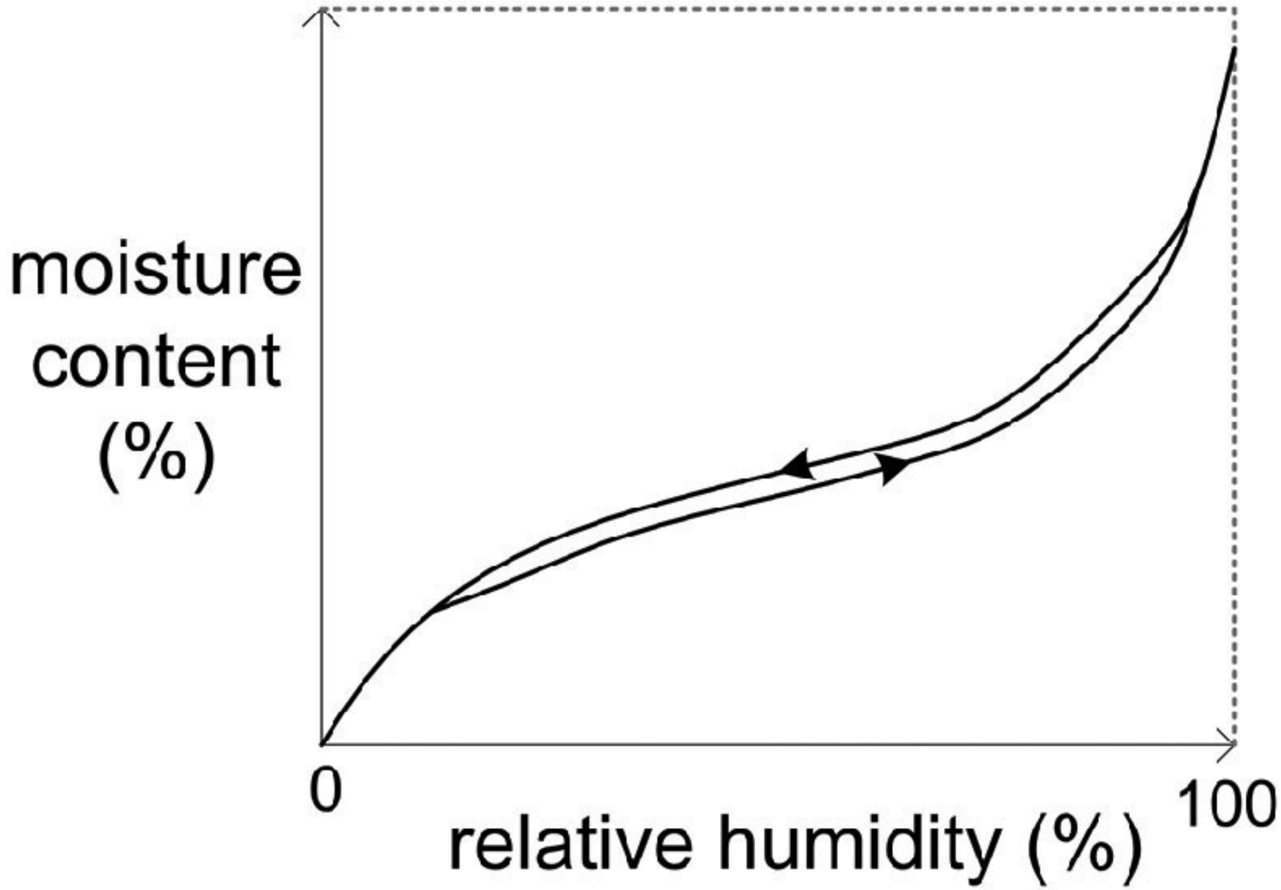

Moisture Flow
Dampproofing
Filter fabric
Coarse gravel
(no fines)
Perforated
drain pipe
Concrete footing
Concrete slab
Polyethylene
vapor barrier
Granular
capillary break
and drainage
pad (no fines)


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

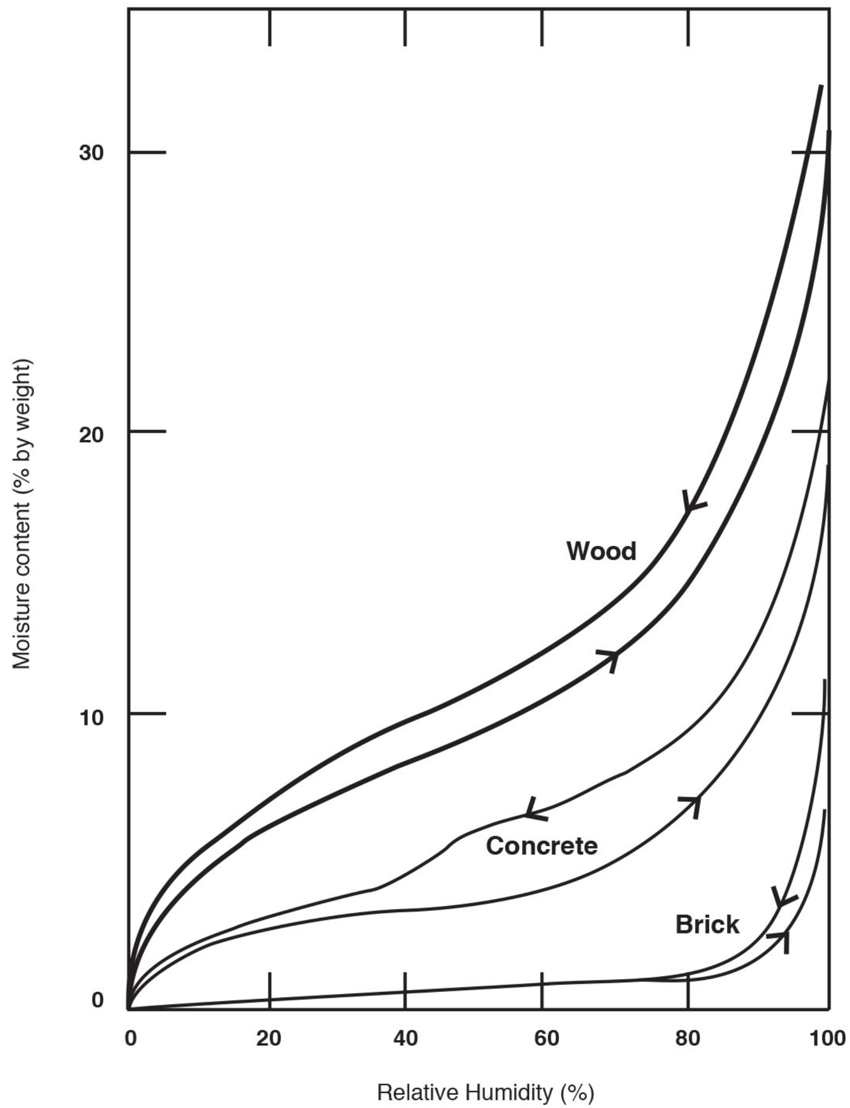


Typical predicted sorption isotherm according to Kelvin equation and modified BET theory

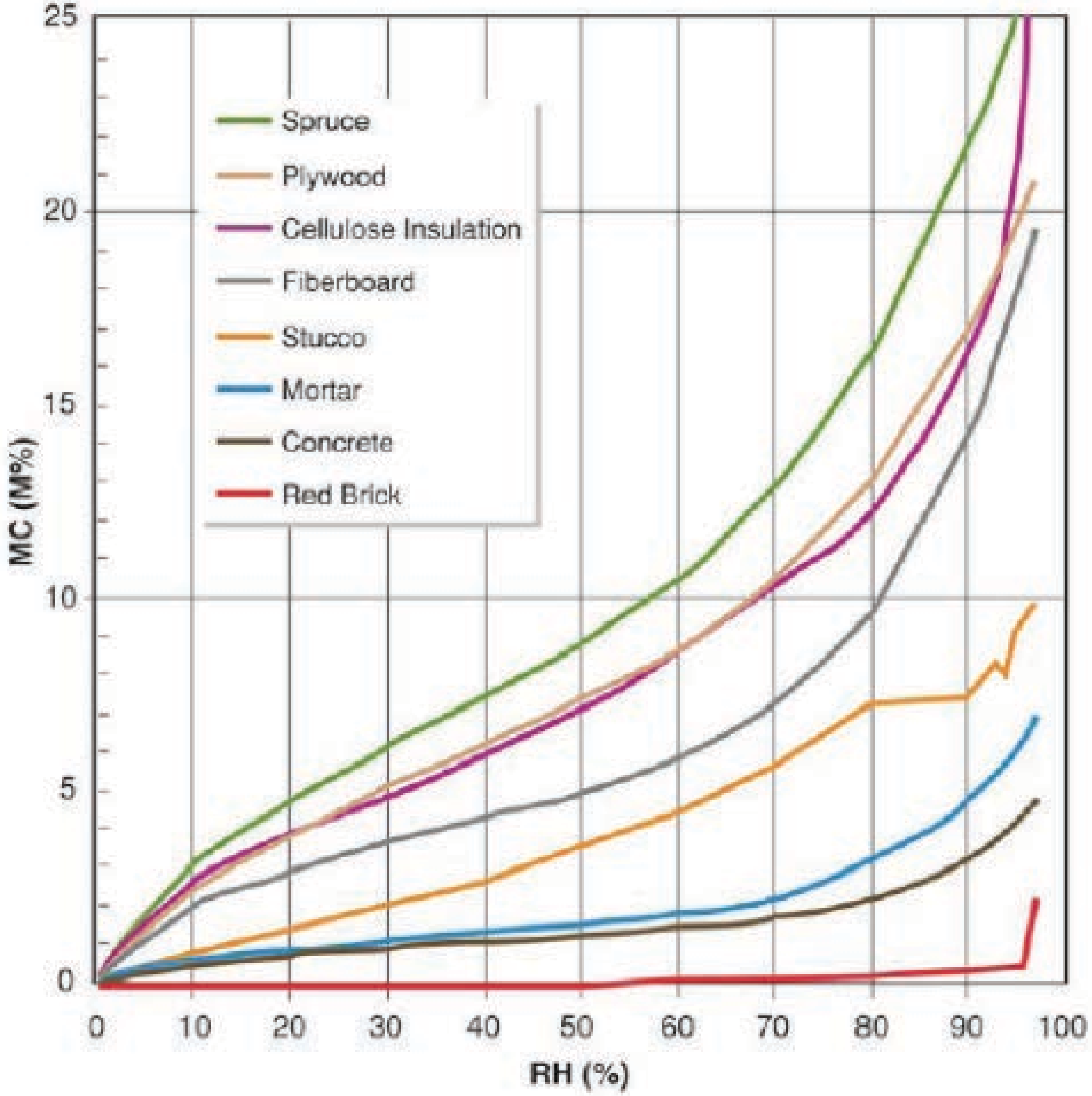
From Straube & Burnett, 2005

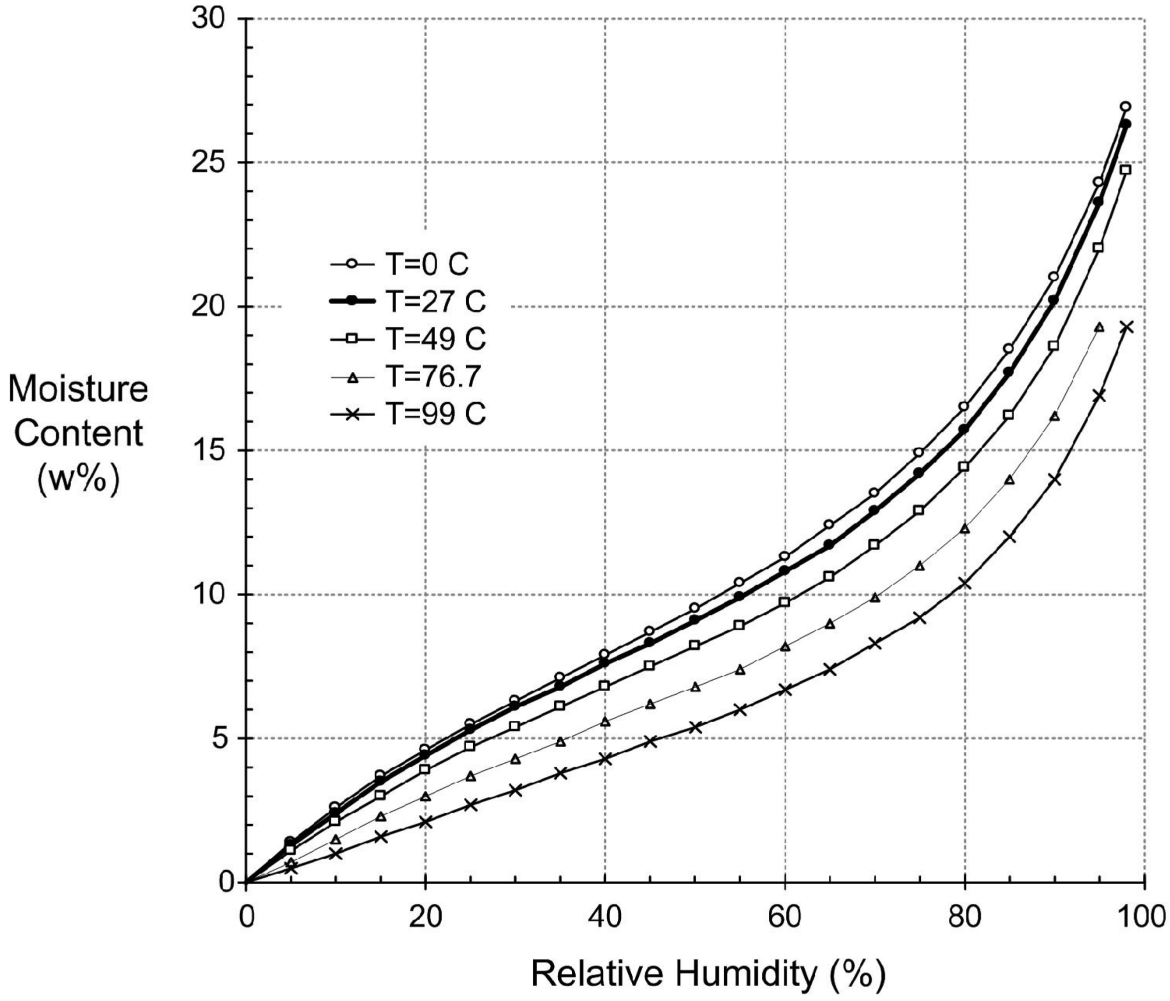


Typical sorption isotherm of a hygroscopic material
From Straube & Burnett, 2005



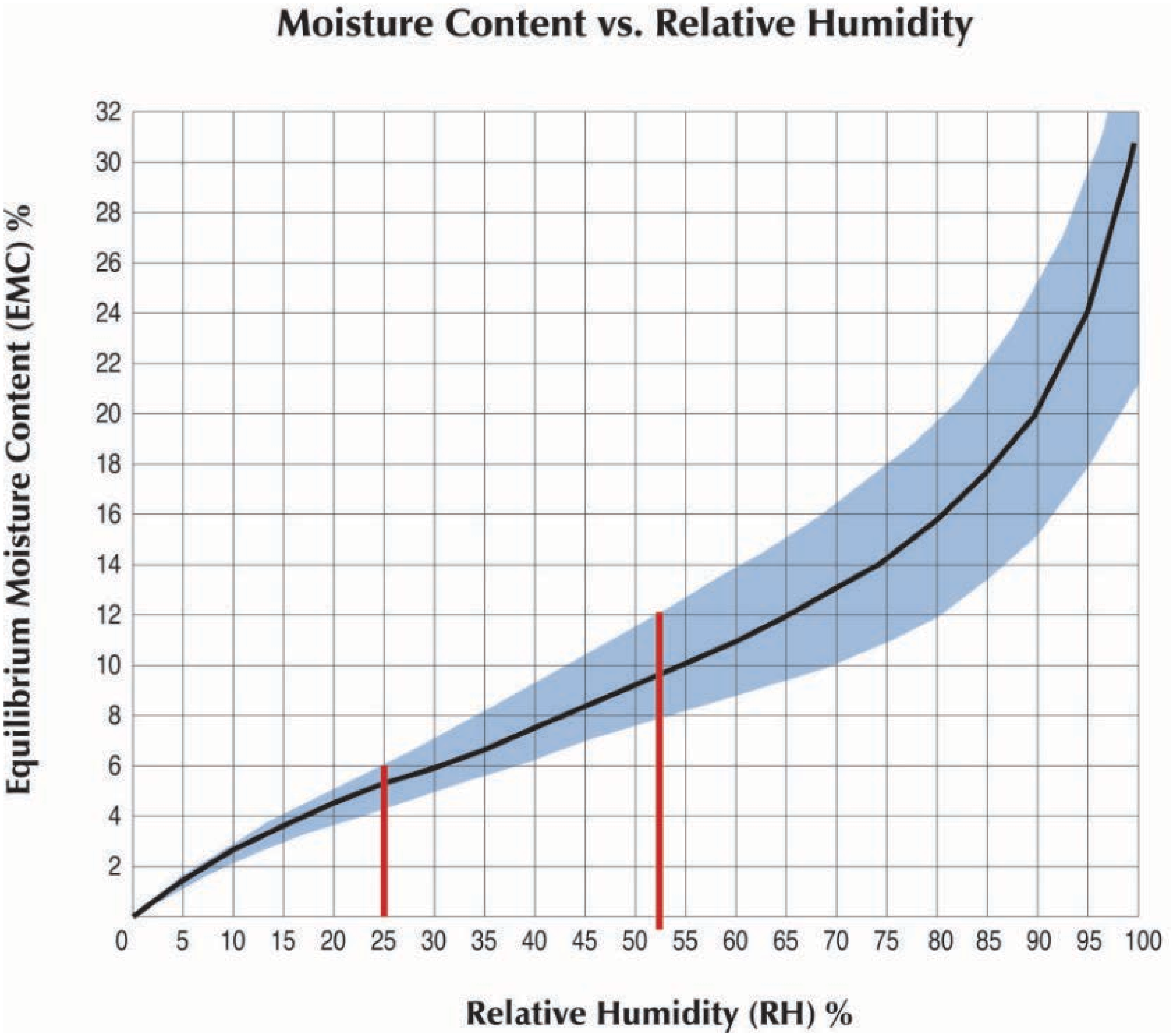
Water held in porous materials at various relative humidities
From Hutcheon & Handegord, 1983

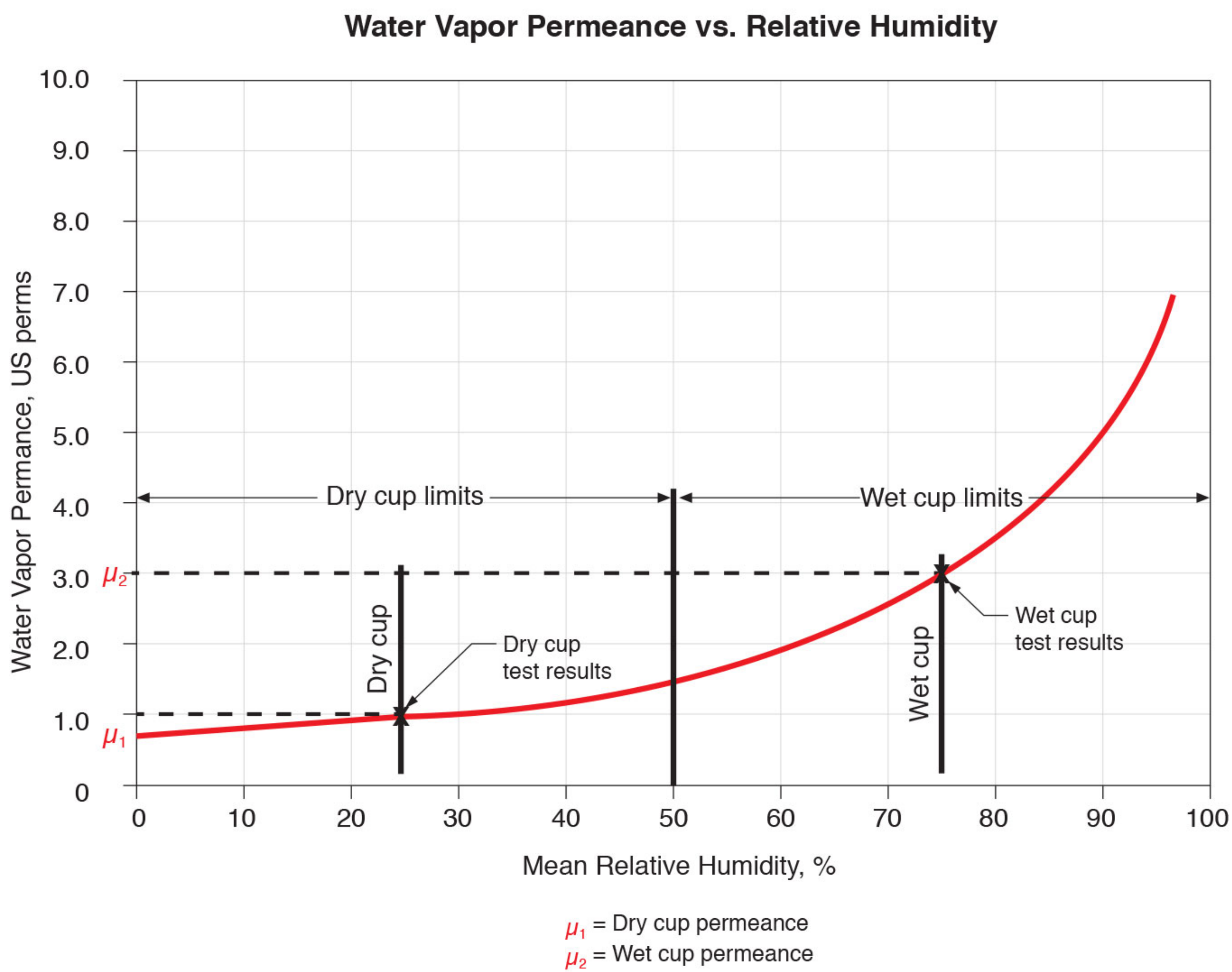

Spruce
Plywood
Cellulose Insulation
Fiberboard
Stucco
Mortar
Concrete
Red Brick
MC (M%)
RH (%)
0
5
10
15
20
25
0
10
20
30
40
50
60
70
80
90
100



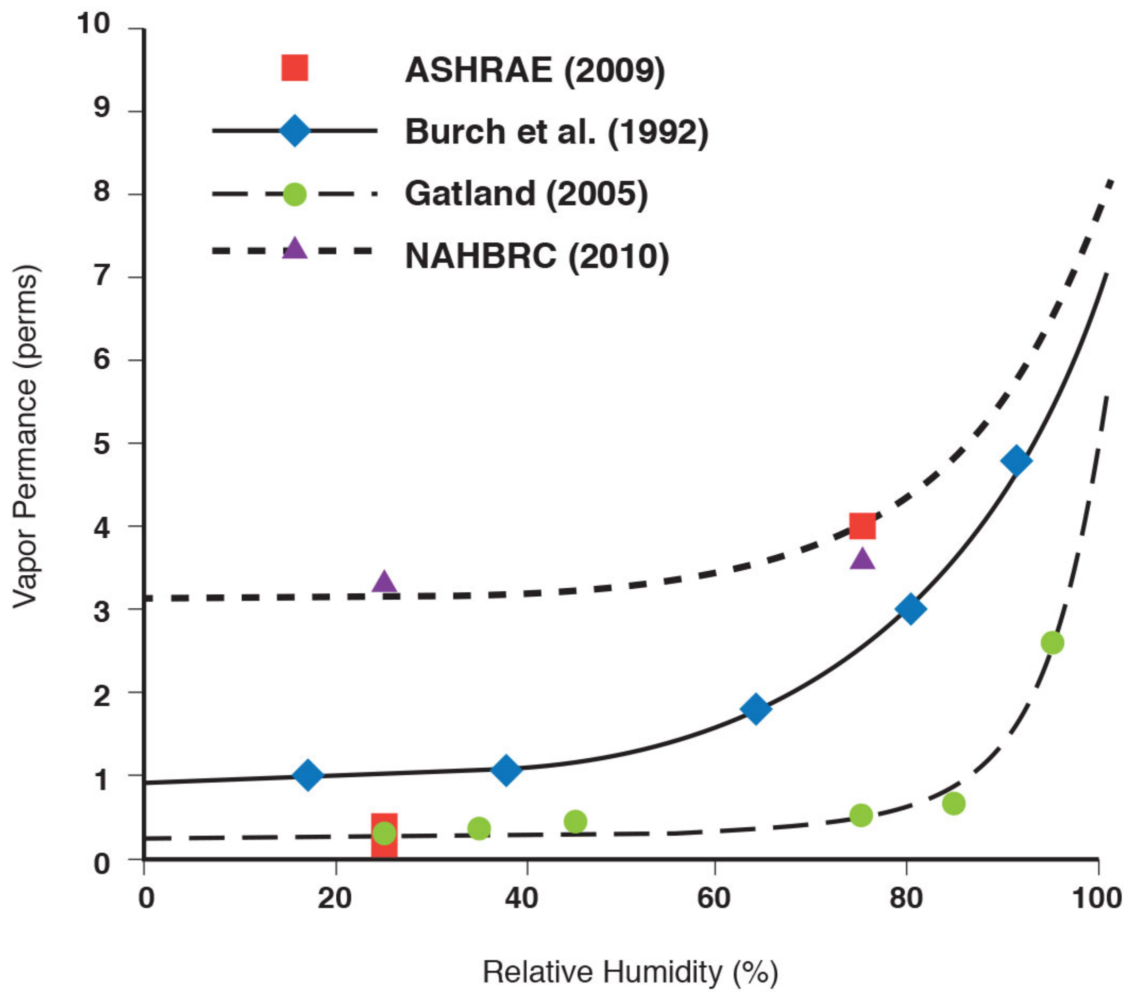
Average sorption isotherm for wood as a function of temperature

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) %

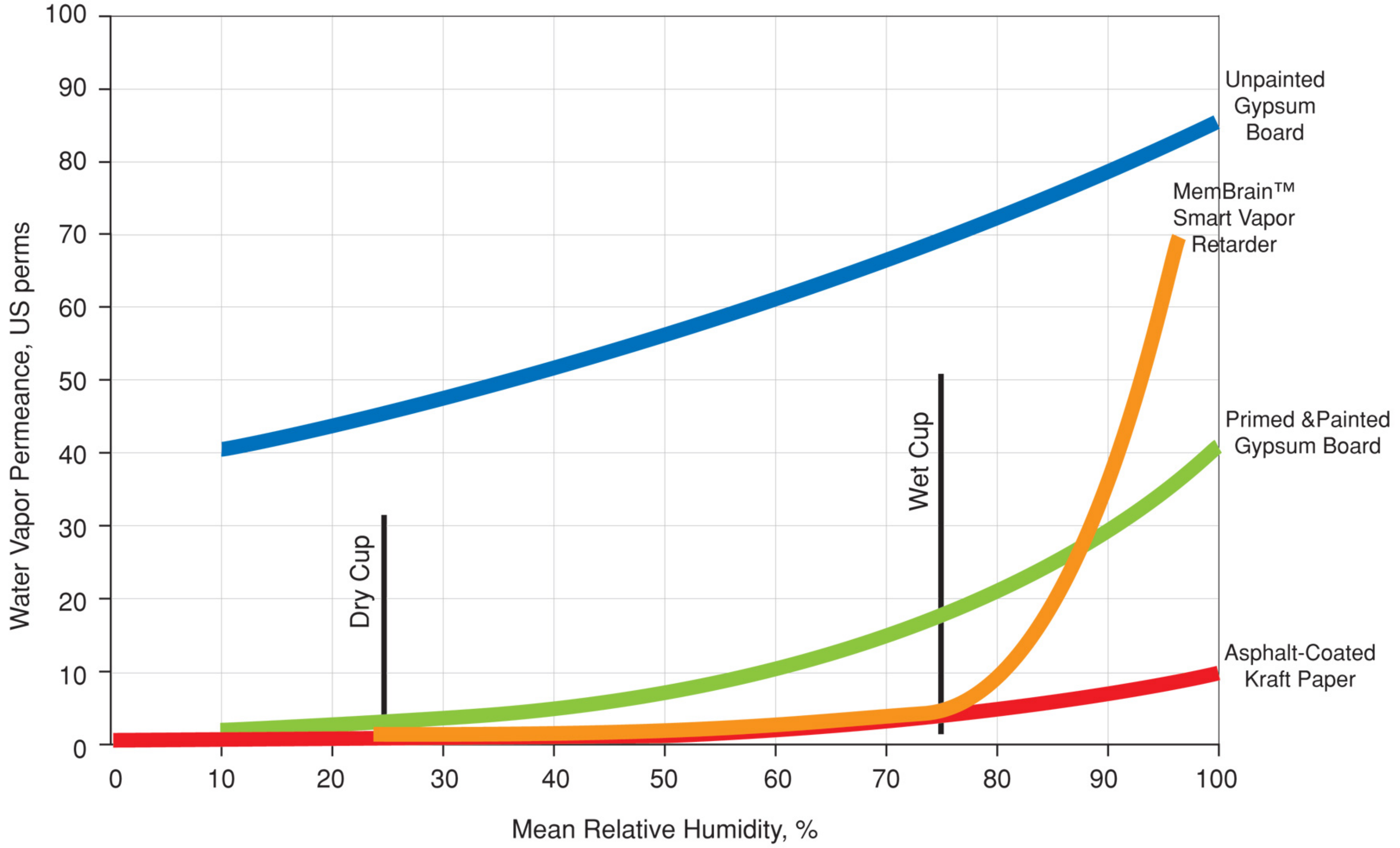

Water Vapor Permeance vs. Relative Humidity
Water Vapor Permance, US perms
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
μ2
μ1
Dry cup limits
Wet cup limits
Dry cup
Wet cup
Dry cup
test results
Wet cup
test results
0
10
20
30
40
50
60
70
80
90
100
Mean Relative Humidity, %
μ1 = Dry cup permeance
μ2 = Wet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

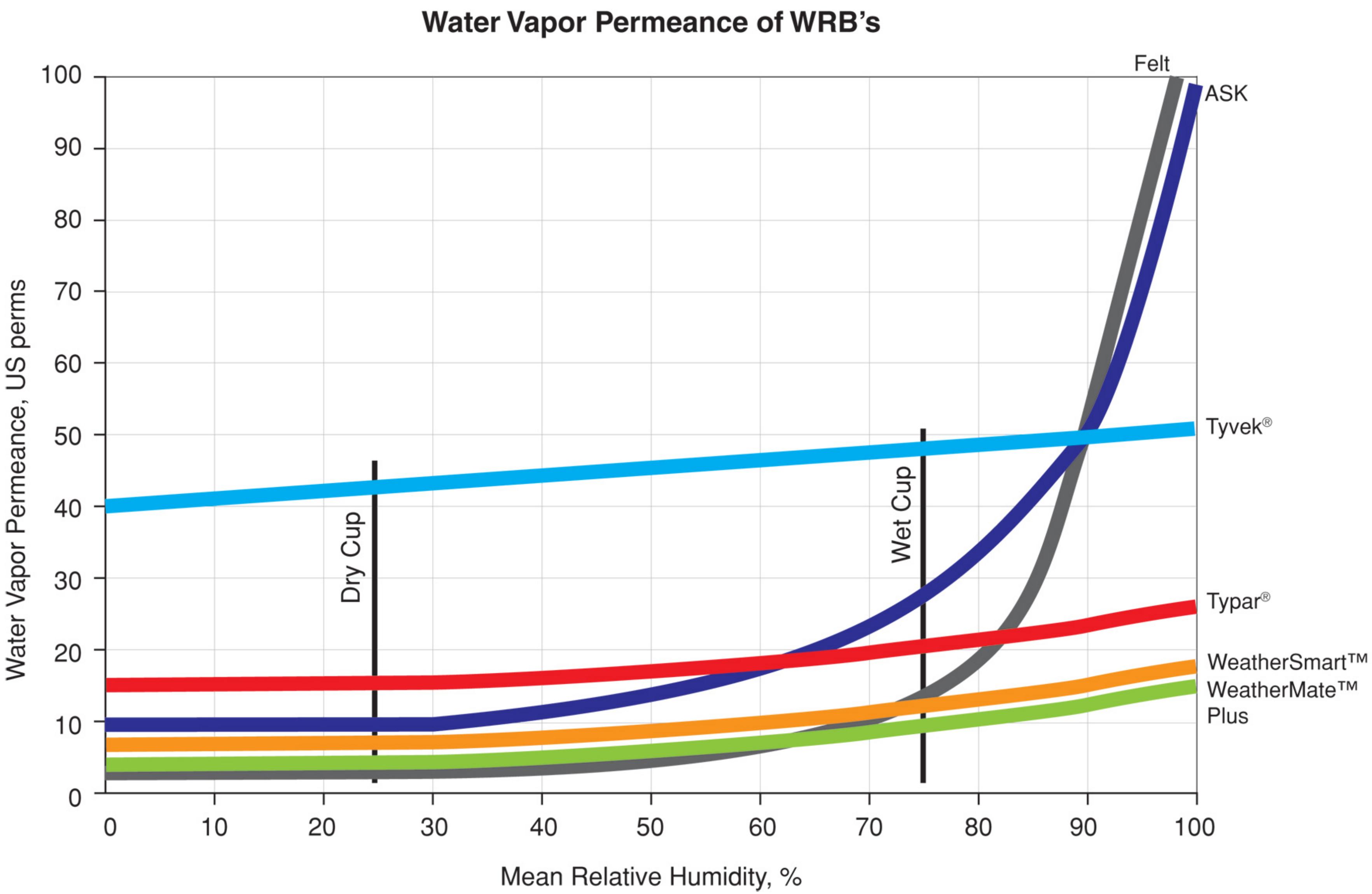

R-11 3½"
OWENS-CORNING
Fiberglas Building Insulation
FIBERGLAS
Apply this side toward living space.
C020686702K
ASSURED THERMAL PERFORMANCE
WARNING: The FACING on the insulation WILL BURN AND SHOULD NOT BE LEFT EXPOSED. Special care should be taken when working close to the facing



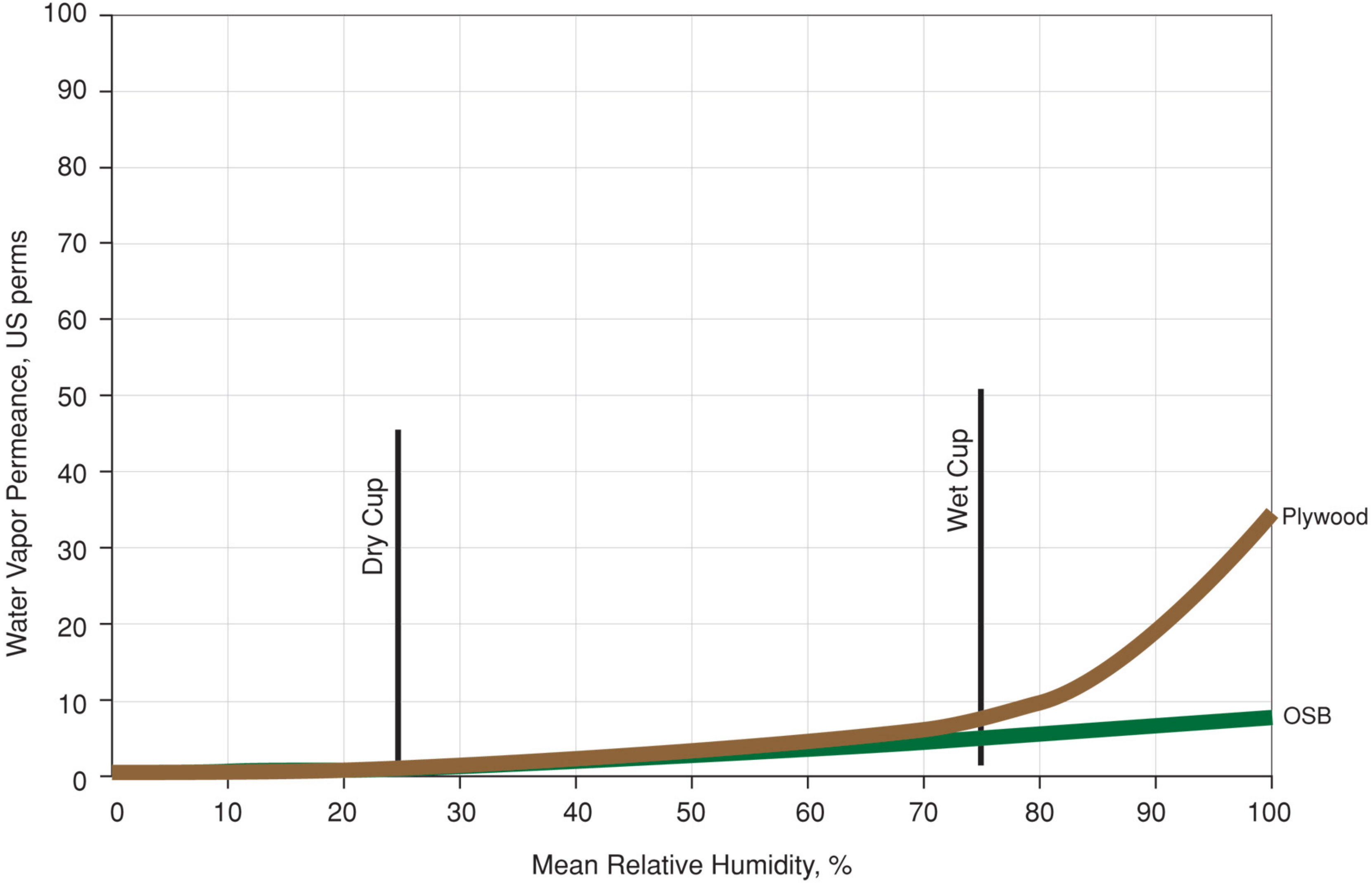
Kraft facing permeance as a function of humidity (Glass 2013)

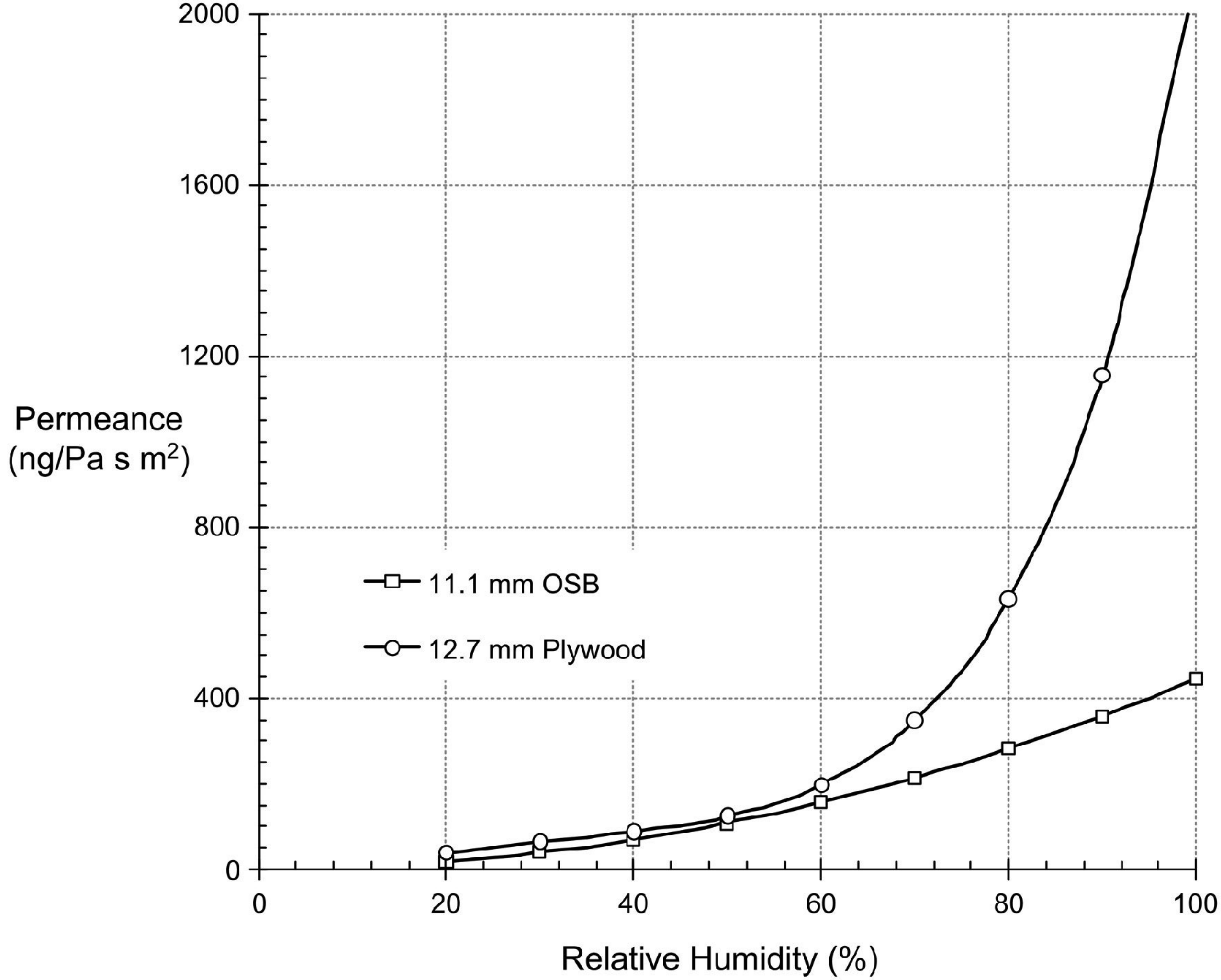
Water Vapor Permeance of MemBrain™ Smart Vapor Retarder, Primed and Painted Gypsum Board, Unpainted Gypsum Board and Asphalt-Coated Kraft Paper



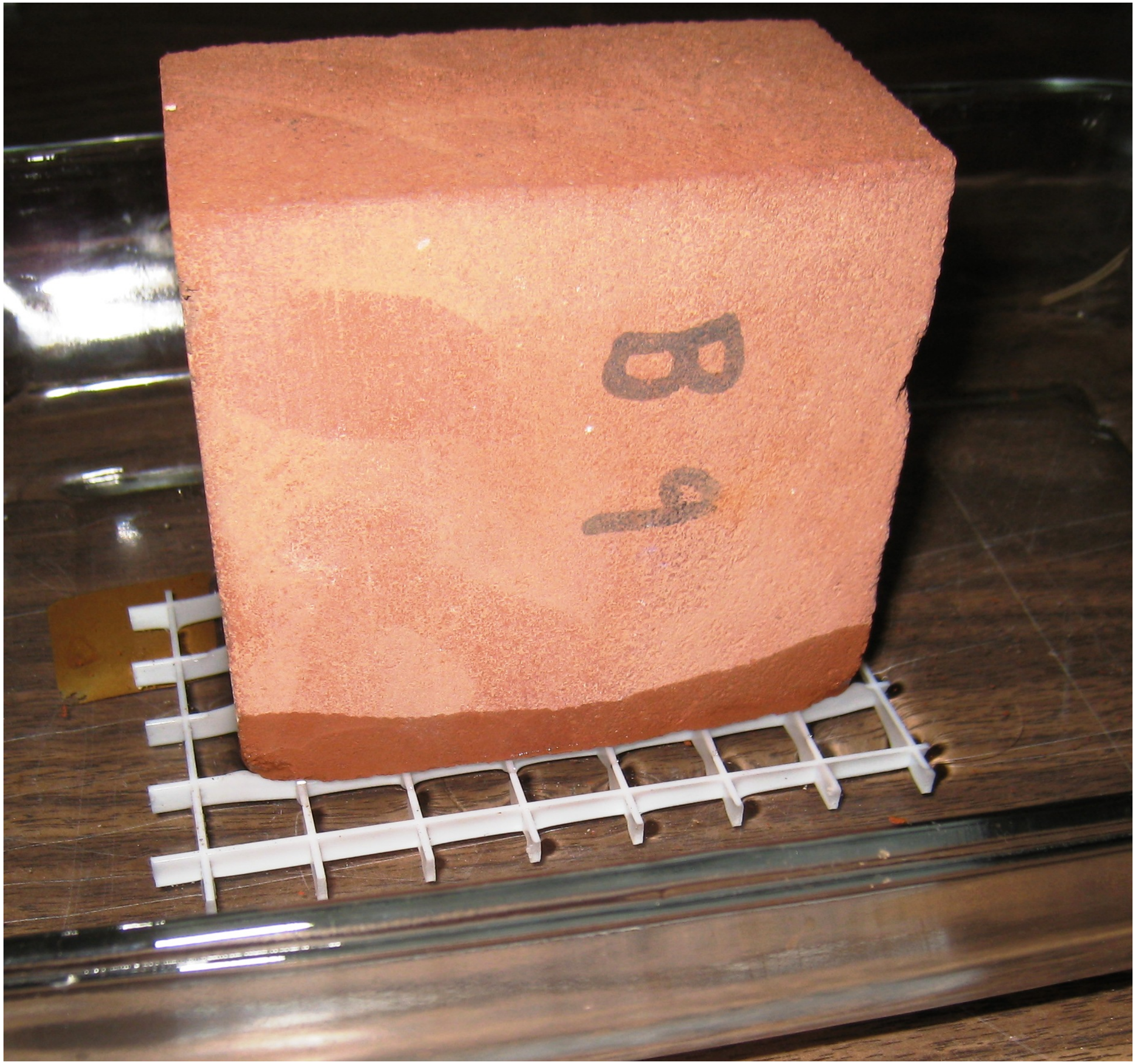

Water Vapor Permeance of WRB's
Water Vapor Permeance, US perms
Mean Relative Humidity, %
0
10
20
30
40
50
60
70
80
90
100
Dry Cup
Wet Cup
Felt
ASK
Tyvek®
Typar®
WeatherSmart™
WeatherMate™ Plus

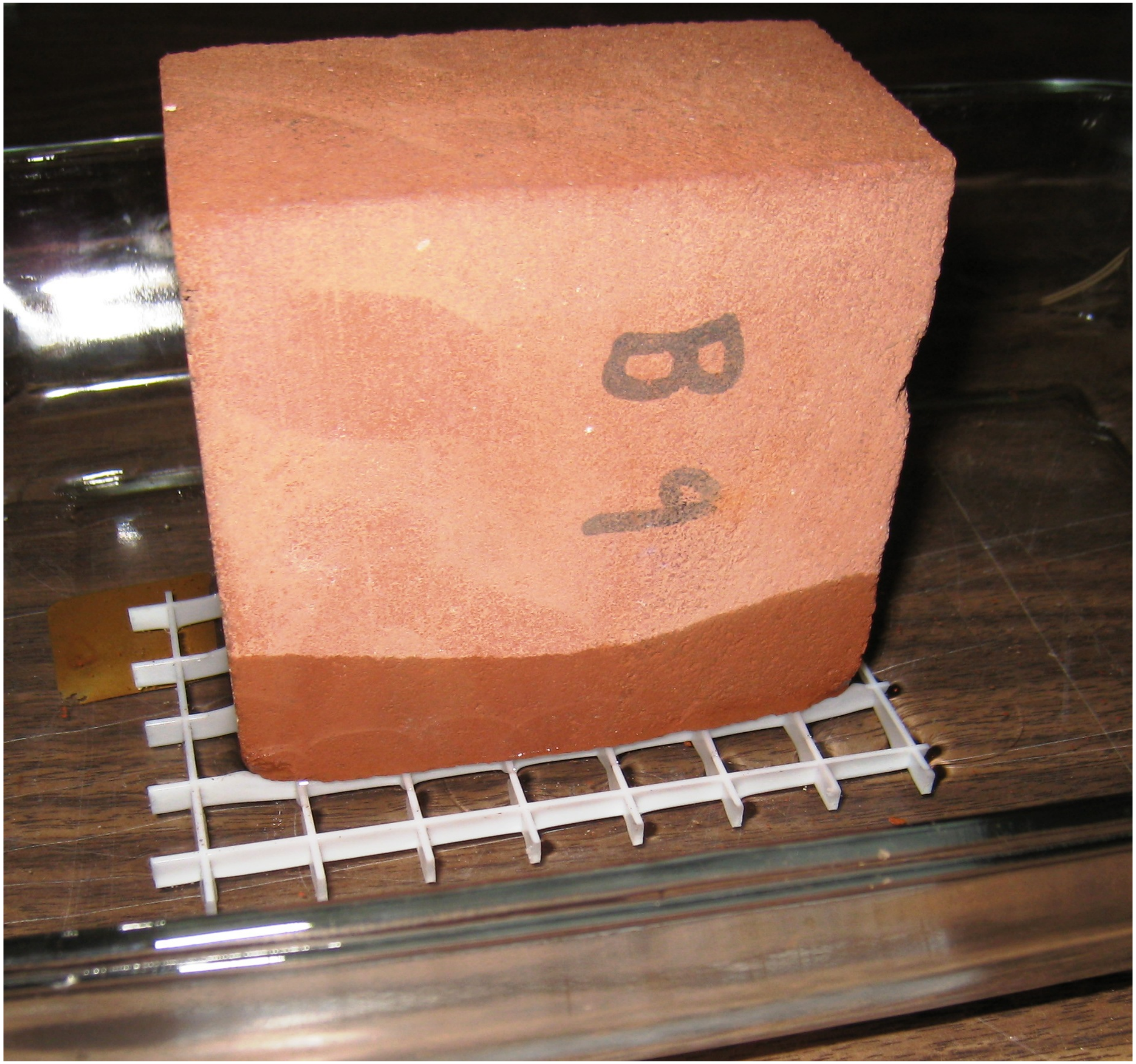
Water Vapor Permeance of Sheathing Materials

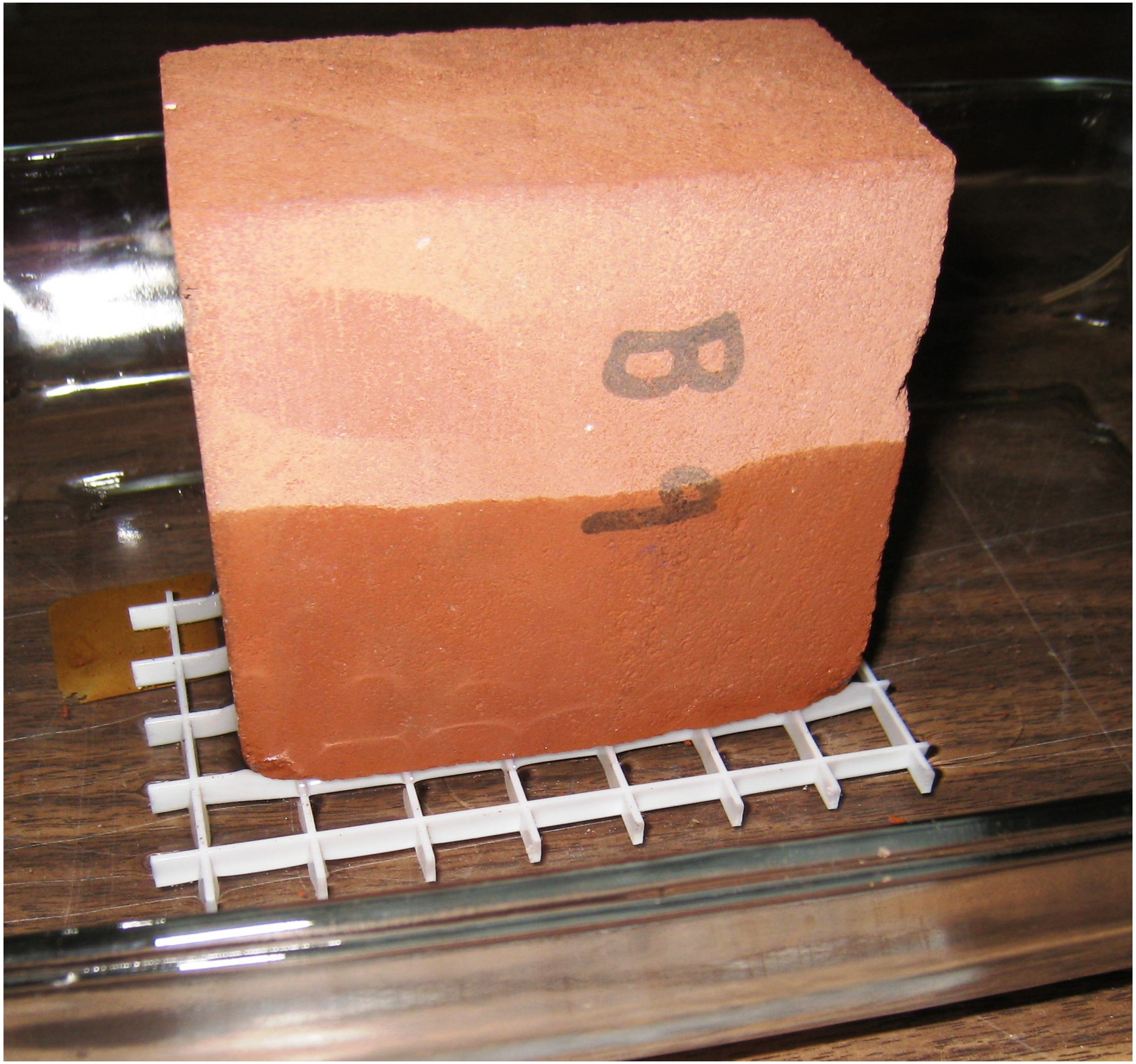


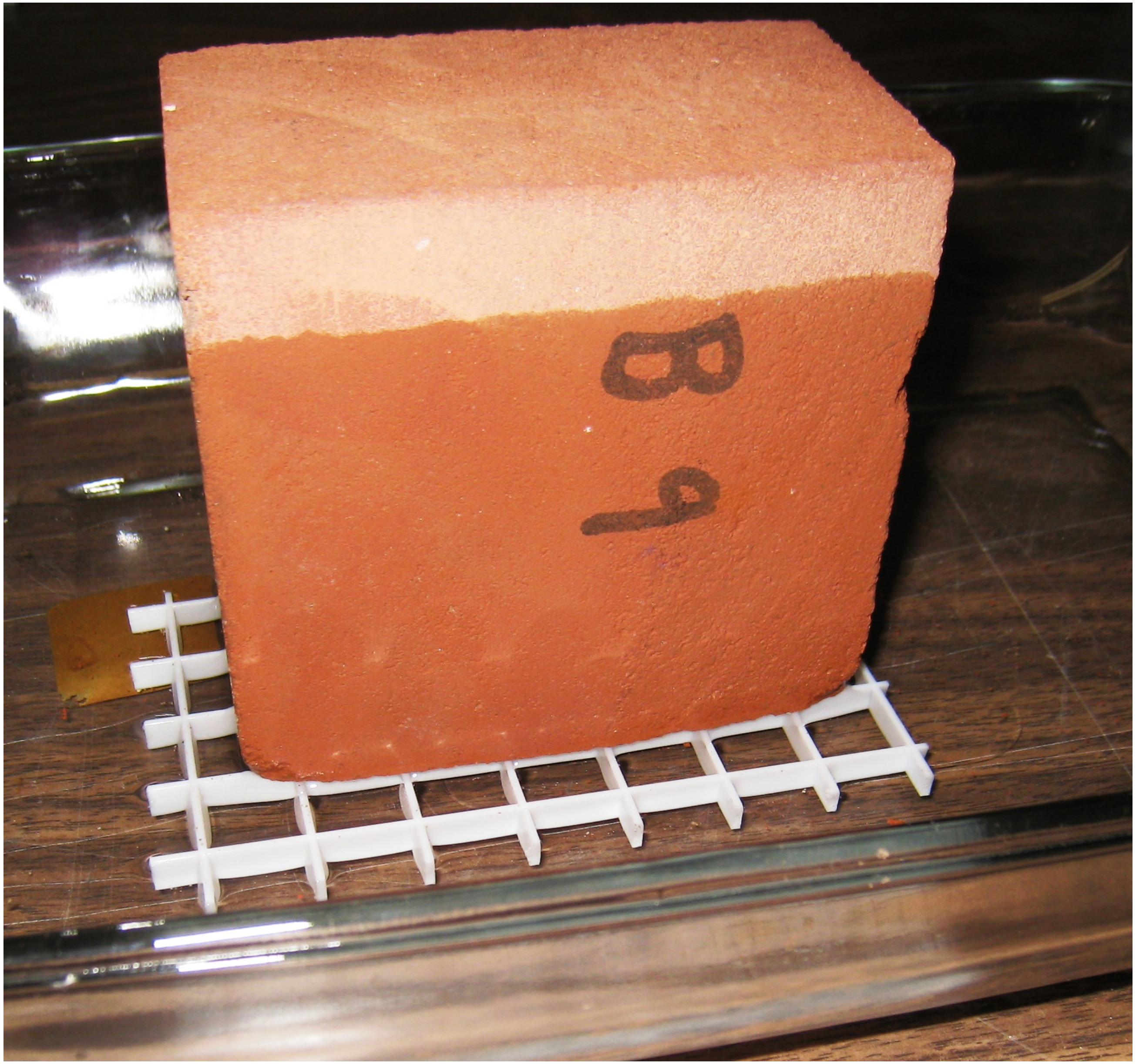


Vapor permeability test results for wood-based products as a function of RH
[Kumaran *et al* 2002]
From Straube & Burnett, 2005




B
9


B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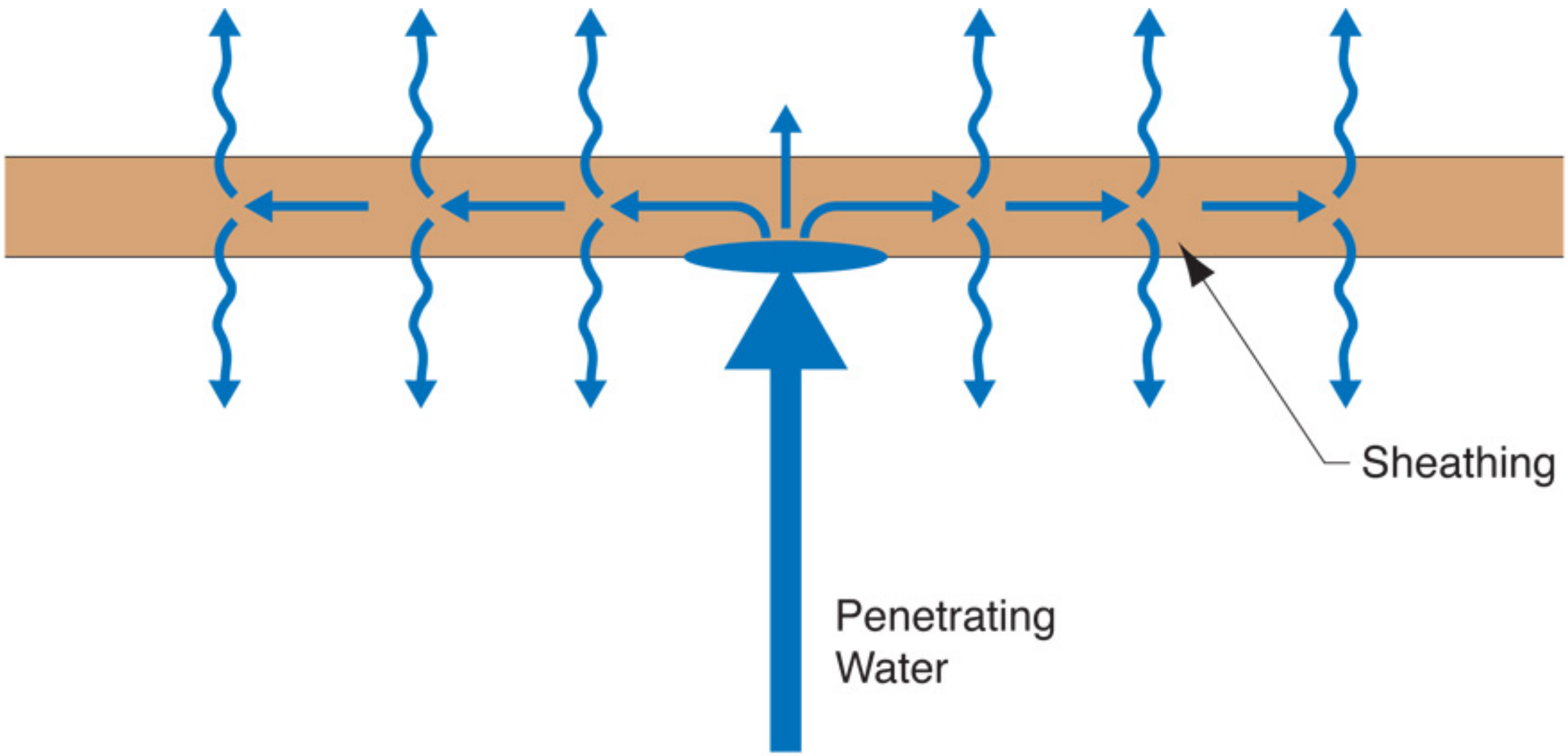
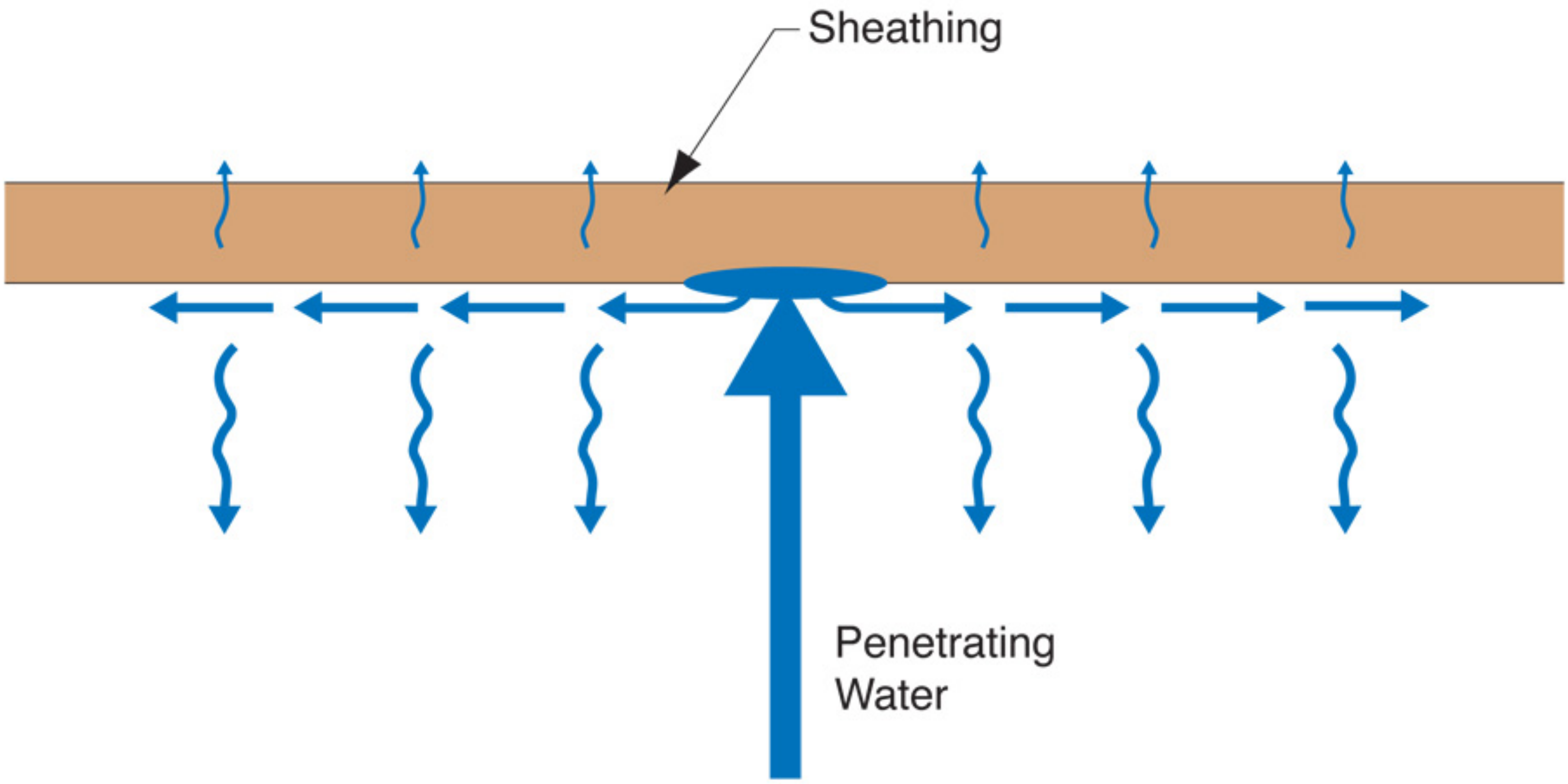

Sheathing
Penetrating
Water


Sheathing
Penetrating Water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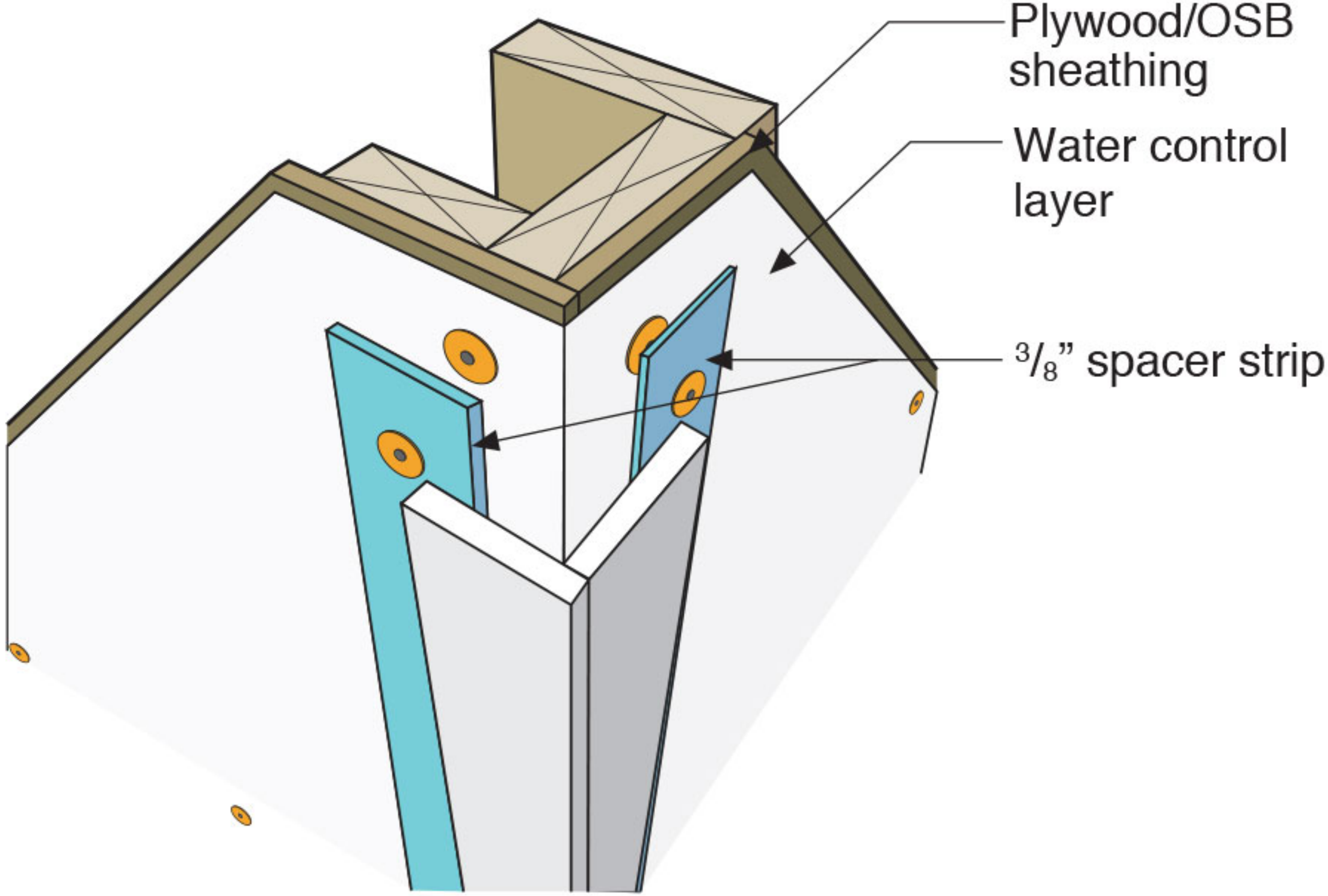
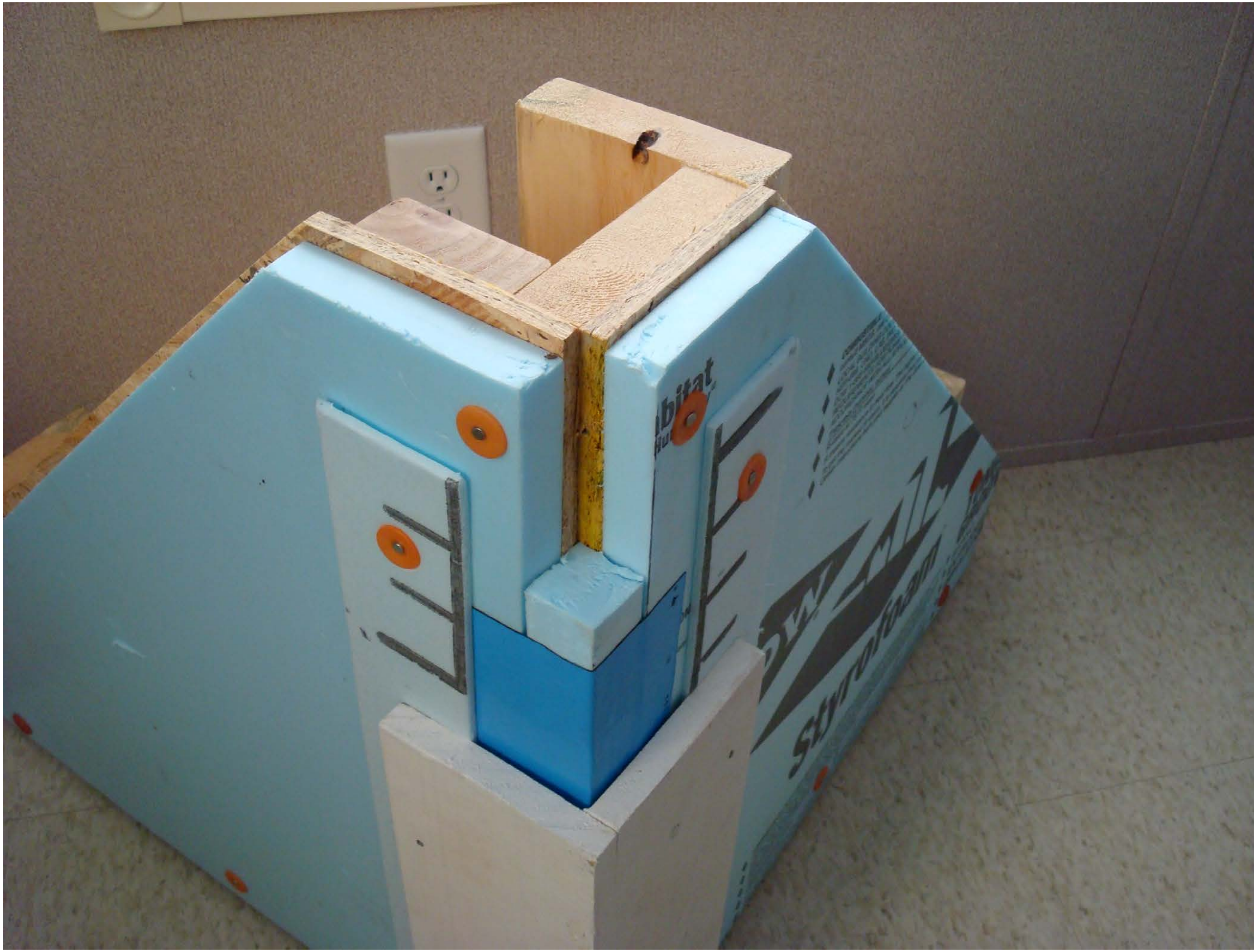

Plywood/OSB sheathing
Water control layer
3/8" spacer strip


Styrofoam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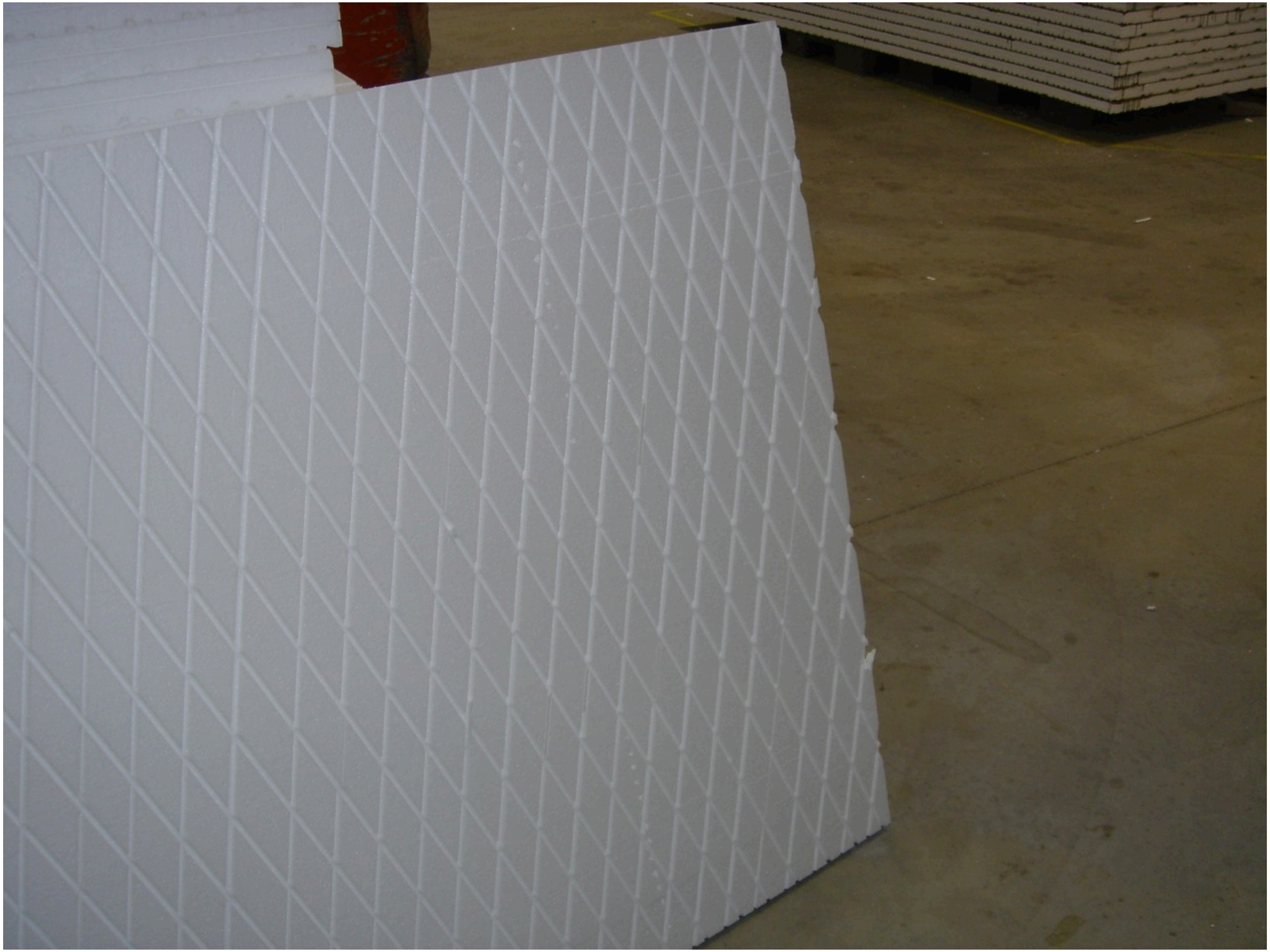
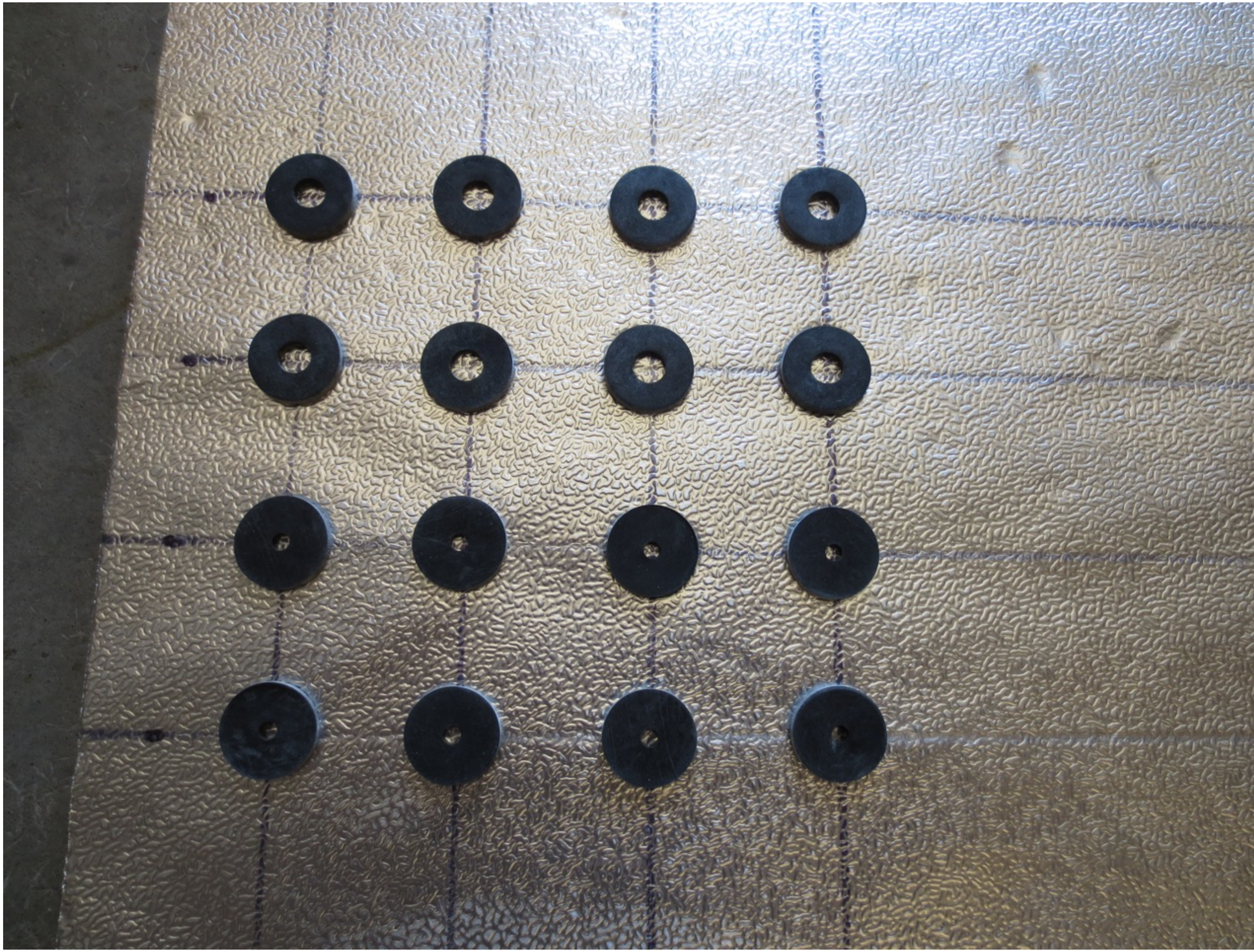
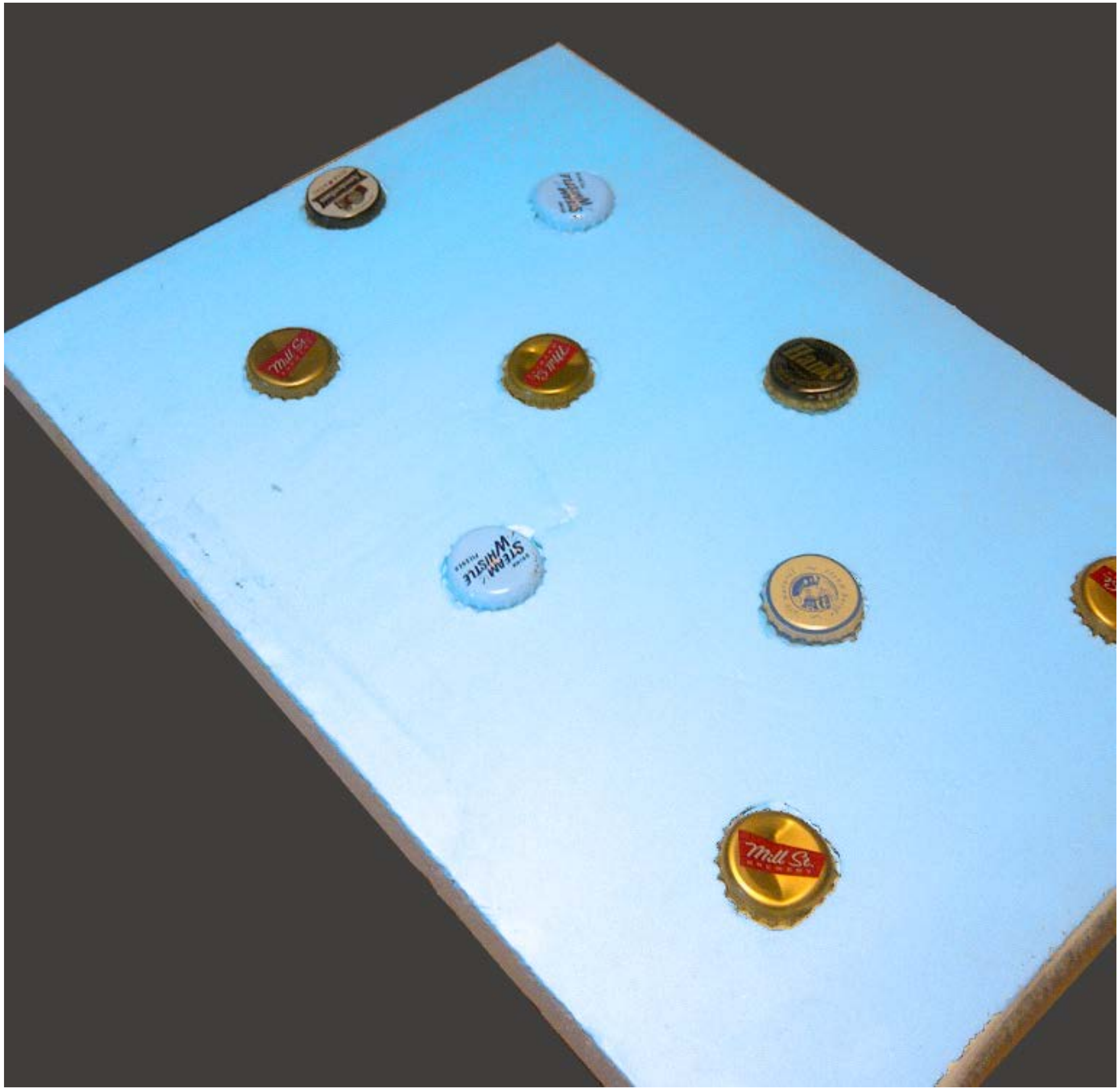
Tape
DuPont™
Tyvek®
Tape

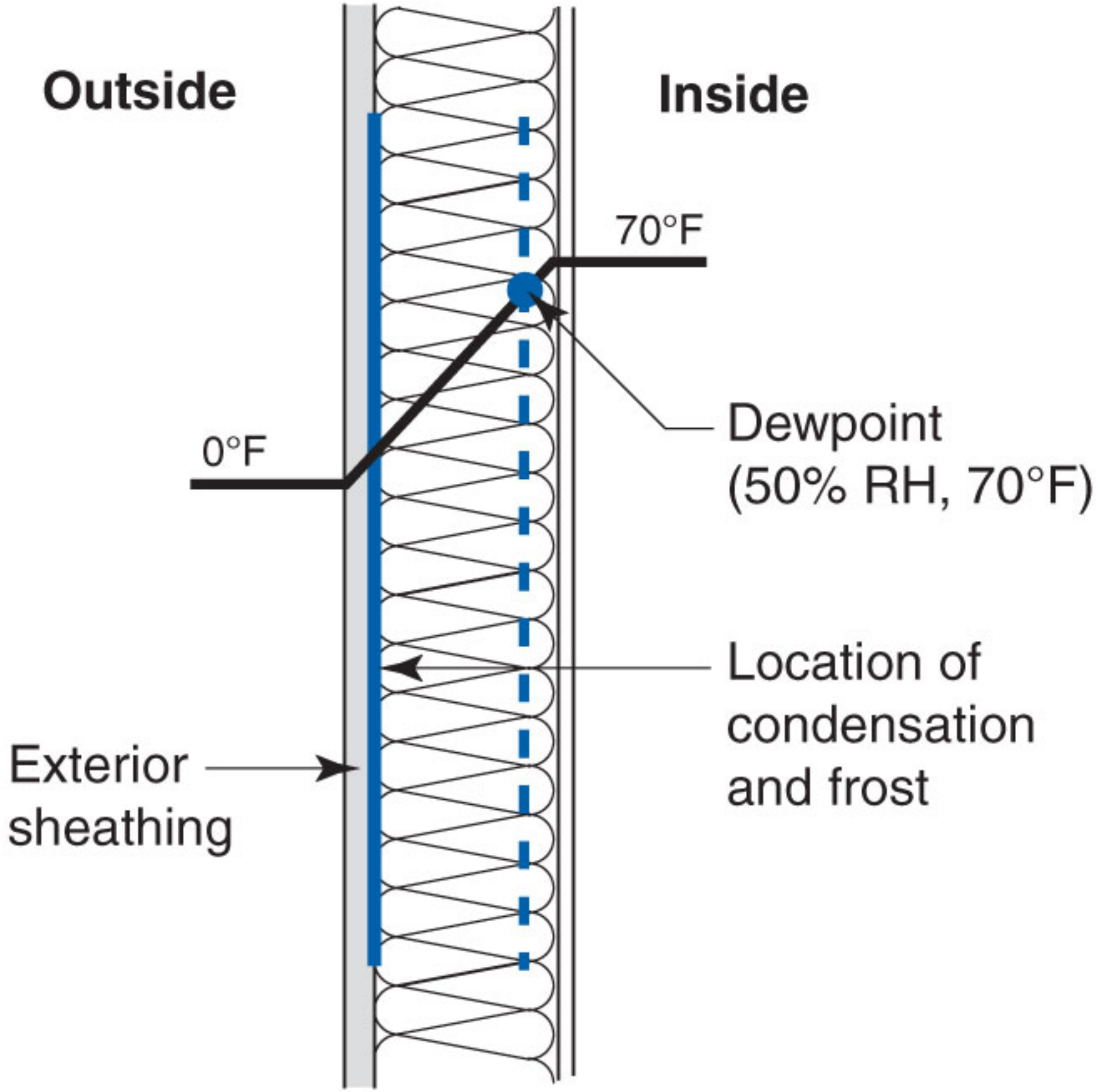


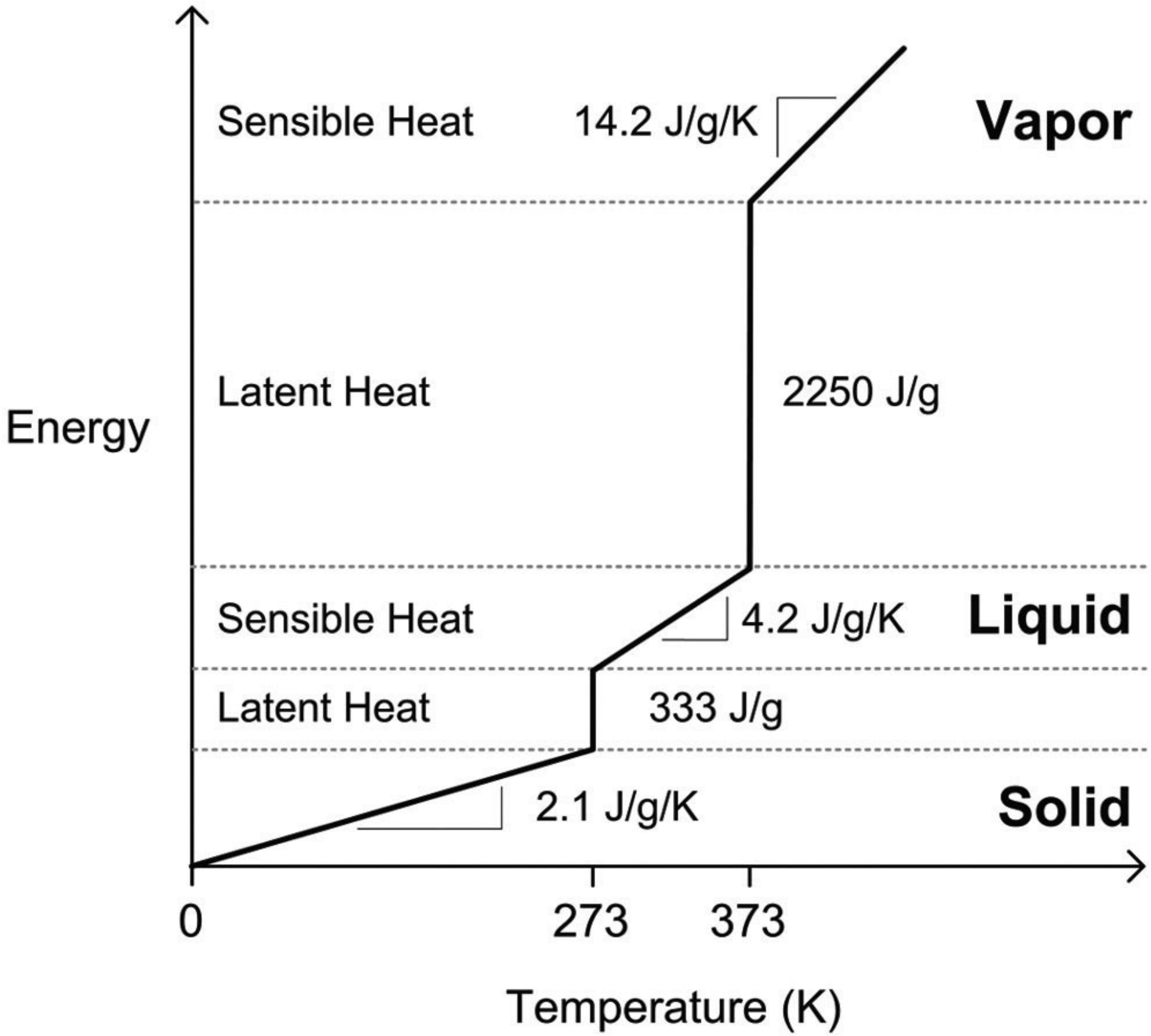
Rain Screen



Beer Screen?

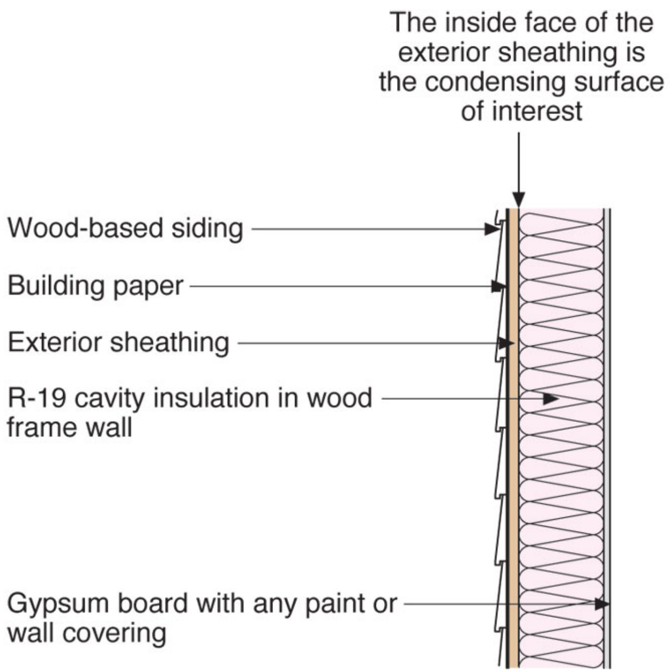

Mill St.
STEAM WHISTLE

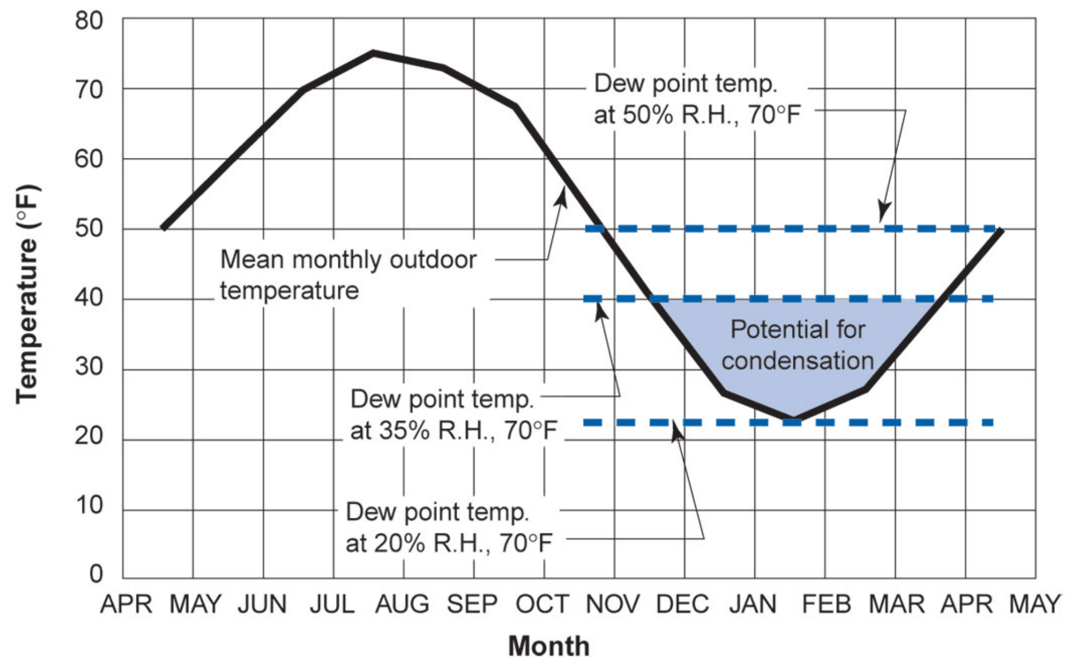

Outside
Inside
70°F
0°F
Dewpoint
(50% RH, 70°F)
Location of
condensation
and frost
Exterior
sheathing

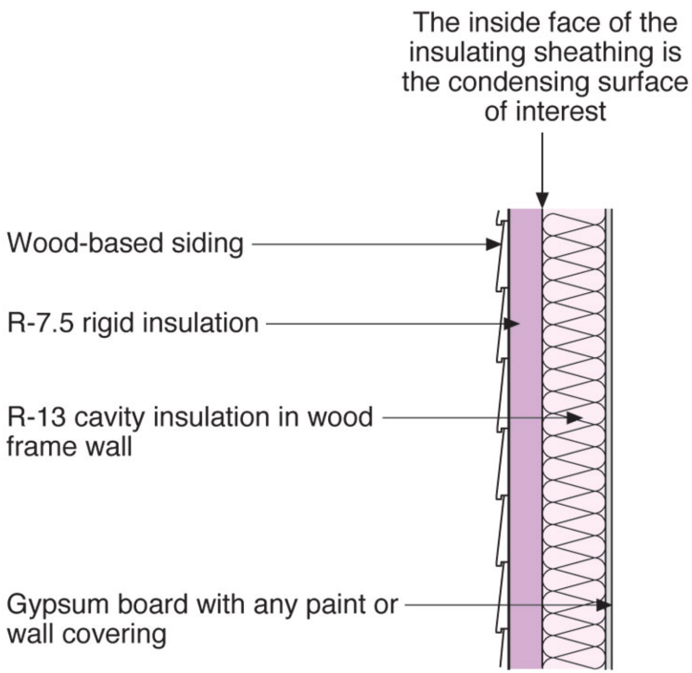


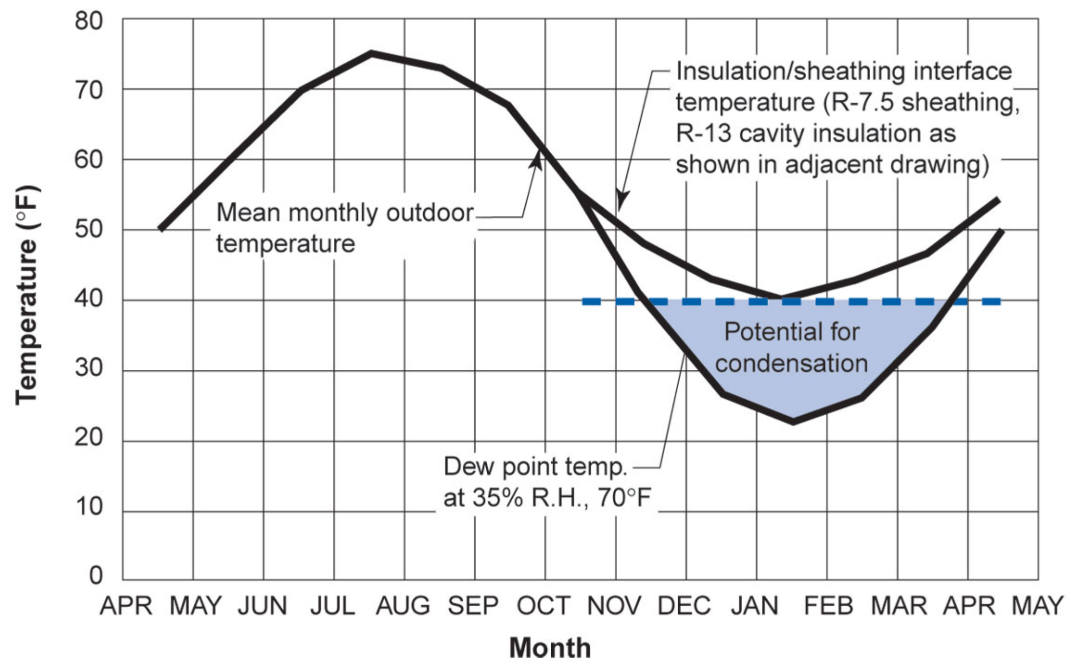
Simple linearized energy-temperature relation for water

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


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
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


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
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

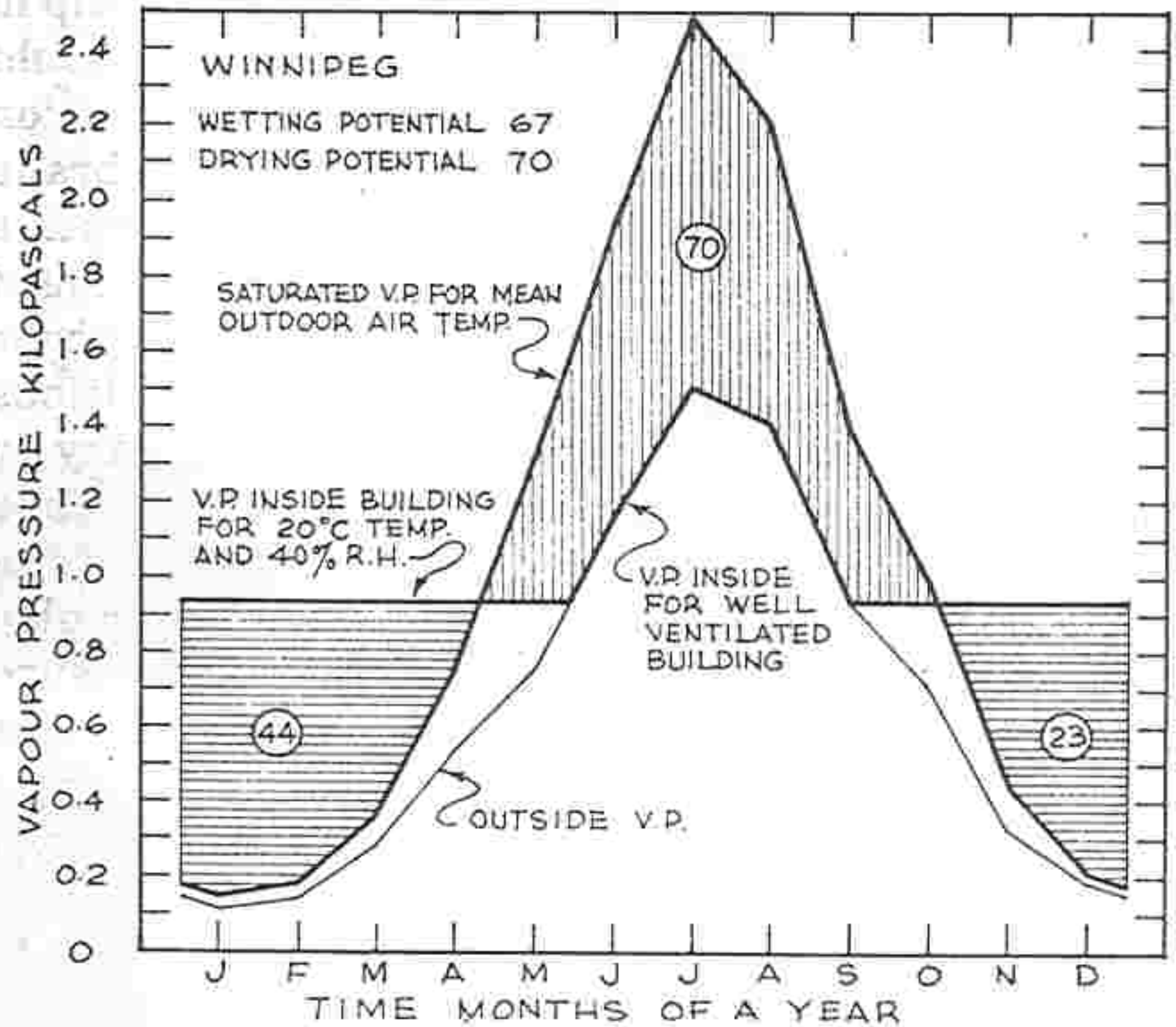
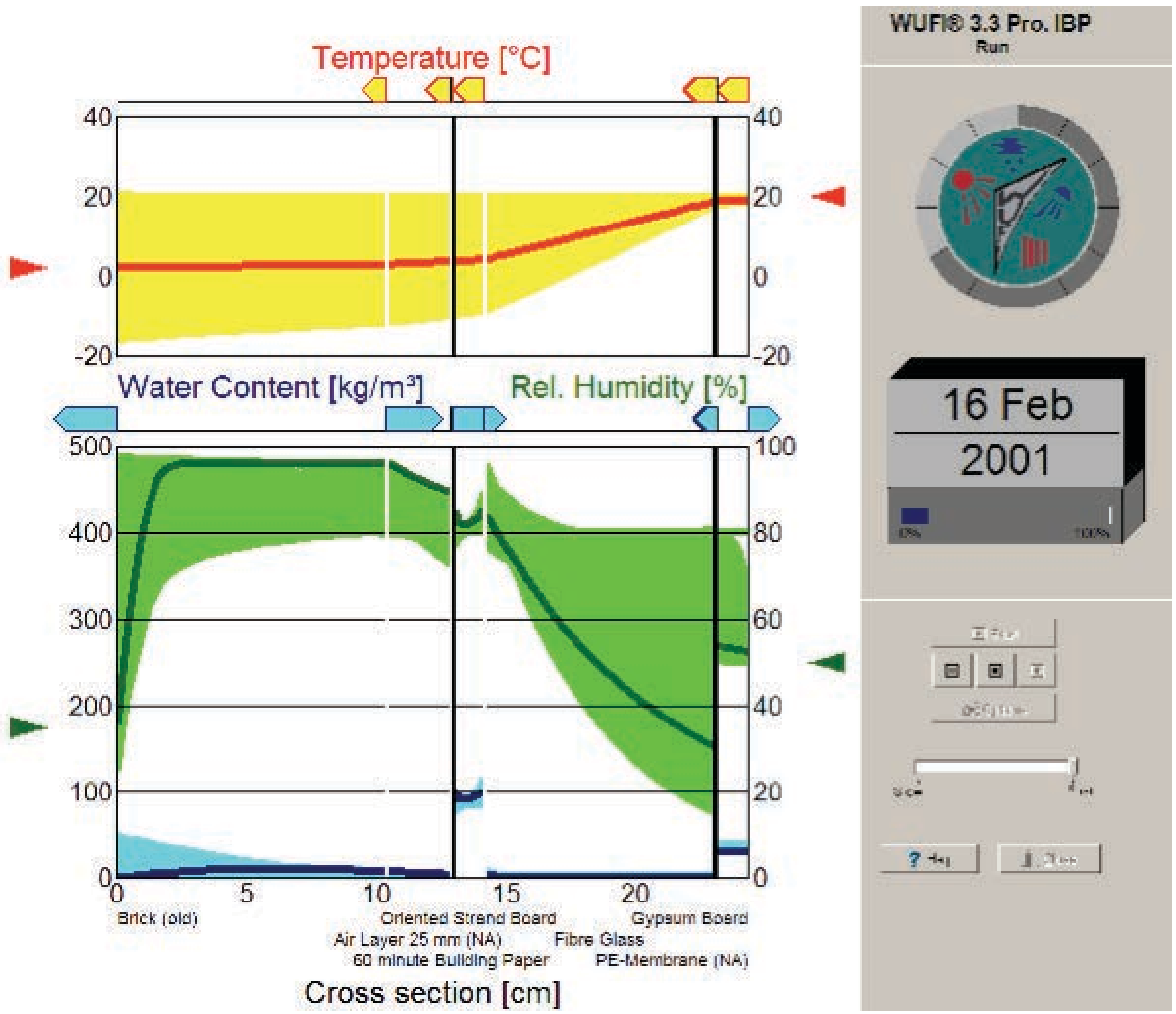
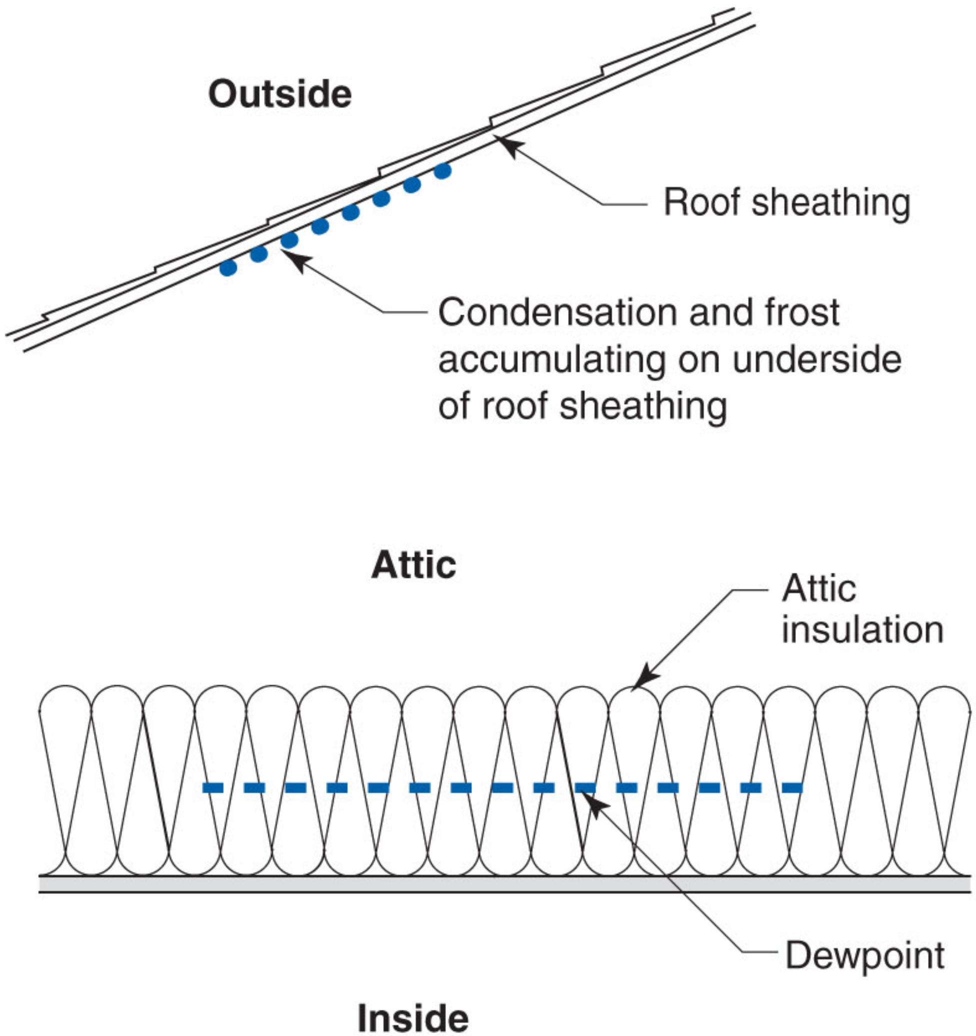
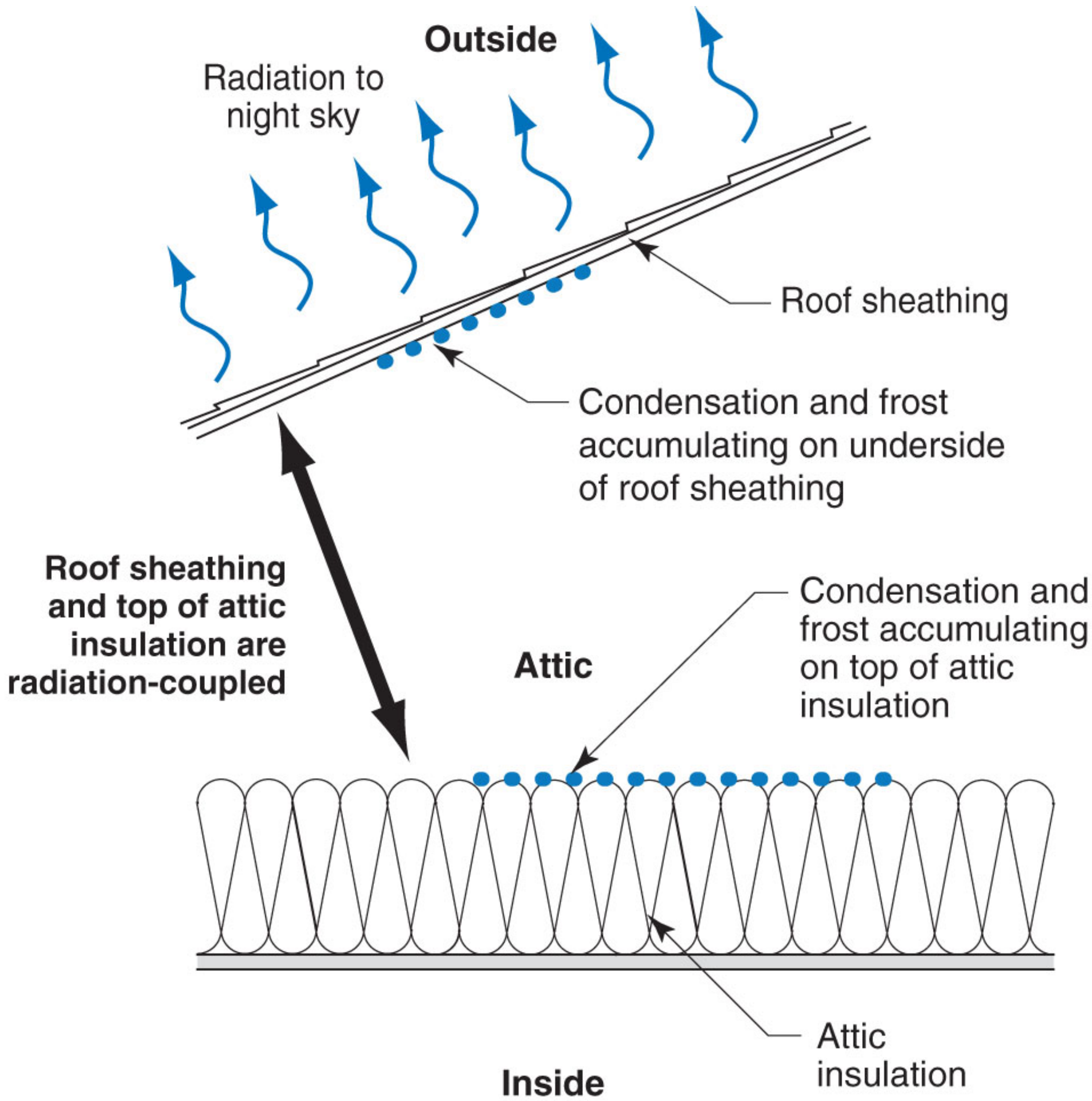


Figure 8-7. Outside vapour pressure, saturated vapour pressure and inside vapour pressure for Winnipeg.

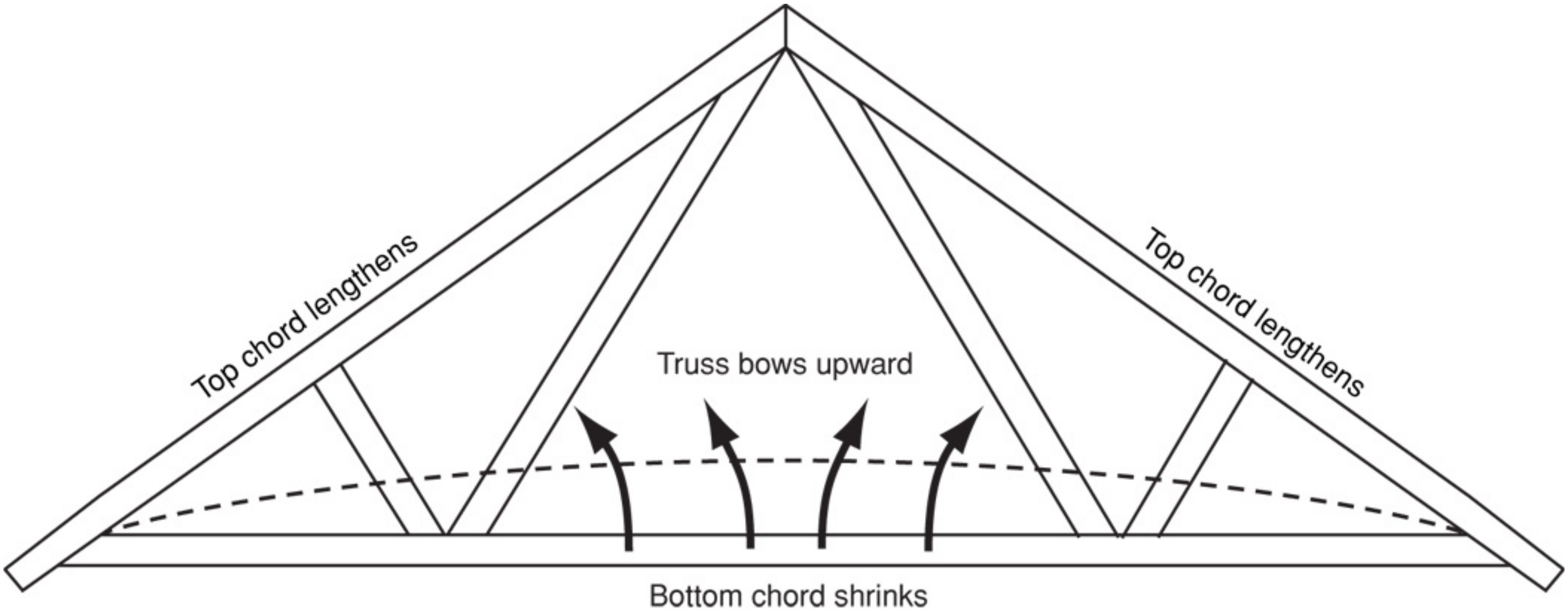


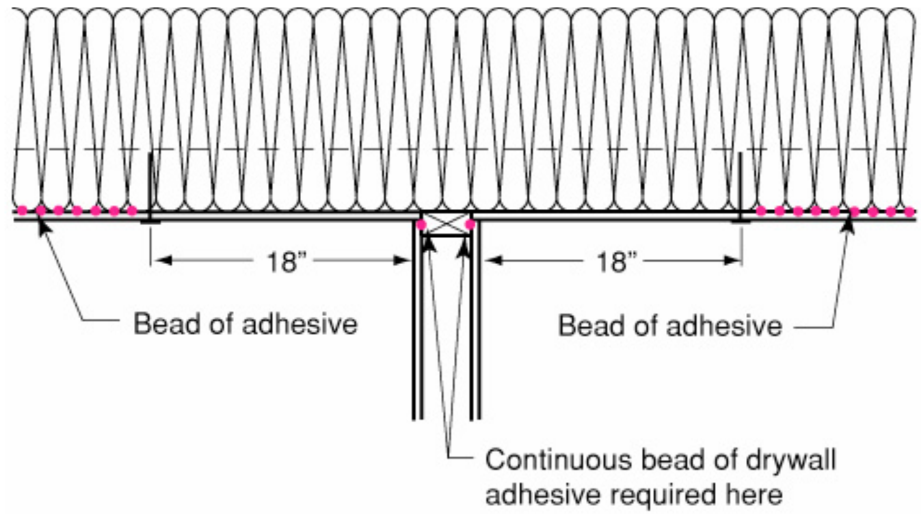
Temperature [°C]
40
20
0
-20
Water Content [kg/m³]
Rel. Humidity [%]
500
400
300
200
100
0
80
60
40
0
5
10
15
20
Brick (old)
Oriented Strand Board
Gypsum Board
Air Layer 25 mm (NA)
Fibre Glass
60 minute Building Paper
PE-Membrane (NA)
Cross section [cm]
WUFI® 3.3 Pro. IBP
Run
16 Feb
2001

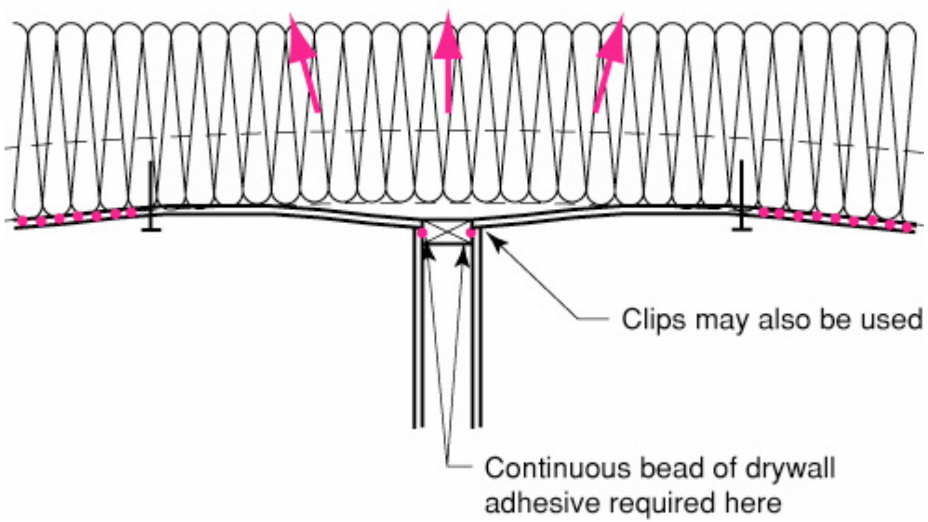

Outside
Roof sheathing
Condensation and frost accumulating on underside of roof sheathing
Attic
Attic insulation
Dewpoint
Inside

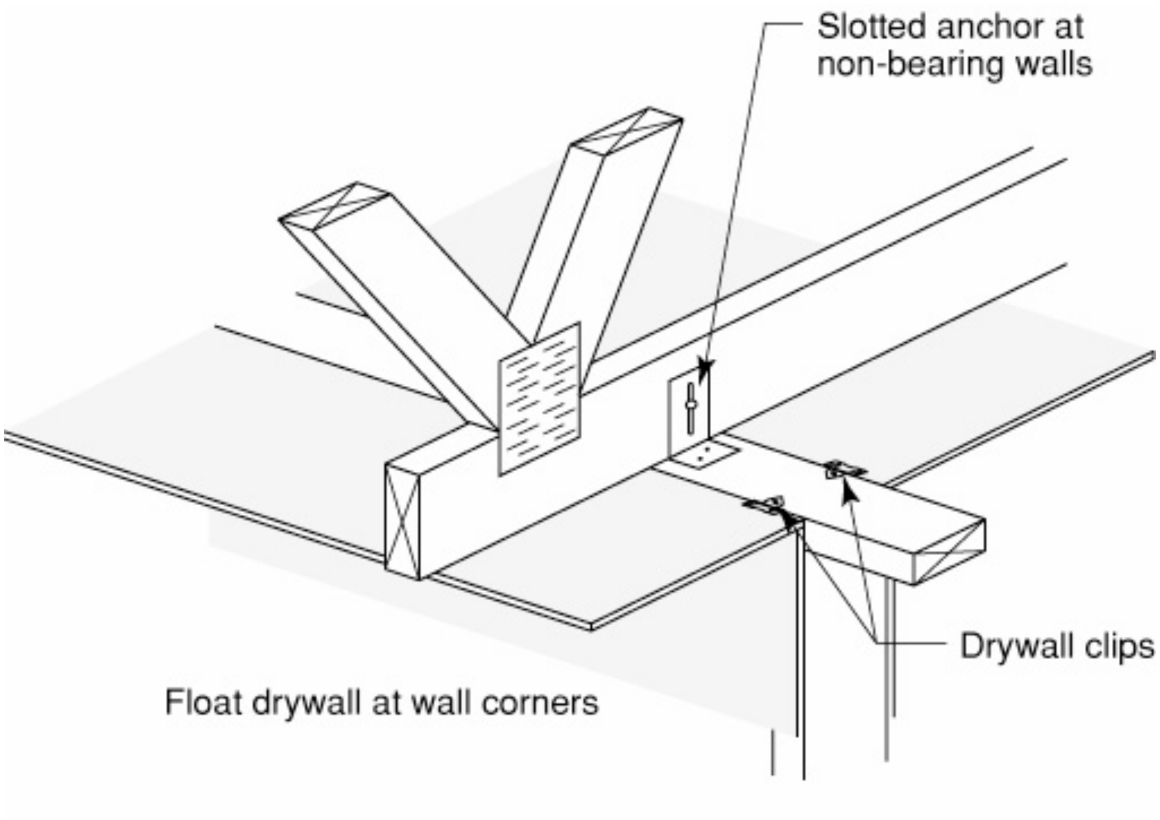

Outside
Radiation to night sky
Roof sheathing
Condensation and frost accumulating on underside of roof sheathing
Roof sheathing and top of attic insulation are radiation-coupled
Attic
Condensation and frost accumulating on top of attic insulation
Attic insulation
Inside


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


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