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

Building Science

Adventures In Building Science

presented by www.buildingscience.com

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

Thermodynamics

Zeroth Law – A=B and B=C therefore A=C

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

There Is No Such Thing As A Free Thermodynamic Lunch

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

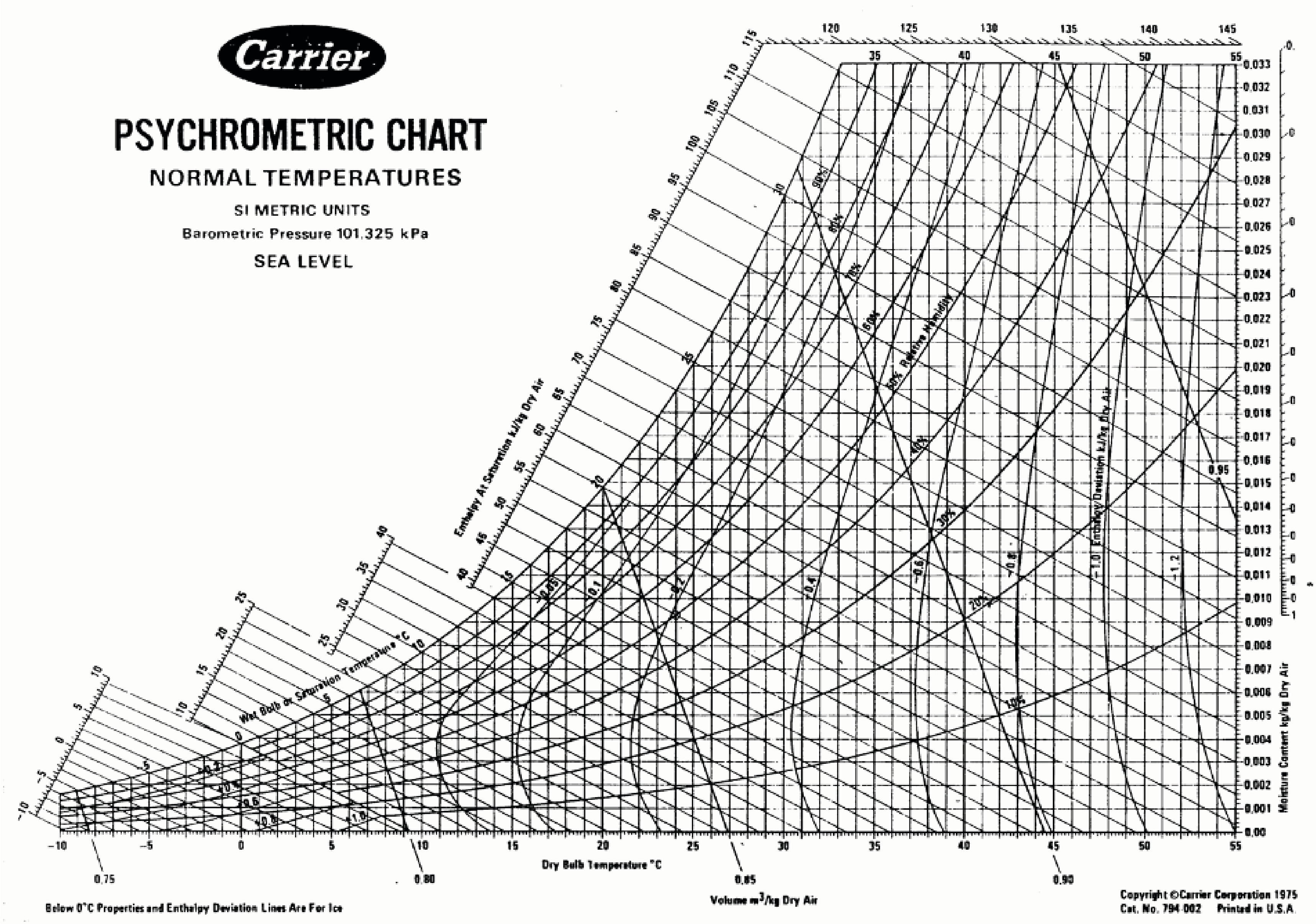
Moisture Flow Is From More To Less

Thermal Gradient – Thermal Diffusion

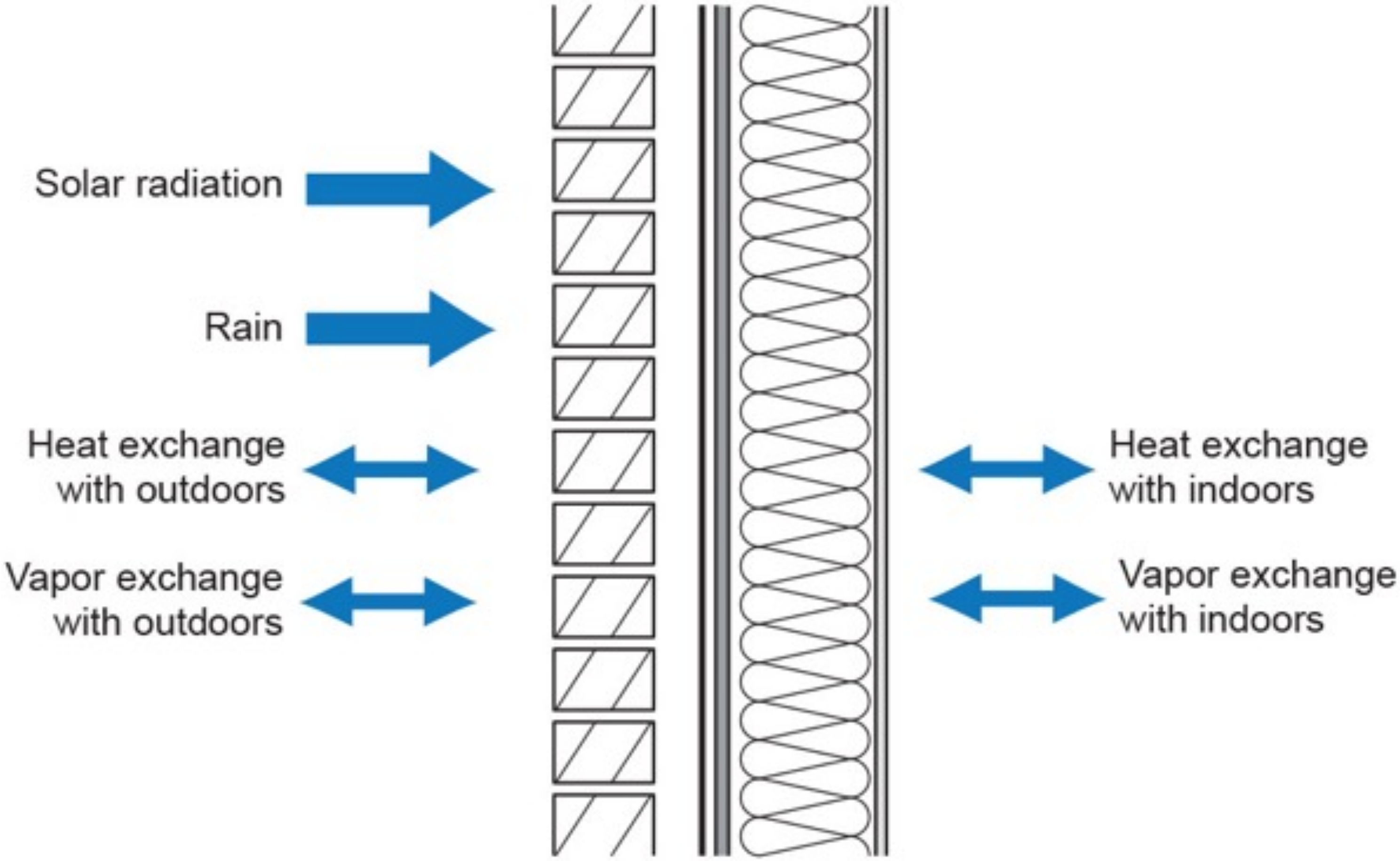
Concentration Gradient – Molecular Diffusion

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
Copyright ©Carrier Corporation 1975
Cat. No. 794-002 Printed in U.S.A.

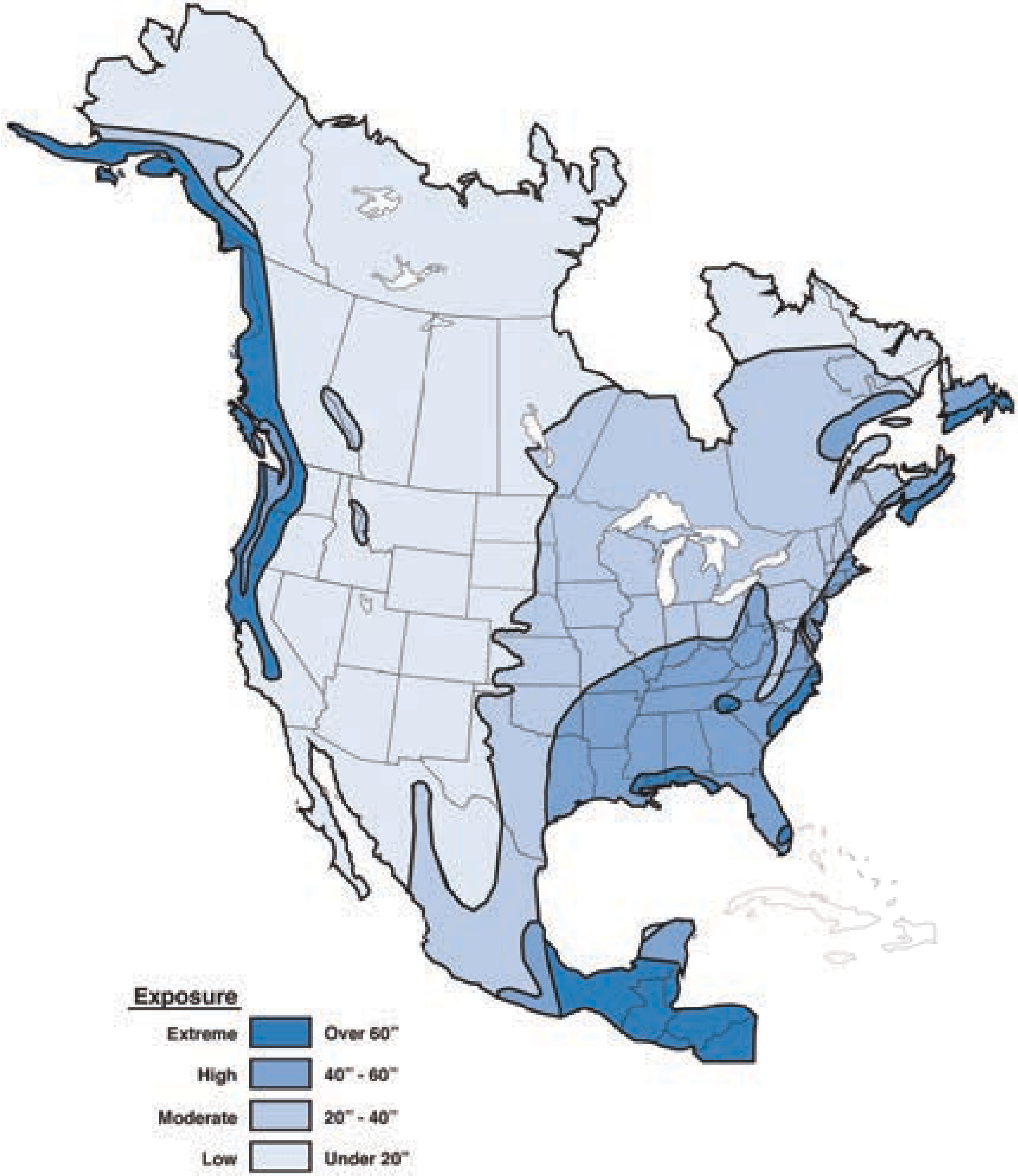
Hygrothermal Analysis


Solar radiation
Rain
Heat exchange with outdoors
Vapor exchange with outdoors
Heat exchange with indoors
Vapor exchange with indoors

Firmness, Commodity and Delight

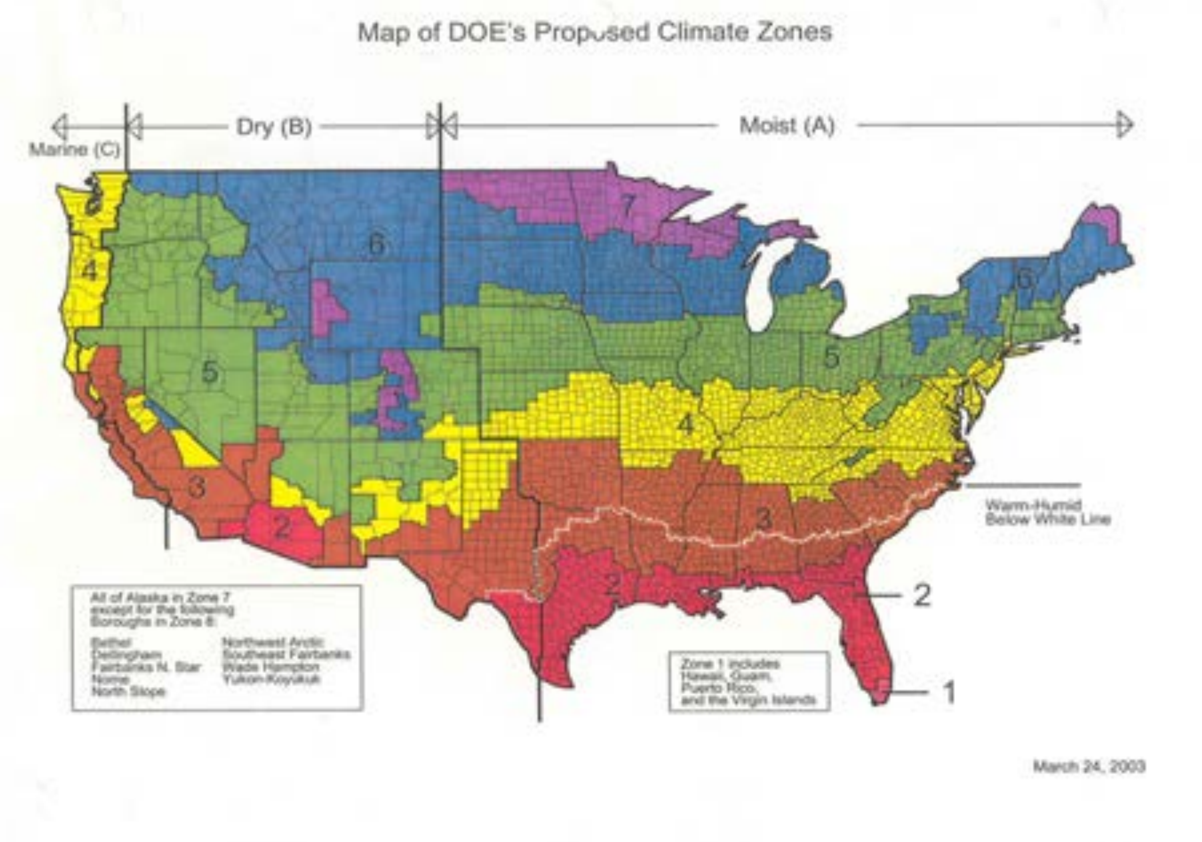
“These are properly designed, when due regard is had to the country and climate in which they are erected. For the method of building which is suited to Egypt would be very improper in Spain, and that in use in Pontus would be absurd at Rome: so in other parts of the world a style suitable to one climate, would be very unsuitable to another”

Marcus Vitruvius Pollio (c.90-20 B.C.E.)

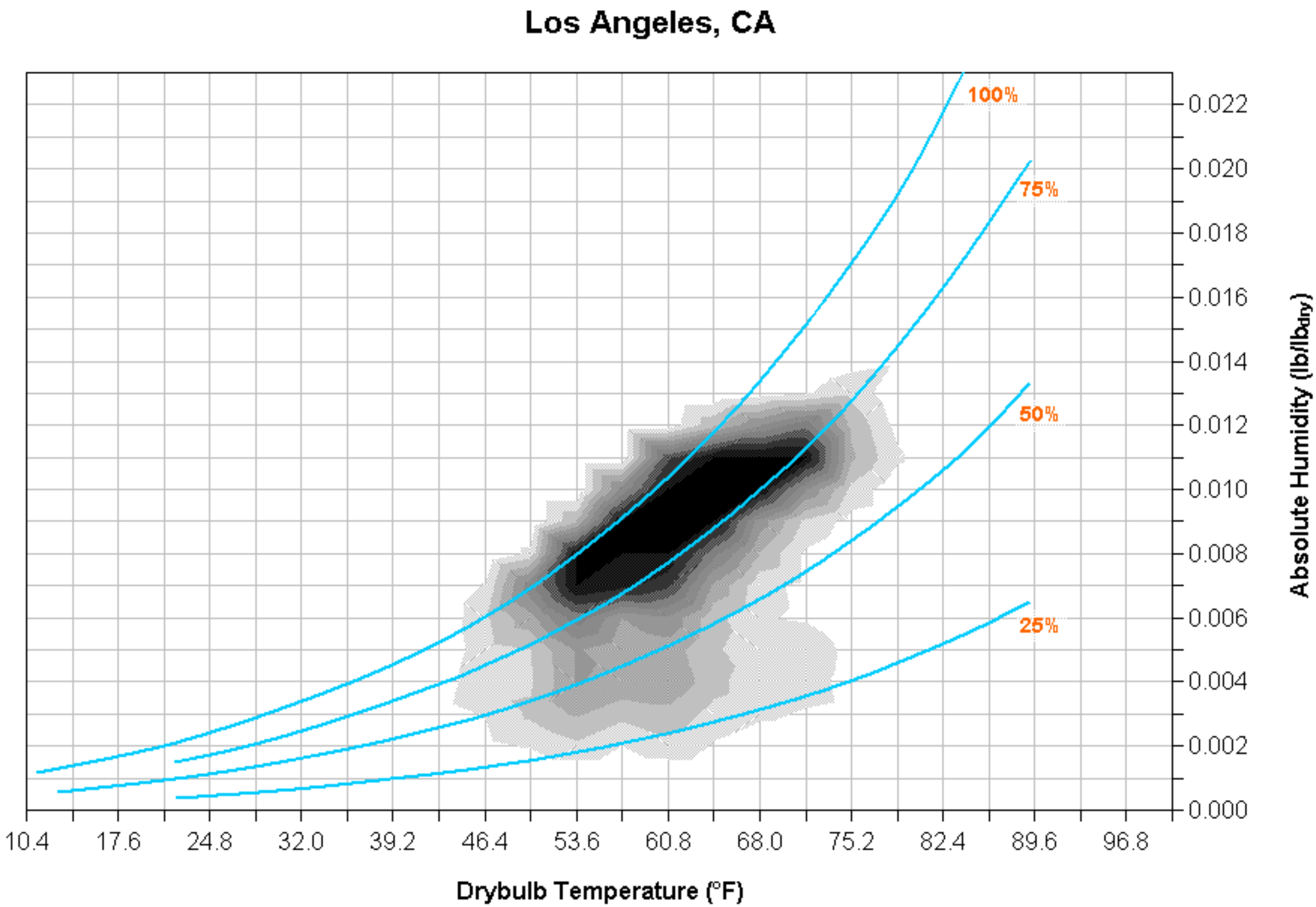

Exposure
Extreme
Over 60"
High
40" - 60"
Moderate
20" - 40"
Low
Under 20"

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

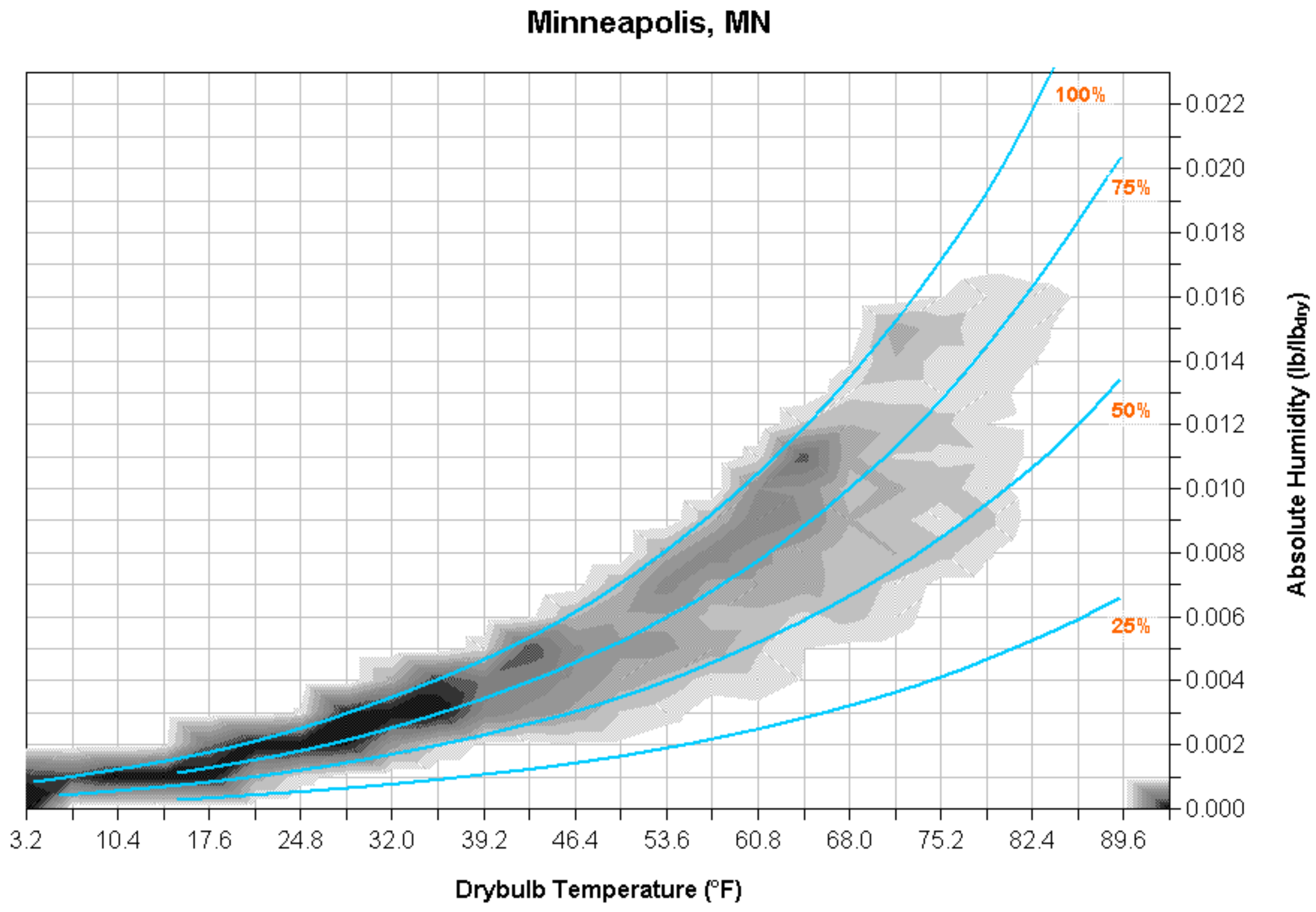

Subarctic/Arctic
Very Cold
Marine
Cold
Mixed-Humid
Mixed-Dry
Hot-Humid
Hot-Dry



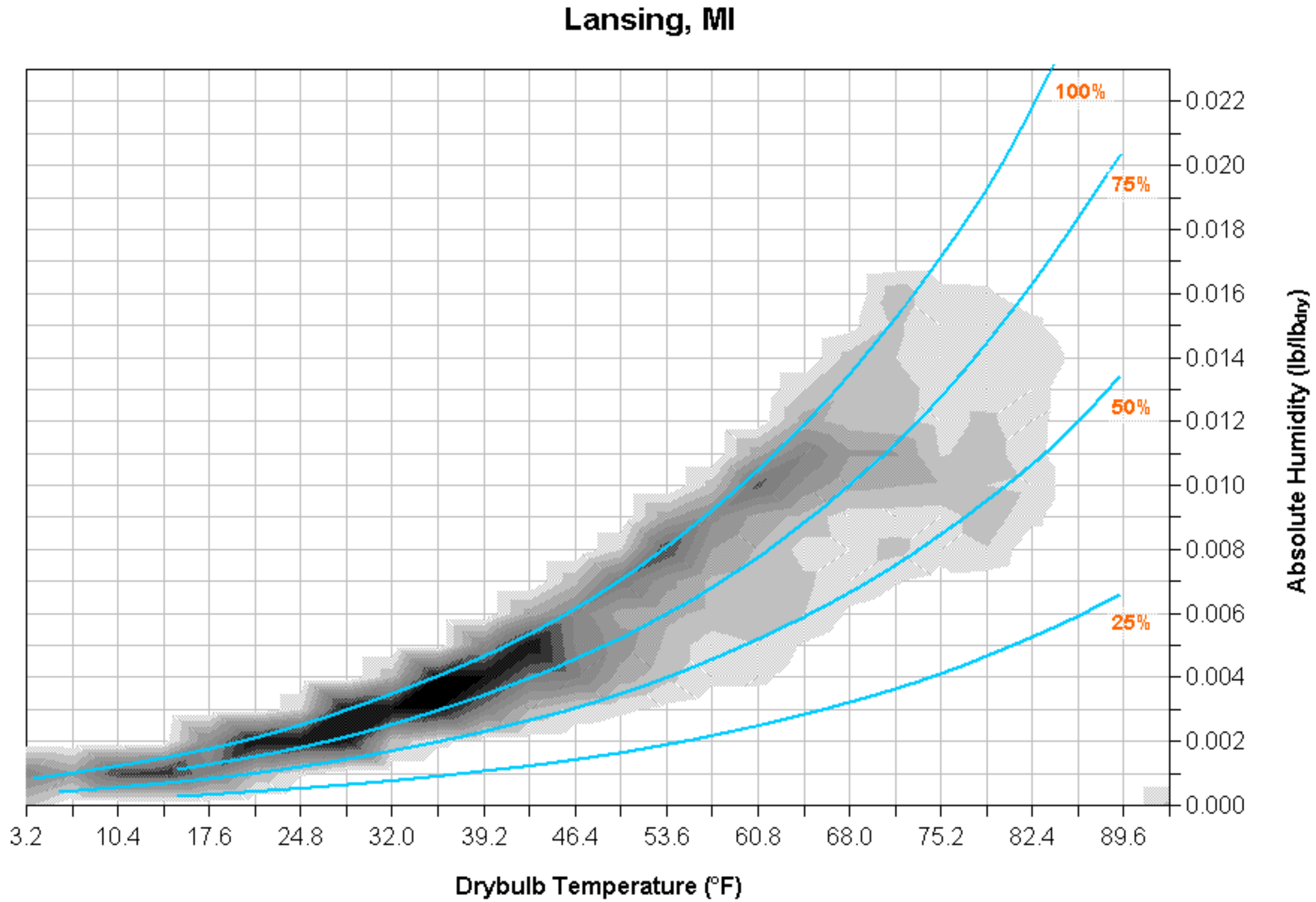
Map of DOE's Proposed Climate Zones
Marine (C)
Dry (B)
Moist (A)
7
6
4
5
3
2
1
Warm-Humid Below White Line
All of Alaska in Zone 7 except for the following Boroughs in Zone 8:
Bethel
Dellingham
Fairbanks N. Star
Nome
North Slope
Northwest Arctic
Southeast Fairbanks
Wade Hampton
Yukon-Koyukuk
Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands
March 24, 2003

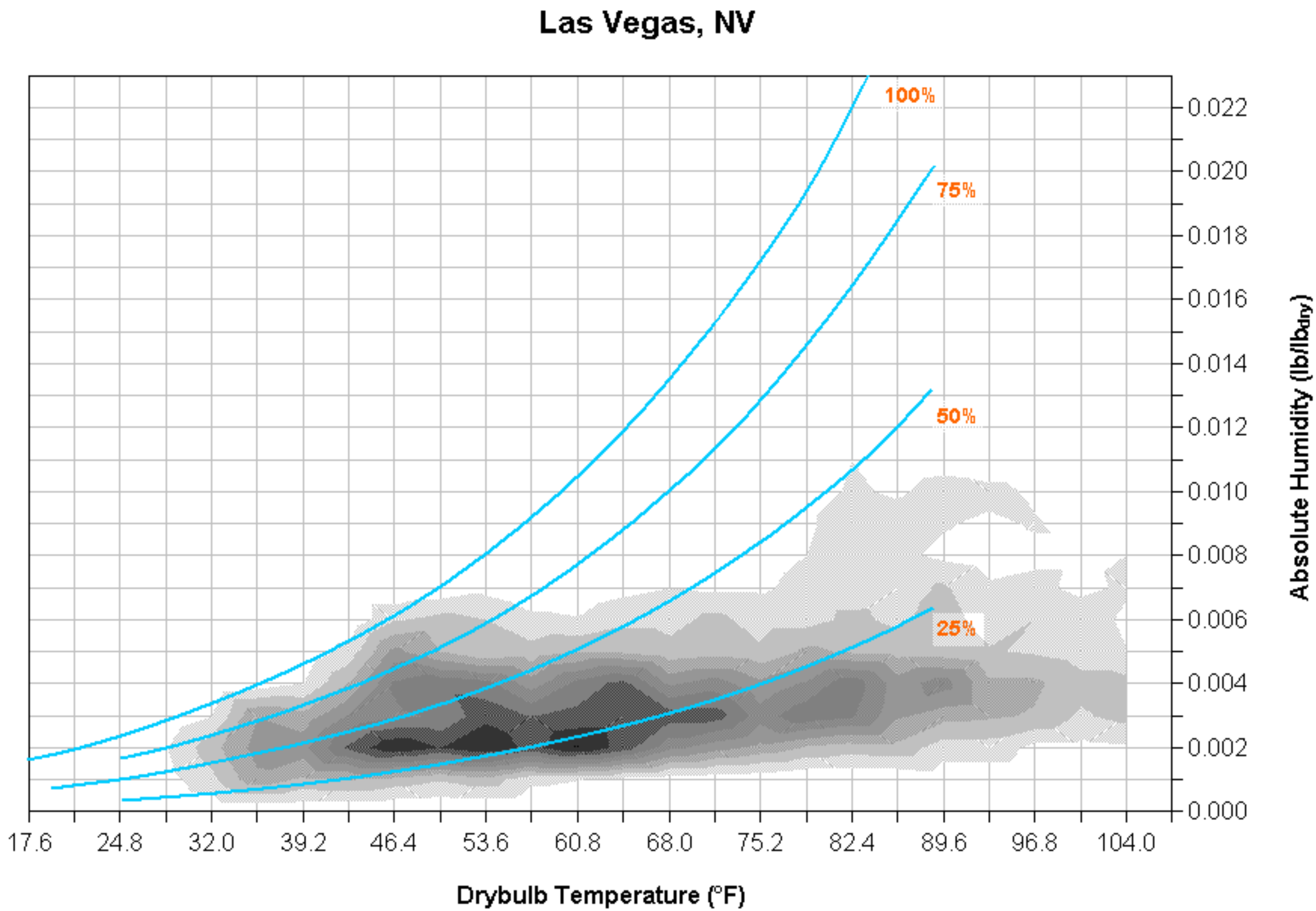


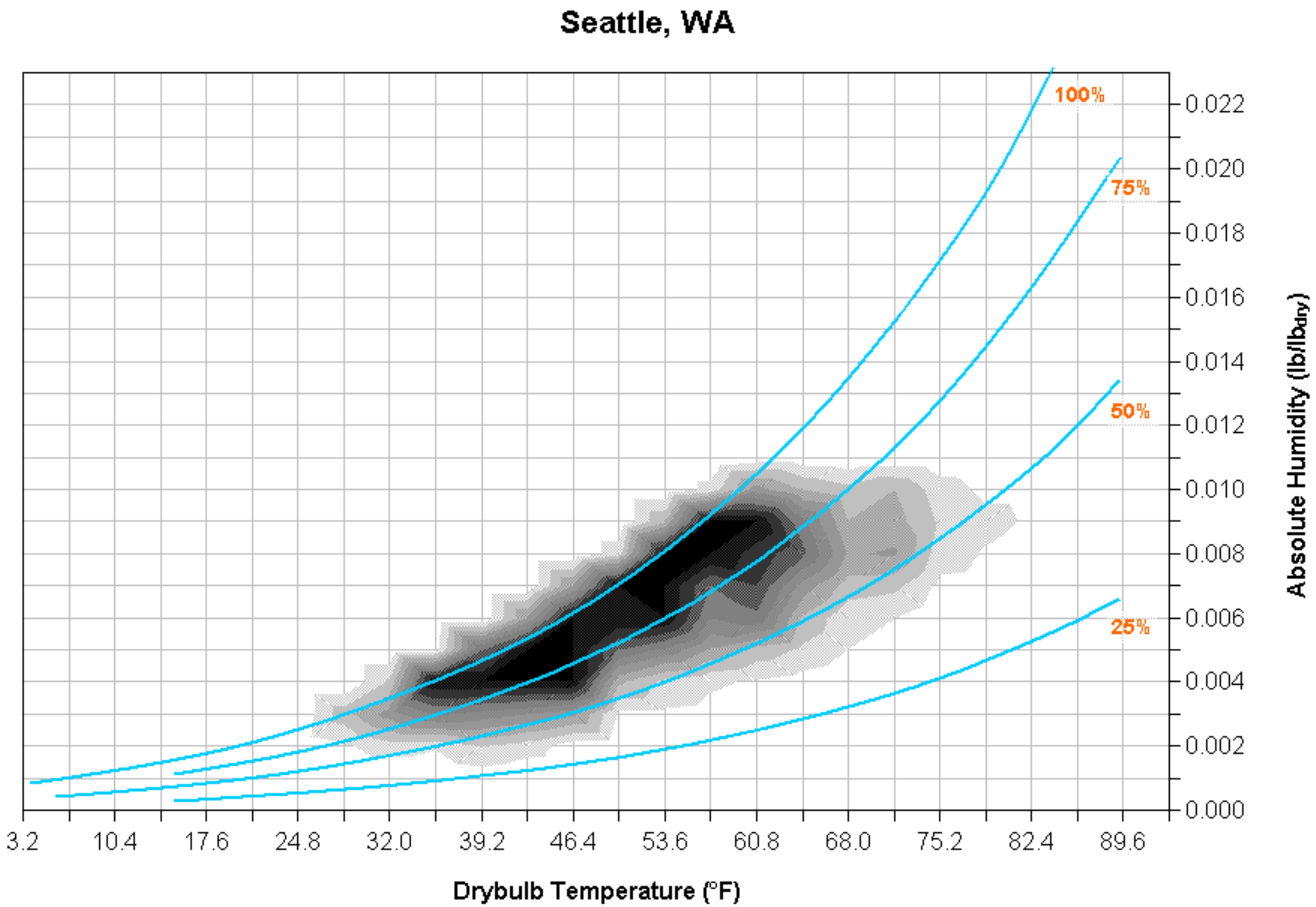
Los Angeles, CA
100%
75%
50%
25%
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Absolute Humidity (lb/lb$_{dry}$)
10.4
17.6
24.8
32.0
39.2
46.4
53.6
60.8
68.0
75.2
82.4
89.6
96.8
Drybulb Temperature (°F)



Minneapolis, MN
100%
75%
50%
25%
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Absolute Humidity (lb/lb$_{dry}$)
3.2
10.4
17.6
24.8
32.0
39.2
46.4
53.6
60.8
68.0
75.2
82.4
89.6
Drybulb Temperature (°F)


Lansing, MI
100%
75%
50%
25%
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Absolute Humidity (lb/lbdry)
3.2
10.4
17.6
24.8
32.0
39.2
46.4
53.6
60.8
68.0
75.2
82.4
89.6
Drybulb Temperature (°F)


Las Vegas, NV
100%
75%
50%
25%
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Absolute Humidity (lb/lb$_{dry}$)
17.6
24.8
32.0
39.2
46.4
53.6
60.8
68.0
75.2
82.4
89.6
96.8
104.0
Drybulb Temperature (°F)



Seattle, WA
100%
75%
50%
25%
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
Absolute Humidity (lb/lb$_{dry}$)
3.2
10.4
17.6
24.8
32.0
39.2
46.4
53.6
60.8
68.0
75.2
82.4
89.6
Drybulb Temperature (°F)

Arrhenius Equation

For Every 10 Degree K Rise

Activation Energy Doubles

$$k = Ae^{-E_a/(RT)}$$

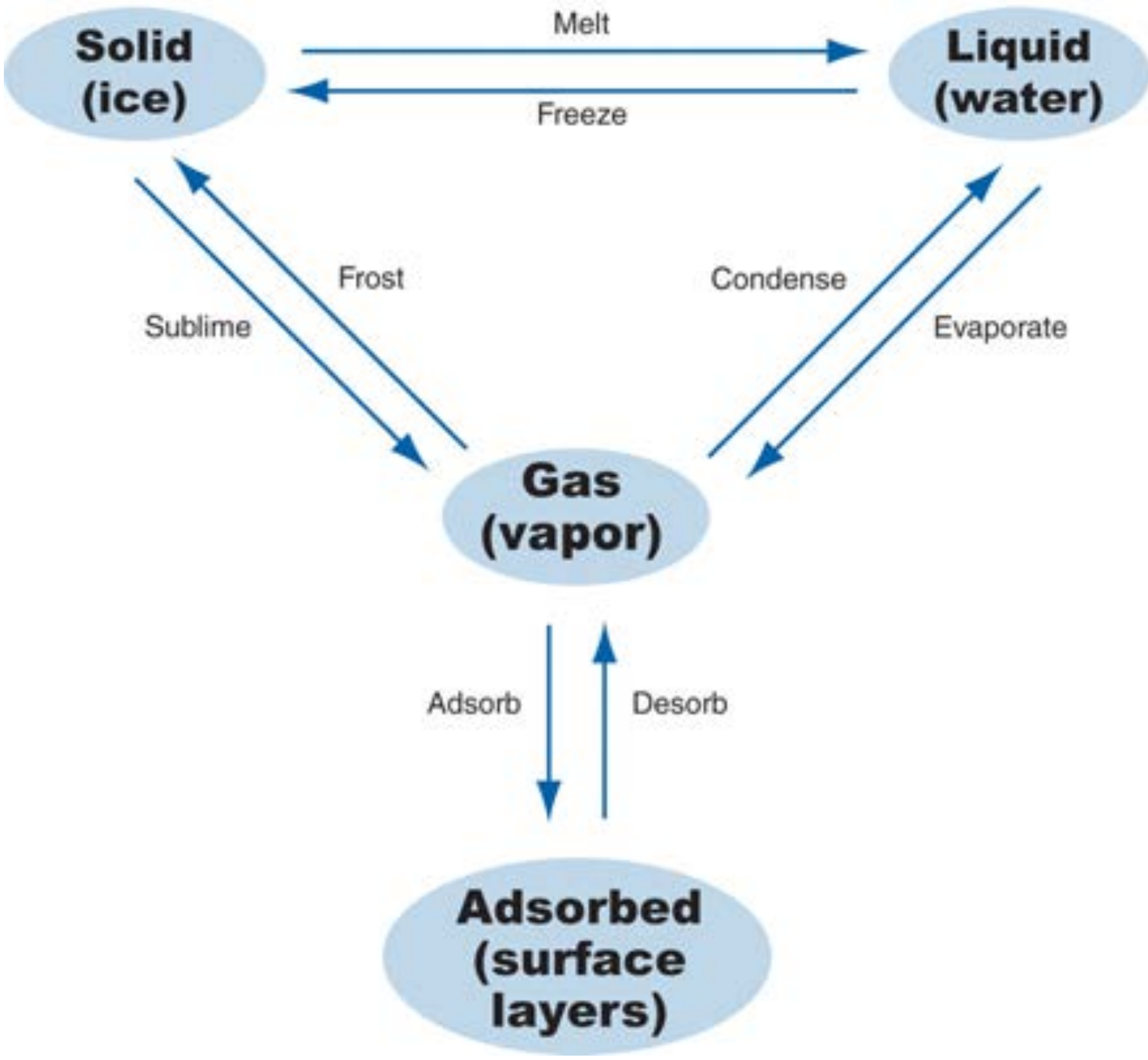
Damage Functions

Water

Heat

Ultra-violet Radiation

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


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

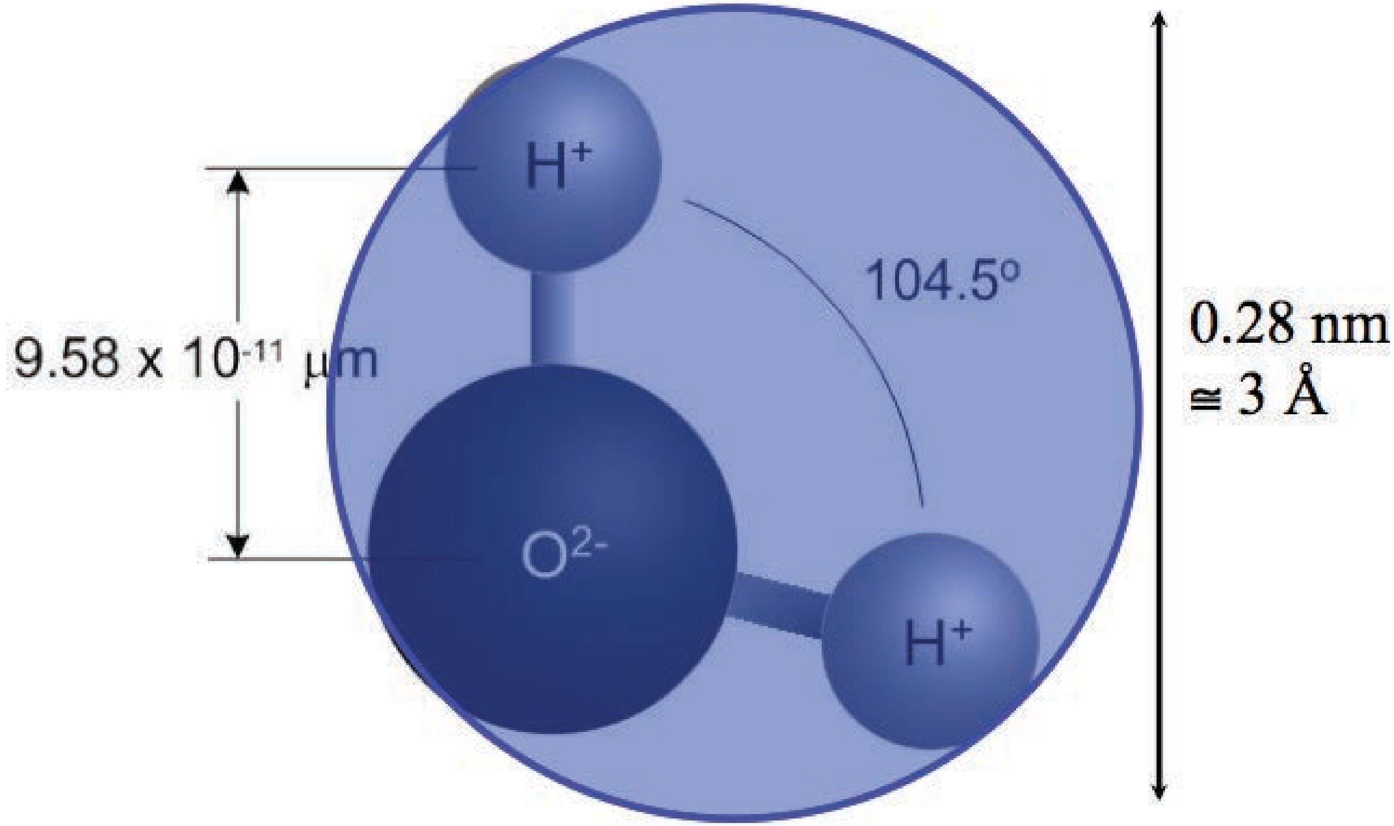
Moisture Transport in Porous Media

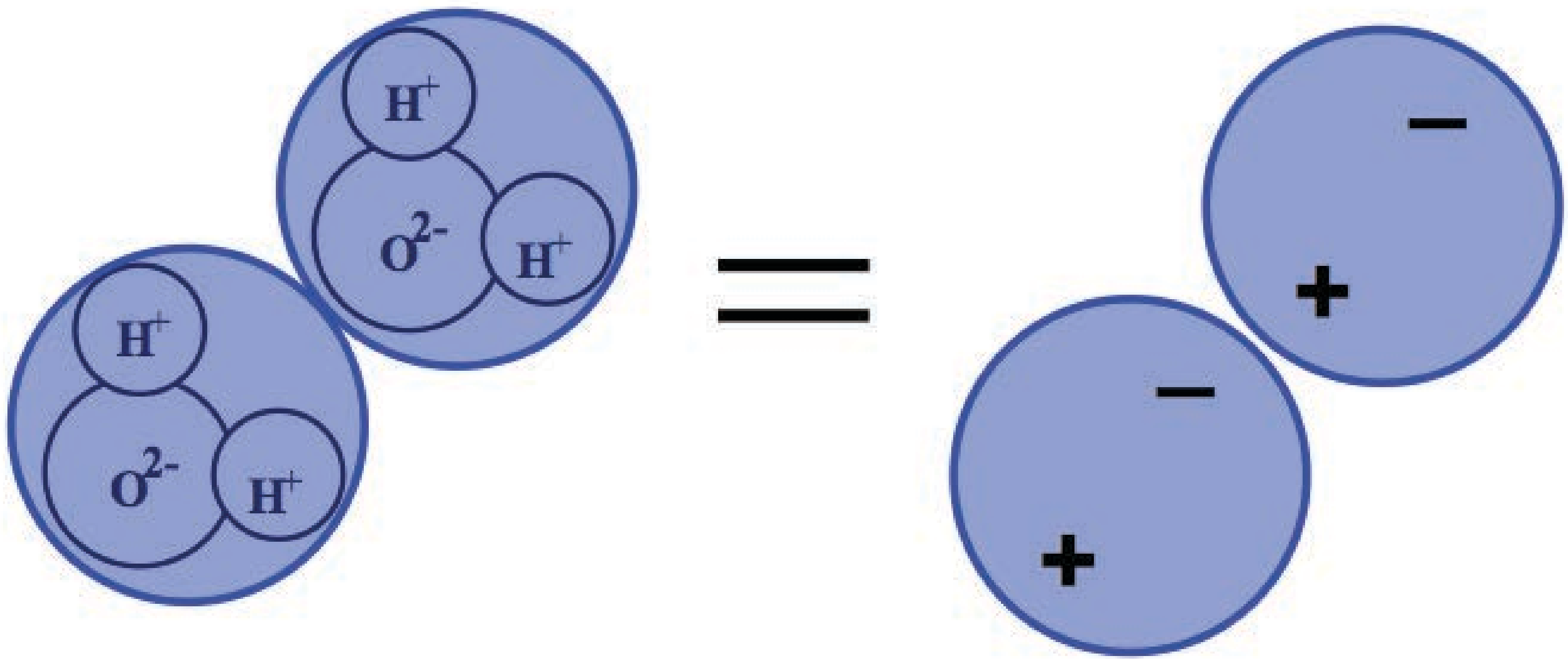
Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration

Moisture Transport in Assemblies

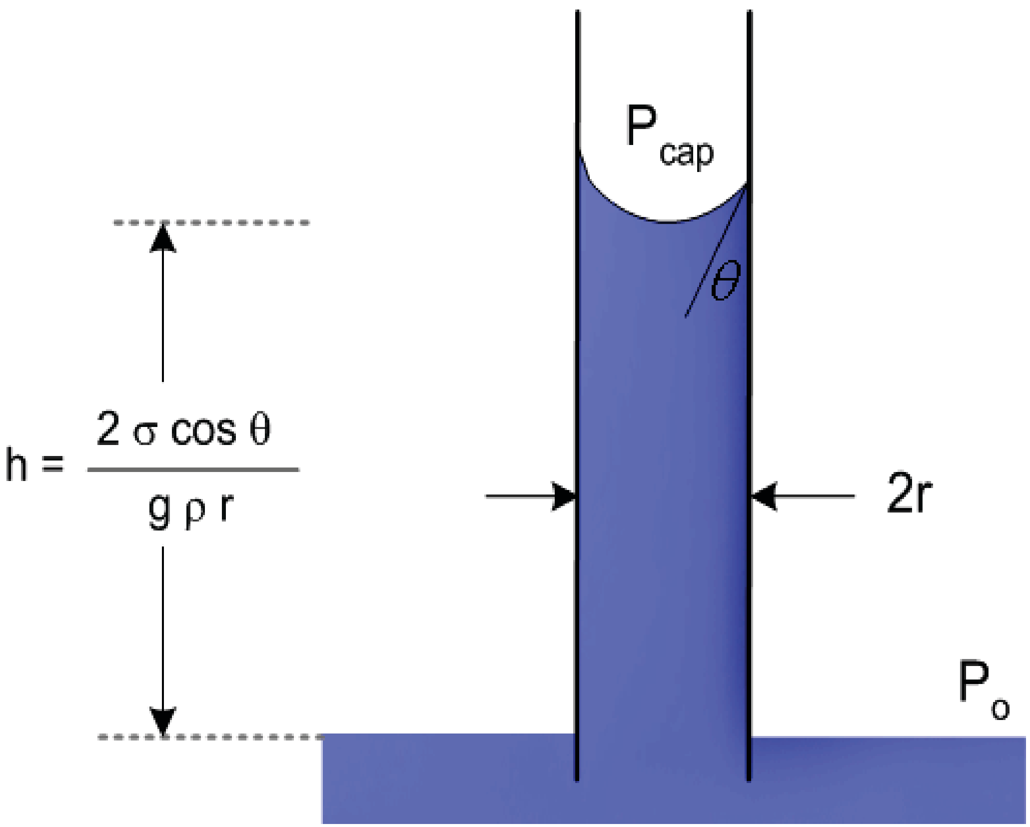
Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration
	Gravitational Flow	Height
	Surface Tension	Surface Energy
	Momentum	Kinetic Energy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

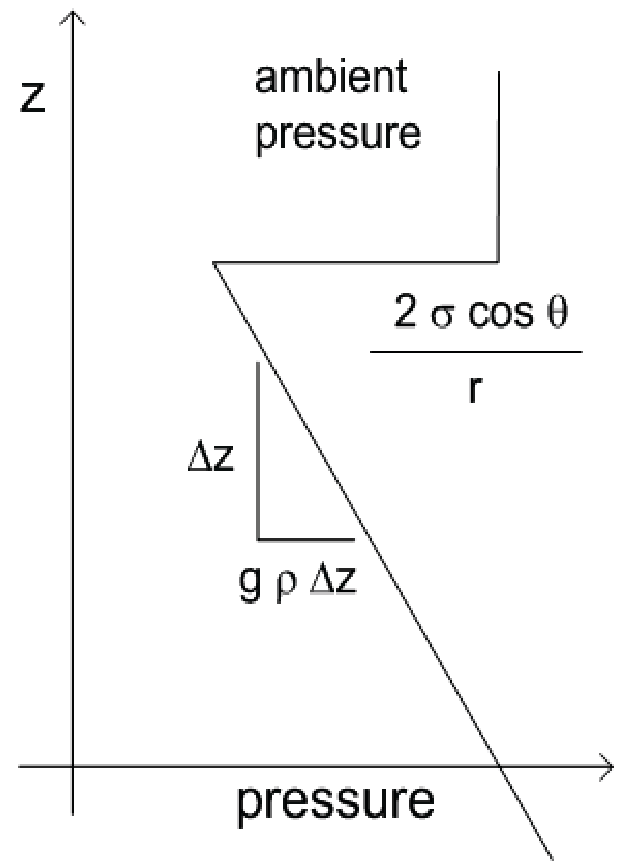
Microclimates and Materials Science


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

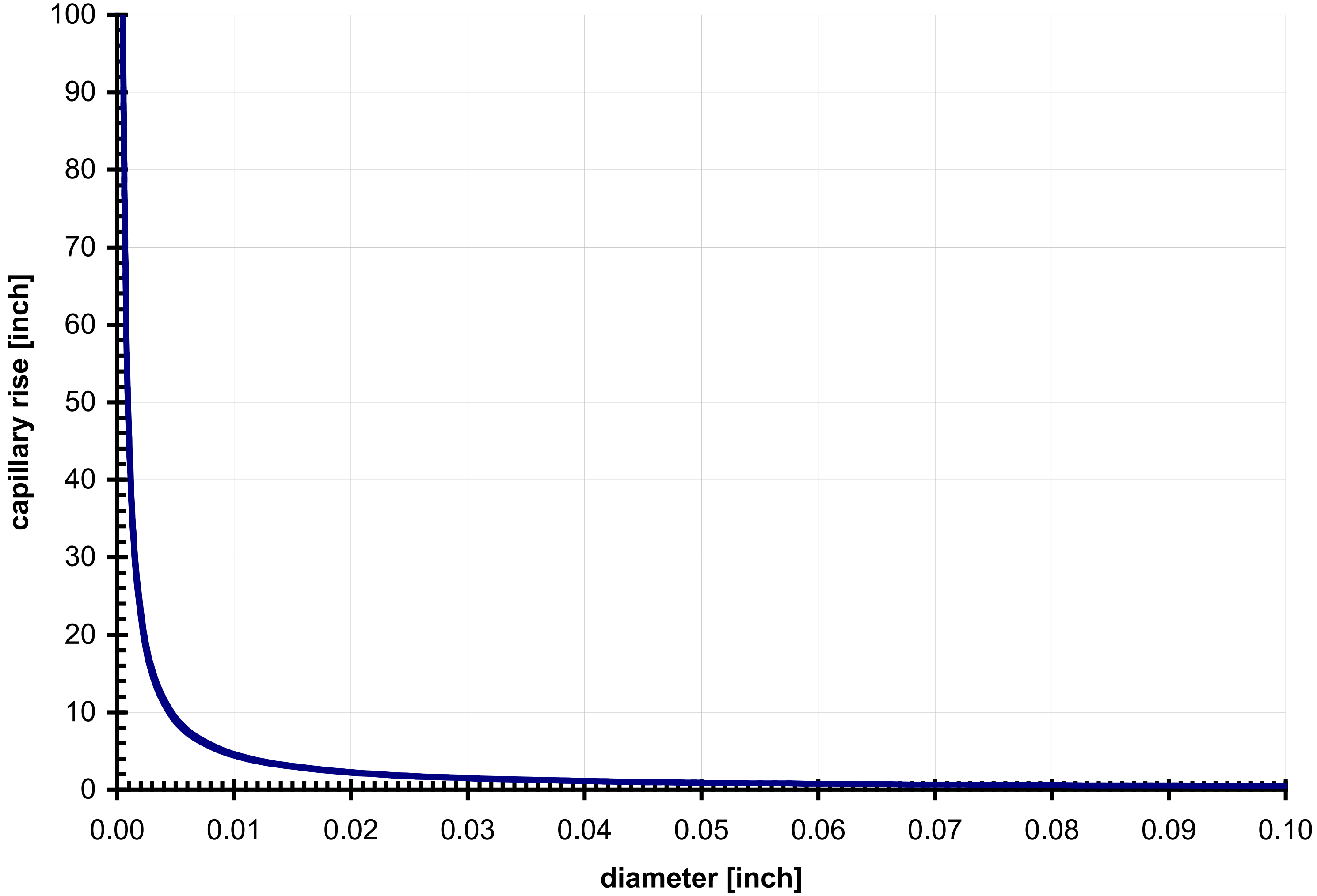

H+
O2-
H+
H+
O2-
H+
–
+
–
+

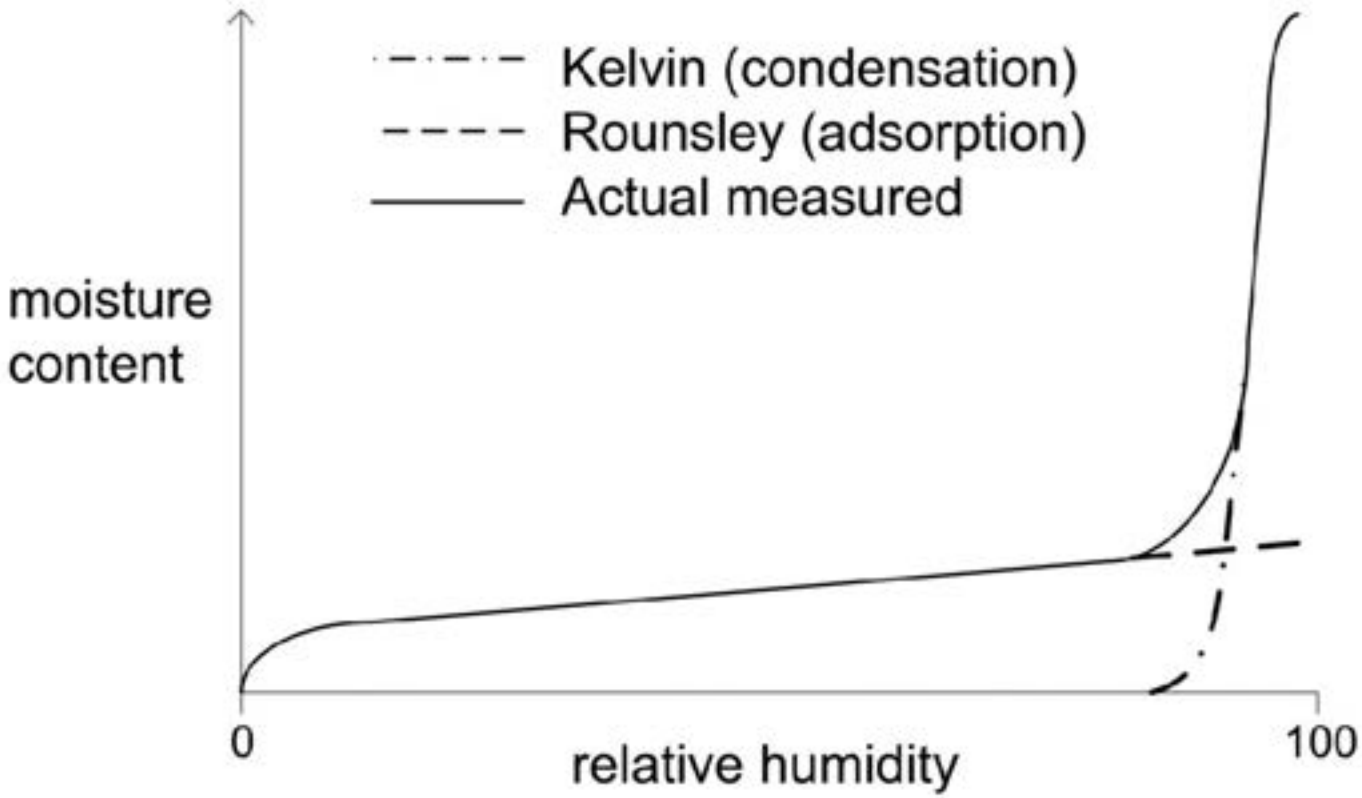
Calculating capillary rise





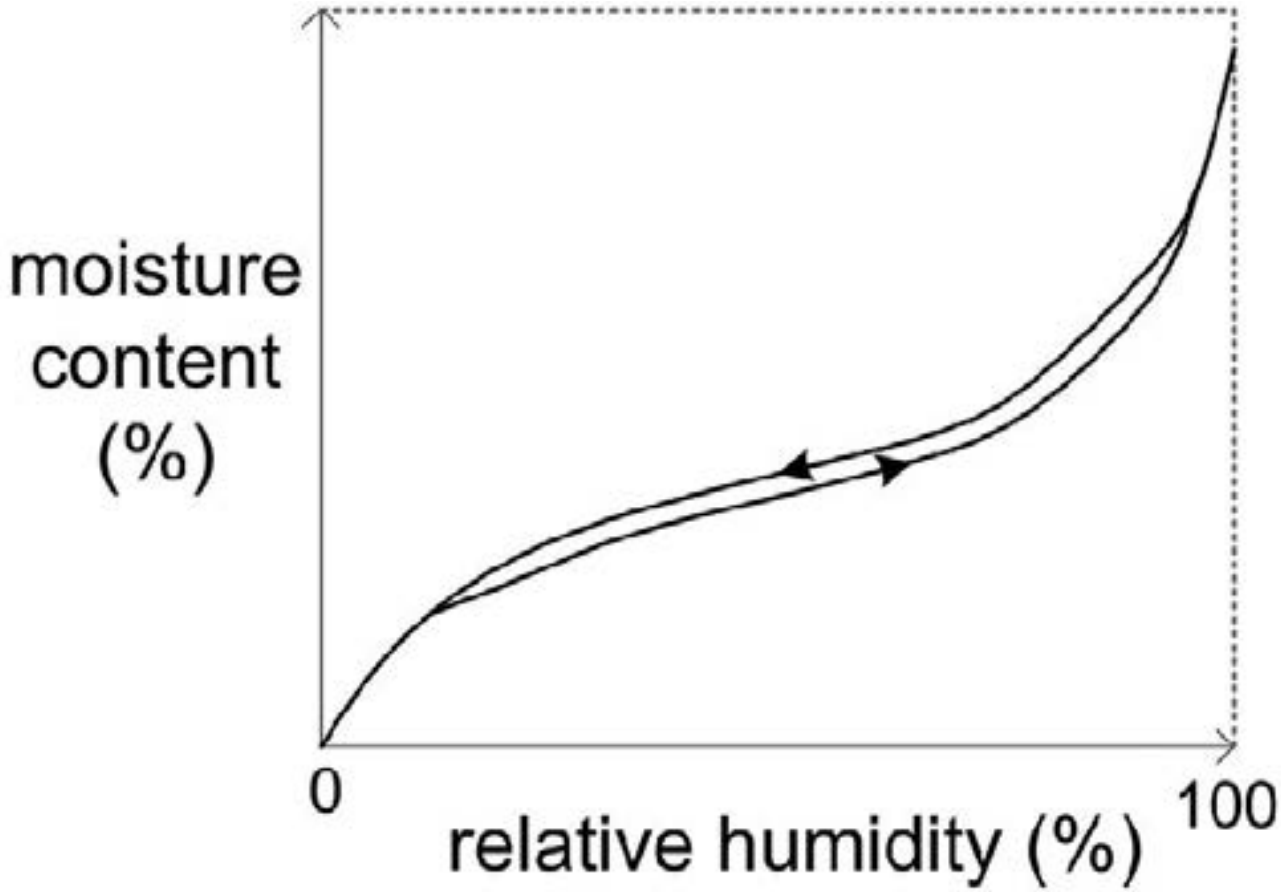
Capillary rise versus diameter





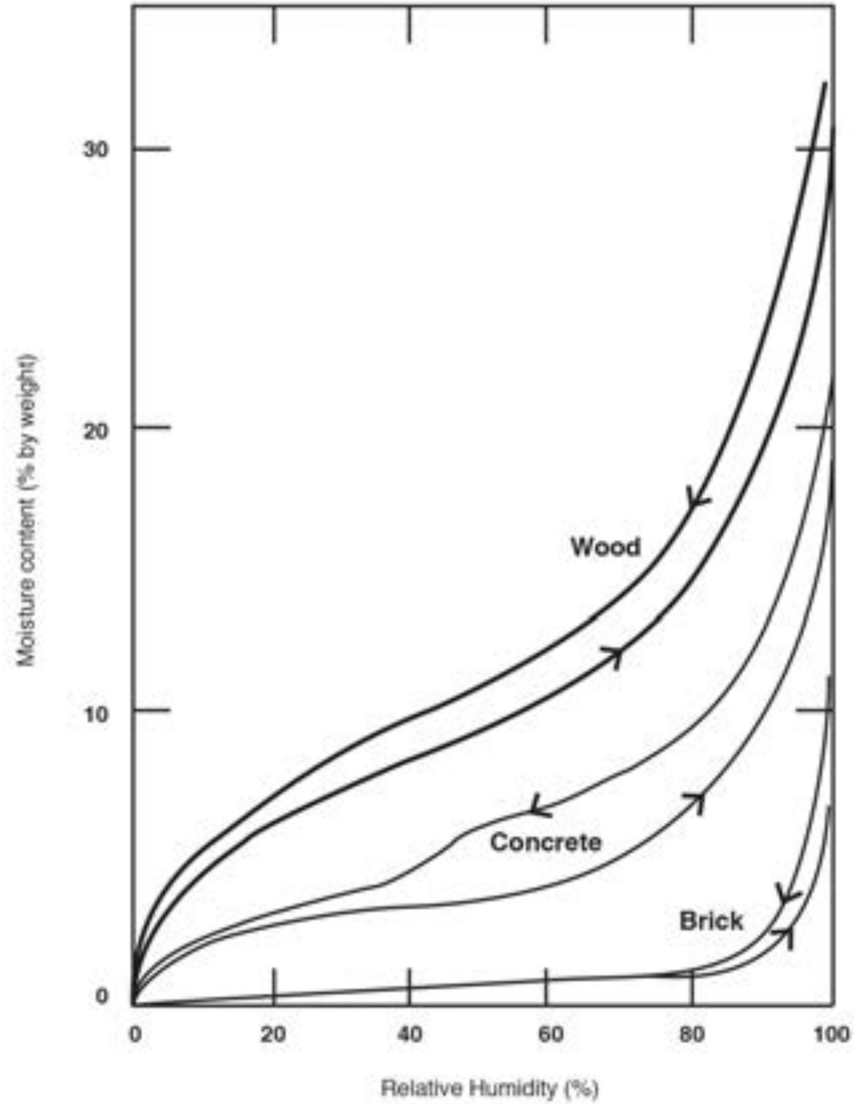
Typical predicted sorption isotherm according to Kelvin equation and modified BET theory

From Straube & Burnett, 2005

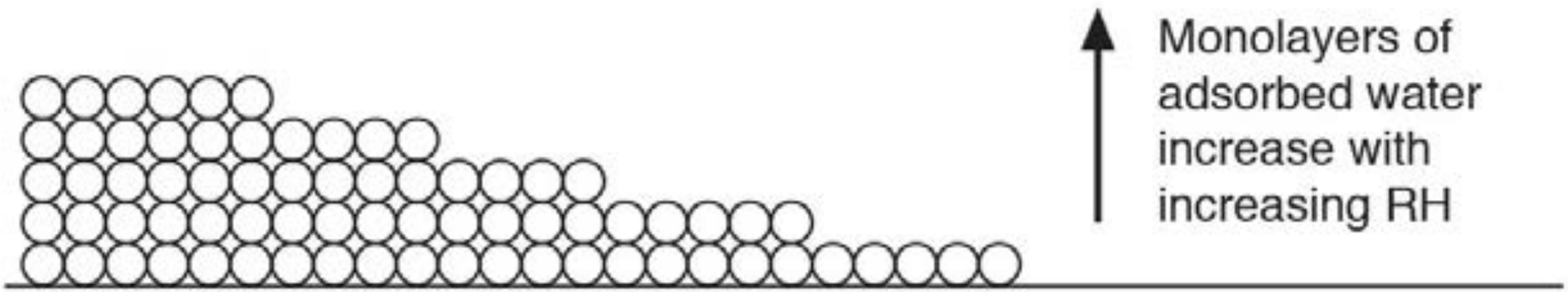


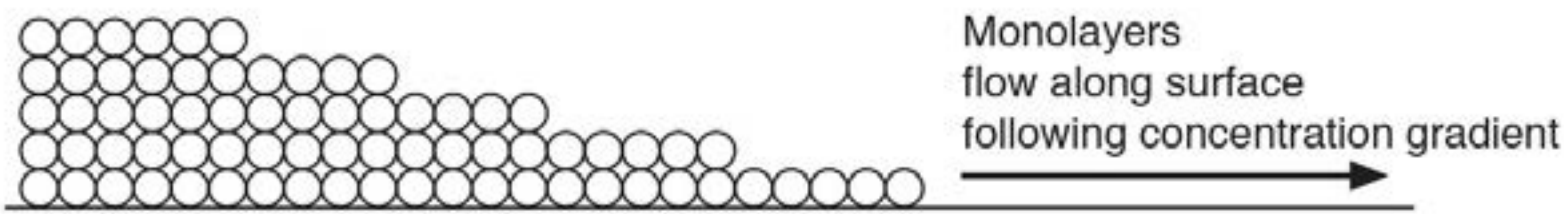
Typical sorption isotherm of a hygroscopic material

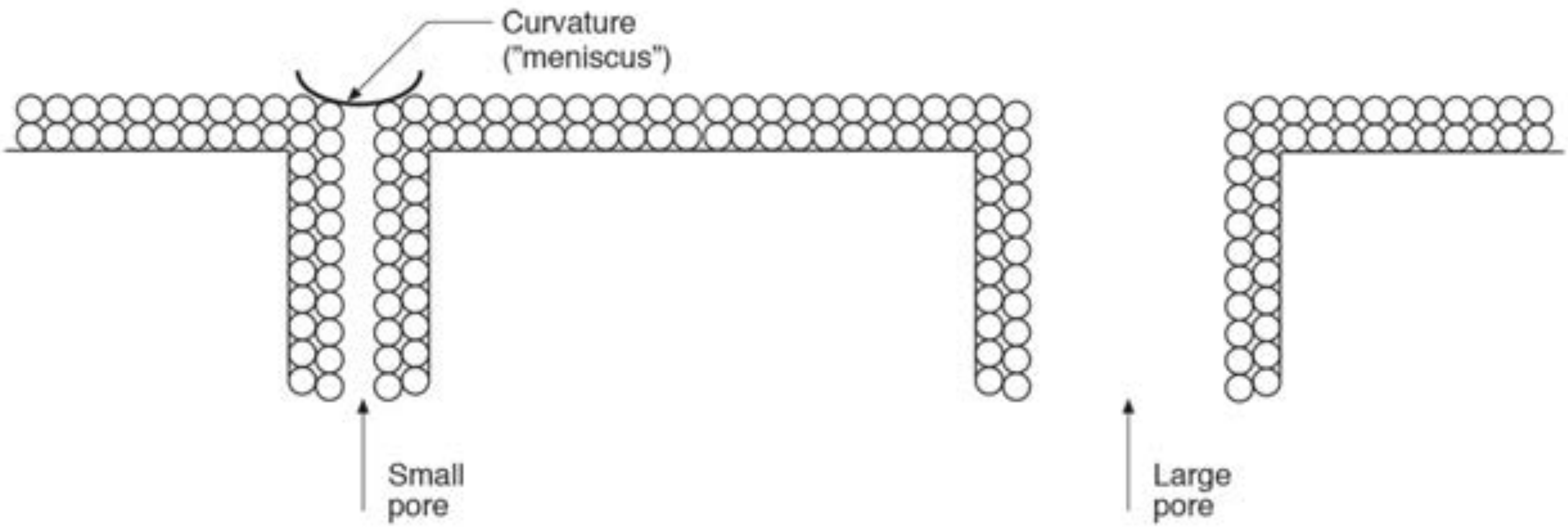
From Straube & Burnett, 2005



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


Monolayers of
adsorbed water
increase with
increasing RH


Monolayers
flow along surface
following concentration gradient



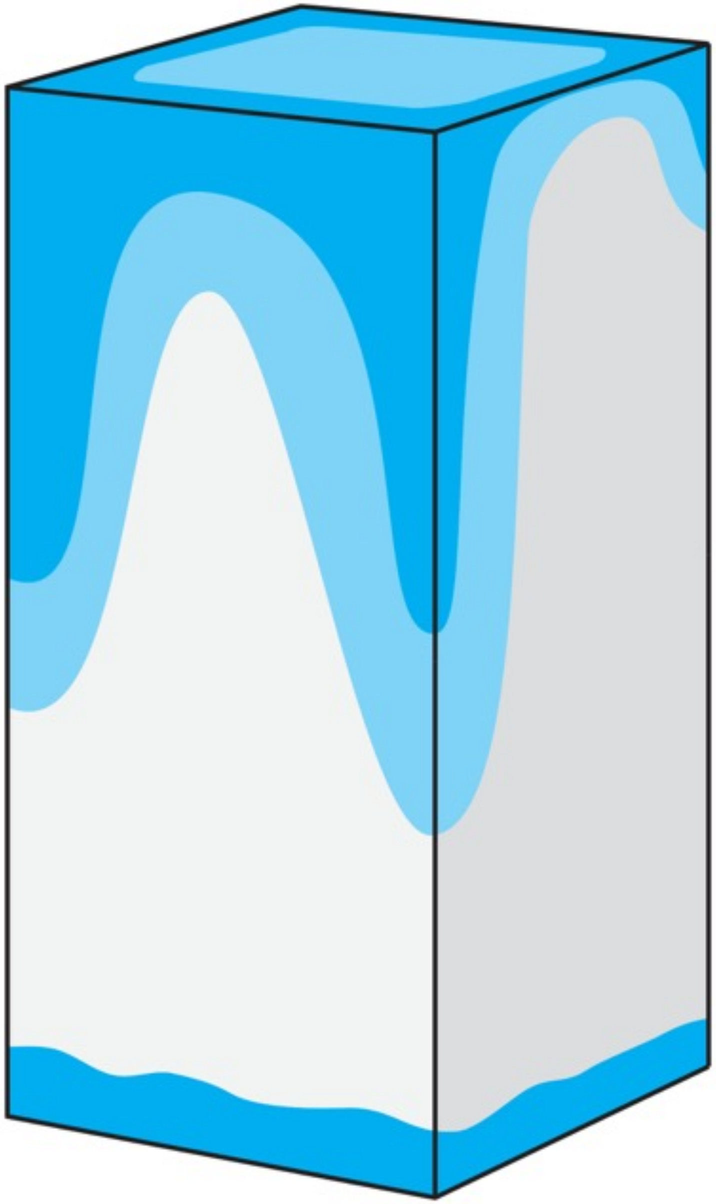
Curvature
("meniscus")
Small
pore
Large
pore

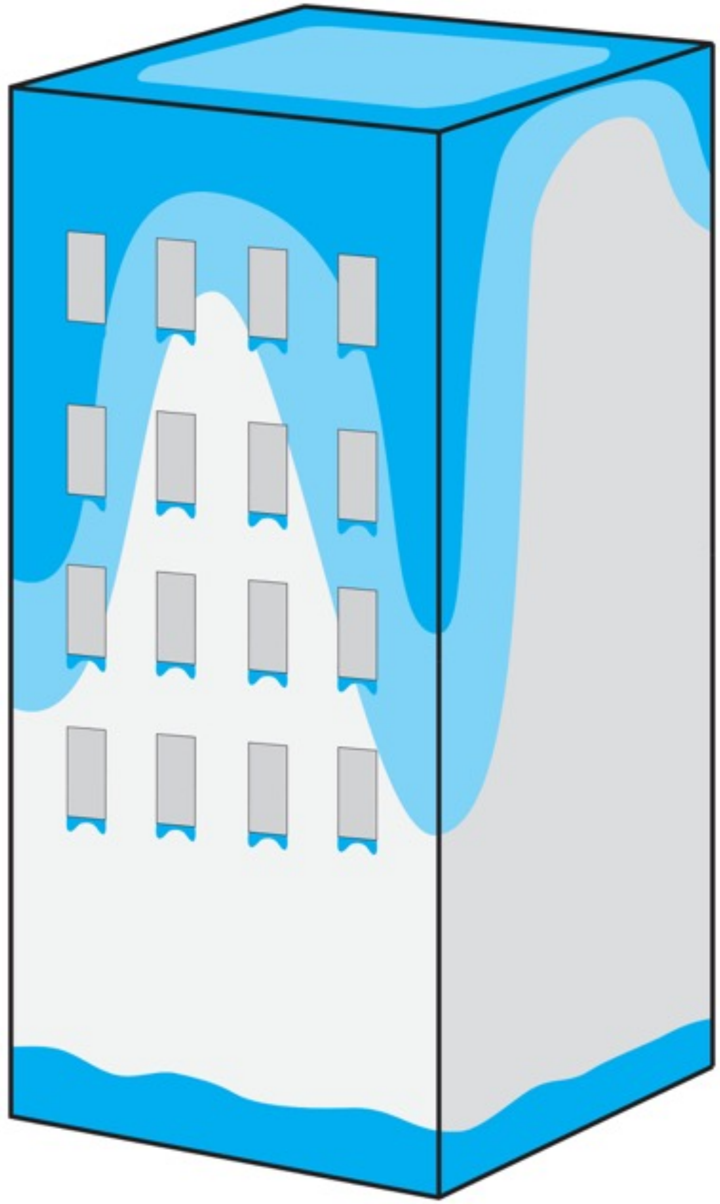
Environmental Loads

Rain Exposure Zone

Hygro-thermal Regions

Interior Climate Class



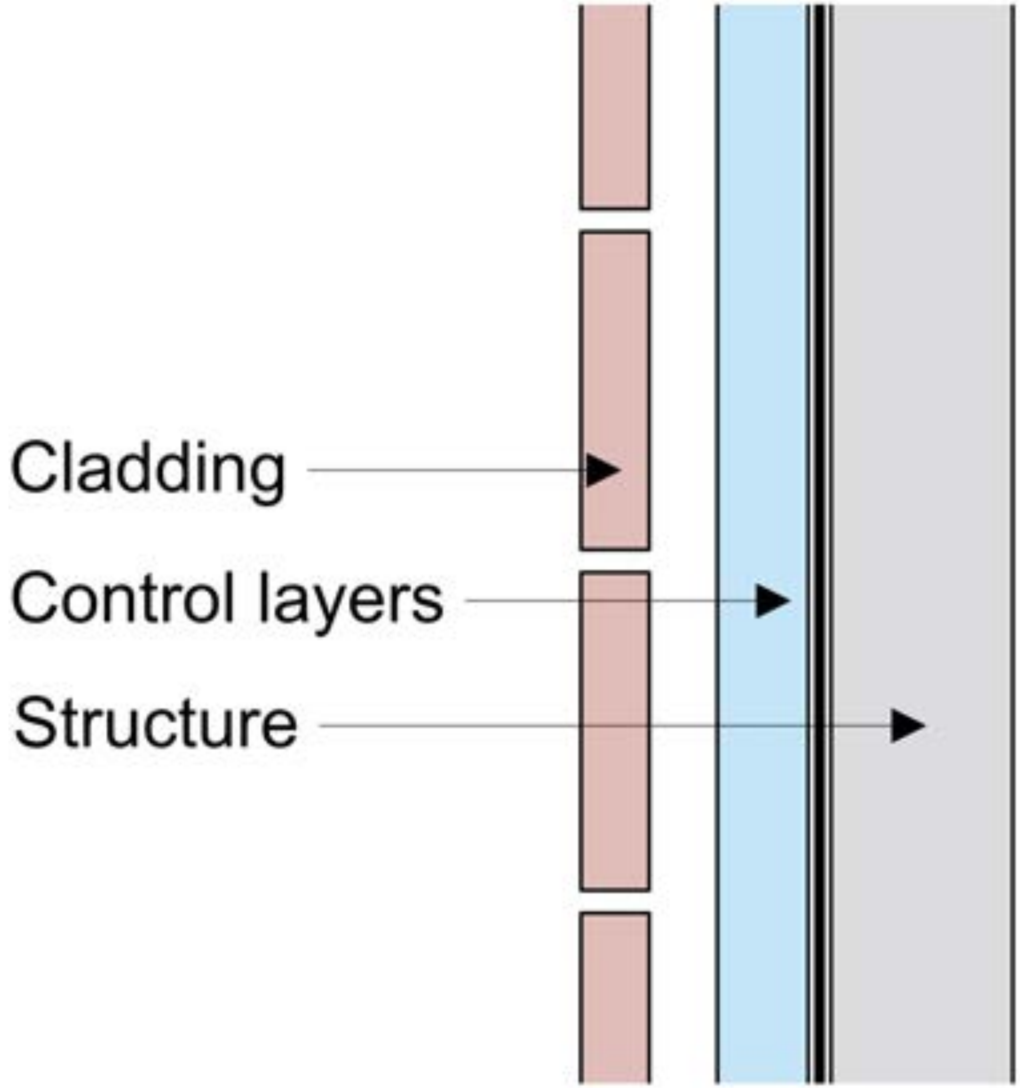


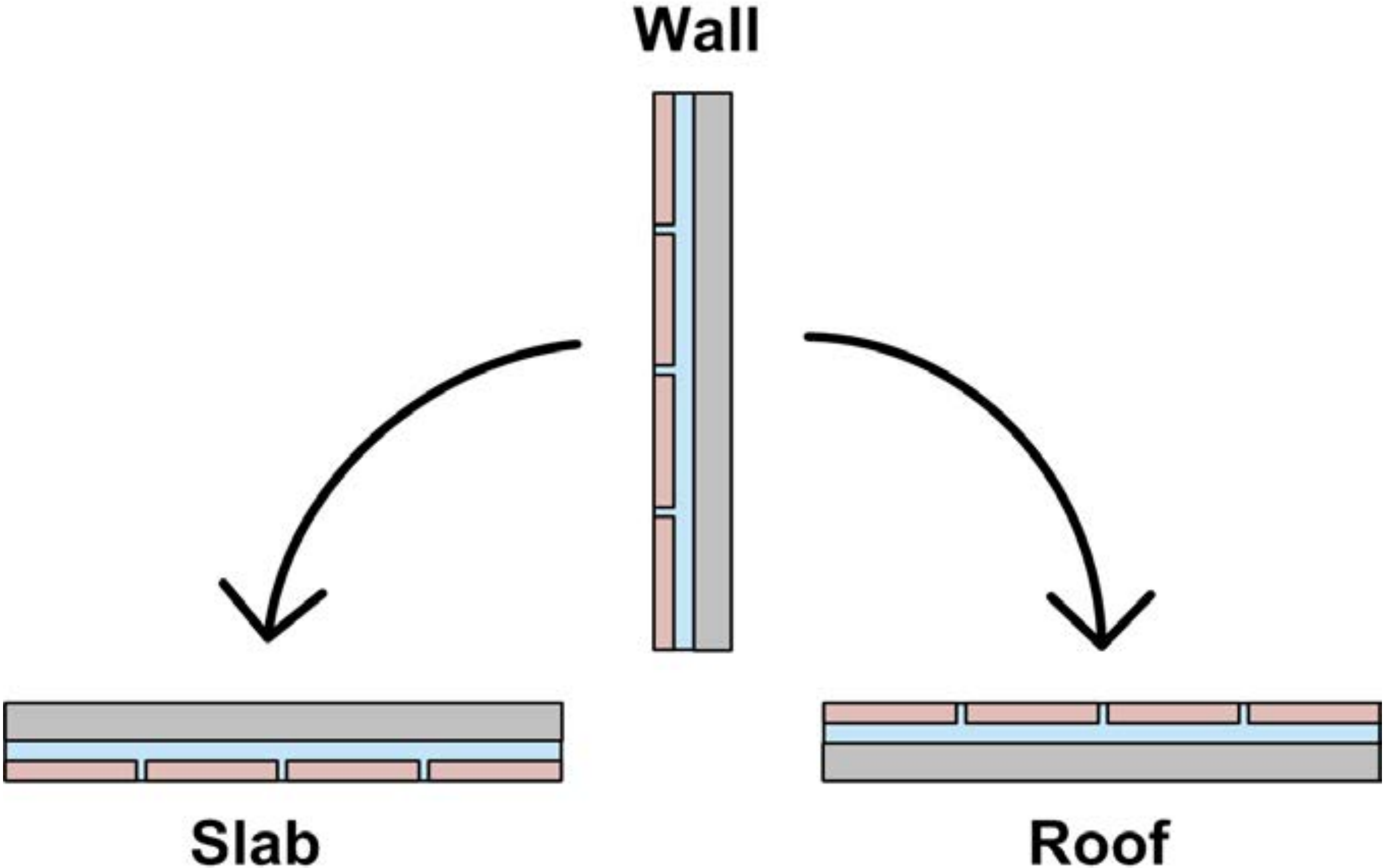
Water Control Layer

Air Control Layer

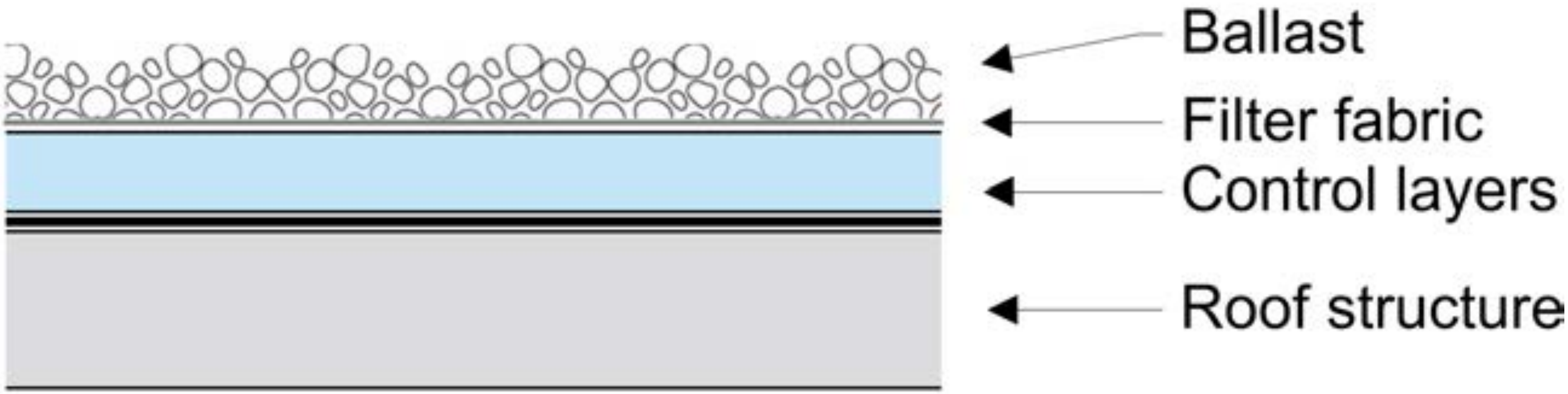
Vapor Control Layer

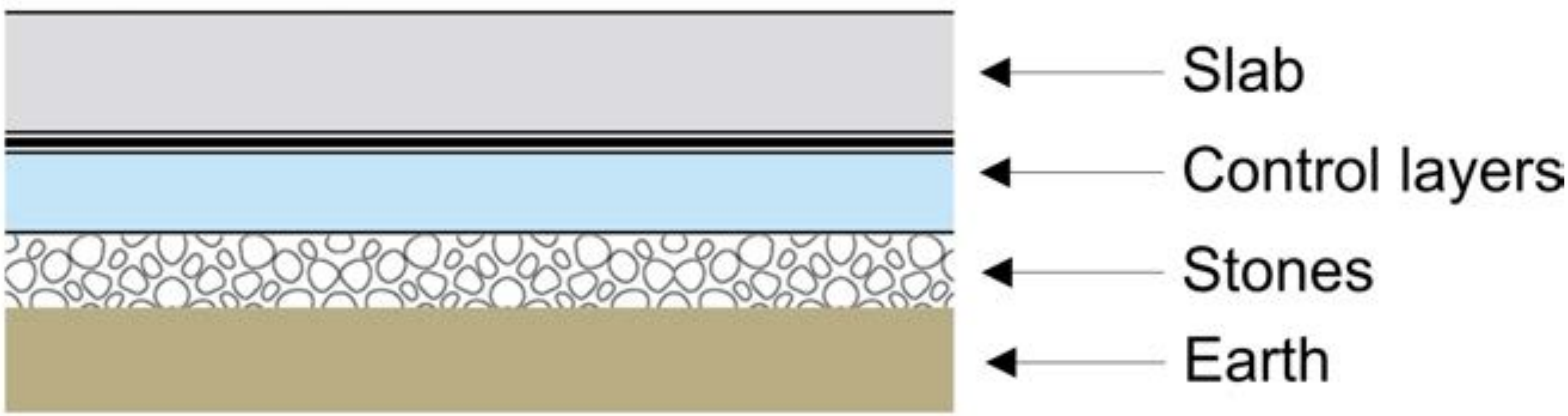
Thermal Control Layer


Cladding
Control layers
Structure

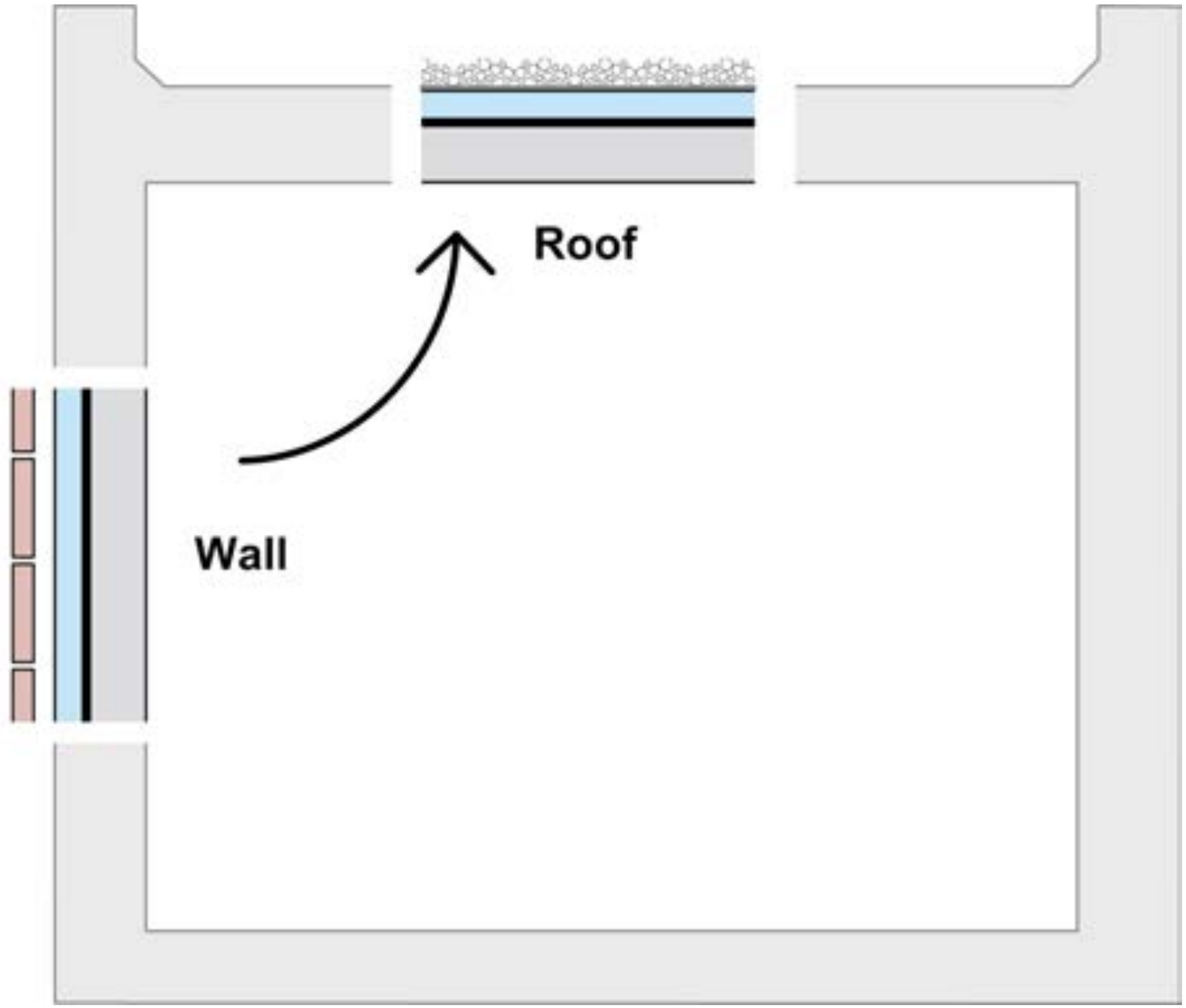


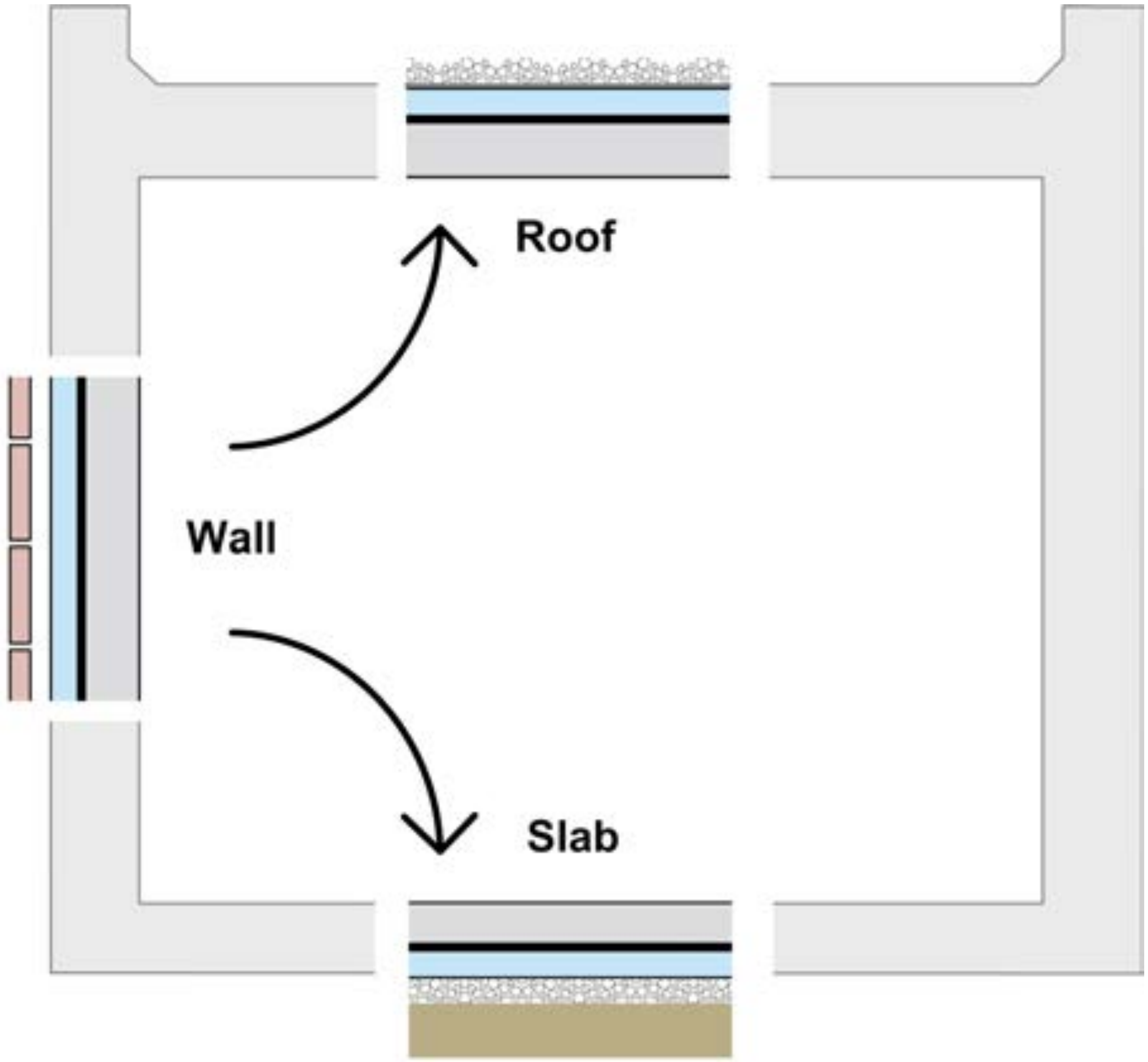
Wall
Slab
Roof

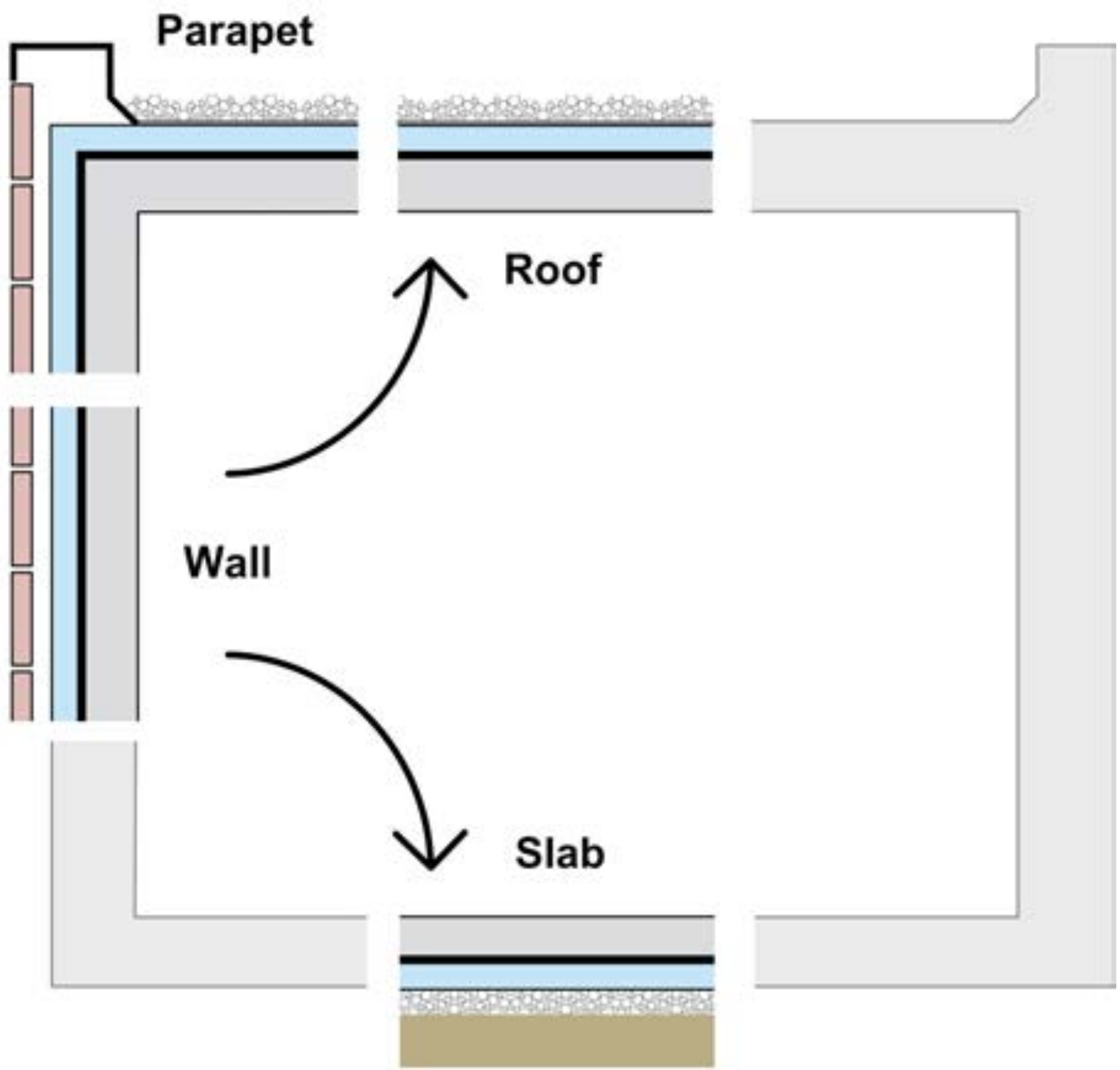

Ballast
Filter fabric
Control layers
Roof structure

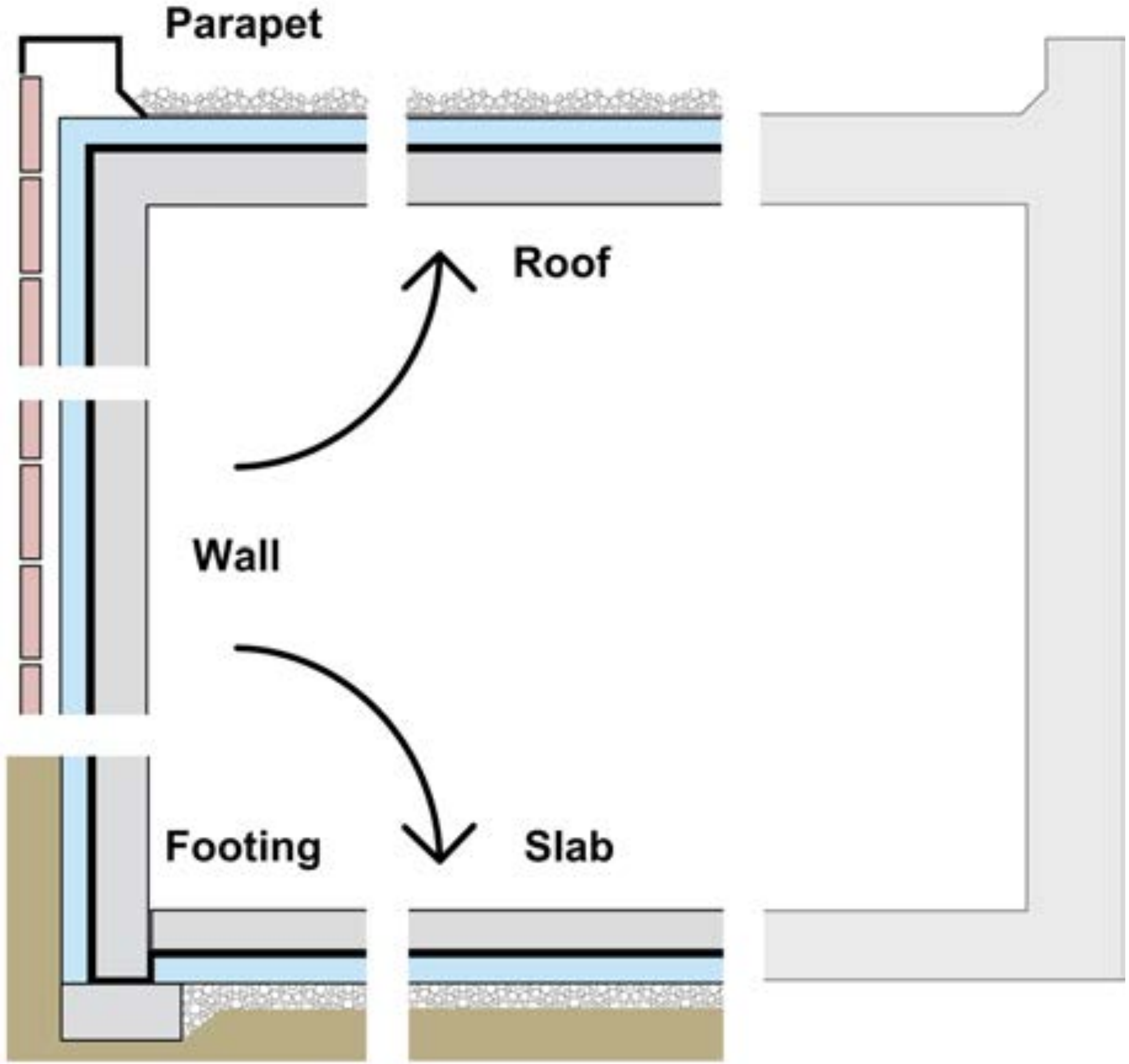

Slab
Control layers
Stones
Earth

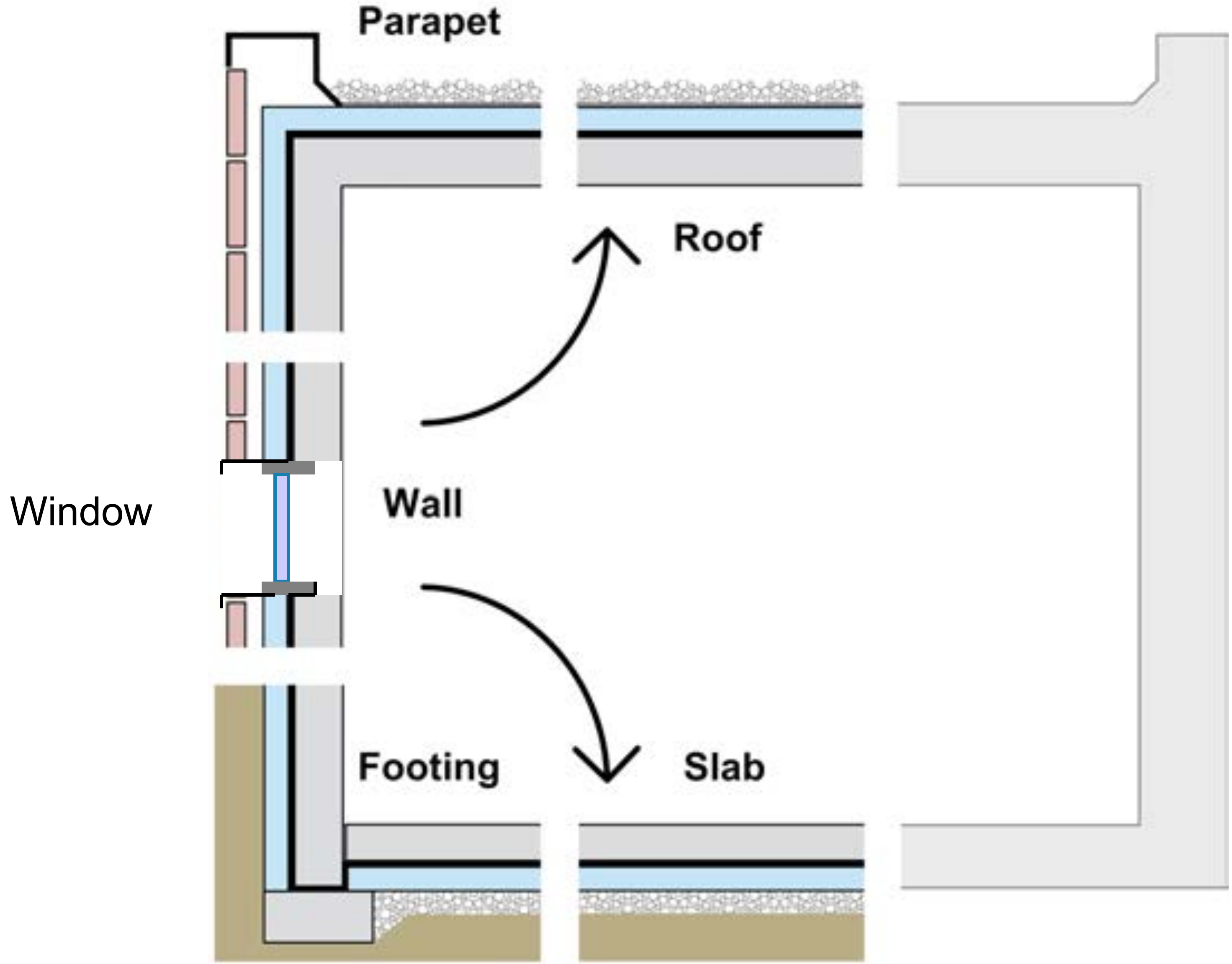

Wall

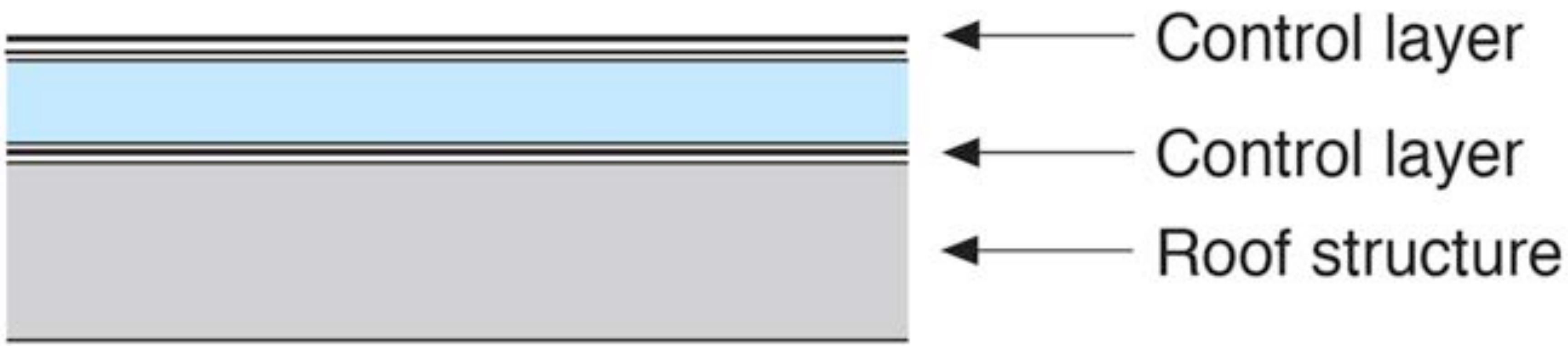

Roof
Wall

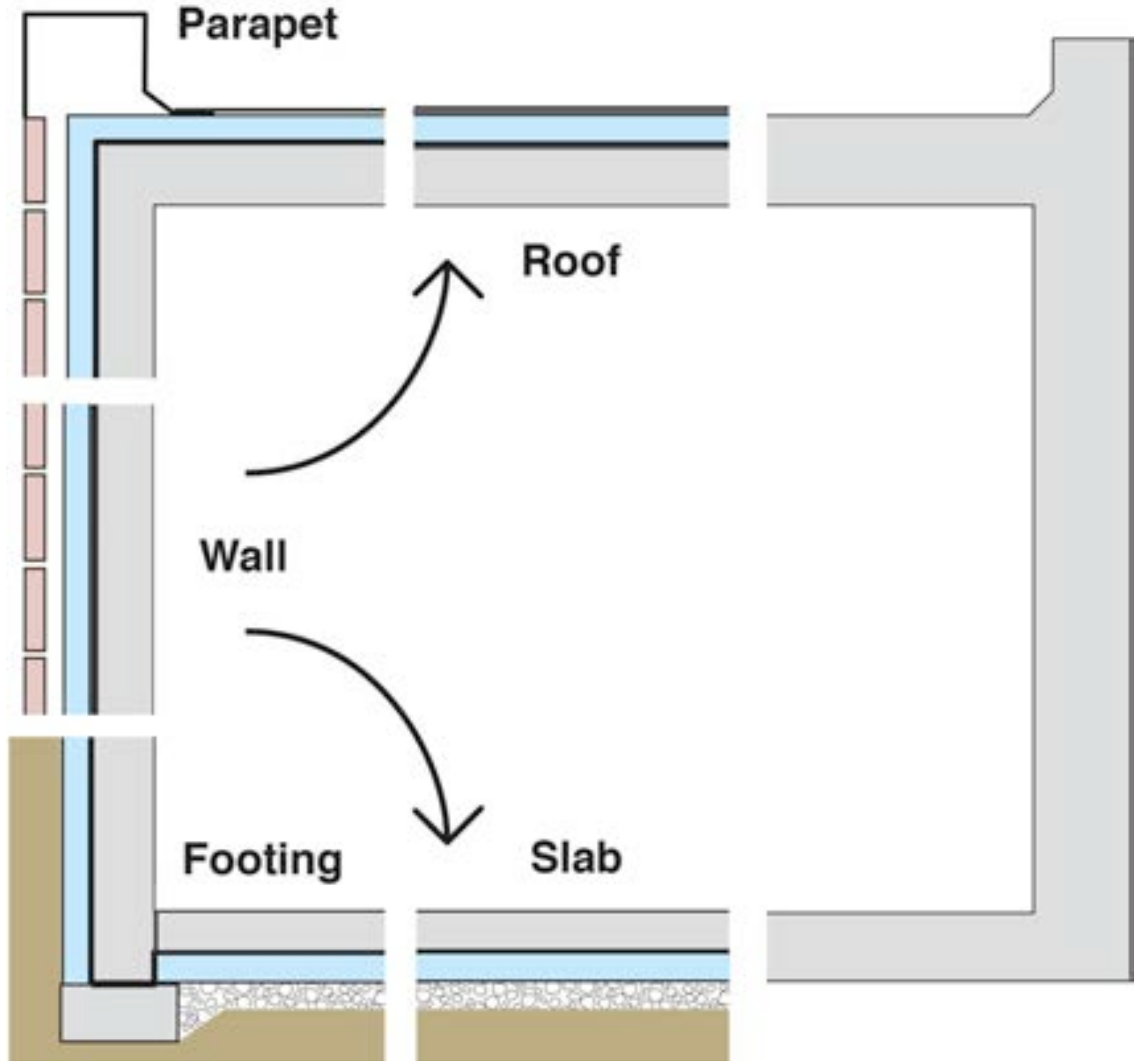

Roof
Wall
Slab

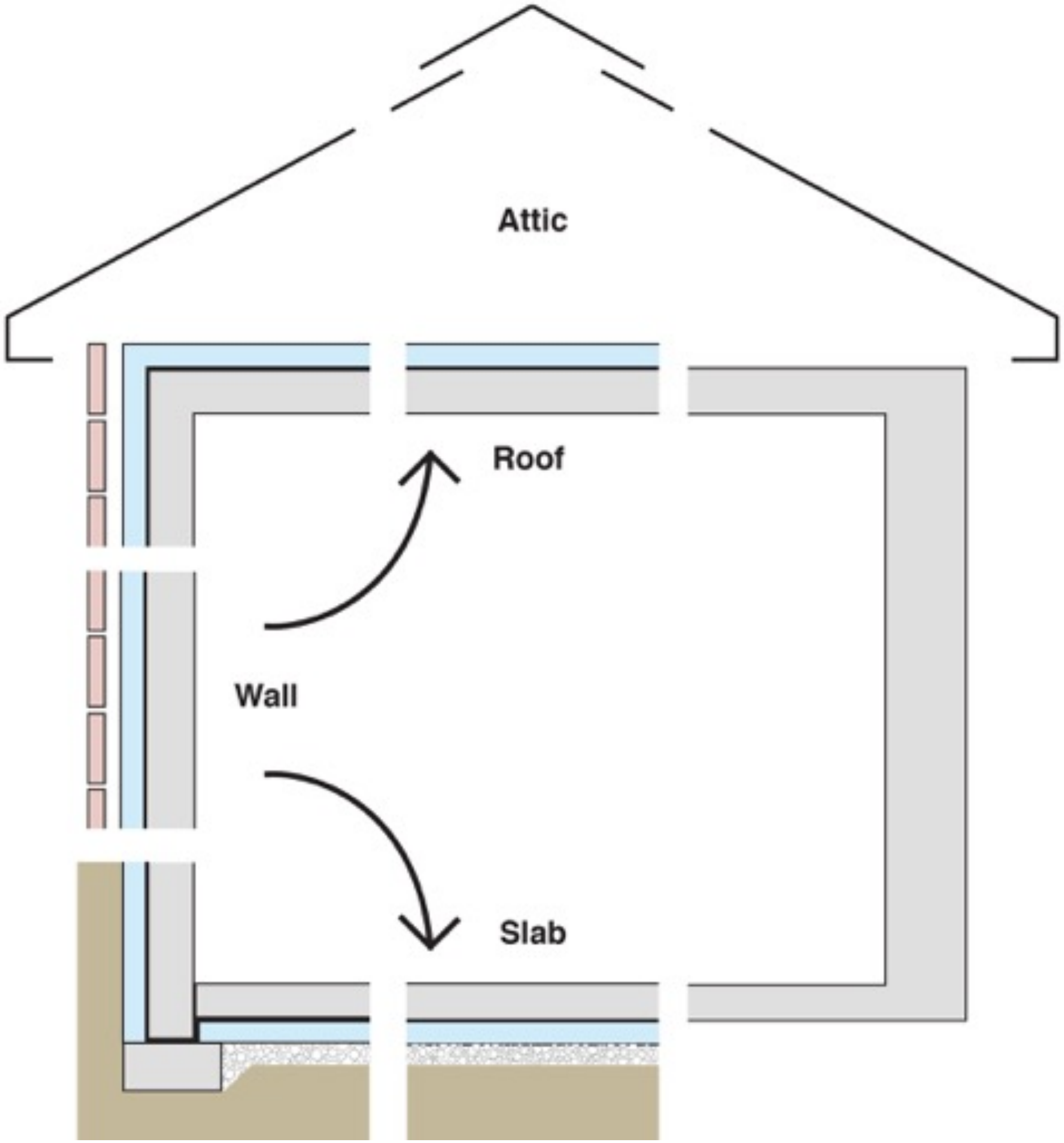

Parapet
Roof
Wall
Slab

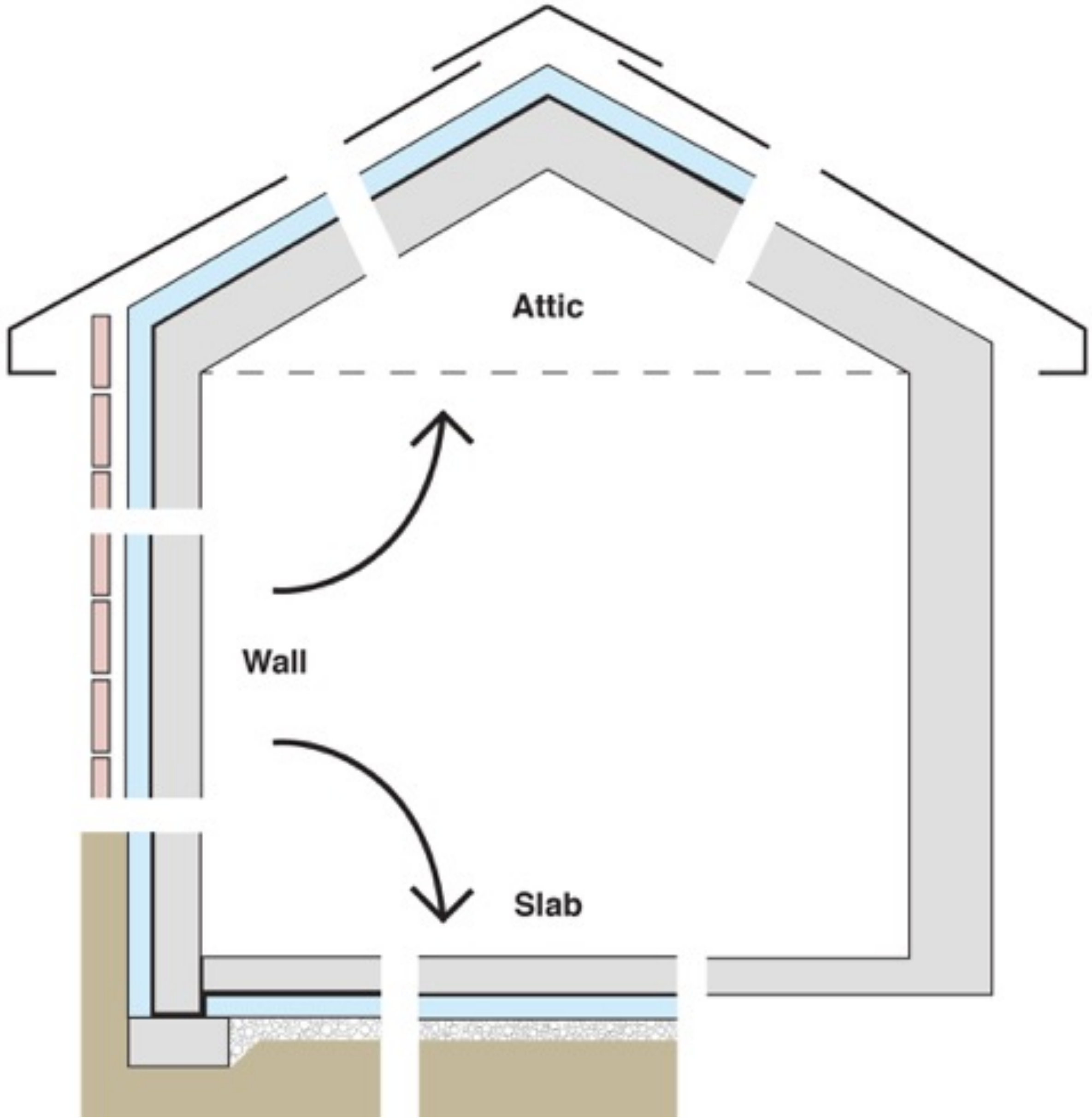

Parapet
Roof
Wall
Footing
Slab

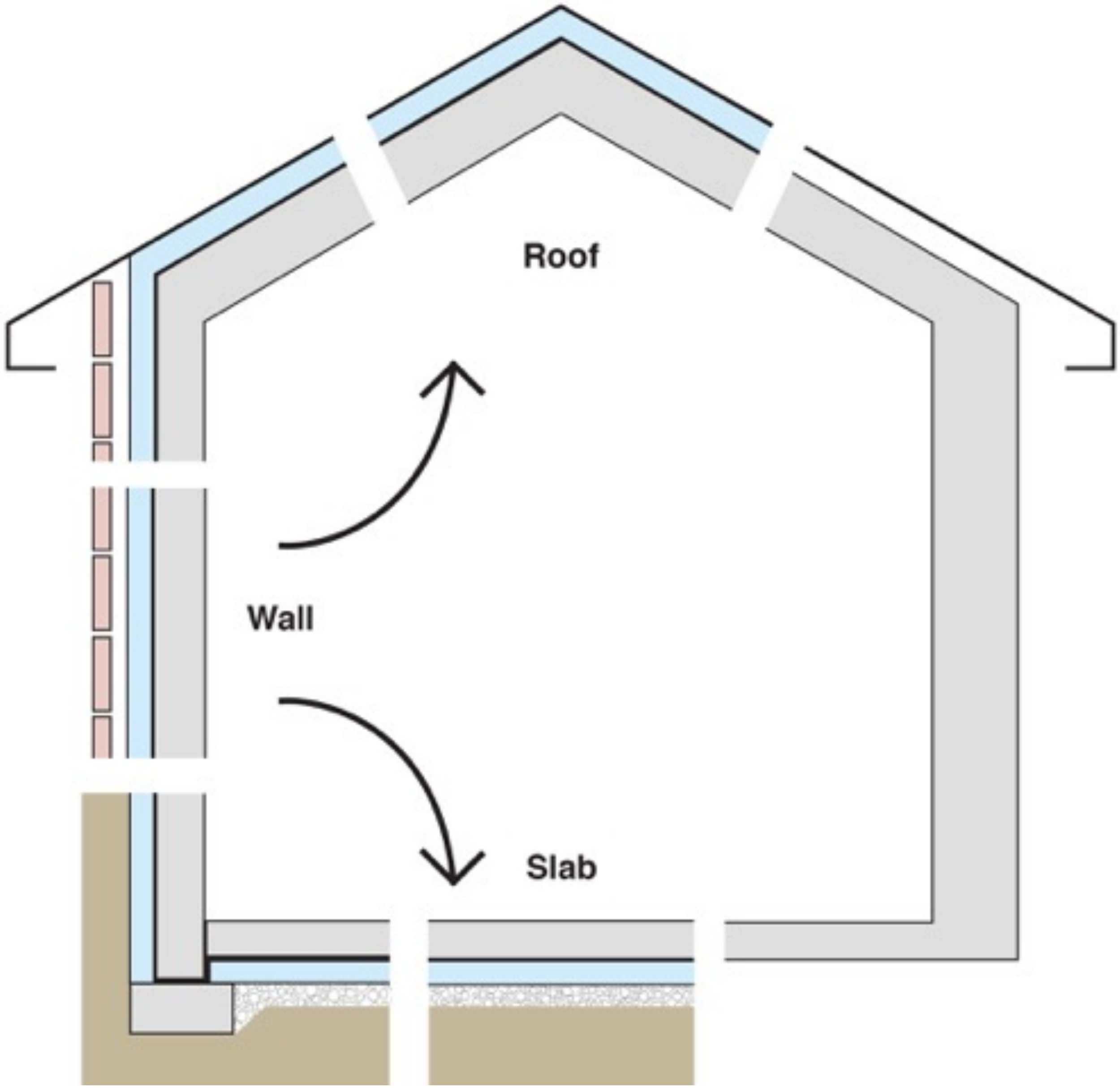

Parapet
Roof
Window
Wall
Footing
Slab

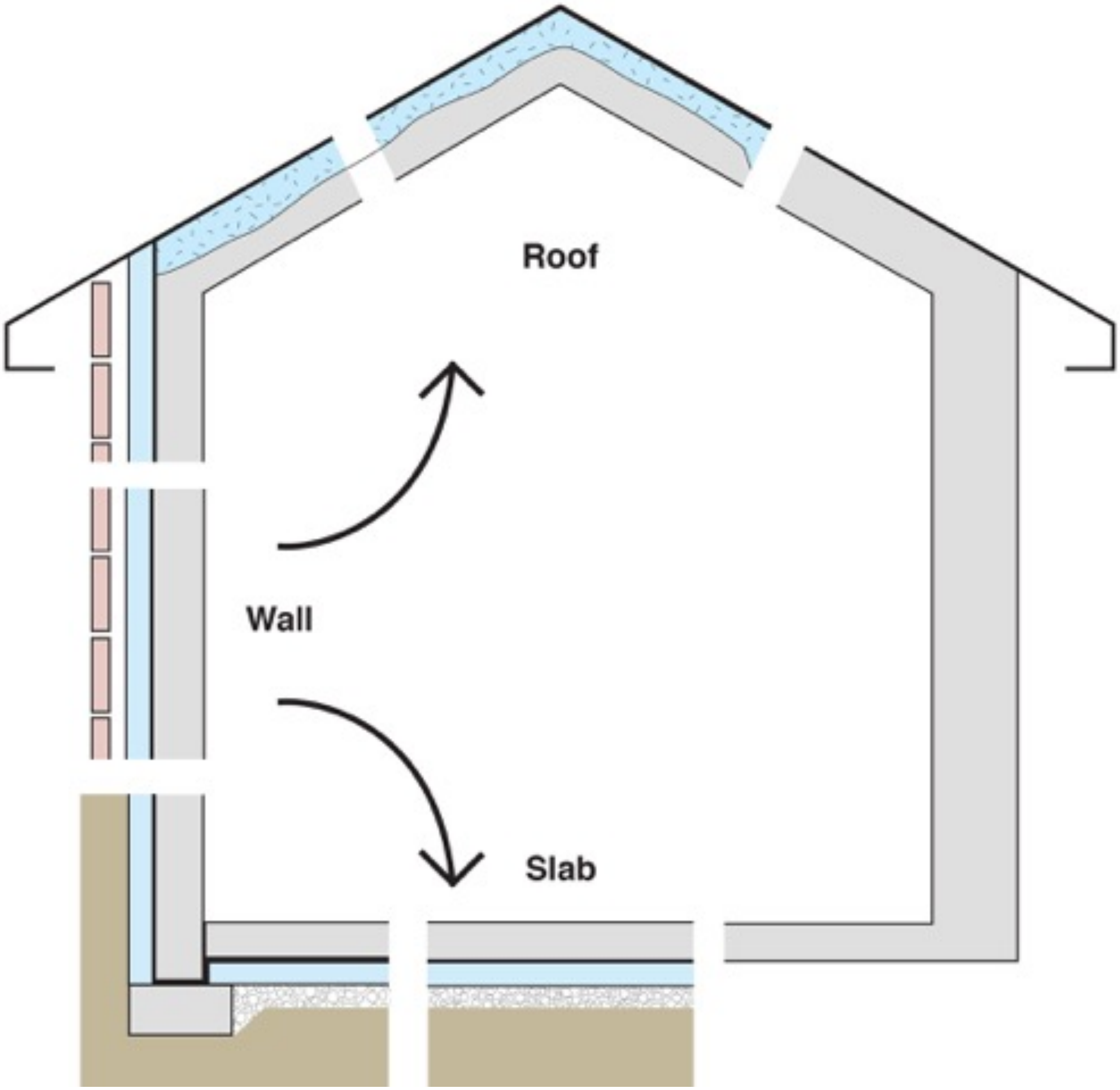

Control layer
Control layer
Roof structure


Parapet
Roof
Wall
Footing
Slab

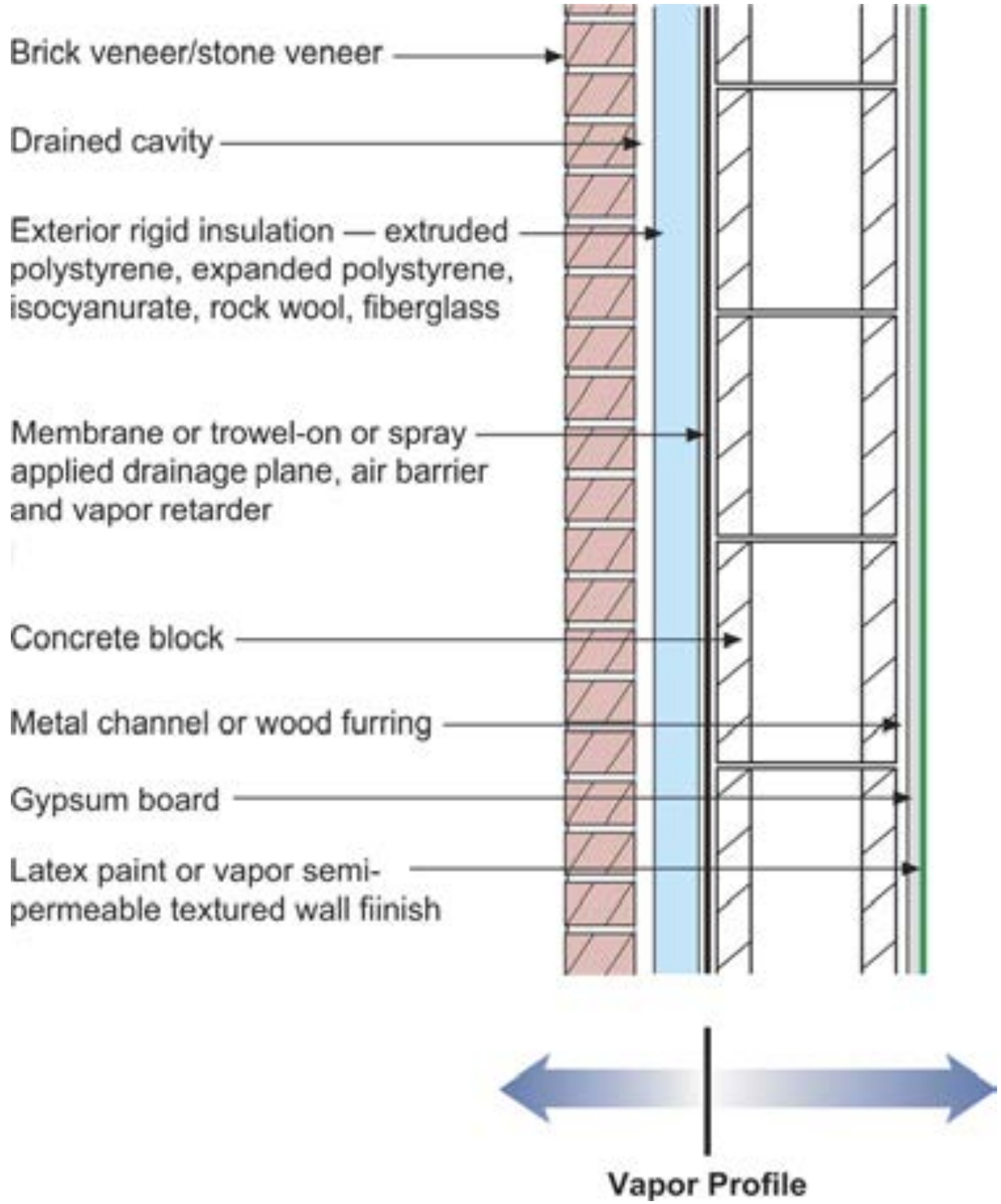

Attic
Roof
Wall
Slab

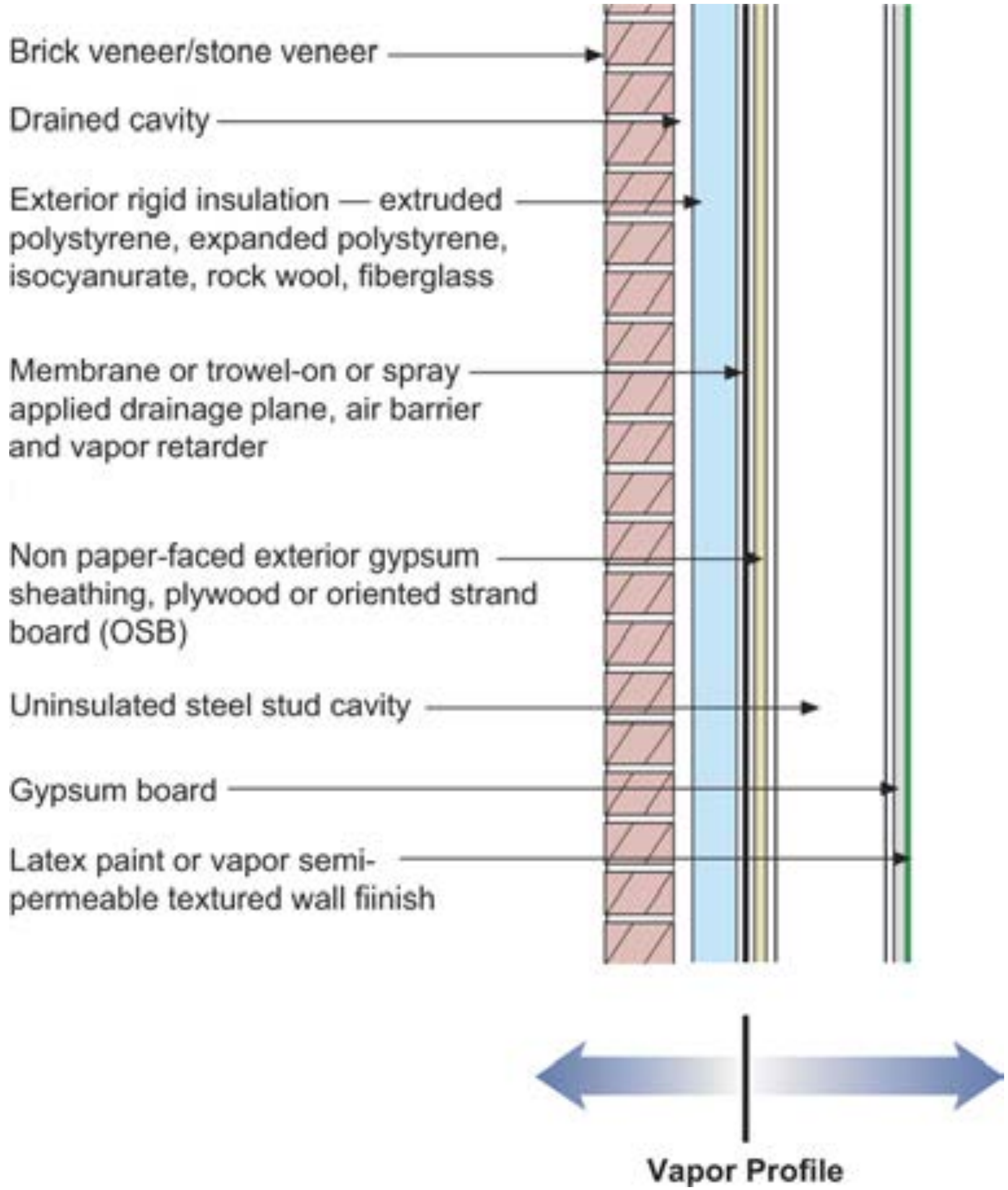

Attic
Wall
Slab

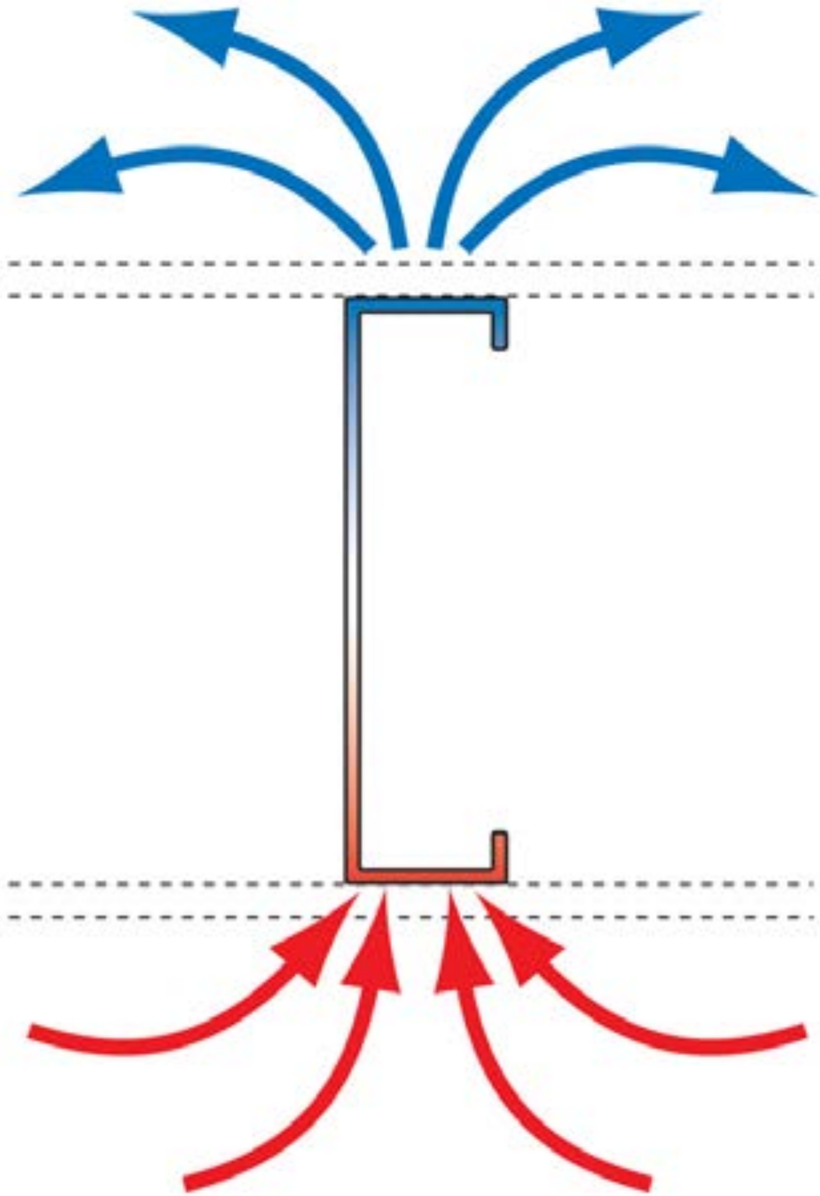

Roof
Wall
Slab

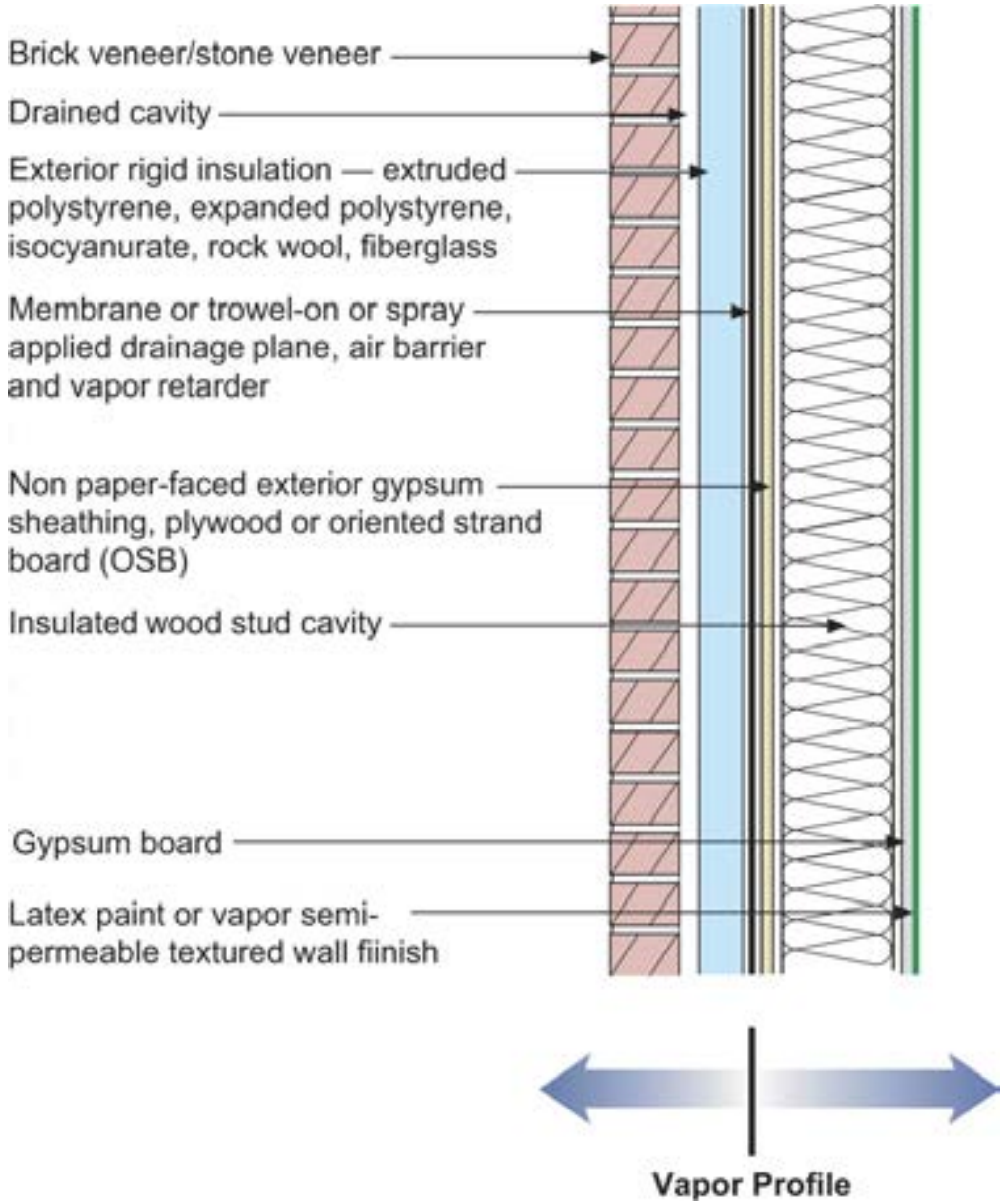

Roof
Wall
Slab

Configurations of the Perfect Wall

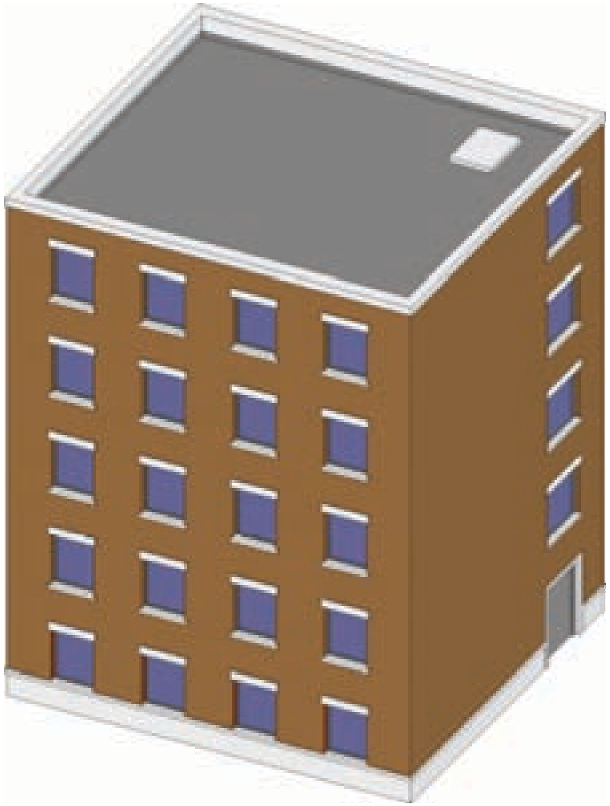

Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Concrete block
Metal channel or wood furring
Gypsum board
Latex paint or vapor semi-permeable textured wall fiinish
Vapor Profile


Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Non paper-faced exterior gypsum sheathing, plywood or oriented strand board (OSB)
Uninsulated steel stud cavity
Gypsum board
Latex paint or vapor semi-permeable textured wall fiinish
Vapor Profile

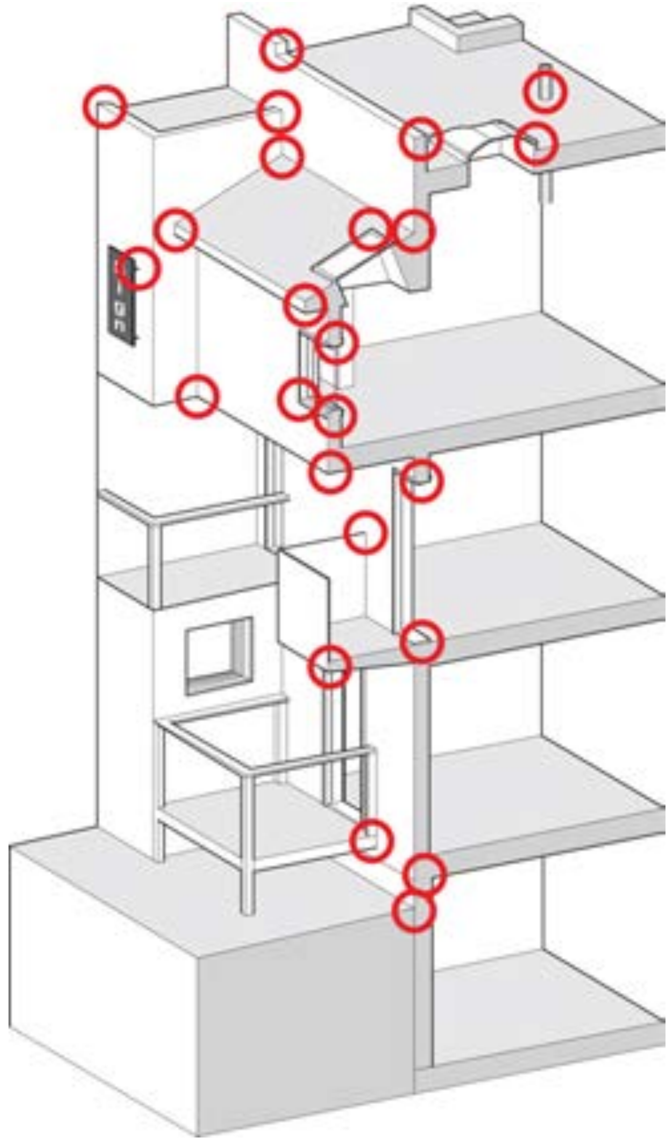



Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Non paper-faced exterior gypsum sheathing, plywood or oriented strand board (OSB)
Insulated wood stud cavity
Gypsum board
Latex paint or vapor semi-permeable textured wall fiinish
Vapor Profile

Commercial Enclosure: Simple Layers



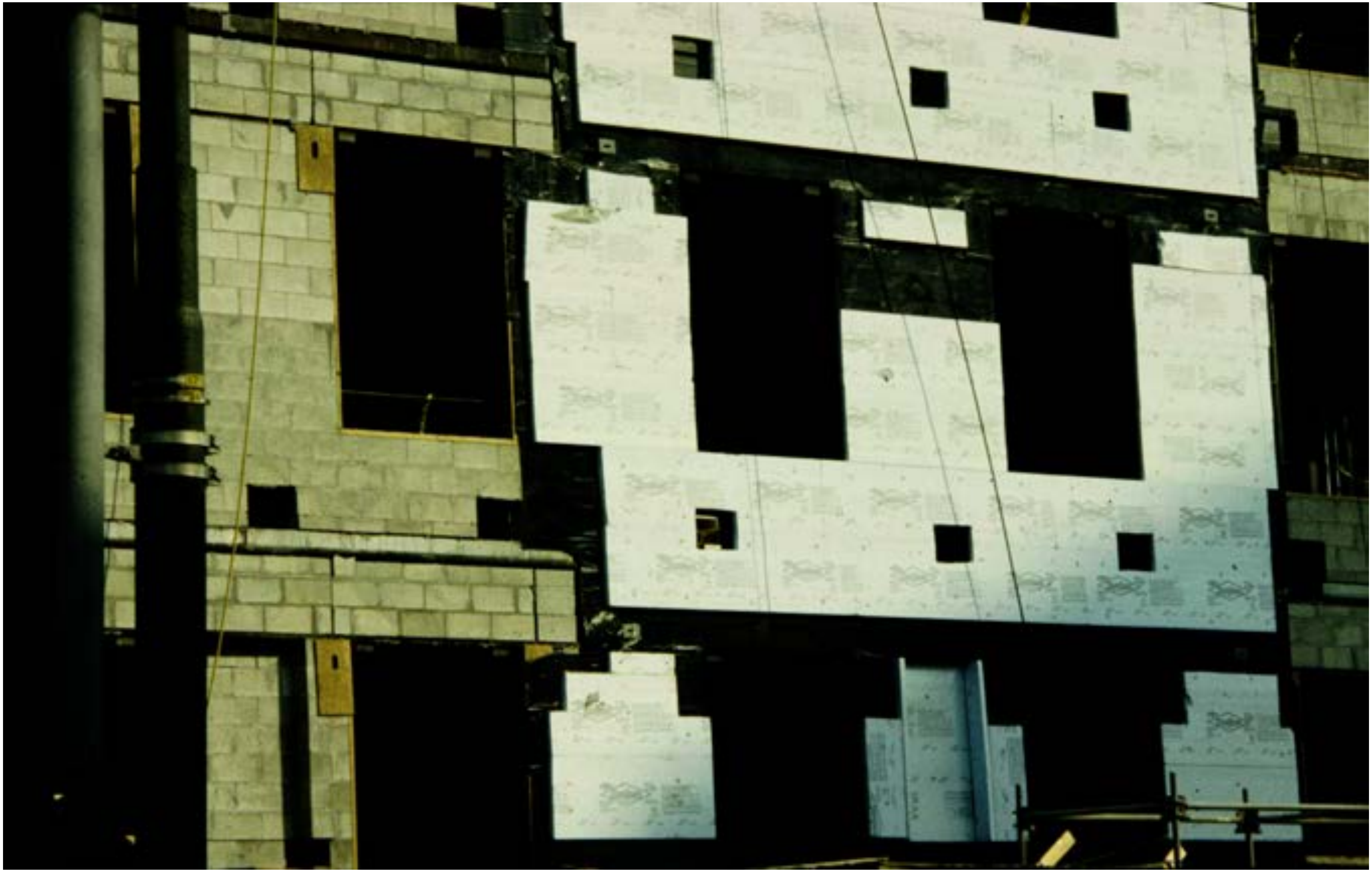
- Structure
- Rain/Air/Vapor
- Insulation
- Finish




GP
DensGlass
Sheathing
Polyguard


MEL-ROL


Straight Flash



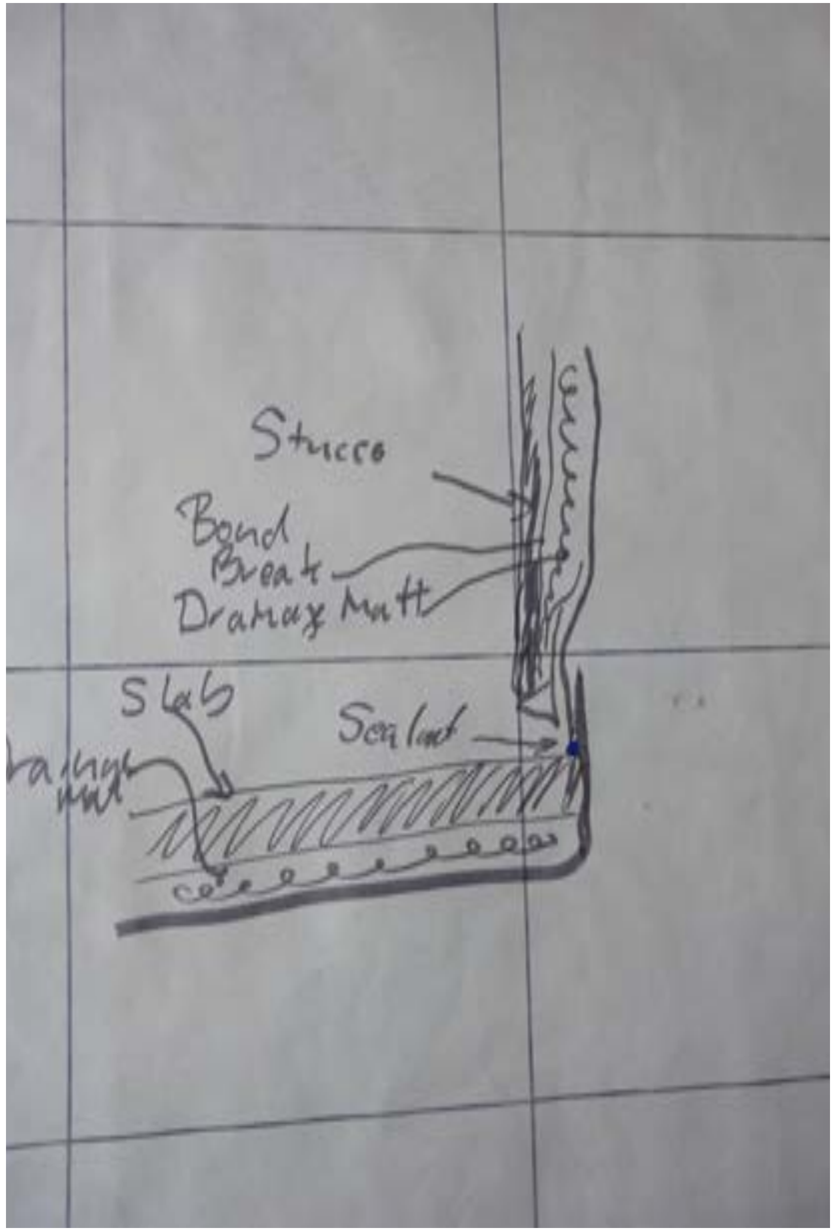

HARVARD SCHOOL OF PUBLIC HEALTH


DENSGLASS GOLD
Exterior Sheathing
ASS GOLD
DENSGLASS GOLD
Exterior Sheathing


Blueskin


MARKET
BASKET


Call 1-800
DUP
NT
yvek


Stucco
Bond Break
Drainage Matt
Slab
Sealant


Call 1-800-44-TYVEK WWW.CONSTRUCTION.TYVEK.COM
DUPONT The miracles of science

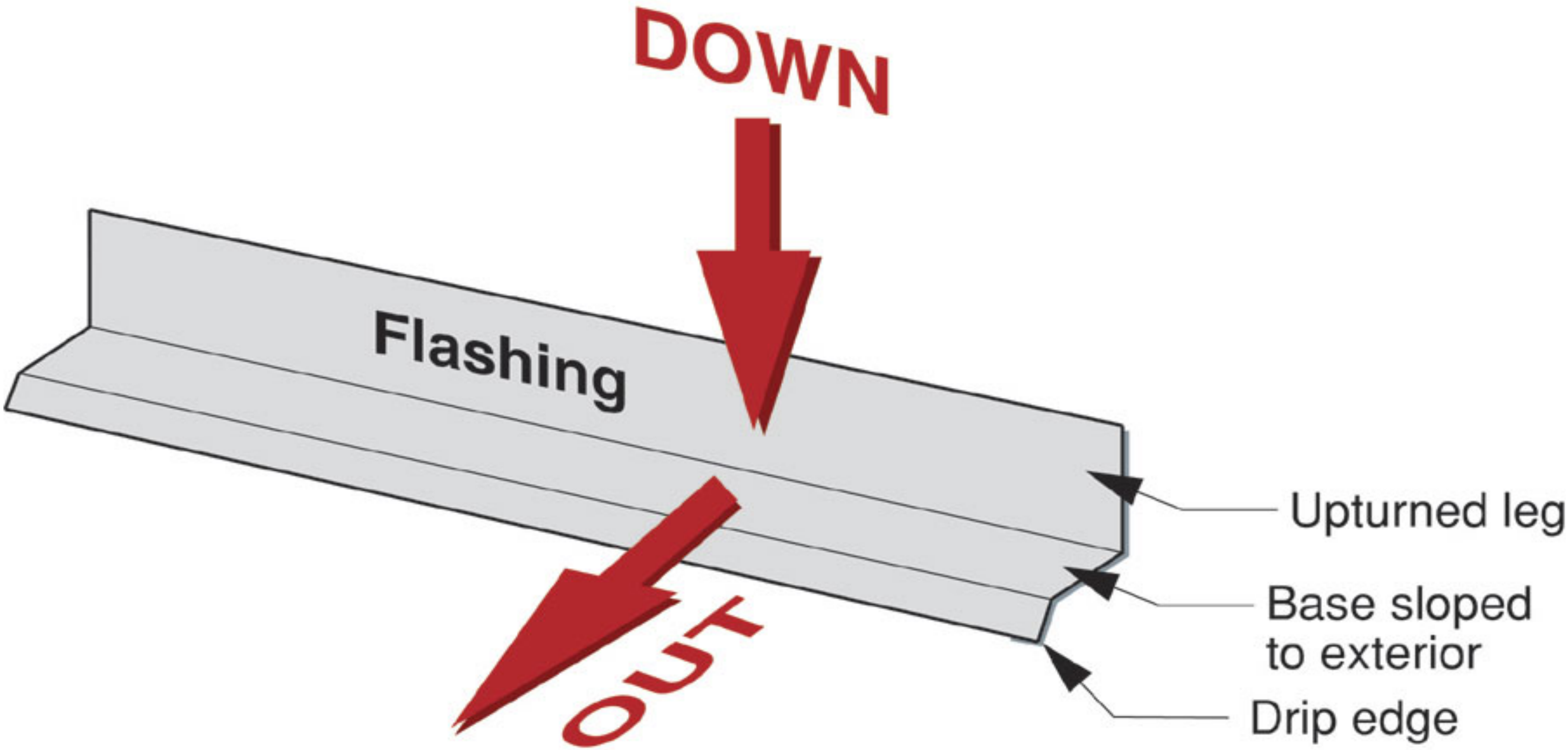

Tyvek
COMMERCIALWRAP
polyguard

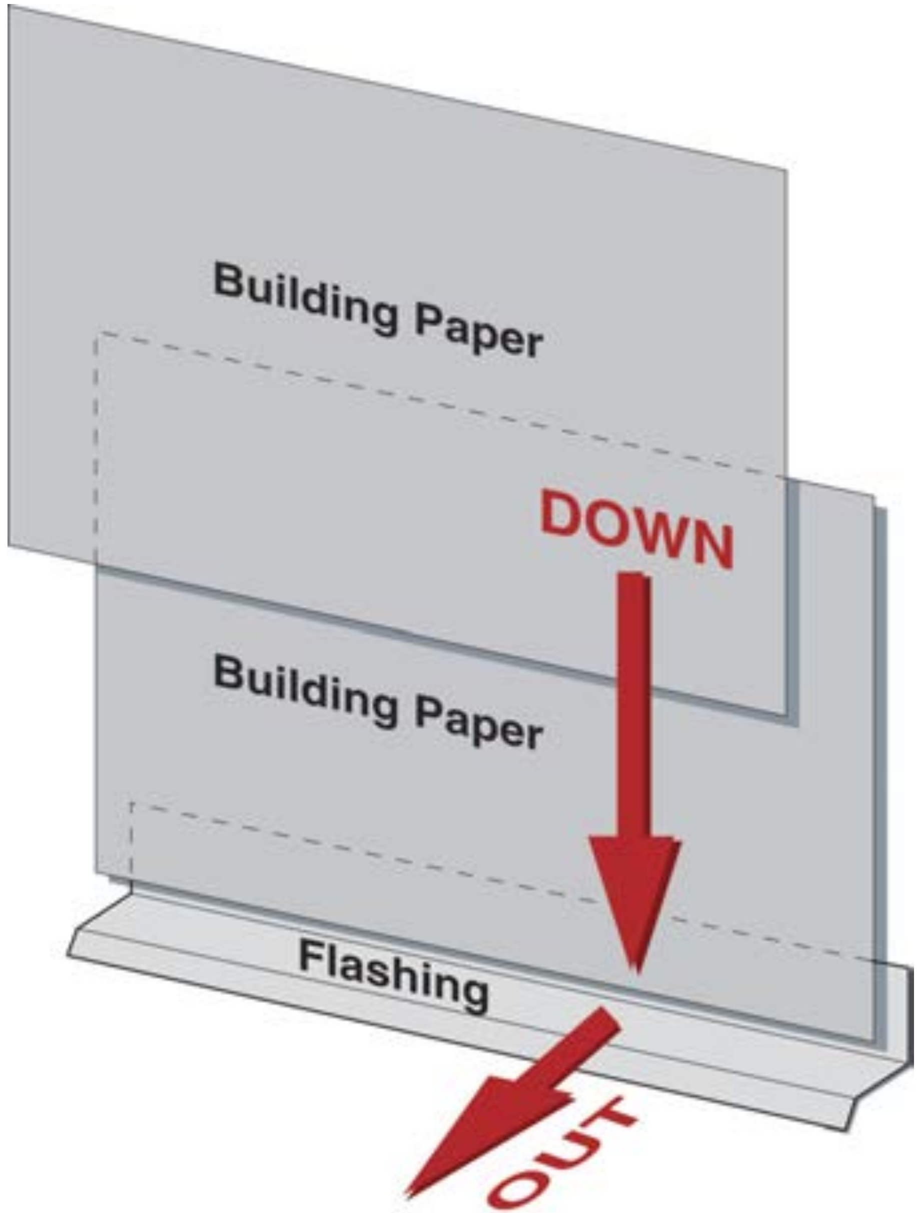

National Gypsum
National Gypsum


ZIPsystem


DANGER
CONSTRUCTION
AREA
KEEP OUT
LUCIANO

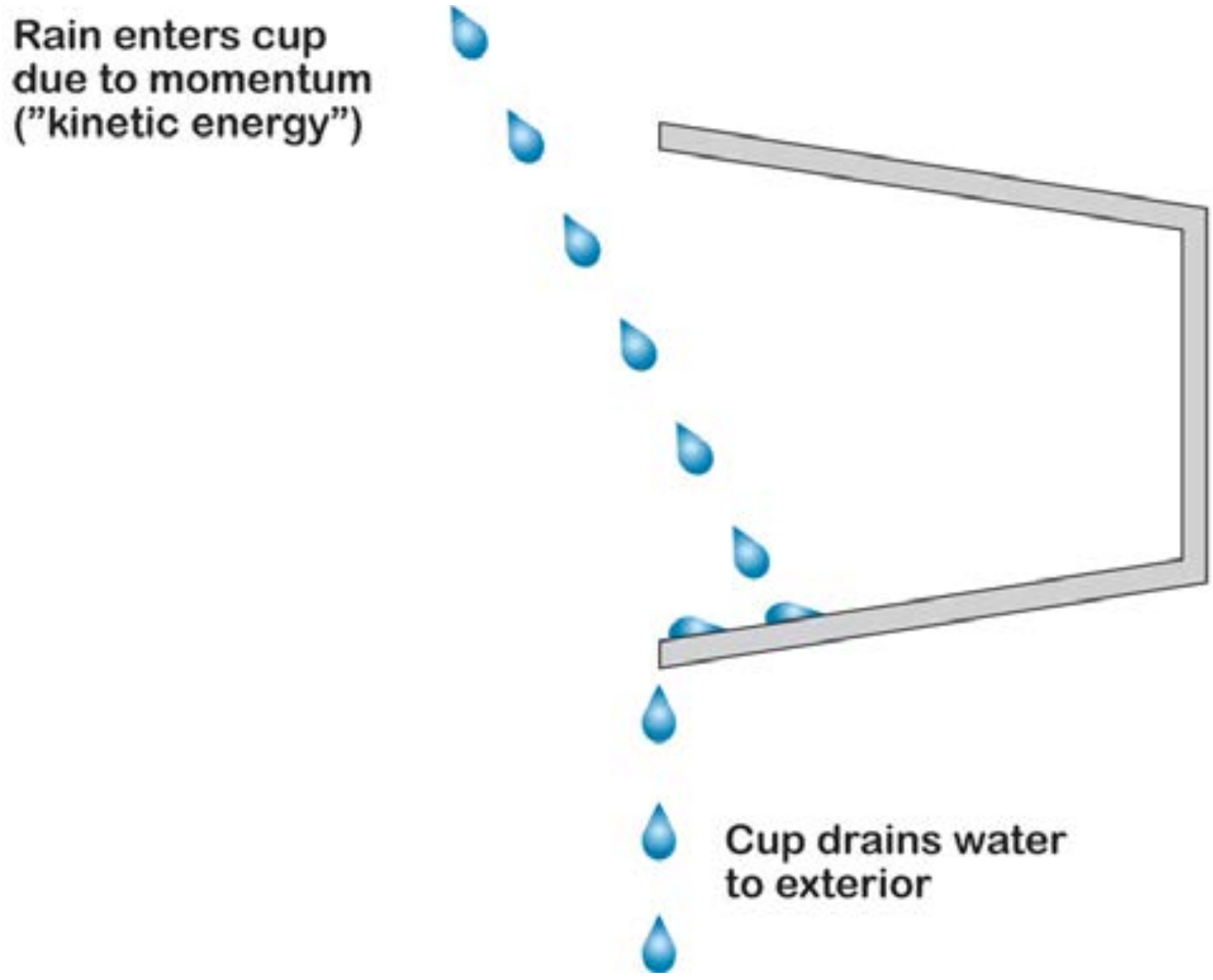
Water Management

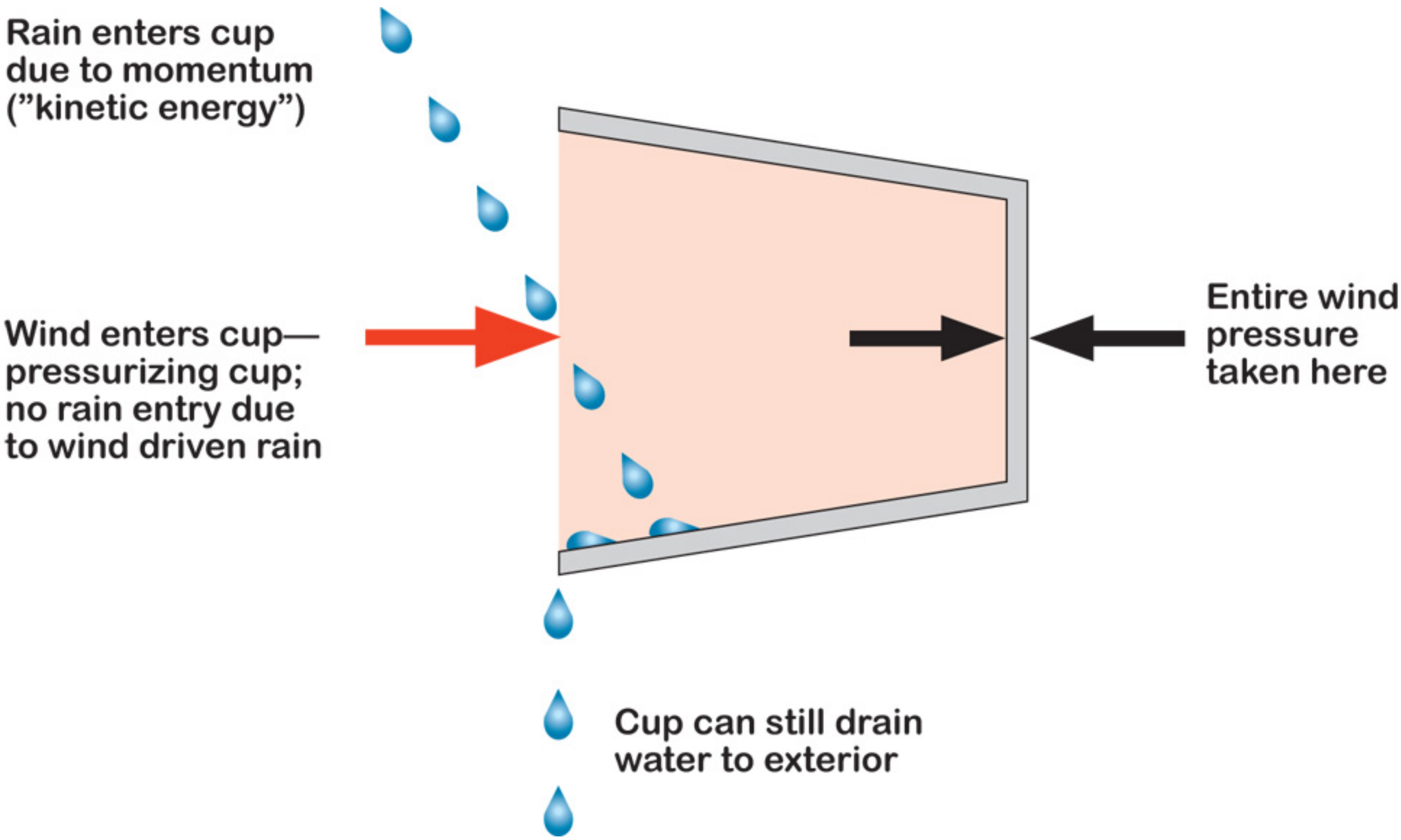

DOWN
Flashing
OUT
Upturned leg
Base sloped
to exterior
Drip edge


Building Paper
DOWN
Building Paper
Flashing
OUT

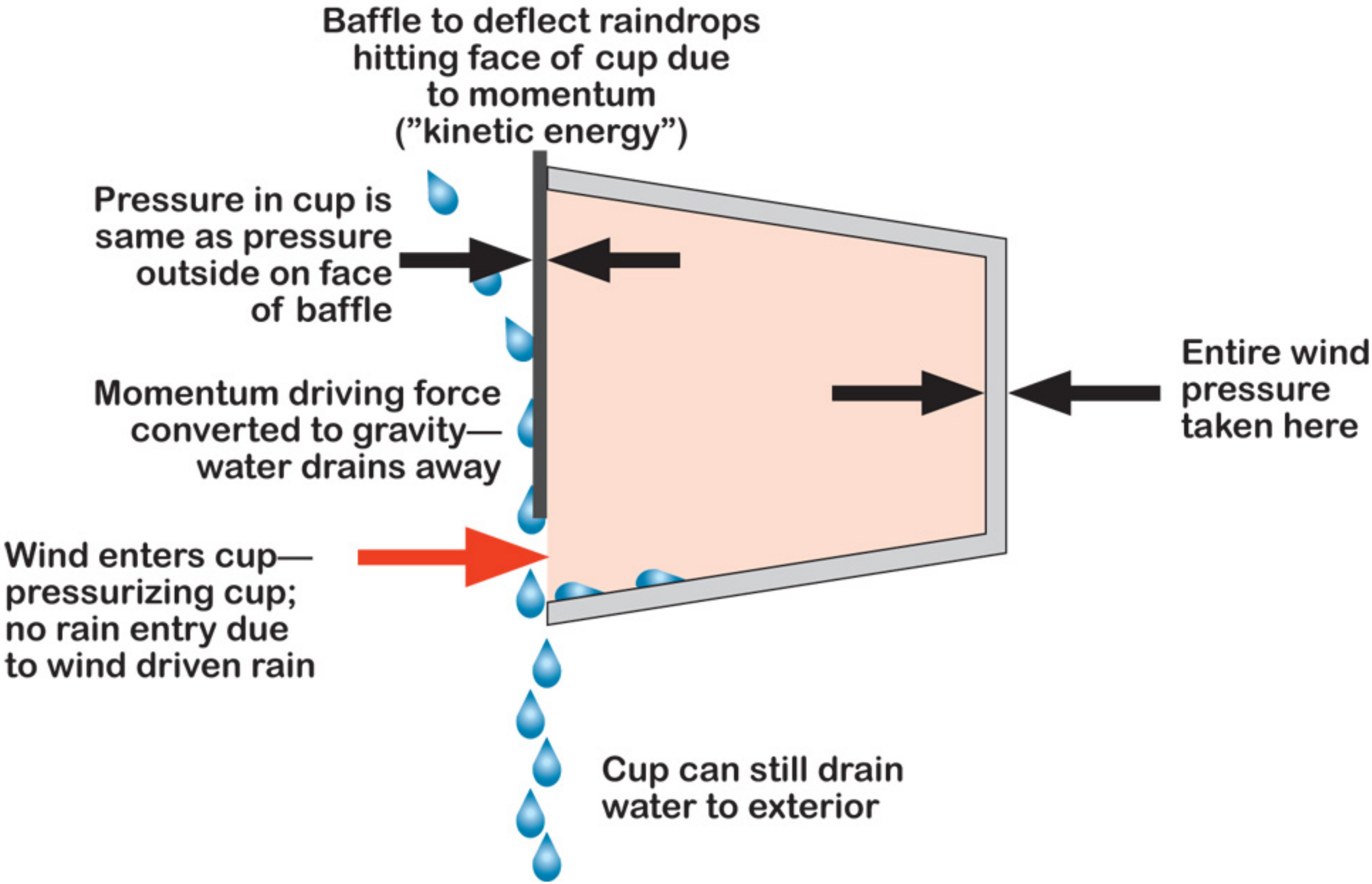

sGlass™
eathing
DensG
Sheathi
THIS SIDE OUT

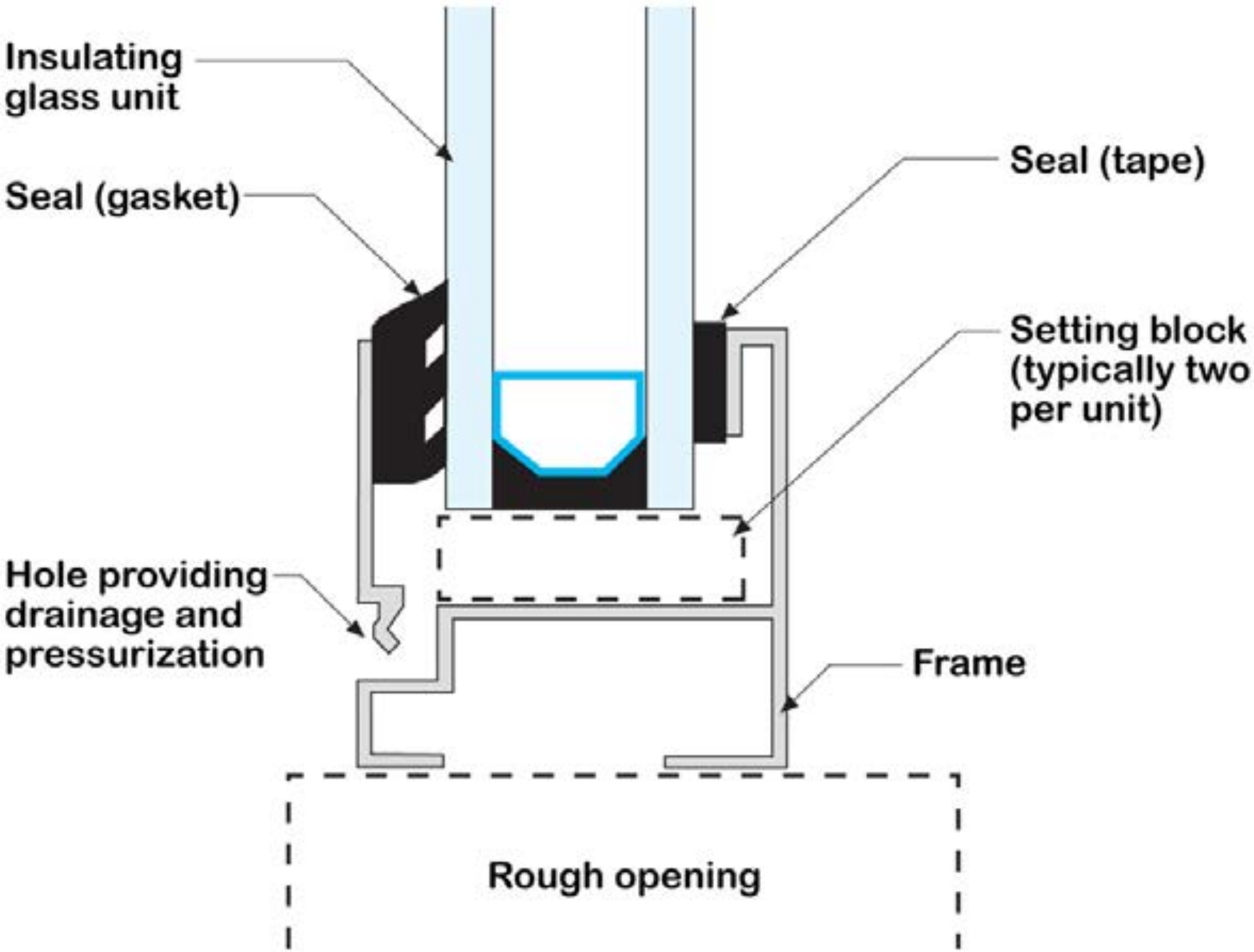

rmax ci
Isolant extérie
Thermax ci
Aislamiento Ext
THERMAX ci

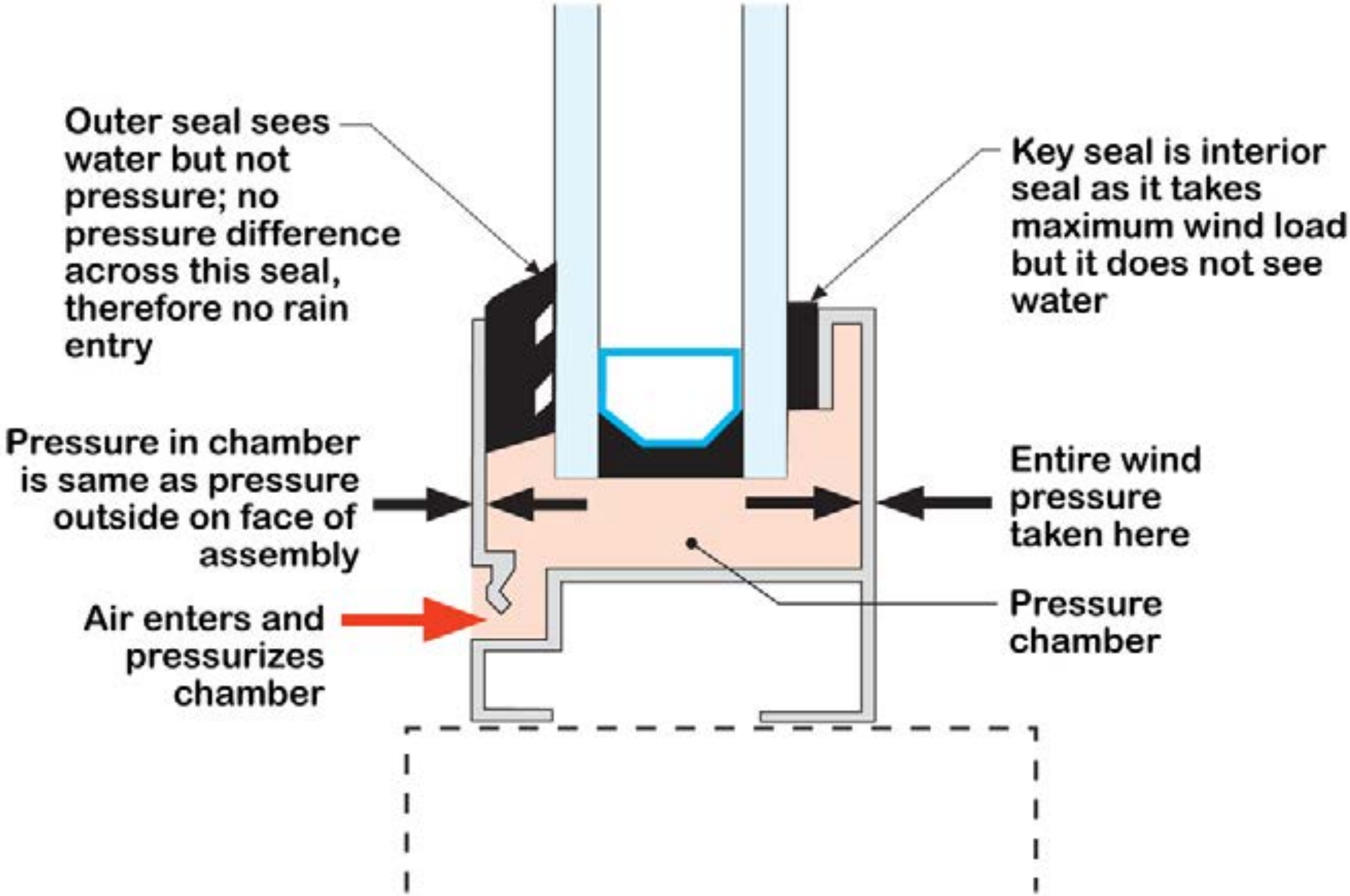

Rain enters cup
due to momentum
("kinetic energy")
Cup drains water
to exterior

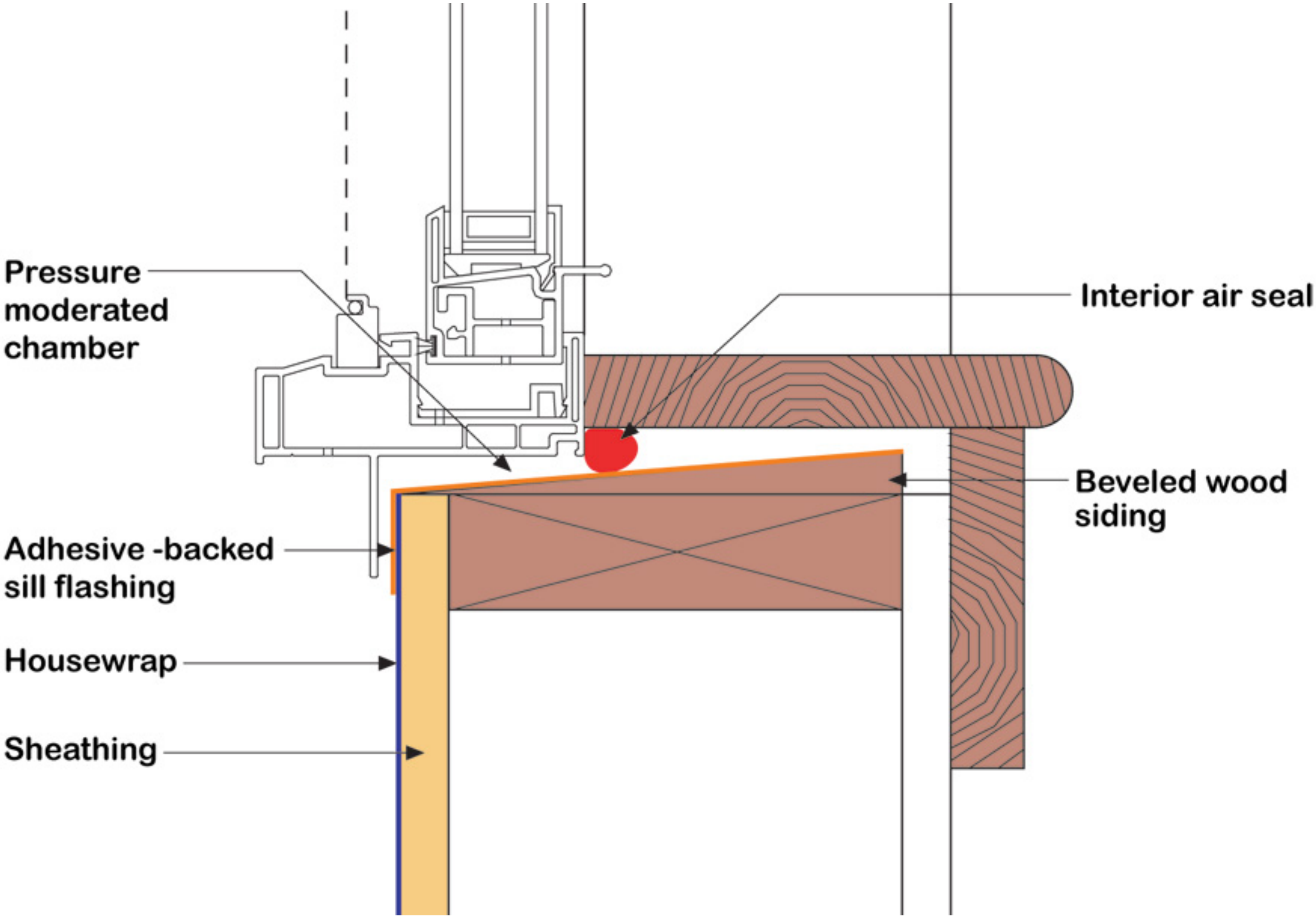


Rain enters cup due to momentum ("kinetic energy")
Wind enters cup—pressurizing cup; no rain entry due to wind driven rain
Entire wind pressure taken here
Cup can still drain water to exterior

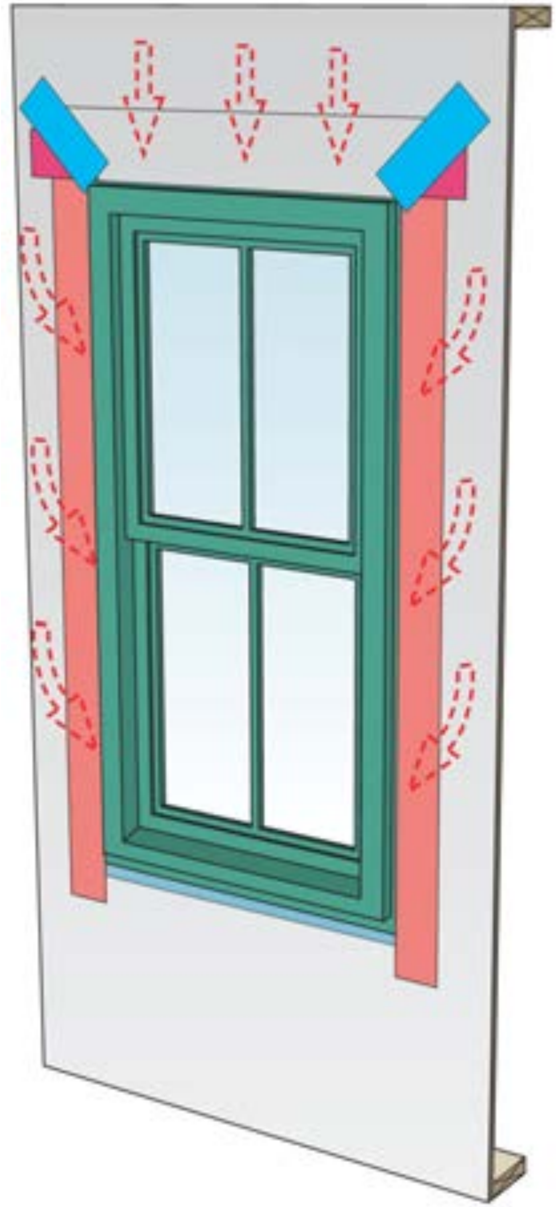

Baffle to deflect raindrops hitting face of cup due to momentum ("kinetic energy")
Pressure in cup is same as pressure outside on face of baffle
Momentum driving force converted to gravity— water drains away
Wind enters cup— pressurizing cup; no rain entry due to wind driven rain
Entire wind pressure taken here
Cup can still drain water to exterior

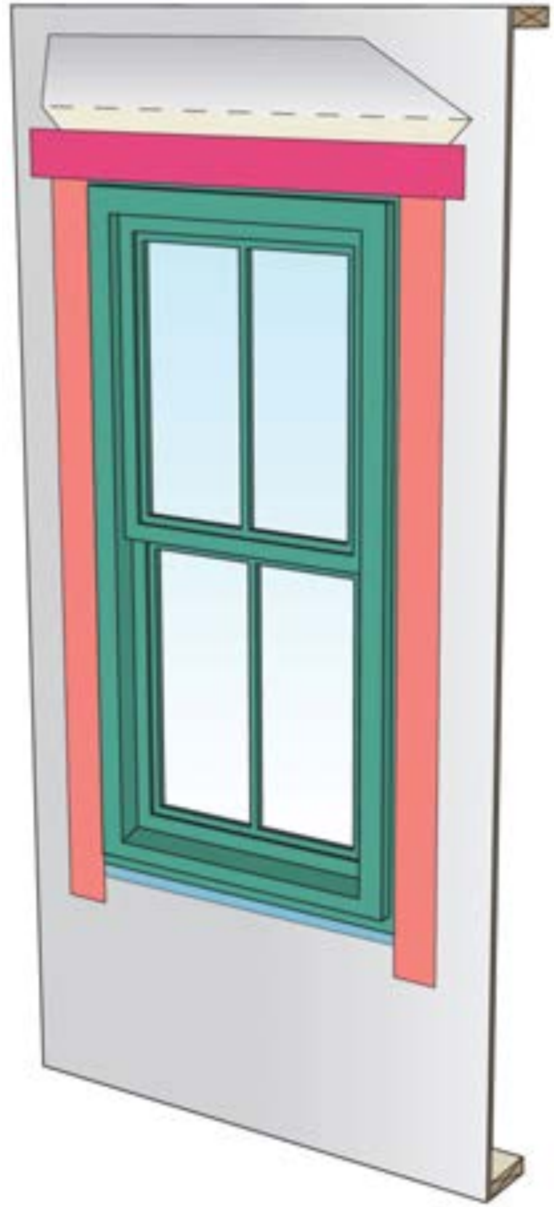

Insulating
glass unit
Seal (gasket)
Seal (tape)
Setting block
(typically two
per unit)
Hole providing
drainage and
pressurization
Frame
Rough opening

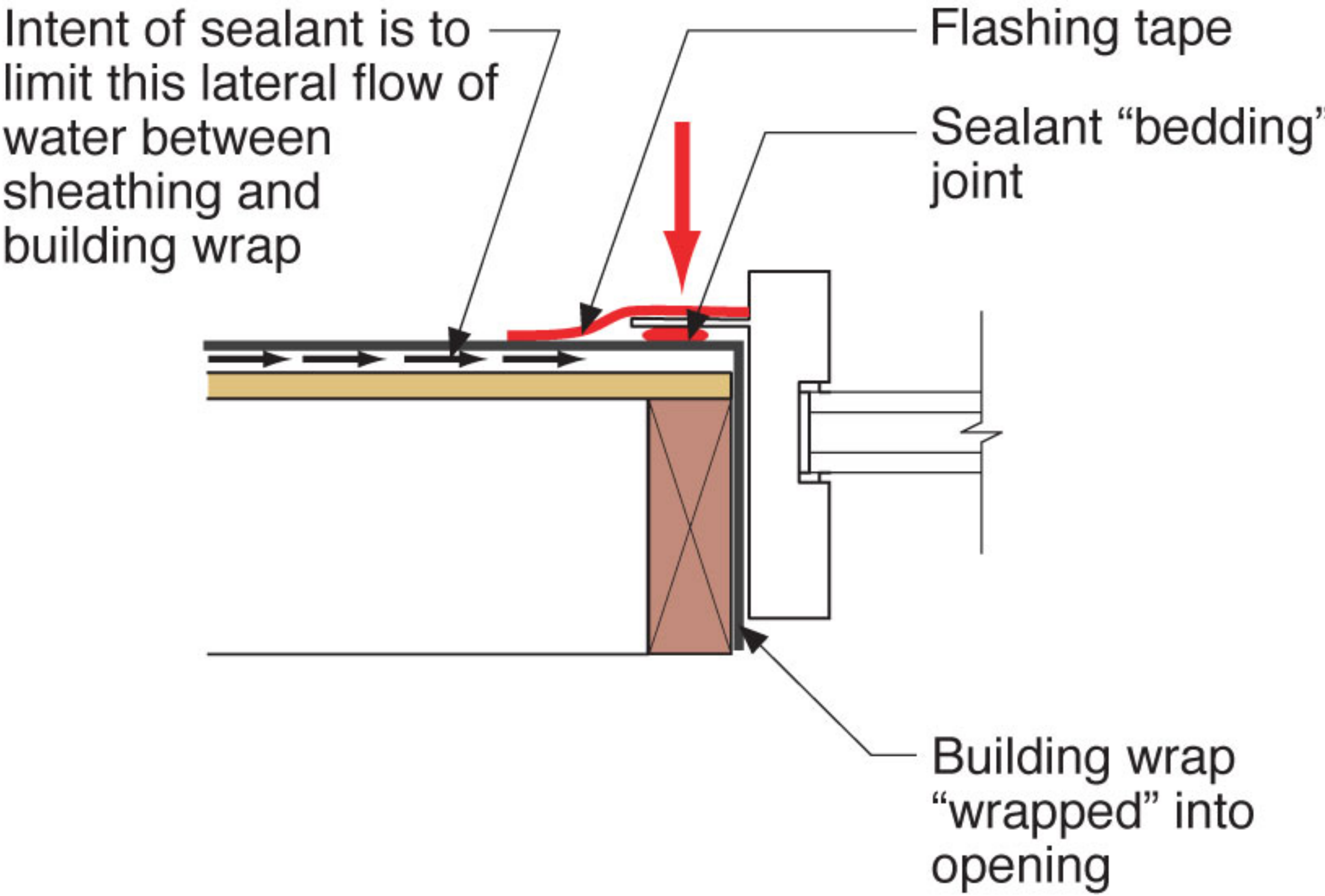

Outer seal sees water but not pressure; no pressure difference across this seal, therefore no rain entry
Key seal is interior seal as it takes maximum wind load but it does not see water
Pressure in chamber is same as pressure outside on face of assembly
Entire wind pressure taken here
Air enters and pressurizes chamber
Pressure chamber

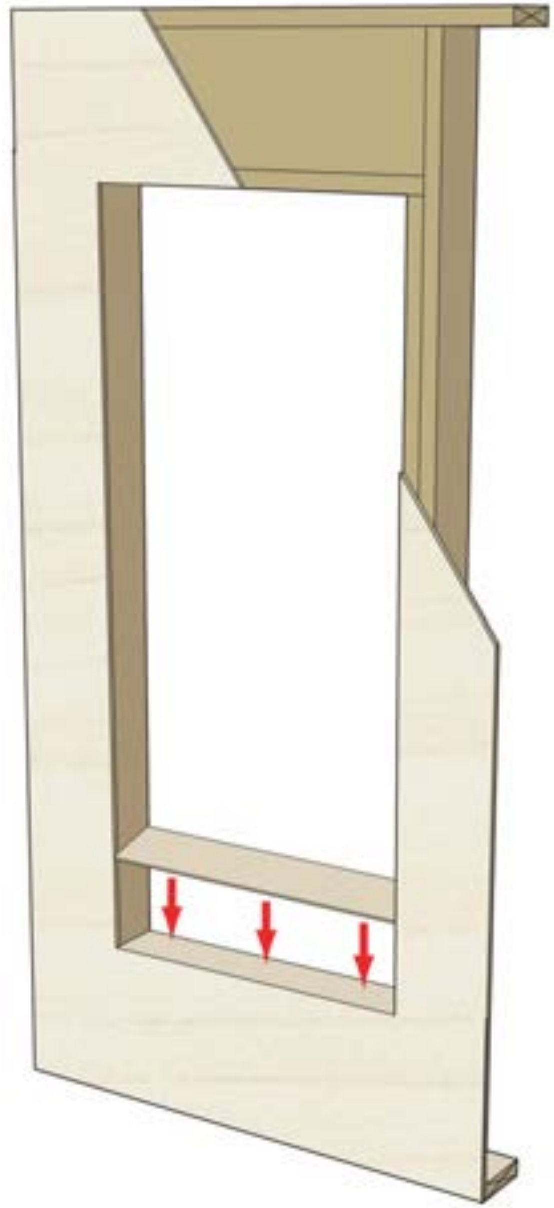

Pressure moderated chamber
Interior air seal
Beveled wood siding
Adhesive -backed sill flashing
Housewrap
Sheathing

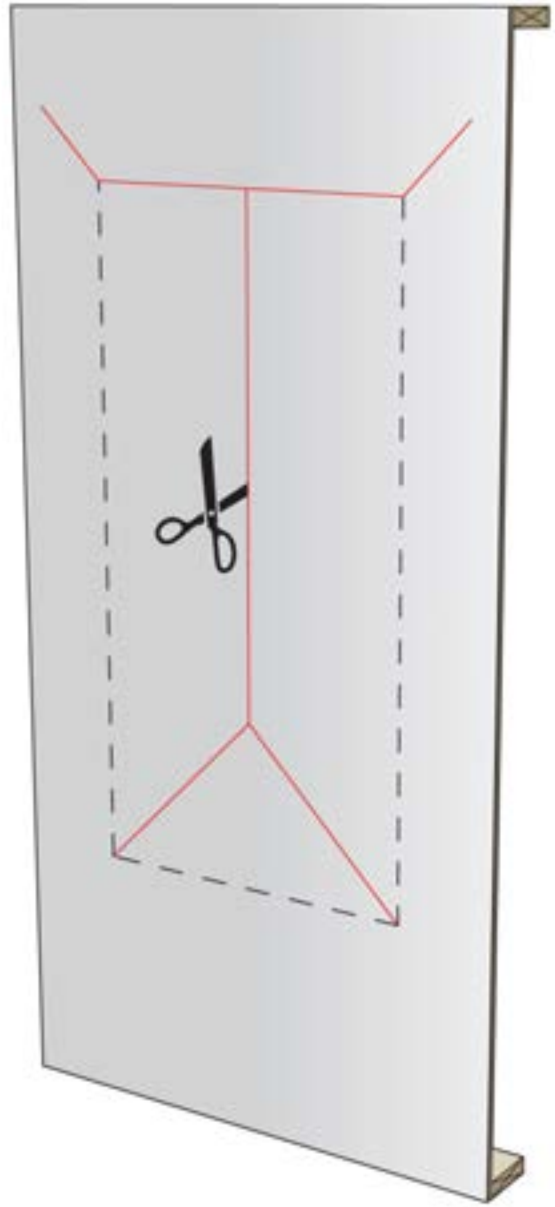

ightFlash

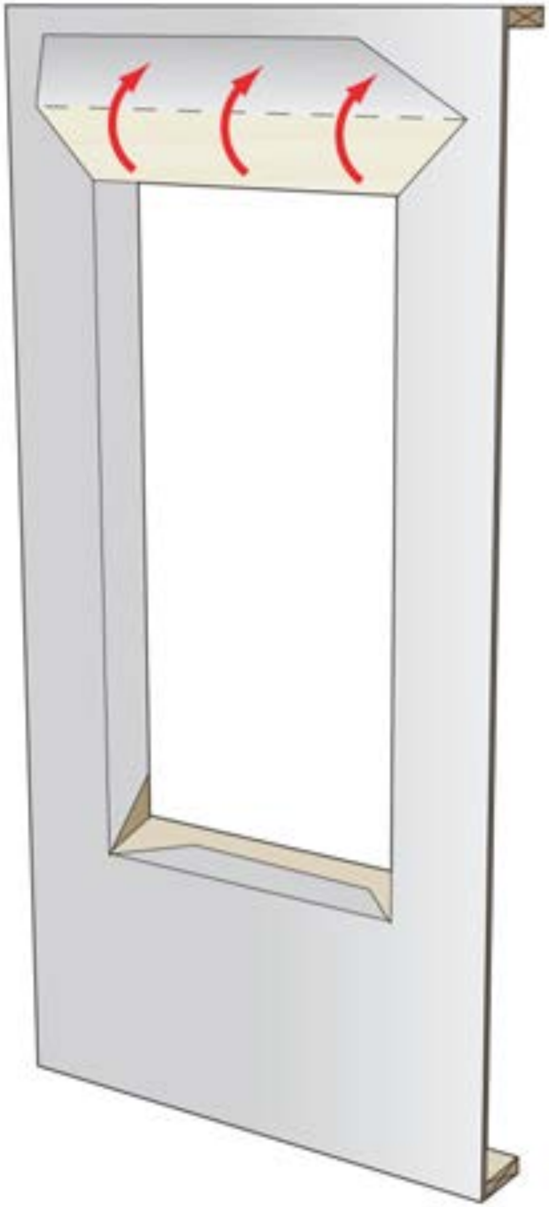


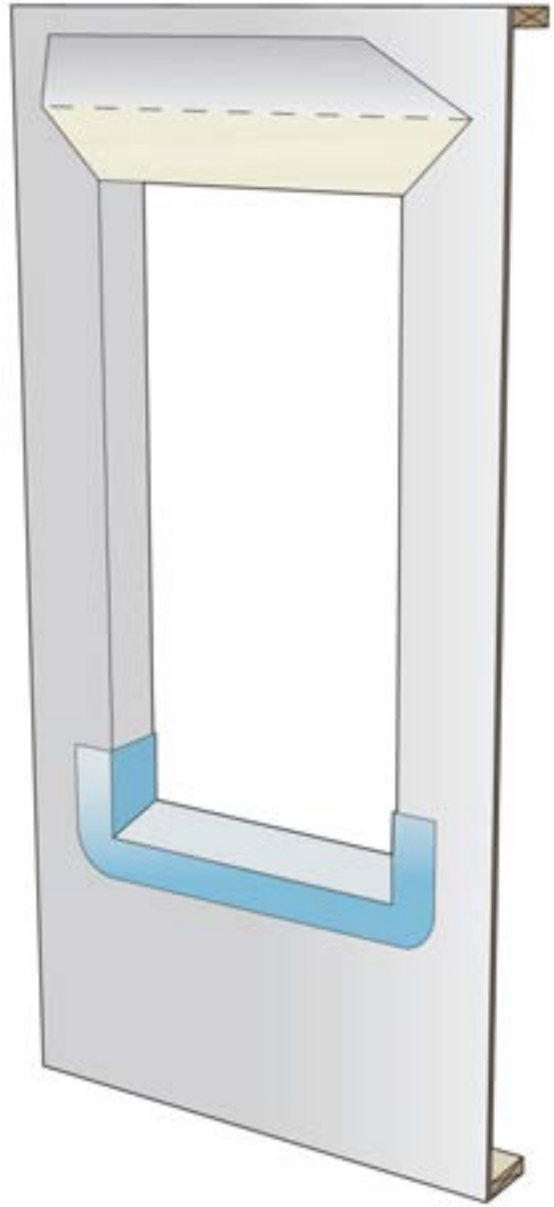


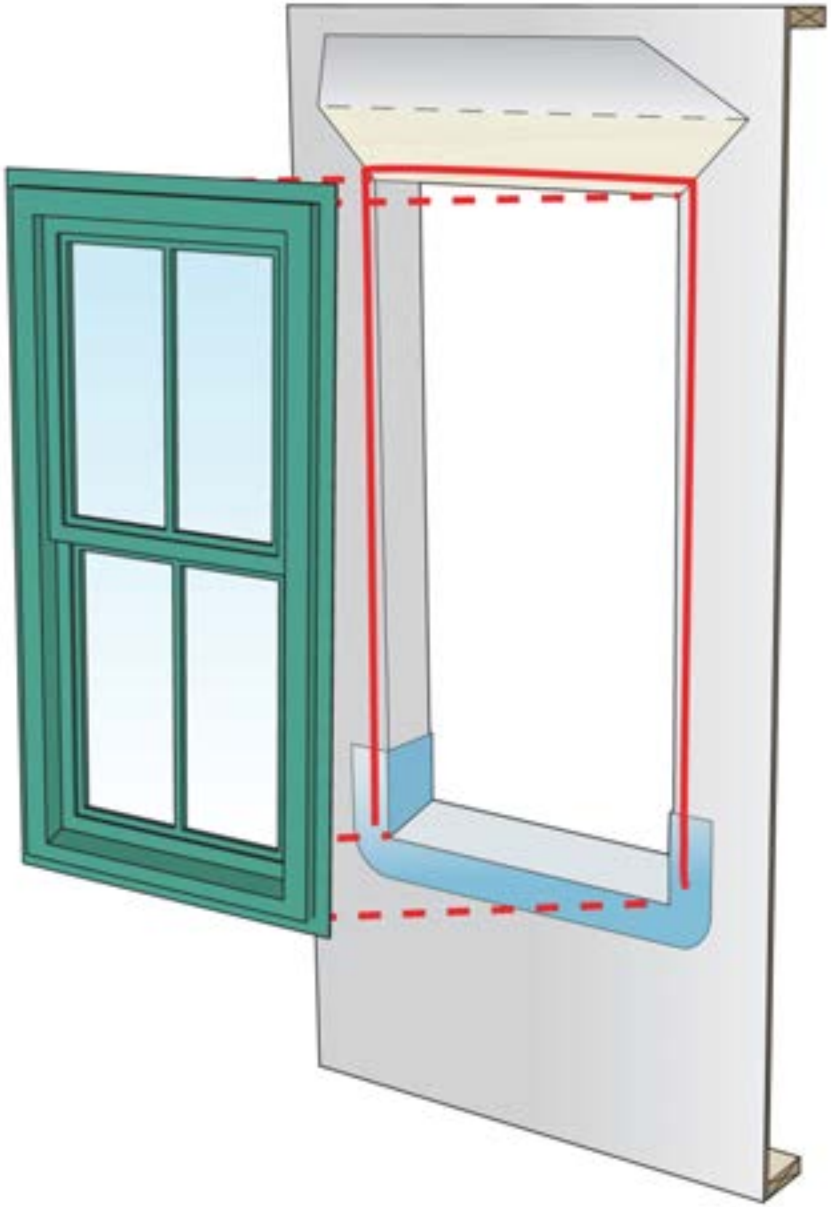

Intent of sealant is to limit this lateral flow of water between sheathing and building wrap
Flashing tape
Sealant "bedding" joint
Building wrap "wrapped" into opening

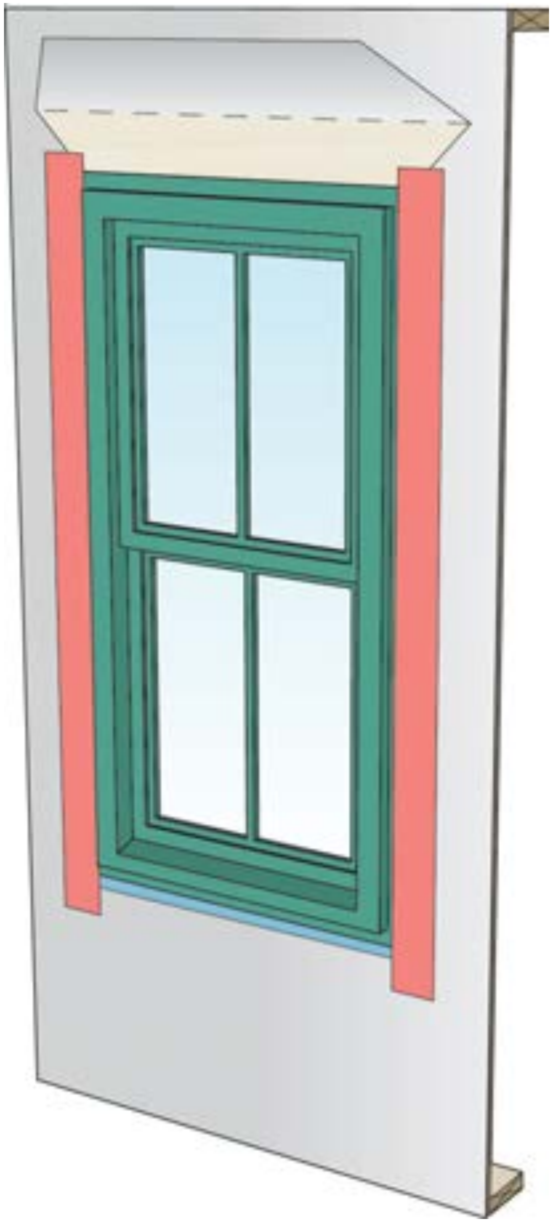


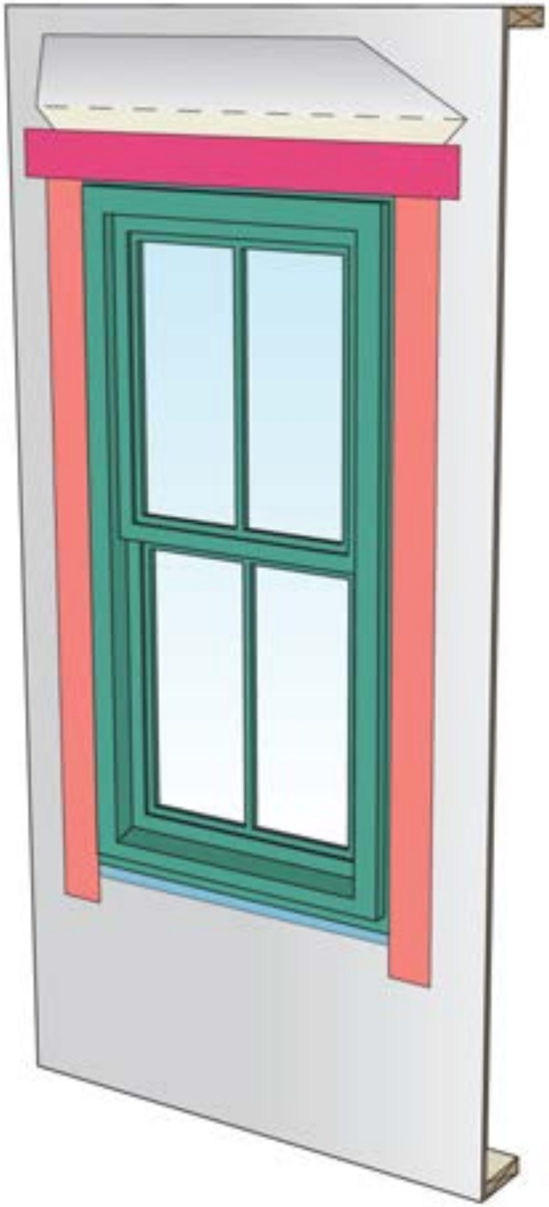


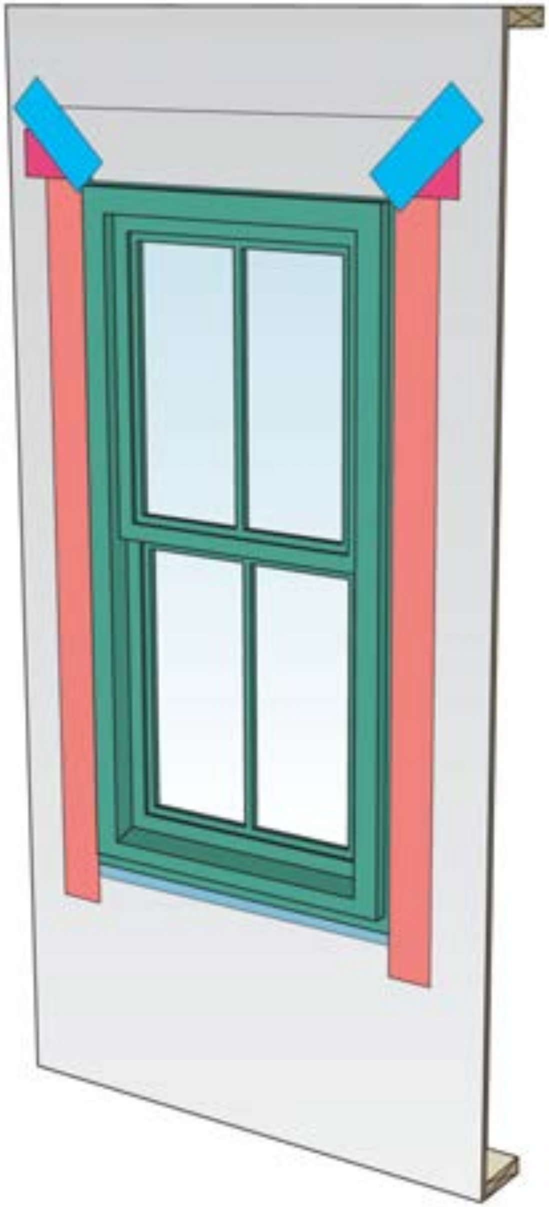


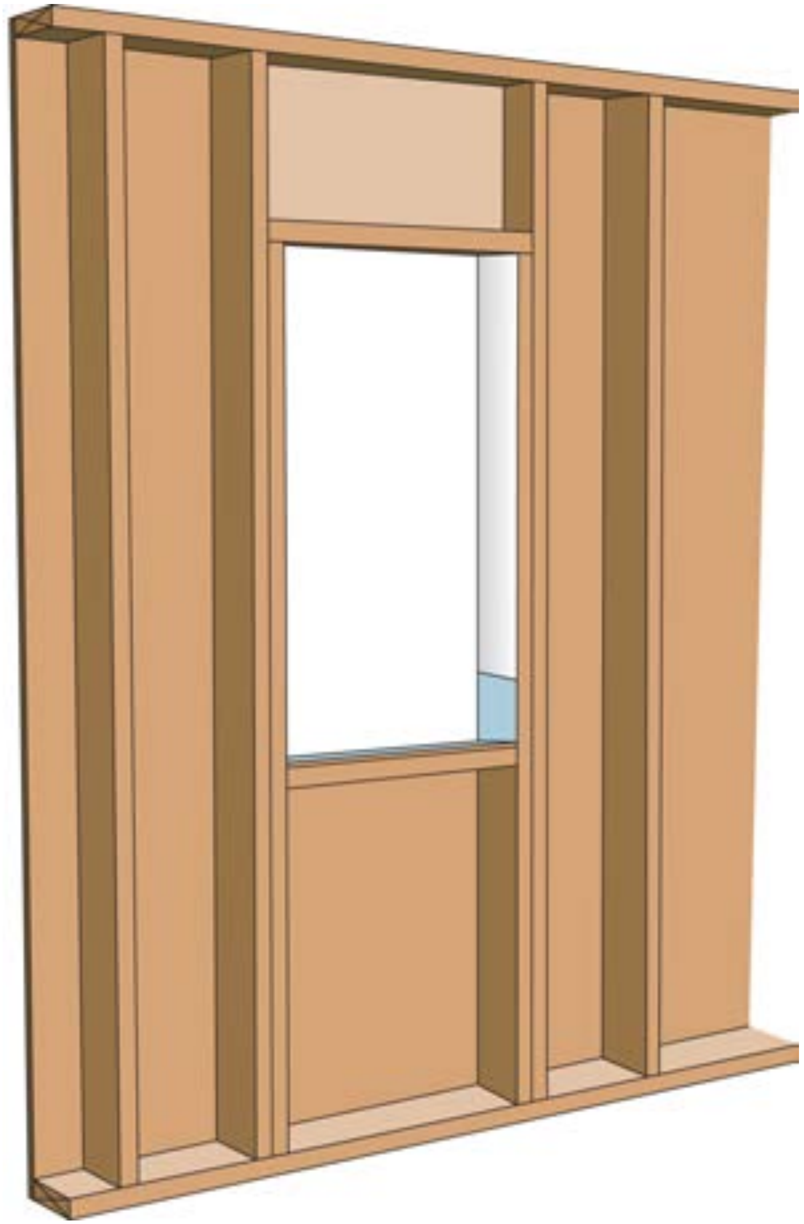




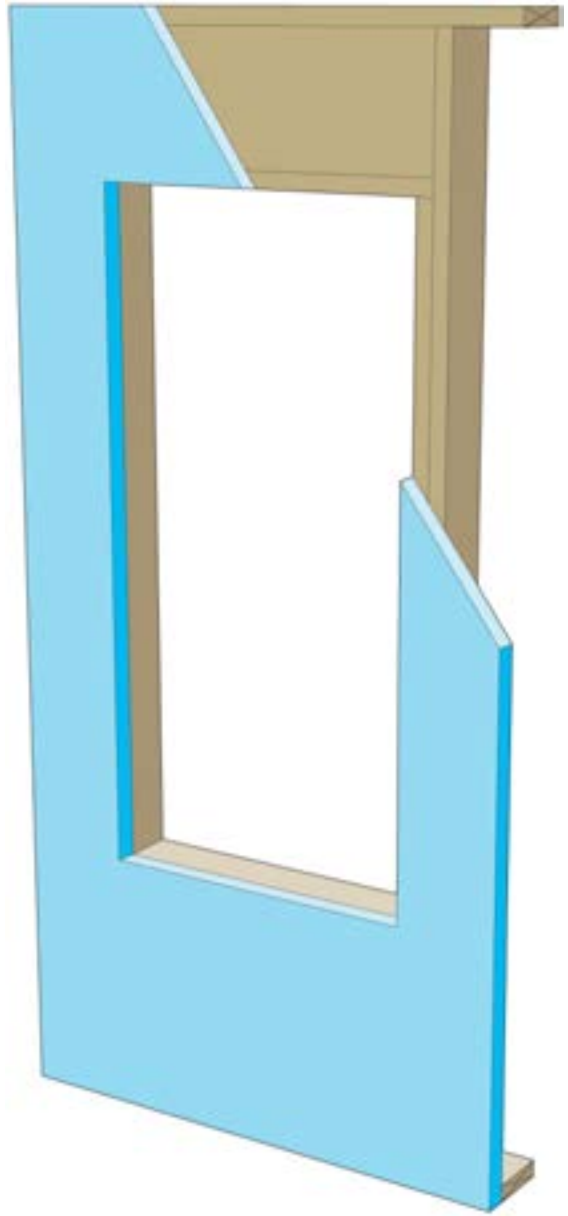


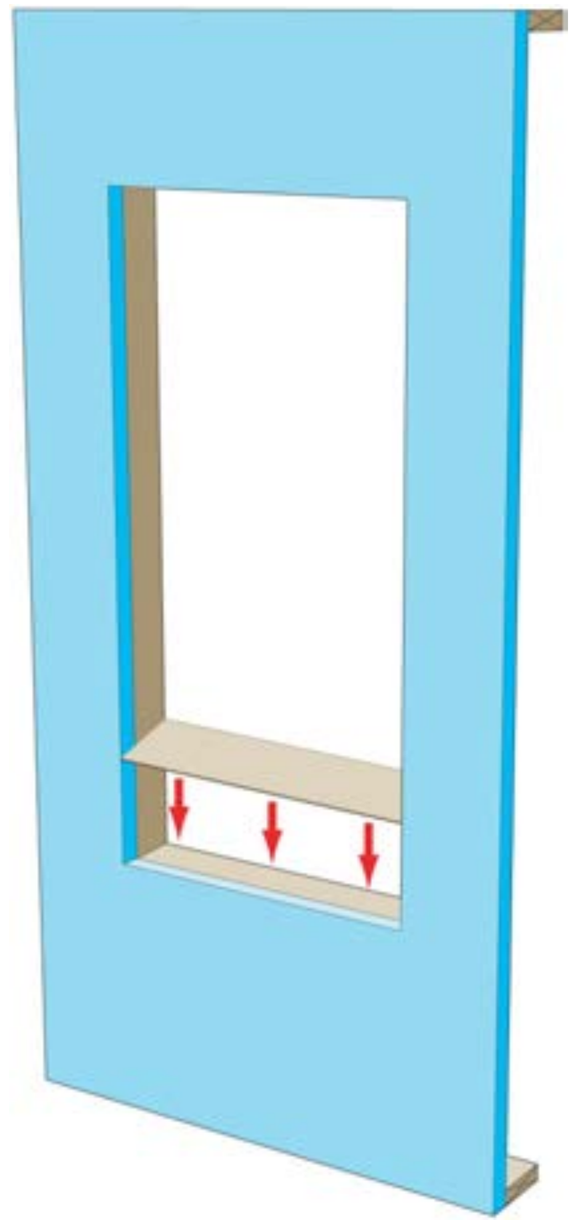


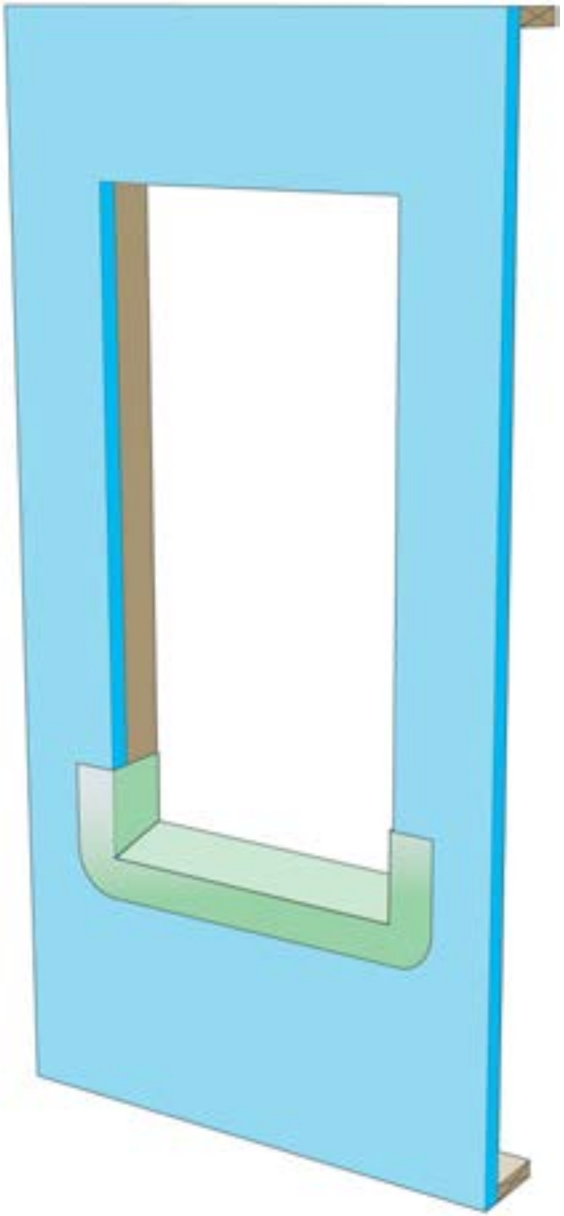


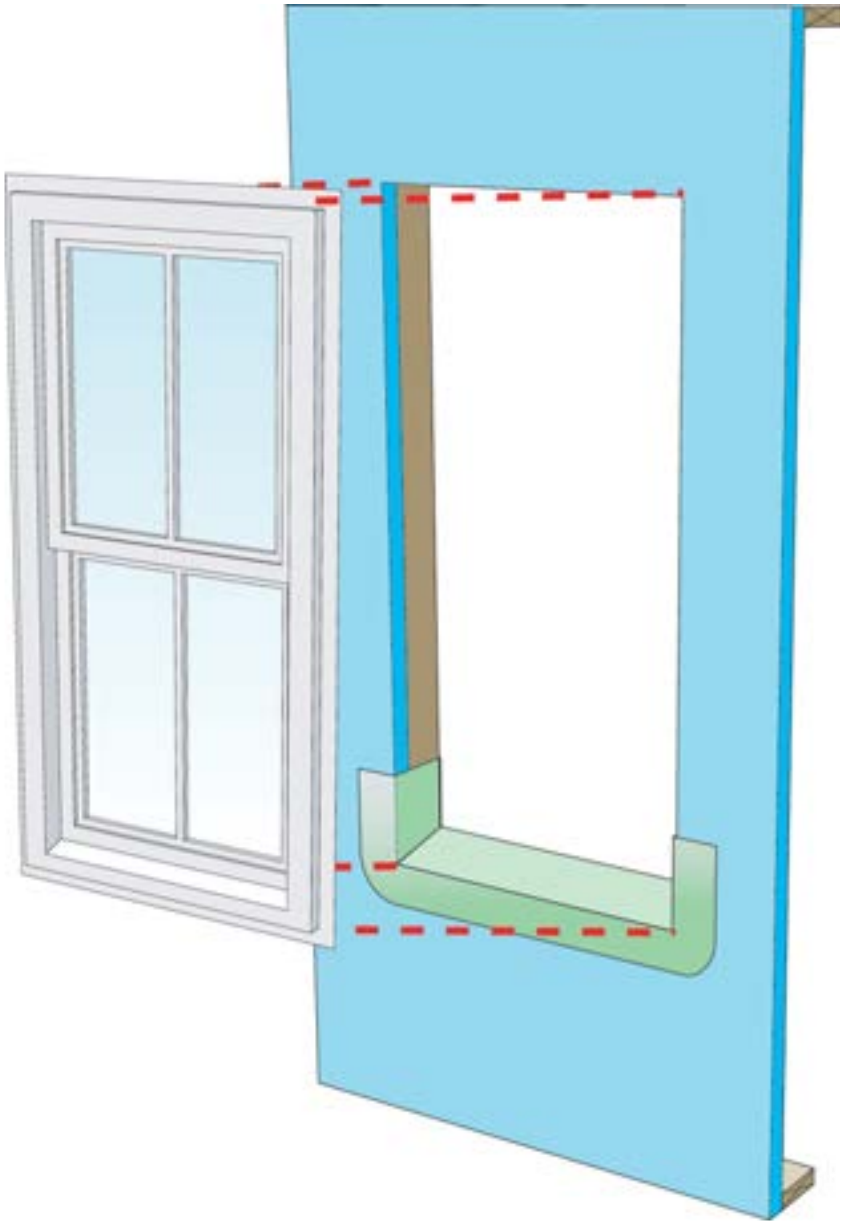


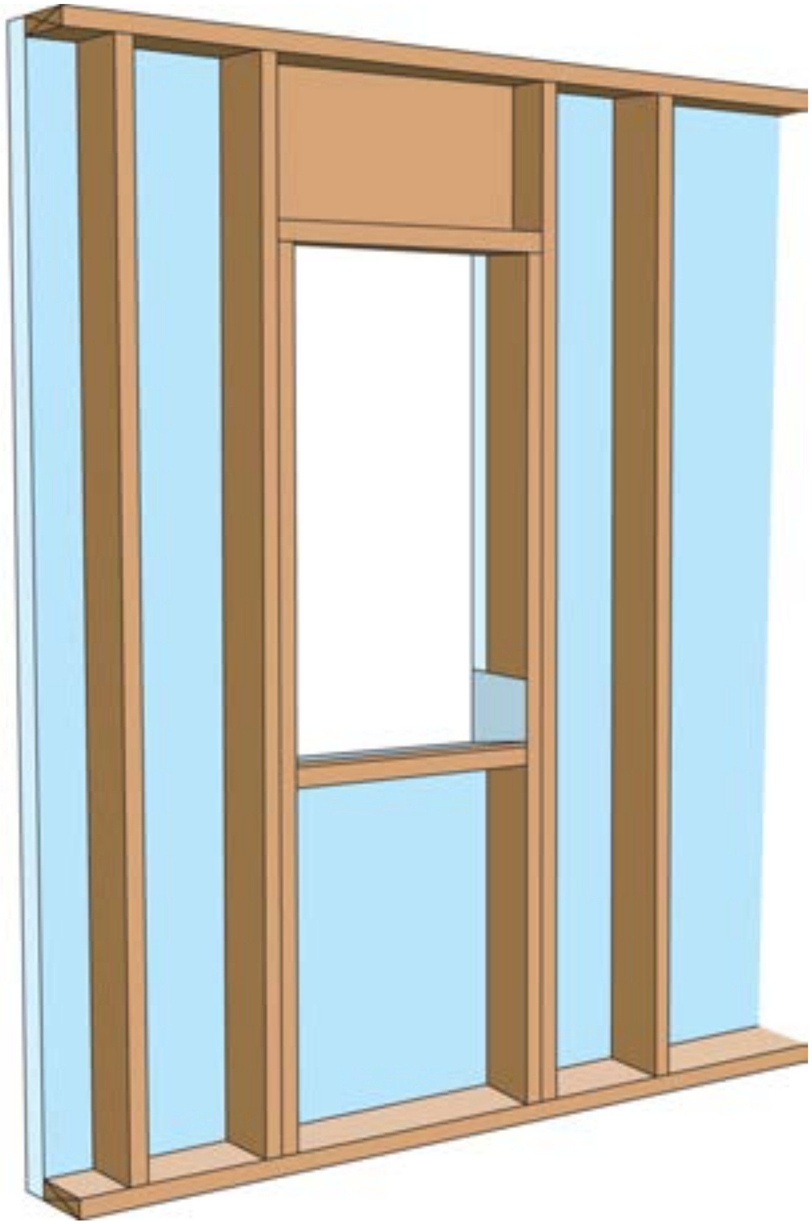

RCI

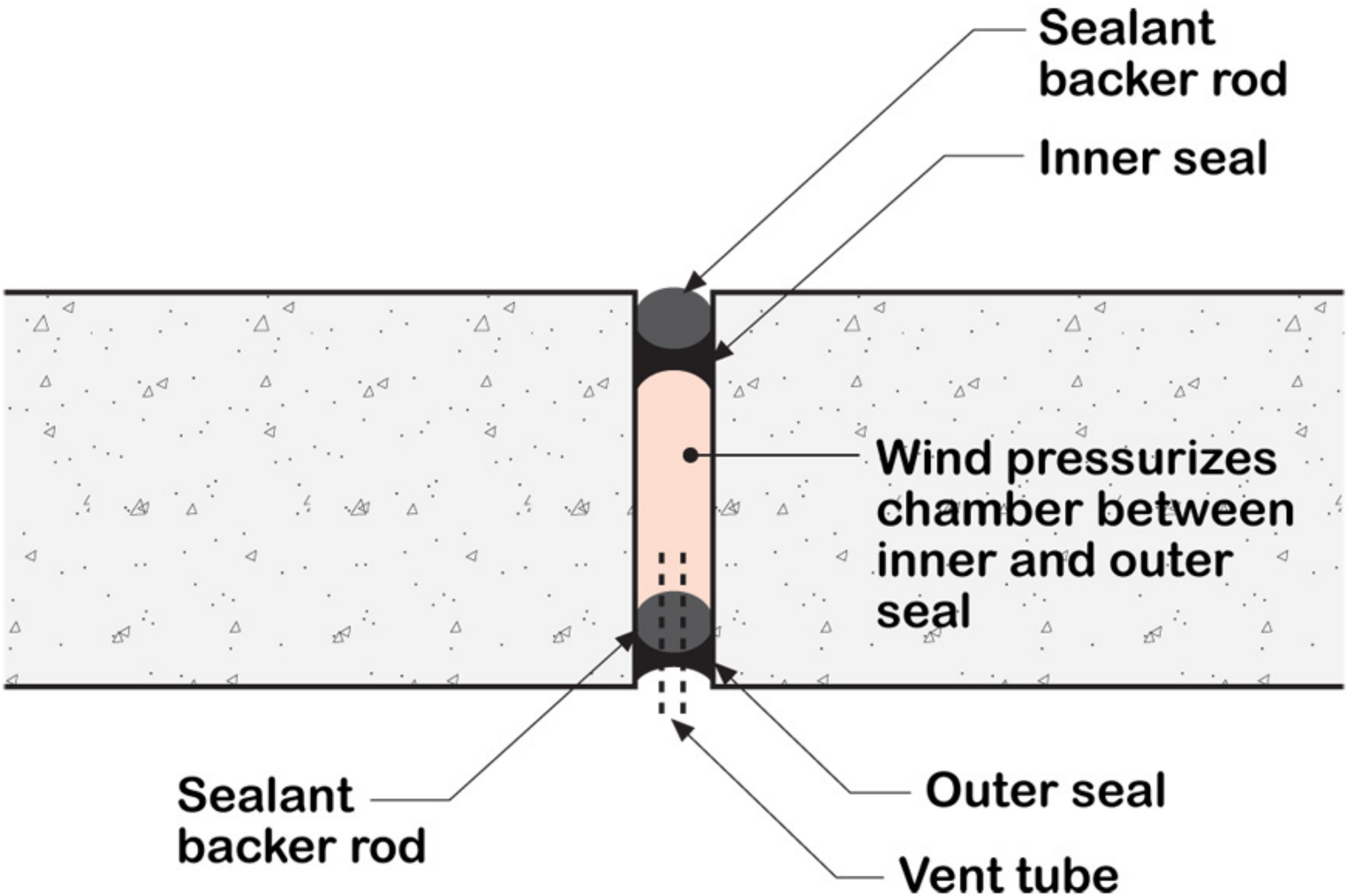


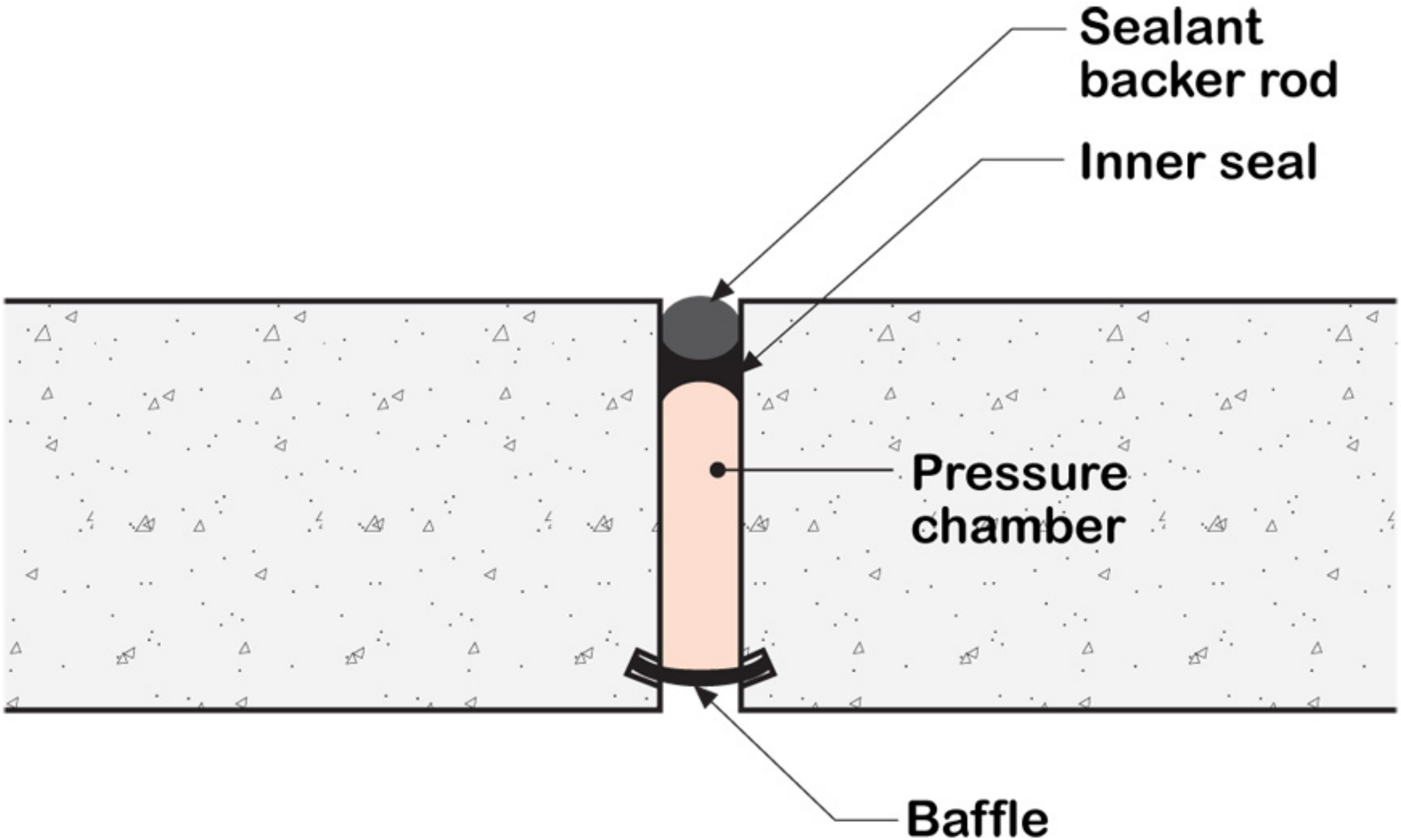


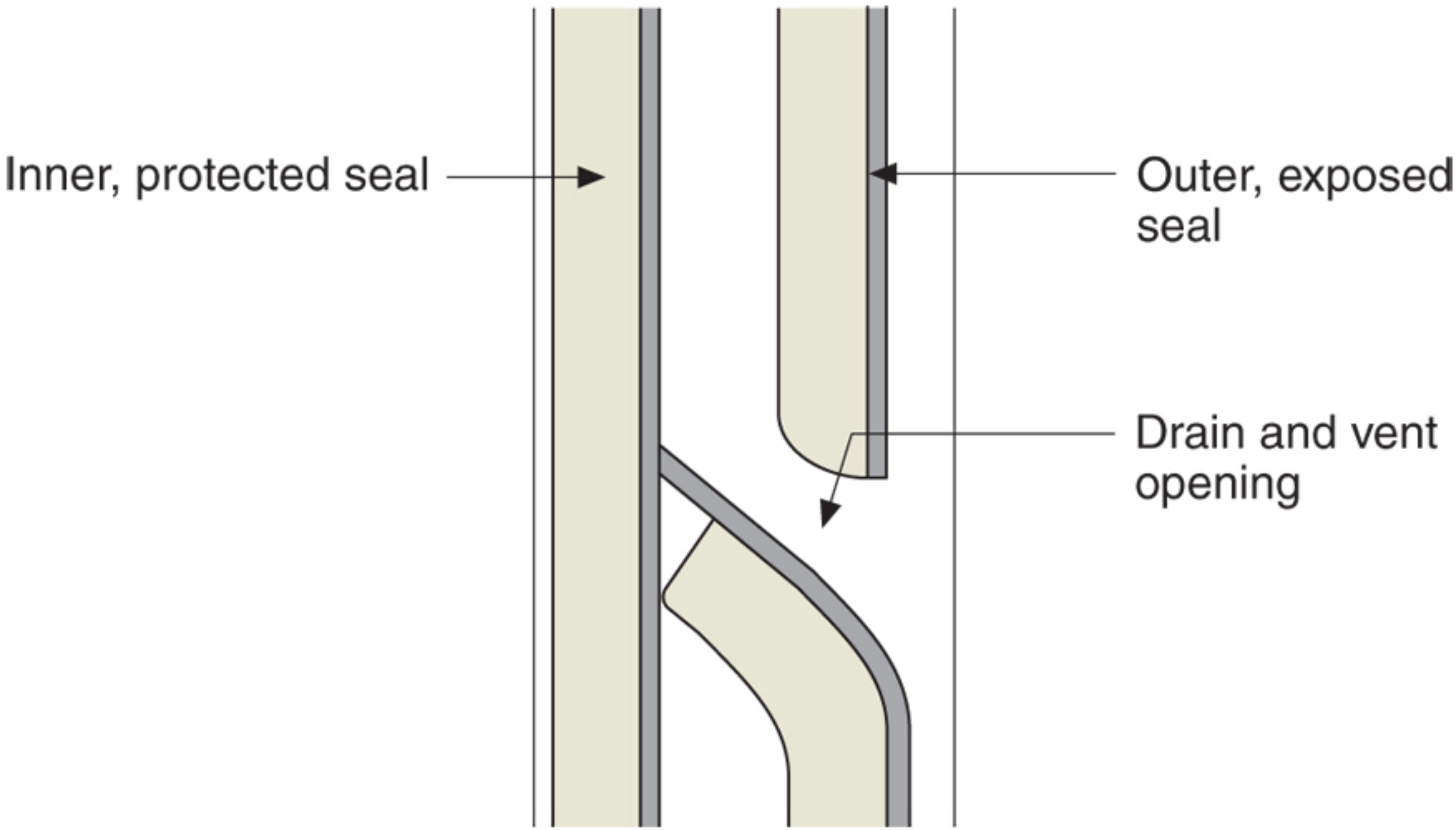


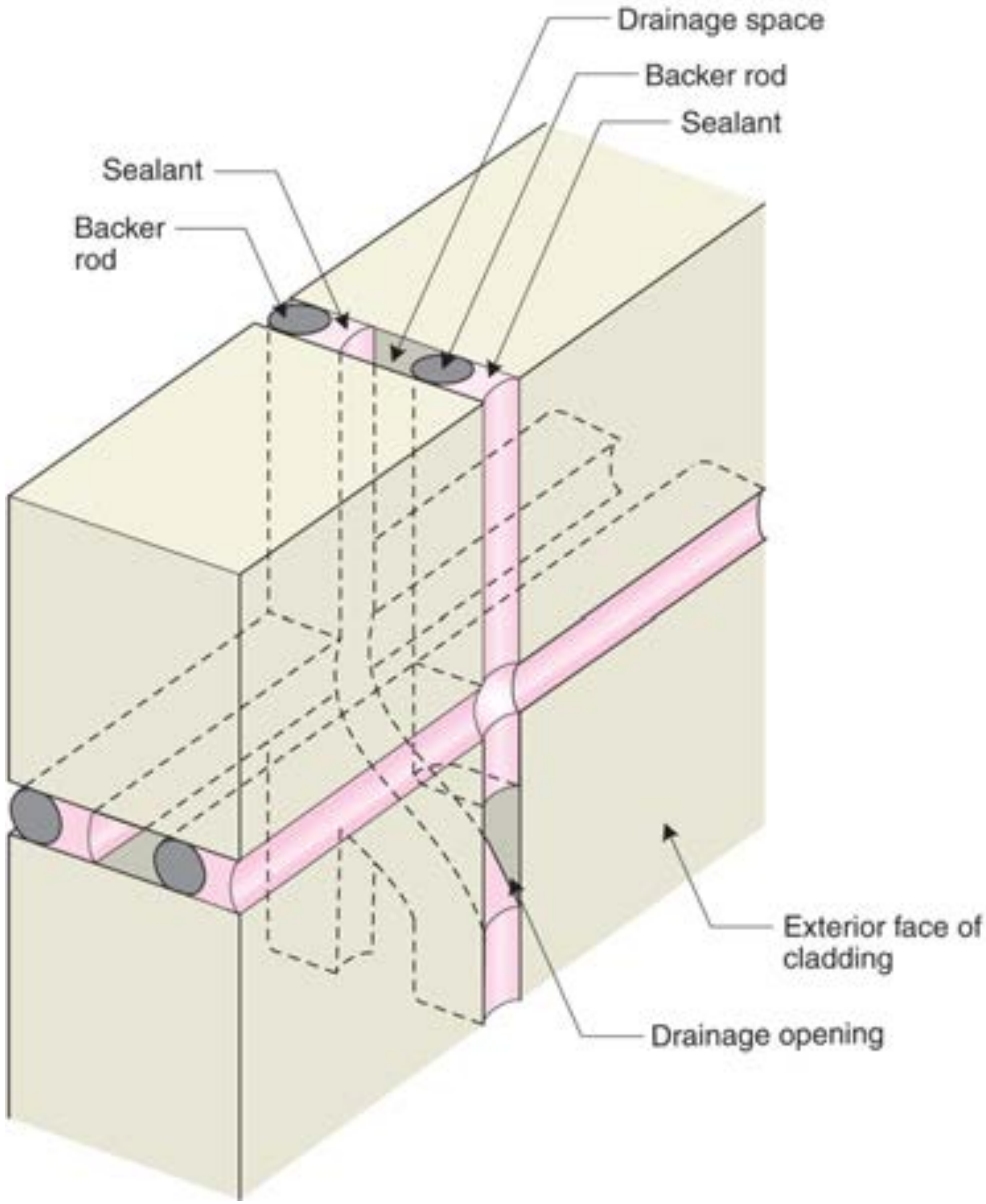


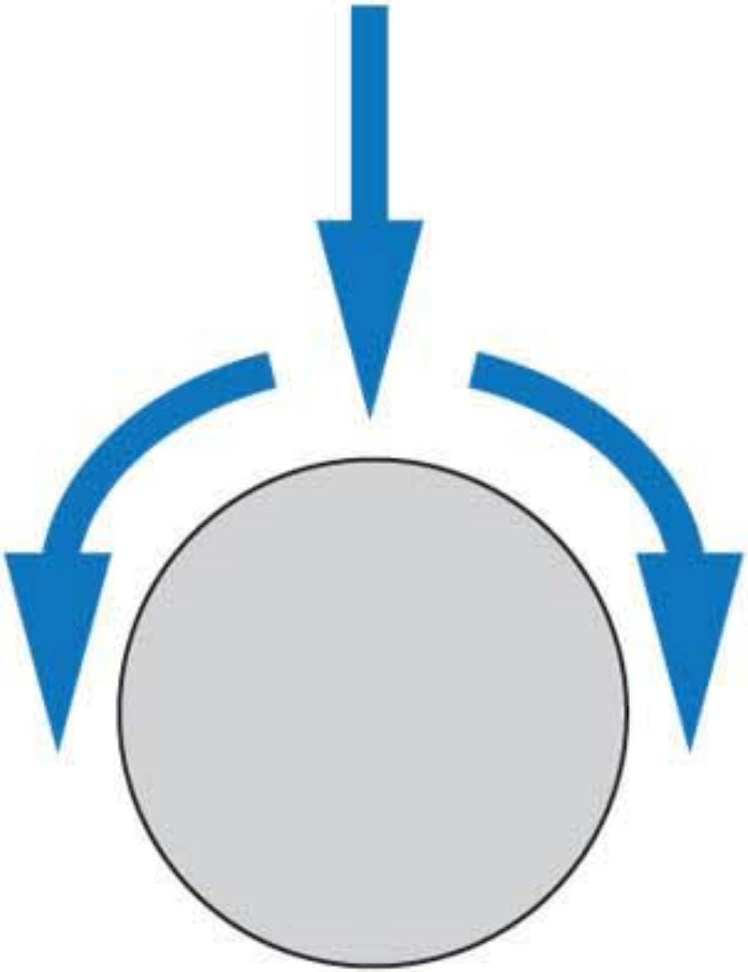


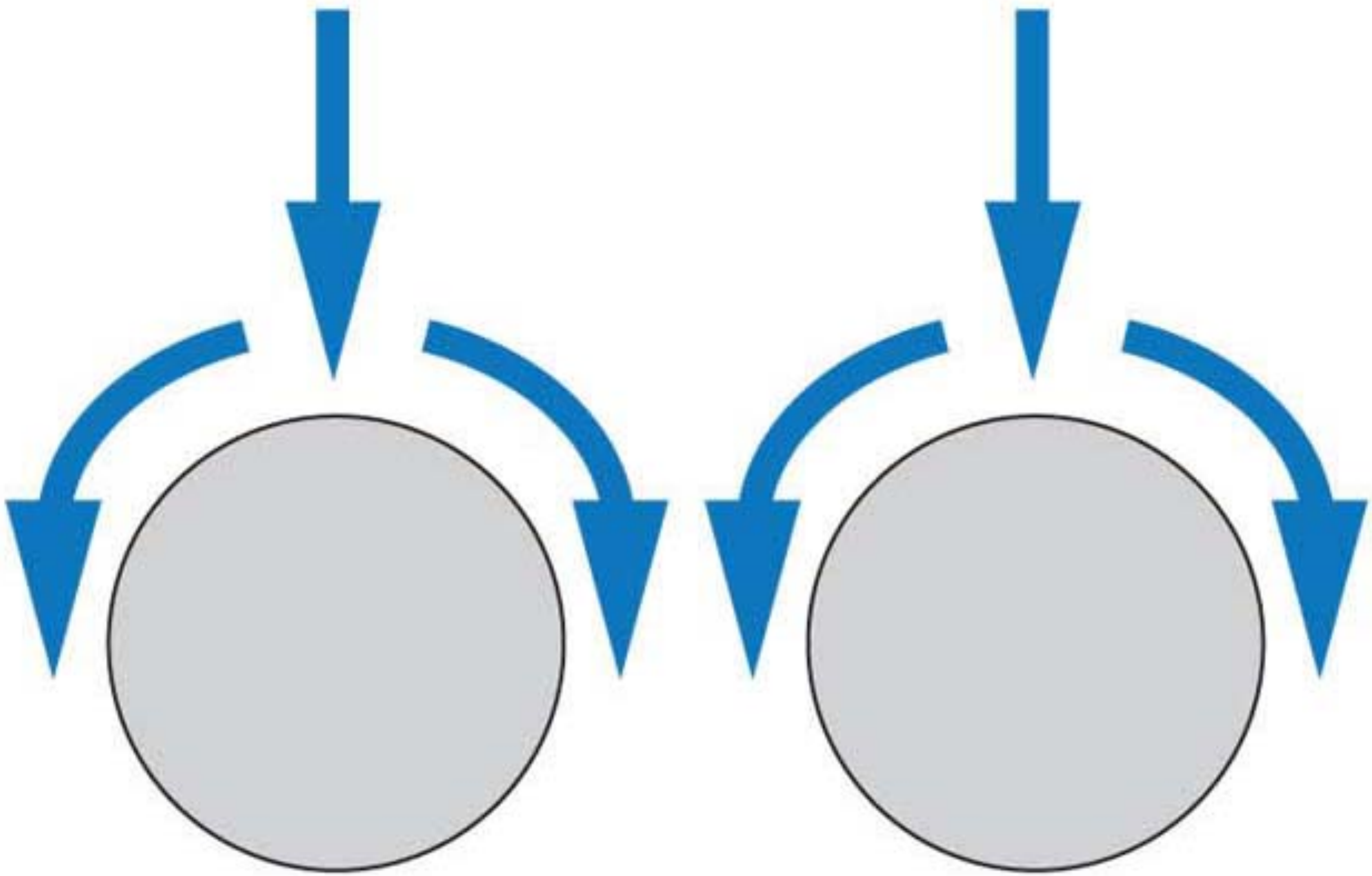

Sealant
backer rod
Inner seal
Wind pressurizes
chamber between
inner and outer
seal
Sealant
backer rod
Outer seal
Vent tube

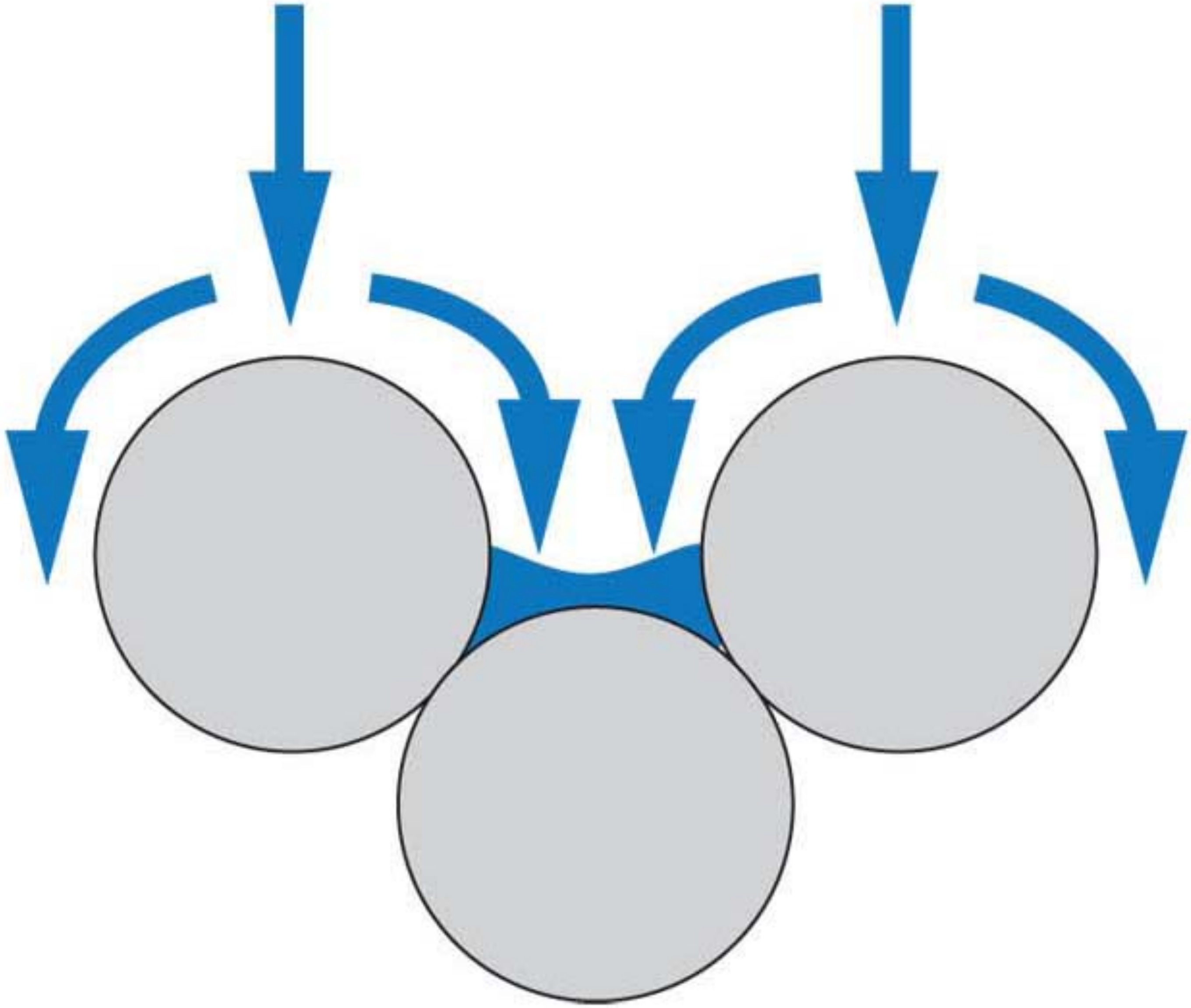

Sealant backer rod
Inner seal
Pressure chamber
Baffle

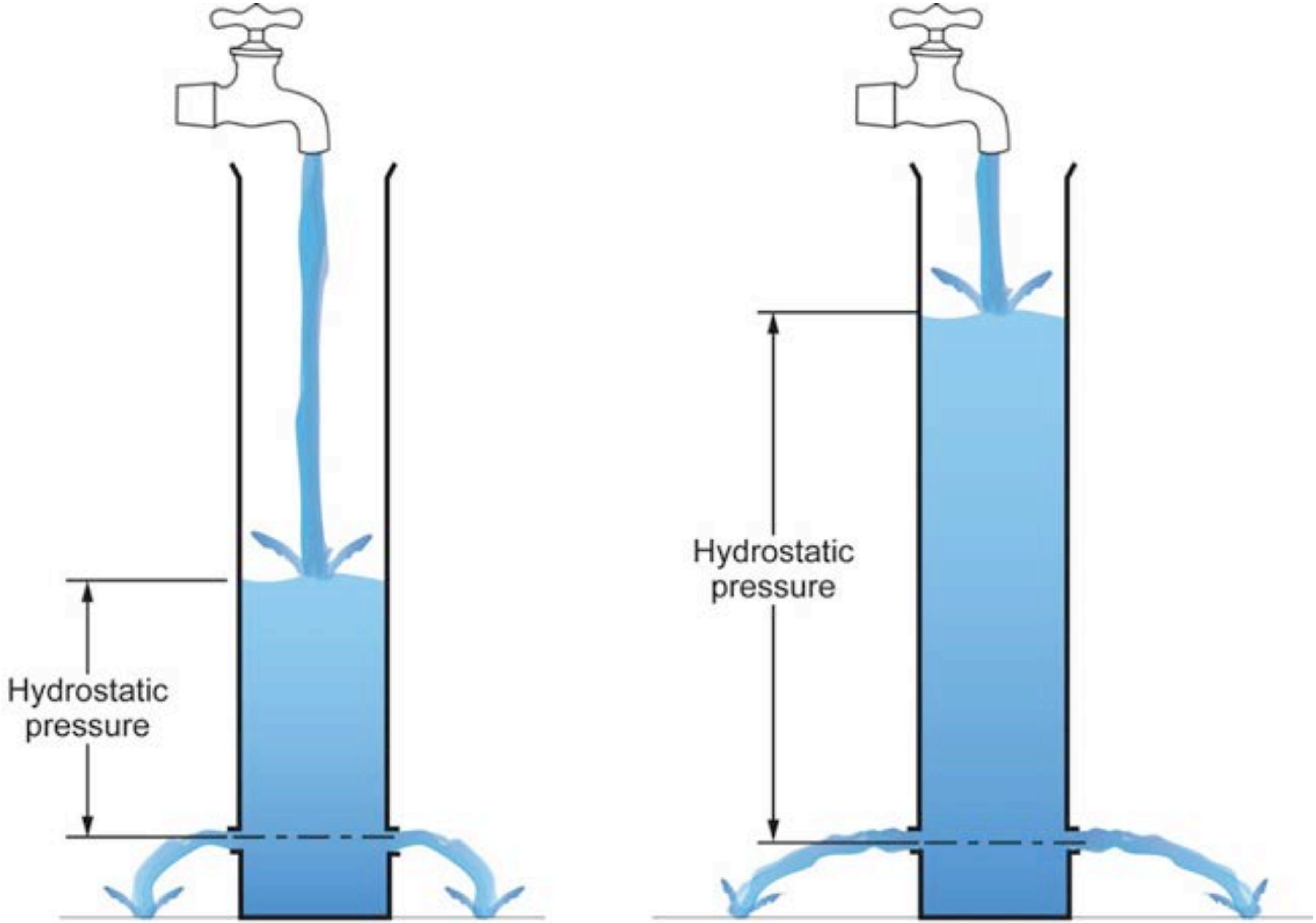

Inner, protected seal
Outer, exposed seal
Drain and vent opening

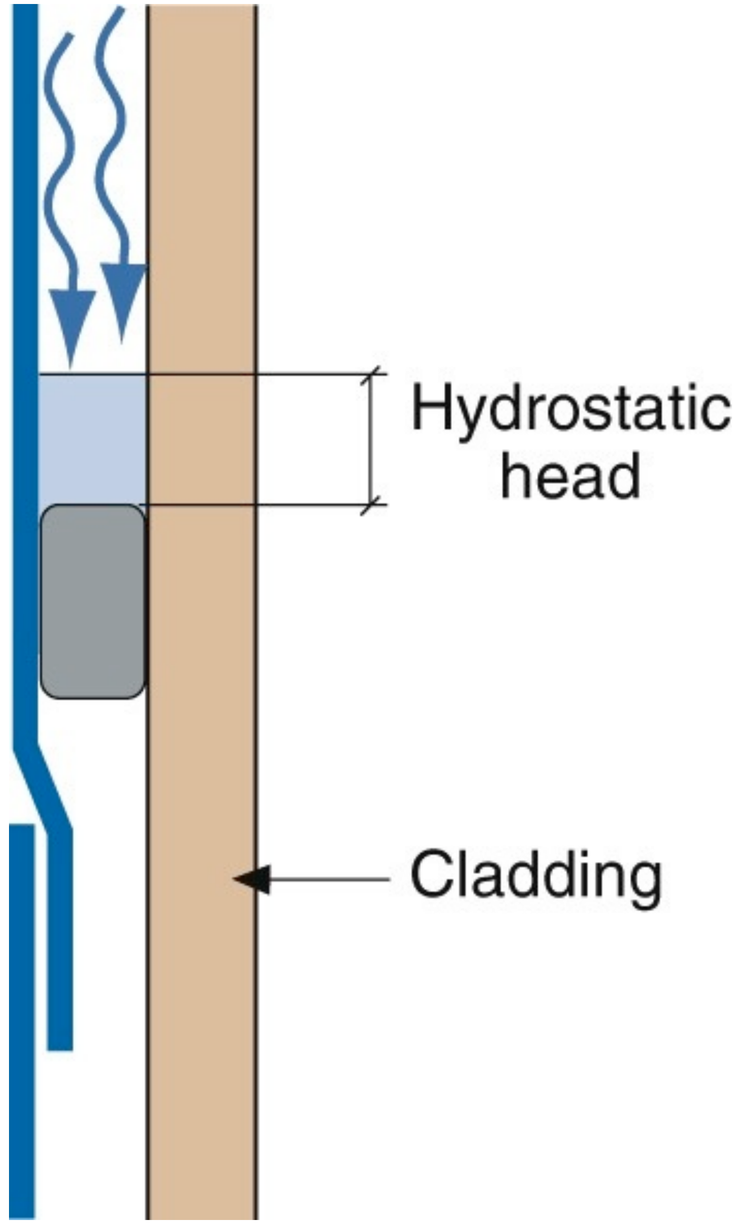

Drainage space
Backer rod
Sealant
Sealant
Backer
rod
Exterior face of
cladding
Drainage opening

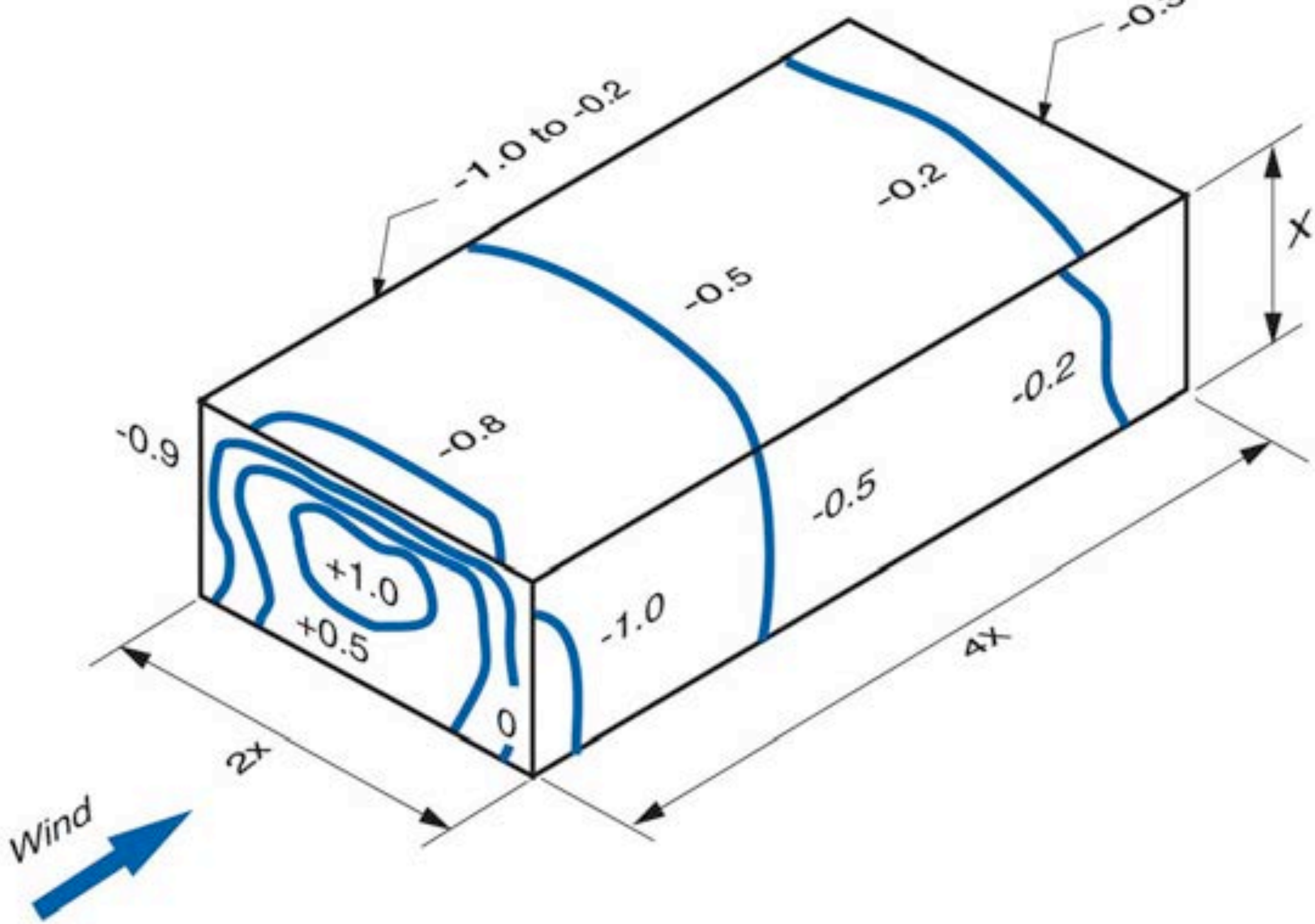




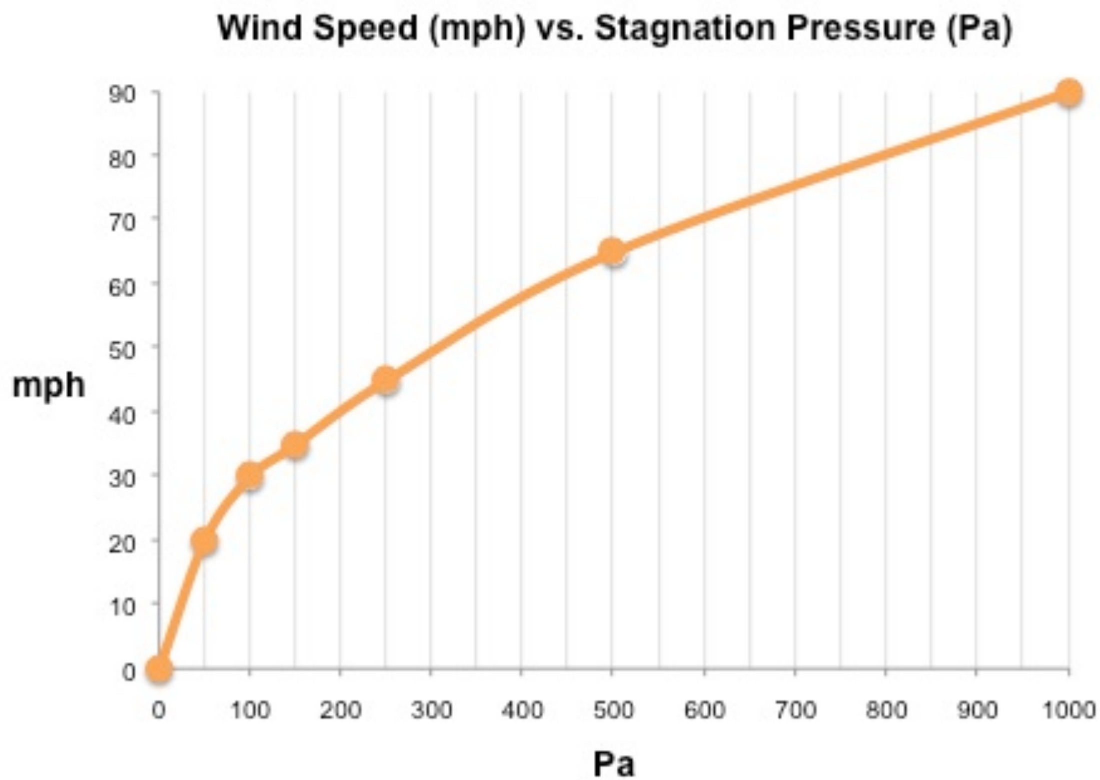



Hydrostatic
pressure
Hydrostatic
pressure


Hydrostatic head
Cladding

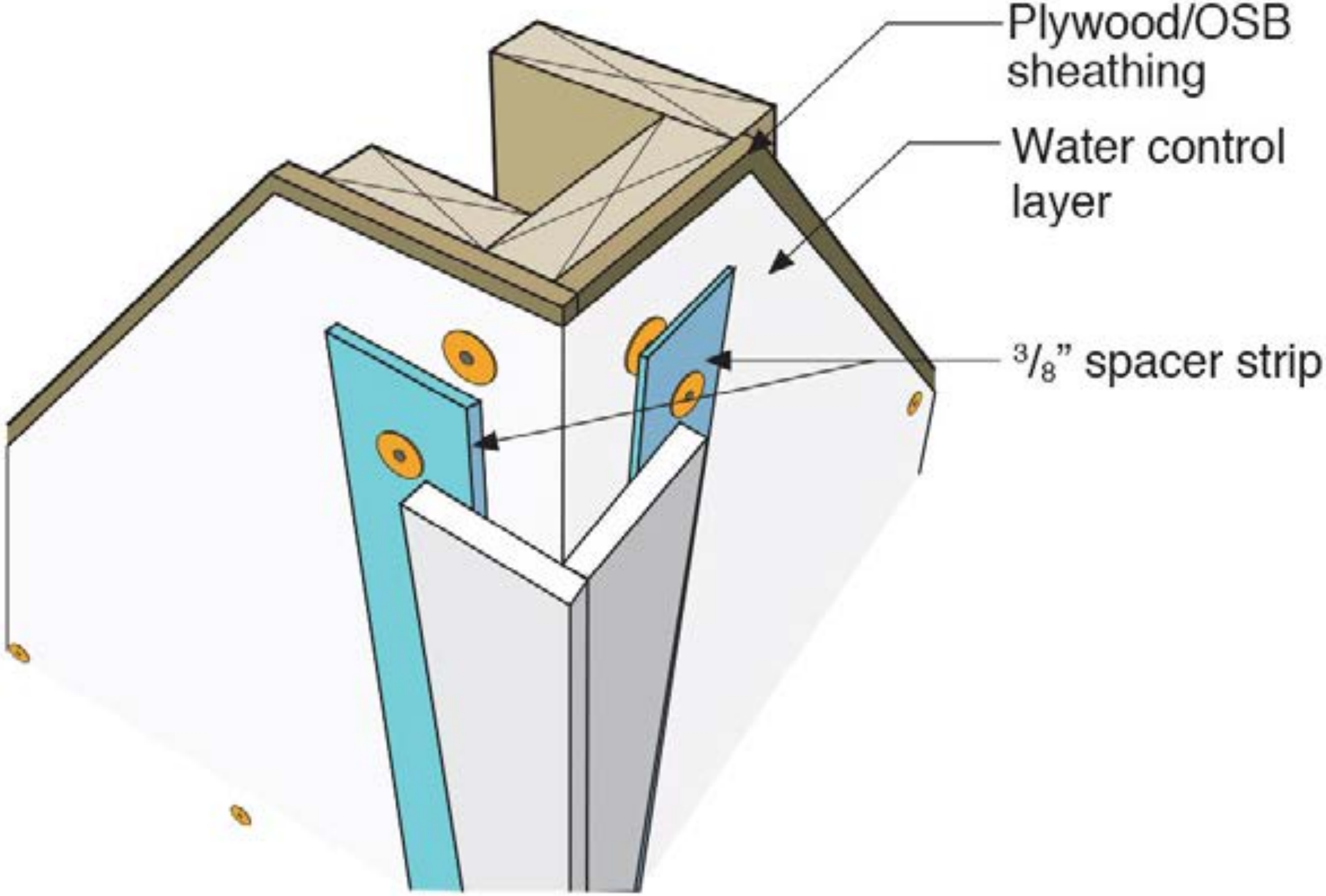

-0.3
-1.0 to -0.2
-0.2
X
-0.5
-0.2
-0.9
-0.8
-0.5
+1.0
-1.0
+0.5
4x
0
2x
Wind

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

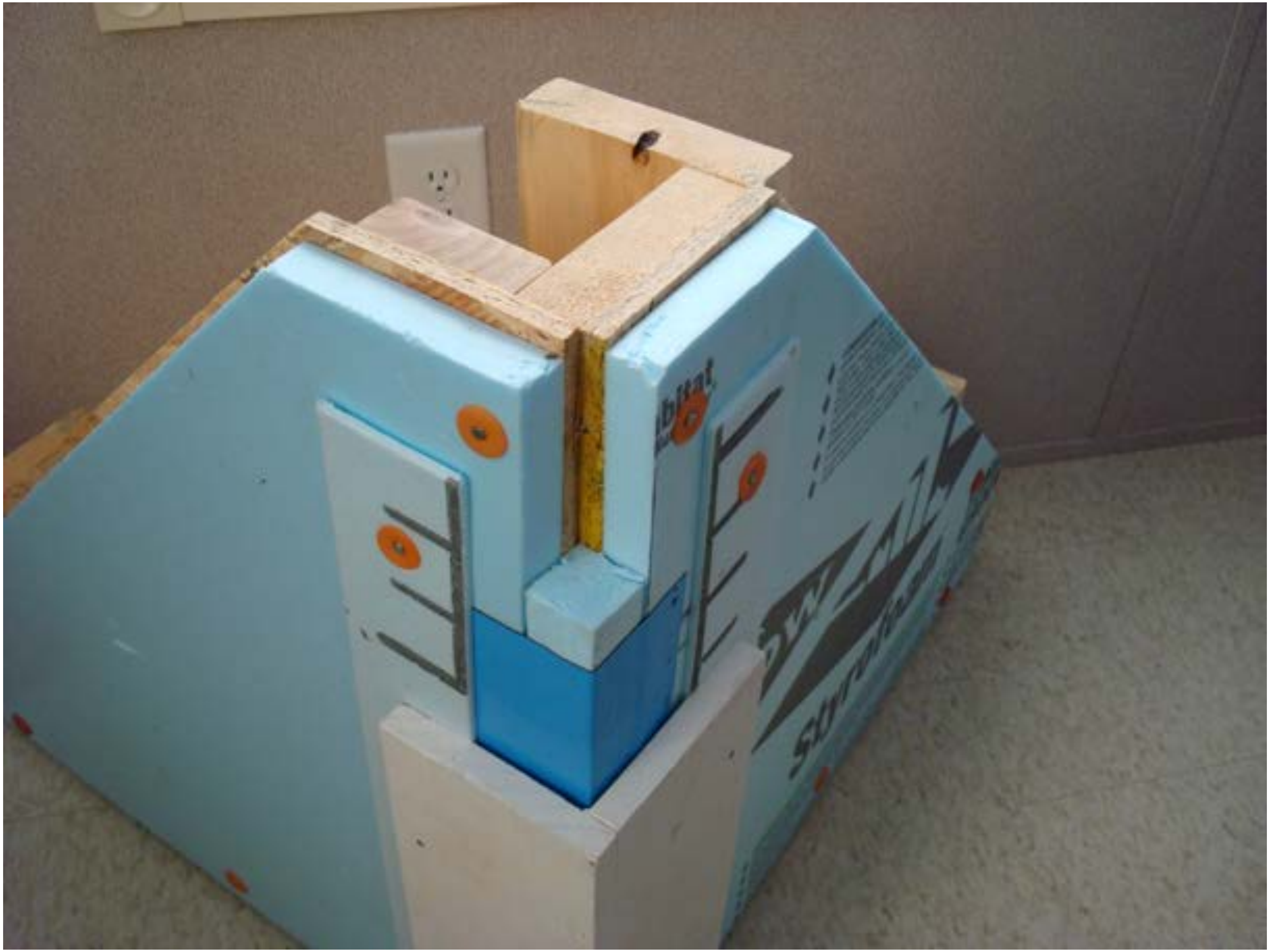



Tyvek
HomeWrap
Tyve
HomeWra
Tyve
HomeWrap

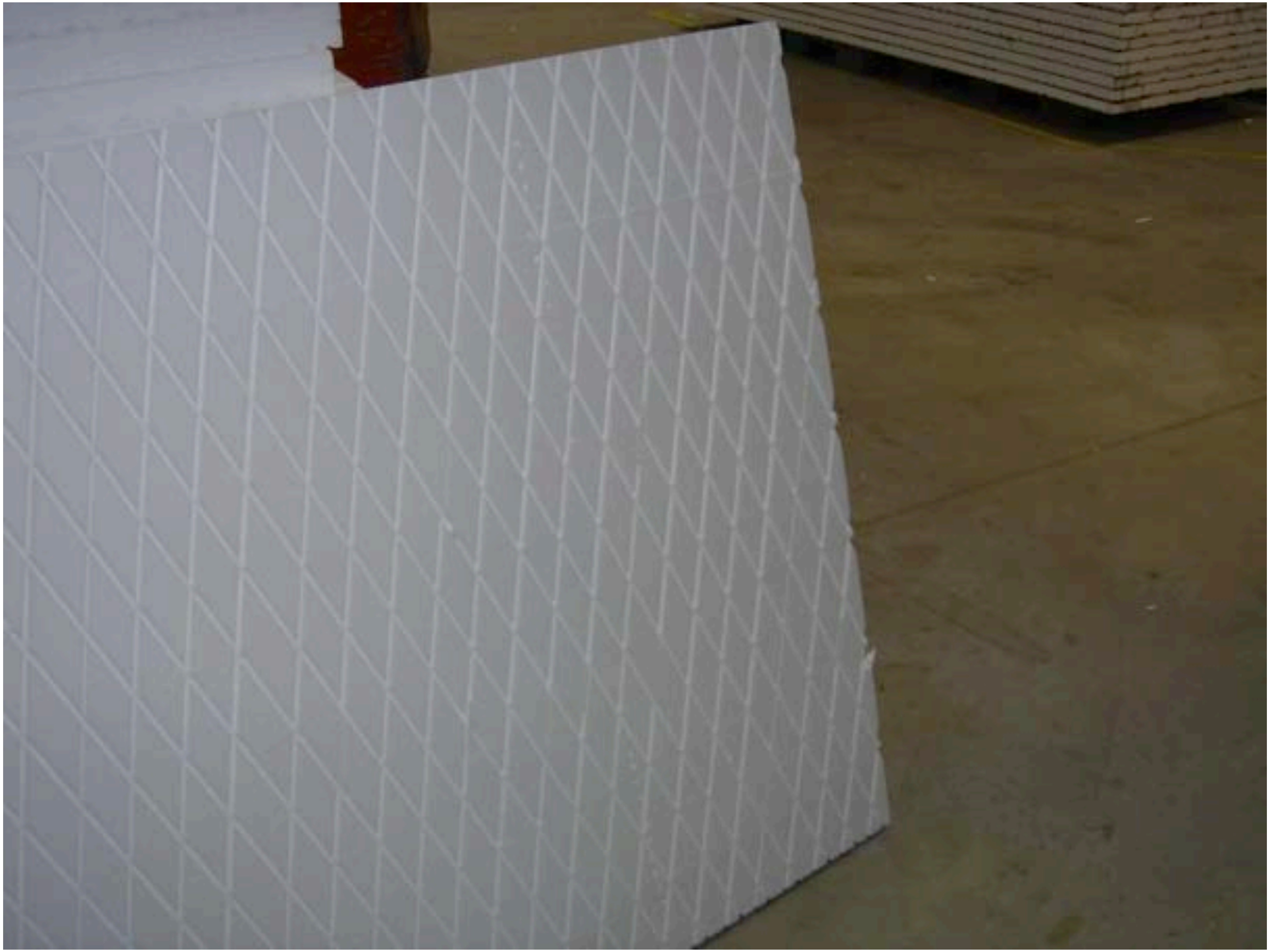

WWW.TYVEK.COM



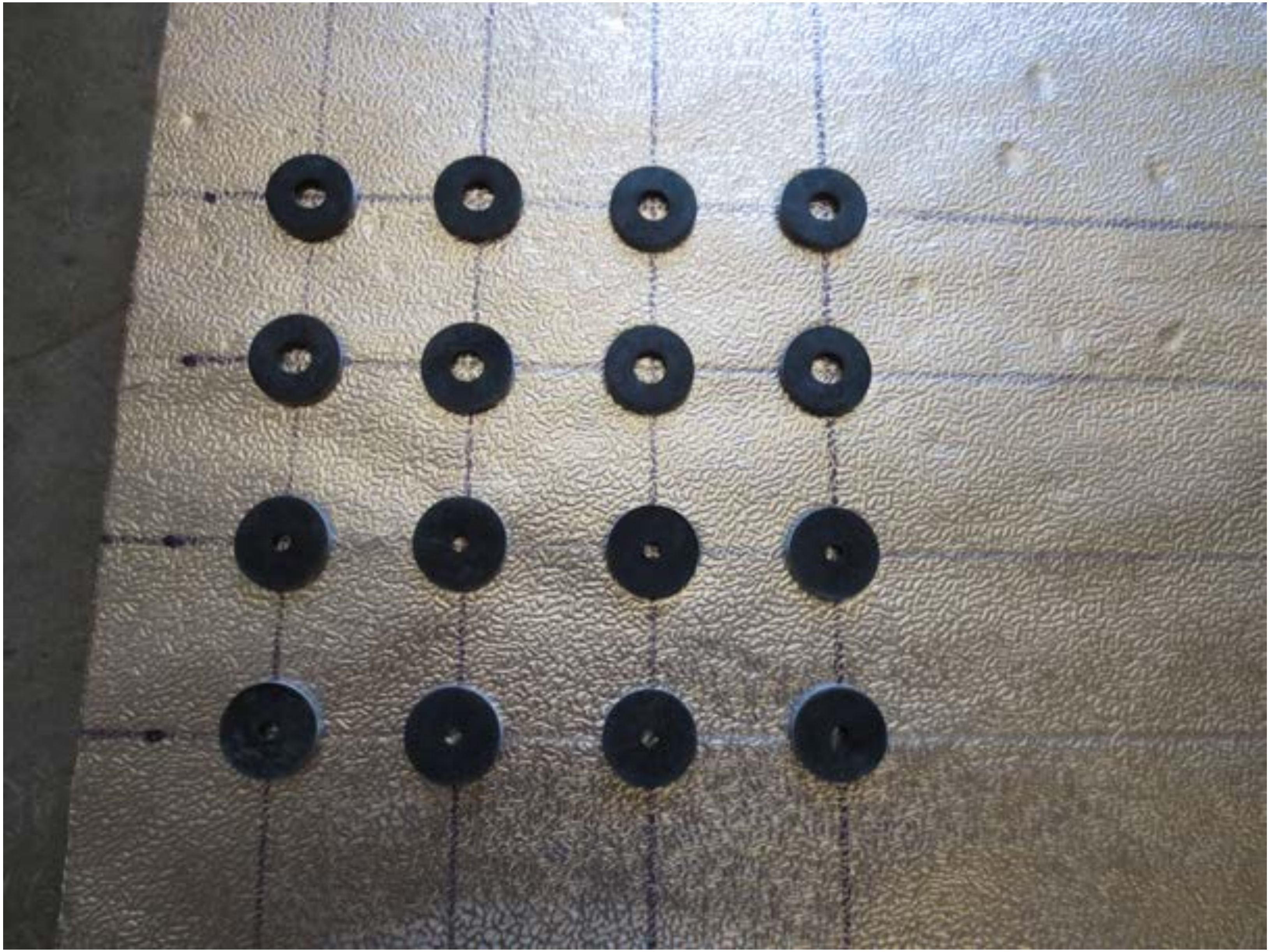
Plywood/OSB sheathing
Water control layer
3/8" spacer strip



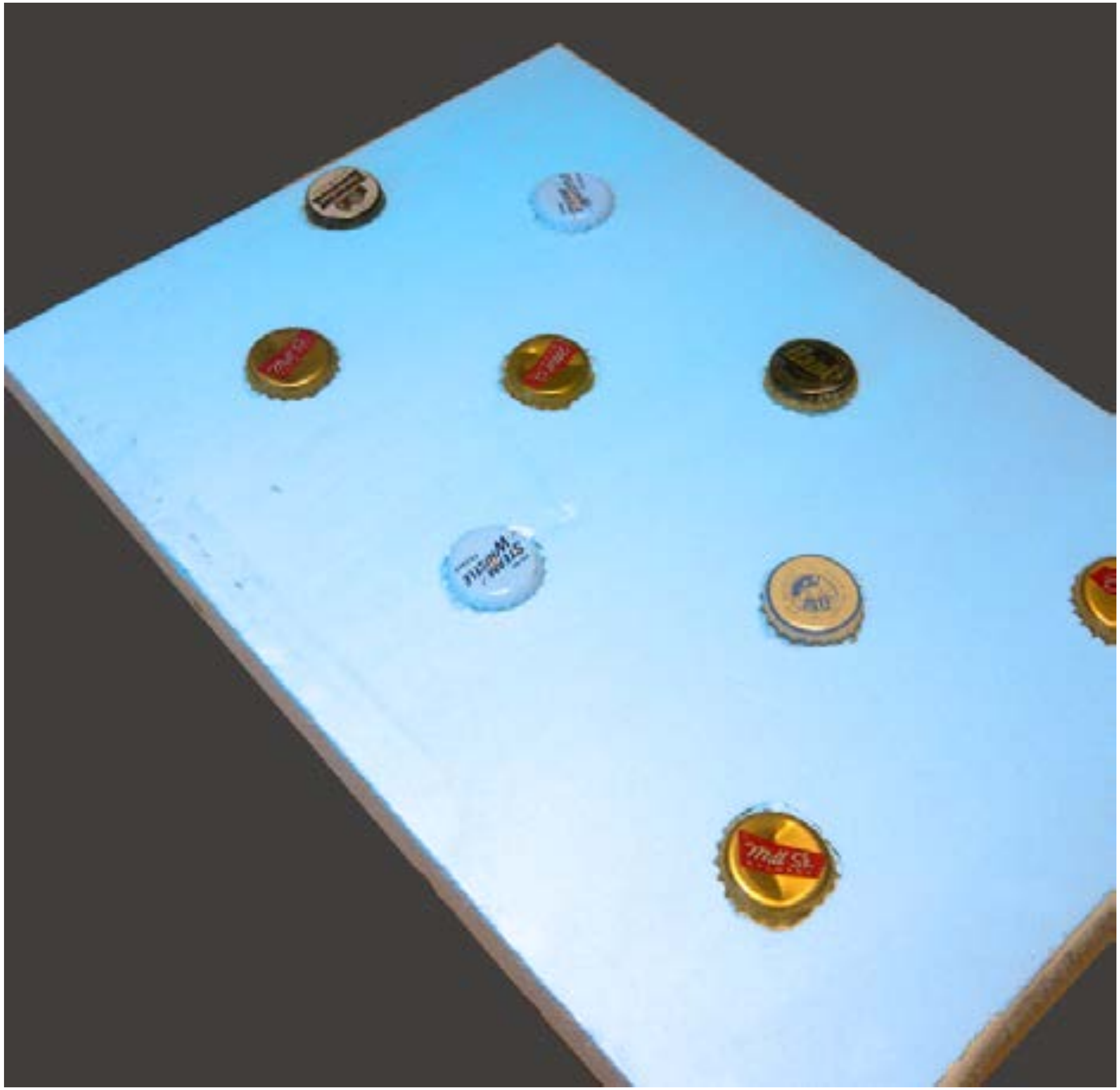

Tyvek
Tyvek
PONT



Rain Screen



Beer Screen?



All We Have To Figure Out Is How Much Hits The Wall

We use Straube/Kuenzel to determine how much rain water impinges on the wall.

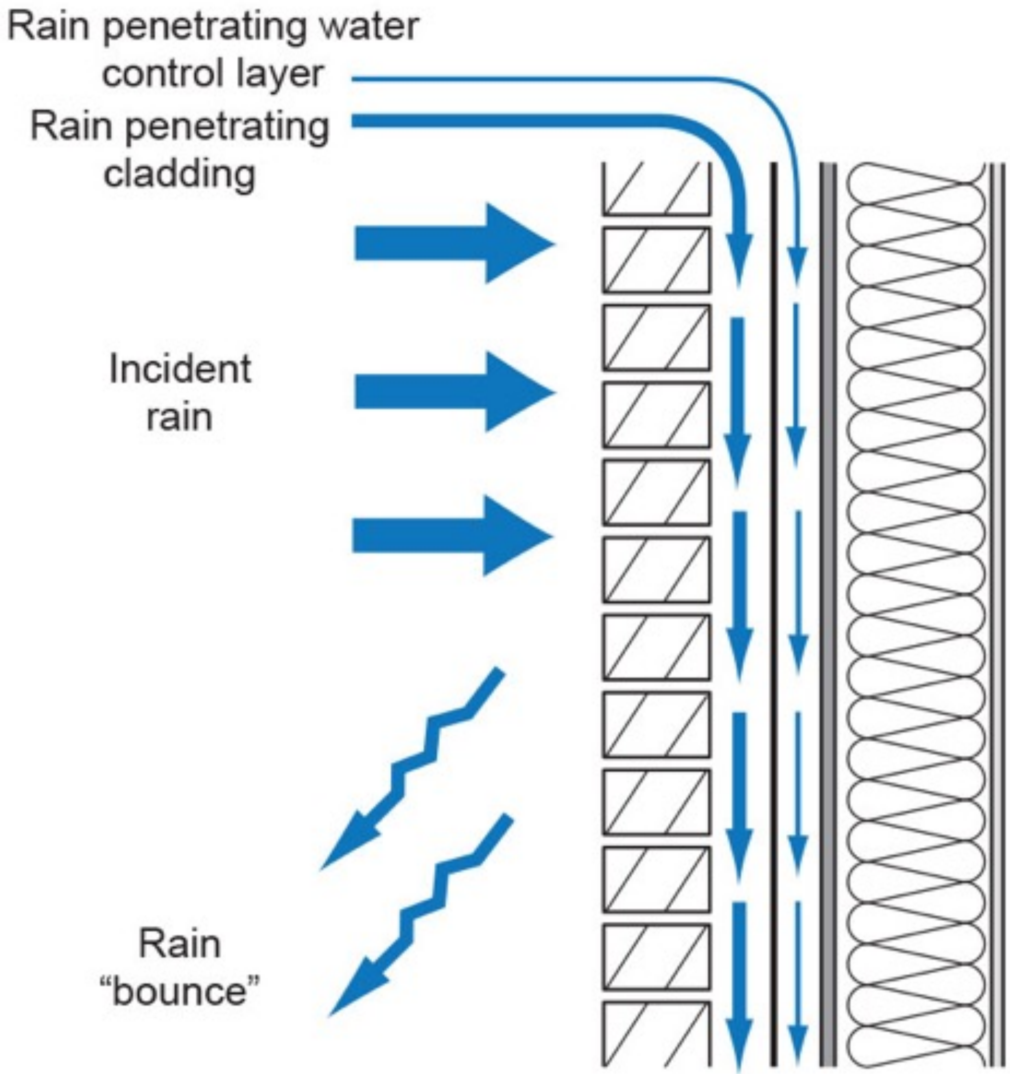
We assume 30% bounces off

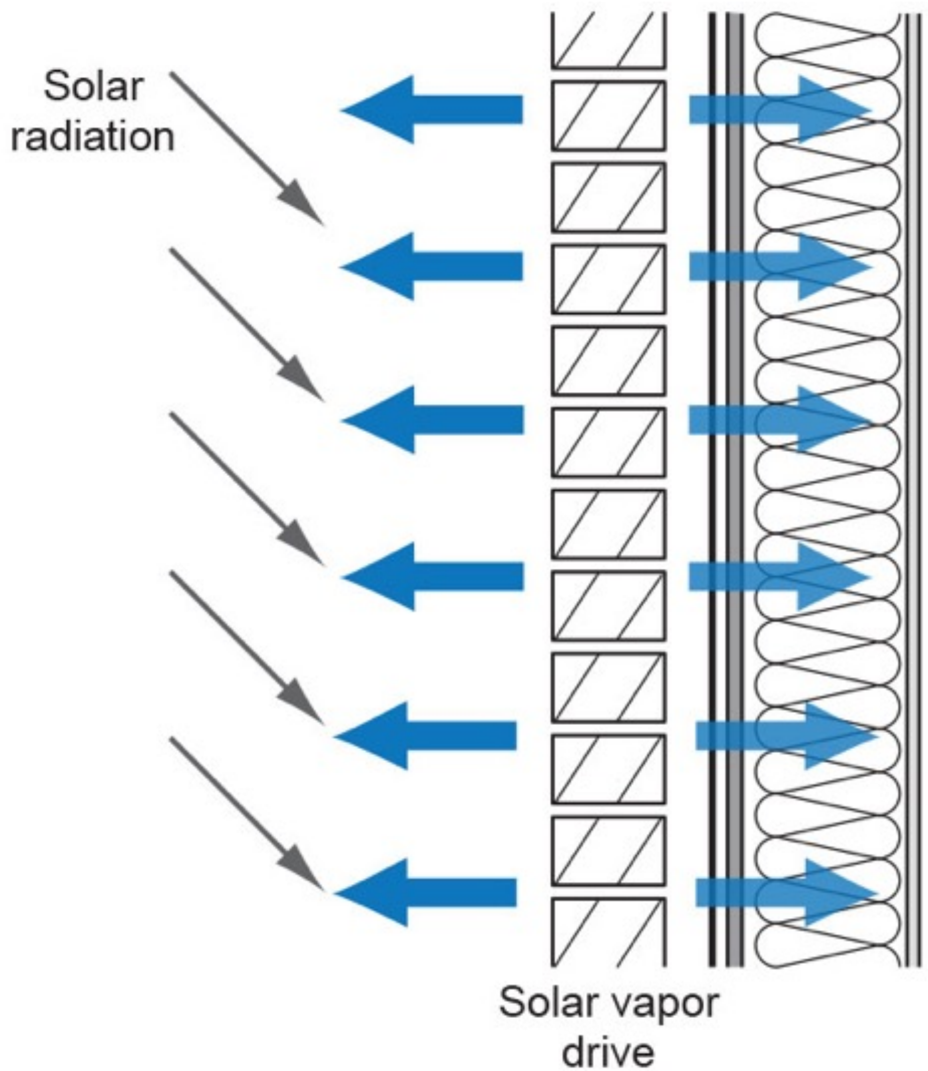
70% stays on the wall.

The 70% that stays on the wall is addressed by liquid conductivity (capillary flow) and vapor diffusion.

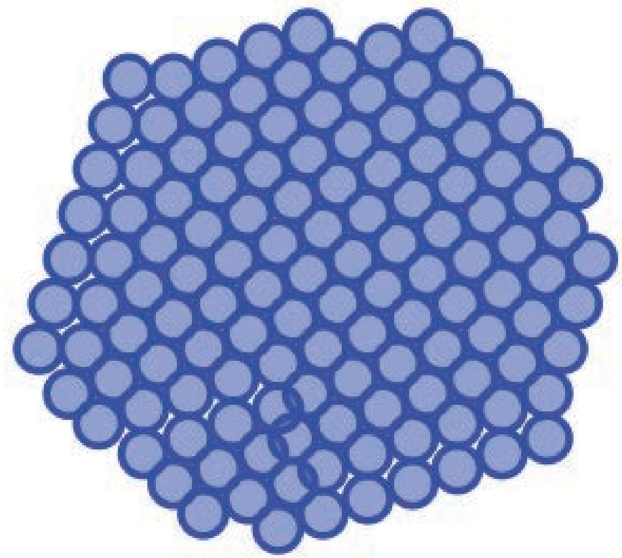
We assume 1% of the 70% penetrates to the back side of the cladding.

We further assume that 1% of the 1% gets past the water control layer into the sheathing.

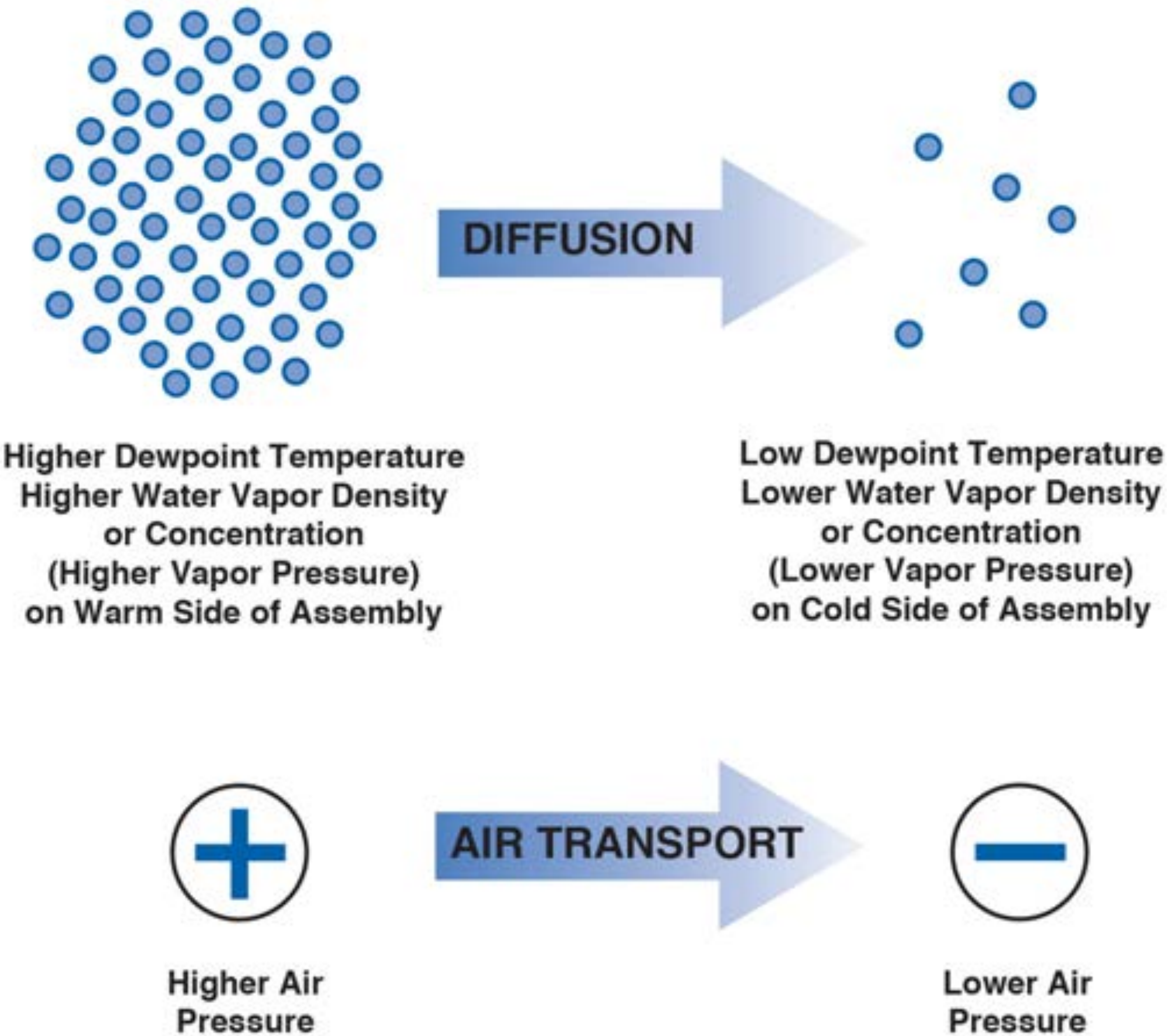

Rain penetrating water control layer
Rain penetrating cladding
Incident rain
Rain "bounce"

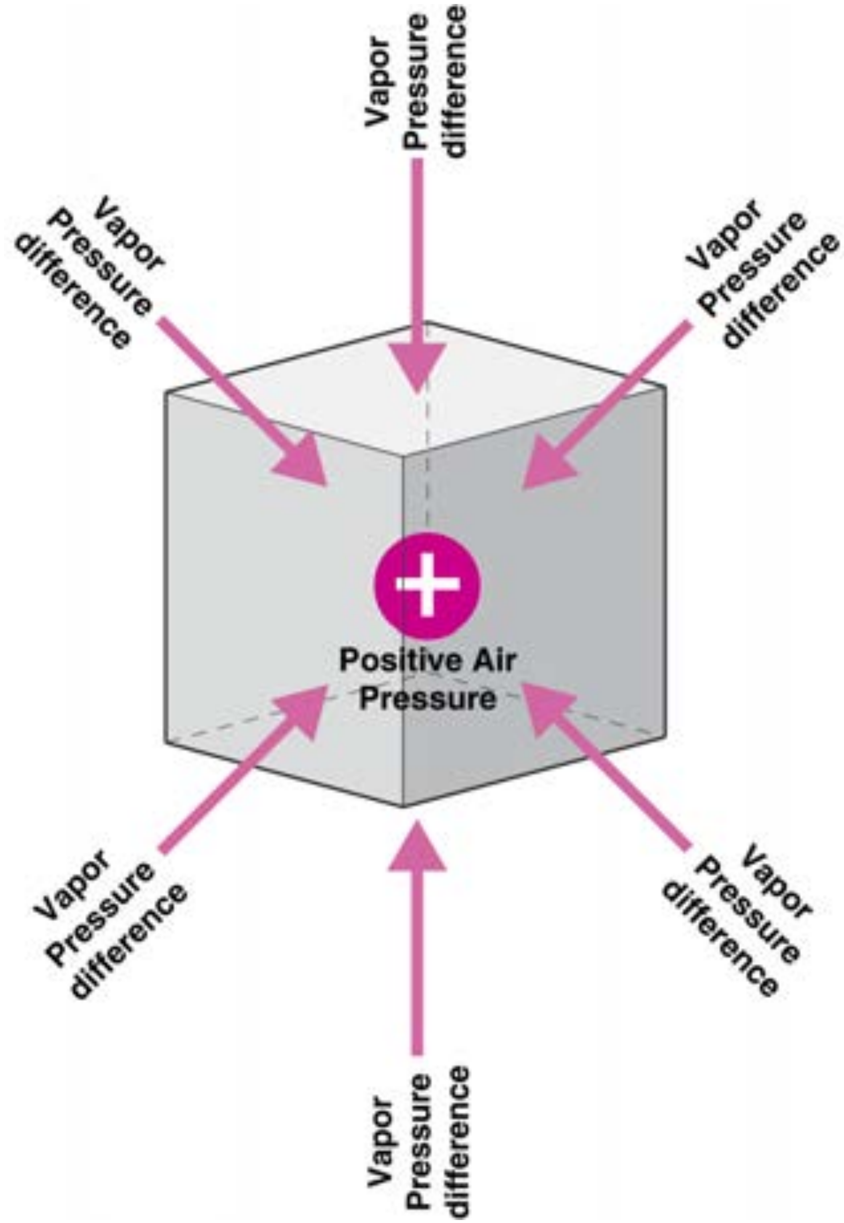

Solar
radiation
Solar vapor
drive

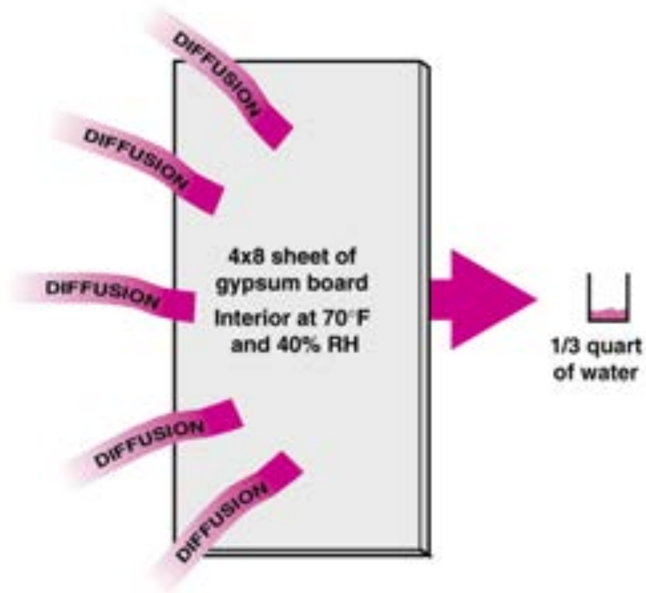
Vapor

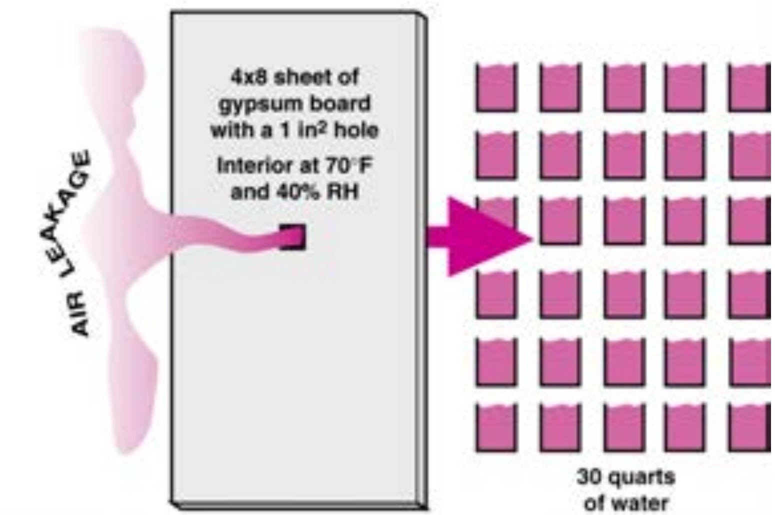


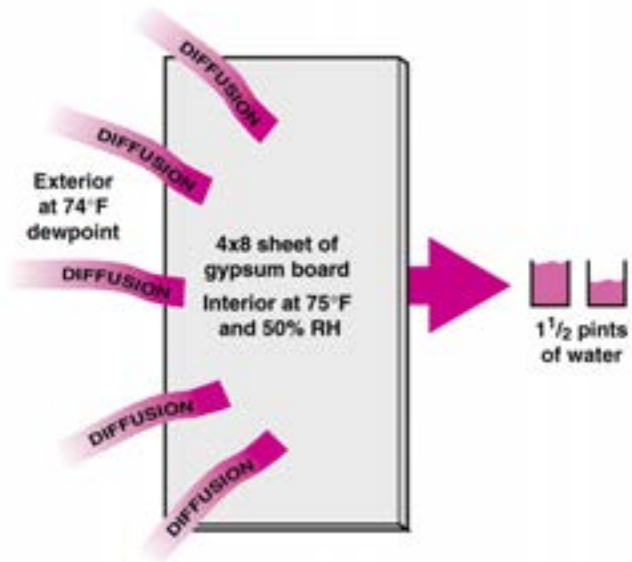
Liquid

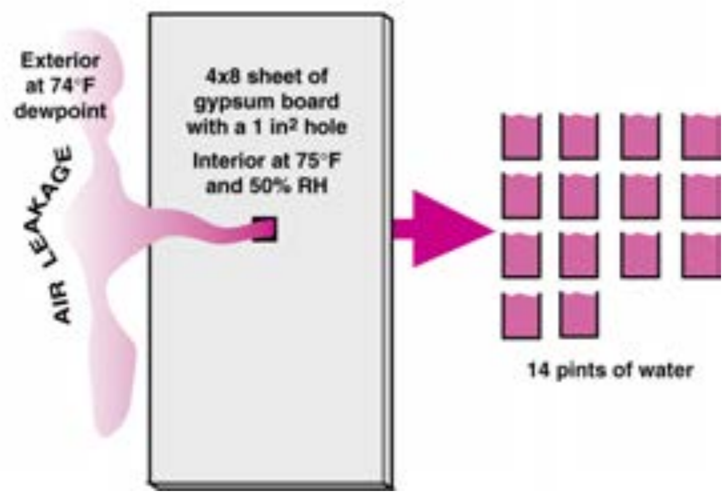

DIFFUSION
Higher Dewpoint Temperature
Higher Water Vapor Density
or Concentration
(Higher Vapor Pressure)
on Warm Side of Assembly
Low Dewpoint Temperature
Lower Water Vapor Density
or Concentration
(Lower Vapor Pressure)
on Cold Side of Assembly
AIR TRANSPORT
Higher Air
Pressure
Lower Air
Pressure

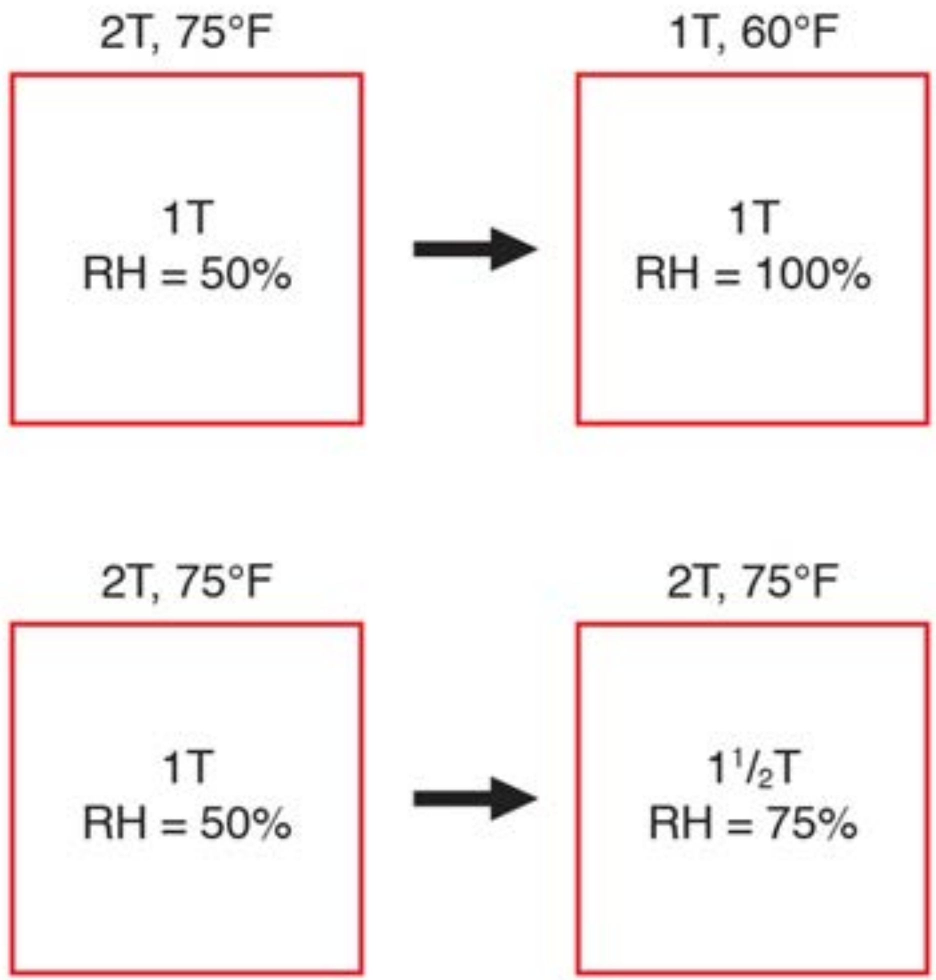

Vapor Pressure difference
Vapor Pressure difference
Vapor Pressure difference
Positive Air Pressure
Vapor Pressure difference
Vapor Pressure difference
Vapor Pressure difference

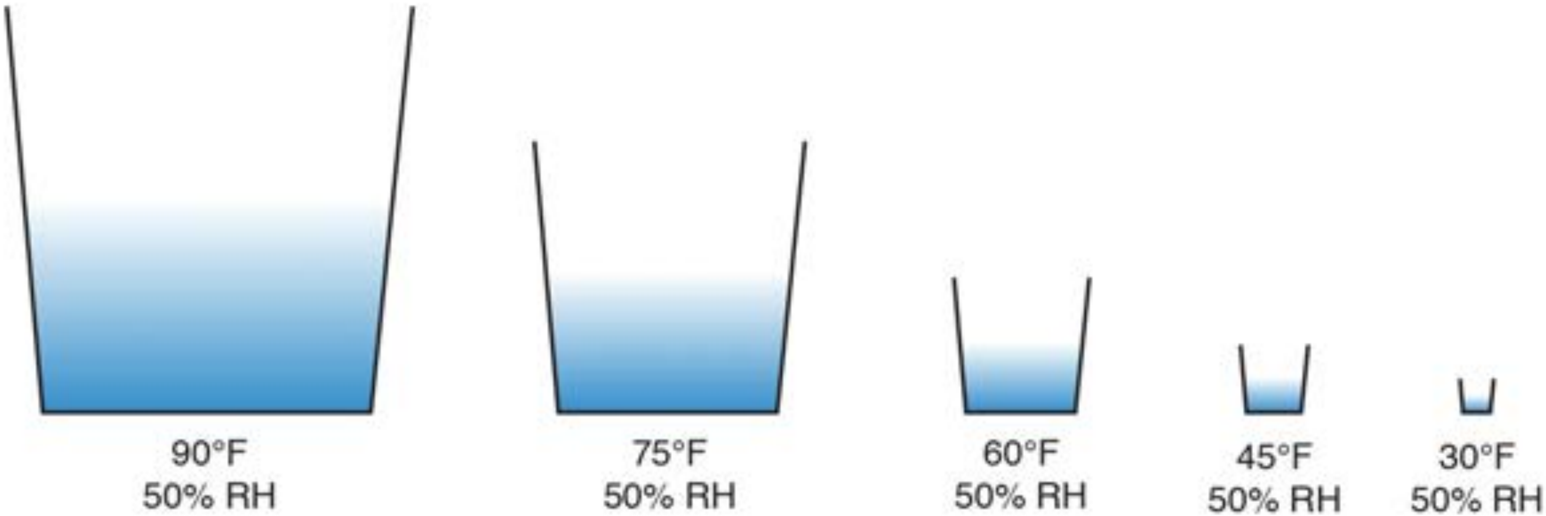

DIFFUSION
DIFFUSION
DIFFUSION
DIFFUSION
DIFFUSION
4x8 sheet of
gypsum board
Interior at 70°F
and 40% RH
1/3 quart
of water

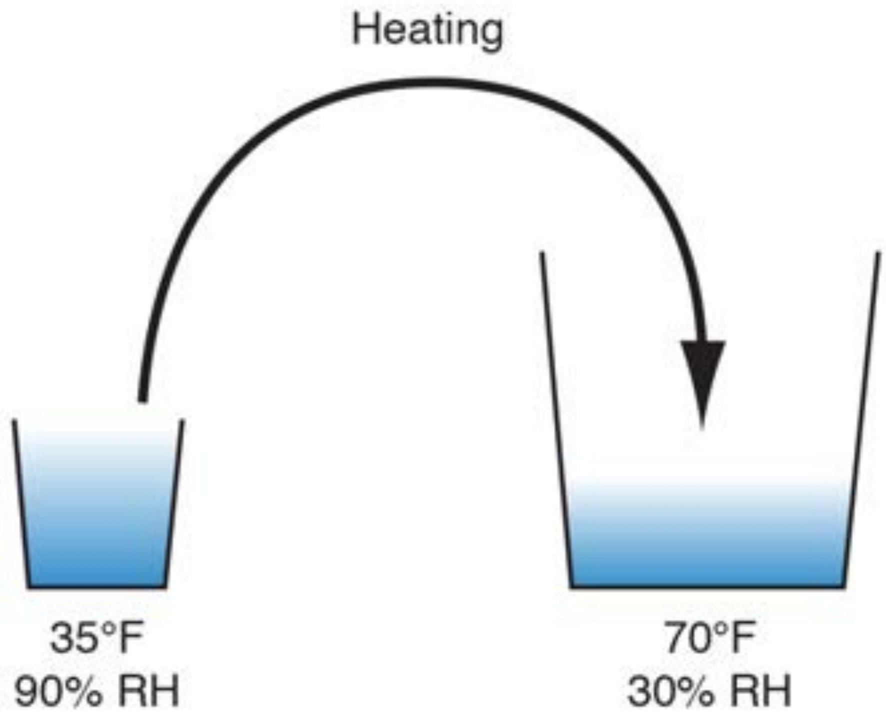

AIR LEAKAGE
4x8 sheet of
gypsum board
with a 1 in2 hole
Interior at 70°F
and 40% RH
30 quarts
of water

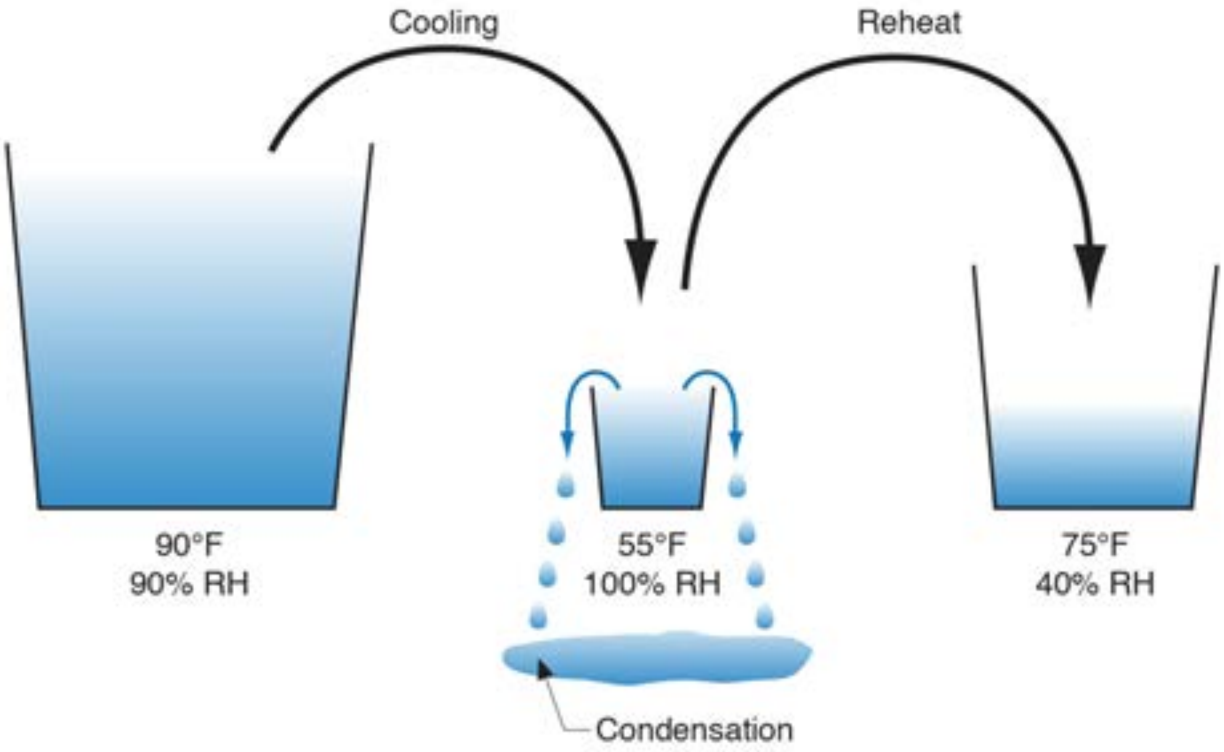

DIFFUSION
DIFFUSION
Exterior
at 74°F
dewpoint
DIFFUSION
4x8 sheet of
gypsum board
Interior at 75°F
and 50% RH
1 1/2 pints
of water
DIFFUSION
DIFFUSION

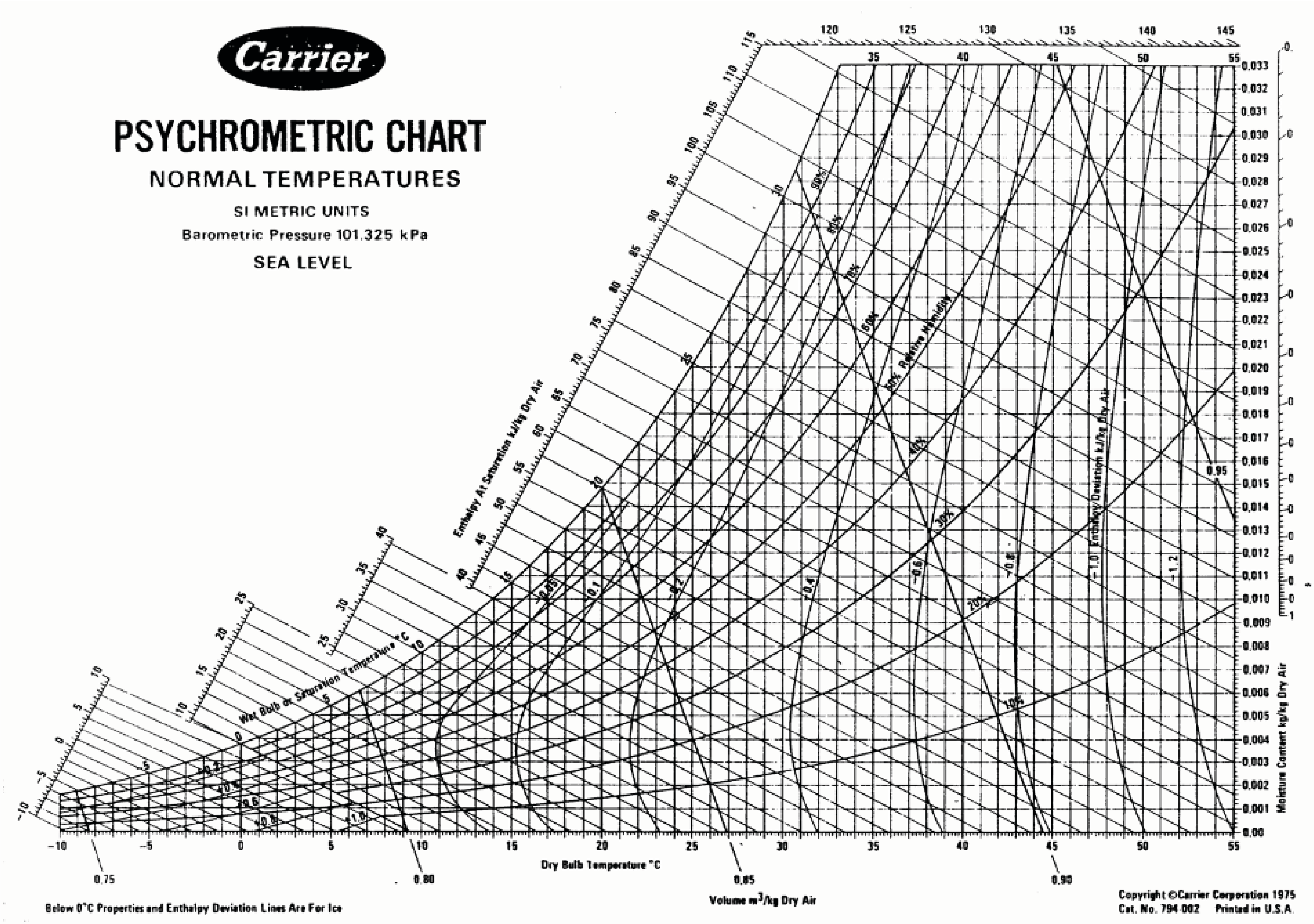

Exterior
at 74°F
dewpoint
4x8 sheet of
gypsum board
with a 1 in² hole
Interior at 75°F
and 50% RH
AIR LEAKAGE
14 pints of water


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

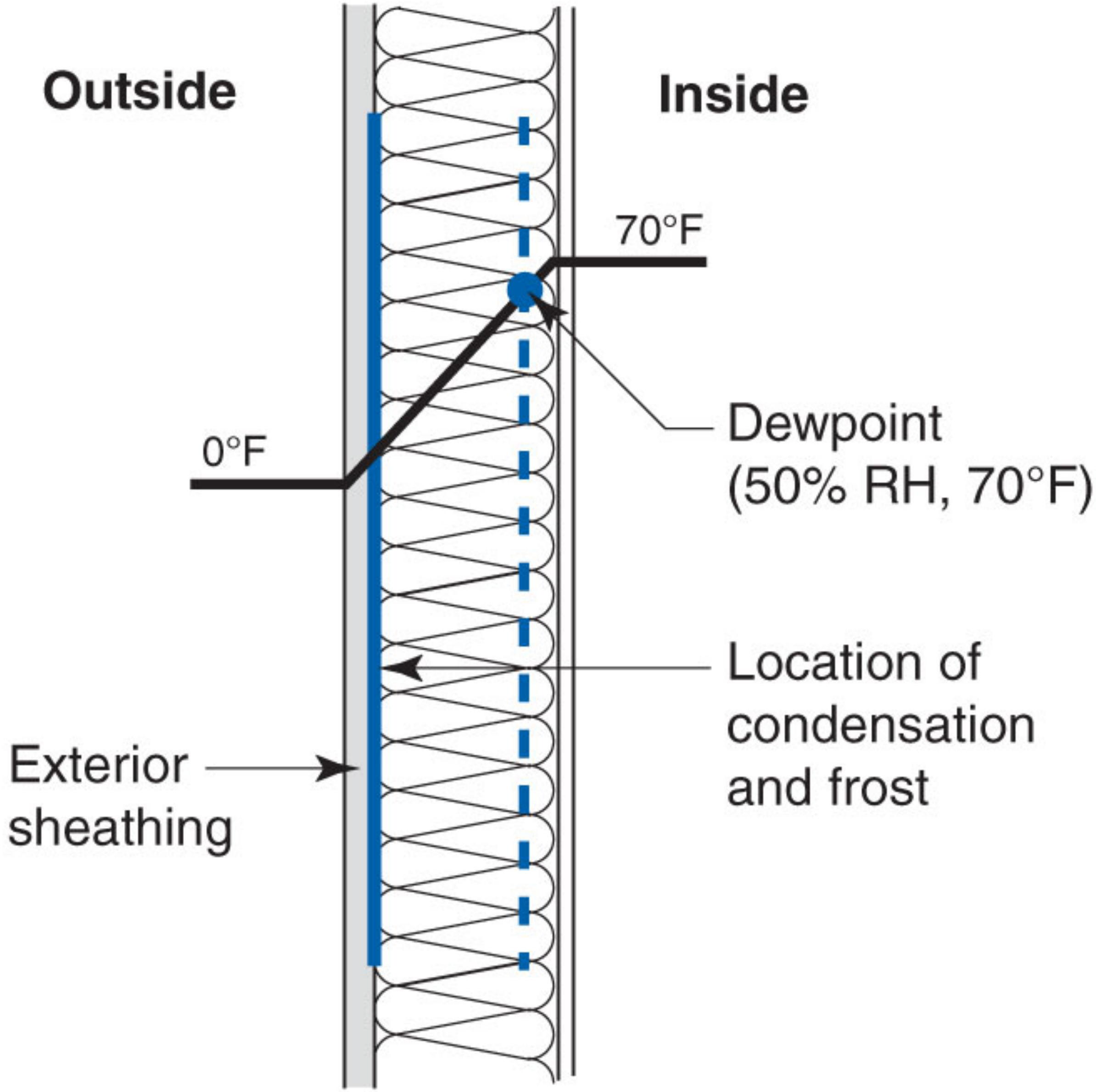

90°F
50% RH
75°F
50% RH
60°F
50% RH
45°F
50% RH
30°F
50% RH

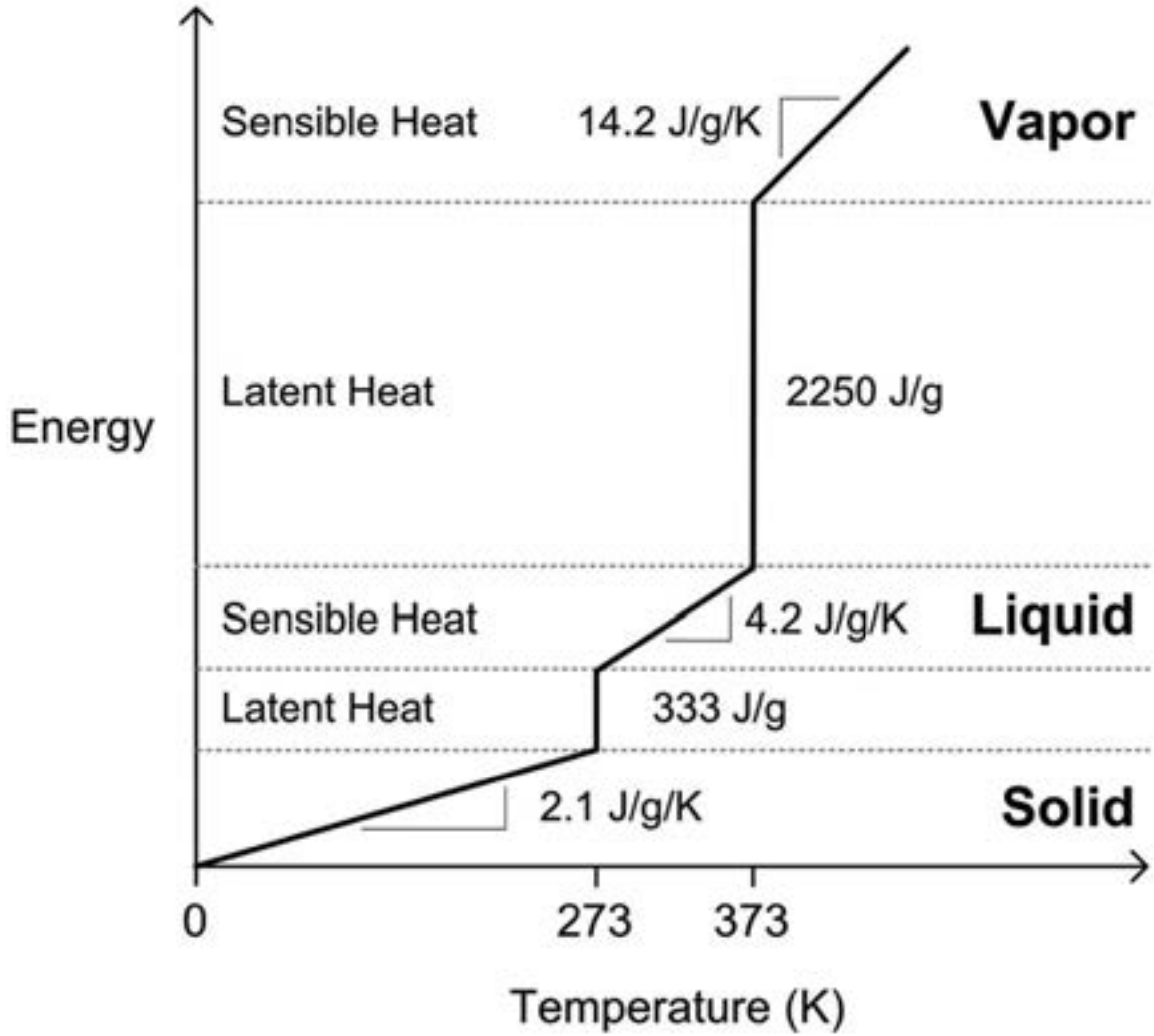

Heating
35°F
90% RH
70°F
30% RH


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


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
Enthalpy Deviation kJ/kg Dry Air
Relative Humidity
Below 0°C Properties and Enthalpy Deviation Lines Are For Ice
Copyright ©Carrier Corporation 1975
Cat. No. 794-002 Printed in U.S.A.

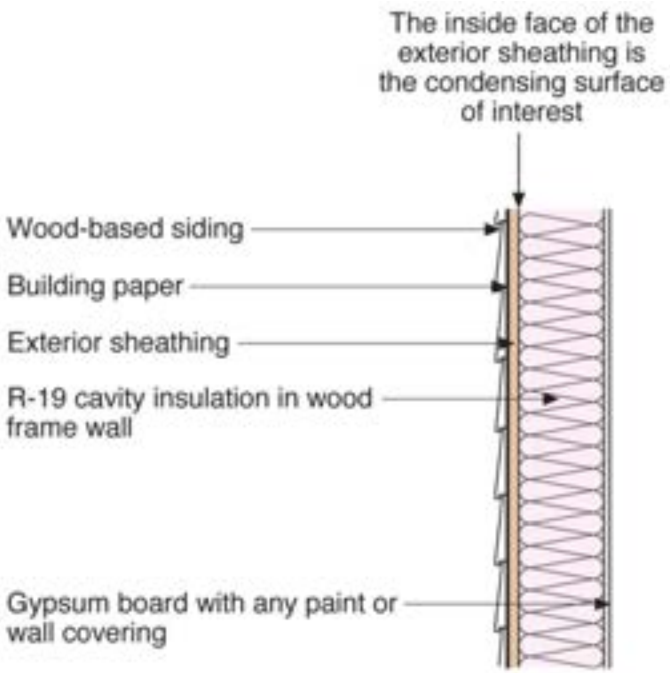
Don’t Do Stupid Things

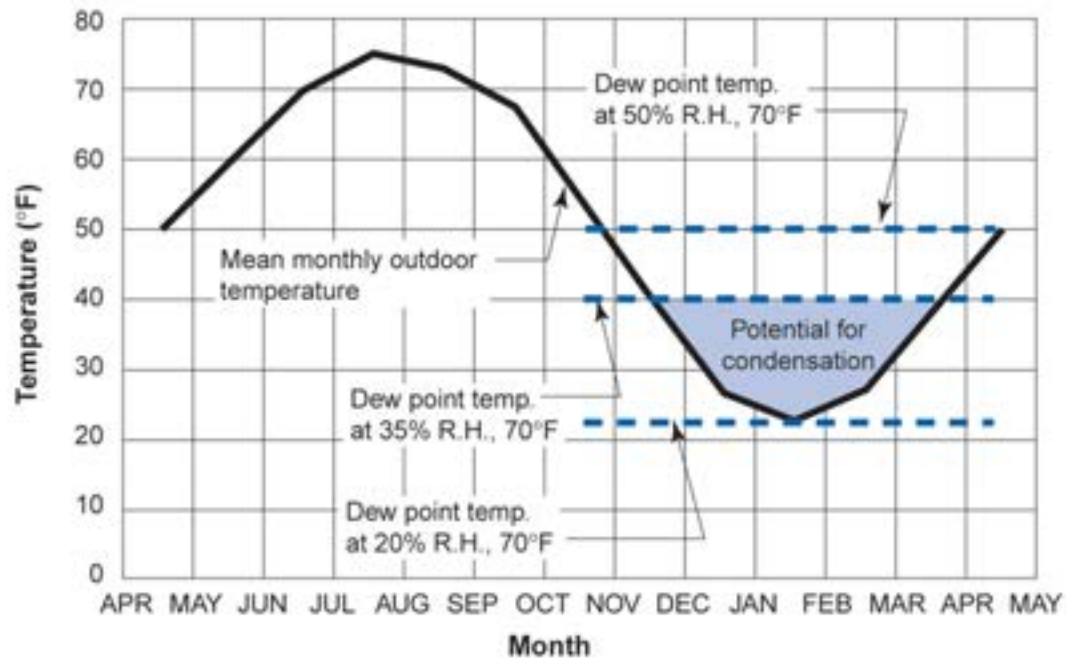

Outside
Inside
70°F
0°F
Dewpoint
(50% RH, 70°F)
Location of
condensation
and frost
Exterior
sheathing

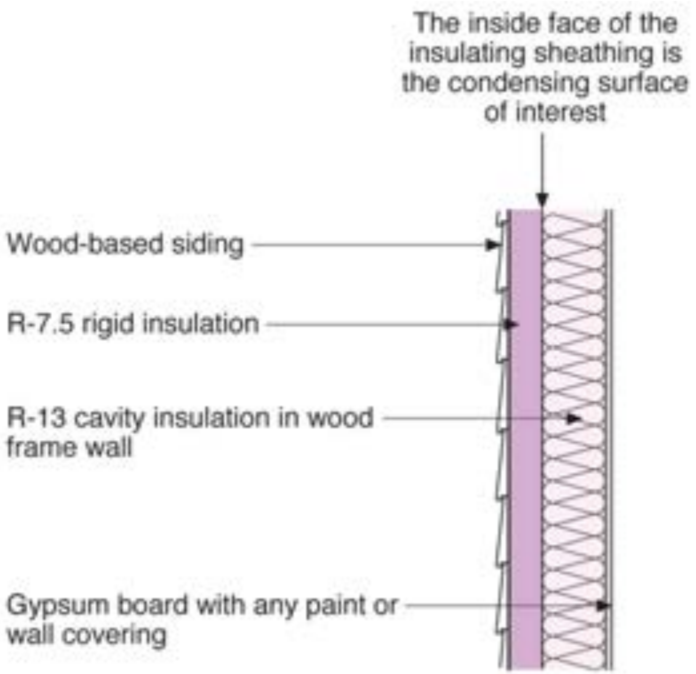


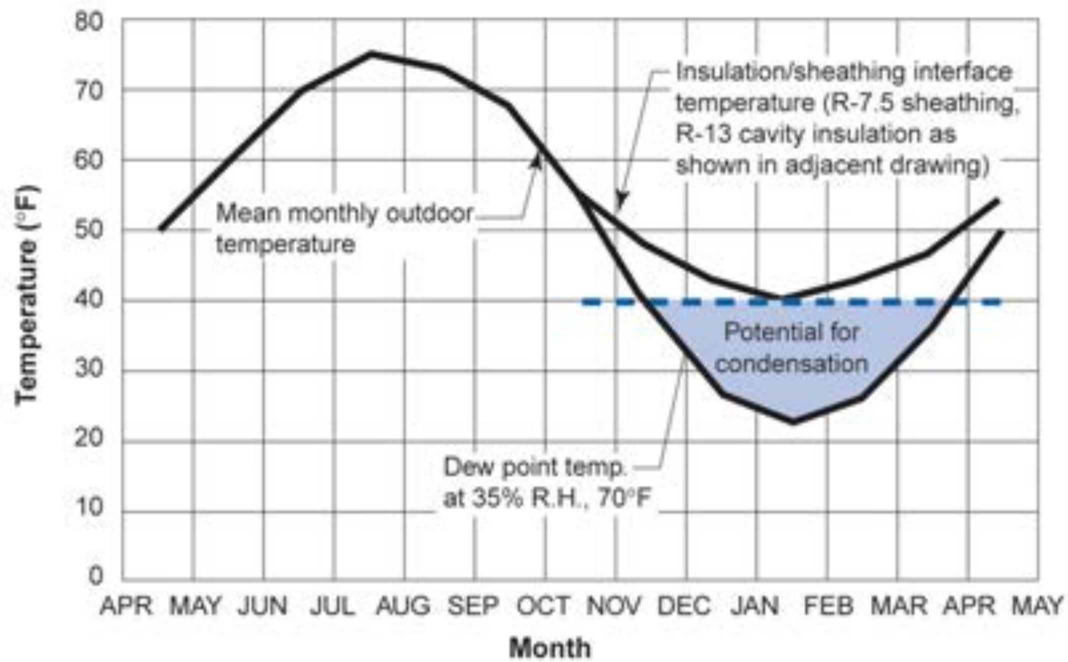
Simple linearized energy-temperature relation for water

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

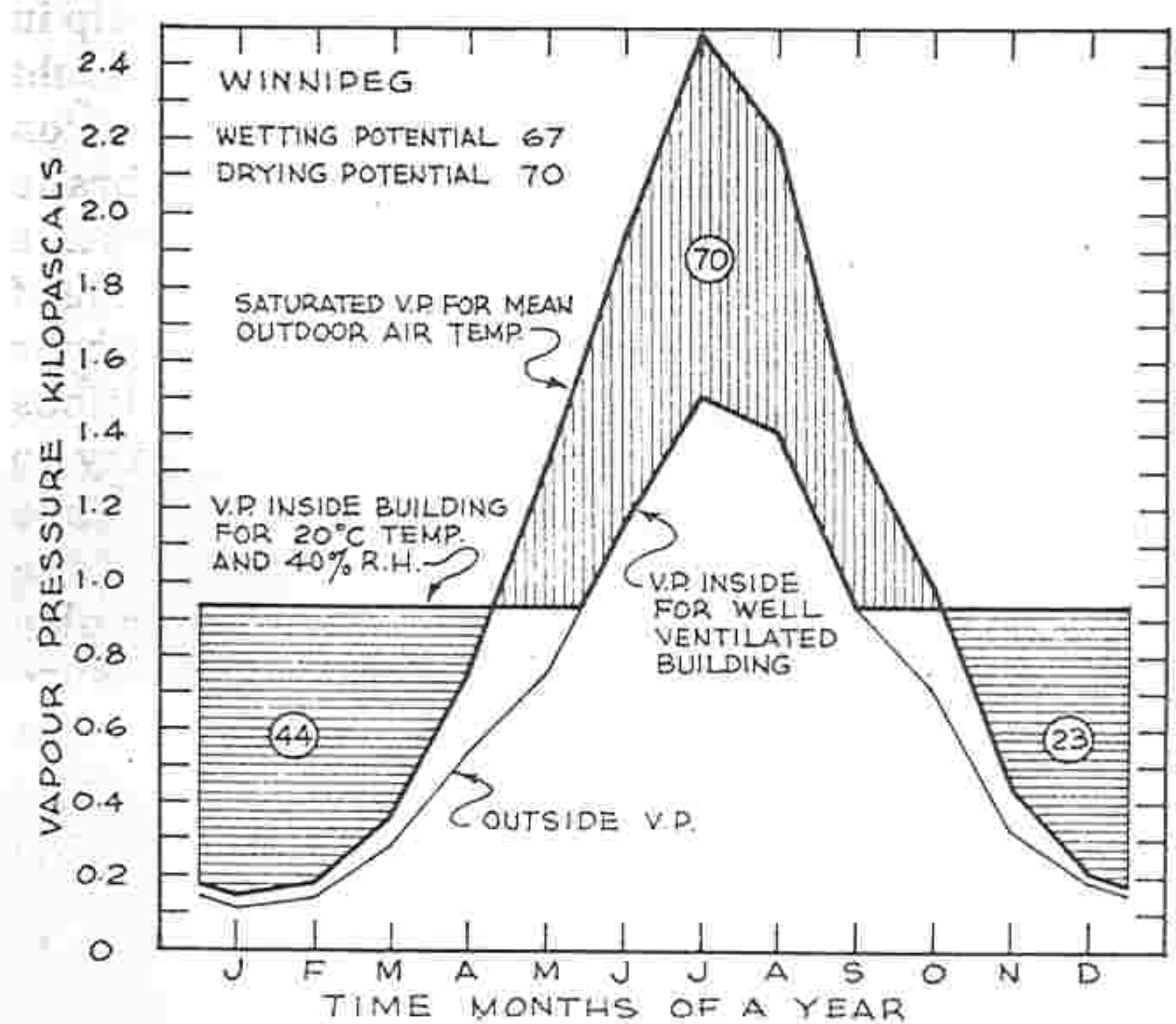
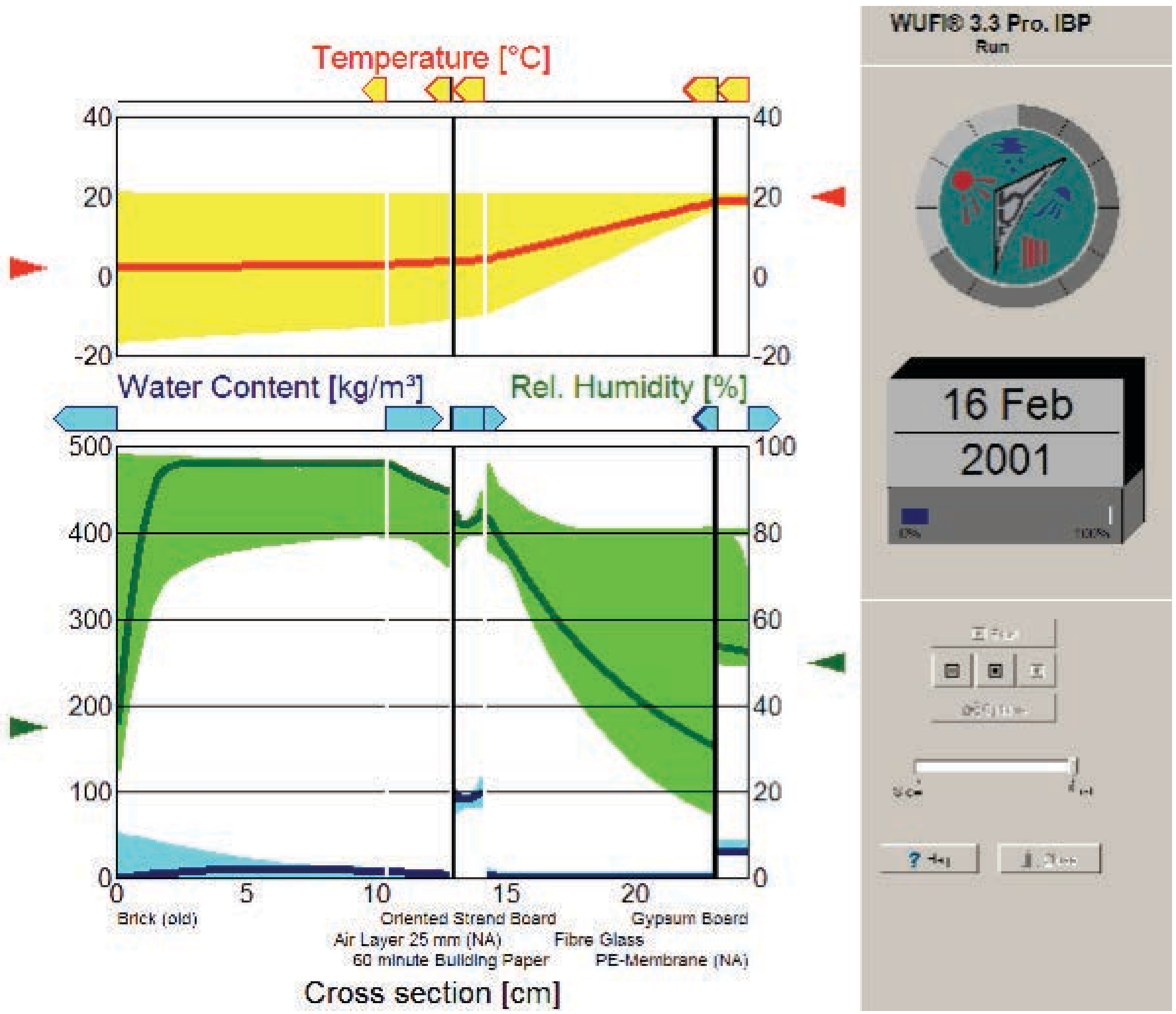
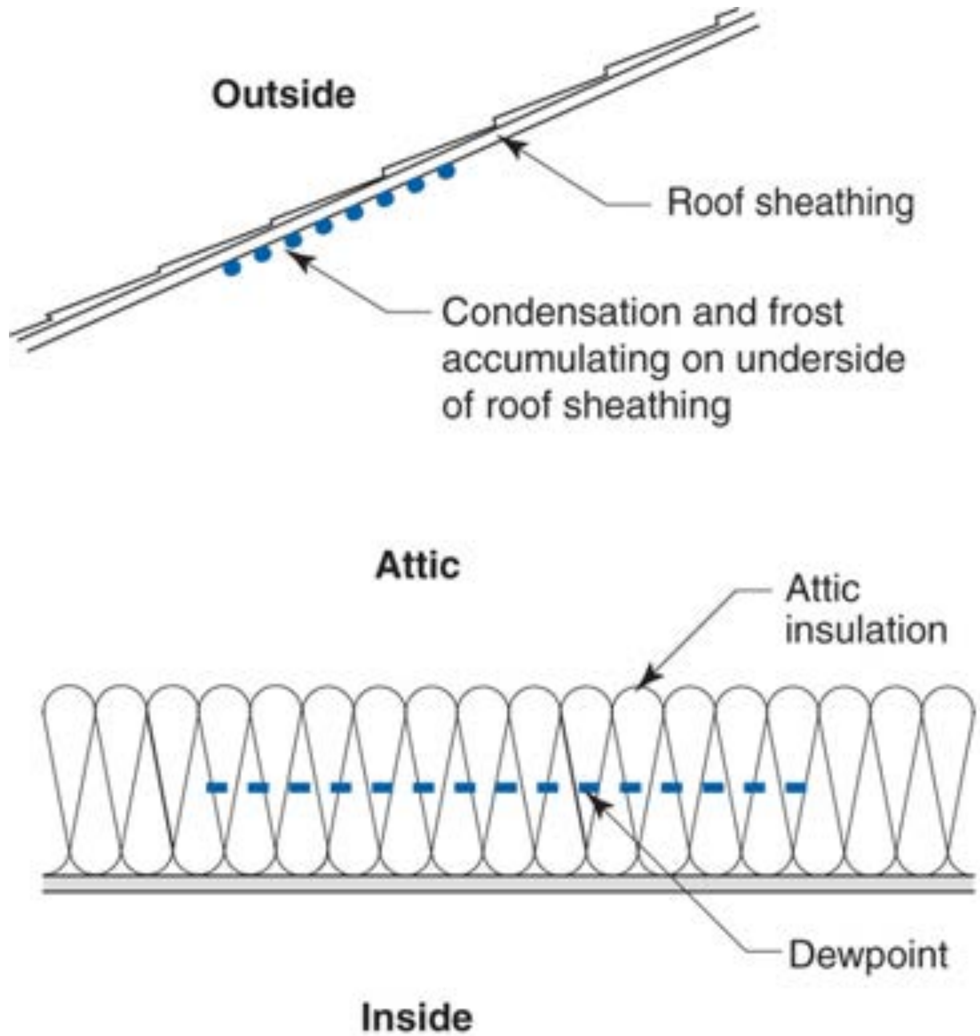
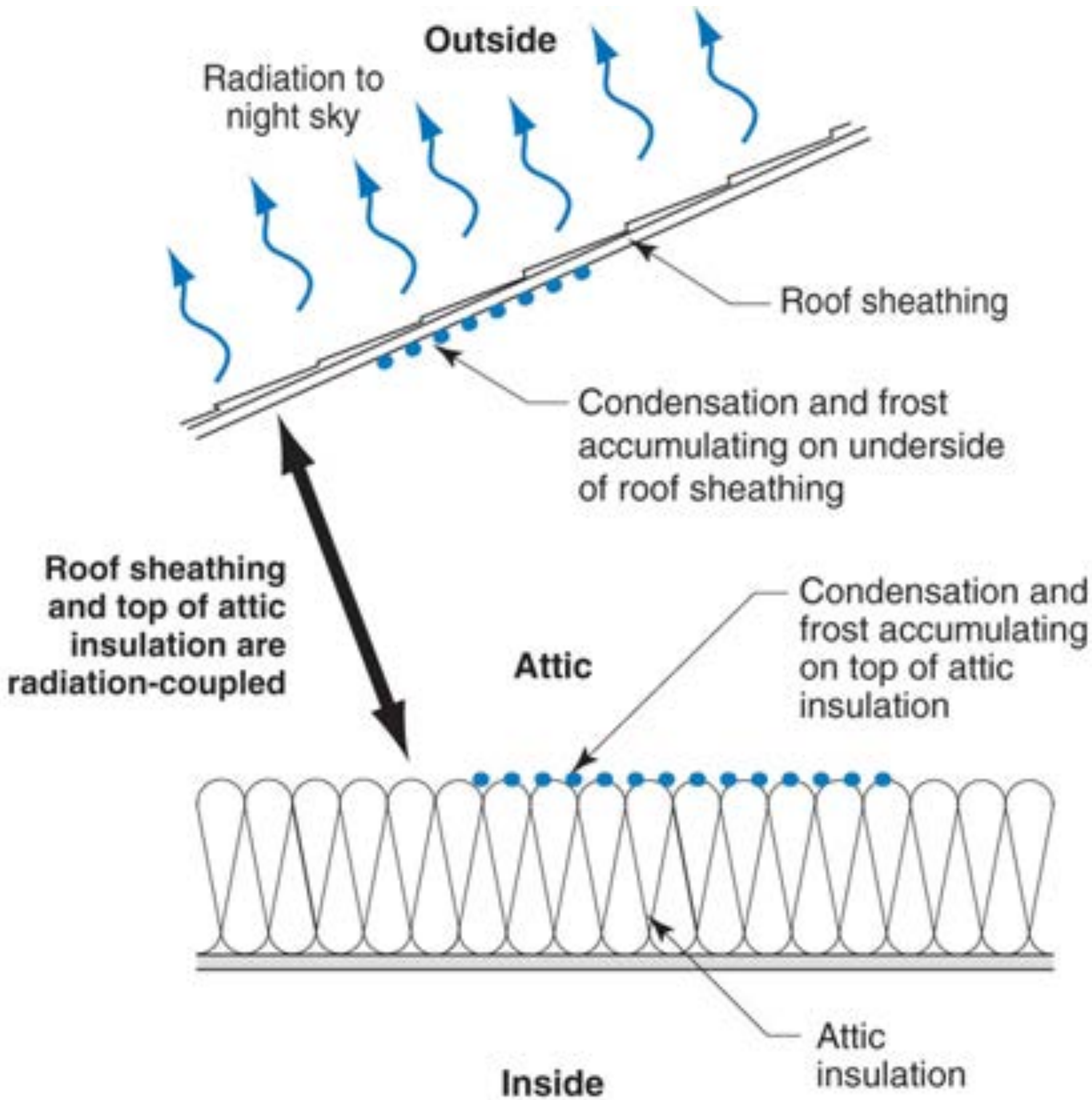


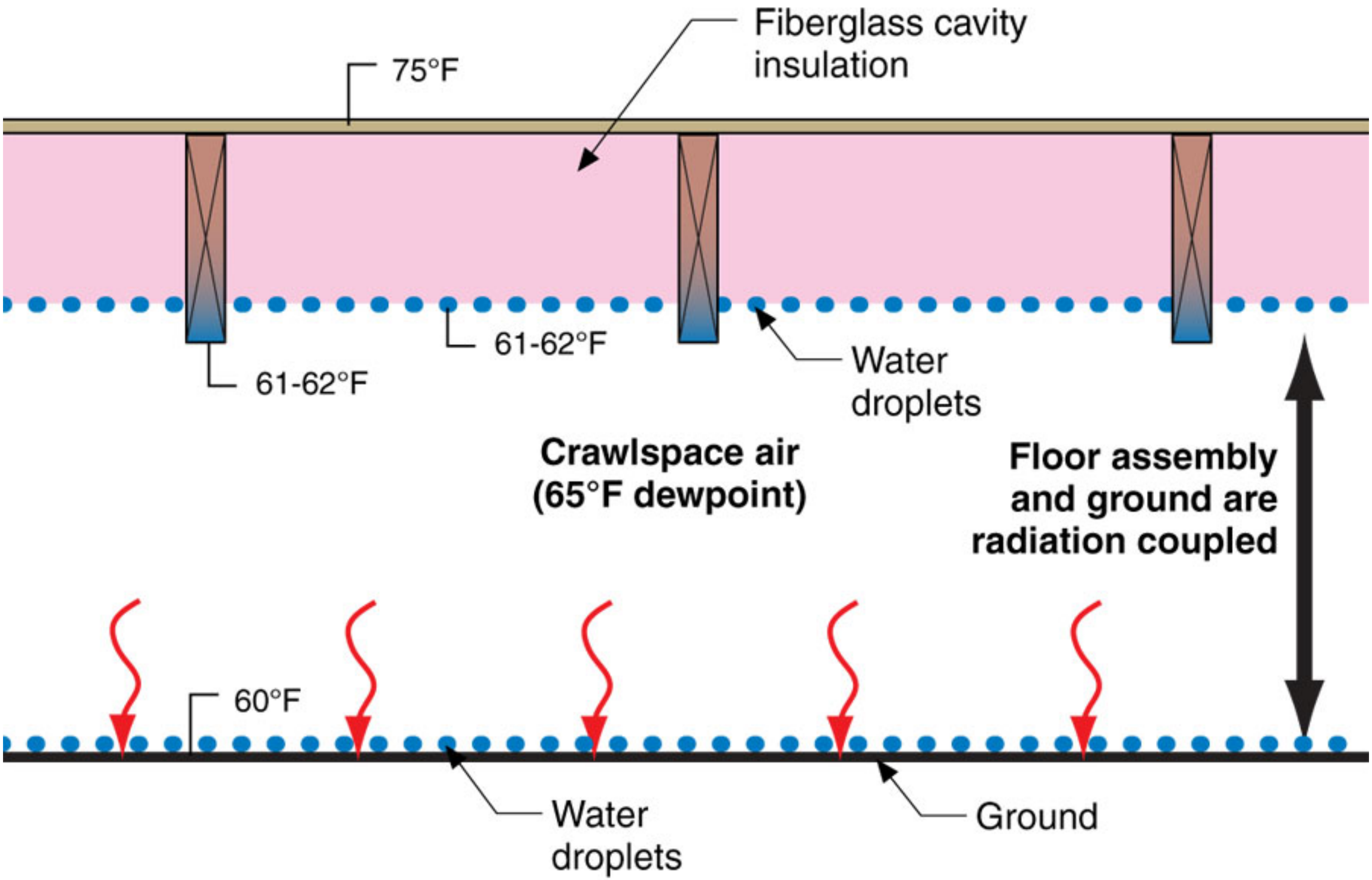
Figure 8-7. Outside vapour pressure, saturated vapour pressure and inside vapour pressure for Winnipeg.

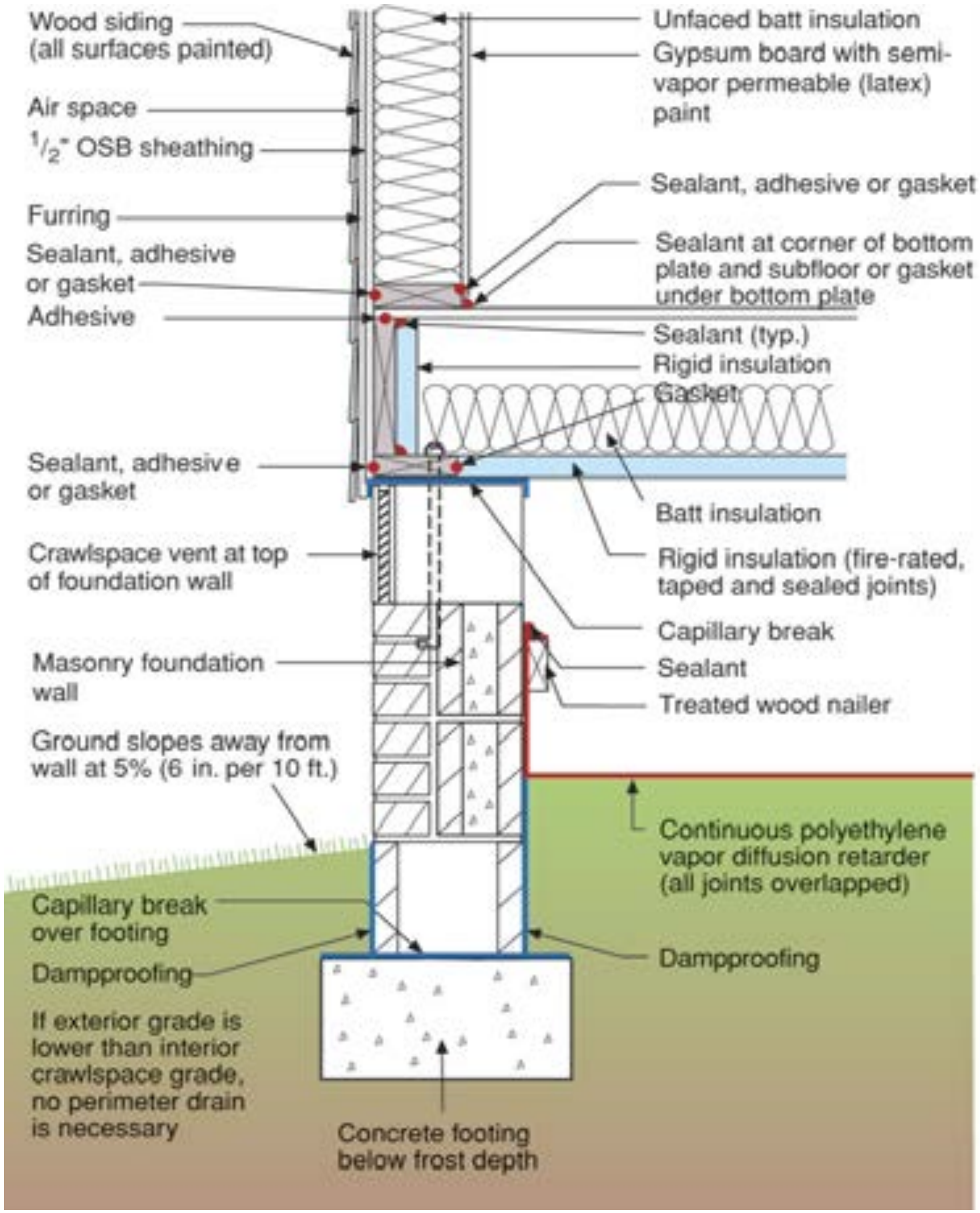


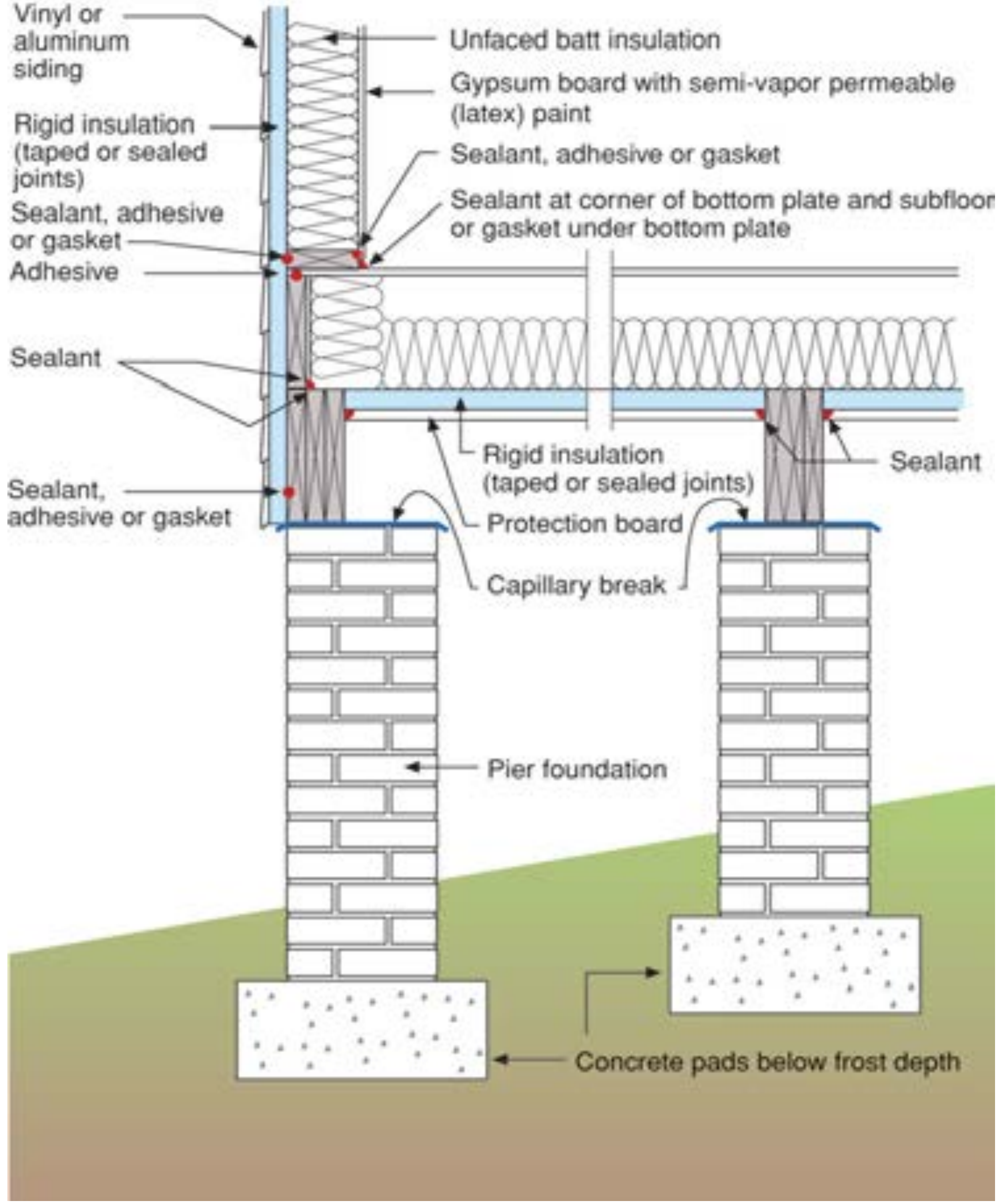
Temperature [°C]
40
20
0
-20
Water Content [kg/m³]
Rel. Humidity [%]
500
400
300
200
100
0
100
80
60
40
20
0
5
10
15
20
Brick (old)
Oriented Strand Board
Gypsum Board
Air Layer 25 mm (NA)
Fibre Glass
60 minute Building Paper
PE-Membrane (NA)
Cross section [cm]
WUFI® 3.3 Pro. IBP
Run
16 Feb
2001


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


Fiberglass cavity insulation
75°F
61-62°F
61-62°F
Water droplets
Crawlspace air (65°F dewpoint)
Floor assembly and ground are radiation coupled
60°F
Water droplets
Ground


Wood siding
(all surfaces painted)
Air space
1/2" OSB sheathing
Furring
Sealant, adhesive
or gasket
Adhesive
Sealant, adhesive
or gasket
Crawlspace vent at top
of foundation wall
Masonry foundation
wall
Ground slopes away from
wall at 5% (6 in. per 10 ft.)
Capillary break
over footing
Dampproofing
If exterior grade is
lower than interior
crawlspace grade,
no perimeter drain
is necessary
Concrete footing
below frost depth
Unfaced batt insulation
Gypsum board with semi-
vapor permeable (latex)
paint
Sealant, adhesive or gasket
Sealant at corner of bottom
plate and subfloor or gasket
under bottom plate
Sealant (typ.)
Rigid insulation
Gasket
Batt insulation
Rigid insulation (fire-rated,
taped and sealed joints)
Capillary break
Sealant
Treated wood nailer
Continuous polyethylene
vapor diffusion retarder
(all joints overlapped)
Dampproofing


Vinyl or aluminum siding
Rigid insulation (taped or sealed joints)
Sealant, adhesive or gasket
Adhesive
Sealant
Sealant, adhesive or gasket
Unfaced batt insulation
Gypsum board with semi-vapor permeable (latex) paint
Sealant, adhesive or gasket
Sealant at corner of bottom plate and subfloor or gasket under bottom plate
Rigid insulation (taped or sealed joints)
Sealant
Protection board
Capillary break
Pier foundation
Concrete pads below frost depth