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

# Building Science

## Adventures In Building Science

www.buildingscience.com

# Building Science is all about Environmental Separation

# Definition of a Building

- 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

# Things have changed..

# Some Physics….

# Arrhenius Equation

For Every 10 Degree K Rise

Reaction Rate Doubles

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

Damage Functions

Water

Heat

Ultra-violet Radiation

# 2nd Law of Thermodynamics

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

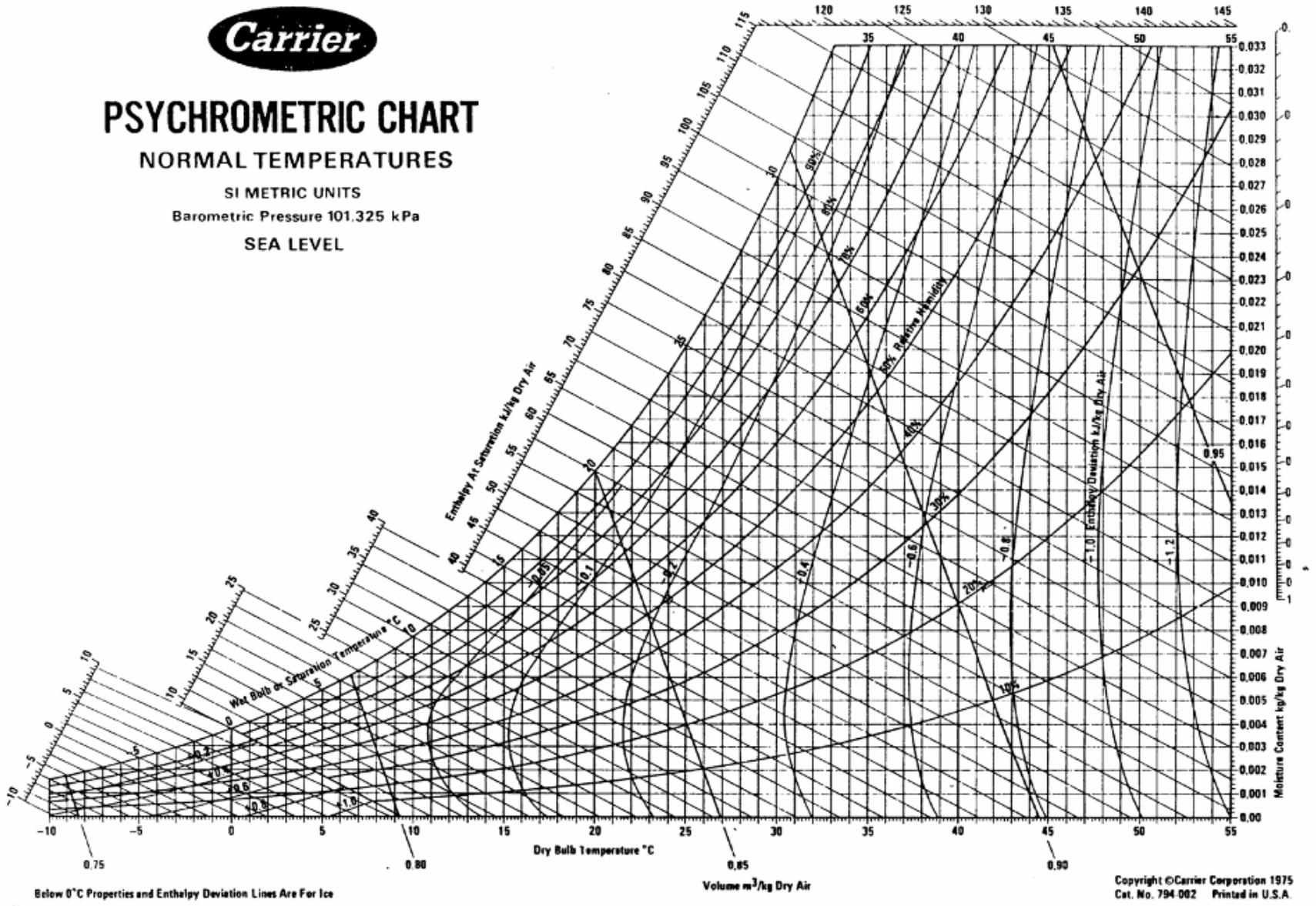
Moisture Flow Is From More To Less

Thermal Gradient – Thermal Diffusion

Concentration Gradient – Molecular Diffusion

Vapor Diffusion

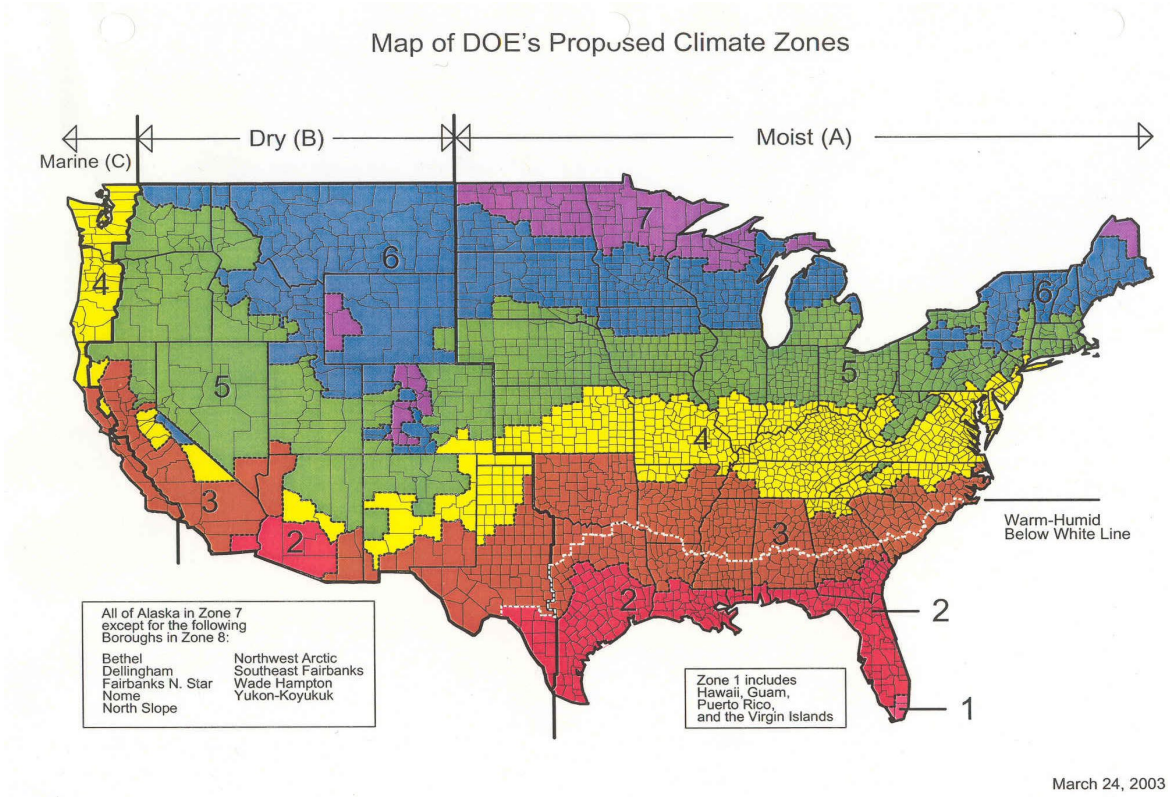
# Thermodynamic Potential

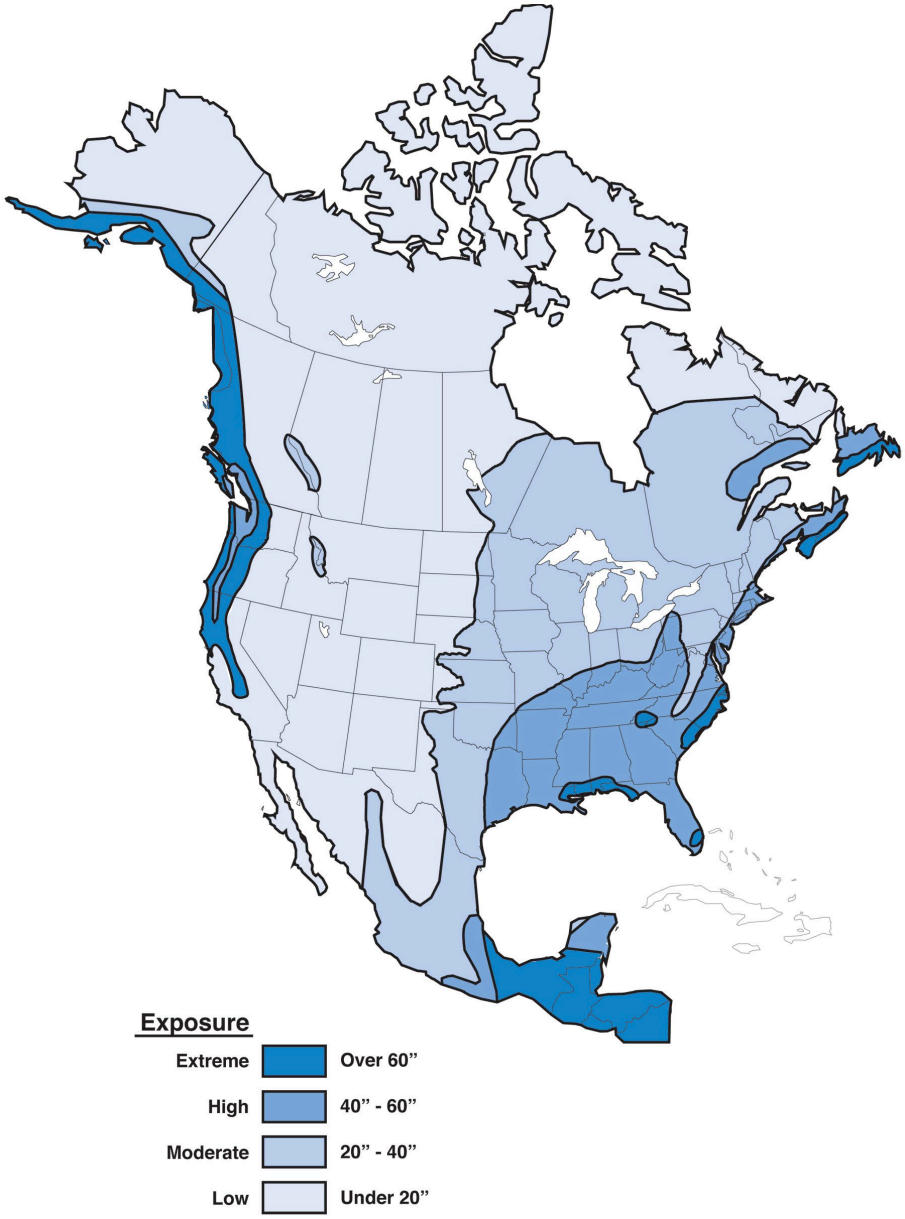

Carrier
PSYCHROMETRIC CHART
NORMAL TEMPERATURES
SI METRIC UNITS
Barometric Pressure 101.325 kPa
SEA LEVEL
Dry Bulb Temperature °C
Wet Bulb or Saturation Temperature °C
Enthalpy At Saturation kJ/kg Dry Air
Moisture Content kg/kg Dry Air
Volume m³/kg Dry Air
Below 0°C Properties and Enthalpy Deviation Lines Are For Ice
Copyright ©Carrier Corporation 1975
Cat. No. 794-002 Printed in U.S.A.

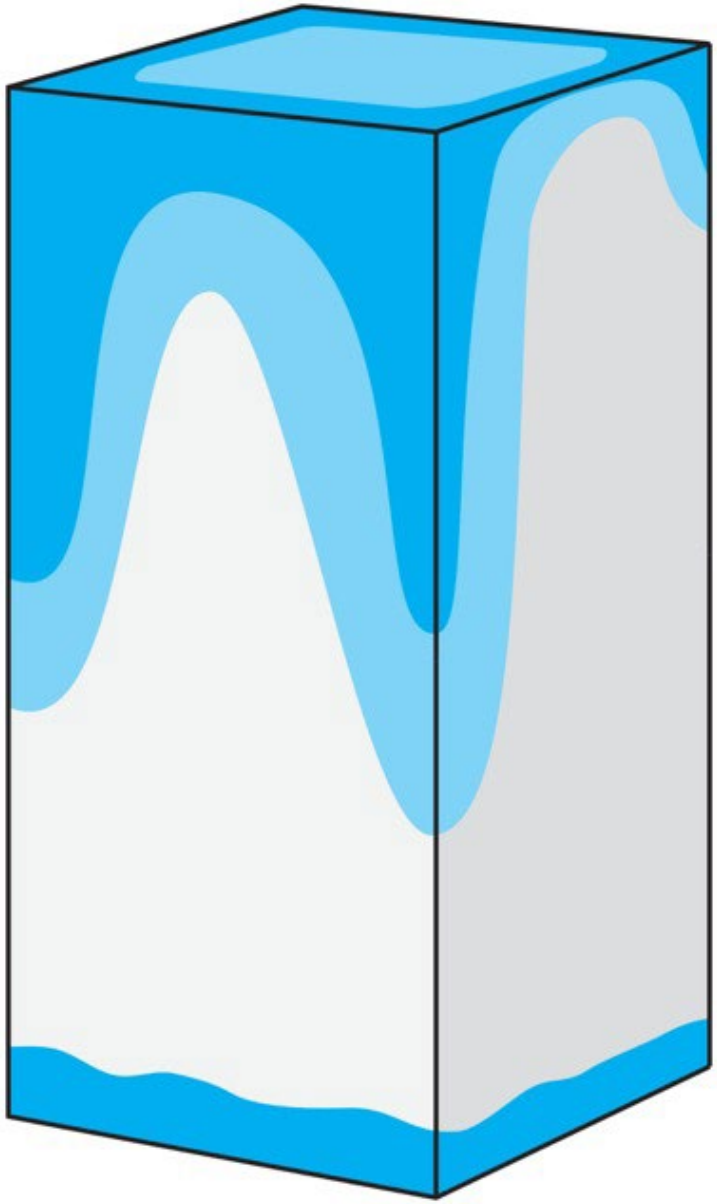
# The Effect of Climate

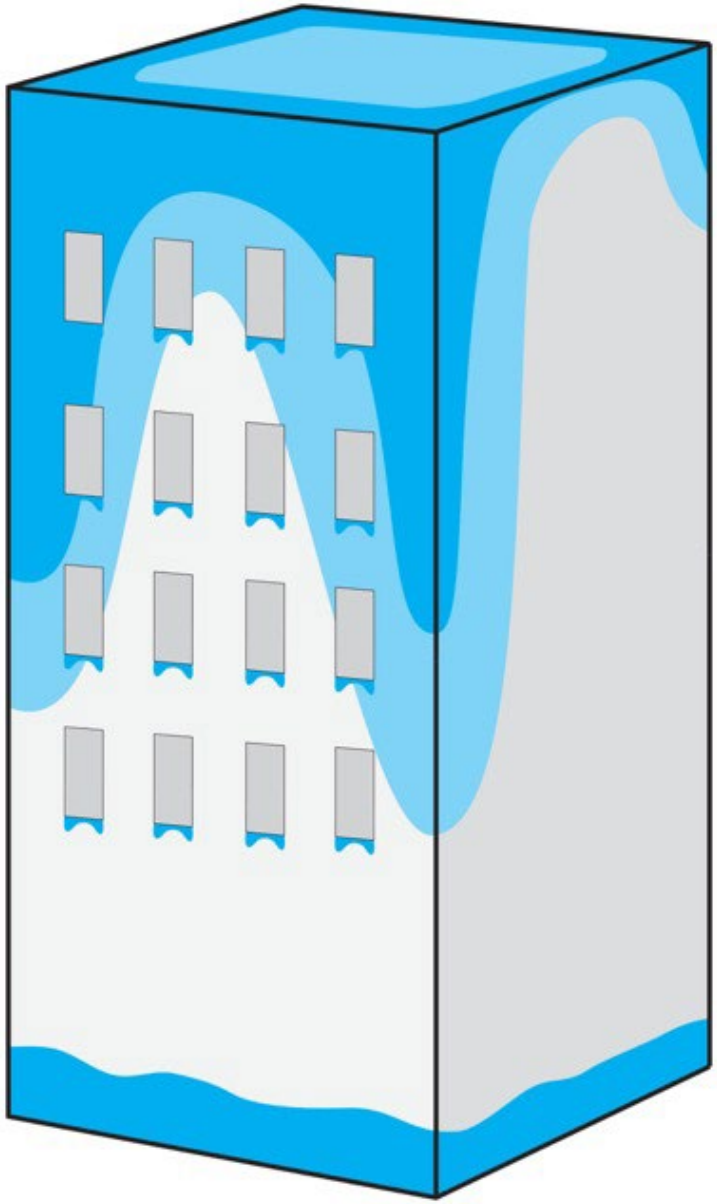
Subarctic/Arctic
Very Cold
Marine
Cold
Mixed-Humid
Mixed-Dry
Hot-Humid
Hot-Dry

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


Map of DOE's Proposed Climate Zones
Marine (C)
Dry (B)
Moist (A)
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


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





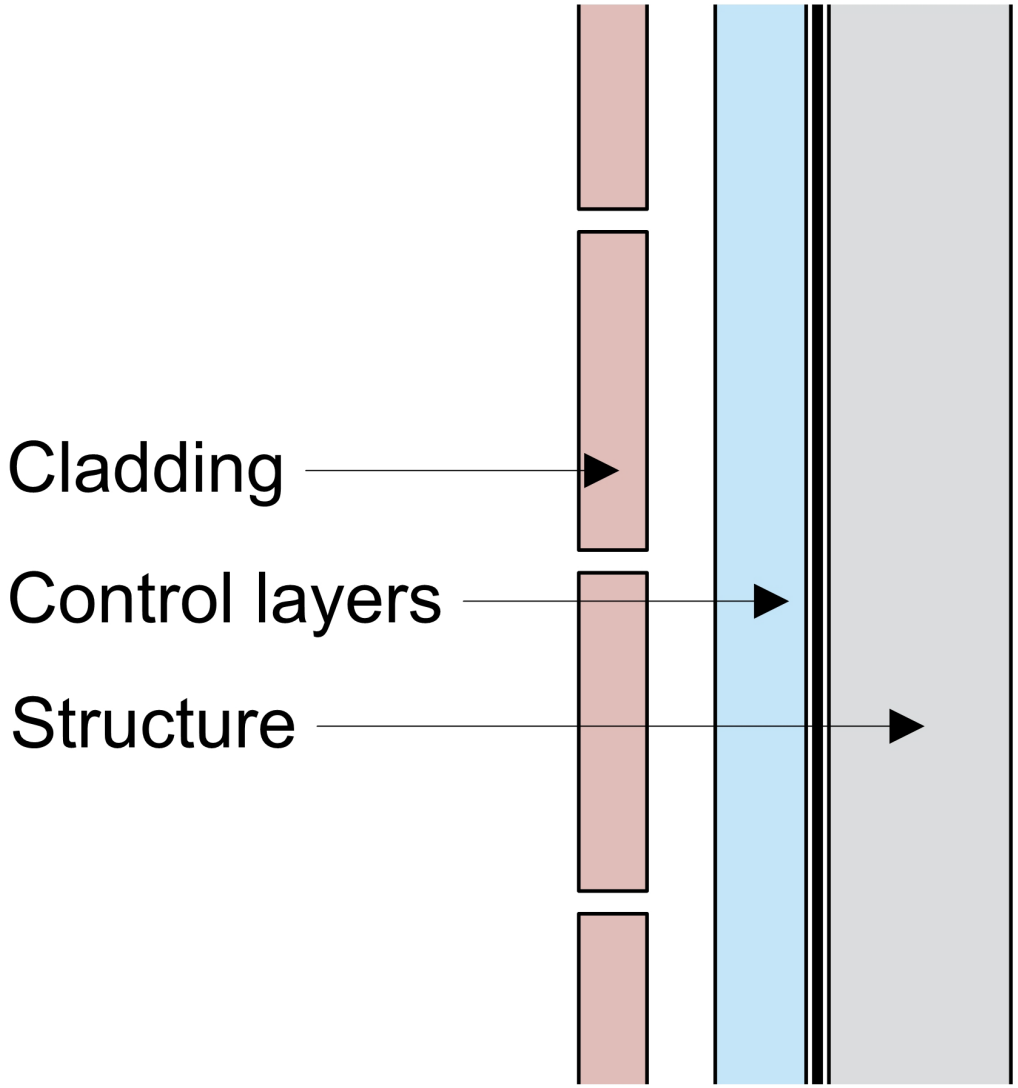
# The Perfect Wall

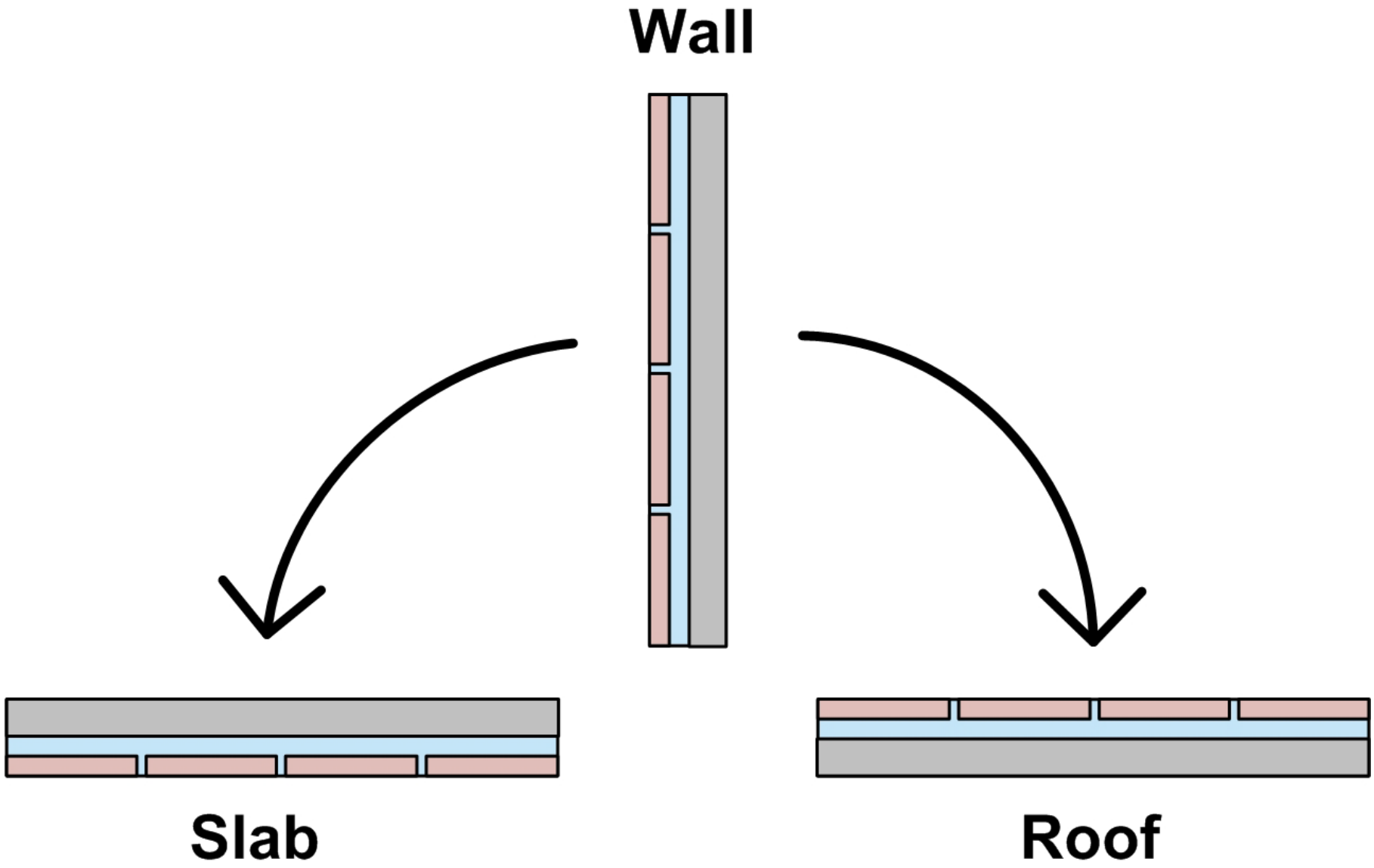
Water Control Layer

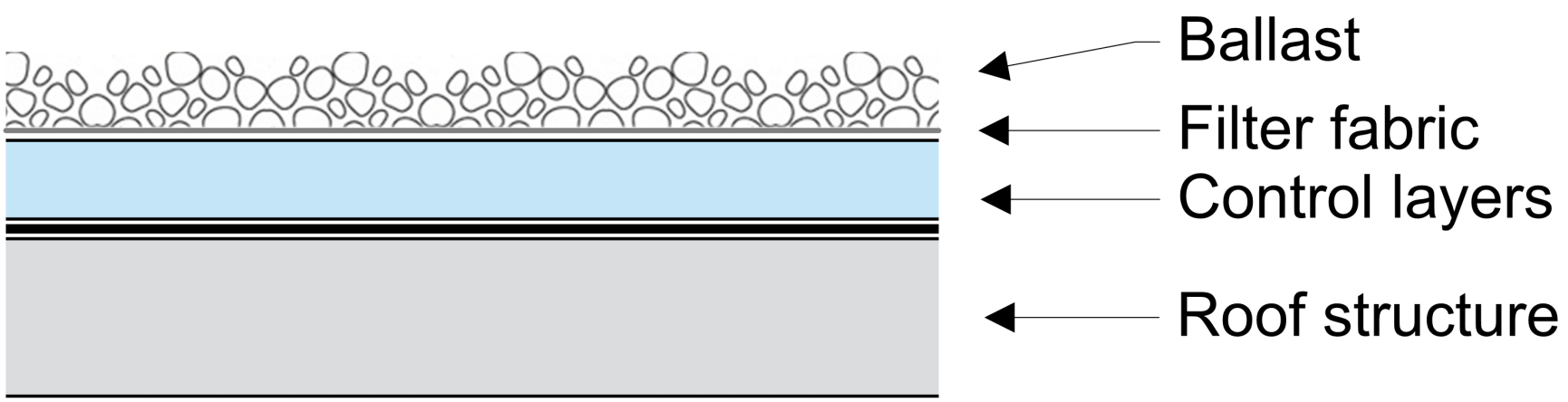
Air Control Layer

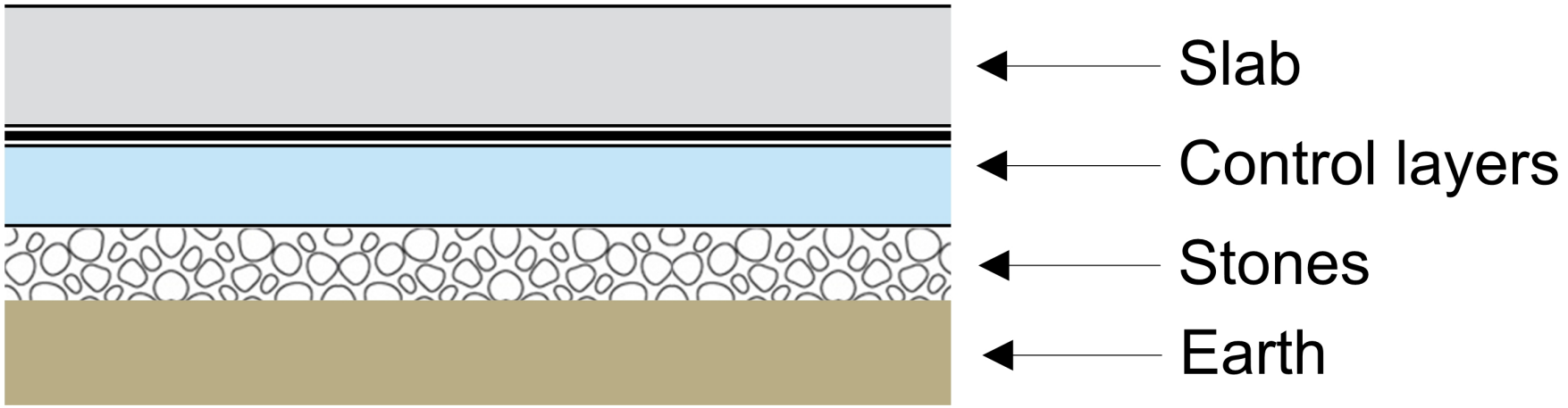
Vapor Control Layer

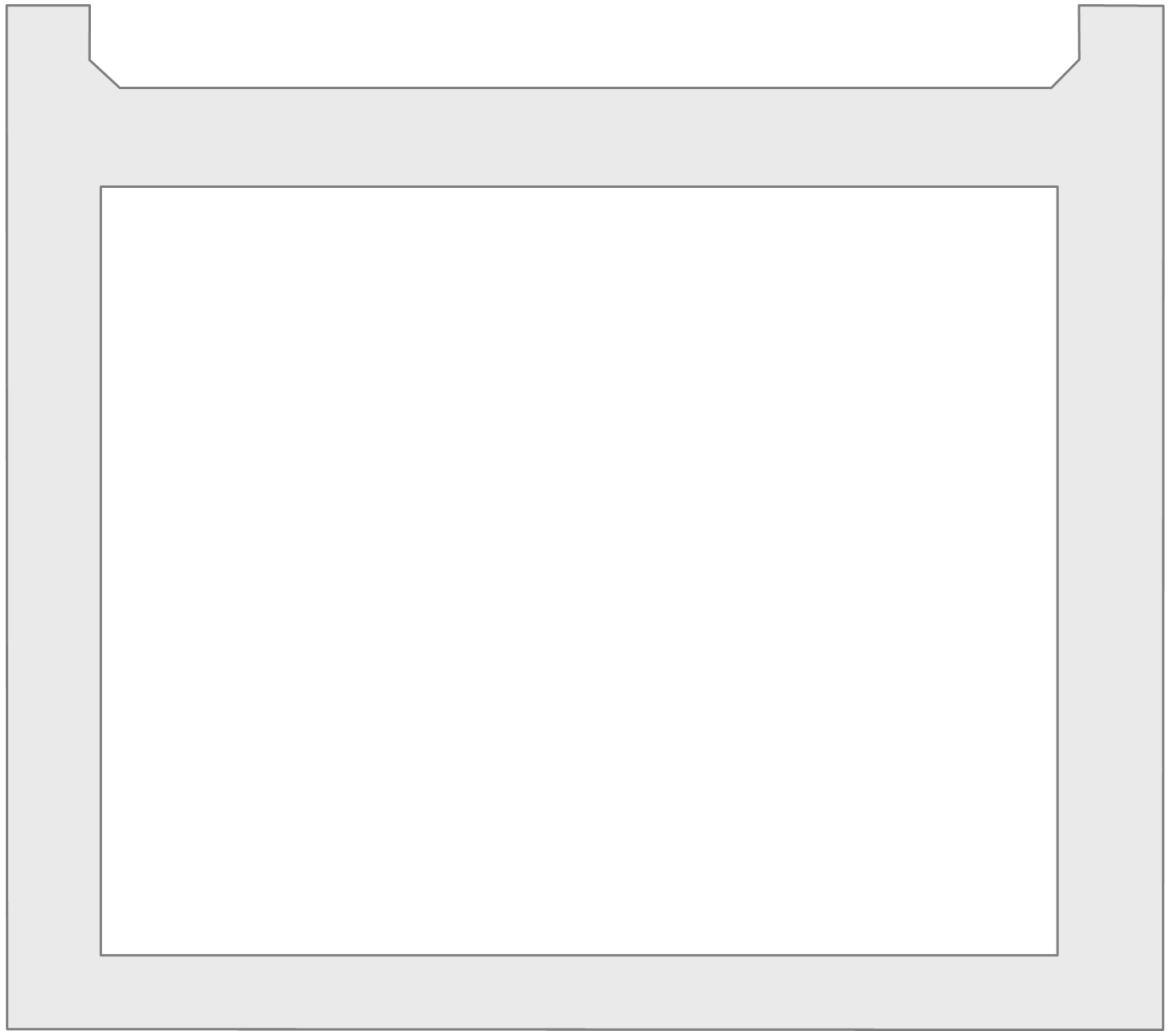
Thermal Control Layer

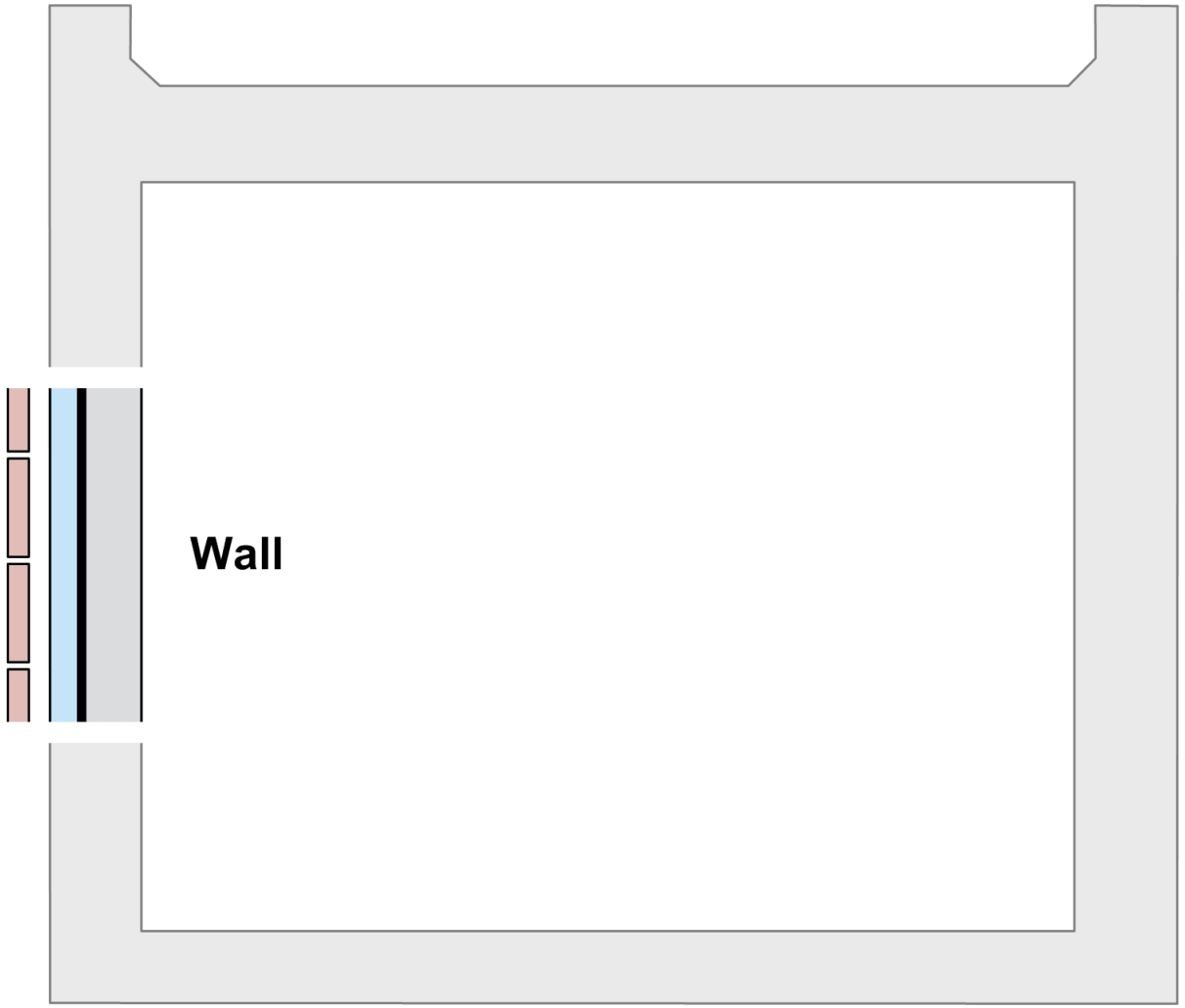

Cladding
Control layers
Structure

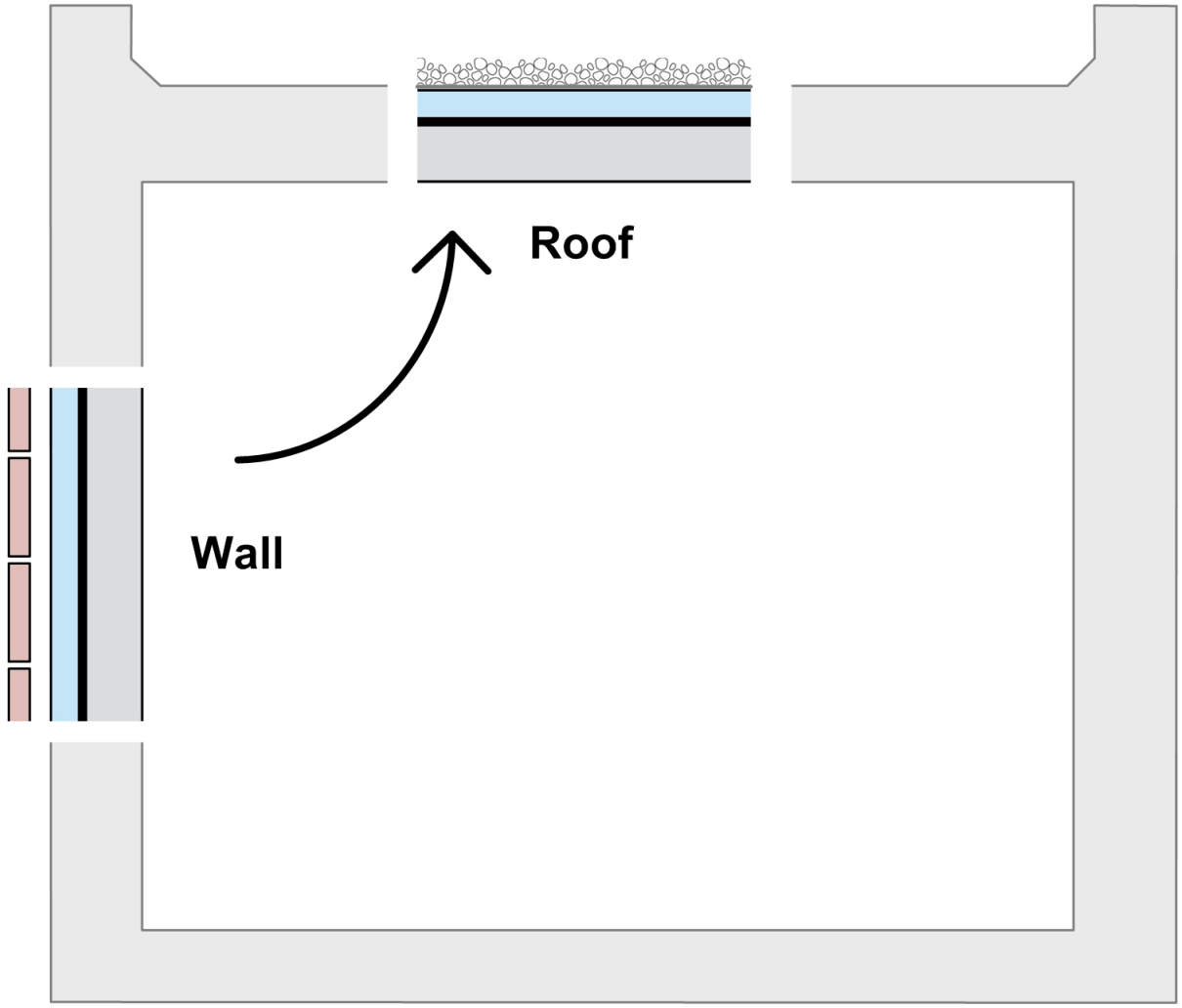

Wall
Slab
Roof

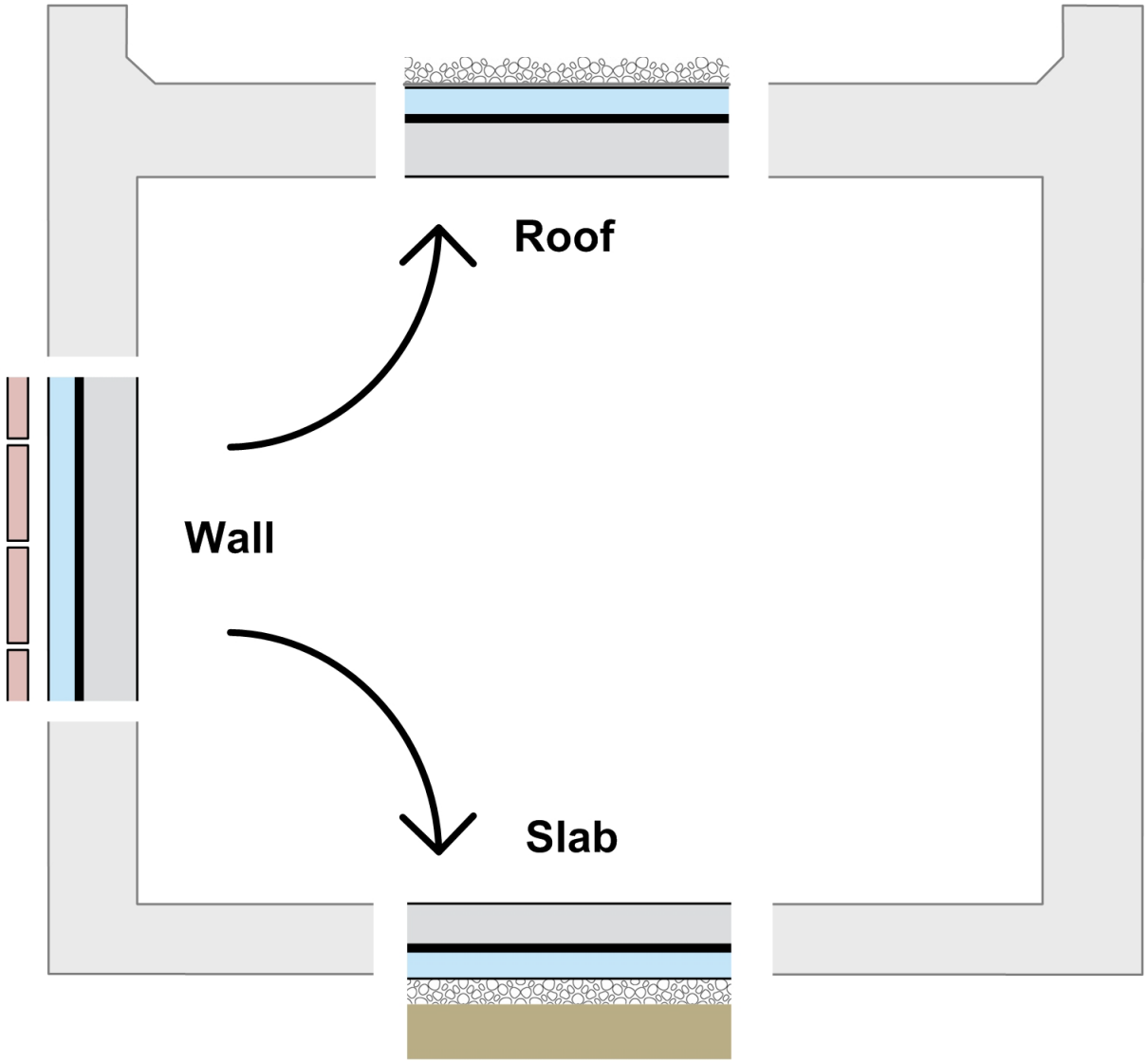

Ballast
Filter fabric
Control layers
Roof structure

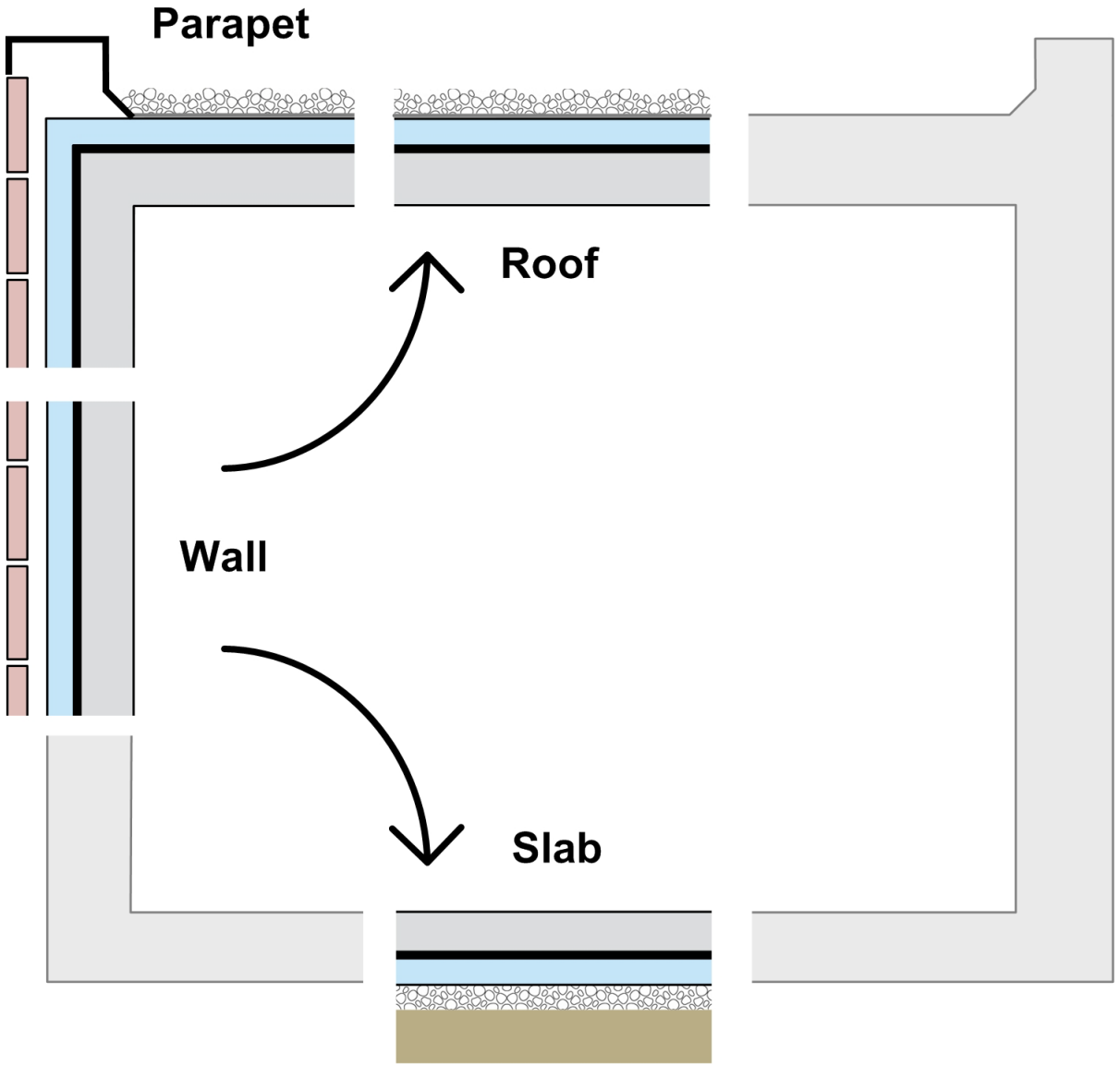

Slab
Control layers
Stones
Earth

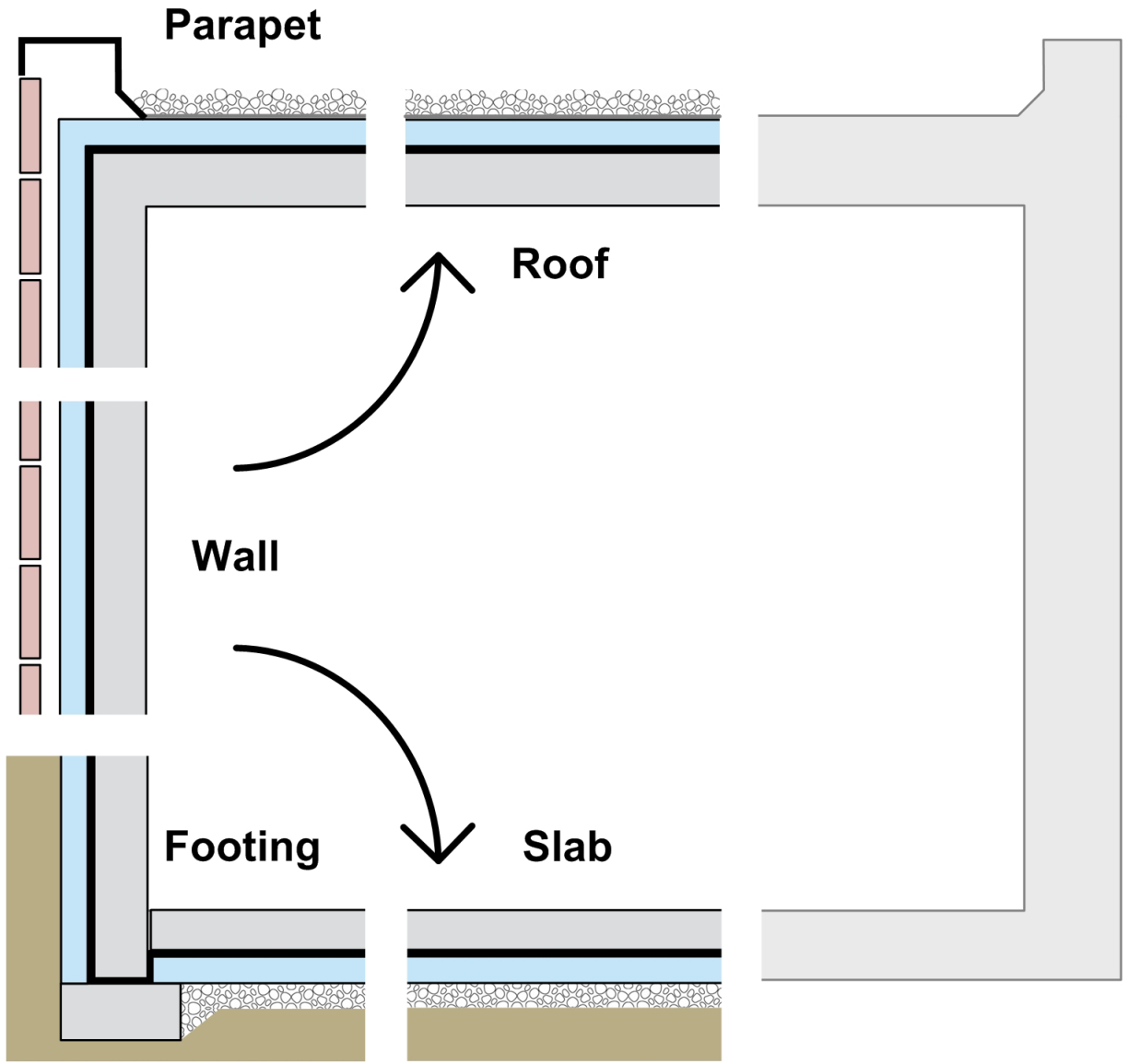


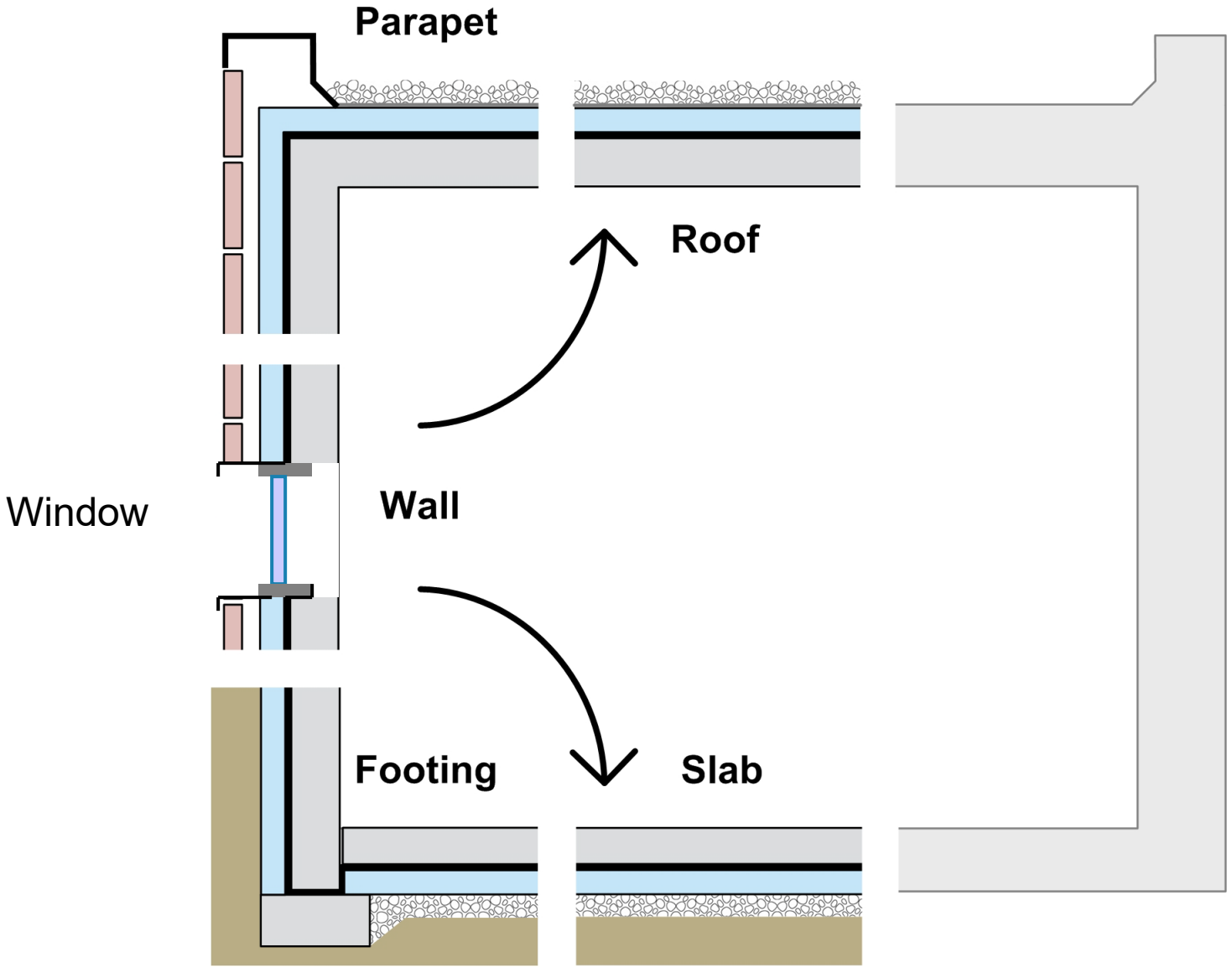

Wall

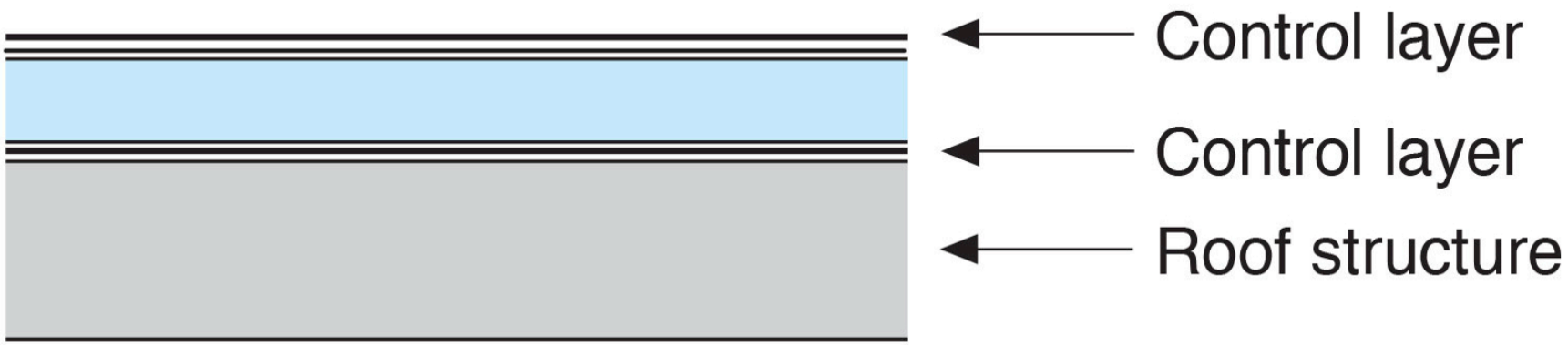

Roof
Wall

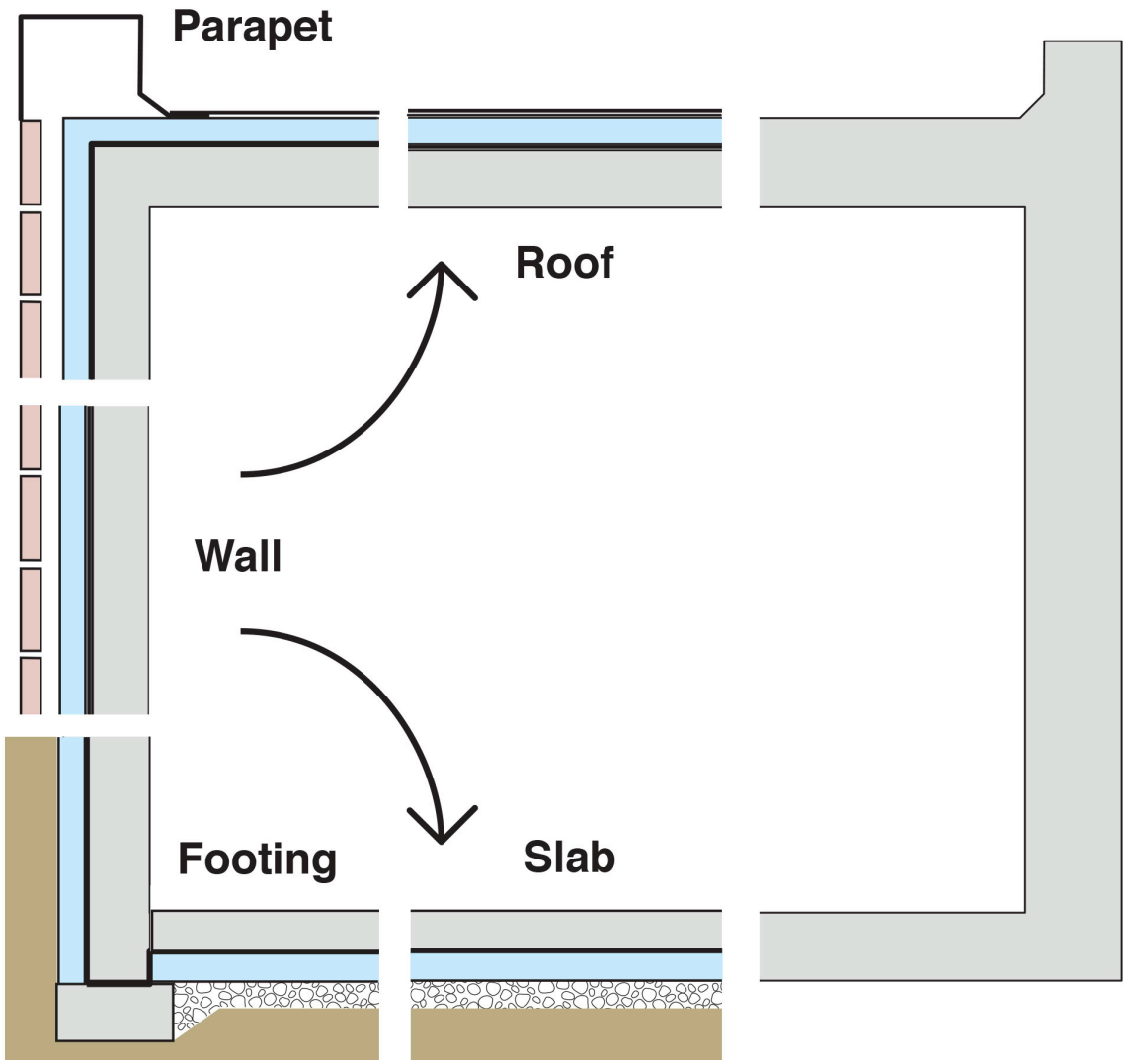

Roof
Wall
Slab

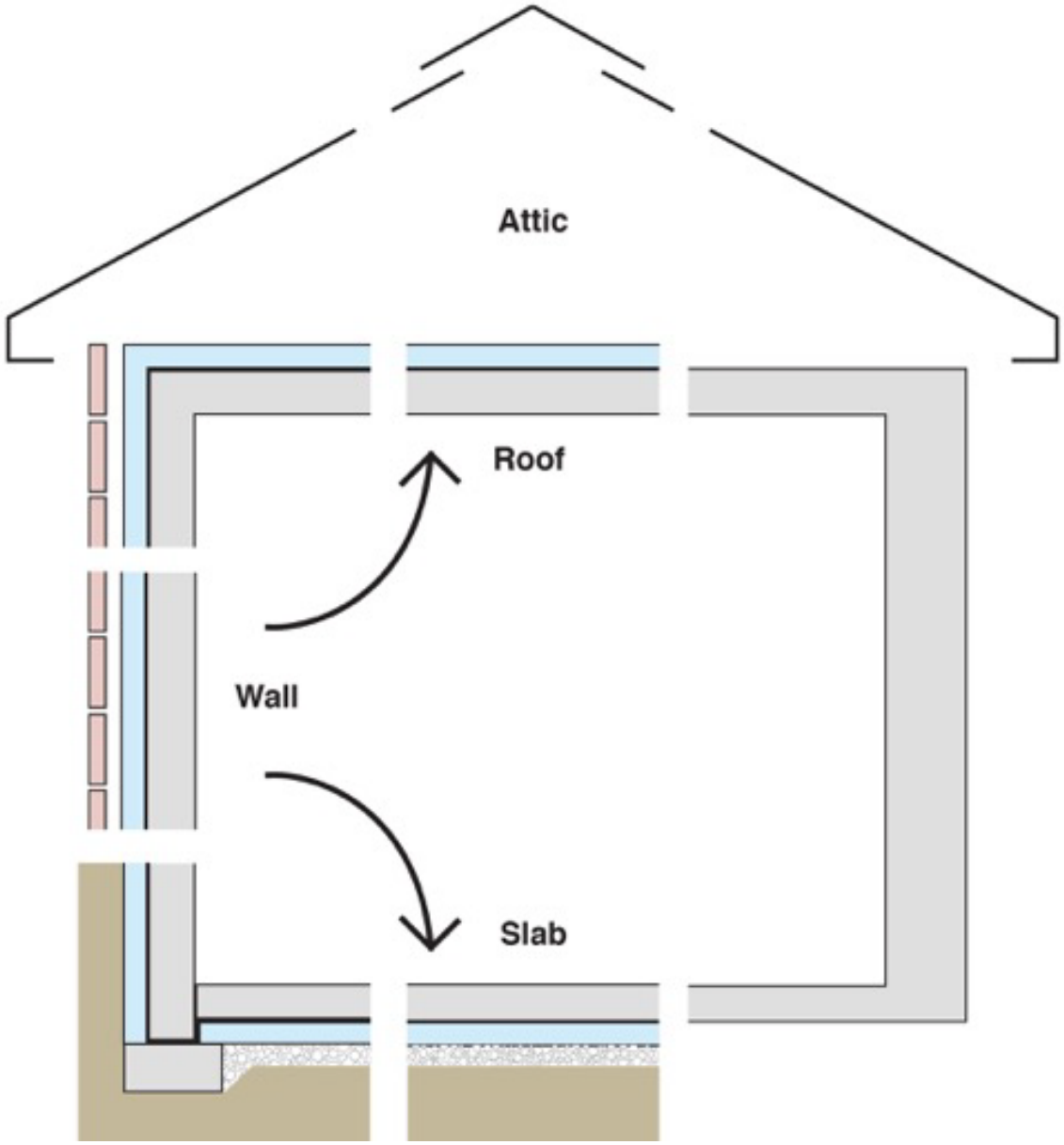

Parapet
Roof
Wall
Slab

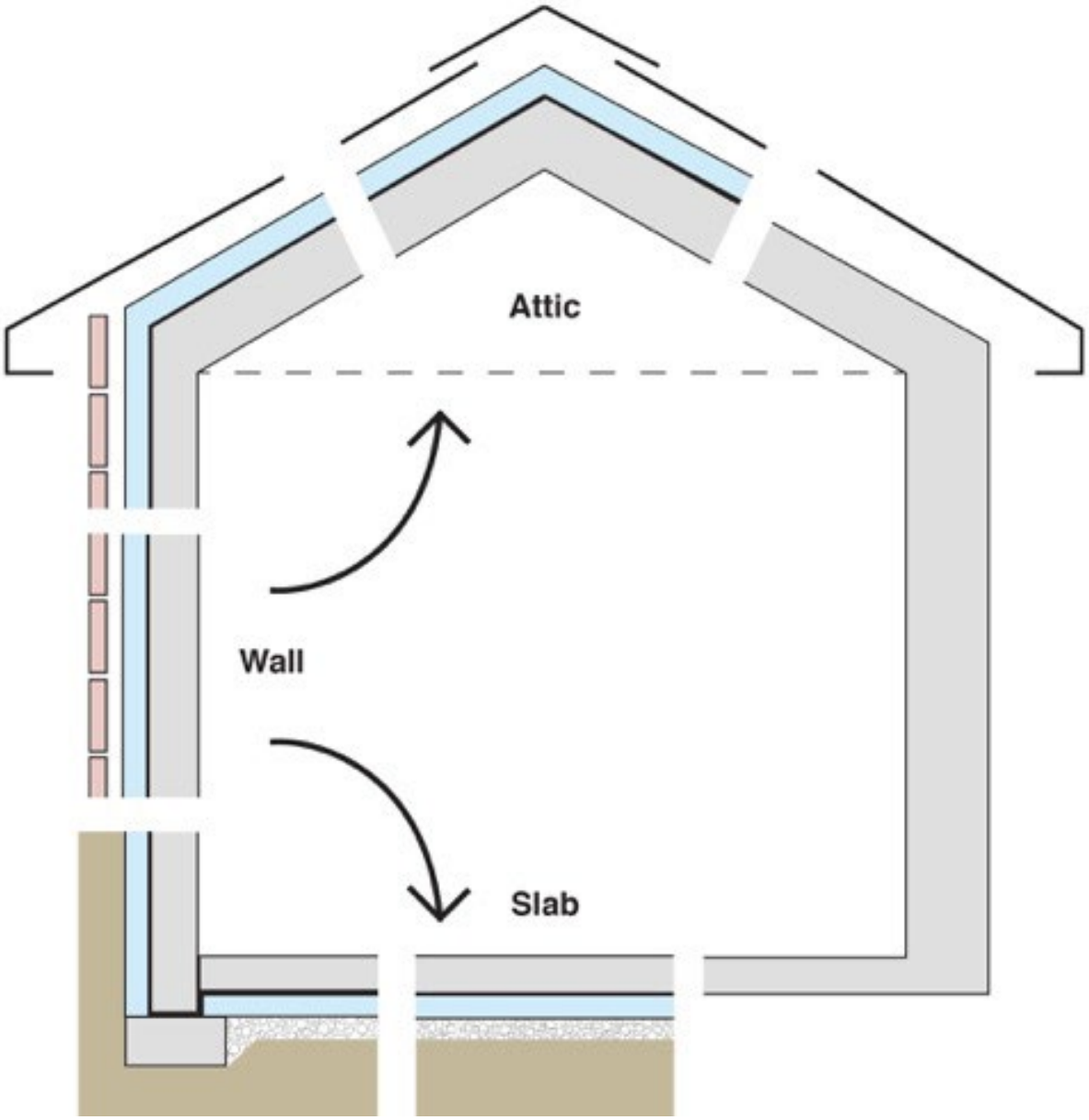

Parapet
Roof
Wall
Footing
Slab

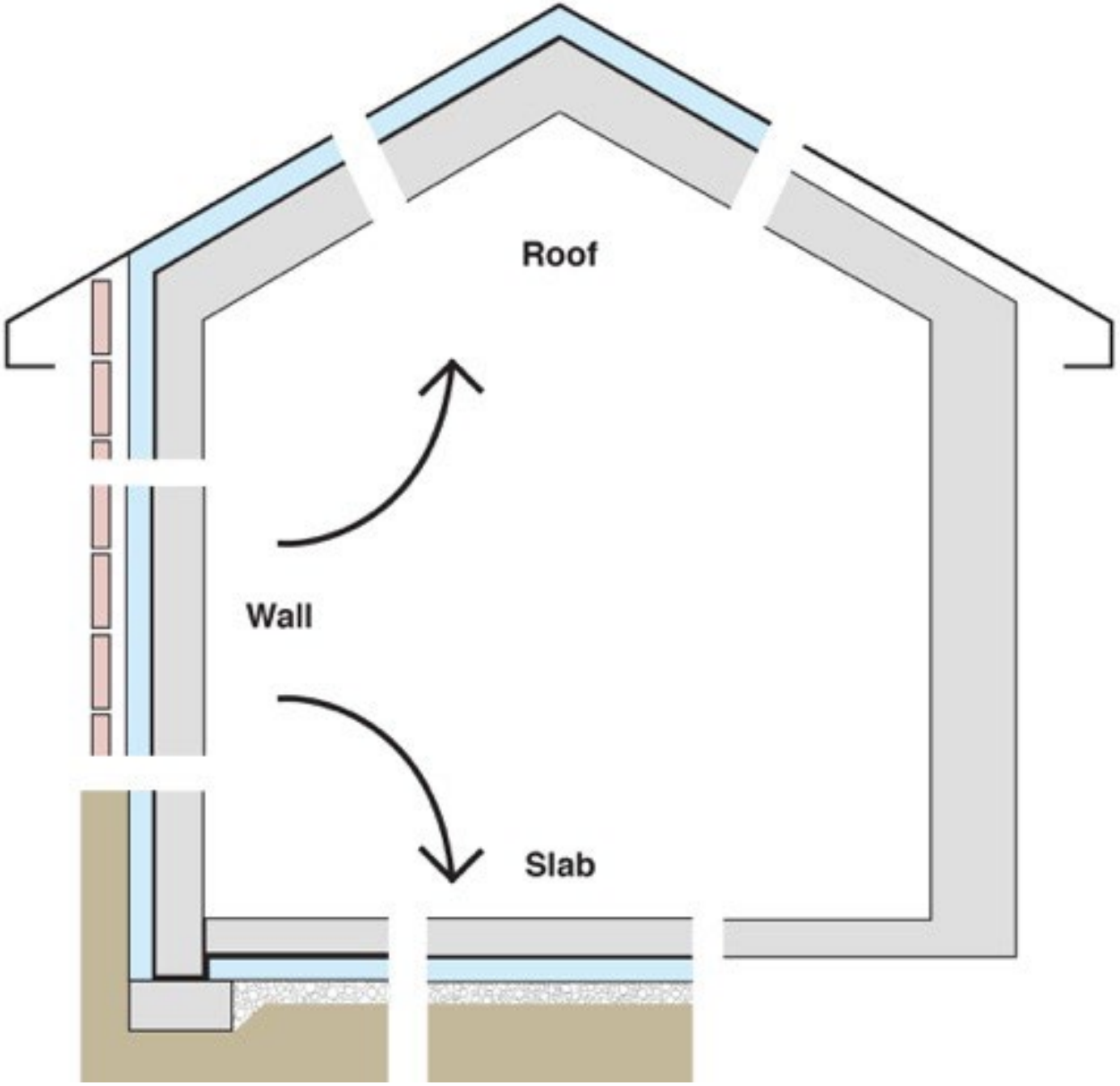

Parapet
Roof
Window
Wall
Footing
Slab

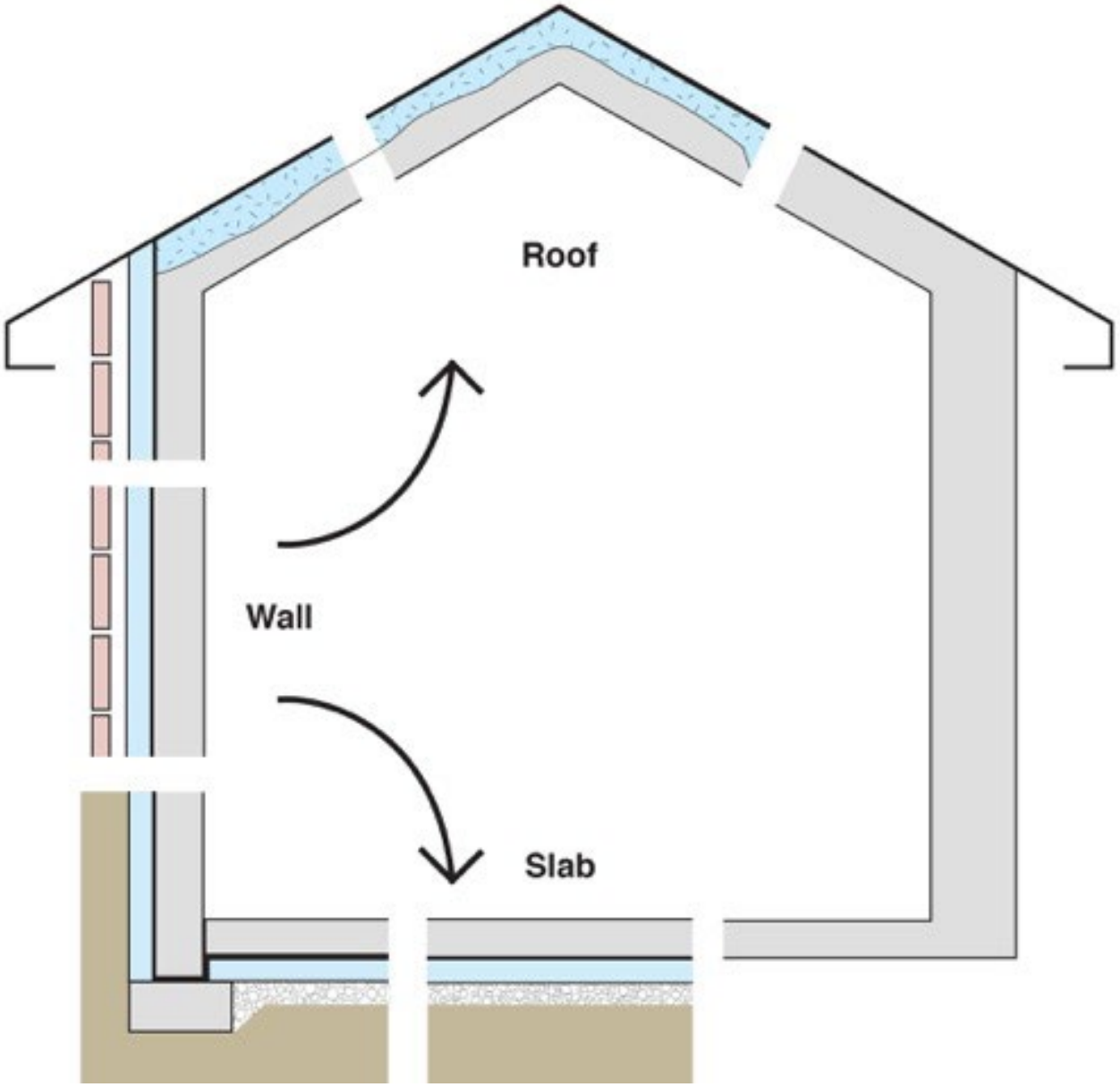

Control layer
Control layer
Roof structure


Parapet
Roof
Wall
Footing
Slab

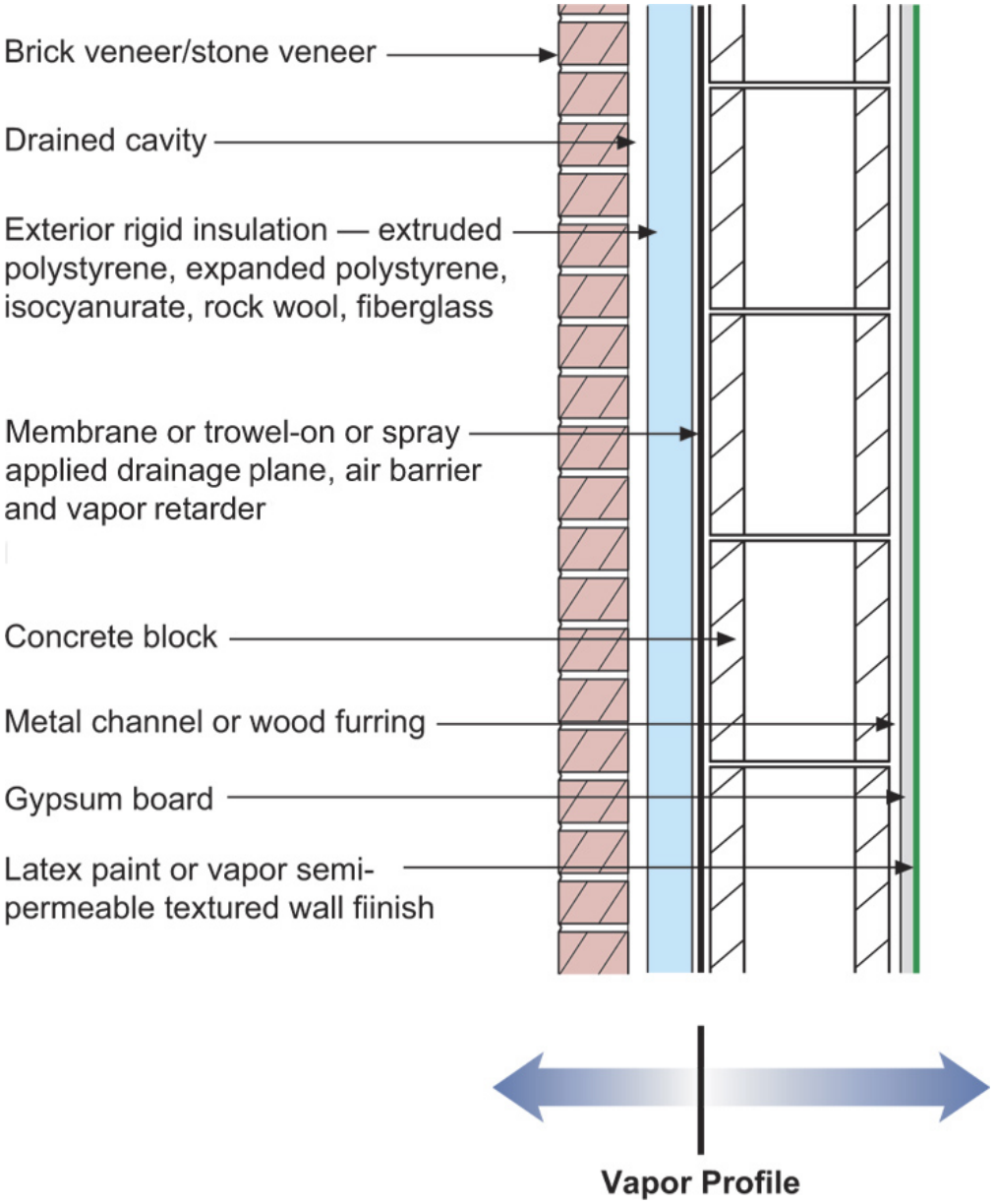

Attic
Roof
Wall
Slab

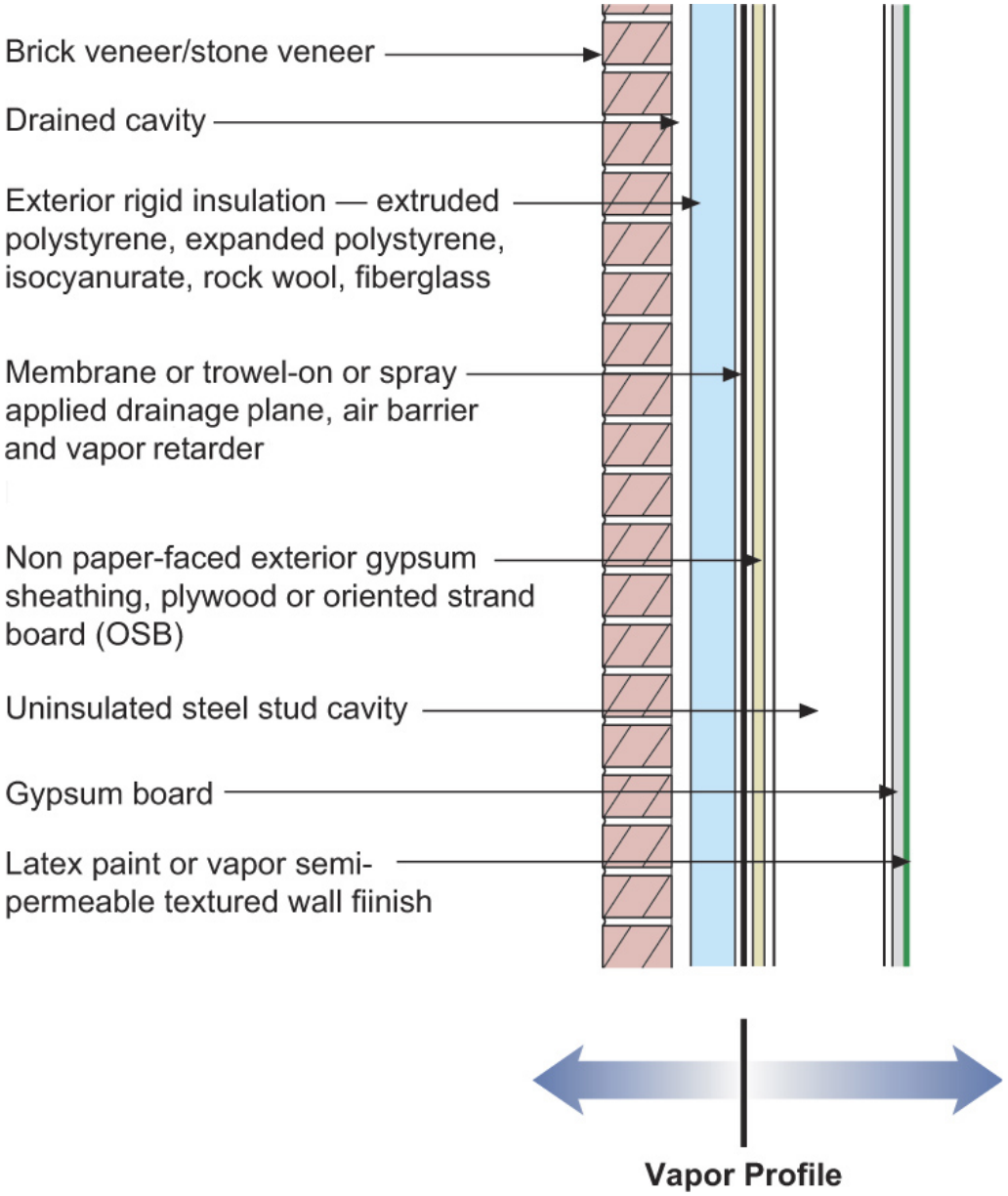

Attic
Wall
Slab

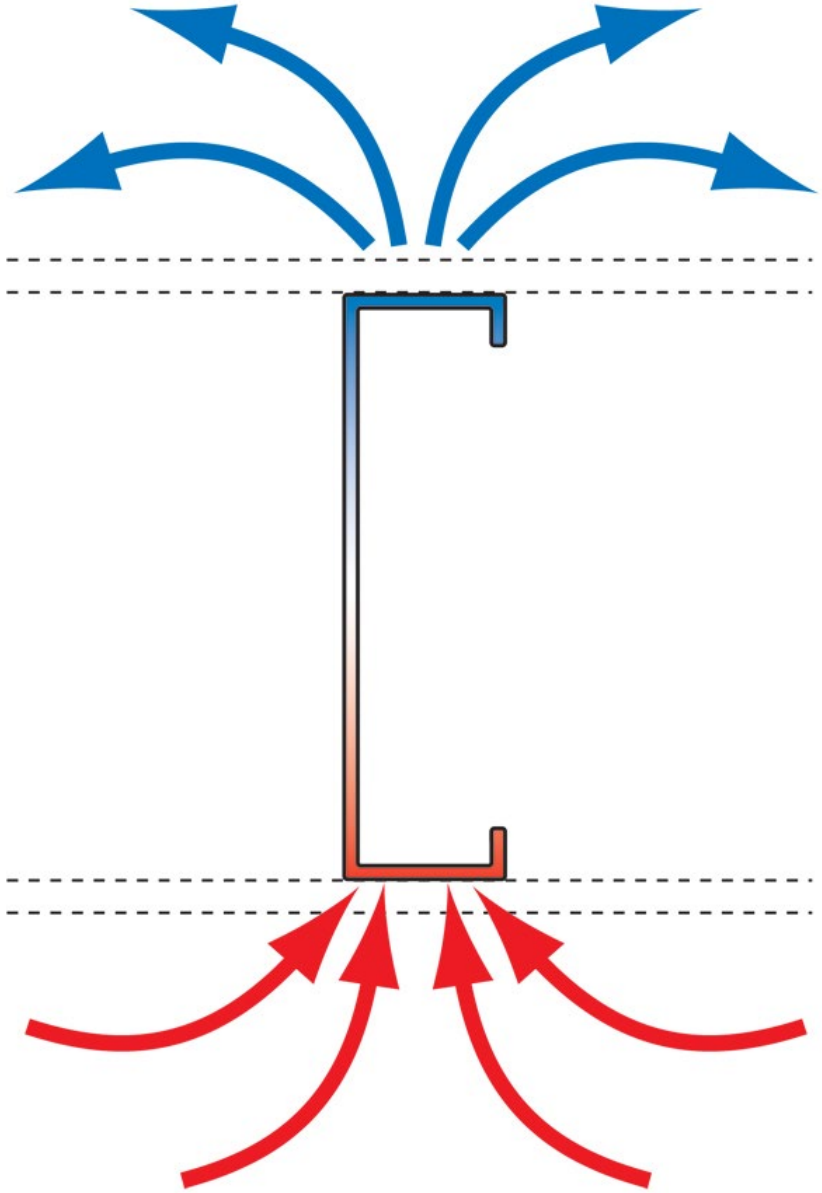

Roof
Wall
Slab

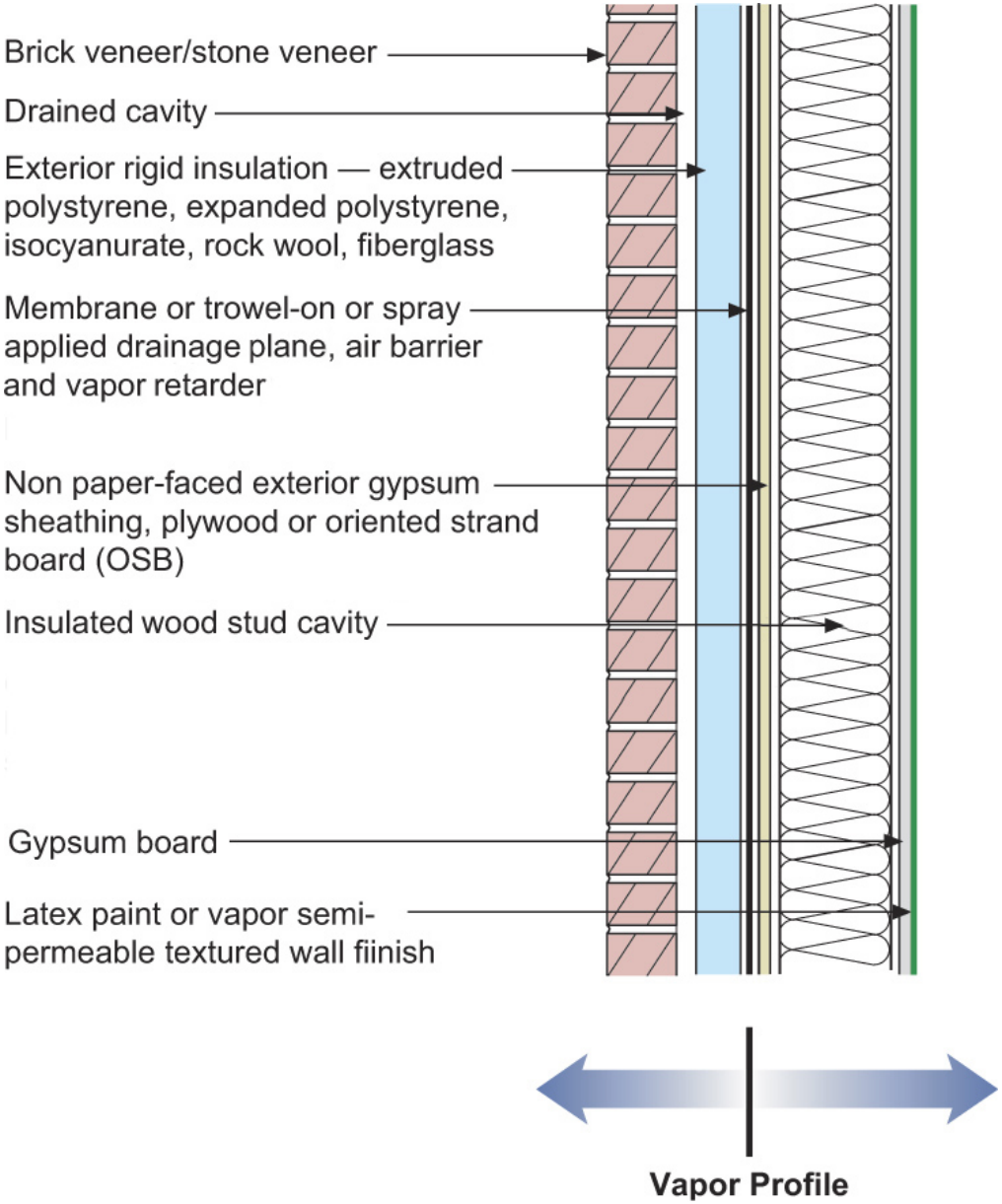

Roof
Wall
Slab

# Configurations of the Perfect Wall

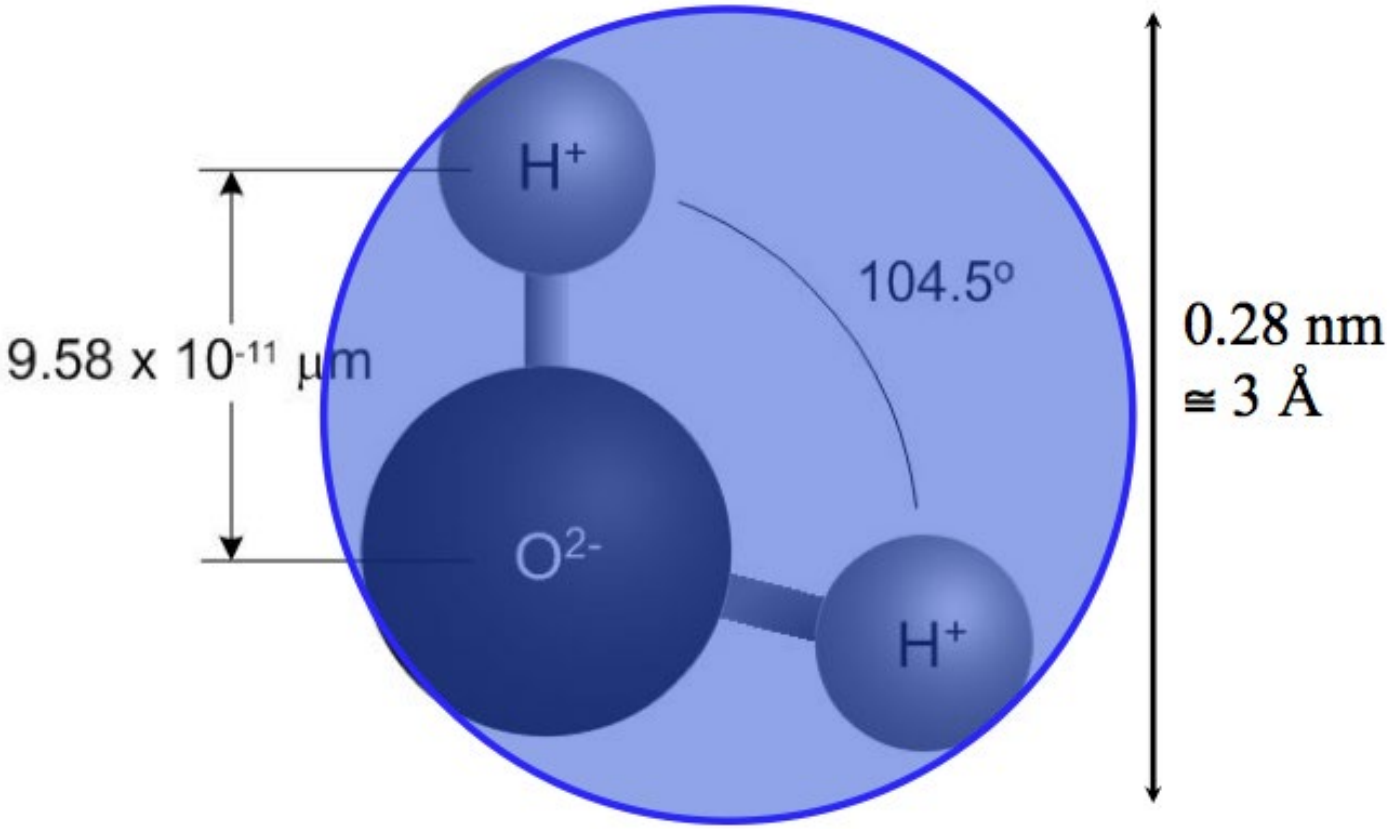

Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Concrete block
Metal channel or wood furring
Gypsum board
Latex paint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

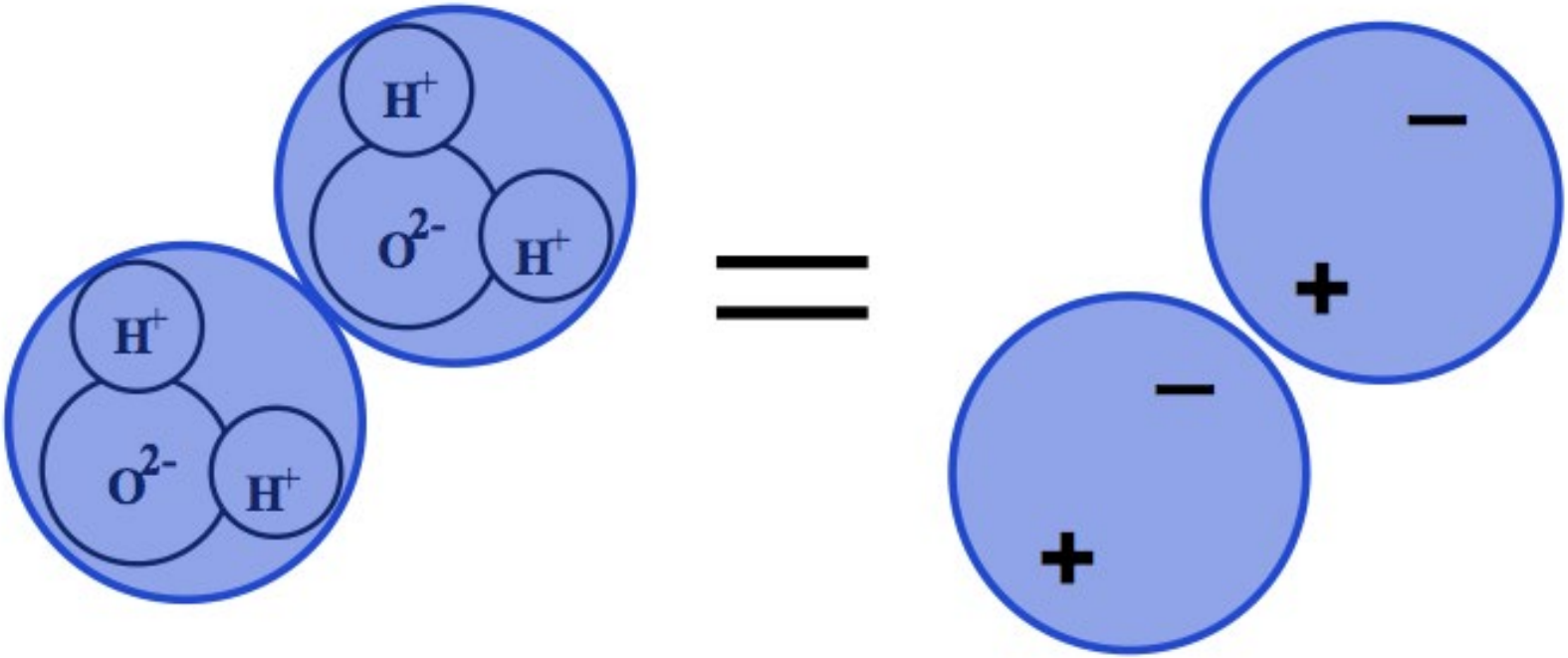



Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Non paper-faced exterior gypsum sheathing, plywood or oriented strand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

# The Water Molecule

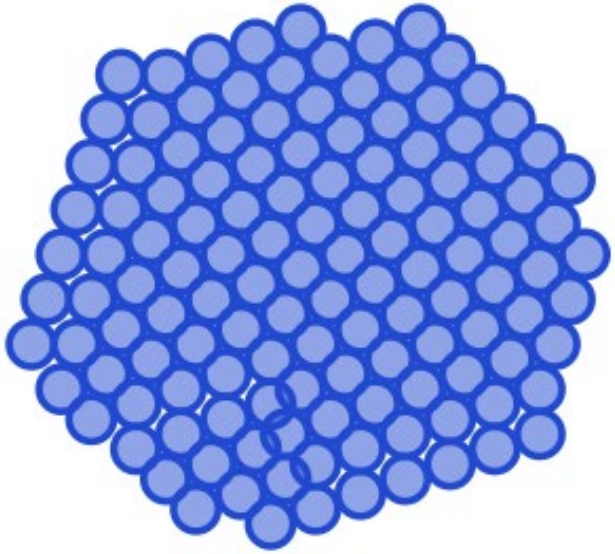

H+
104.5°
9.58 x 10-11 µm
O2-
H+
0.28 nm
≅ 3 Å

# Polar Molecule


H+
O2-
H+
H+
O2-
H+
=
−
+
−
+

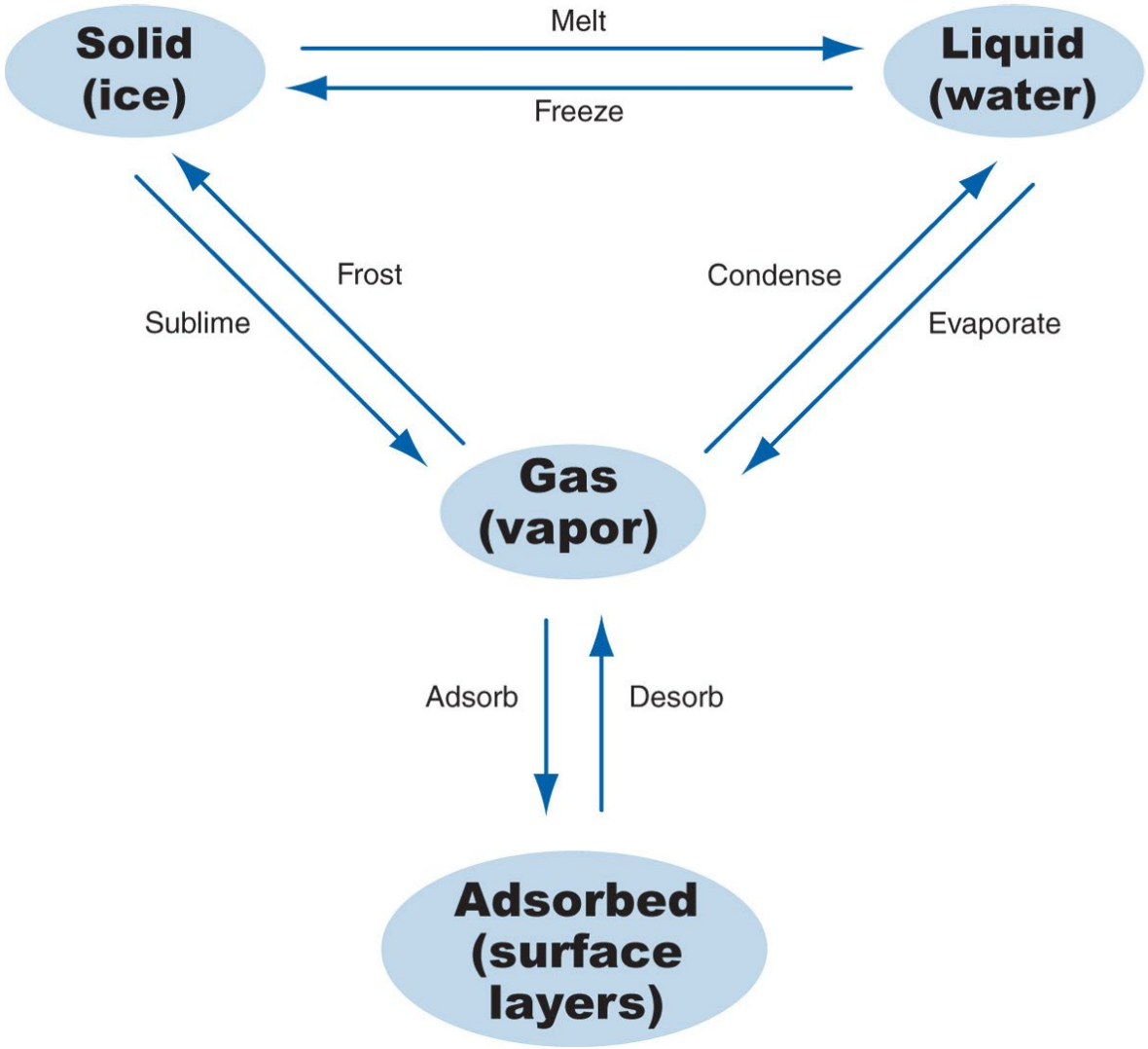
# Size Matters

Vapor



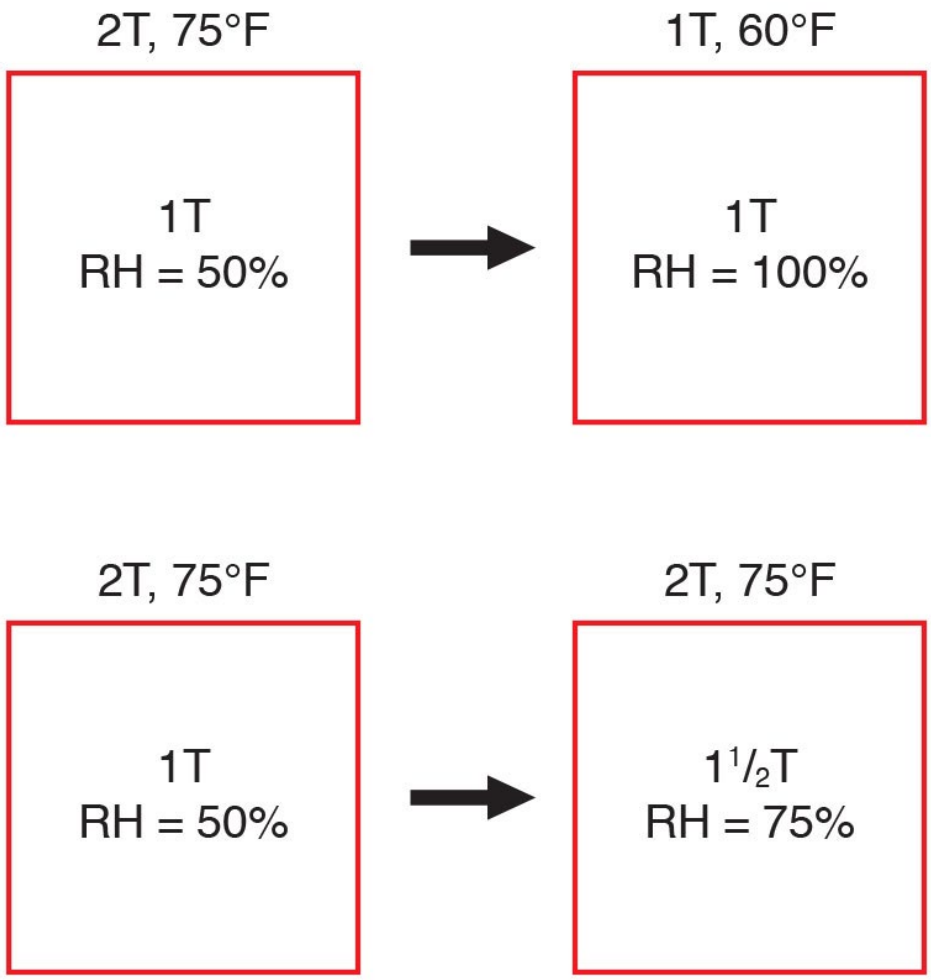
Liquid

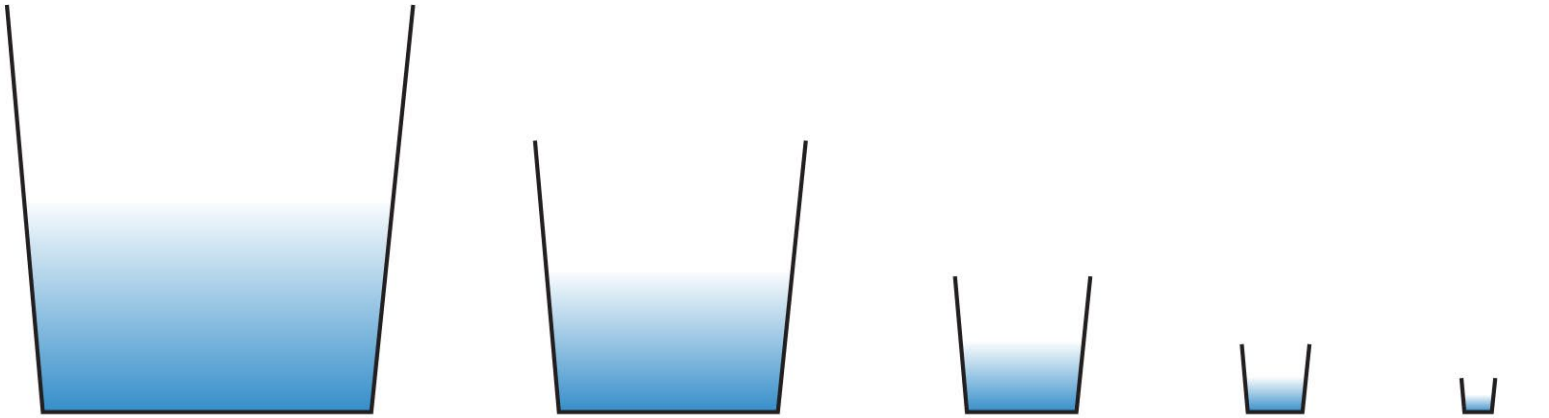
# Phases of Water

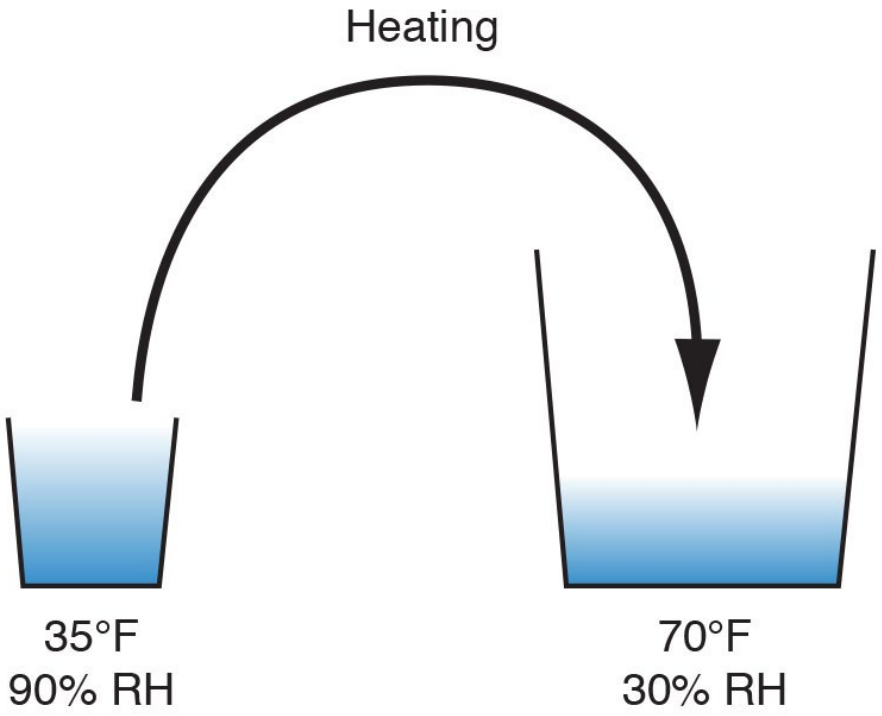

Solid (ice)
Melt
Freeze
Liquid (water)
Frost
Sublime
Condense
Evaporate
Gas (vapor)
Adsorb
Desorb
Adsorbed (surface layers)

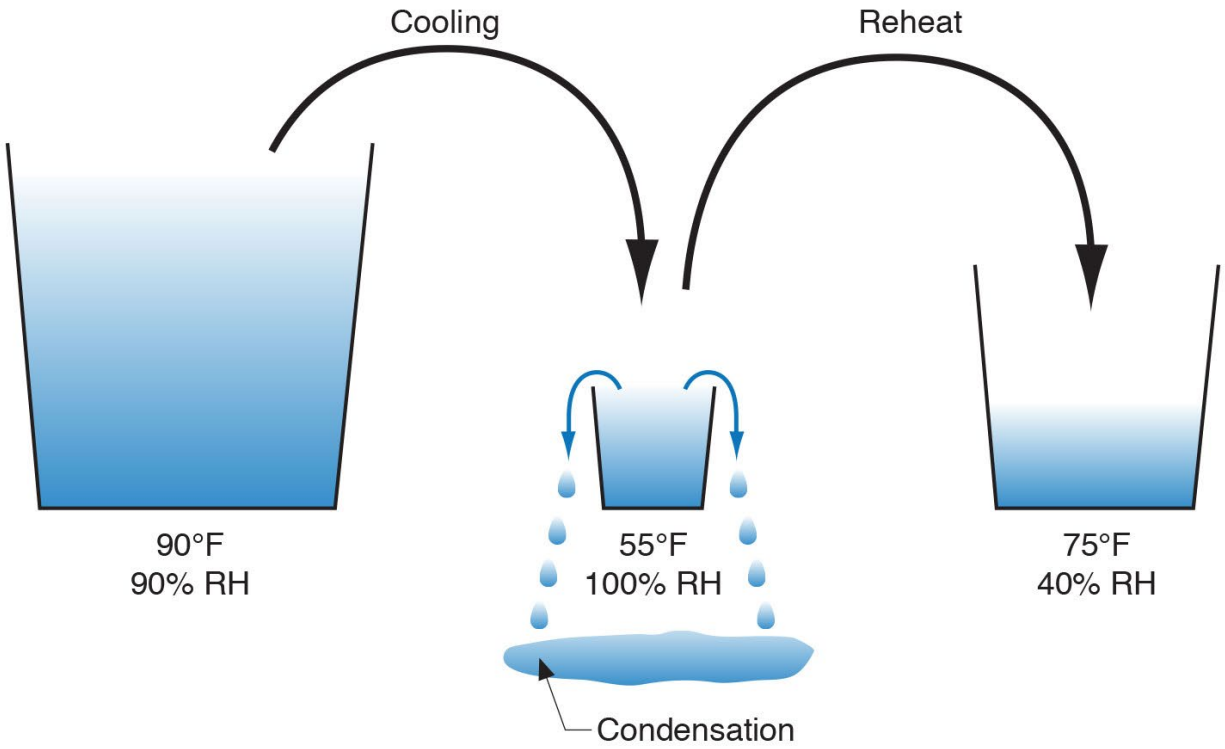
Relative Humidity

Vapor Pressure

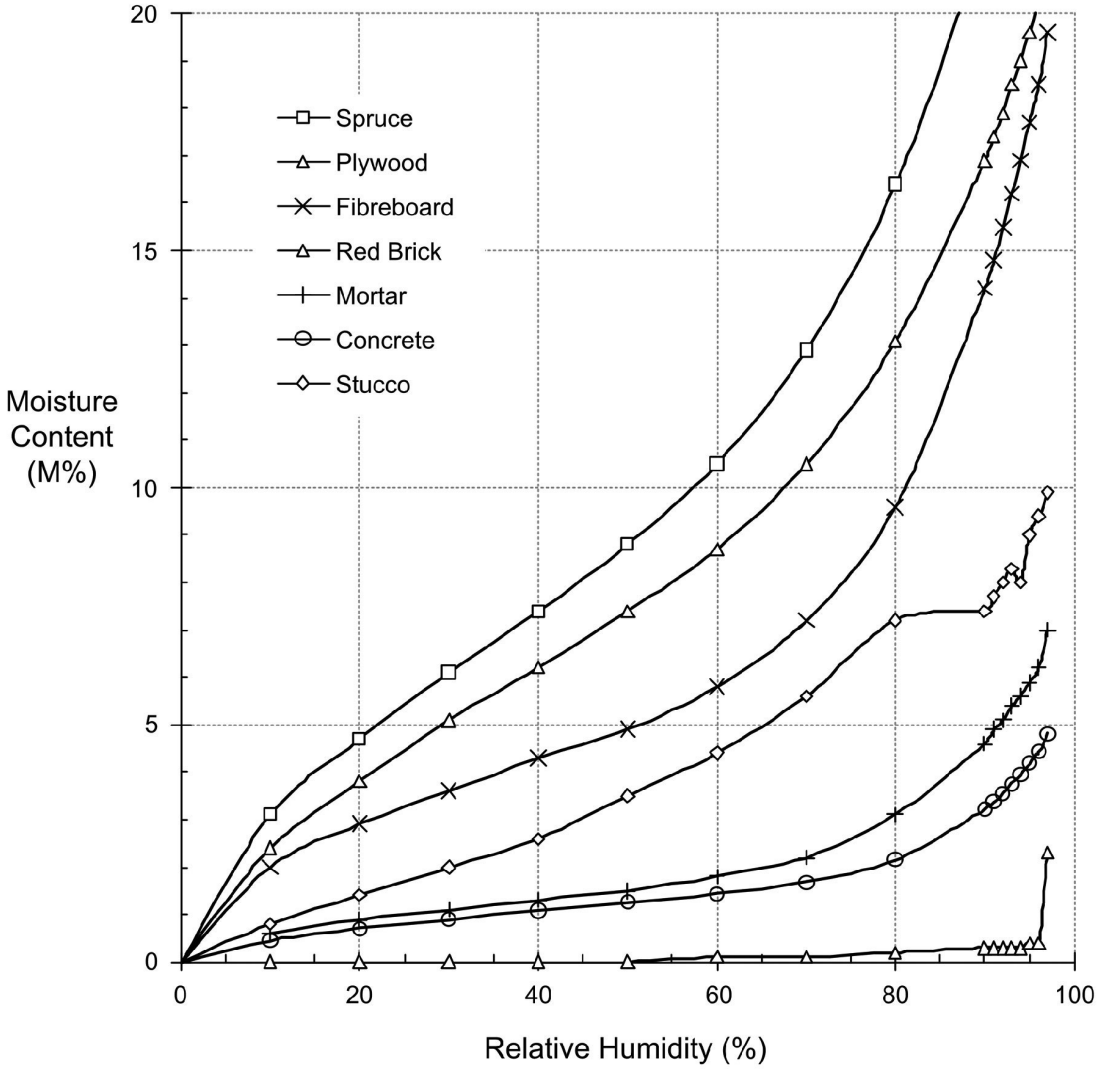

2T, 75°F
1T
RH = 50%
1T, 60°F
1T
RH = 100%
2T, 75°F
1T
RH = 50%
2T, 75°F
1 1/2T
RH = 75%


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

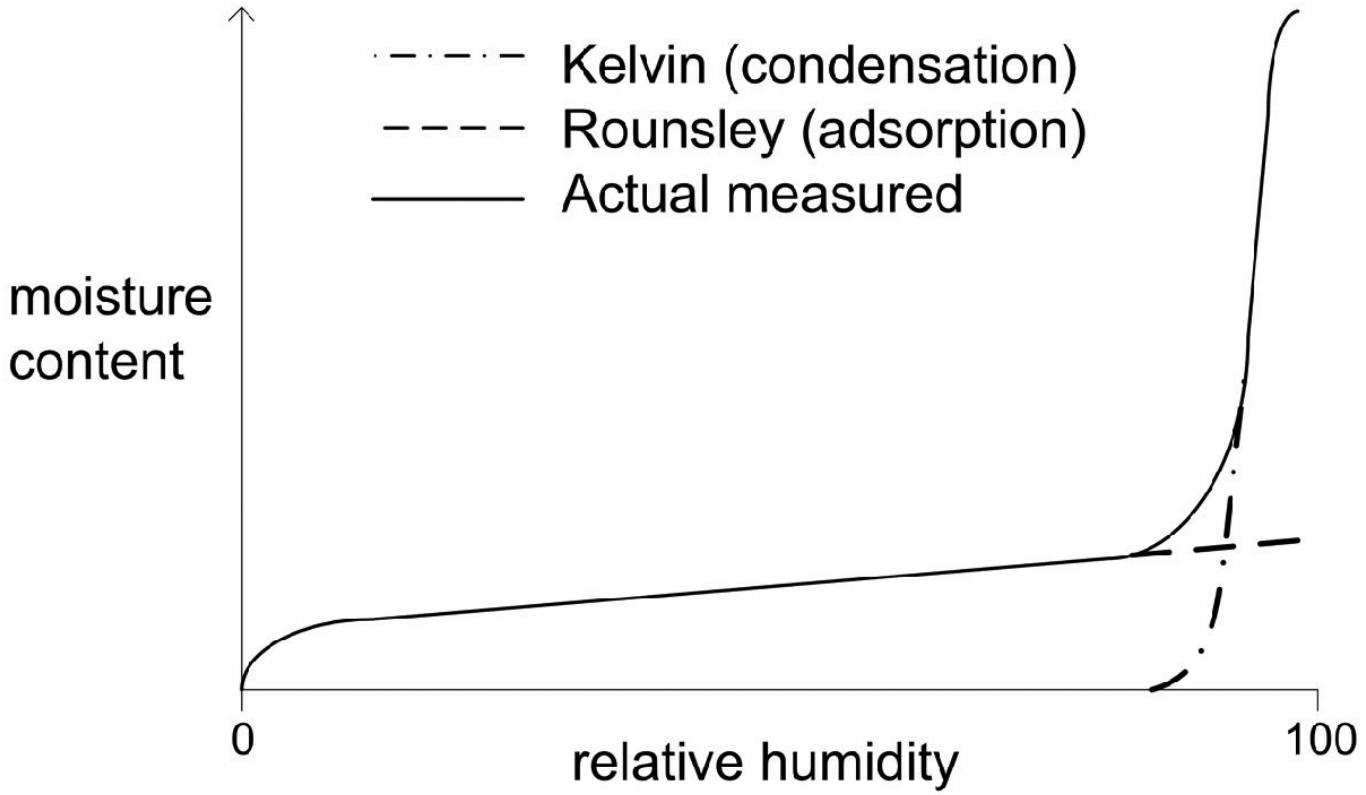
# BET Theory

BET Theory

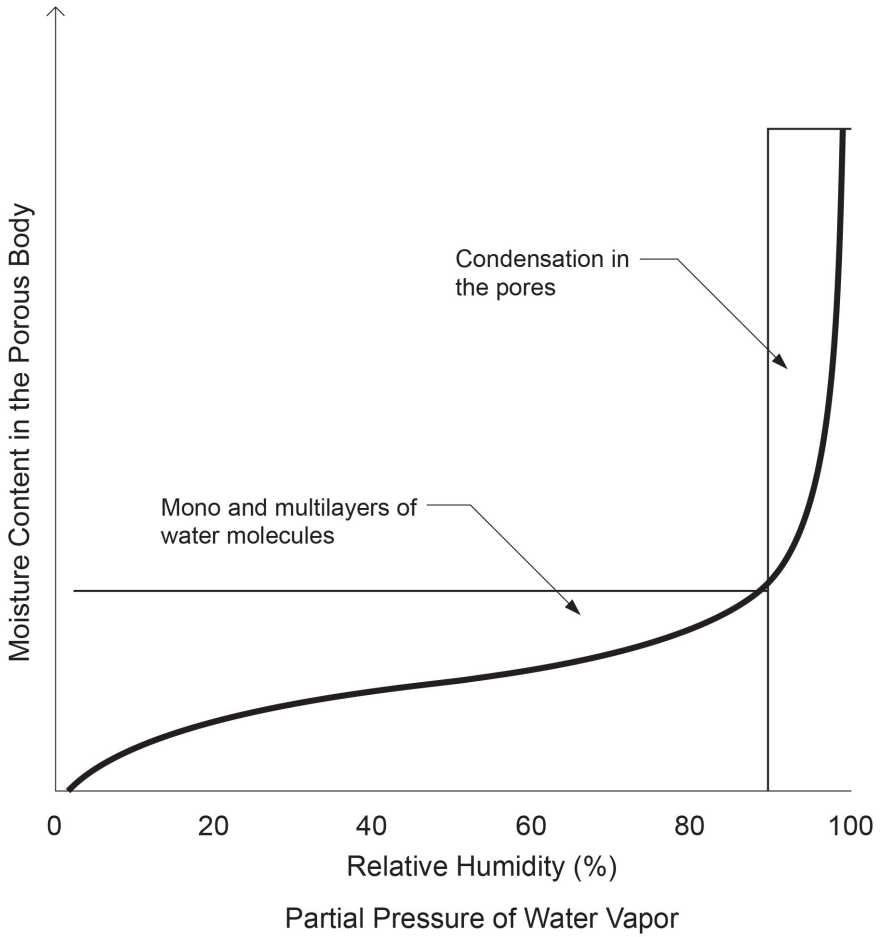
Stephen Brunauer

Paul Emmett

Edward Teller



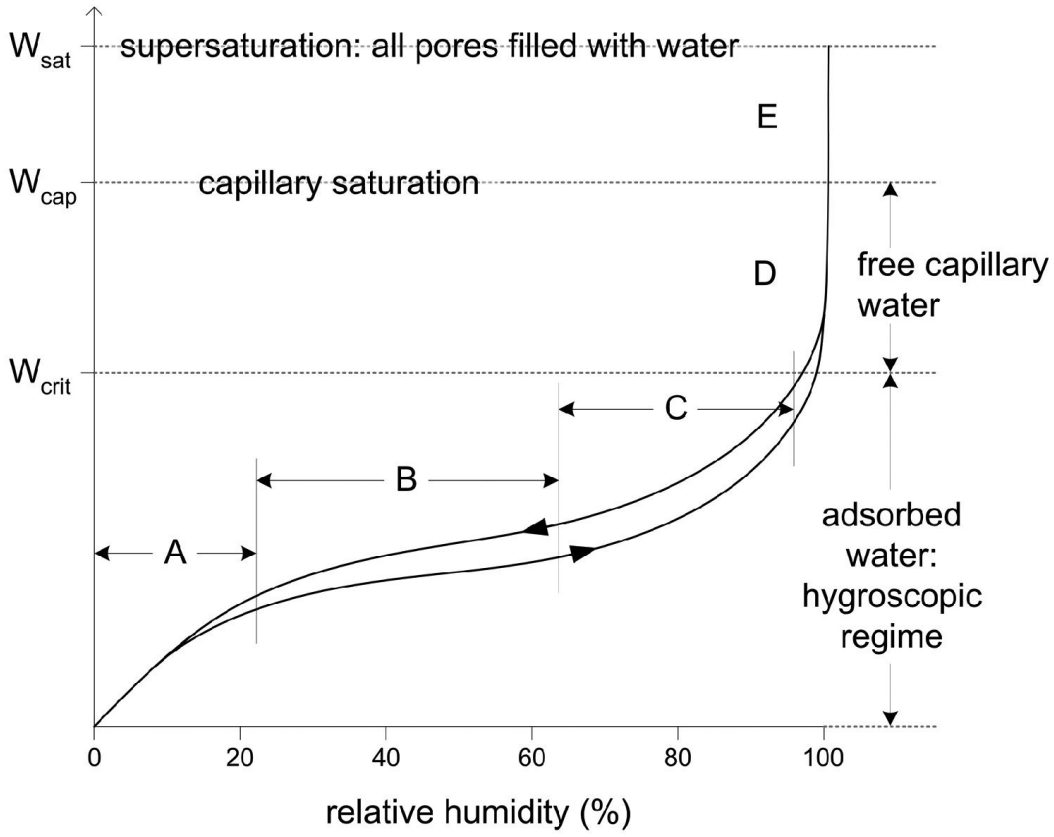

**Typical predicted sorption isotherm according to Kelvin equation and modified BET theory**
From Straube & Burnett, 2005




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.

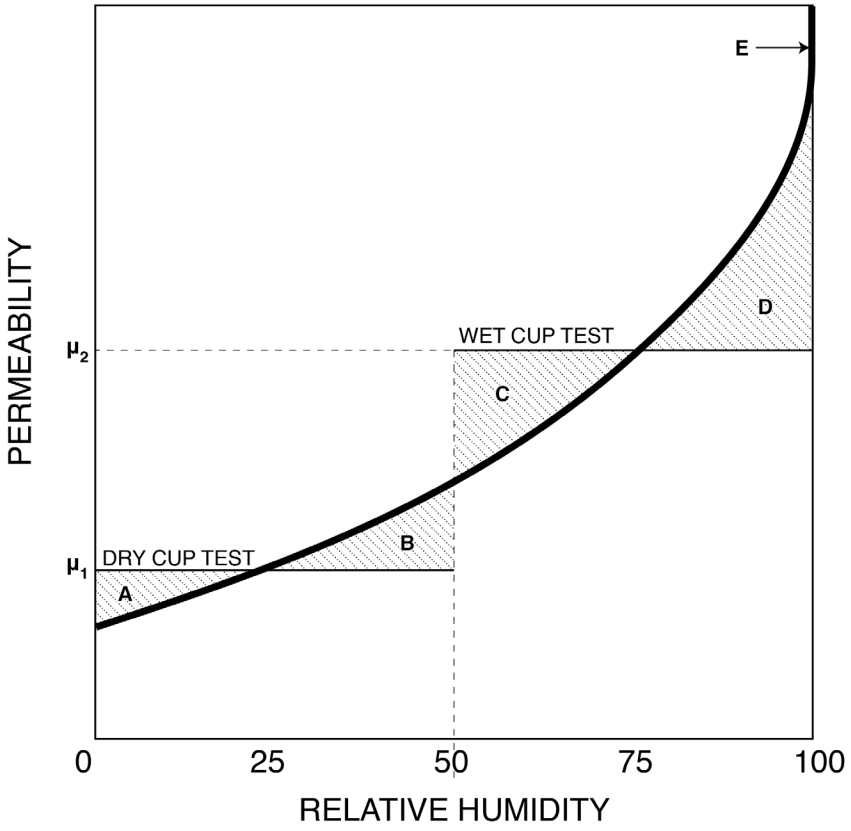
**Sorption Curve**

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




A: Single-layer of adsorbed molecules
B: Multiple layers of adsorbed molecules
C: Interconnected layers (internal capillary condensation
D: Free water in Pores, capillary suction
E: Supersaturated Regime

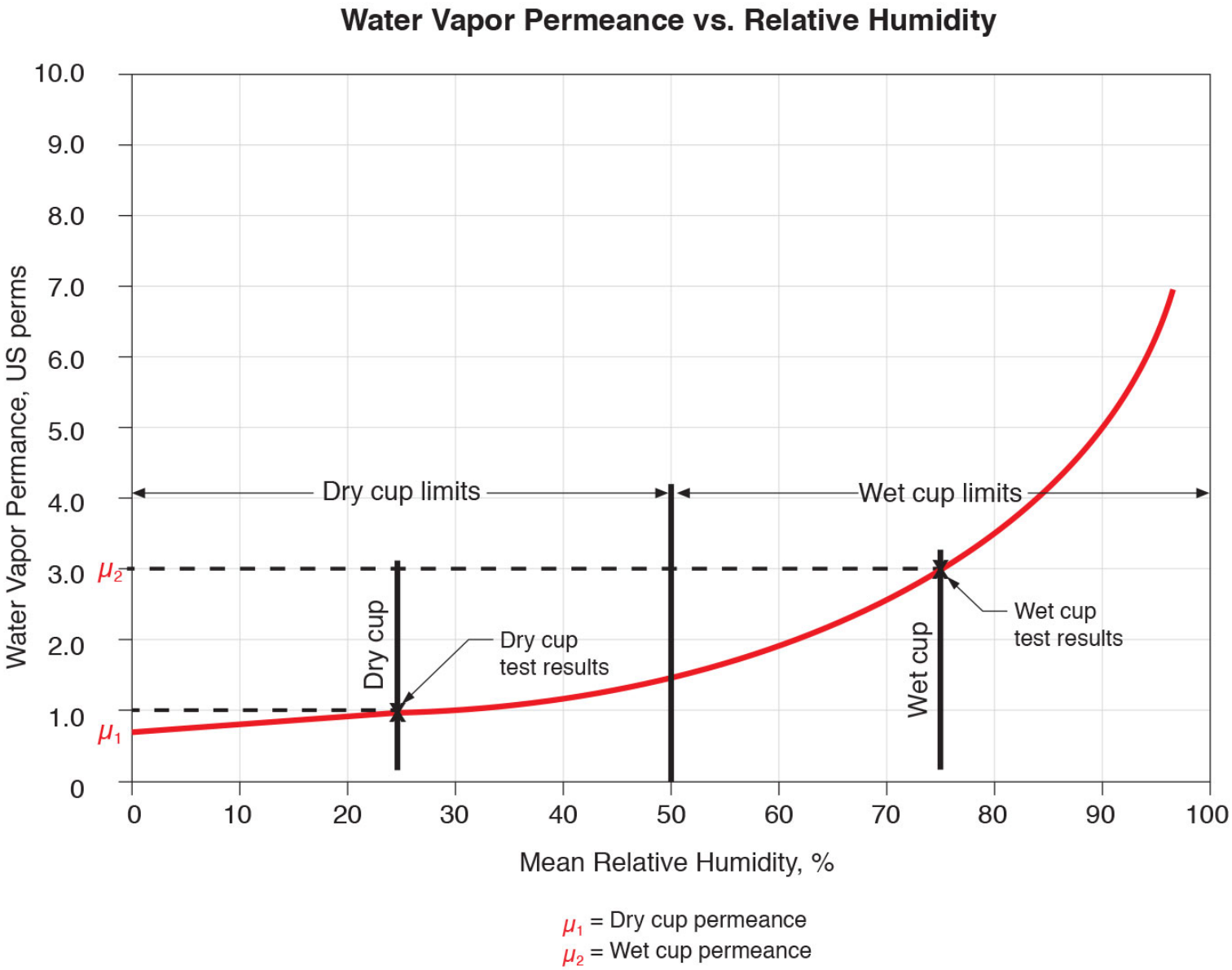
**Regimes of moisture storage in a hygroscopic porous material**
From Straube & Burnett, 2005

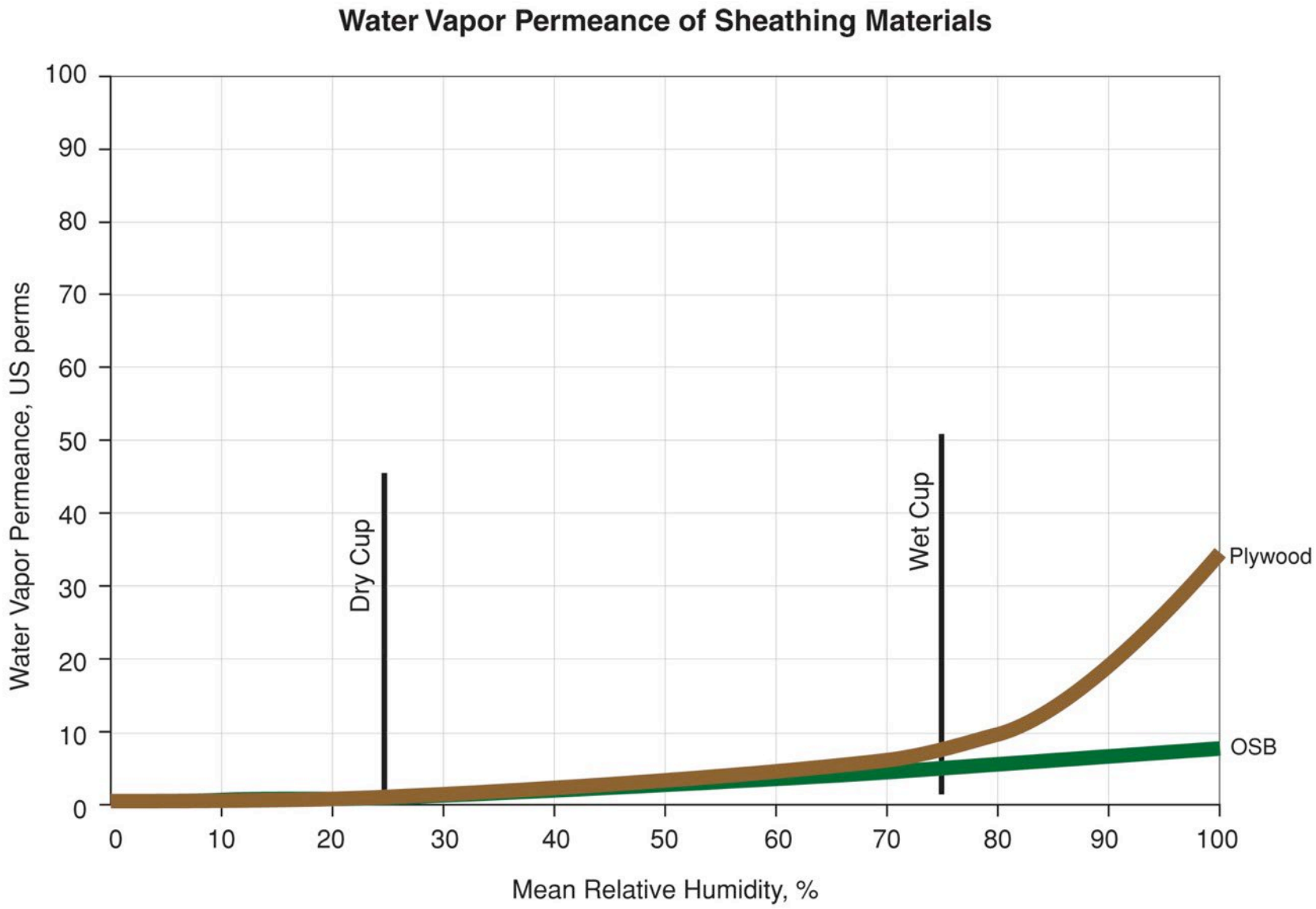


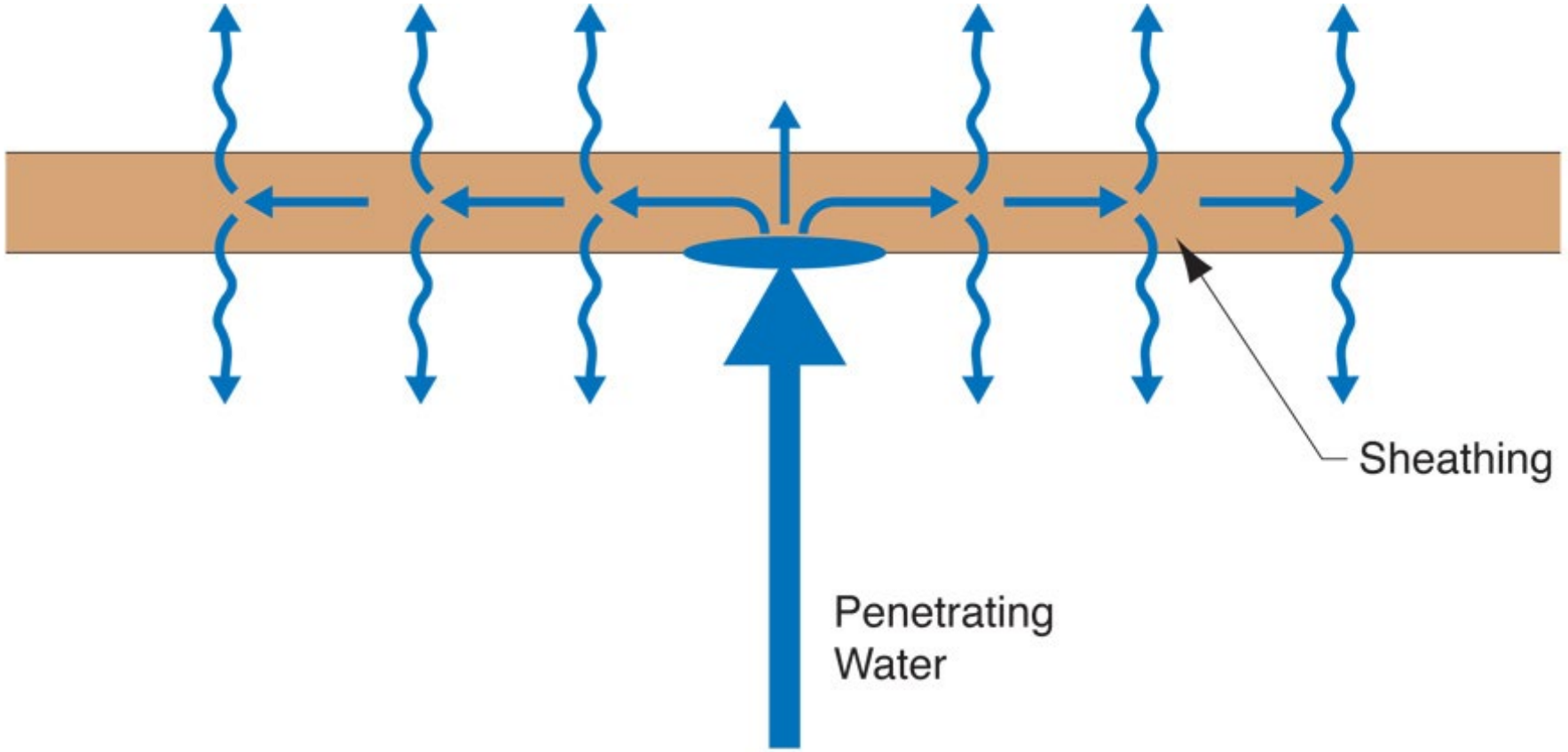

A - Single-layer of absorbed molecules
B - Multiple layers of absorbed molecules
C - Interconnected layers (internal capillary condensation)
D - Free water in pores, capillary suction
E - Supersaturated regime

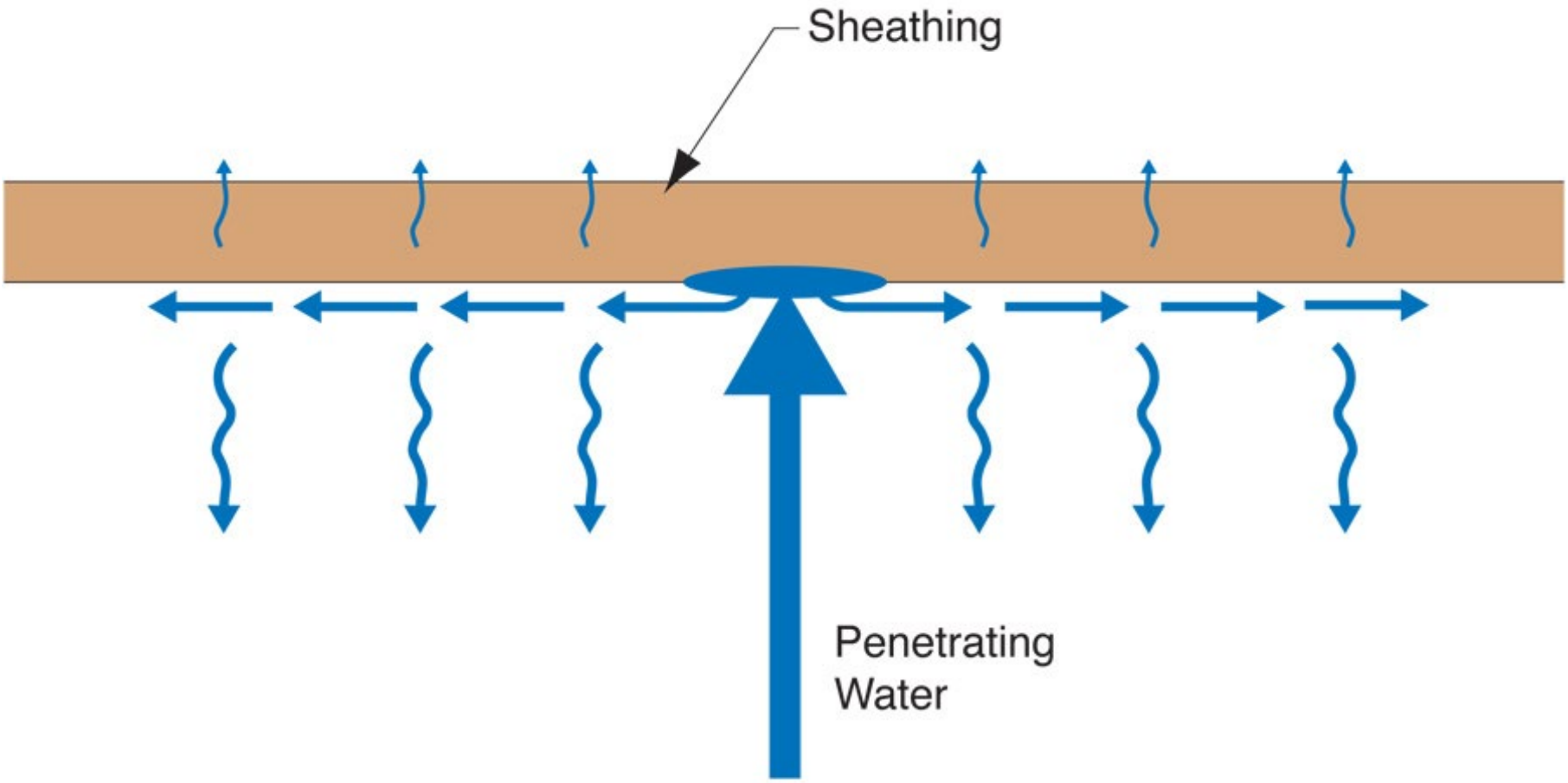
Relationship between Dry Cup and Wet Cup
Adapted from Joy & Wilson, 1963

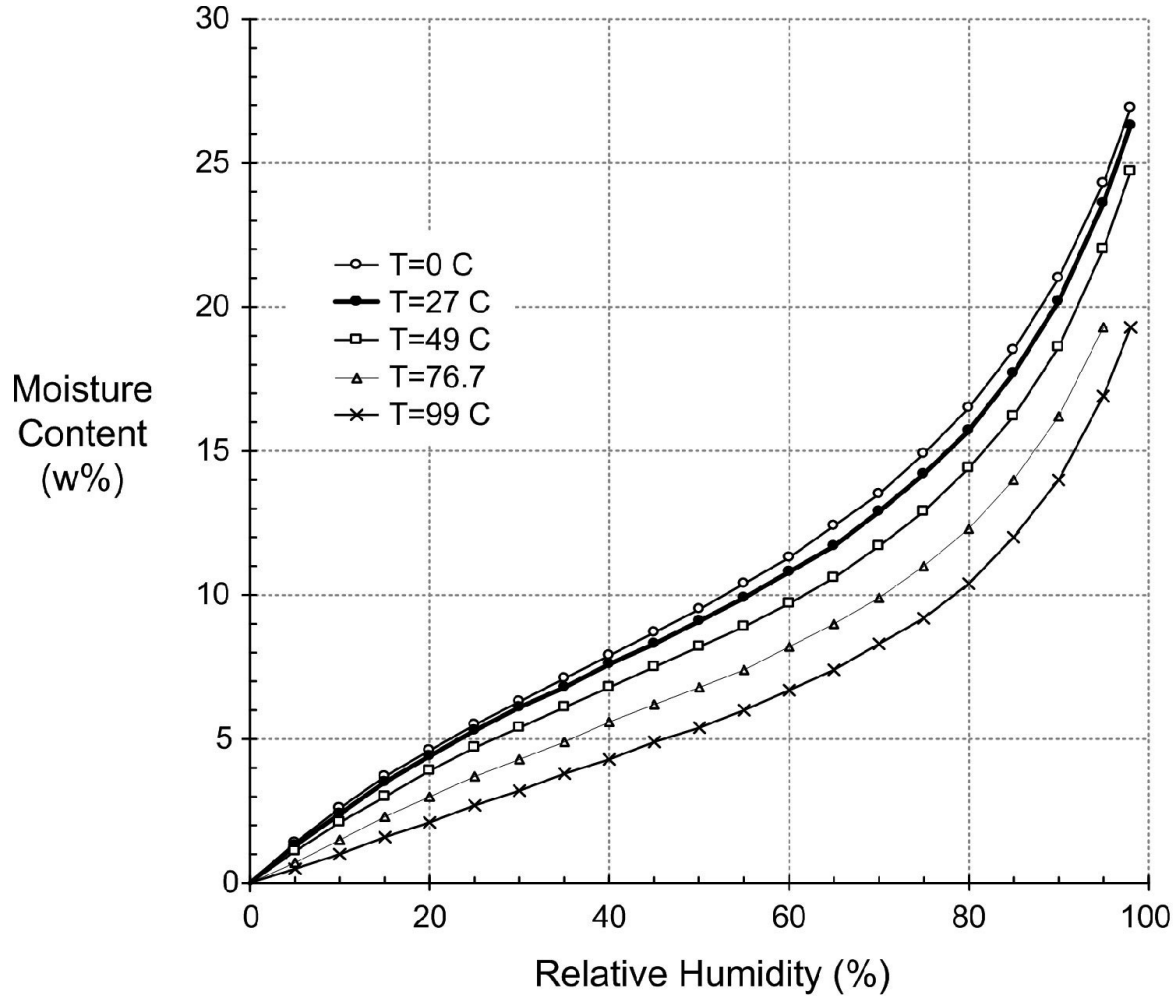
OWENS-CORNING
Fiberglas
Building
Insulation
FIBERGLAS
R-11
3½"
ASSURED THERMAL
PERFORMANCE
WARNING: The FACING on this insulation will BURN AND SHOULD NOT BE LEFT EXPOSED. Special care should be taken when working close to the facing


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
$\mu_2$
$\mu_1$
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, %
$\mu_1$ = Dry cup permeance
$\mu_2$ = Wet cup permeance

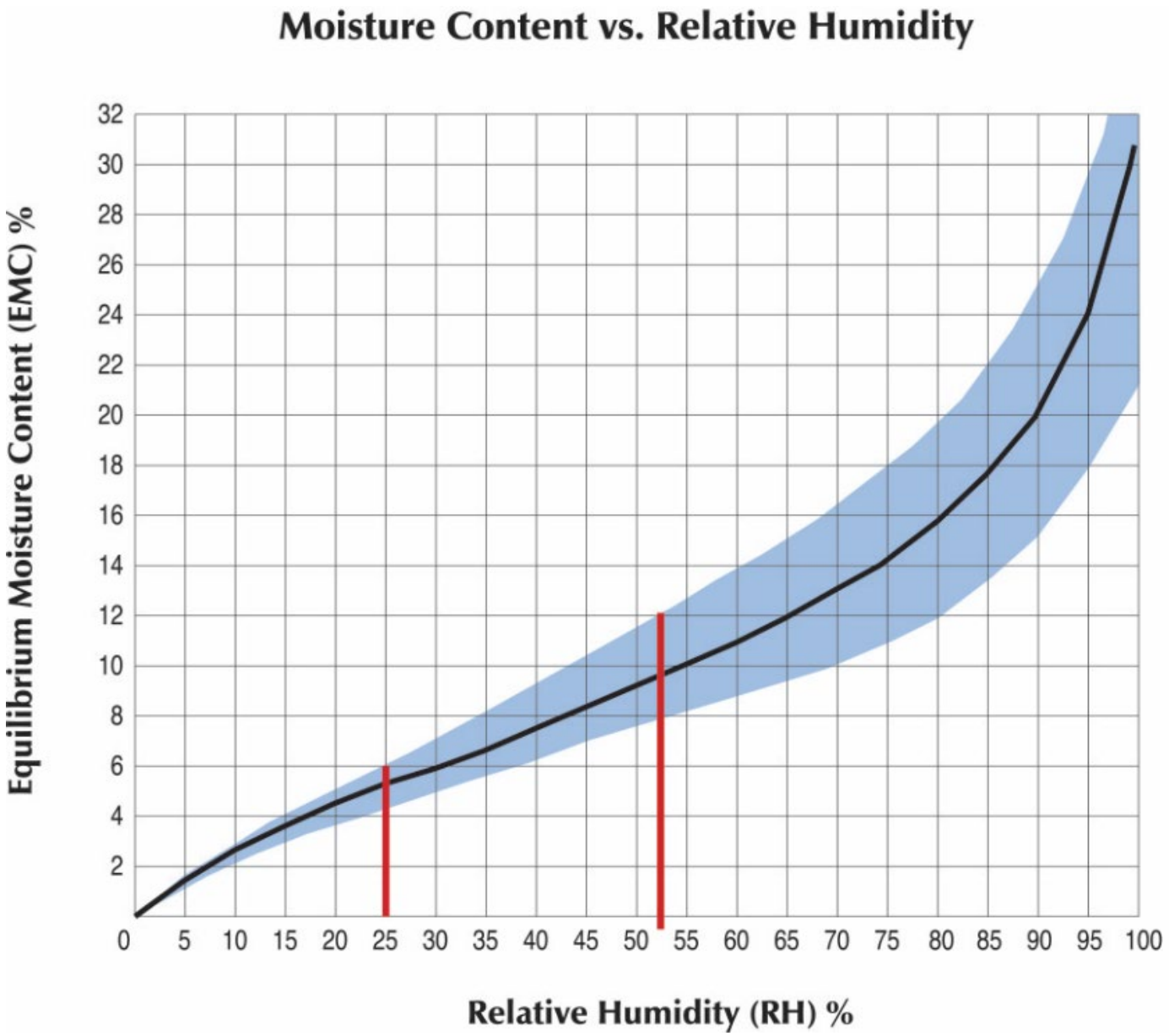

Water Vapor Permeance of Sheathing Materials
Water Vapor Permeance, US perms
100
90
80
70
60
50
40
30
20
10
0
Dry Cup
Wet Cup
Plywood
OSB
0
10
20
30
40
50
60
70
80
90
100
Mean Relative Humidity, %

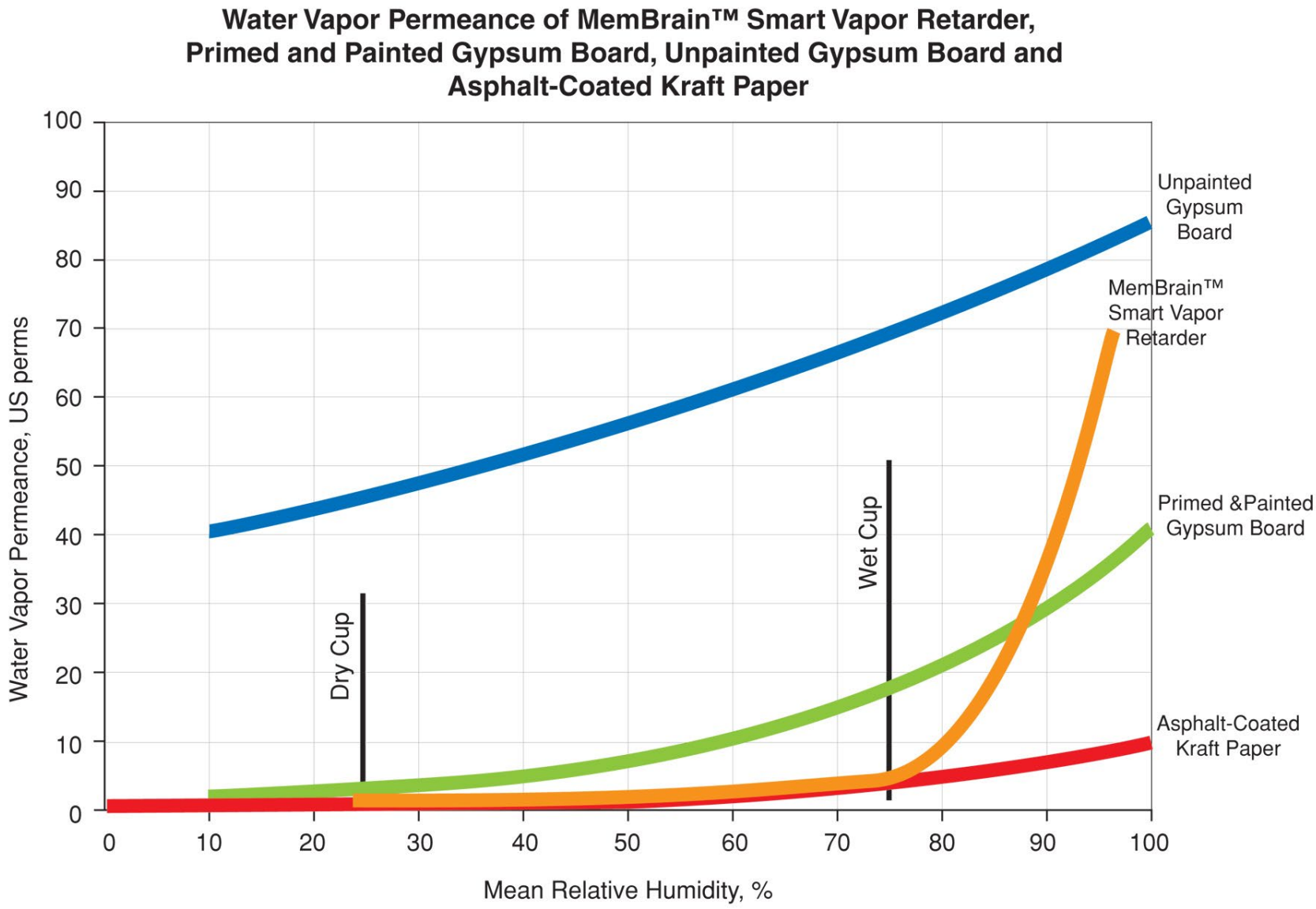

Sheathing
Penetrating
Water

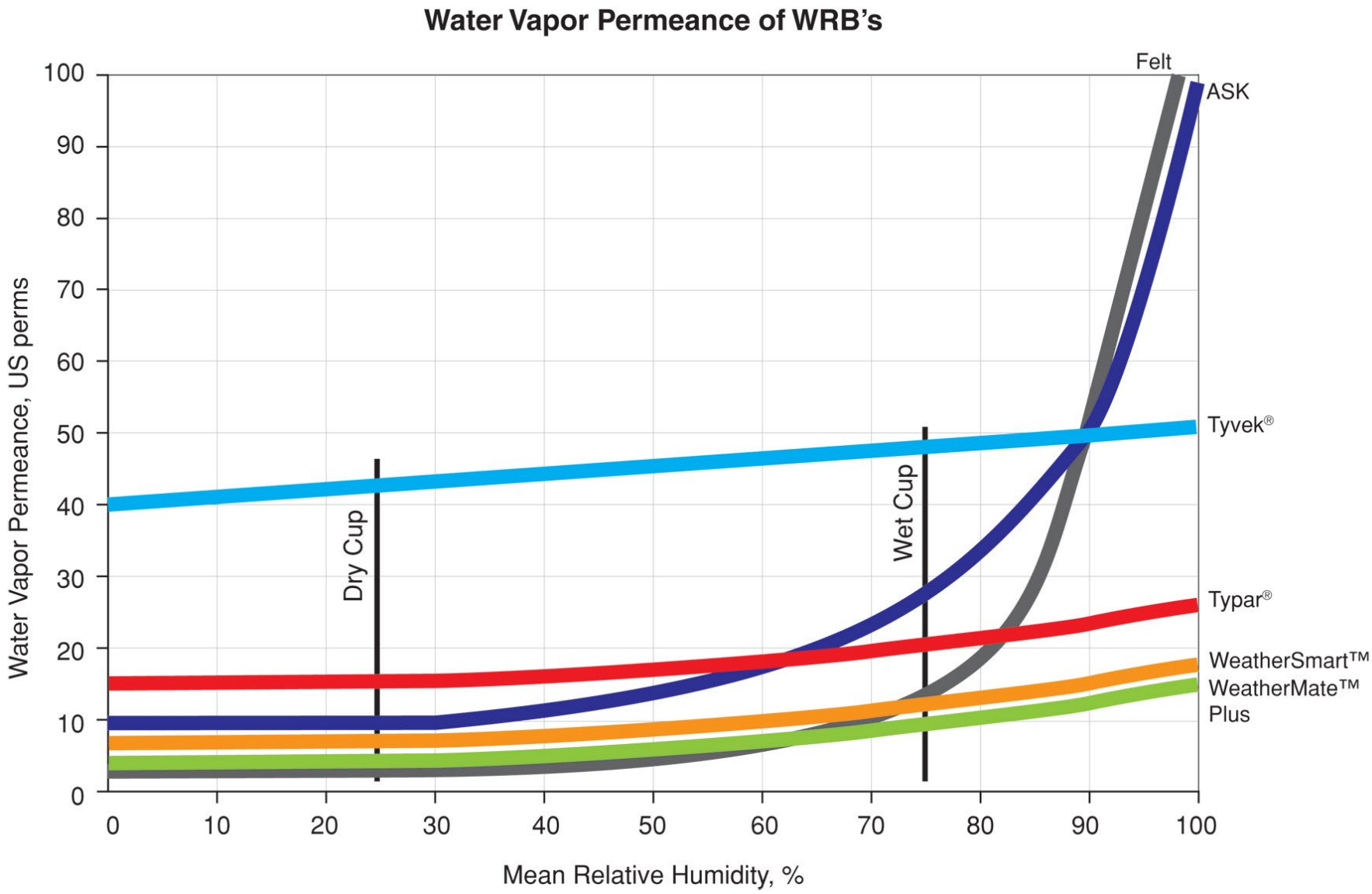

Sheathing
Penetrating
Water




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

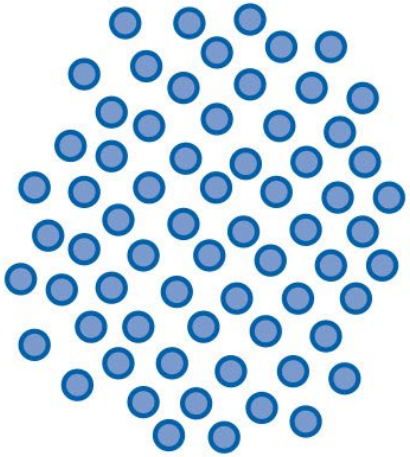

Moisture Content vs. Relative Humidity
Equilibrium Moisture Content (EMC) %
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
Relative Humidity (RH) %


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

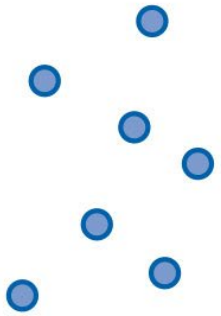

Water Vapor Permeance of WRB's
Water Vapor Permeance, US perms
Mean Relative Humidity, %
0
10
20
30
40
50
60
70
80
90
100
Dry Cup
Wet Cup
Felt
ASK
Tyvek®
Typar®
WeatherSmart™
WeatherMate™
Plus

# Air Flow and Vapor Diffusion

| | | |
|---|---|---|
| Vapor | Diffusion | Vapor Concentration |
| | Convective Flow | Air Pressure |



**DIFFUSION**



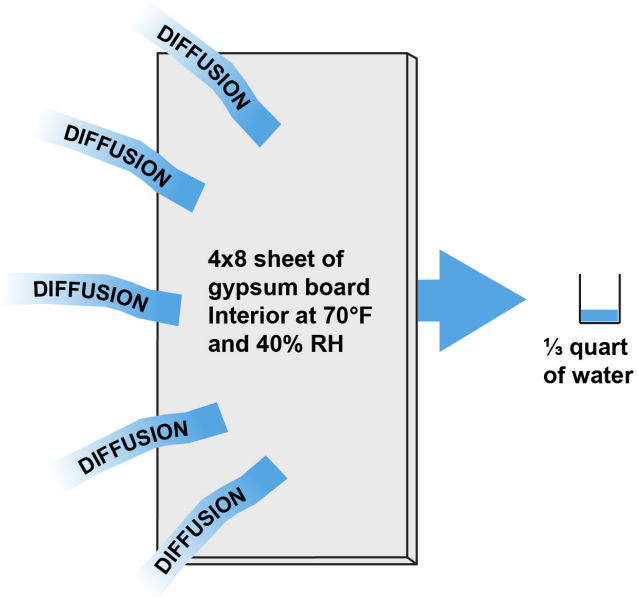
**Higher Dewpoint Temperature**
**Higher Water Vapor Density**
**or Concentration**
**(Higher Vapor Pressure)**
**on Warm Side of Assembly**

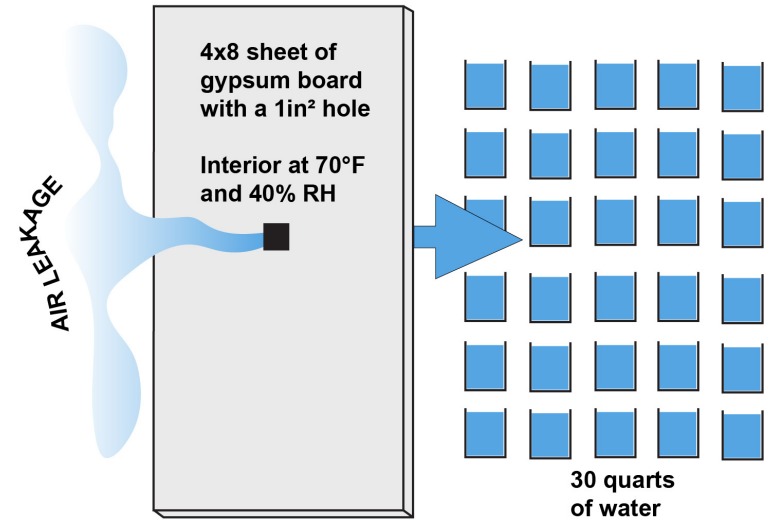
**Low Dewpoint Temperature**
**Lower Water Vapor Density**
**or Concentration**
**(Lower Vapor Pressure)**
**on Cold Side of Assembly**

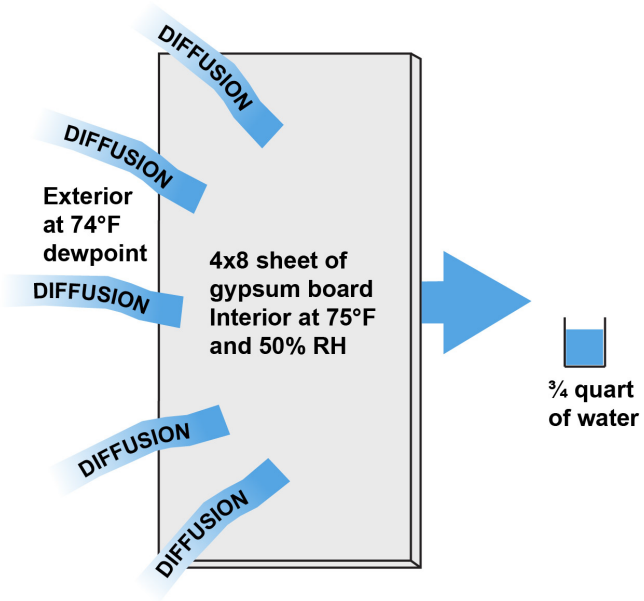
**AIR TRANSPORT**

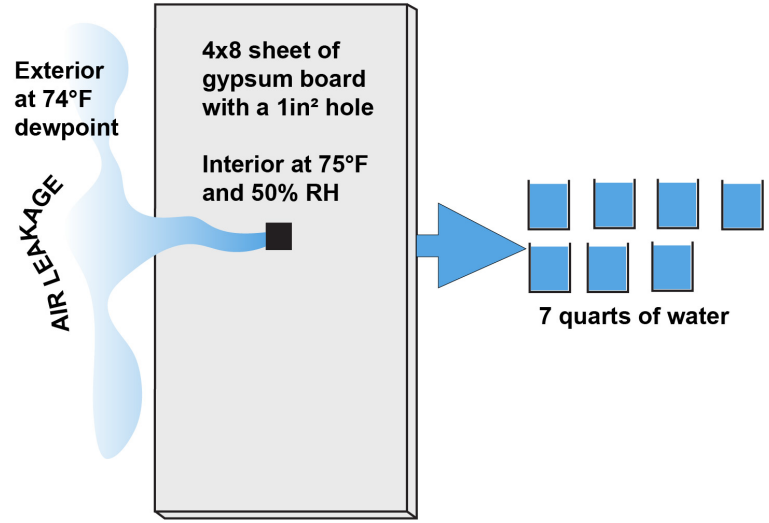
**Higher Air Pressure**

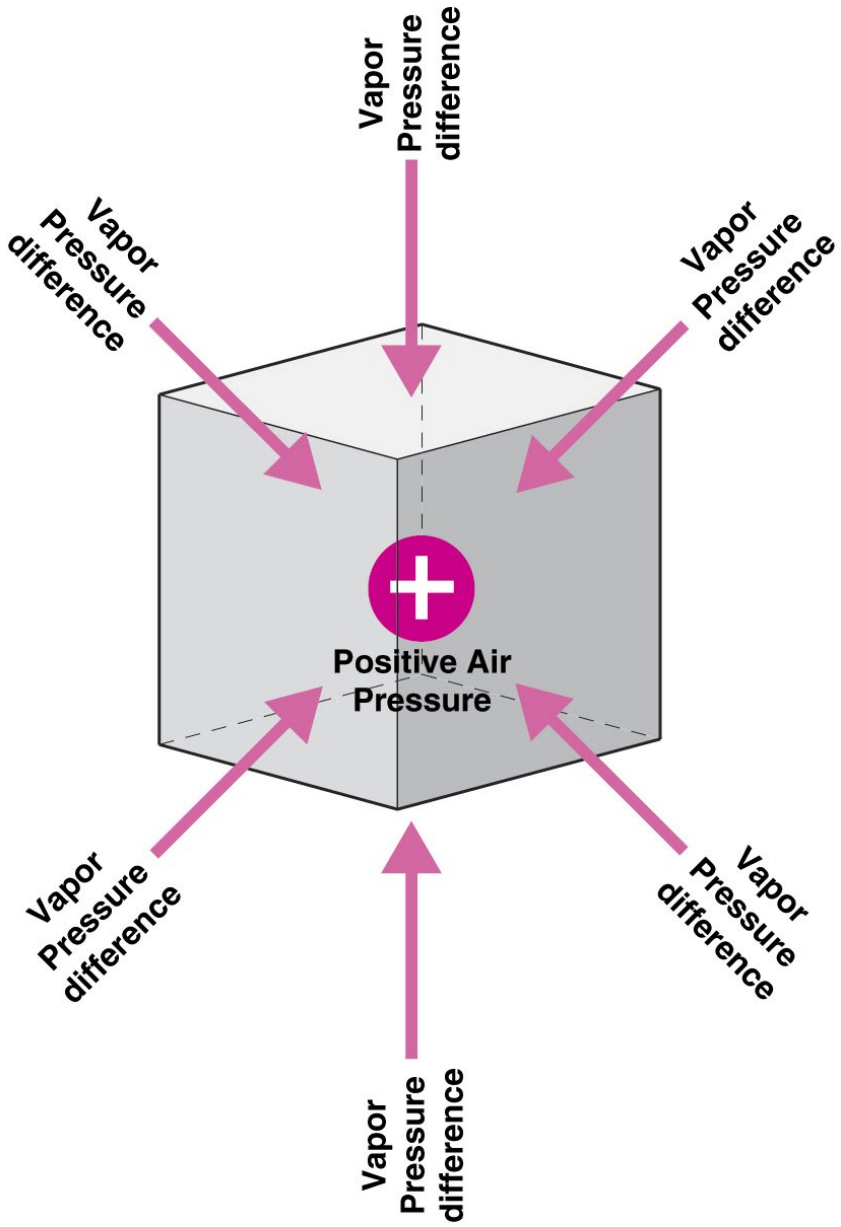
**Lower Air Pressure**


DIFFUSION
DIFFUSION
DIFFUSION
DIFFUSION
DIFFUSION
4x8 sheet of gypsum board Interior at 70°F and 40% RH
⅓ quart of water


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

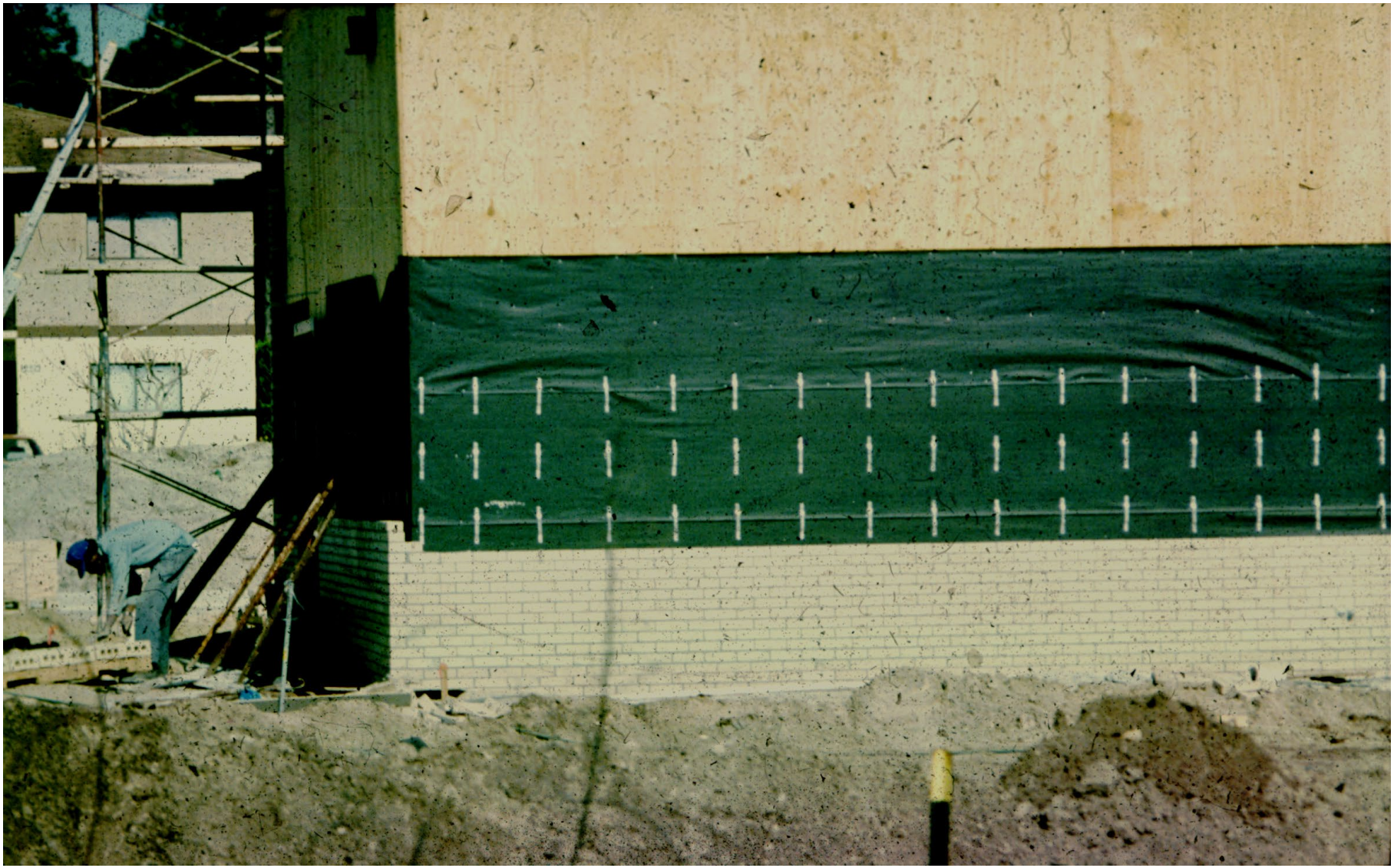

DIFFUSION
DIFFUSION
Exterior
at 74°F
dewpoint
DIFFUSION
4x8 sheet of
gypsum board
Interior at 75°F
and 50% RH
DIFFUSION
DIFFUSION
¾ quart
of water

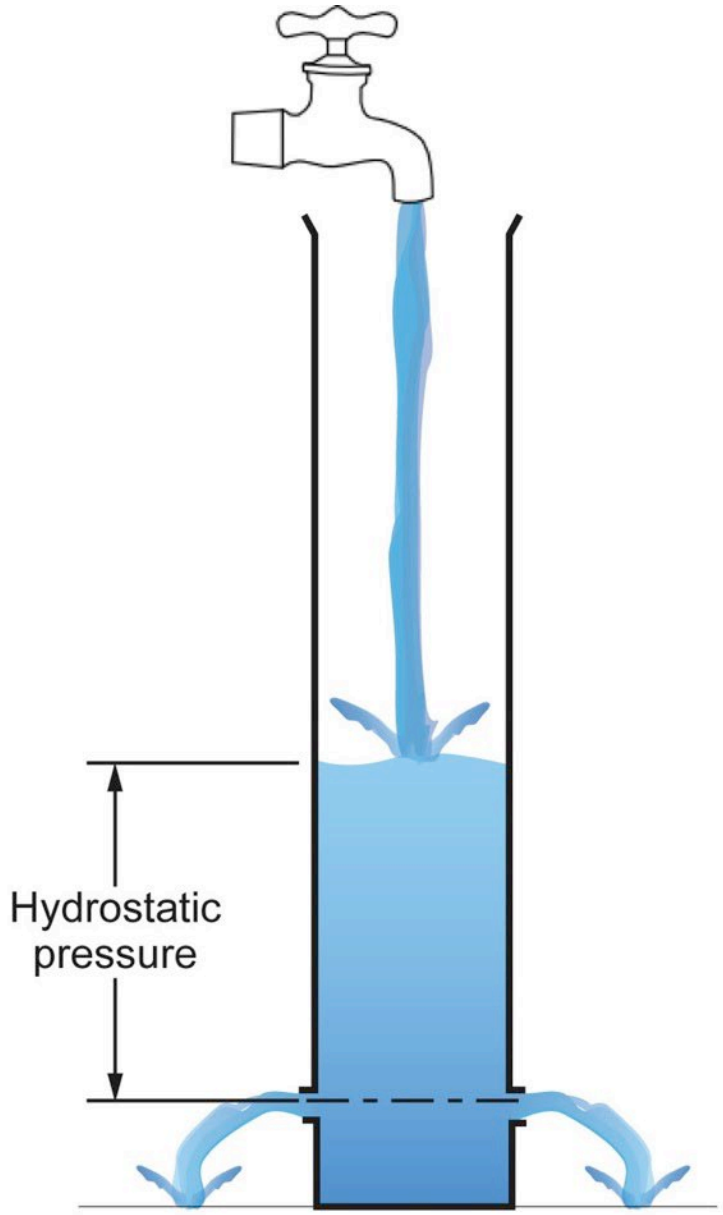

Exterior
at 74°F
dewpoint
AIR LEAKAGE
4x8 sheet of
gypsum board
with a 1in² hole
Interior at 75°F
and 50% RH
7 quarts of water

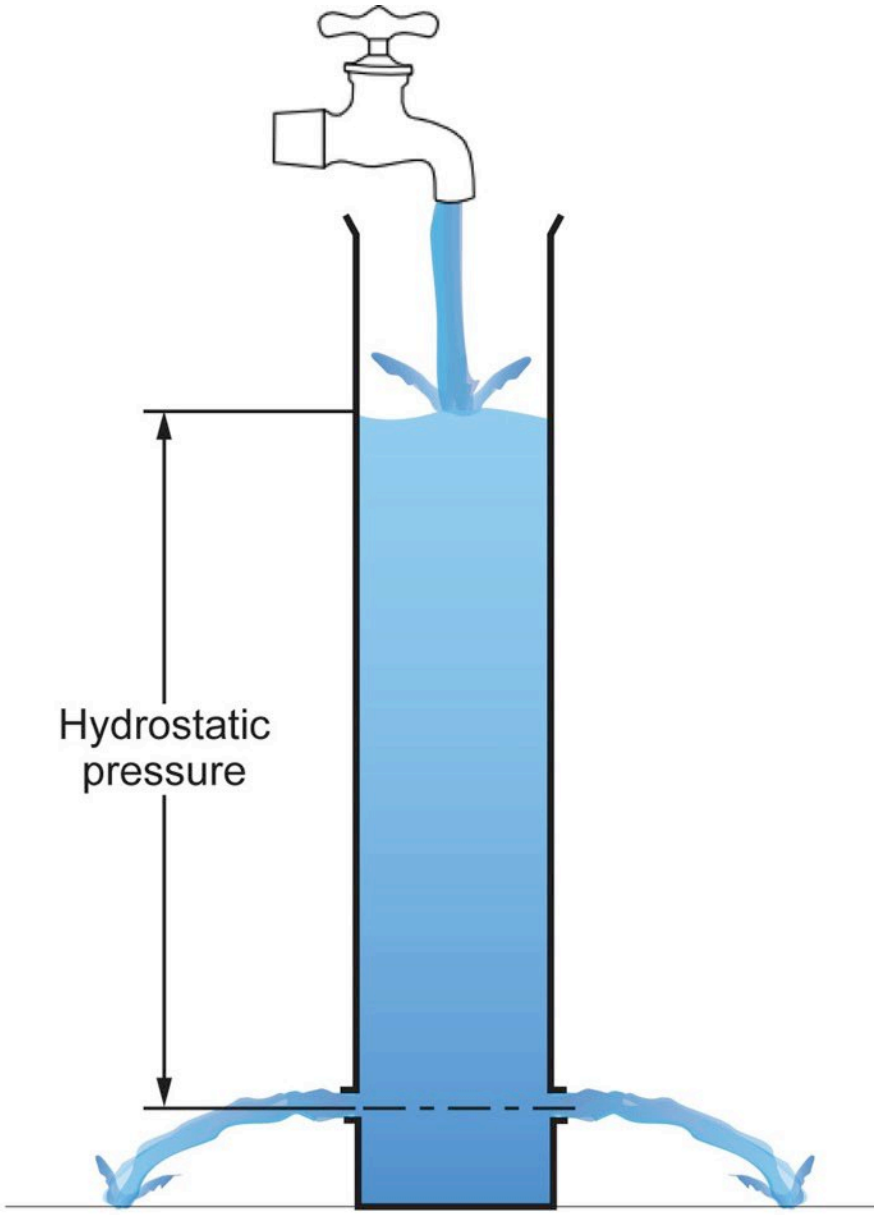

Vapor Pressure difference
Vapor Pressure difference
Vapor Pressure difference
Positive Air Pressure
Vapor Pressure difference
Vapor Pressure difference
Vapor Pressure difference

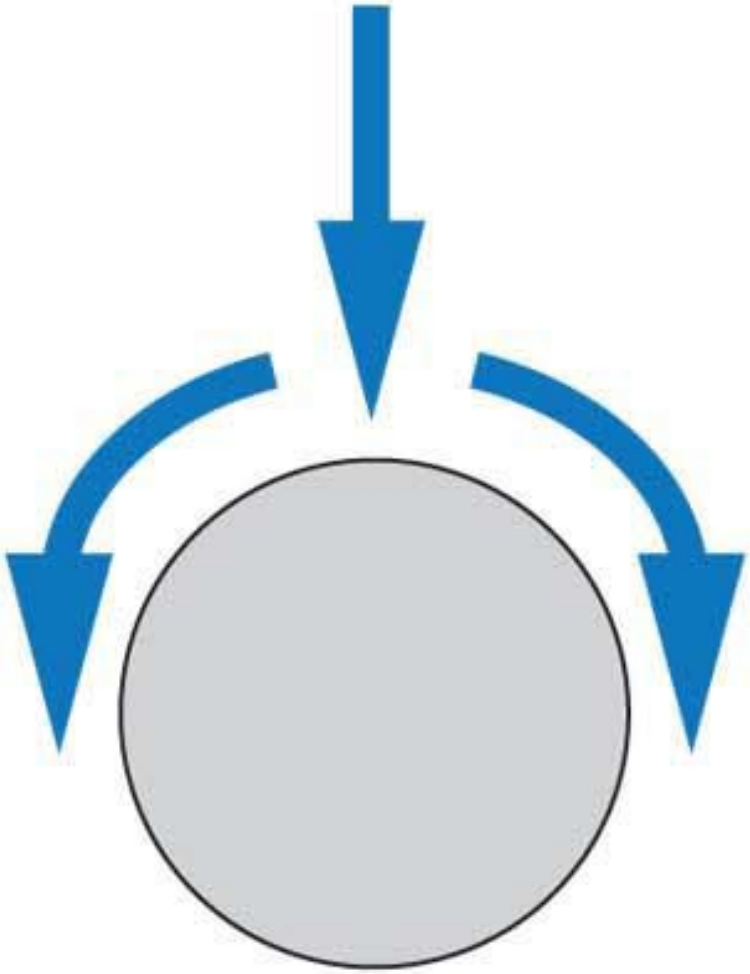
# Moisture Movement

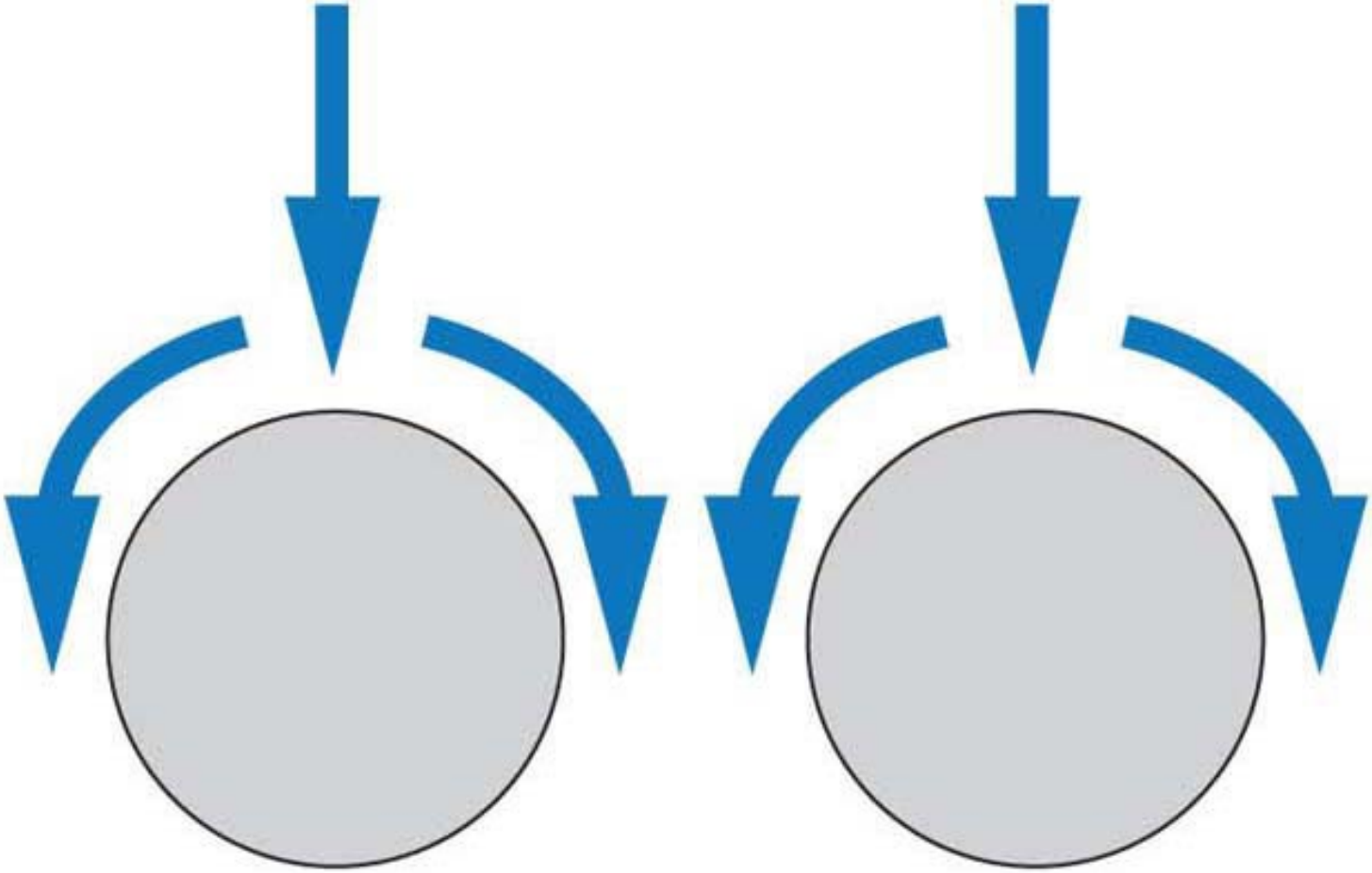
# Rain

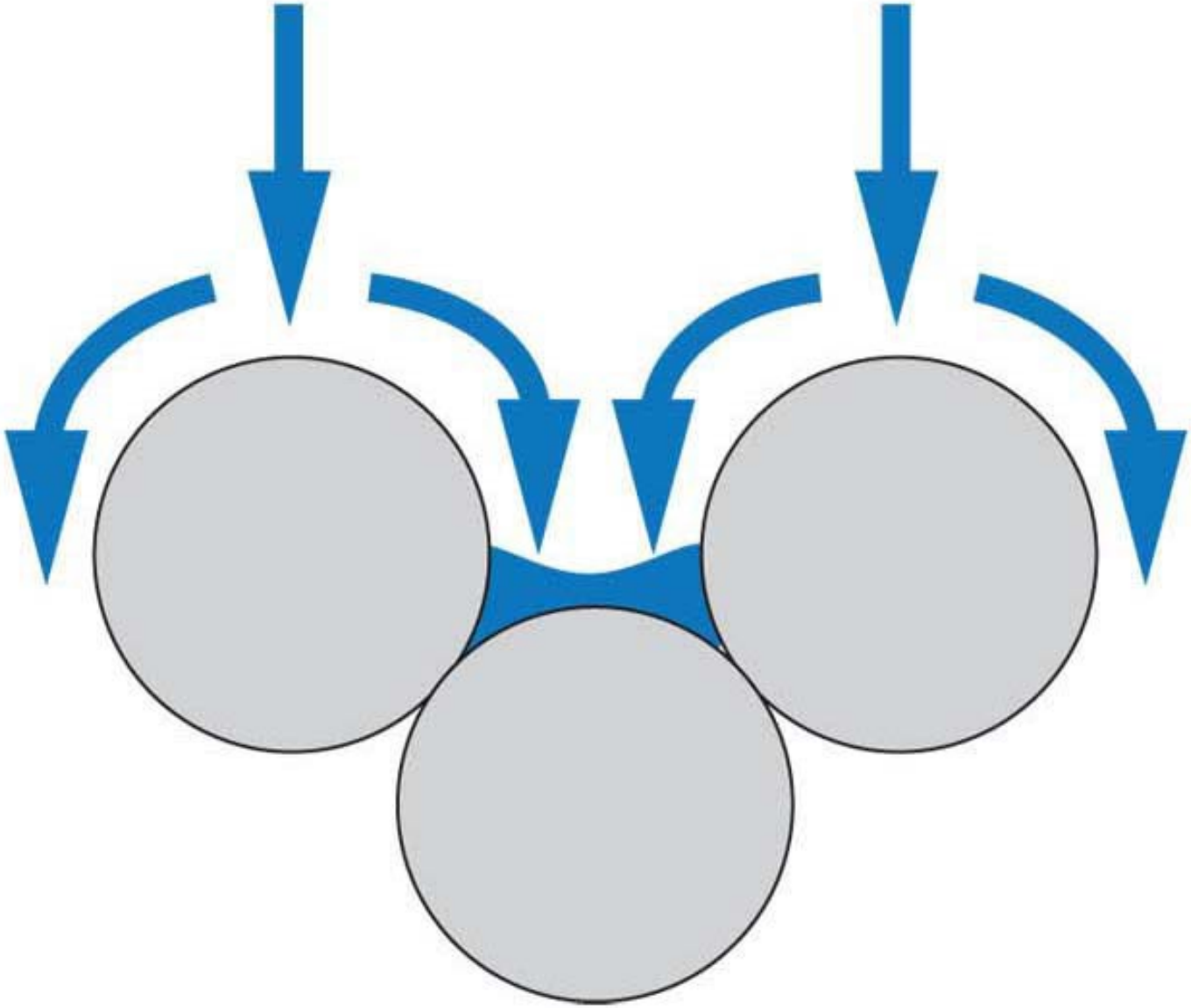


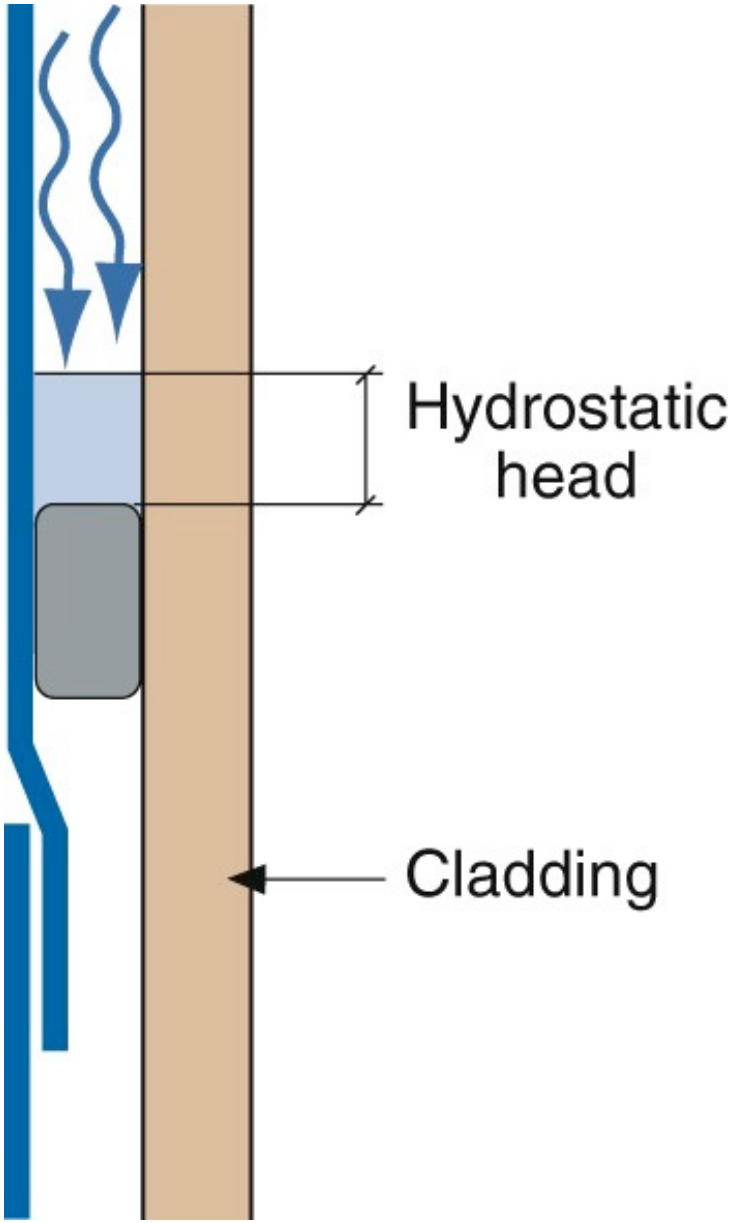

Hydrostatic
pressure

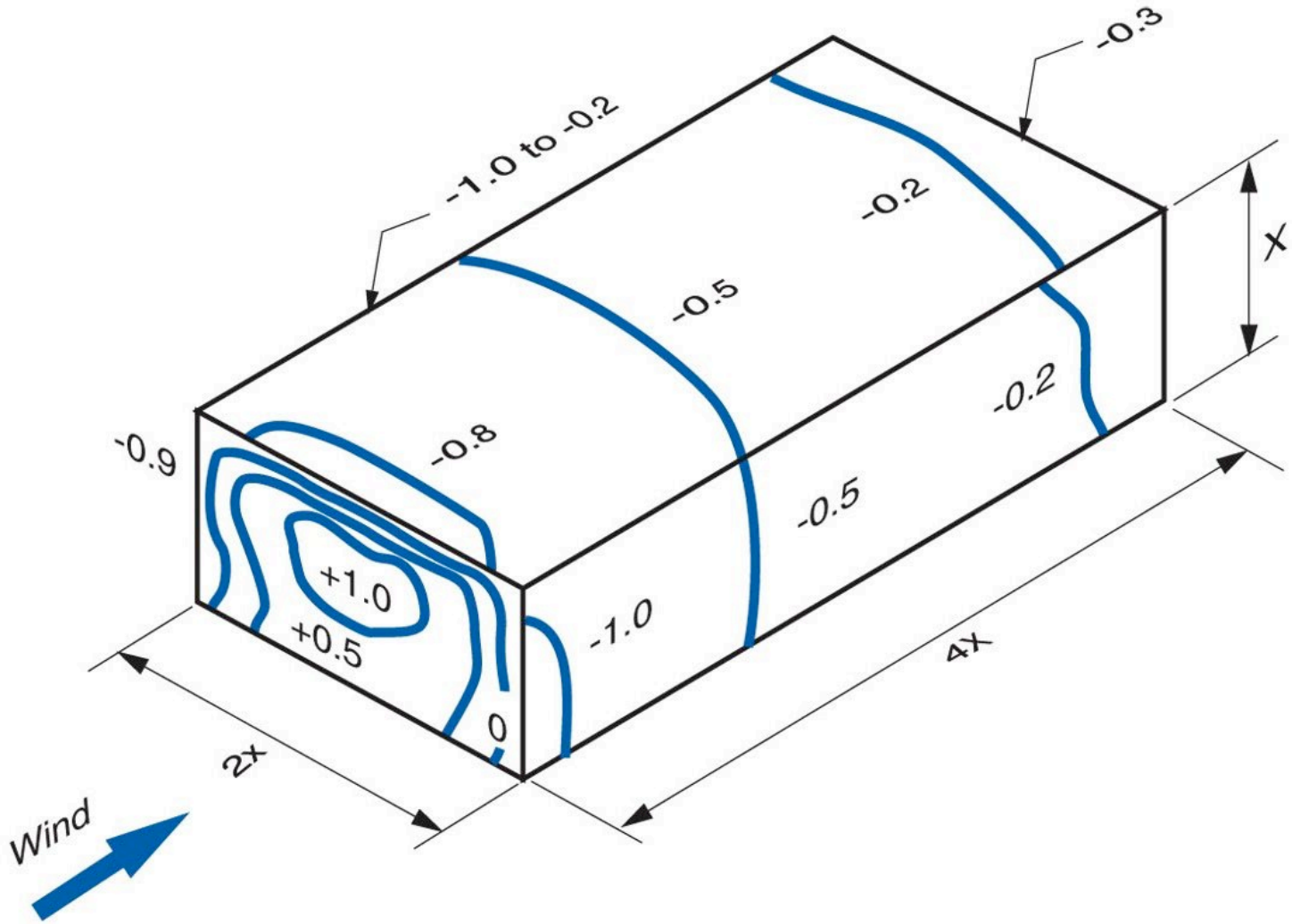

Hydrostatic
pressure



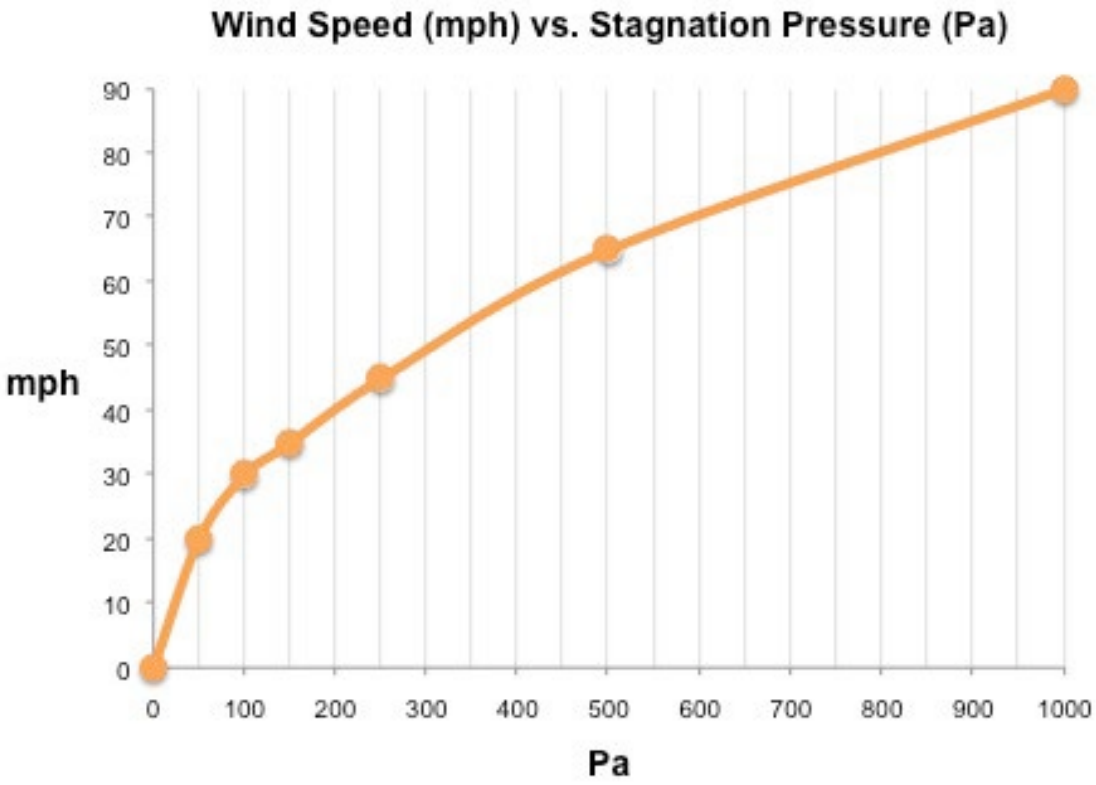





Hydrostatic
head
Cladding

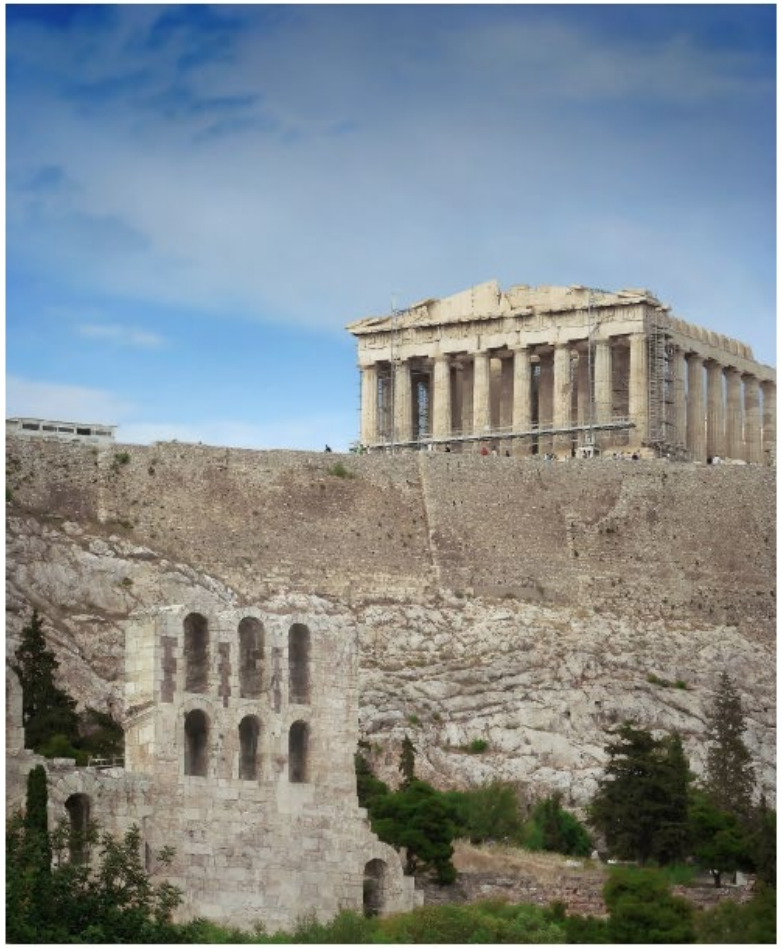

-0.3
-1.0 to -0.2
-0.2
-0.5
-0.2
-0.9
-0.8
-0.5
+1.0
+0.5
-1.0
0
X
2x
4x
Wind

| 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 |



panago
QUILTED TREASURES

panago
QUILTED TREASURES



Tyvek
DrainWrap
The miracles of science

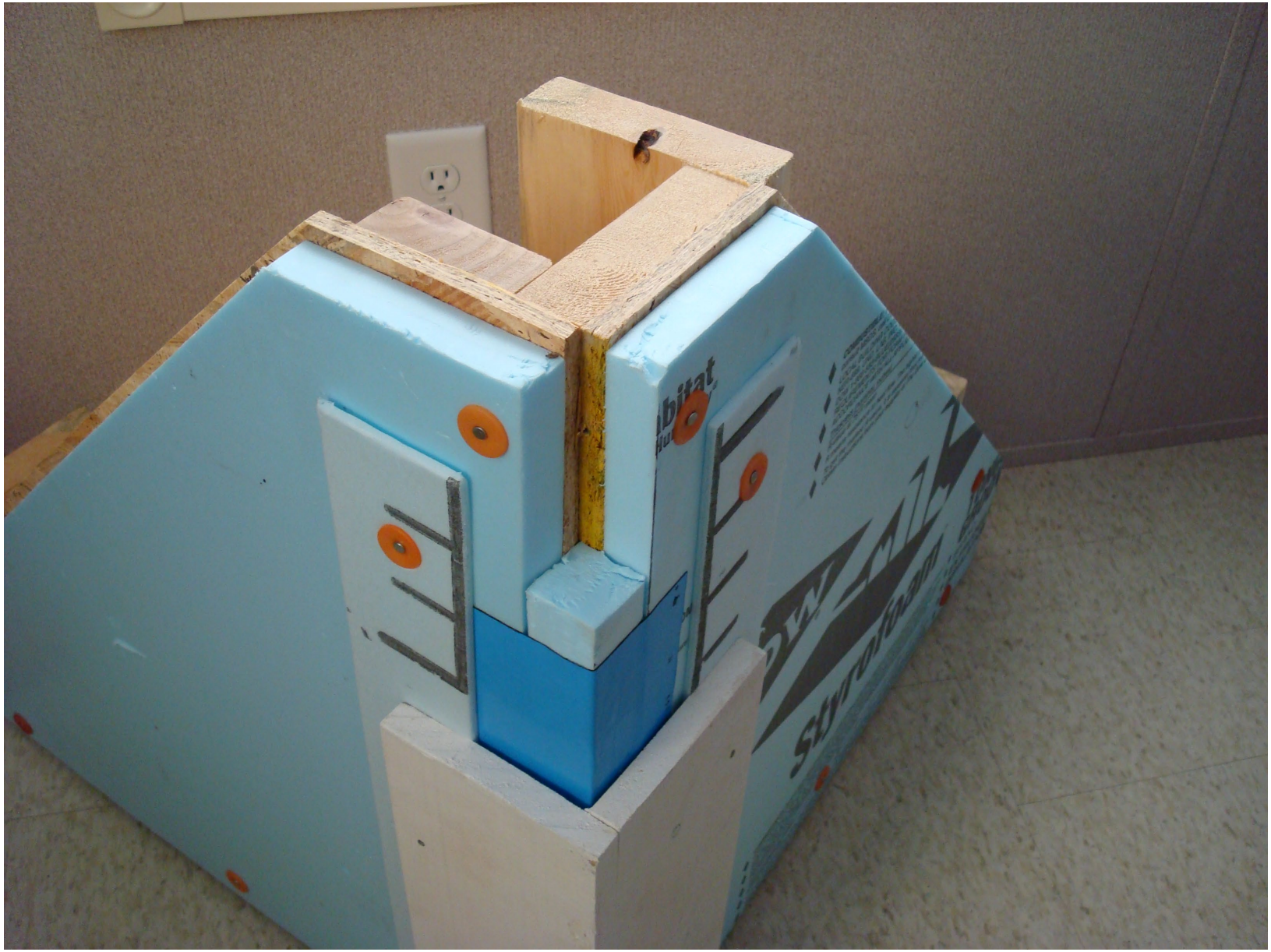
EVÊTEMENT
HOUSEW
ONT
N-6
IV-7

W1
W3

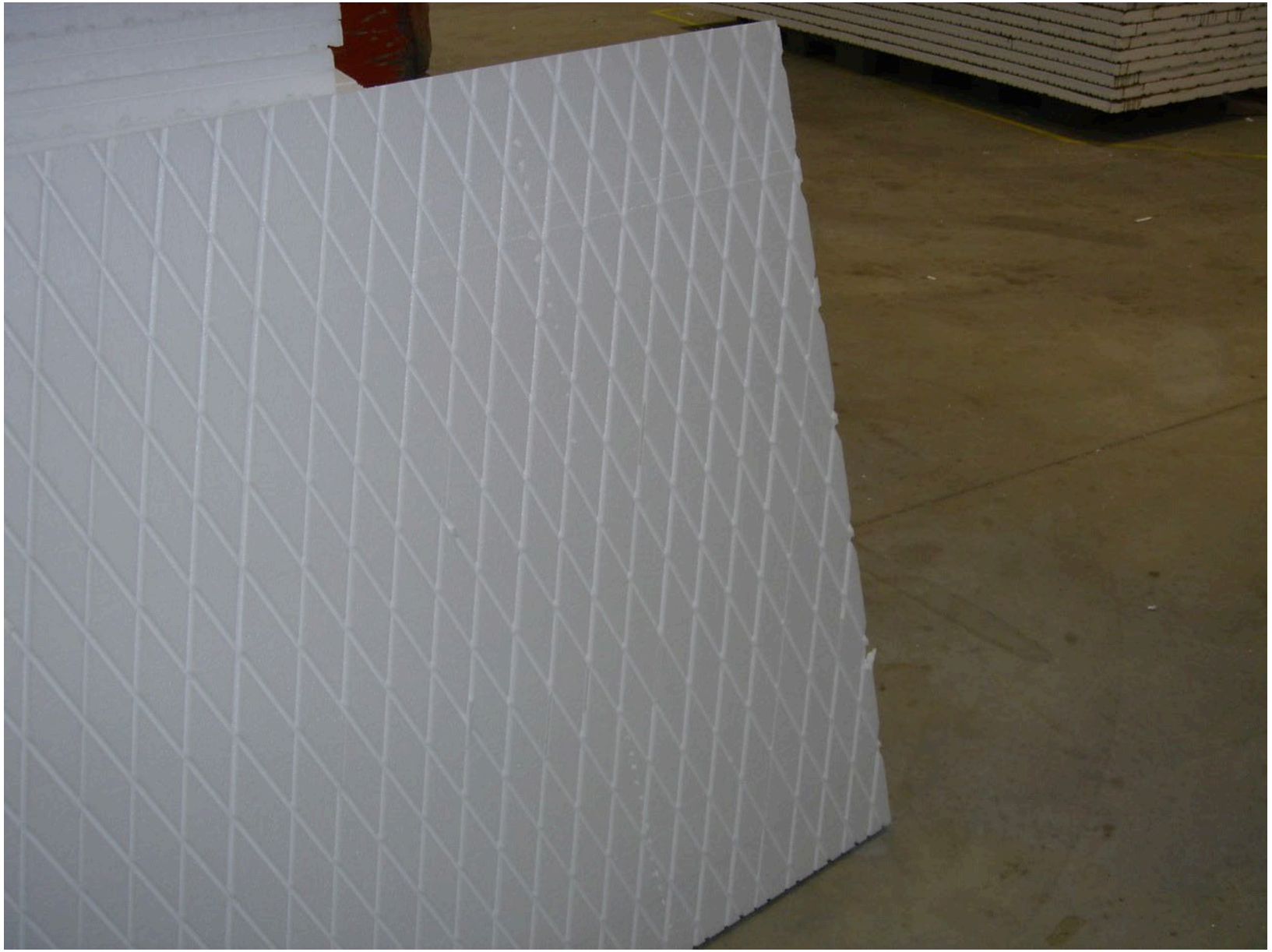
LOWER
N-2

yvek
omeWrap
Tyvek
HomeWrap

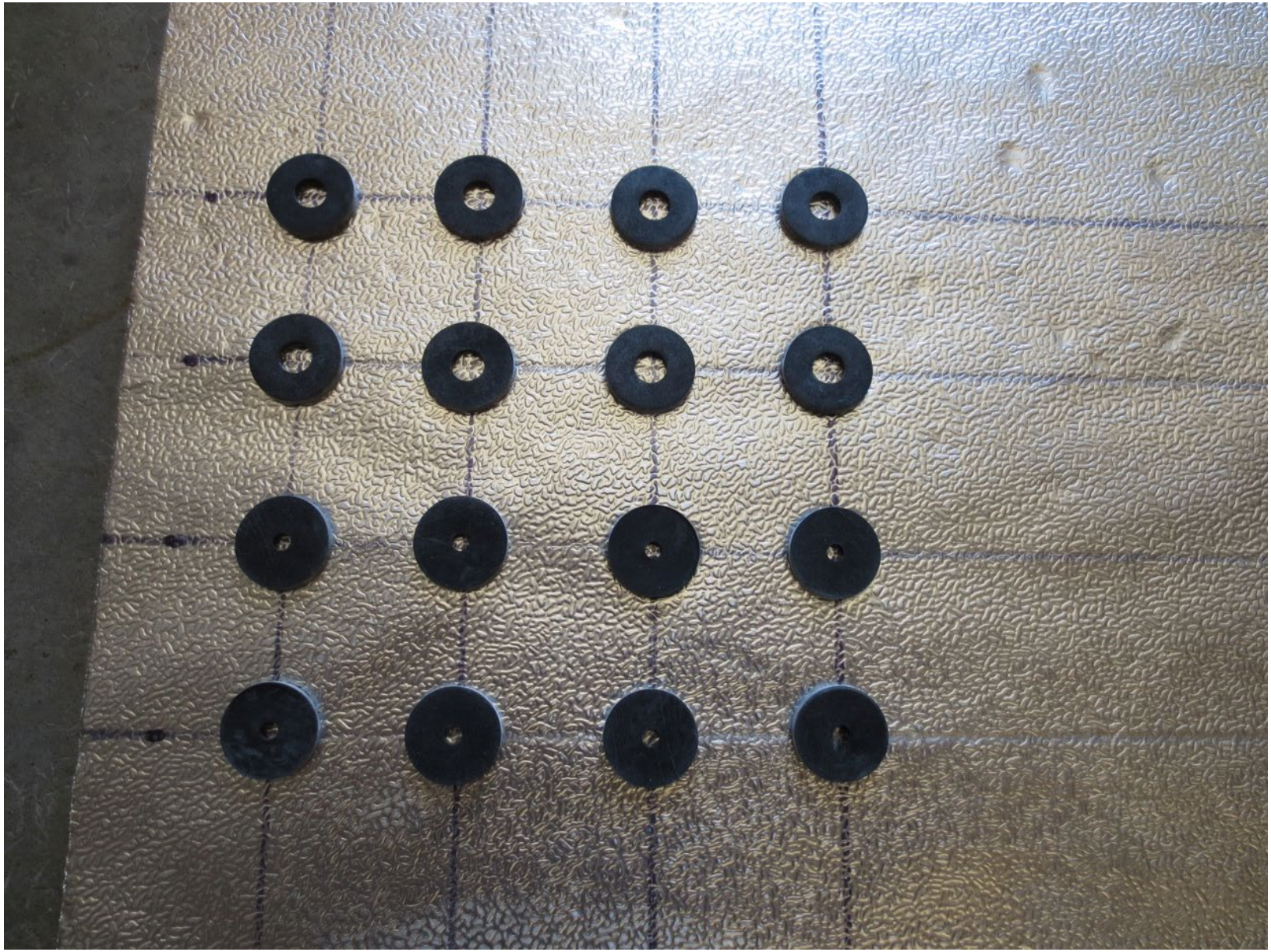
Call 1-800-44TYVEK
WWW.TYVEK.COM


Styrofoam

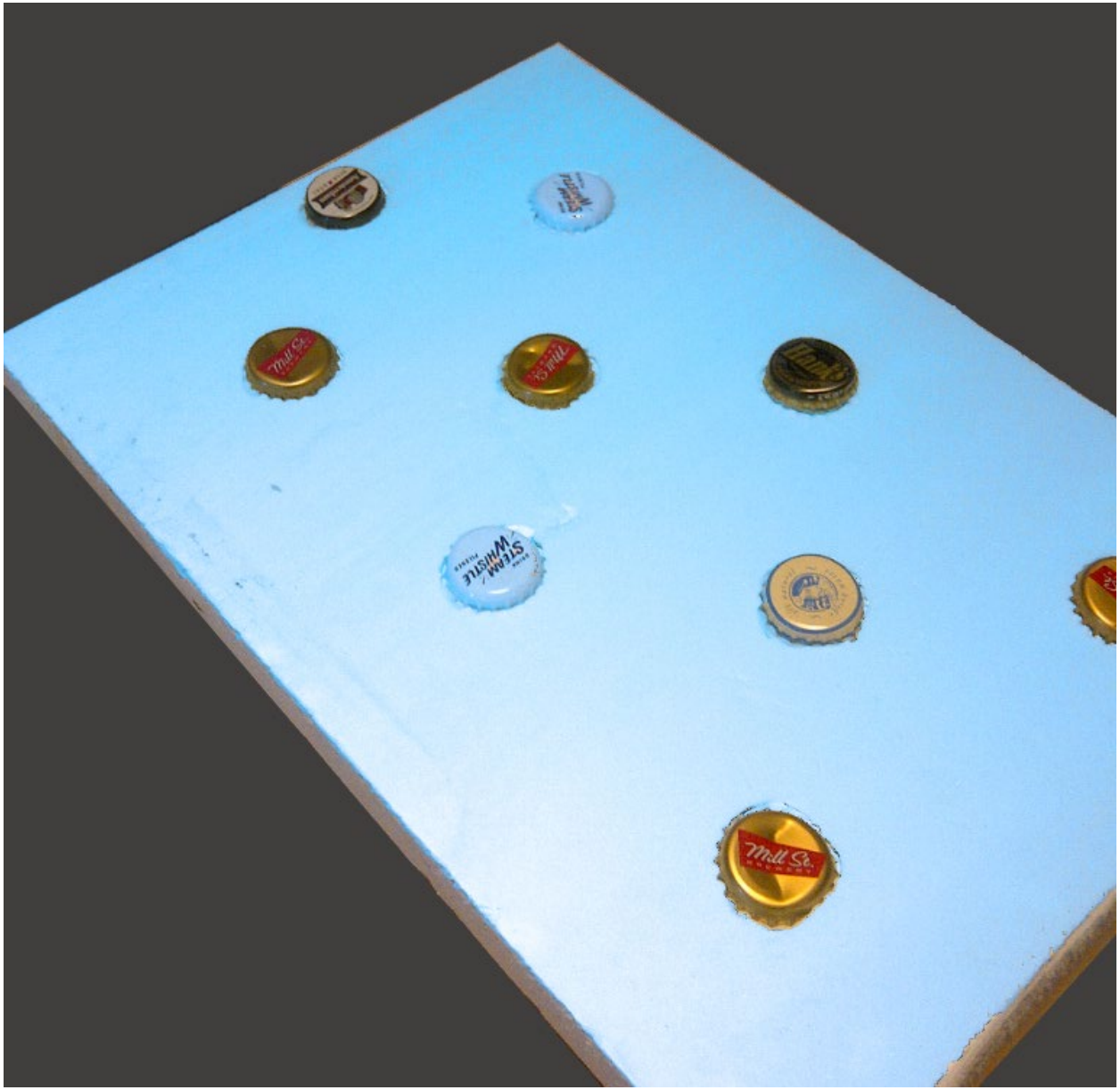
DuPont
Tyvek
Tape
DuPont
Tyvek
Tape



# Rain Screen

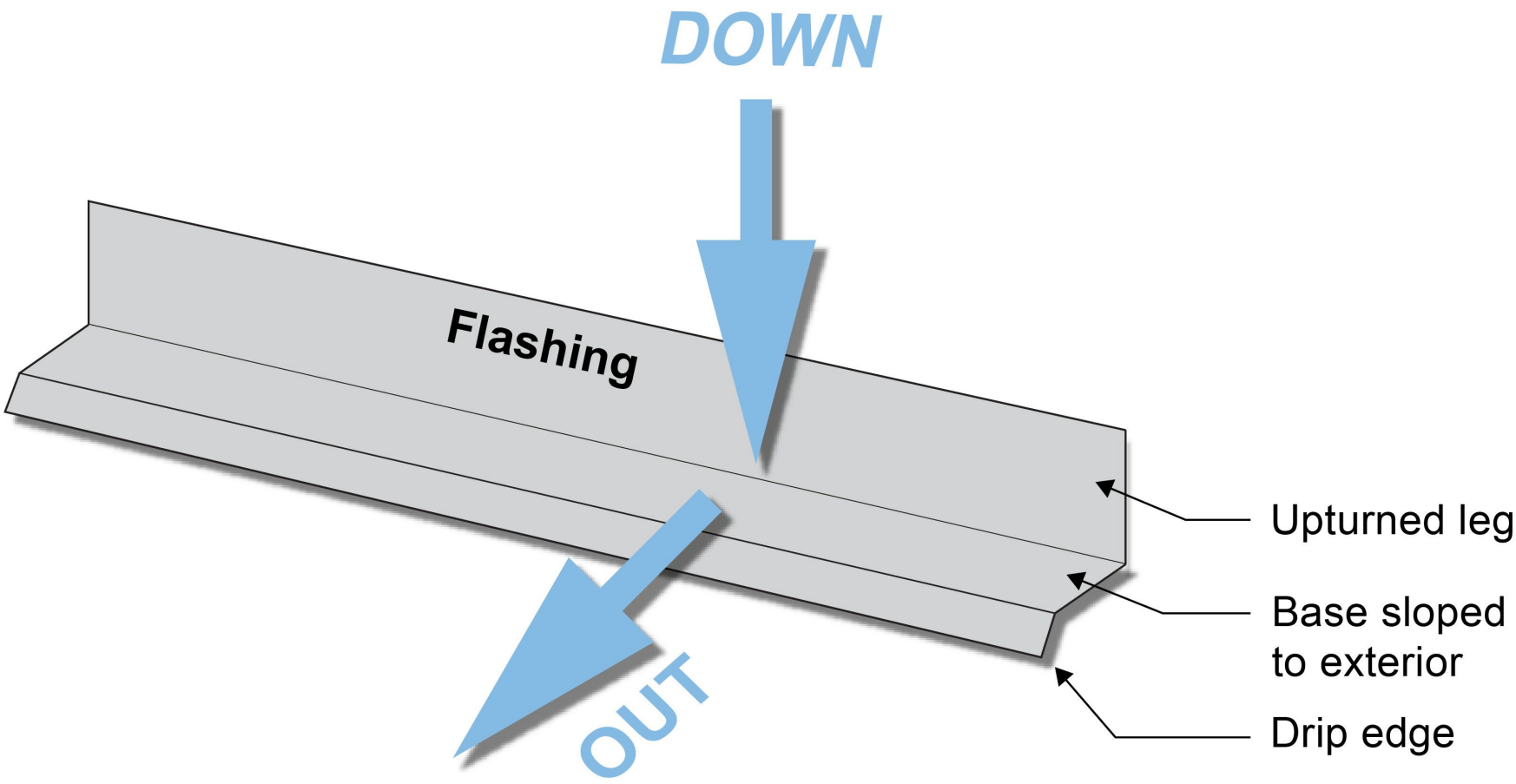


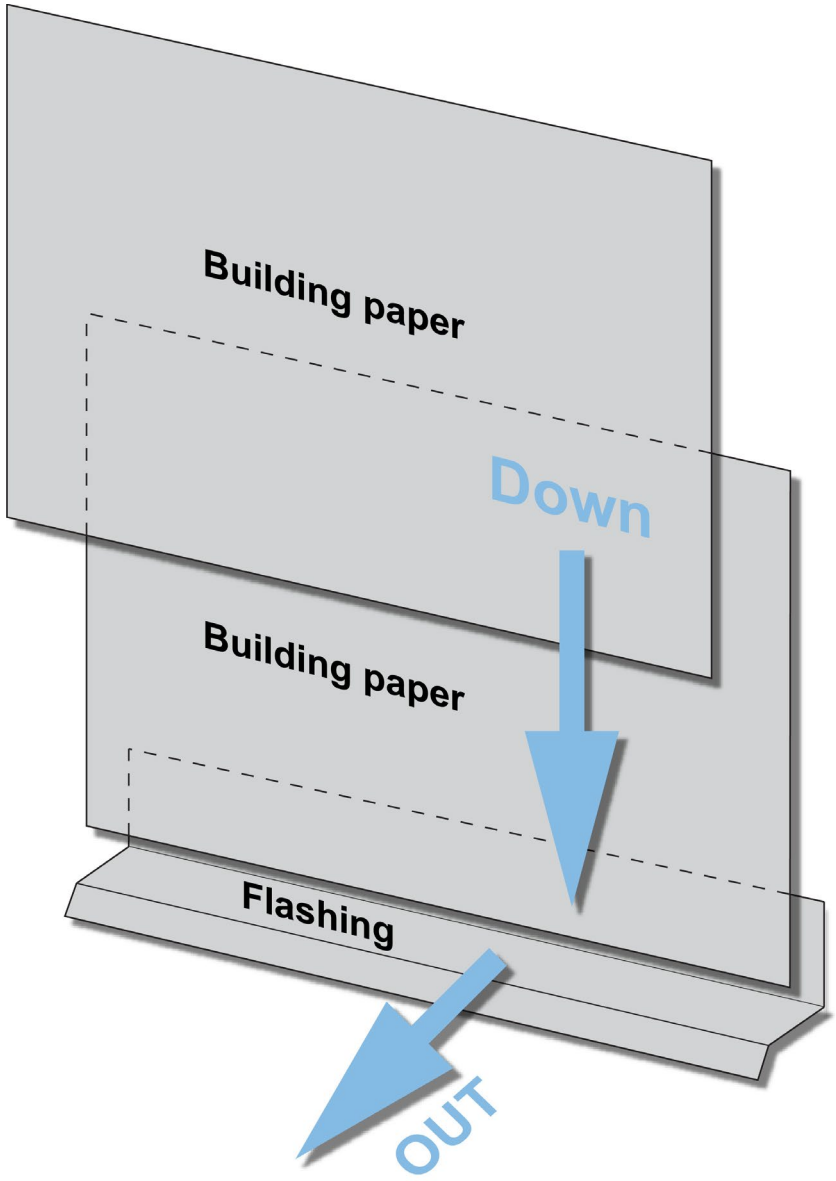
# Beer Screen?


Mill St.
Steam Whistle
Mill St.

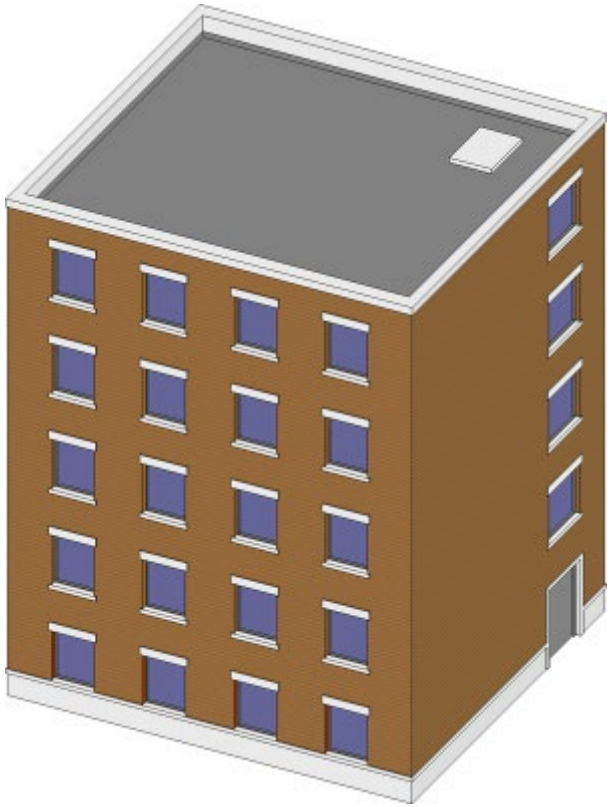
Drain the Rain on the Plane

If You Want to Save Cash…Flash

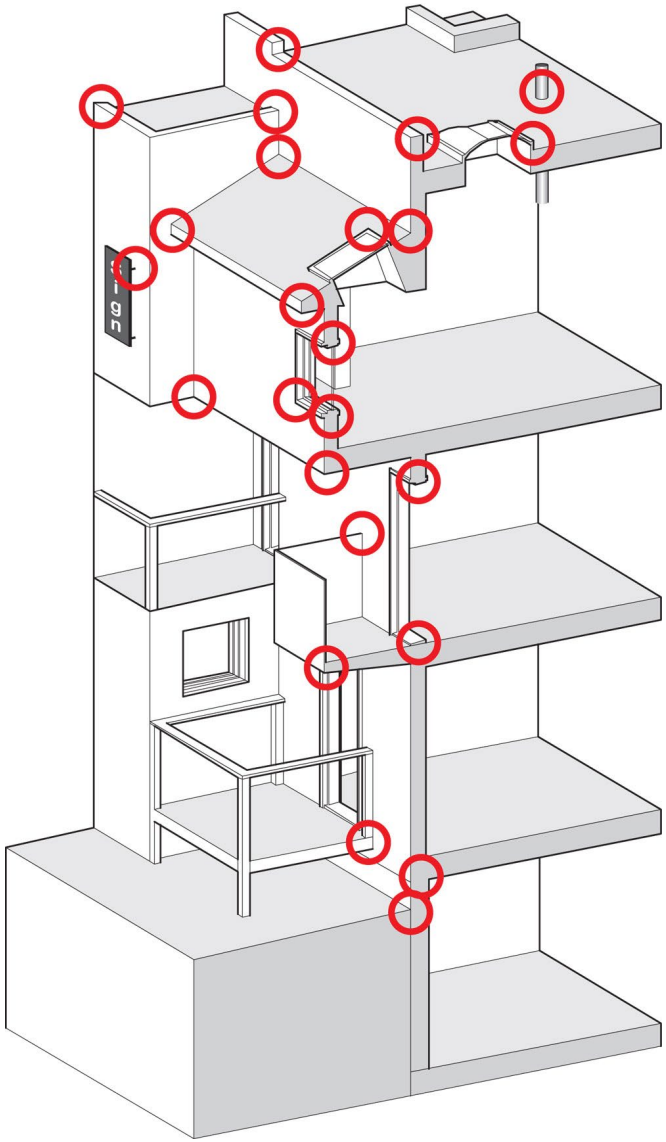

DOWN
Flashing
OUT
Upturned leg
Base sloped
to exterior
Drip edge

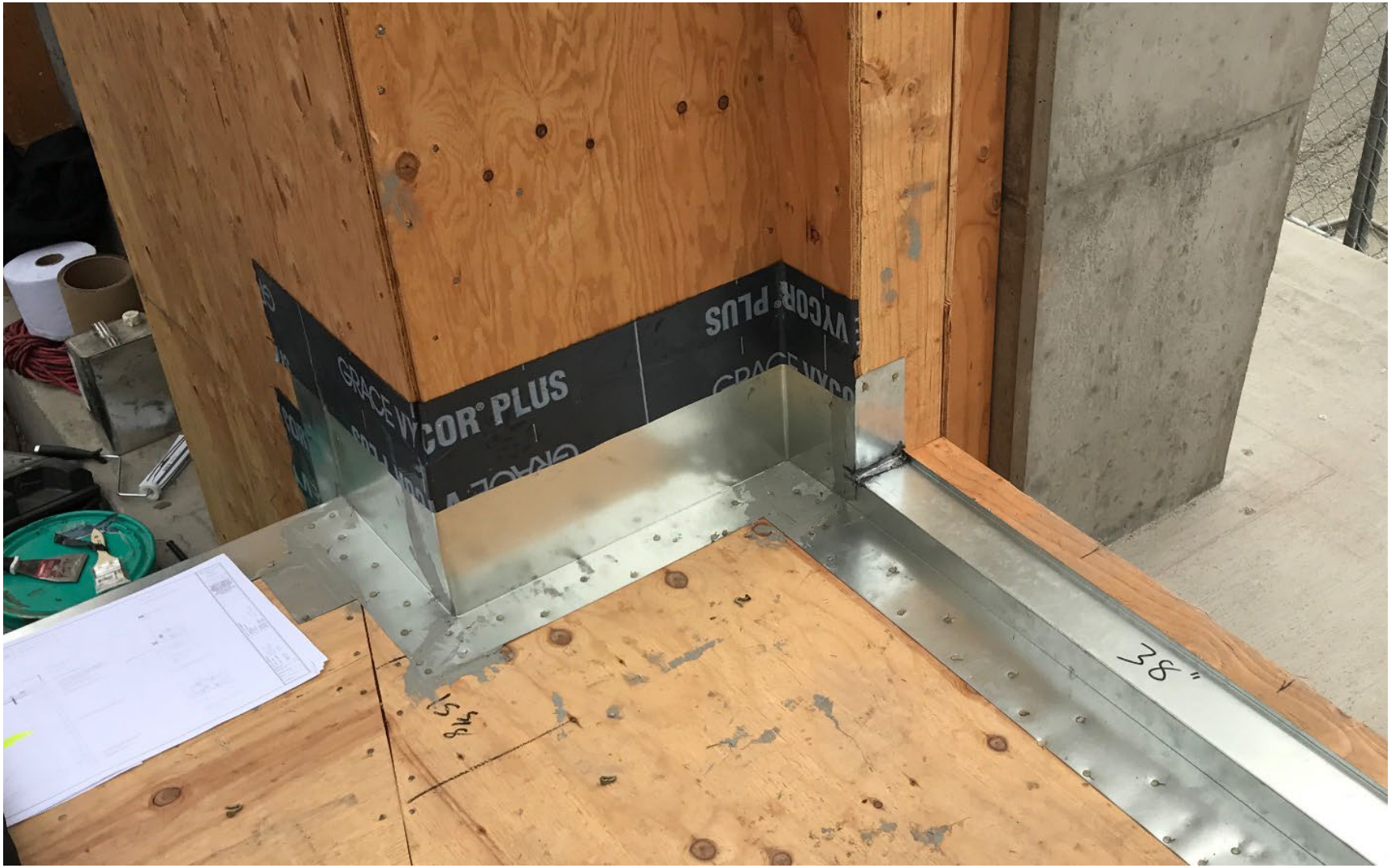

Building paper
Down
Building paper
Flashing
OUT

# Commercial Enclosure: Simple Layers



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

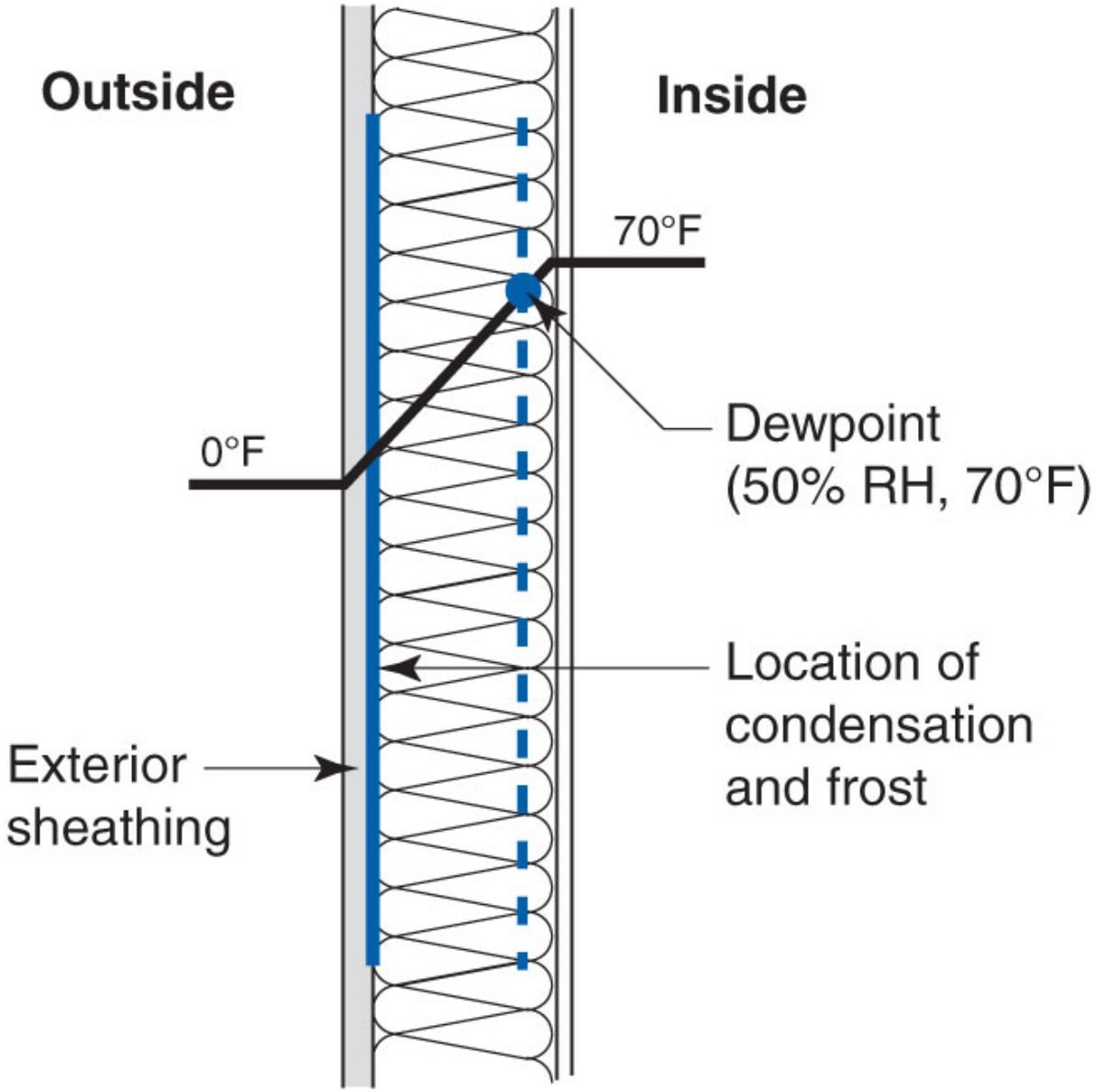


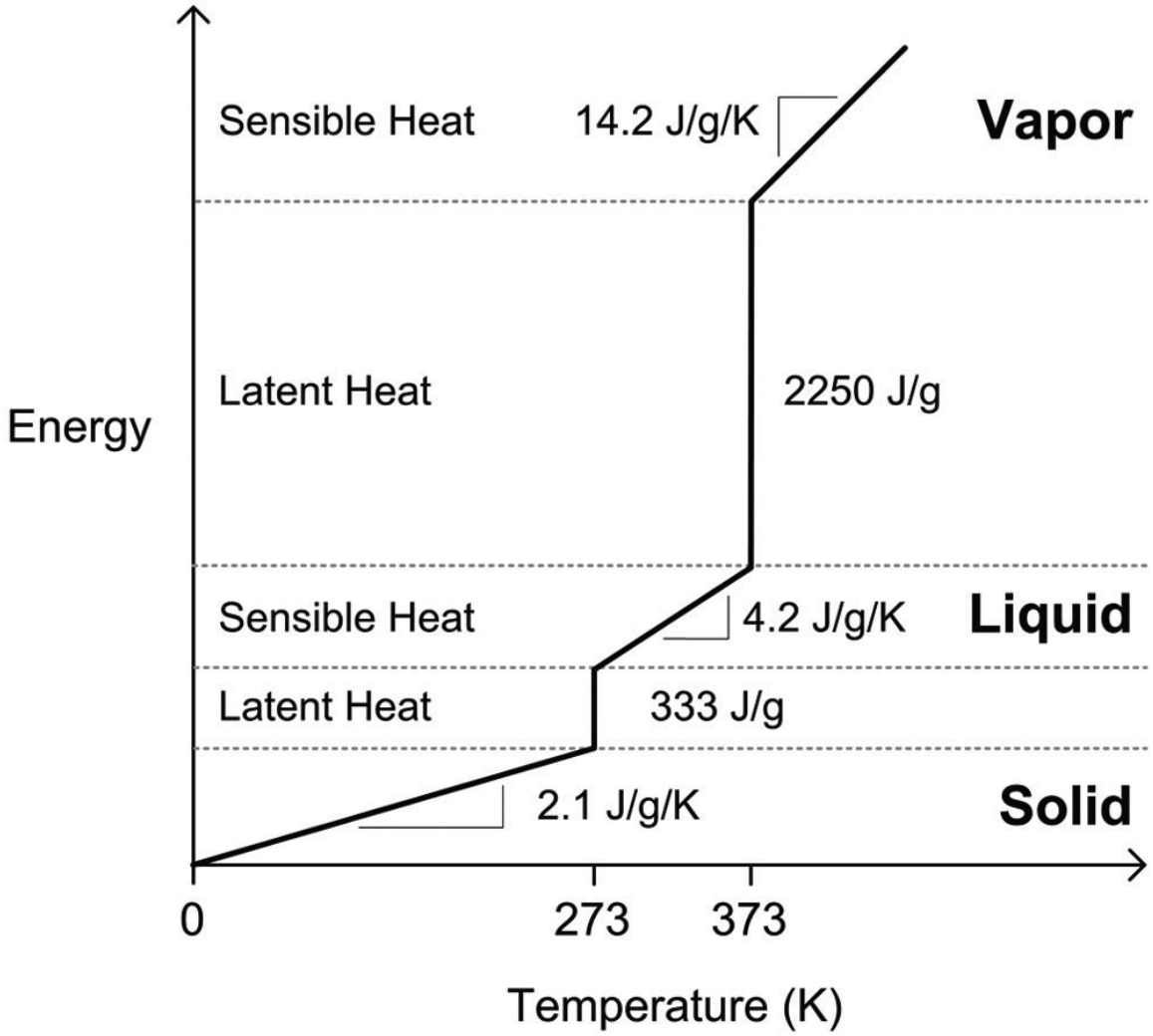

GRACE VYCOR® PLUS
36"

GP
DensGlass
Sheathing
Polyguard
www.polyguardproducts.com

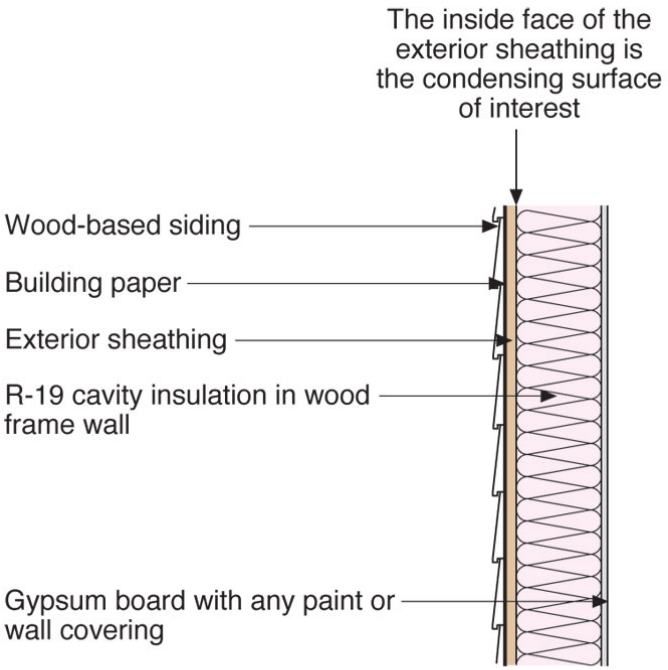
StraightFlash

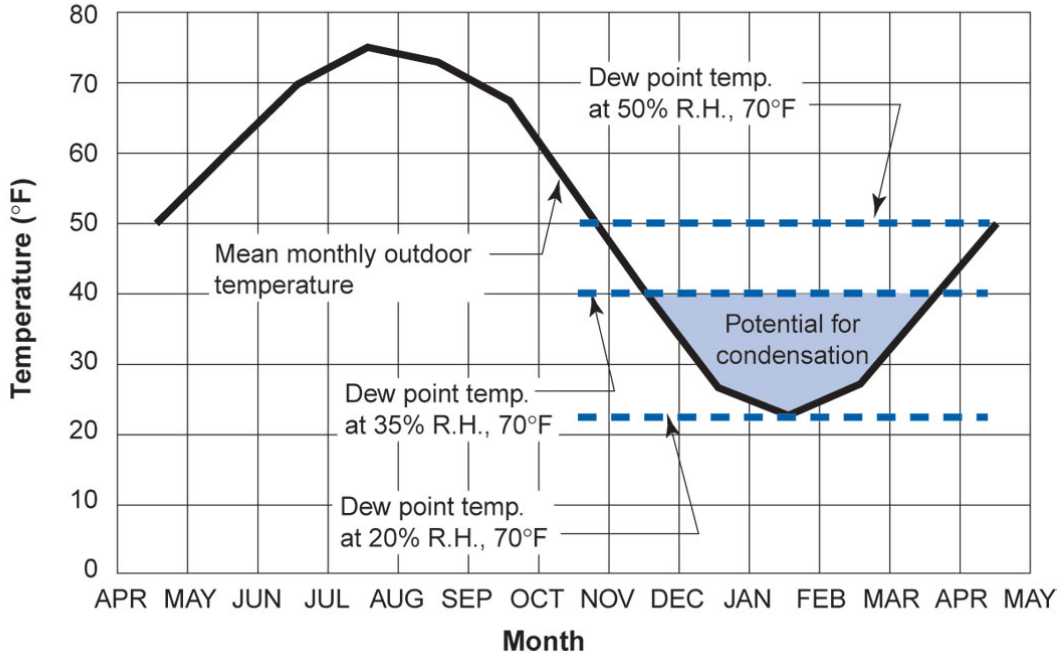
# The Myth of the Dew Point

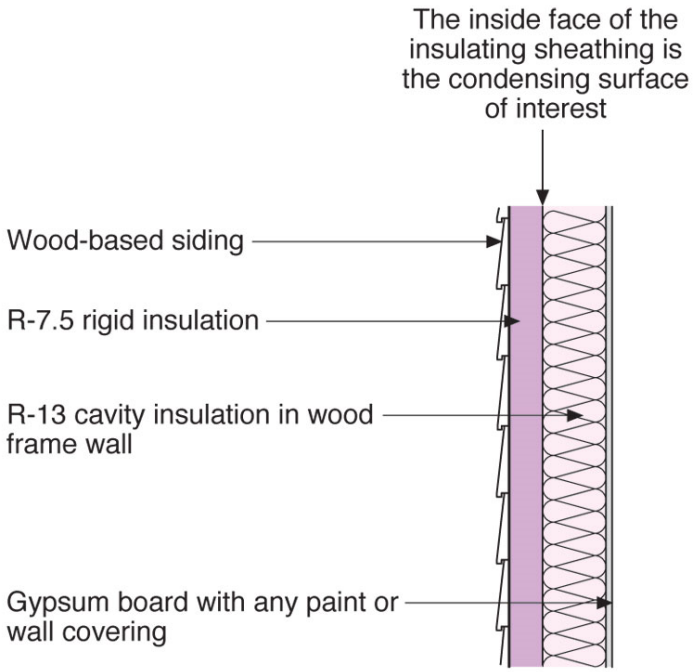

Outside
Inside
70°F
0°F
Dewpoint
(50% RH, 70°F)
Location of
condensation
and frost
Exterior
sheathing

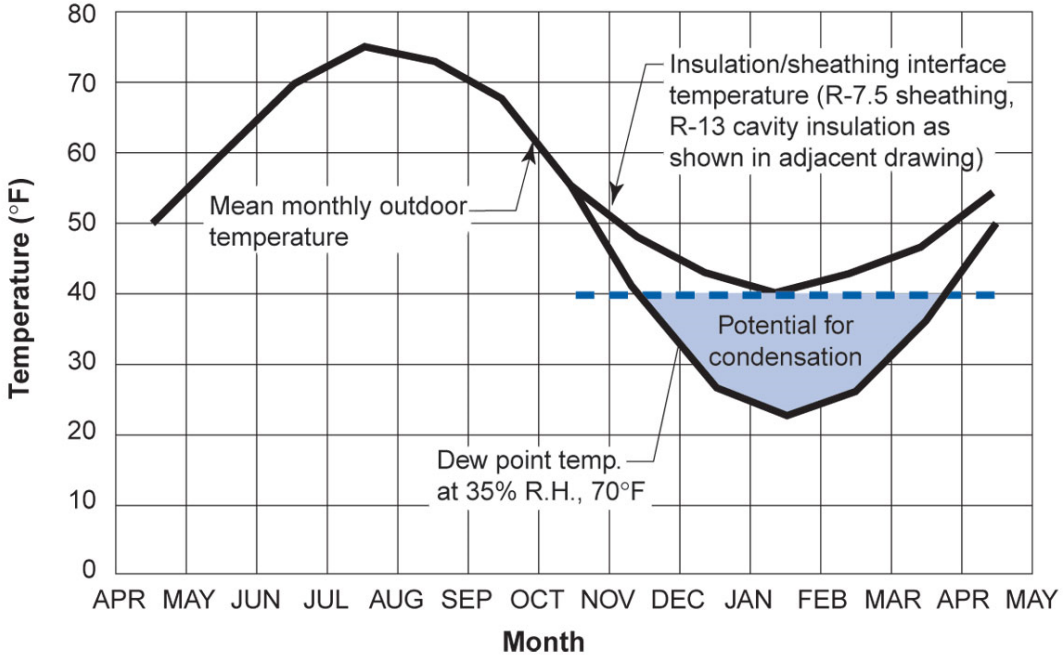



**Simple linearized energy-temperature relation for water**
From Straube & Burnett, 2005


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
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
APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY
Month


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

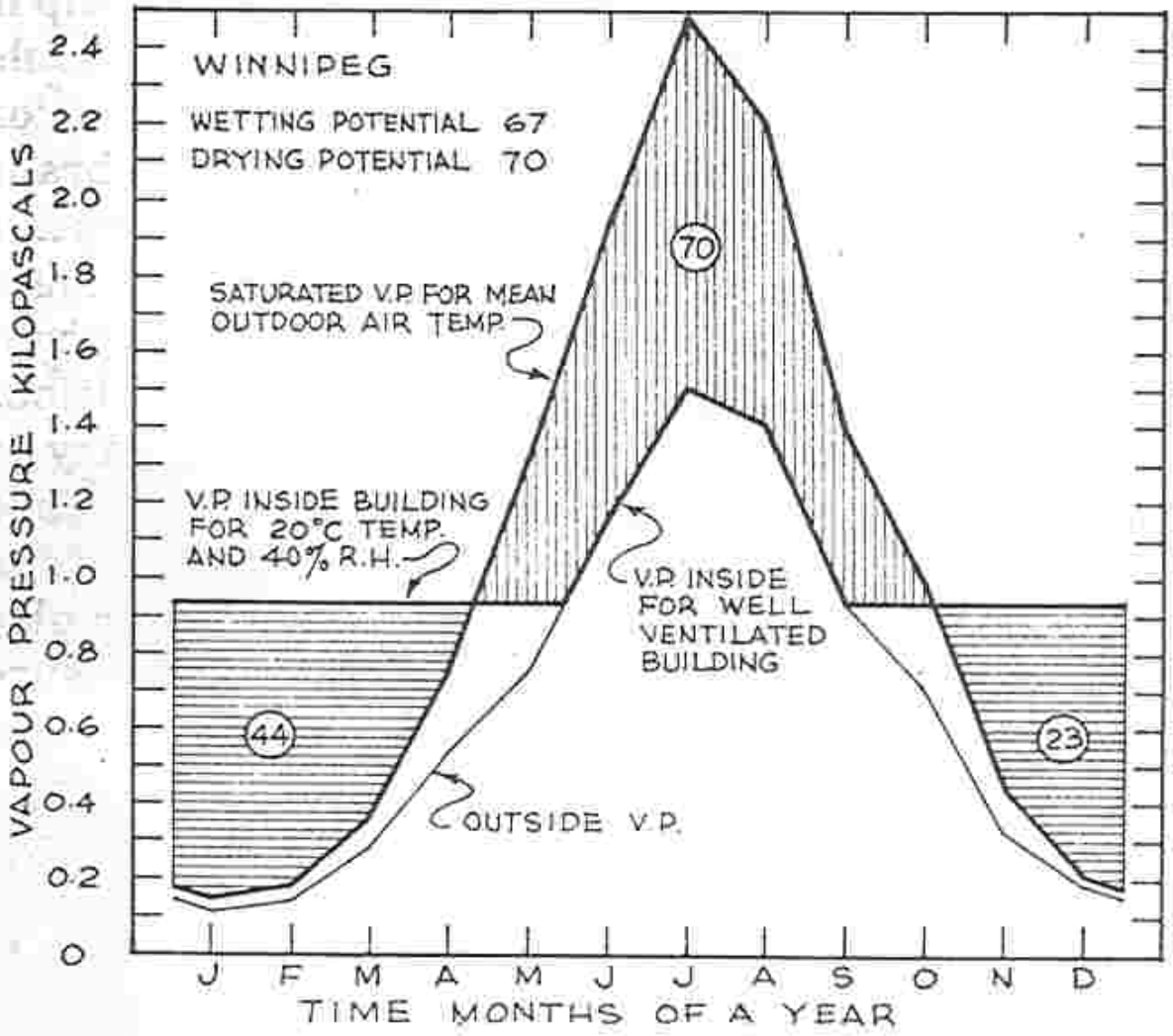
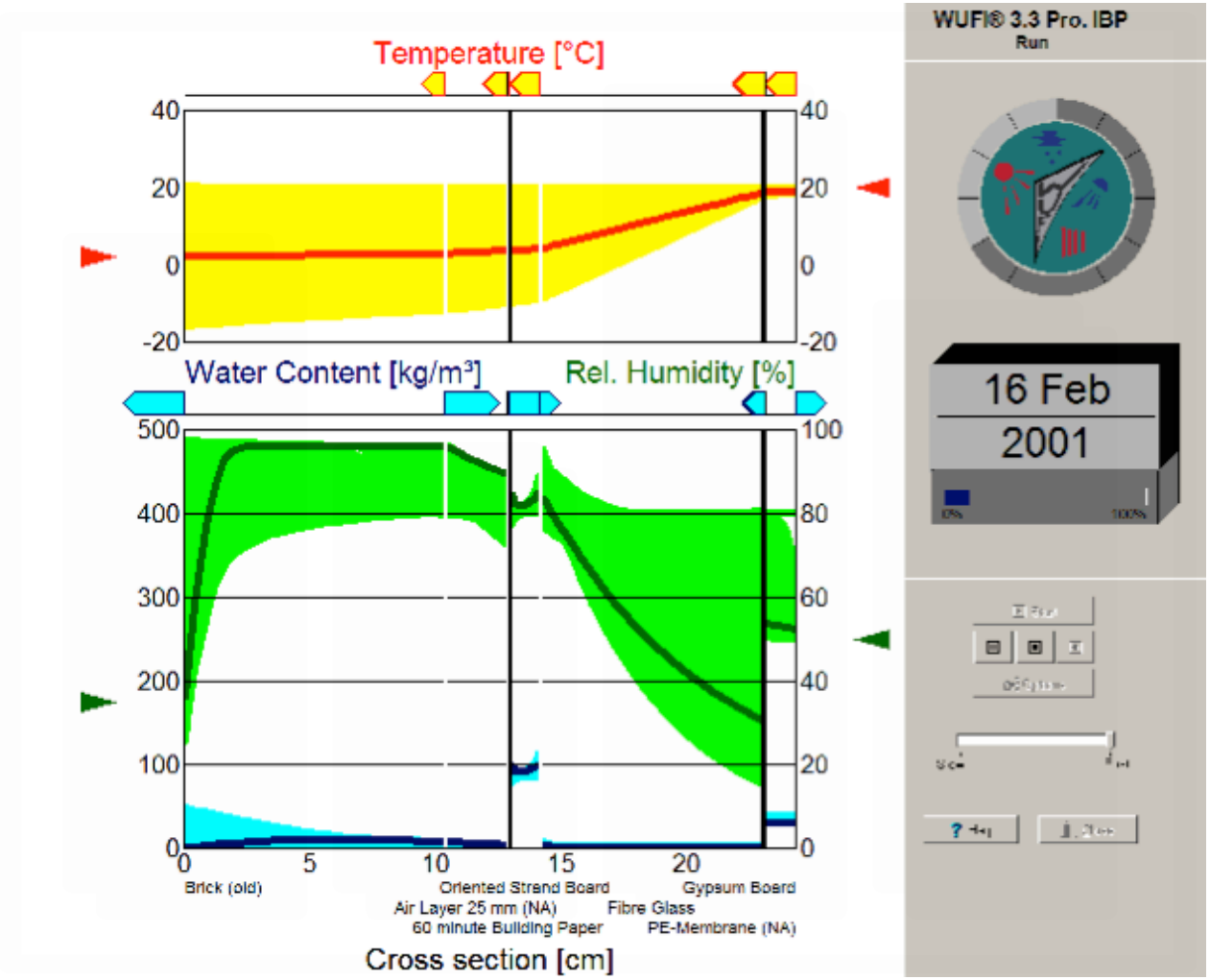


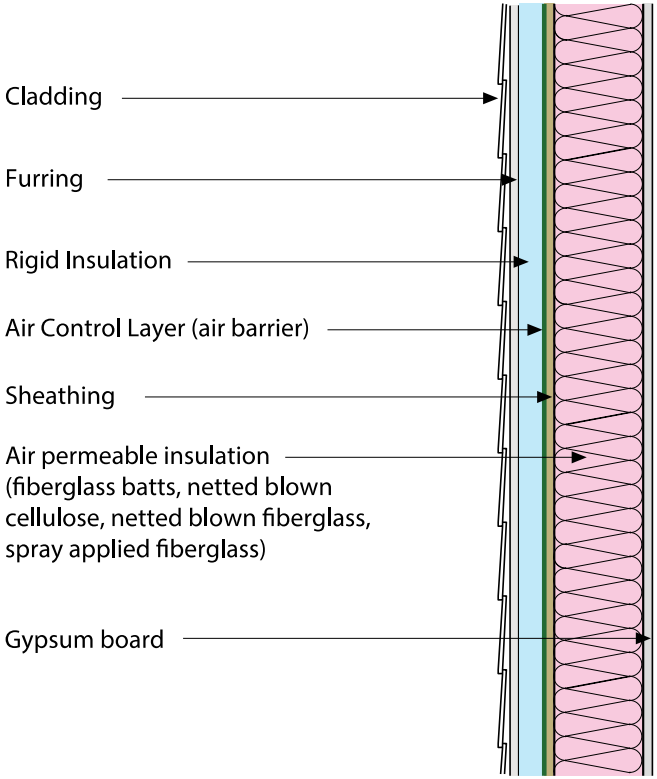

Figure 8-7. Outside vapour pressure, saturated vapour pressure and inside vapour pressure for Winnipeg.

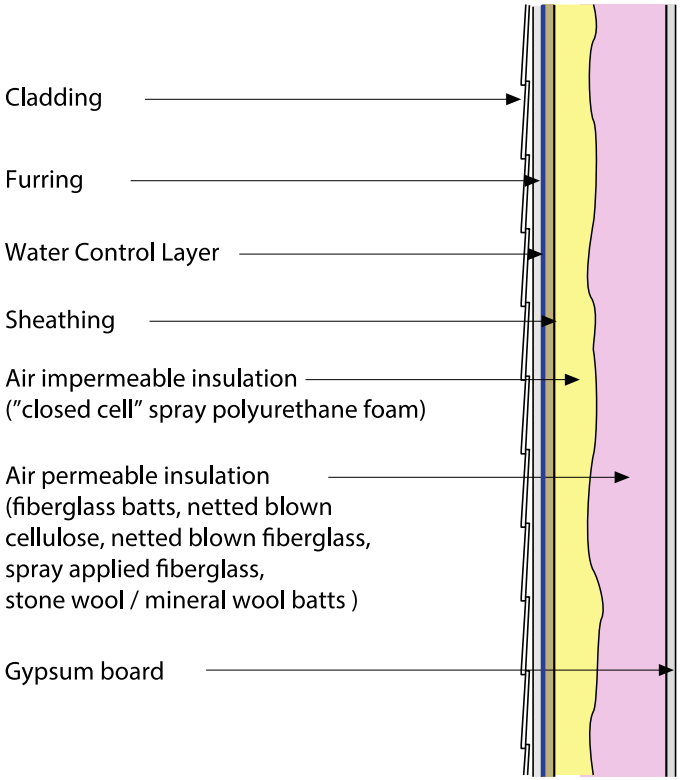

Temperature [°C]
40
20
0
-20
Water Content [kg/m³]
Rel. Humidity [%]
500
400
300
200
100
0
100
80
60
40
20
0
0
5
10
15
20
Brick (old)
Oriented Strand Board
Air Layer 25 mm (NA)
60 minute Building Paper
Fibre Glass
PE-Membrane (NA)
Gypsum Board
Cross section [cm]
WUFI® 3.3 Pro. IBP
Run
16 Feb
2001

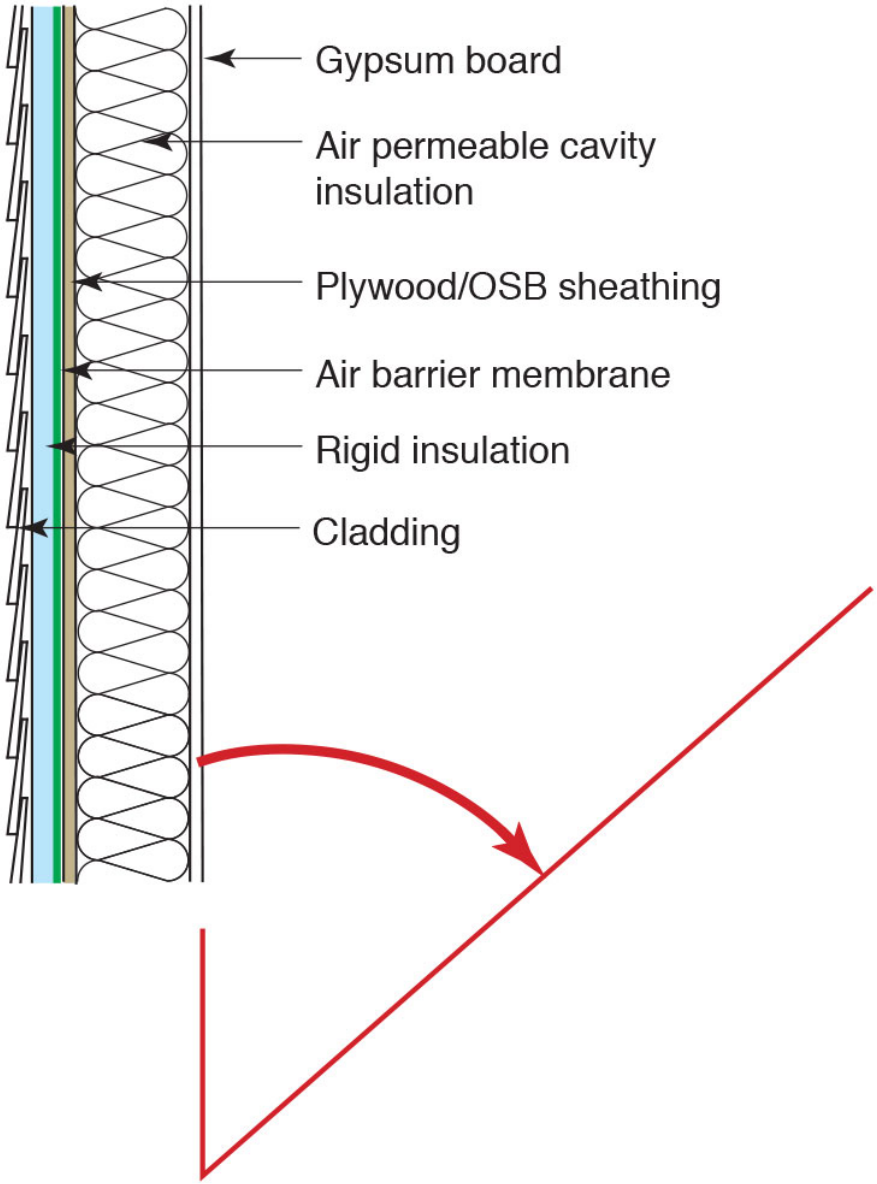
**Insulation for Condensation Control***

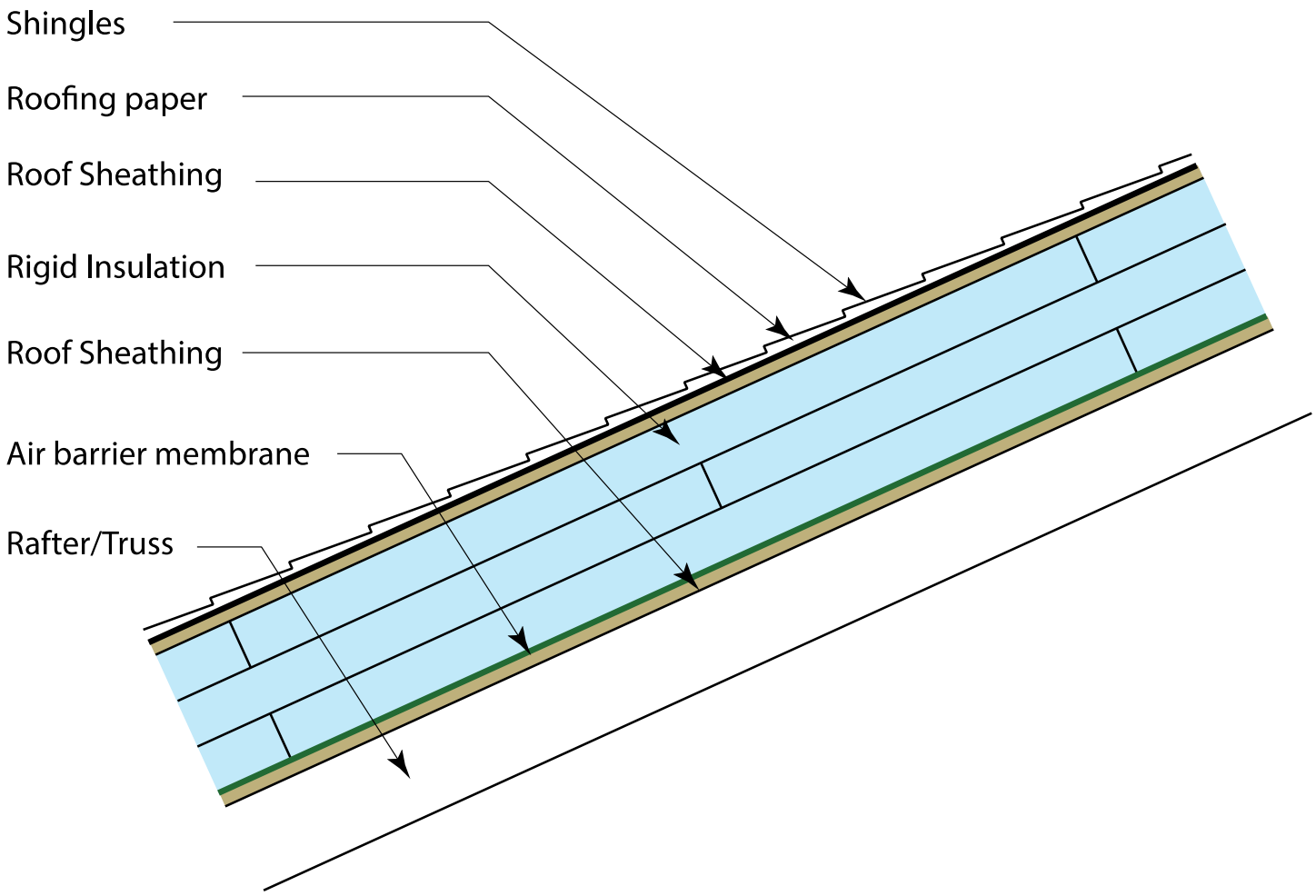
| Climate Zone | Rigid Board or Air Impermeable Insulation | Total Cavity Insulation | Total Wall Assembly Insulation | Ratio of Rigid Board Insulation or Air Impermeable R-Value to Total Insulation R-Value |
|---|---|---|---|---|
| 4C | R-2.5 | R-13 | R-15.5 | 15% |
| | R-3.75 | R-20 | R-23.75 | 15% |
| 5 | R-5 | R-13 | R-18 | 30% |
| | R-7.5 | R-20 | R-27.5 | 30% |
| 6 | R-7.5 | R-13 | R-20.5 | 35% |
| | R-11.25 | R-20 | R-31.25 | 35% |
| 7 | R-10 | R-13 | R-28 | 45% |
| | R-15 | R-20 | R-35 | 45% |
| 8 | R-15 | R-13 | R-28 | 50% |
| | R-20 | R-20 | R-40 | 50% |

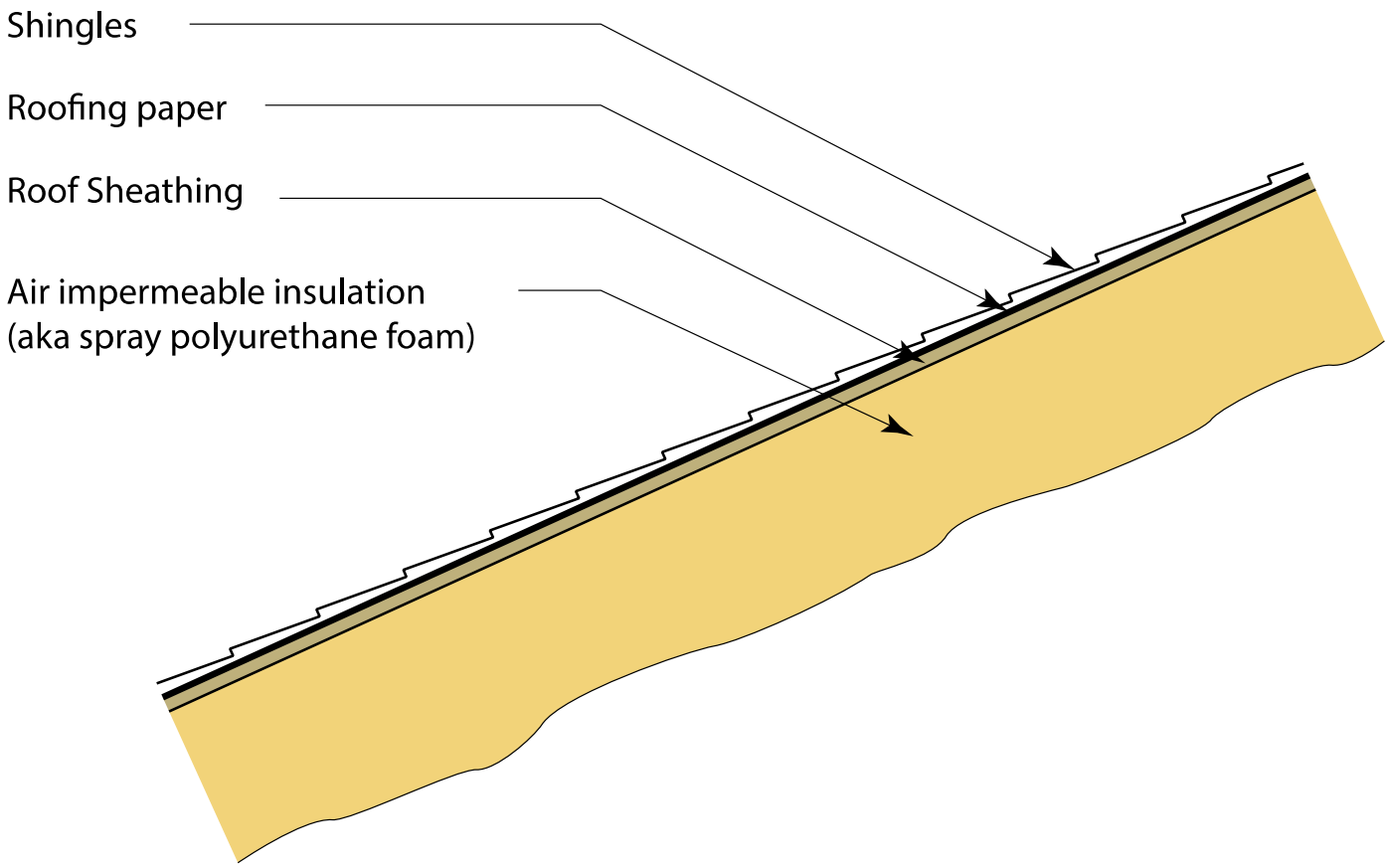
*Adapted from Table R 702.1 2015 International Residential Code

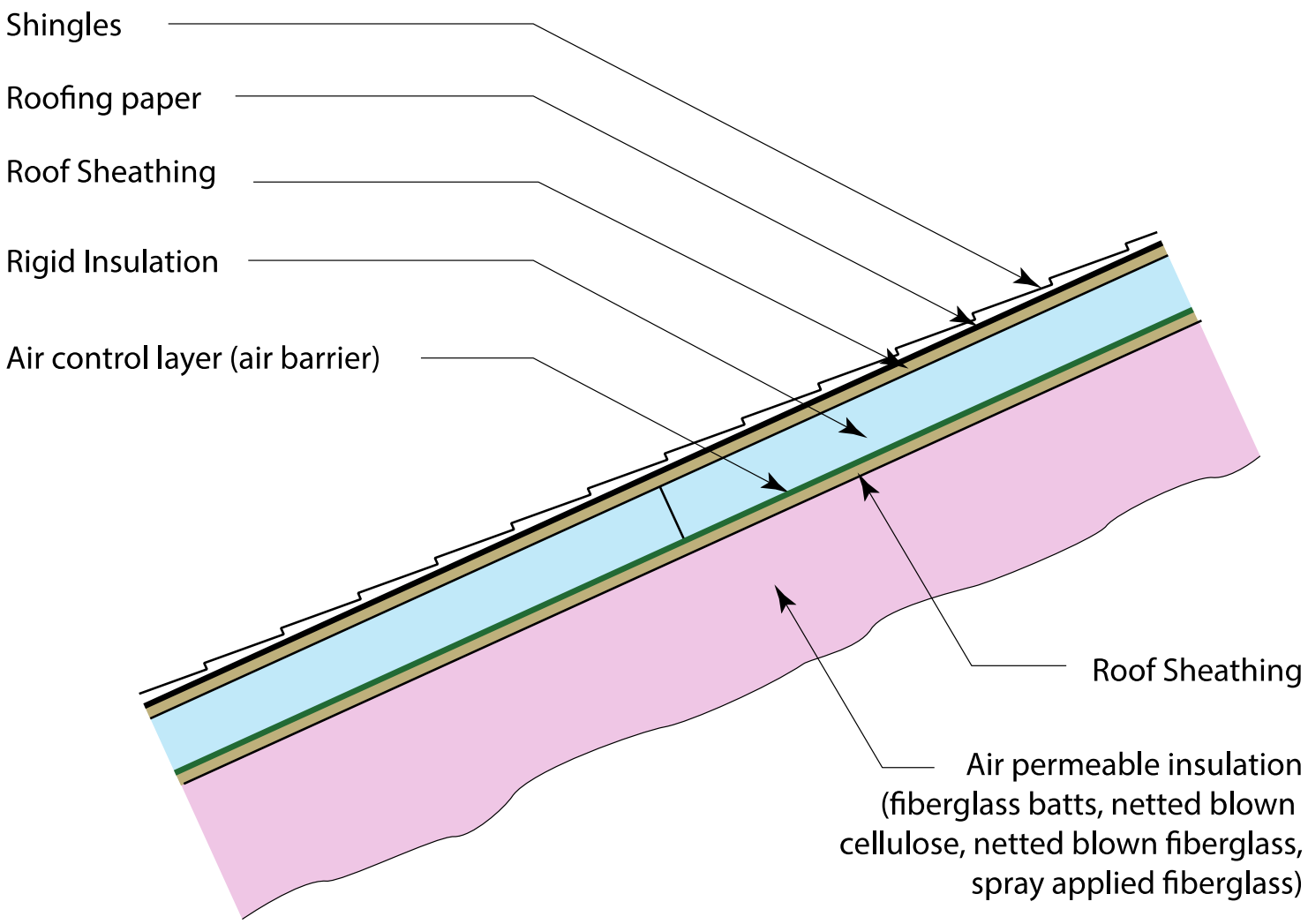

Cladding
Furring
Rigid Insulation
Air Control Layer (air barrier)
Sheathing
Air permeable insulation
(fiberglass batts, netted blown
cellulose, netted blown fiberglass,
spray applied fiberglass)
Gypsum board

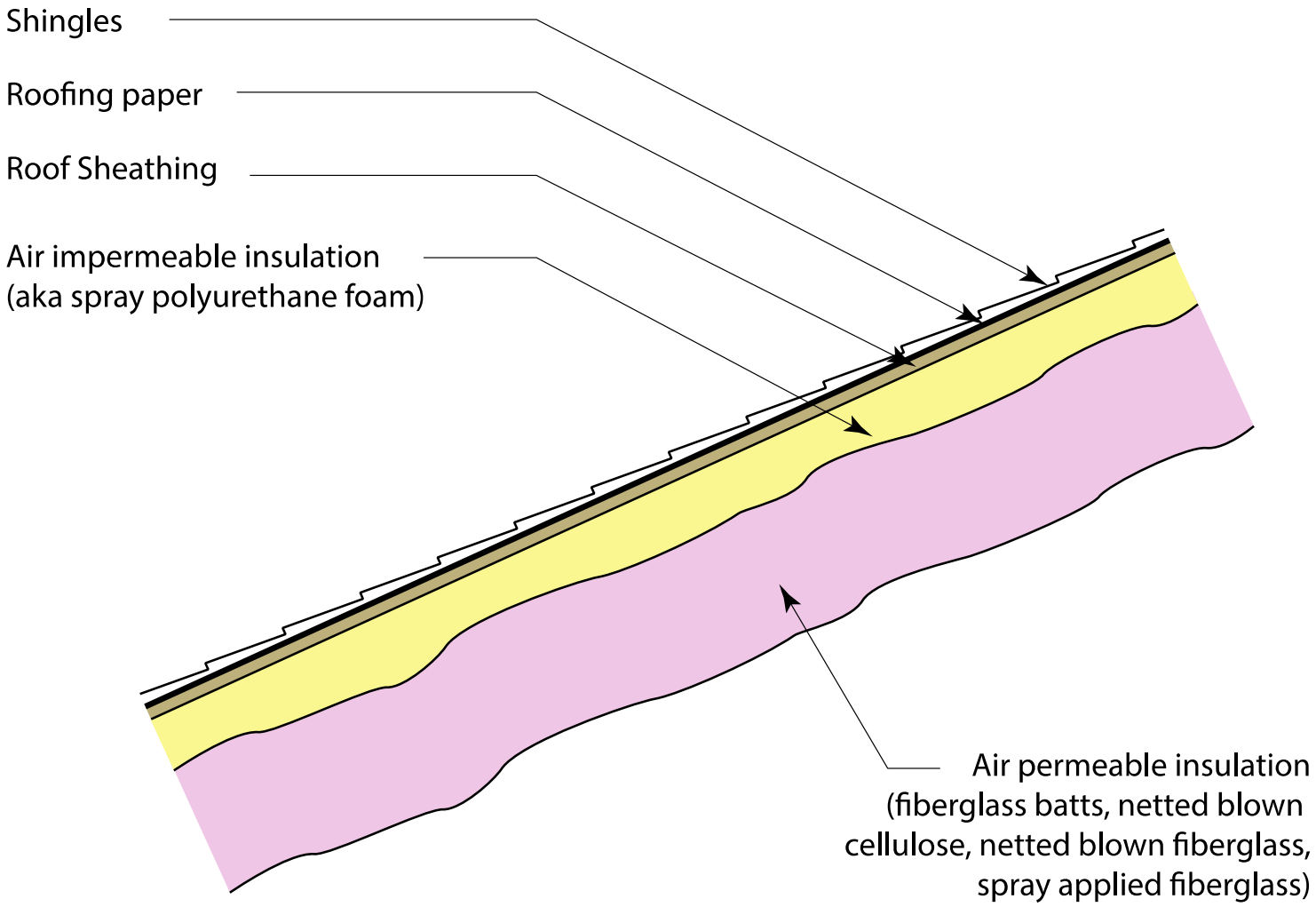

Cladding
Furring
Water Control Layer
Sheathing
Air impermeable insulation
("closed cell" spray polyurethane foam)
Air permeable insulation
(fiberglass batts, netted blown
cellulose, netted blown fiberglass,
spray applied fiberglass,
stone wool / mineral wool batts )
Gypsum board

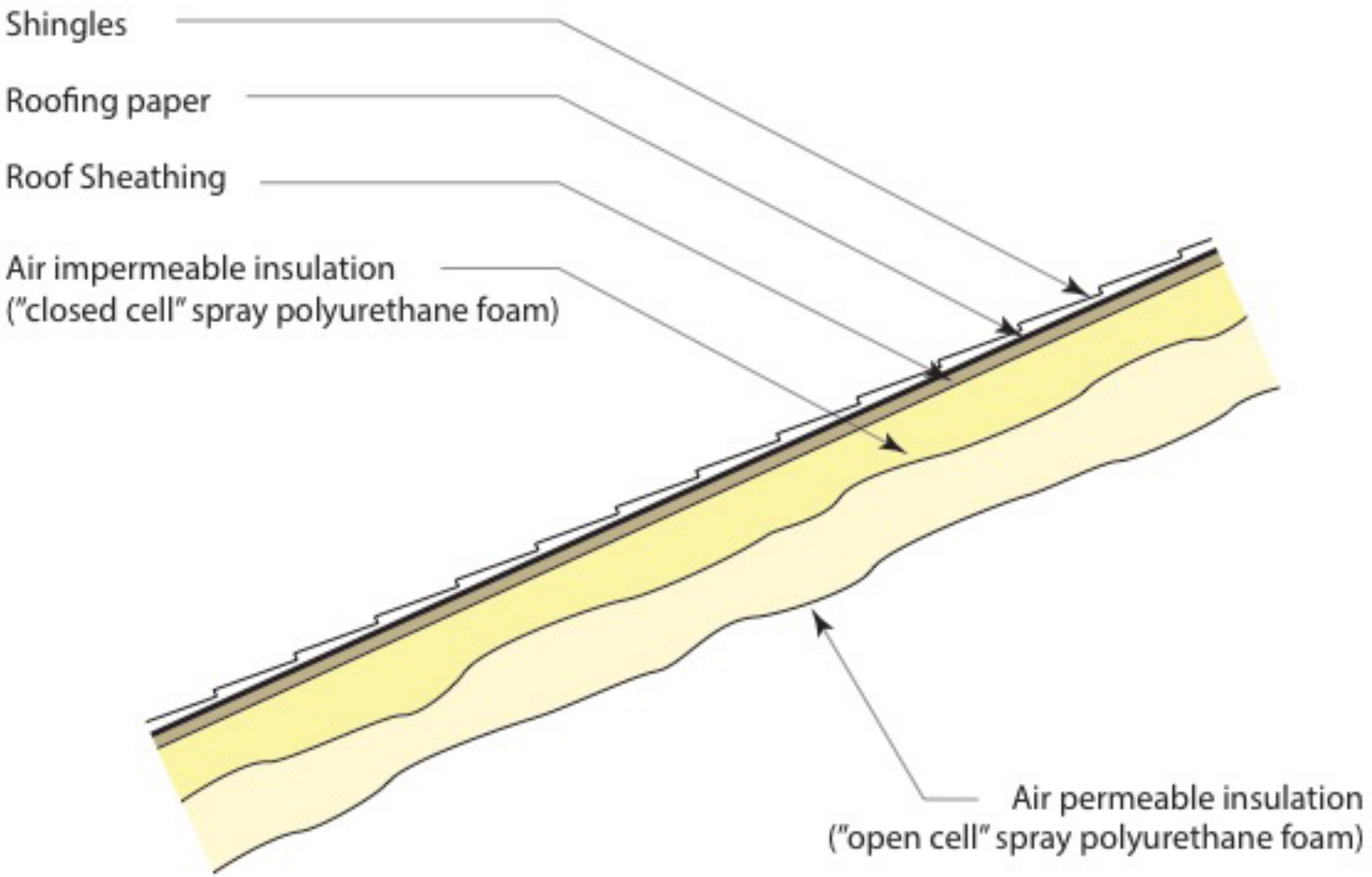

Gypsum board
Air permeable cavity insulation
Plywood/OSB sheathing
Air barrier membrane
Rigid insulation
Cladding


Shingles
Roofing paper
Roof Sheathing
Rigid Insulation
Roof Sheathing
Air barrier membrane
Rafter/Truss


Shingles
Roofing paper
Roof Sheathing
Air impermeable insulation
(aka spray polyurethane foam)


Shingles
Roofing paper
Roof Sheathing
Rigid Insulation
Air control layer (air barrier)
Roof Sheathing
Air permeable insulation
(fiberglass batts, netted blown
cellulose, netted blown fiberglass,
spray applied fiberglass)


Shingles
Roofing paper
Roof Sheathing
Air impermeable insulation
(aka spray polyurethane foam)
Air permeable insulation
(fiberglass batts, netted blown
cellulose, netted blown fiberglass,
spray applied fiberglass)

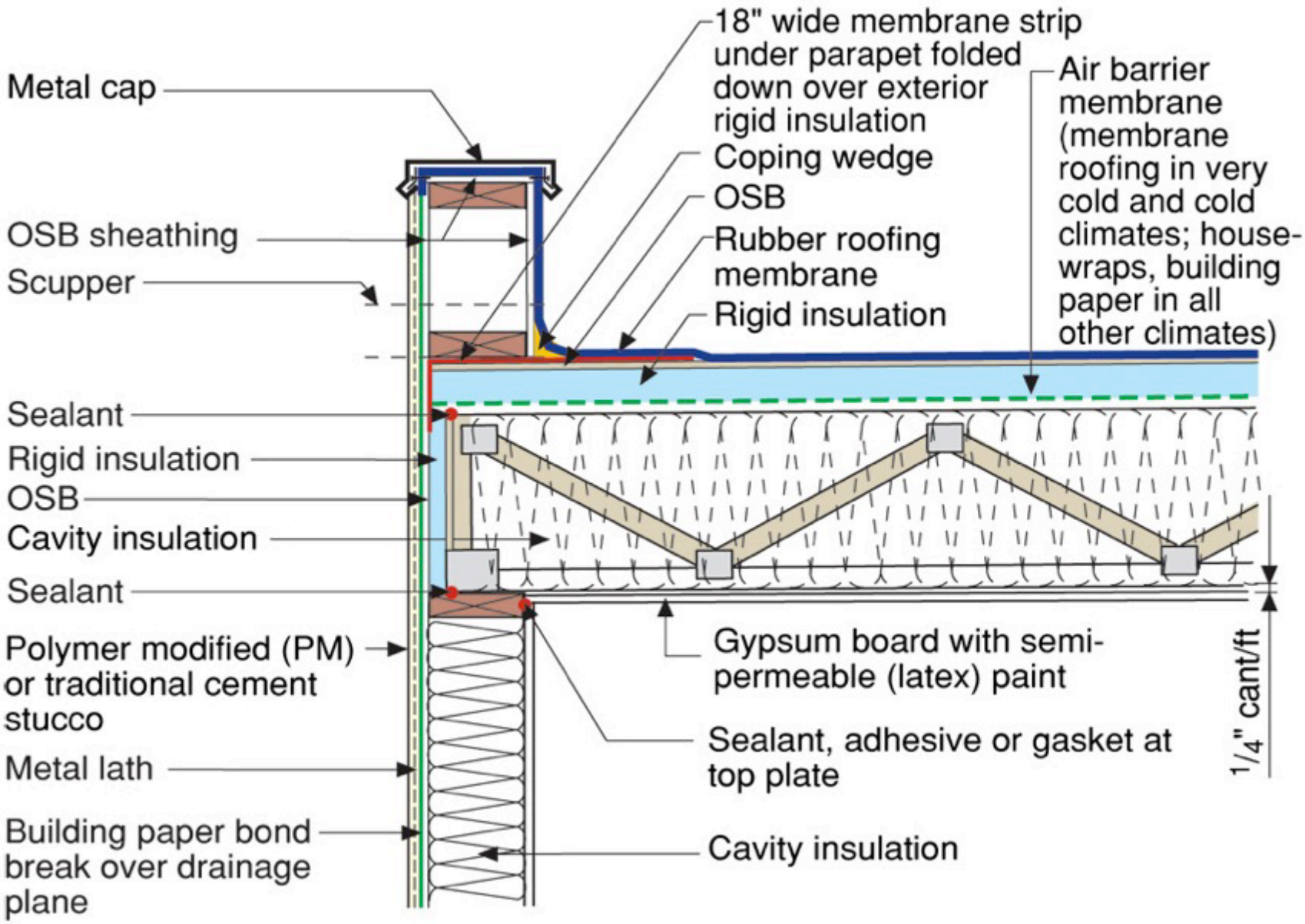

Shingles
Roofing paper
Roof Sheathing
Air impermeable insulation
("closed cell" spray polyurethane foam)
Air permeable insulation
("open cell" spray polyurethane foam)

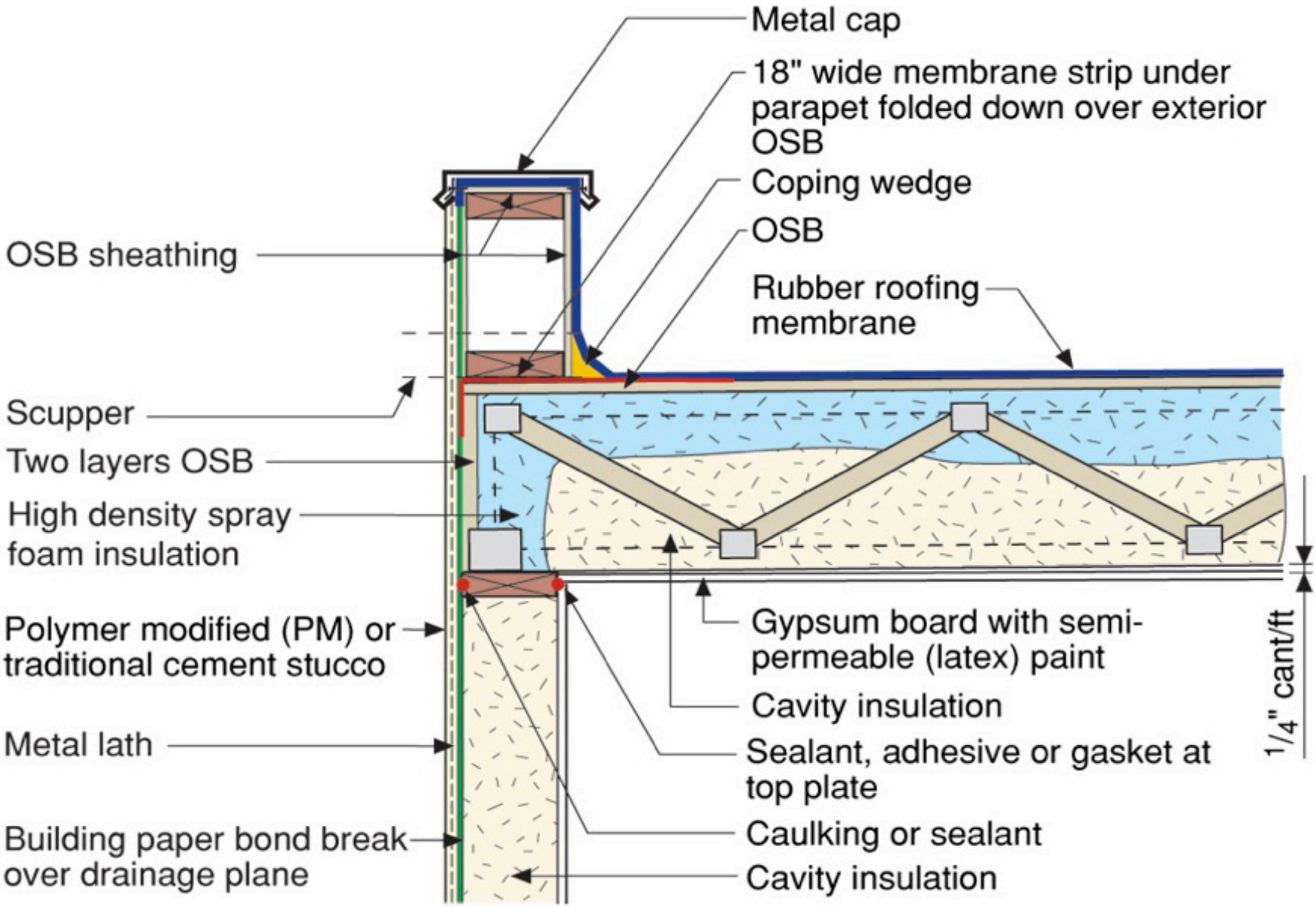
**Insulation for Condensation Control***

| Climate Zone | Rigid Board or Air Impermeable Insulation | Code Required R-Value | Ratio of Rigid Board Insulation or Air Impermeable R-Value to Total Insulation R-Value |
|---|---|---|---|
| 1,2,3 | R-5 | R-38 | 10% |
| 4C | R-10 | R-49 | 20% |
| 4A, 4B | R-15 | R-49 | 30% |
| 5 | R-20 | R-49 | 40% |
| 6 | R-25 | R-49 | 50% |
| 7 | R-30 | R-49 | 60% |
| 8 | R-35 | R-49 | 70% |

*Adapted from Table R 806.5 2015 International Residential Code

**Table 1**


Metal cap
OSB sheathing
Scupper
Sealant
Rigid insulation
OSB
Cavity insulation
Sealant
Polymer modified (PM) or traditional cement stucco
Metal lath
Building paper bond break over drainage plane
18" wide membrane strip under parapet folded down over exterior rigid insulation
Coping wedge
OSB
Rubber roofing membrane
Rigid insulation
Air barrier membrane (membrane roofing in very cold and cold climates; house-wraps, building paper in all other climates)
Gypsum board with semi-permeable (latex) paint
Sealant, adhesive or gasket at top plate
Cavity insulation
1/4" cant/ft


Metal cap
18" wide membrane strip under parapet folded down over exterior OSB
Coping wedge
OSB
OSB sheathing
Rubber roofing membrane
Scupper
Two layers OSB
High density spray foam insulation
Polymer modified (PM) or traditional cement stucco
Metal lath
Building paper bond break over drainage plane
Gypsum board with semi-permeable (latex) paint
Cavity insulation
Sealant, adhesive or gasket at top plate
Caulking or sealant
Cavity insulation
1/4" cant/ft

# Modeling and Other Lies