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

Building Science

presented by www.buildingscience.com

Arrhenius Equation

For Every 10 Degree K Rise

Rate of Reaction Doubles

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

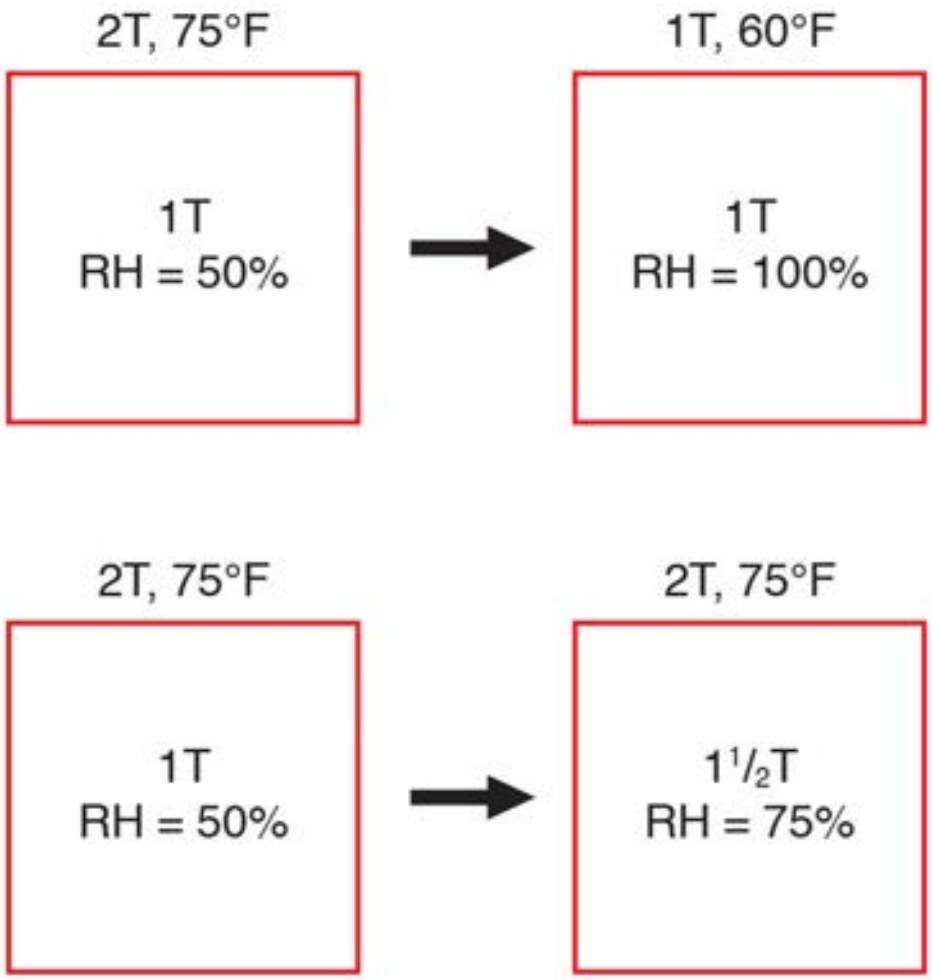
Damage Functions

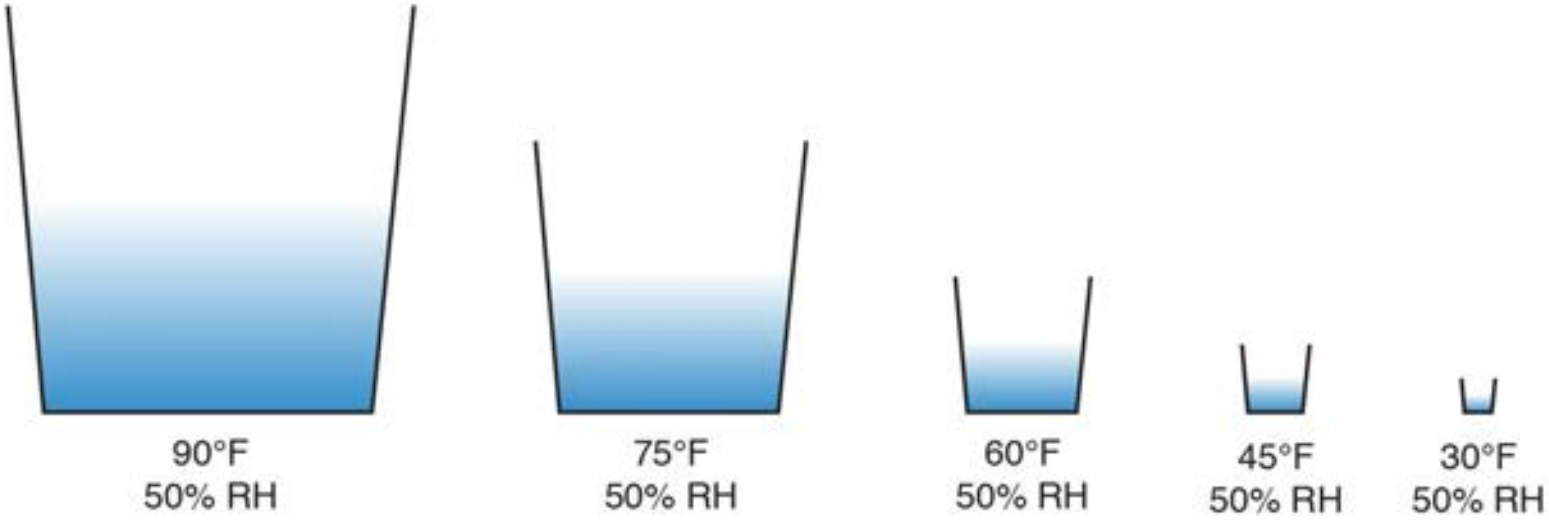
Water

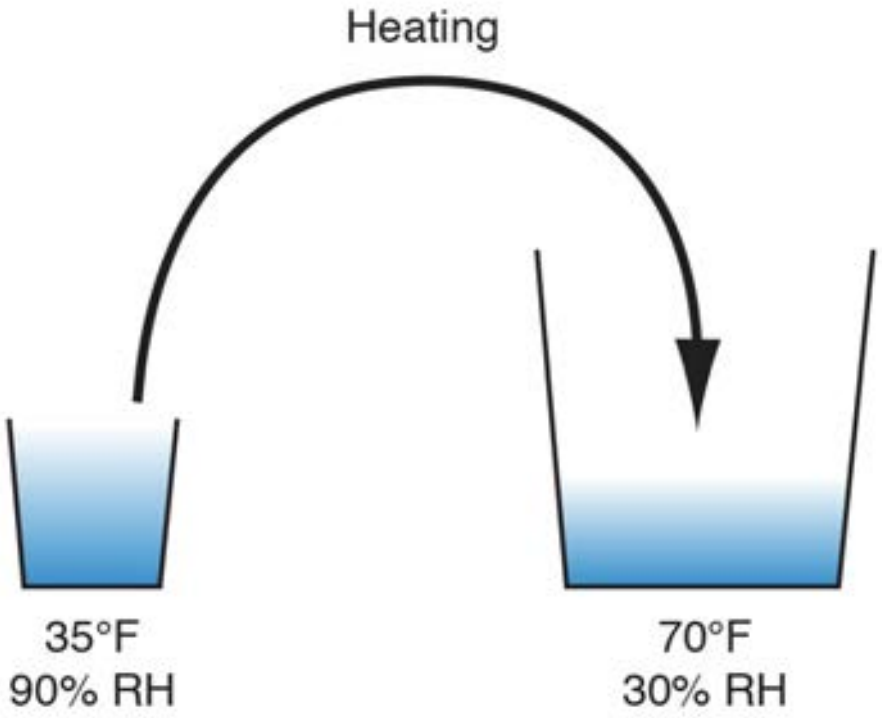
Heat

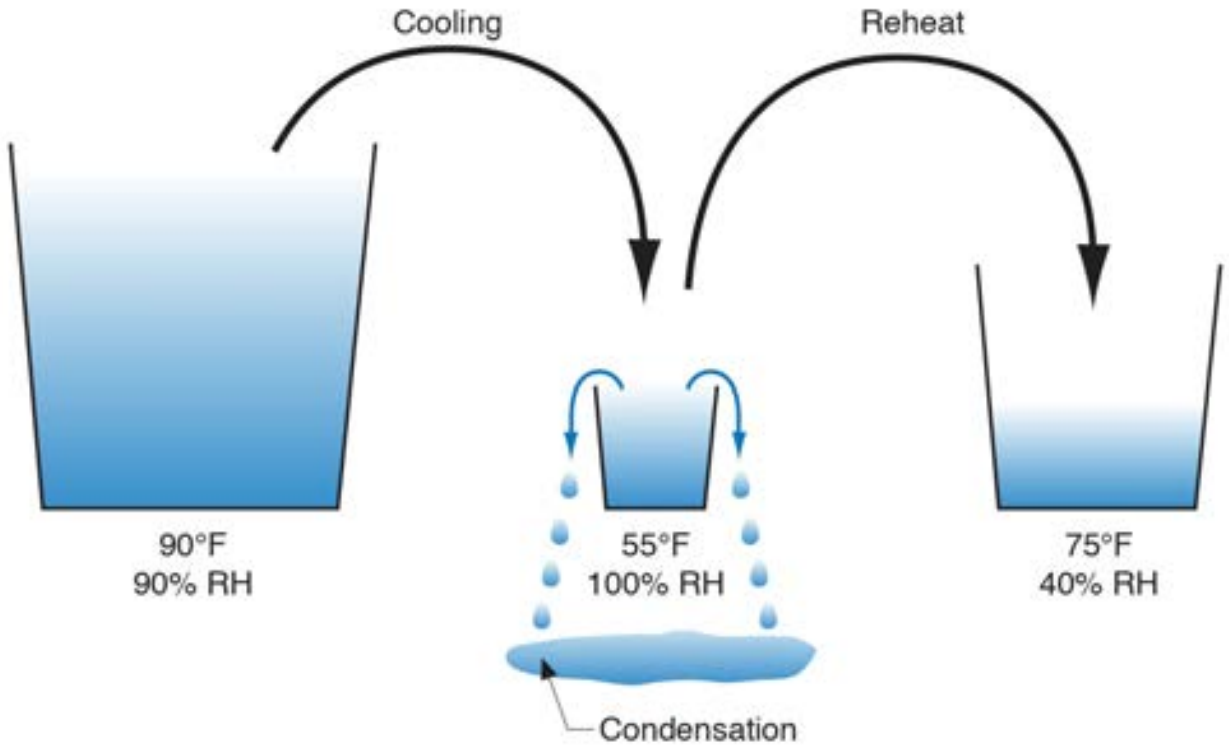
Ultra-violet Radiation

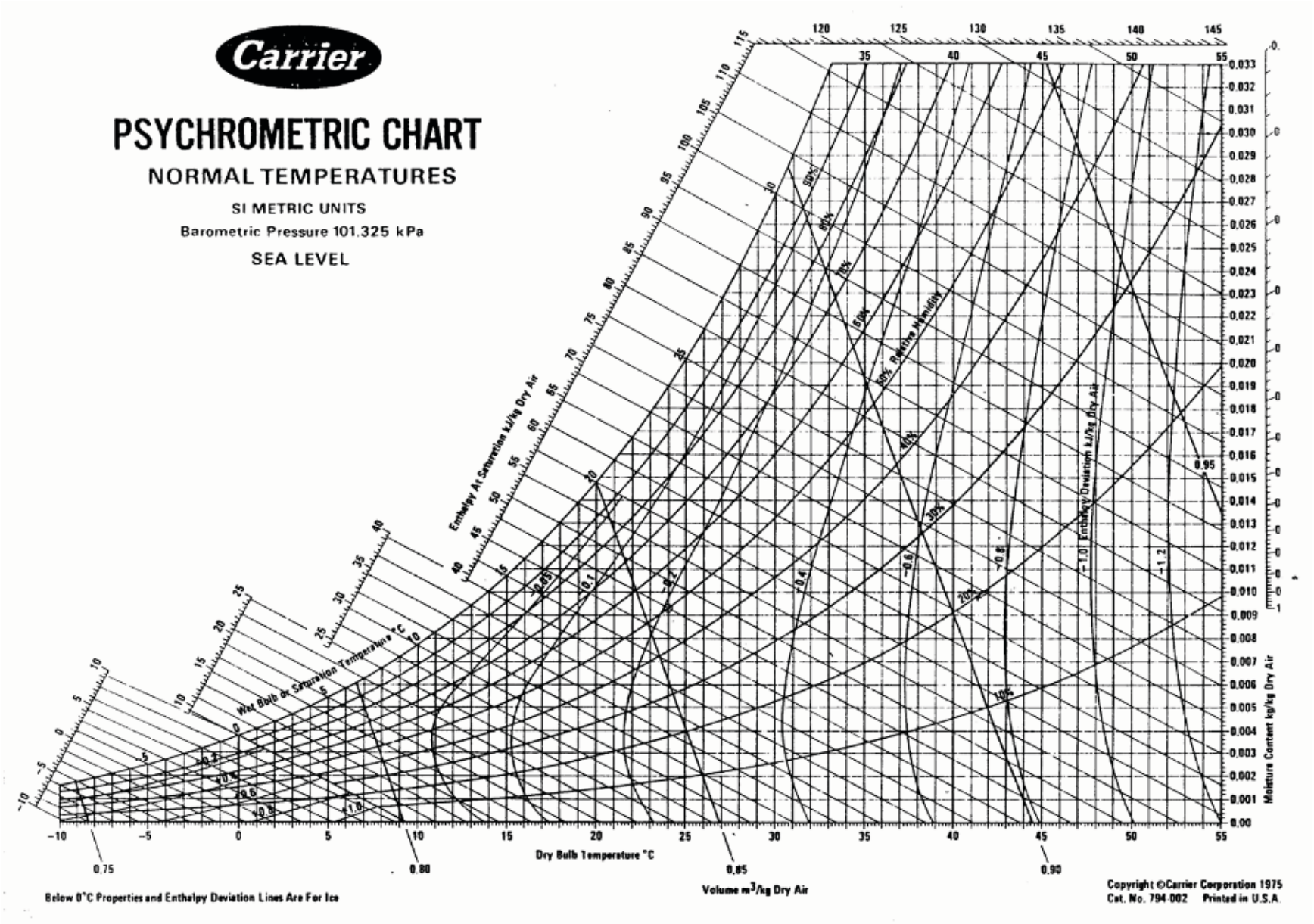
Vapor Pressure and Relative Humidity


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%

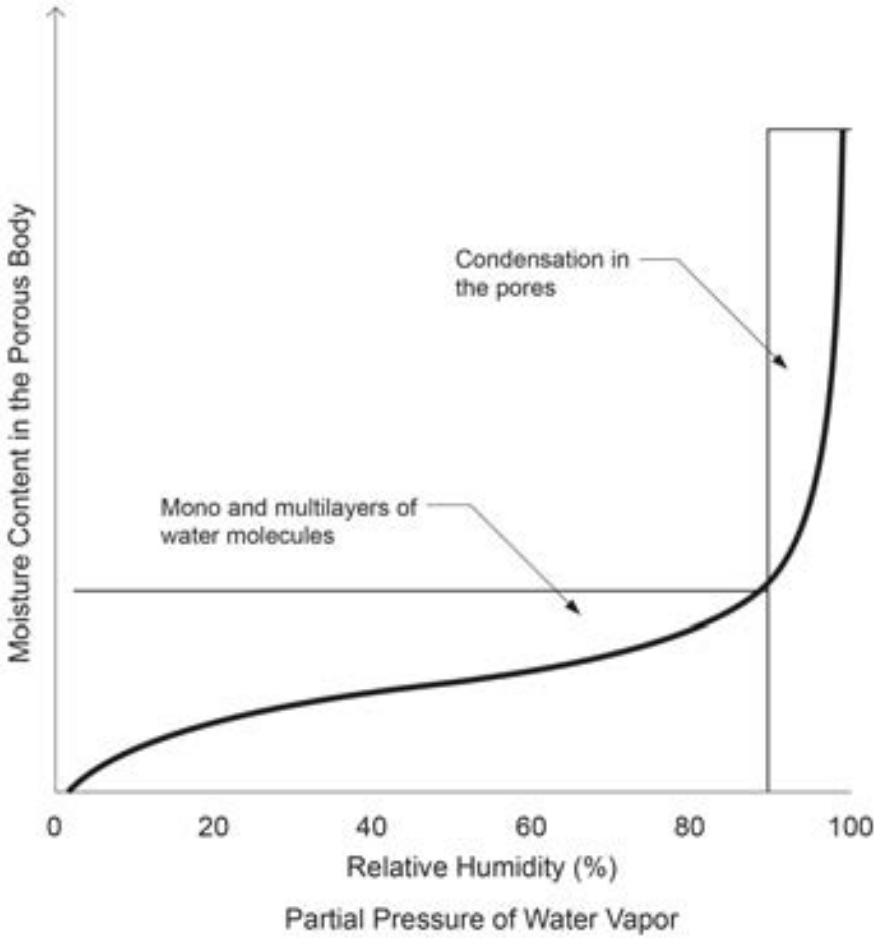

90°F
50% RH
75°F
50% RH
60°F
50% RH
45°F
50% RH
30°F
50% RH


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
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.

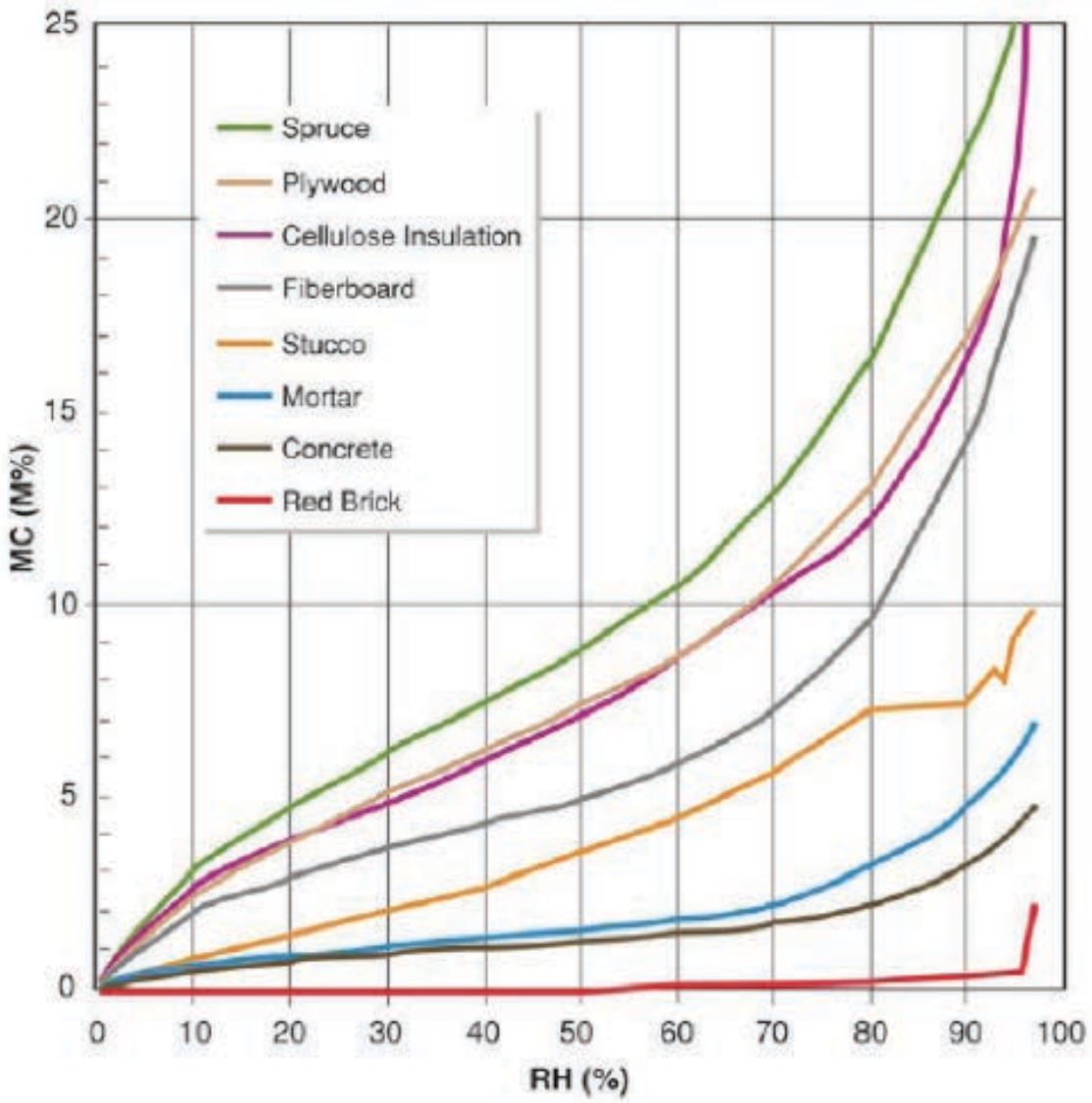
Sorption Isotherms

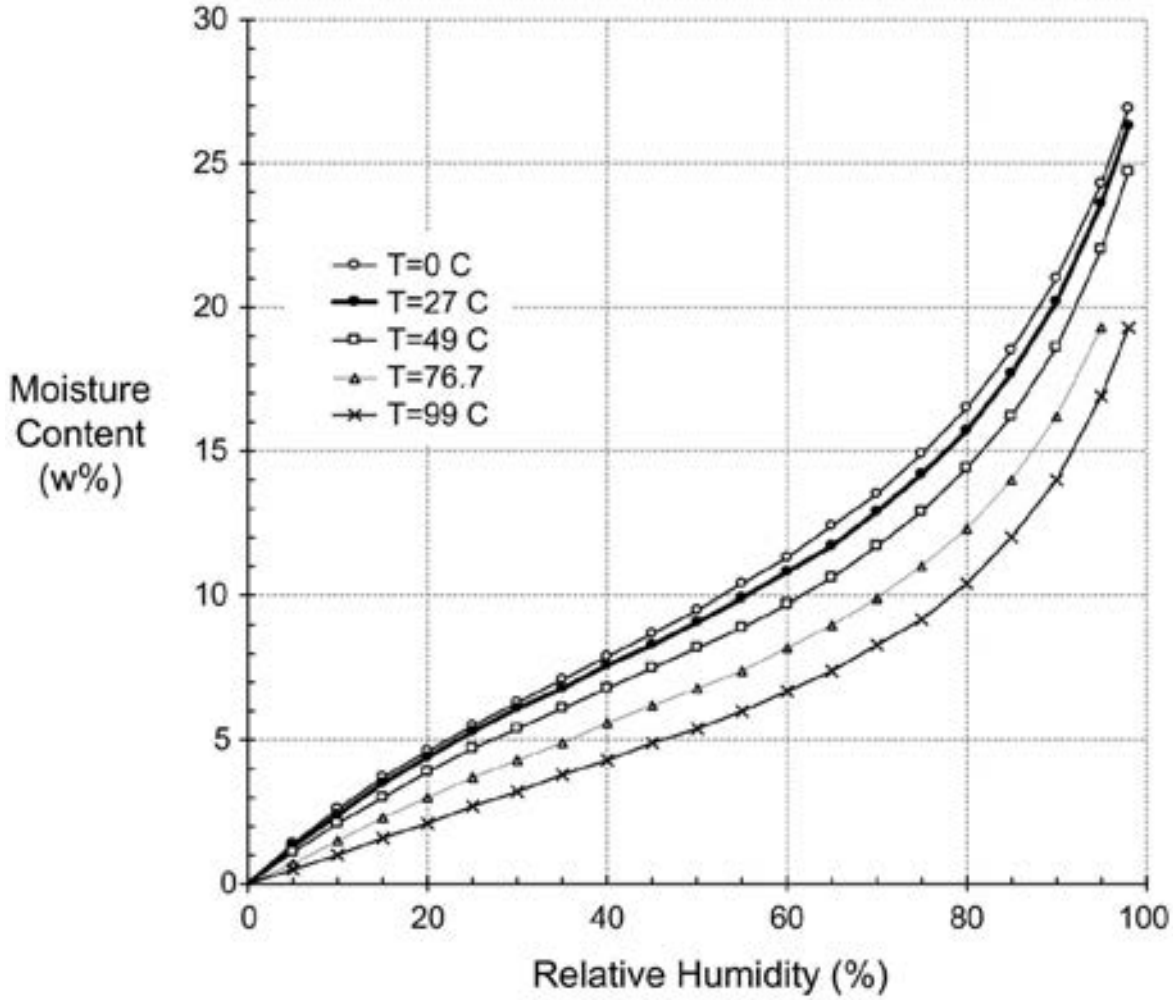


Change in the storage of moisture in a porous building material as the partial pressure of water vapor in the ambient air increases from zero to full saturation value at a given temperature.

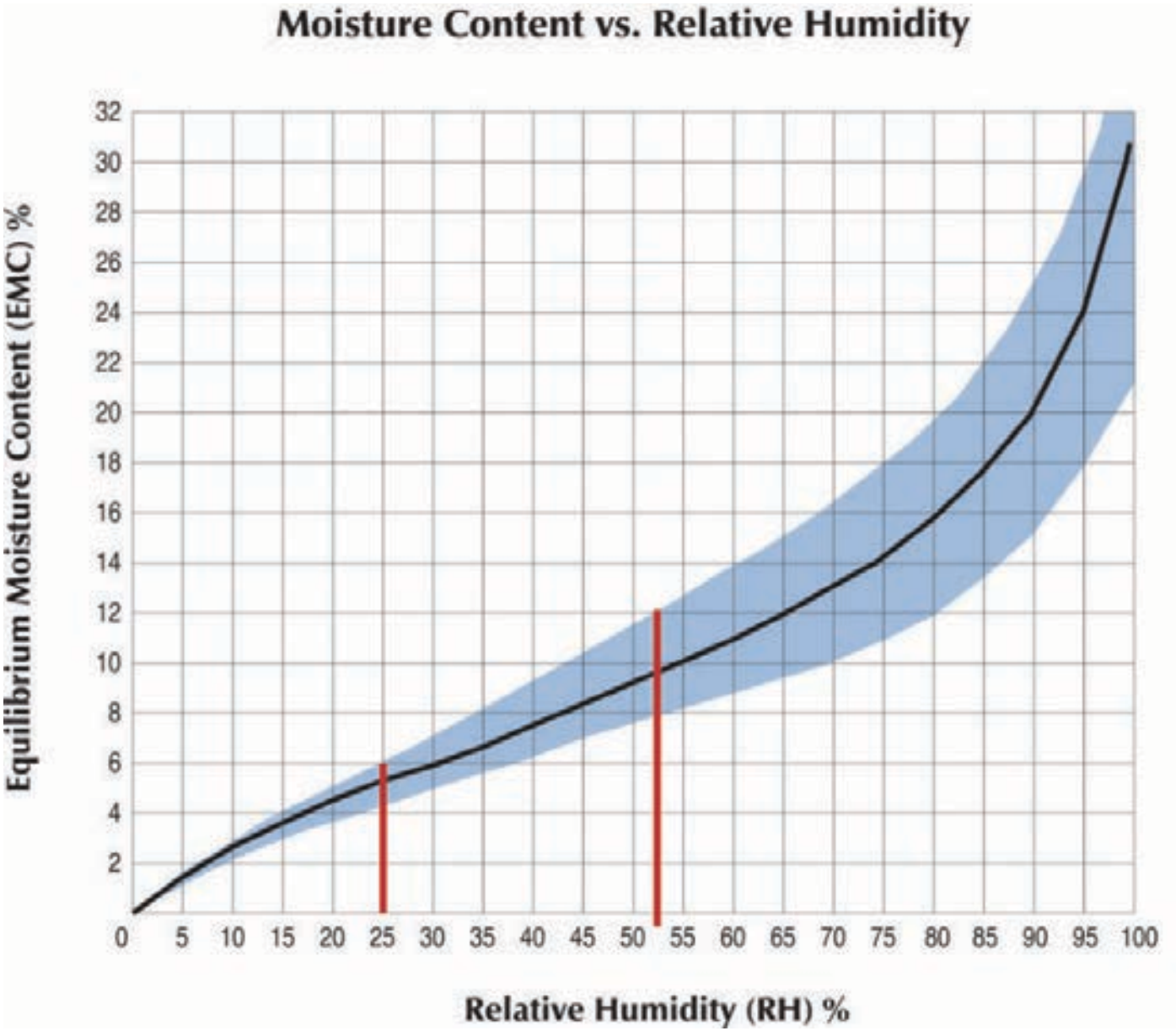
Sorption Curve

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


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) %

2nd Law of Thermodynamics

Heat Flow Is From Warm To Cold

Moisture Flow Is From Warm To Cold

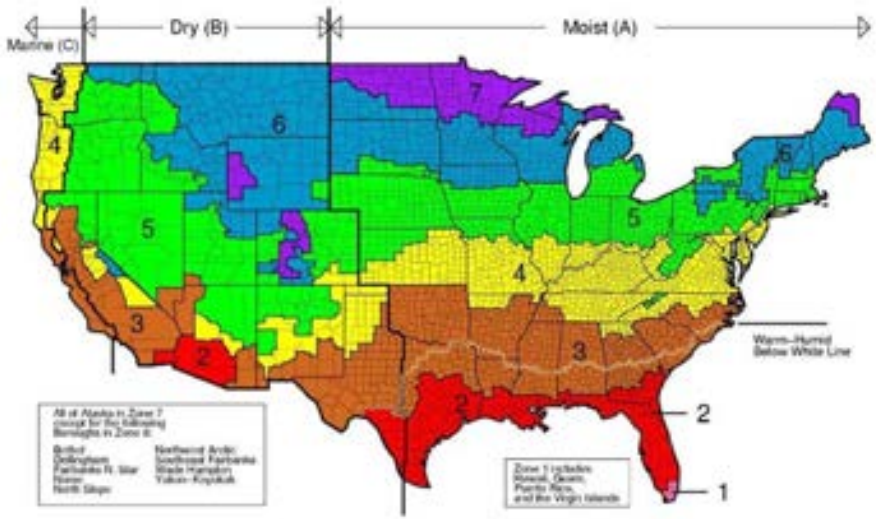
Moisture Flow Is From More To Less

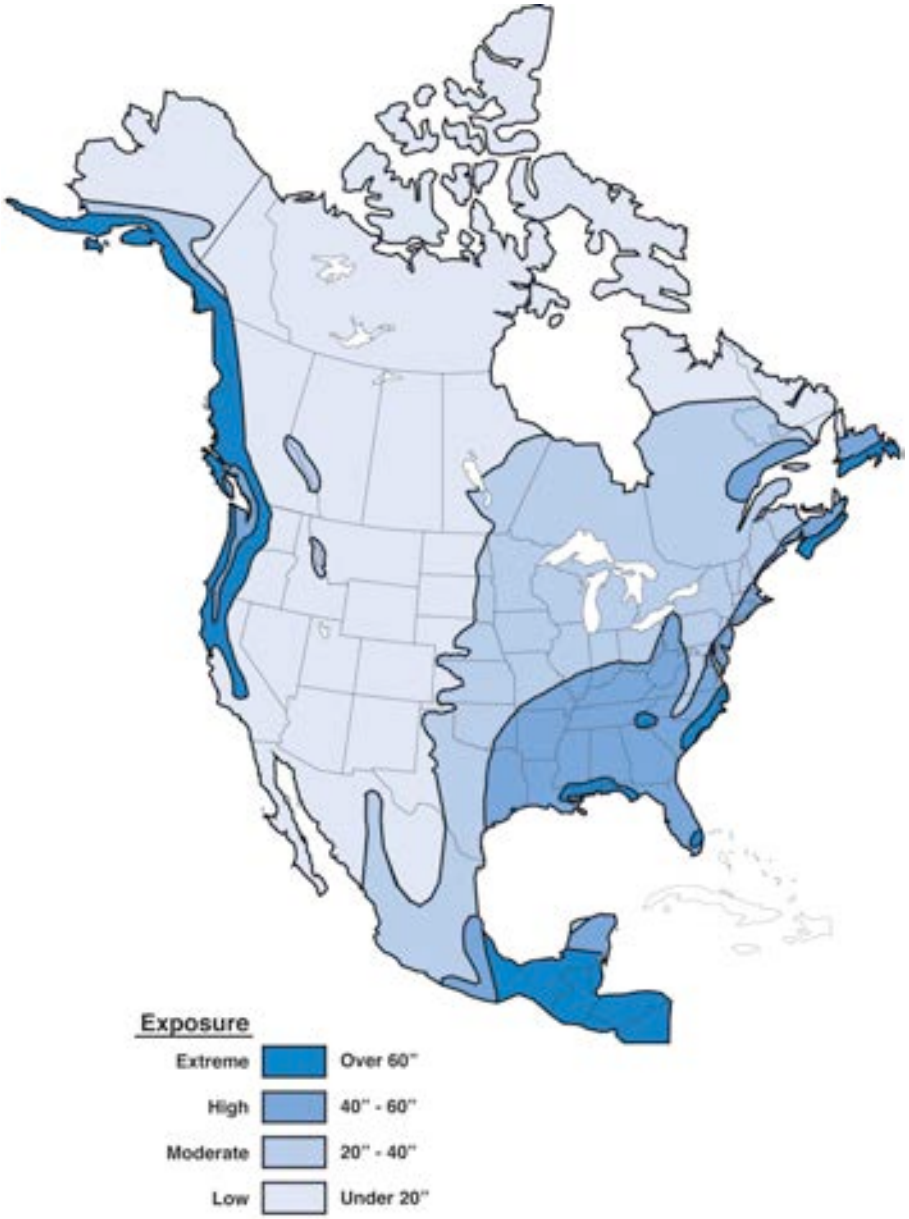
Air Flow Is From A Higher Pressure to a Lower Pressure

Gravity Acts Down

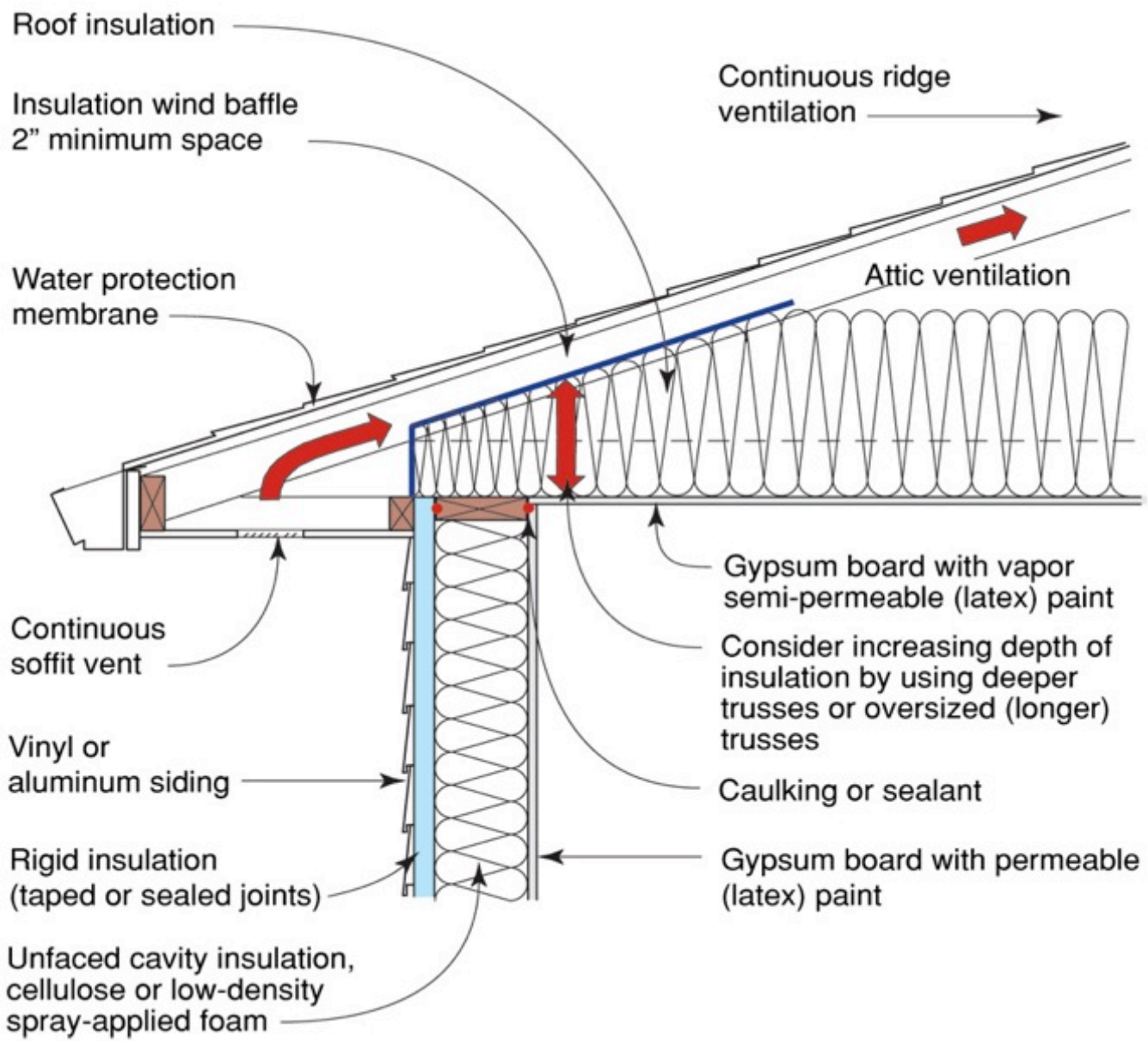

Subarctic/Arctic
Very Cold
Marine
Cold
Mixed-Humid
Mixed-Dry
Hot-Humid
Hot-Dry

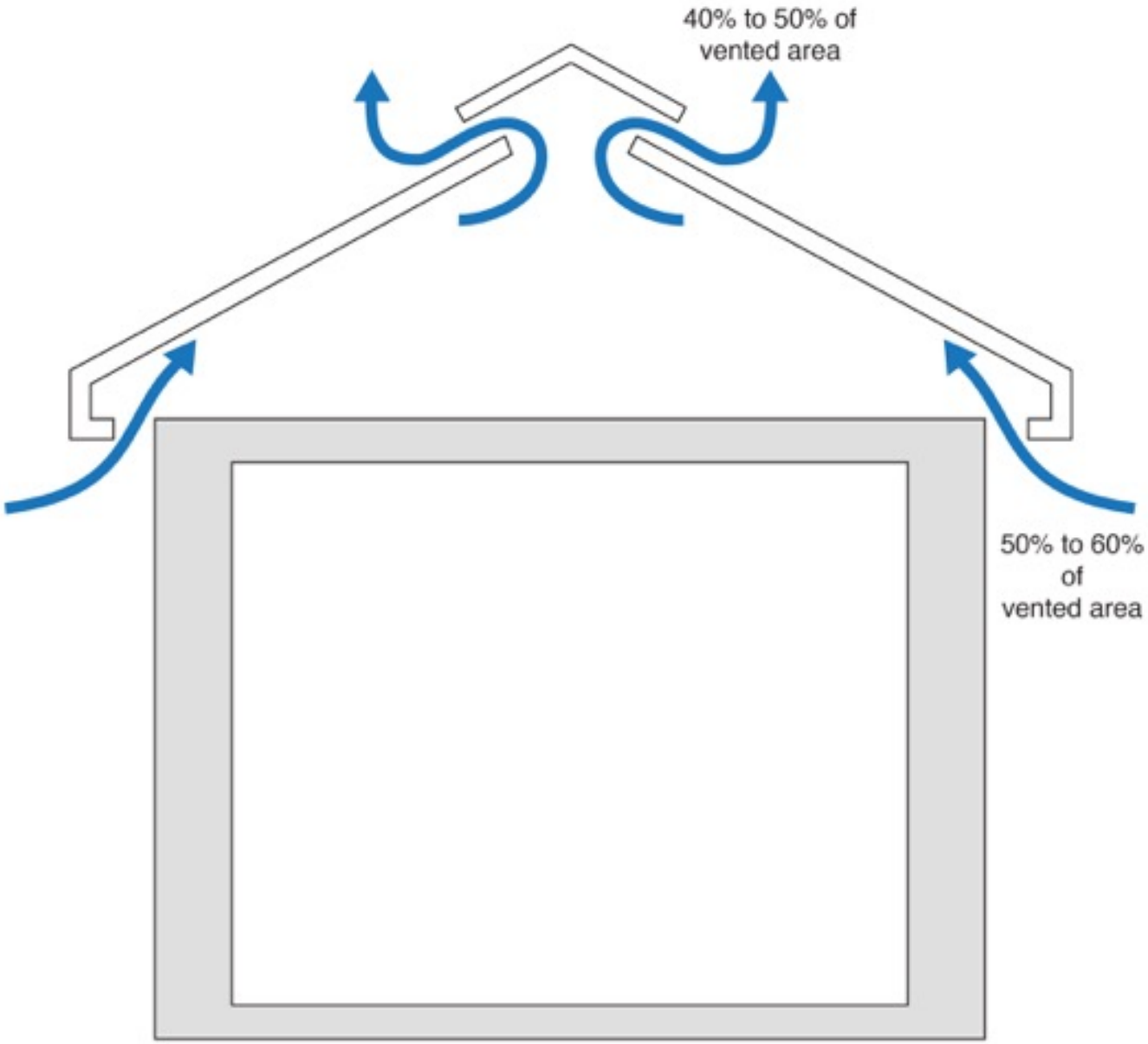

Arctic Bay
Anchorage
Seattle
Minneapolis
Los Angeles
El Paso
Houston
Monterrey
Havana
Belize City
Tropical Wet
Tropical Wet-Dry
Steppe
Desert
Mediterranean
Subtropical humid
Marine West Coast
Continental humid
Subarctic
Tundra
Ice sheet
Highlands

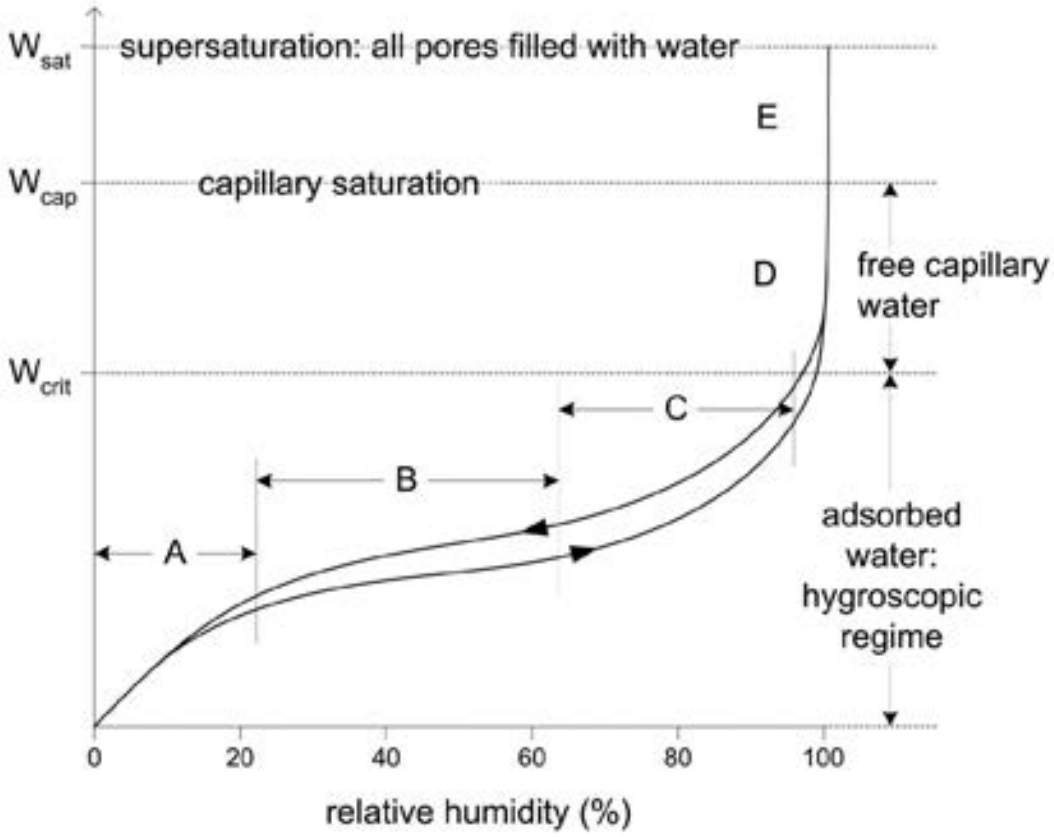

Marine (C)
Dry (B)
Moist (A)
7
6
6
4
5
5
4
3
3
2
2
1
Warm–Humid
Below White Line


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

Vented Attics Are Climate Dependant

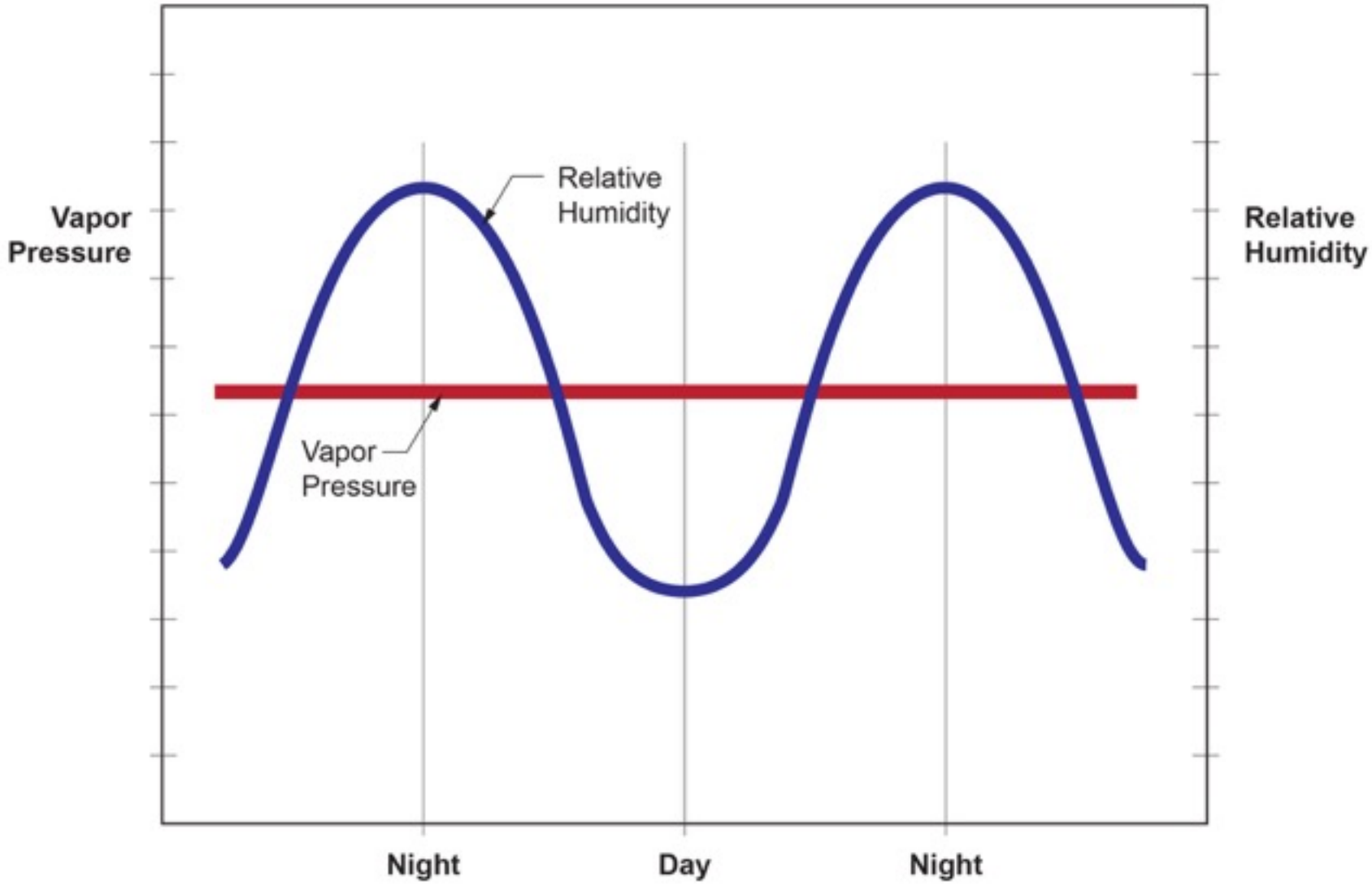

Roof insulation
Insulation wind baffle
2" minimum space
Continuous ridge
ventilation
Water protection
membrane
Attic ventilation
Gypsum board with vapor
semi-permeable (latex) paint
Continuous
soffit vent
Consider increasing depth of
insulation by using deeper
trusses or oversized (longer)
trusses
Vinyl or
aluminum siding
Caulking or sealant
Rigid insulation
(taped or sealed joints)
Gypsum board with permeable
(latex) paint
Unfaced cavity insulation,
cellulose or low-density
spray-applied foam


40% to 50% of
vented area
50% to 60%
of
vented area



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

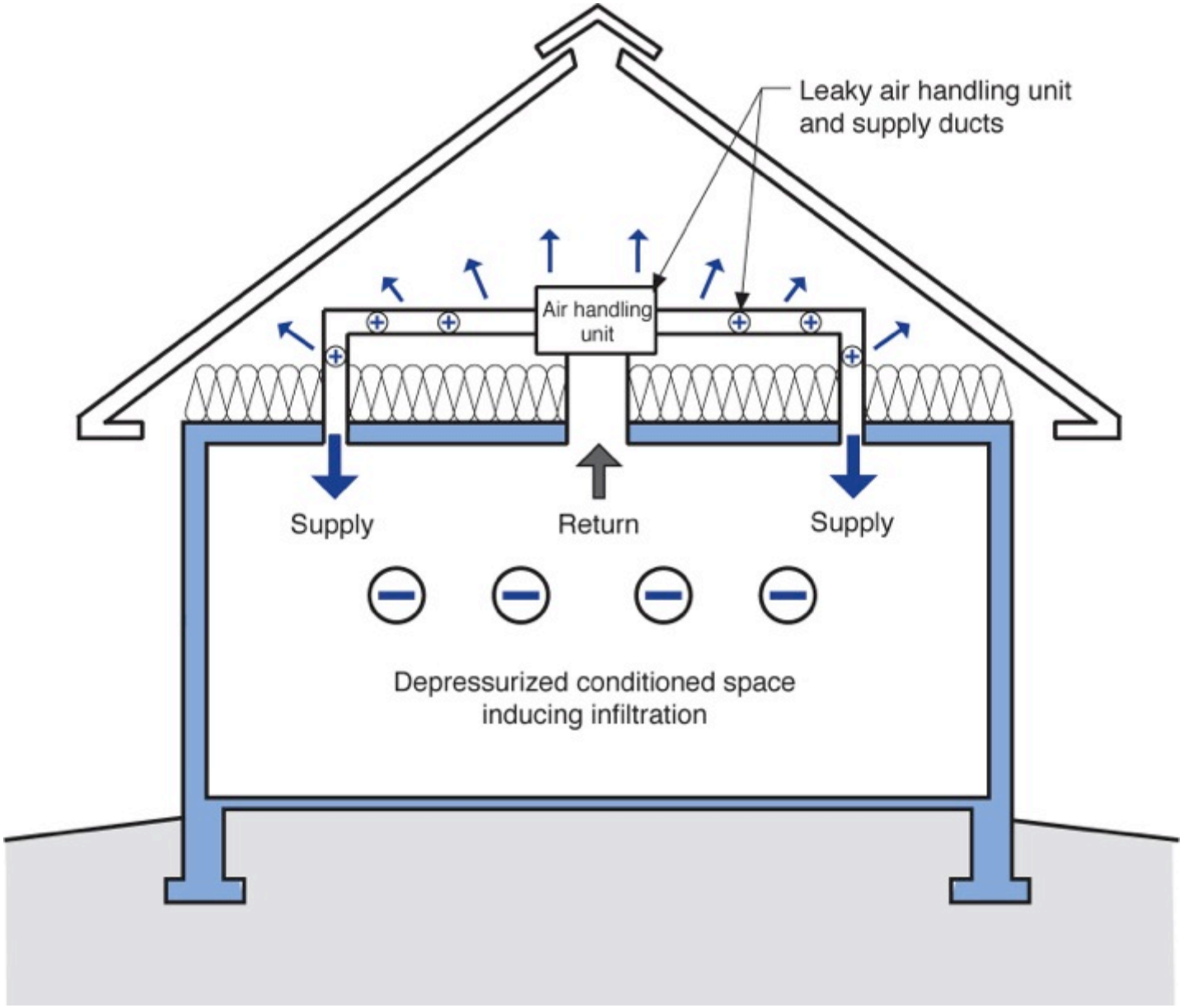
Regimes of moisture storage in a hygroscopic porous material
From Straube & Burnett, 2005

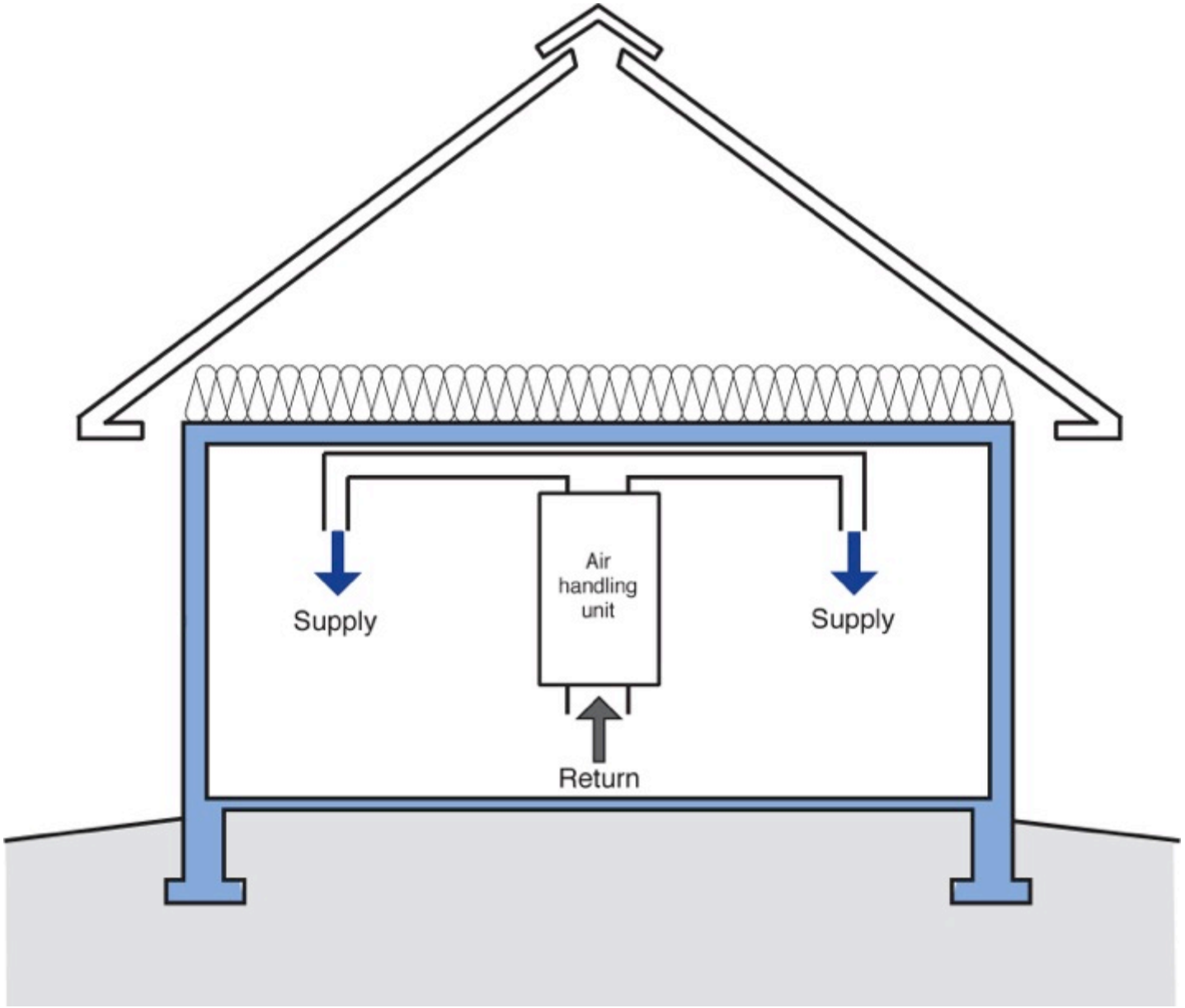

Vapor Pressure
Relative Humidity
Relative Humidity
Vapor Pressure
Night
Day
Night

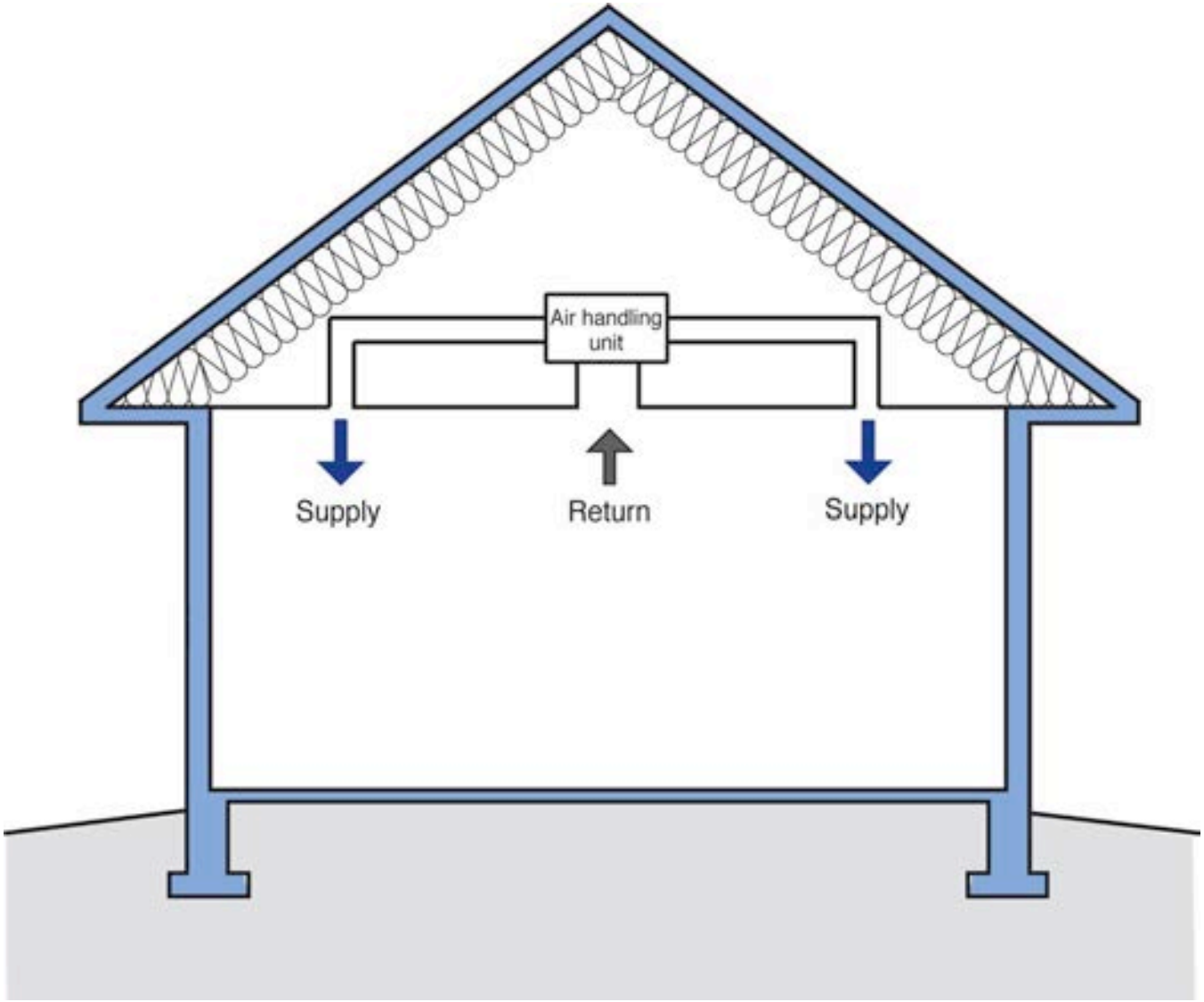
Houses With Vented Attics Suck

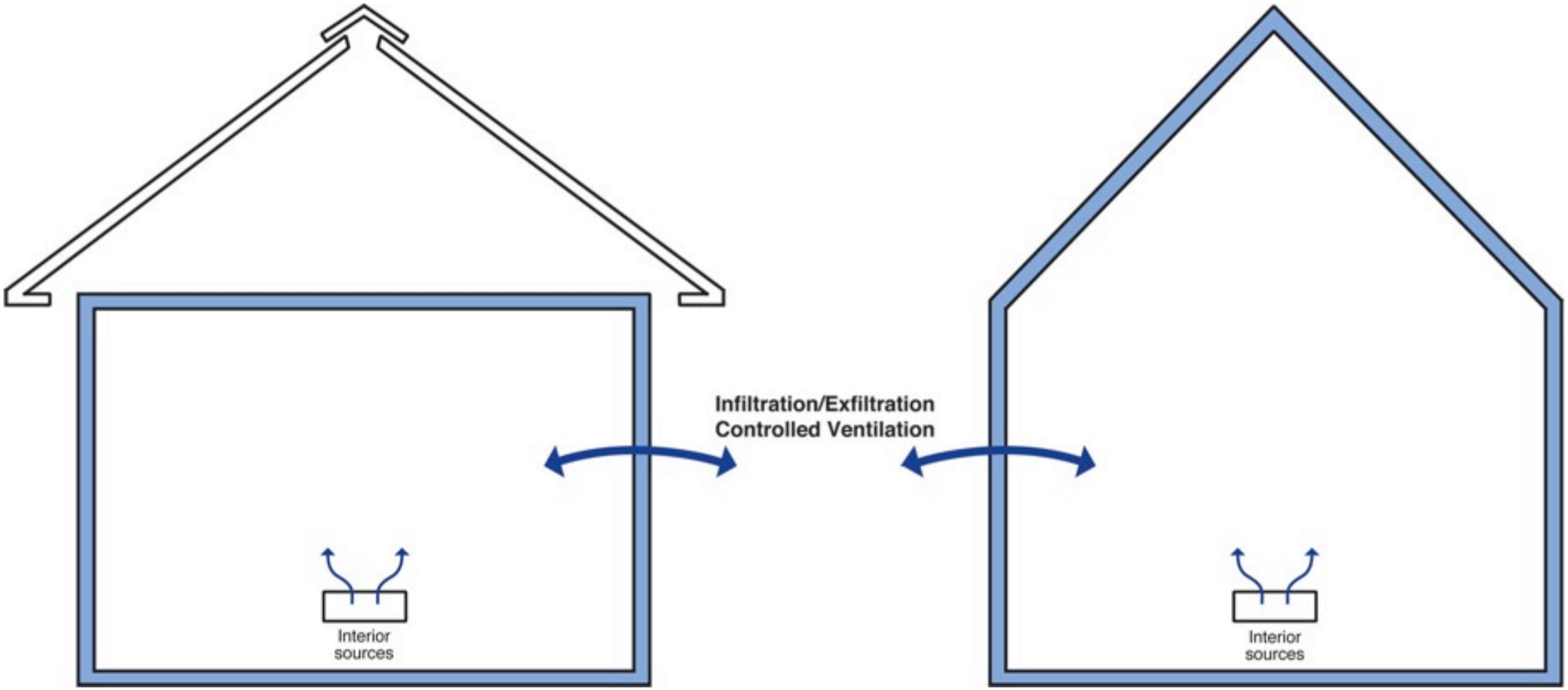
Houses With Vented Attics Suck

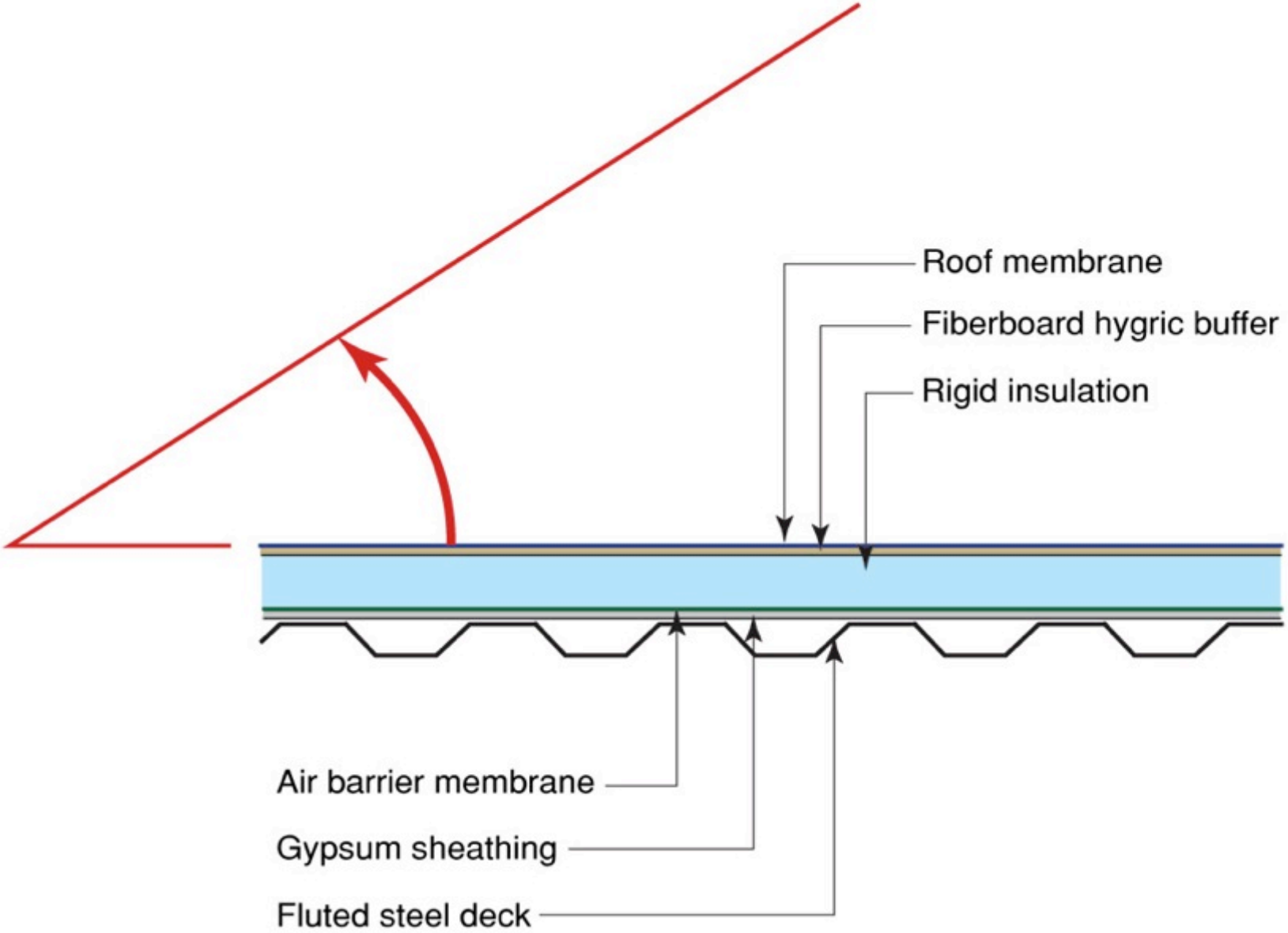
Not all the Time…..but.....

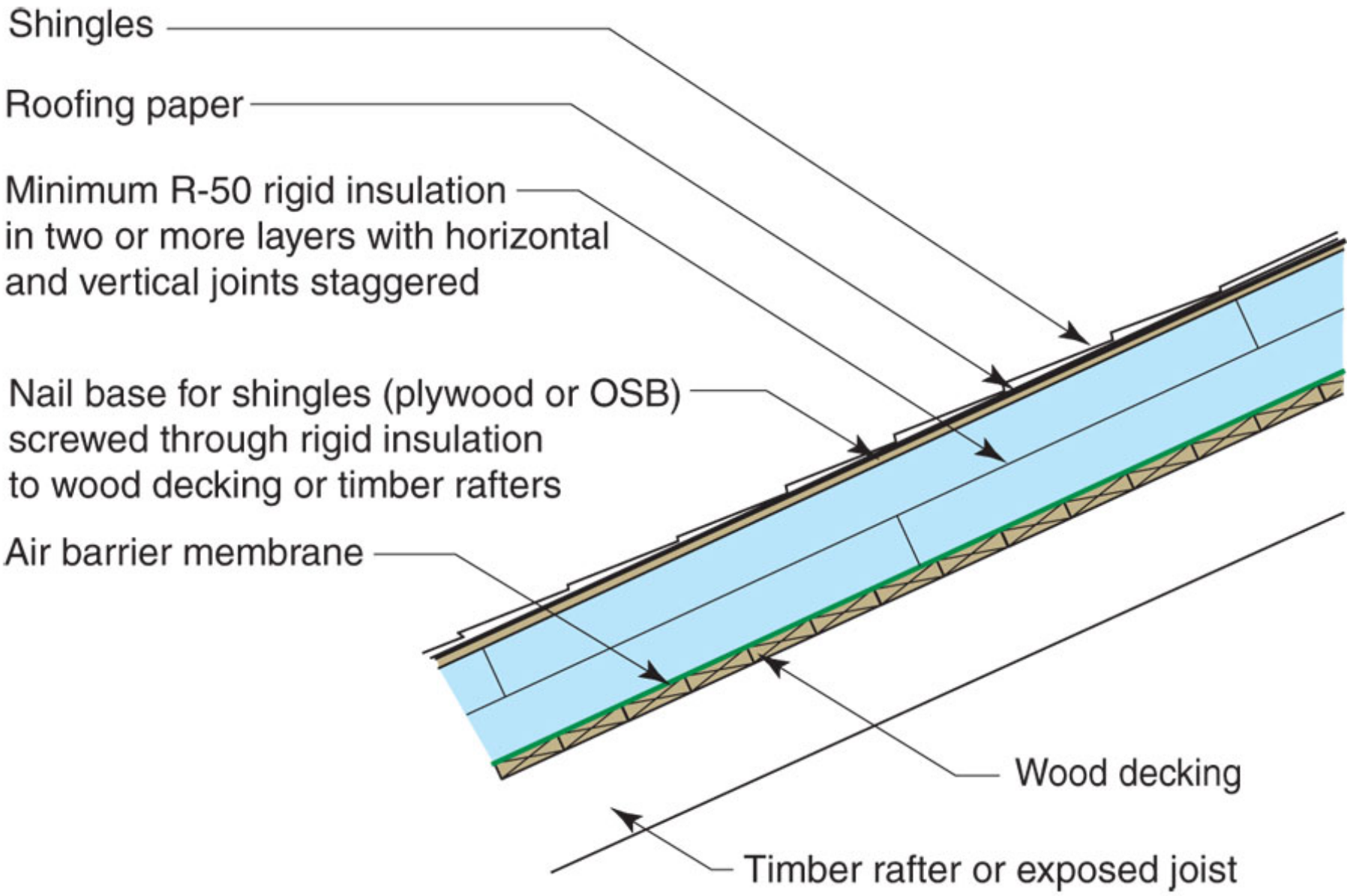

Leaky air handling unit
and supply ducts
Air handling
unit
Supply
Return
Supply
Depressurized conditioned space
inducing infiltration

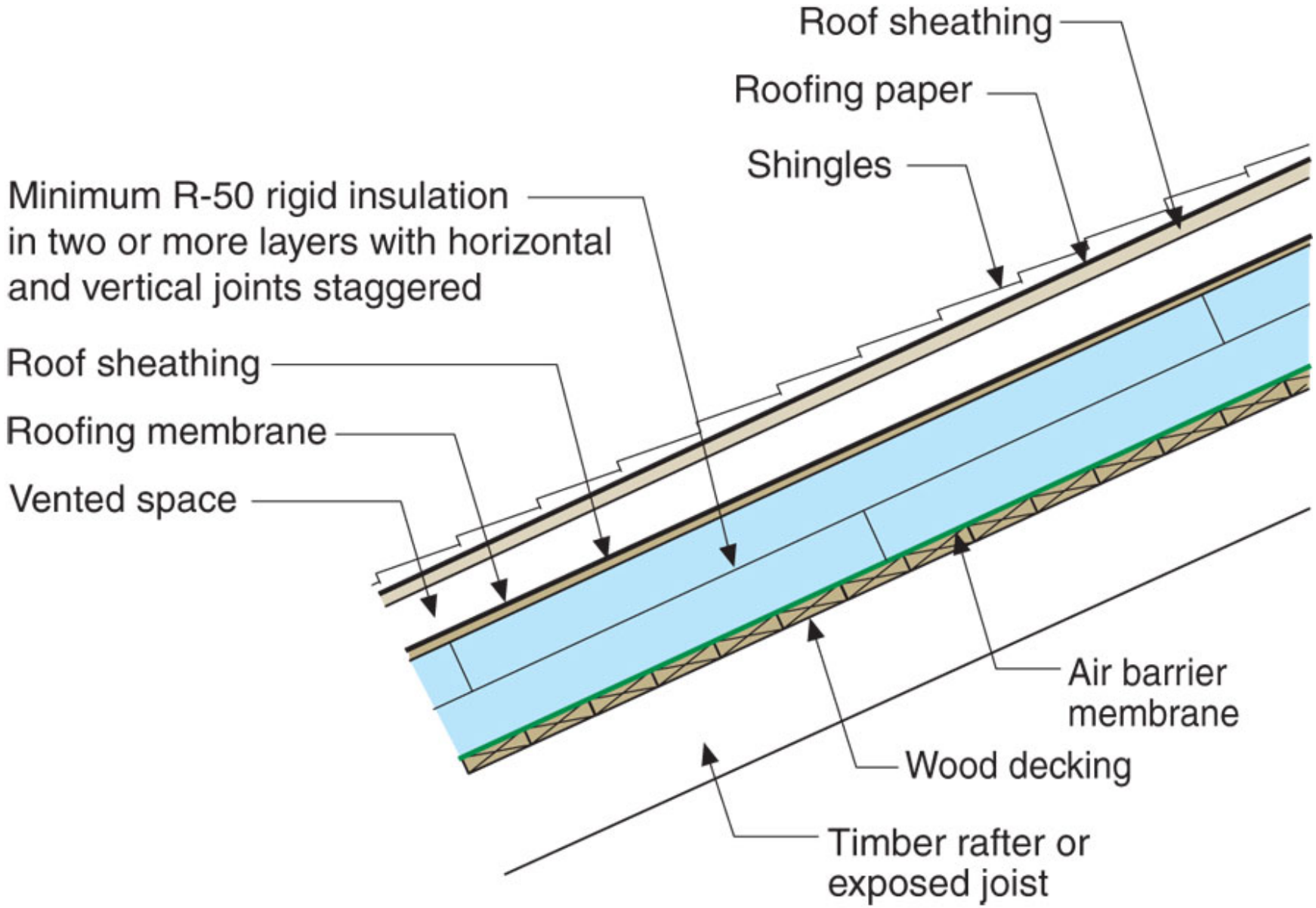

Supply
Air handling unit
Supply
Return

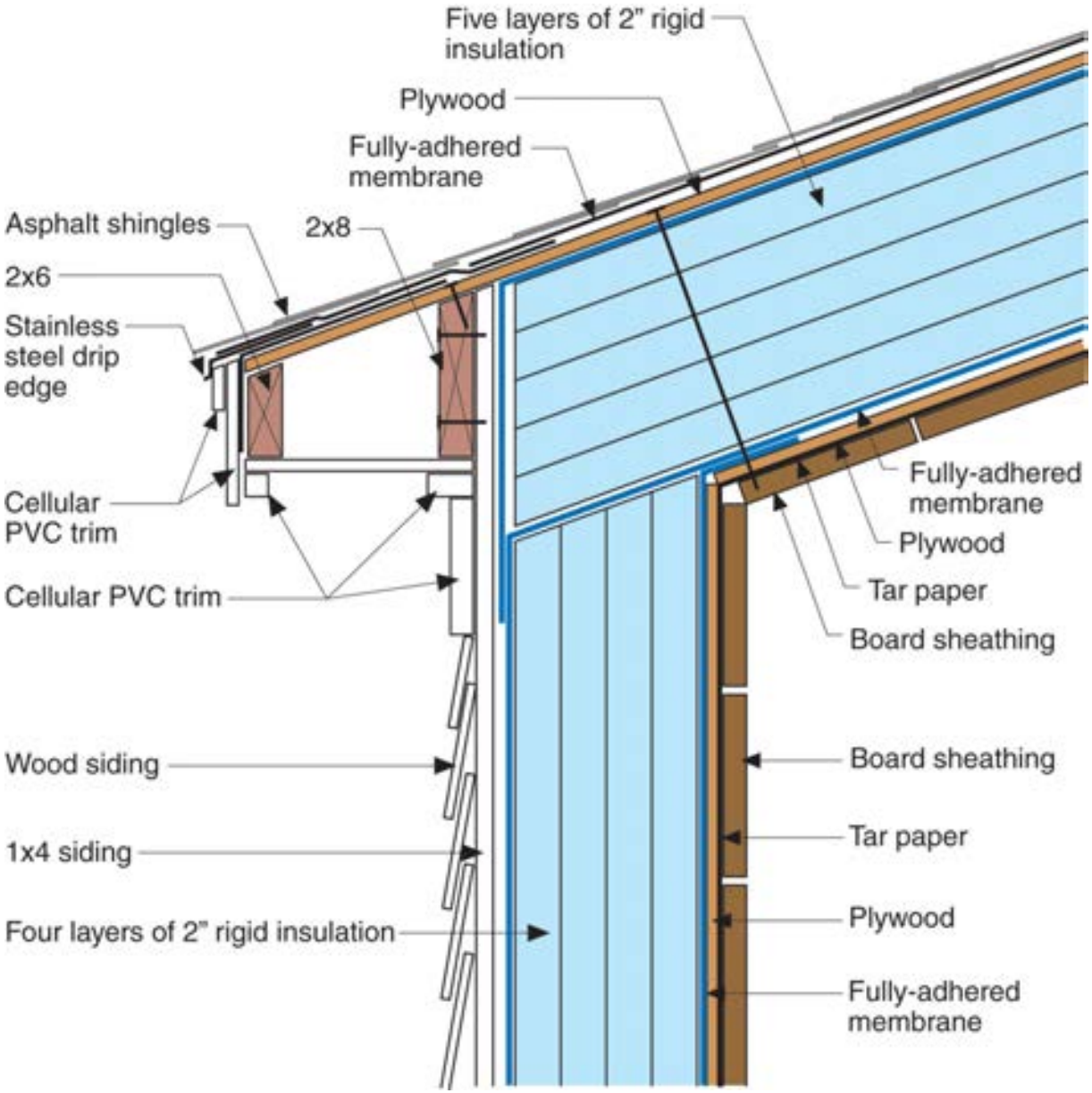

Air handling unit
Supply
Return
Supply


Infiltration/Exfiltration
Controlled Ventilation
Interior sources
Interior sources

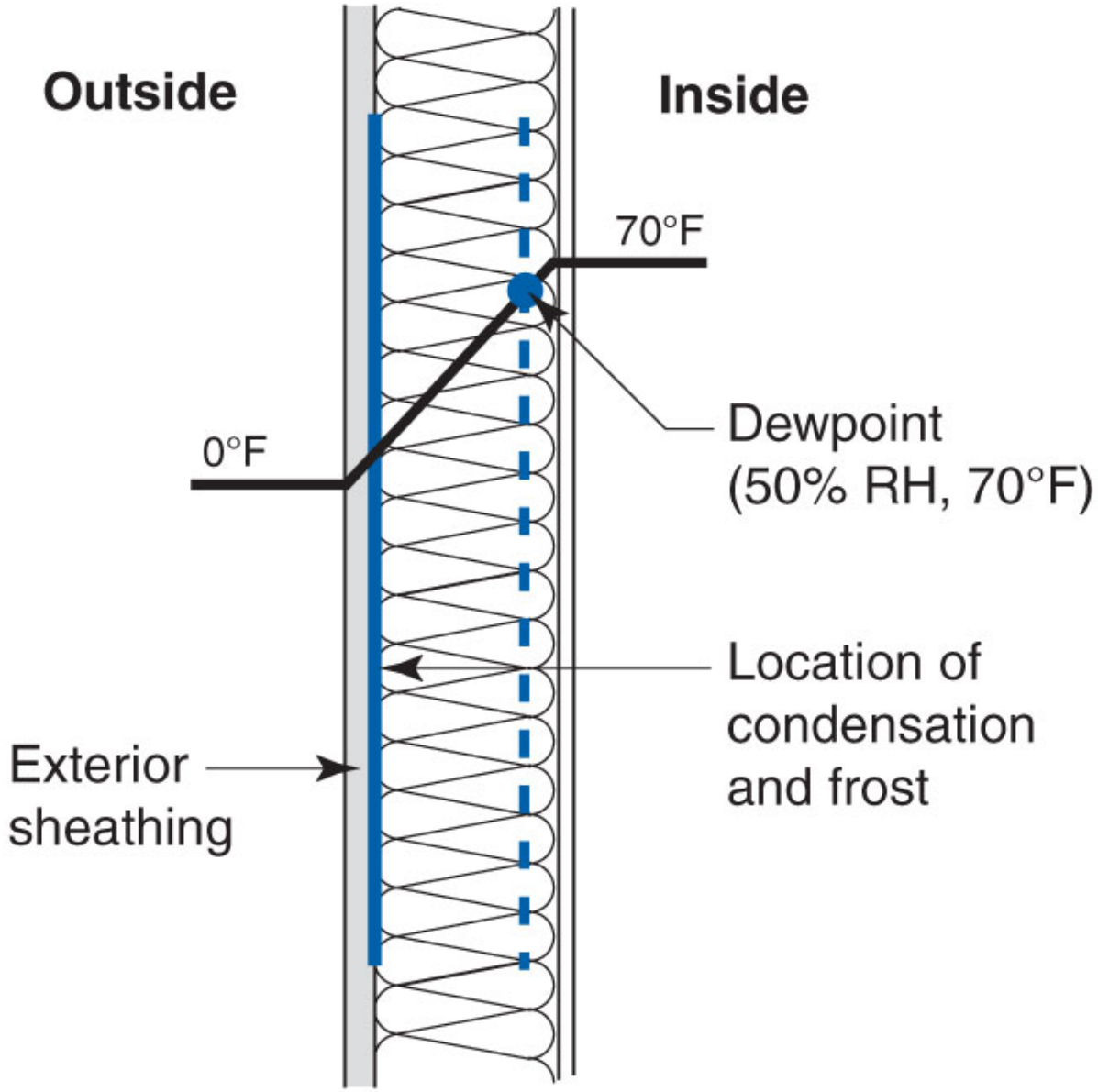

Roof membrane
Fiberboard hygric buffer
Rigid insulation
Air barrier membrane
Gypsum sheathing
Fluted steel deck

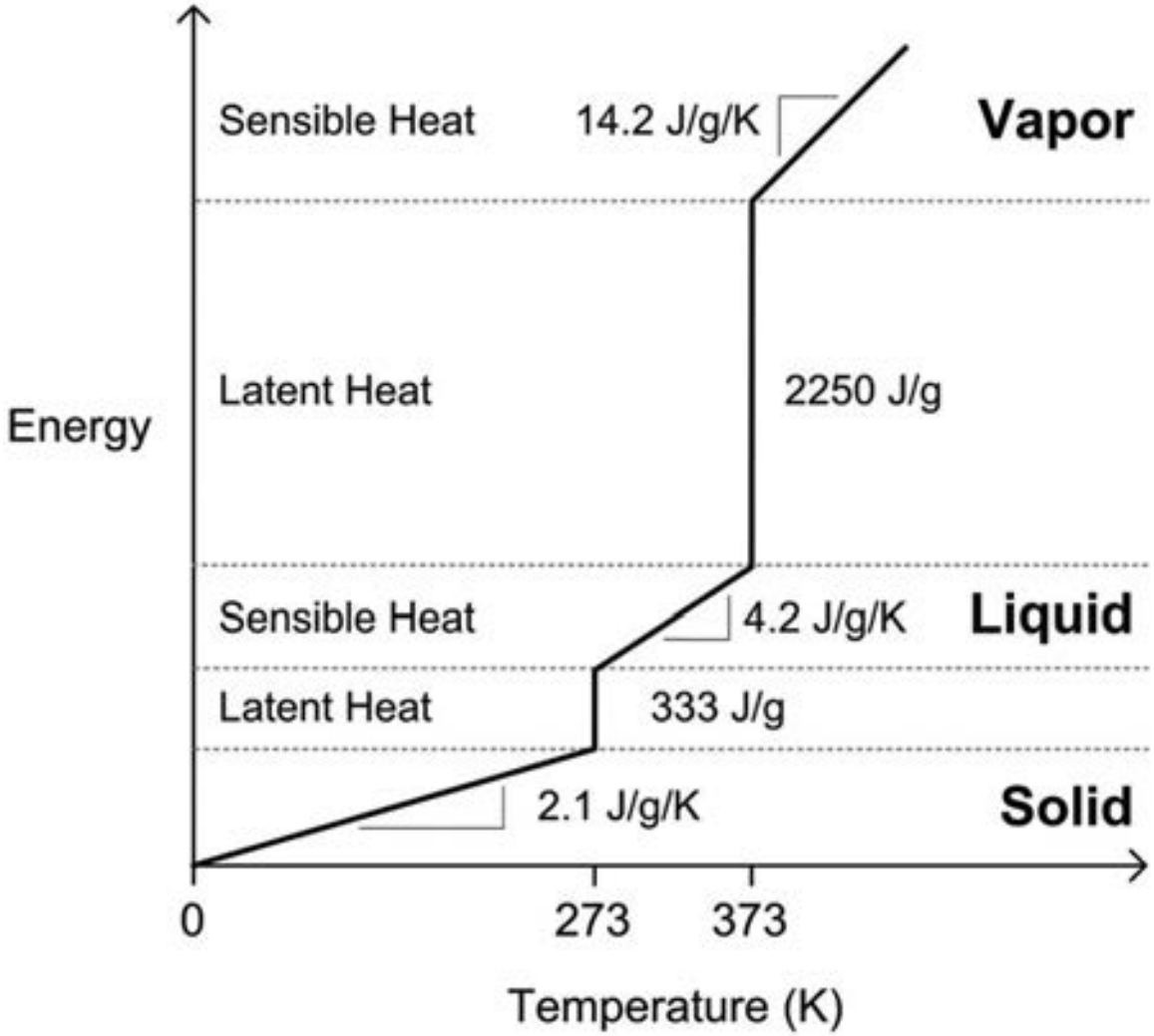

Shingles
Roofing paper
Minimum R-50 rigid insulation
in two or more layers with horizontal
and vertical joints staggered
Nail base for shingles (plywood or OSB)
screwed through rigid insulation
to wood decking or timber rafters
Air barrier membrane
Wood decking
Timber rafter or exposed joist


Roof sheathing
Roofing paper
Shingles
Minimum R-50 rigid insulation
in two or more layers with horizontal
and vertical joints staggered
Roof sheathing
Roofing membrane
Vented space
Air barrier
membrane
Wood decking
Timber rafter or
exposed joist

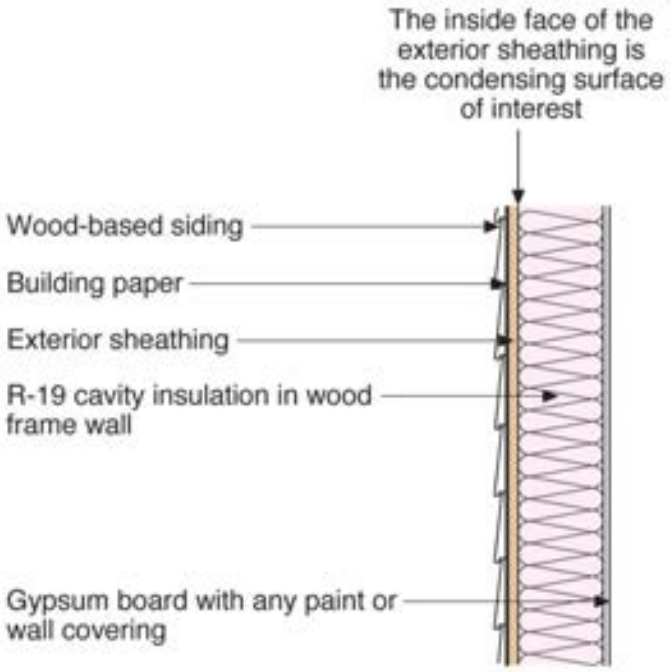

Five layers of 2" rigid insulation
Plywood
Fully-adhered membrane
Asphalt shingles
2x8
2x6
Stainless steel drip edge
Cellular PVC trim
Cellular PVC trim
Wood siding
1x4 siding
Four layers of 2" rigid insulation
Fully-adhered membrane
Plywood
Tar paper
Board sheathing
Board sheathing
Tar paper
Plywood
Fully-adhered membrane

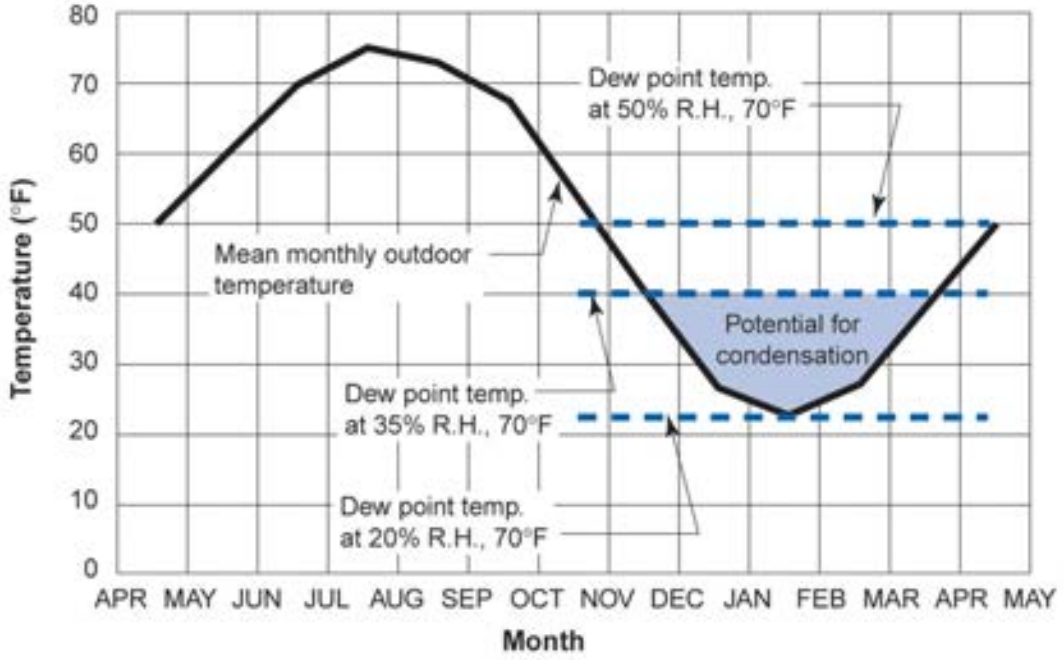

DOW
Super TUFF-R
Commercial Insulation
DOW
Super TUFF-R
Commercial Insulation
DOW
Super TUFF-R
Commercial Insulation

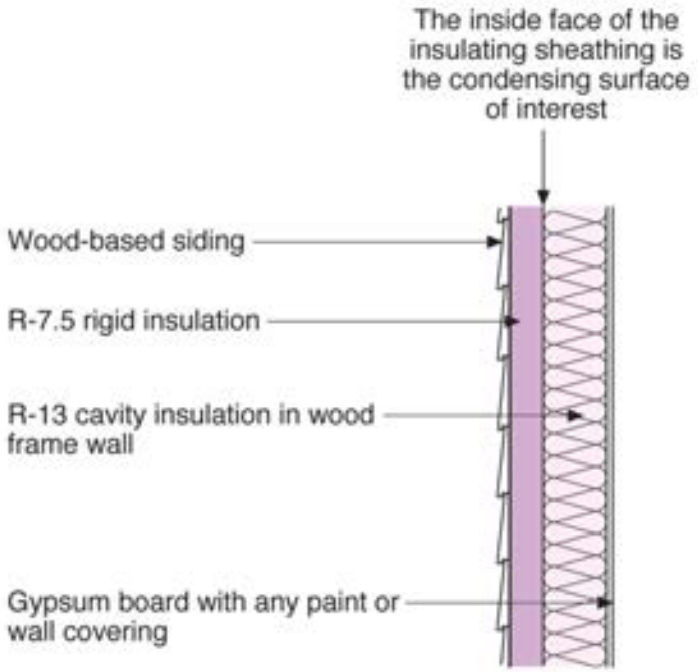

Outside
Inside
70°F
0°F
Dewpoint
(50% RH, 70°F)
Location of
condensation
and frost
Exterior
sheathing

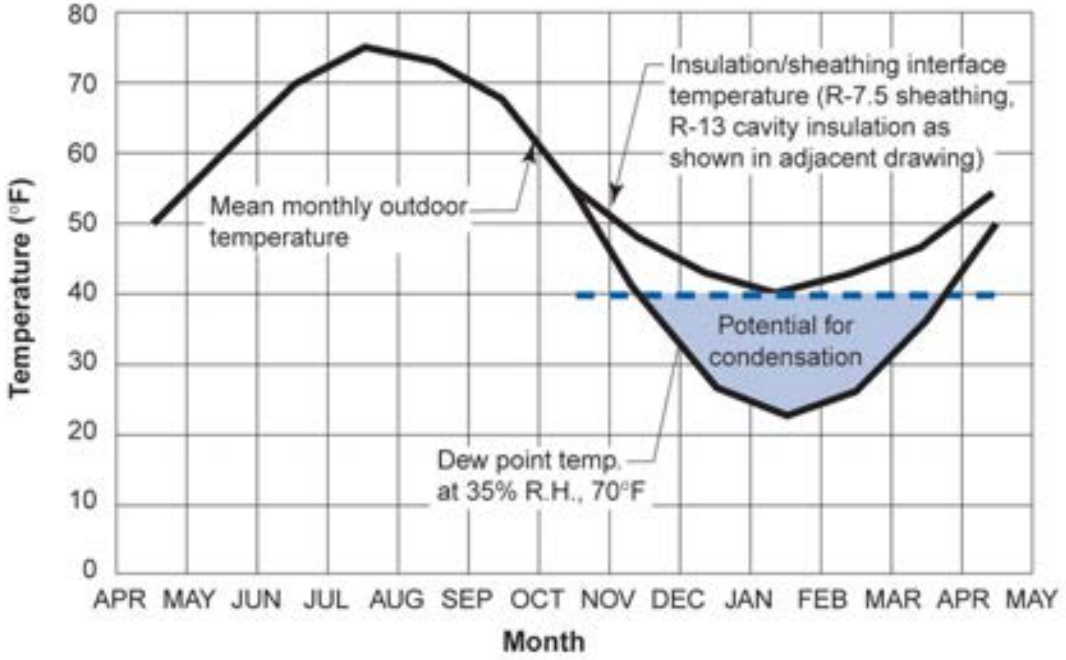


Simple linearized energy-temperature relation for water
From Straube & Burnett, 2005


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

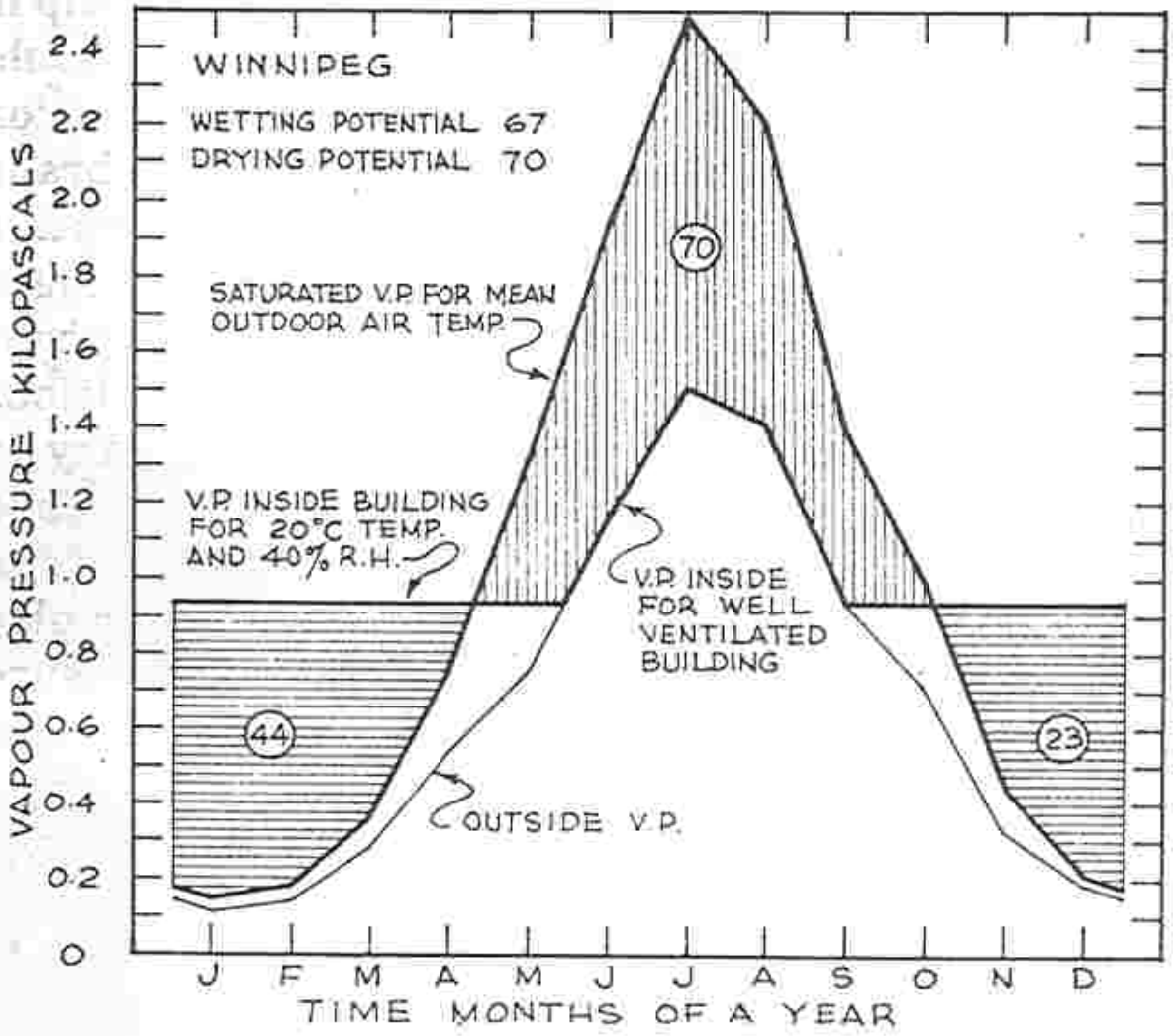
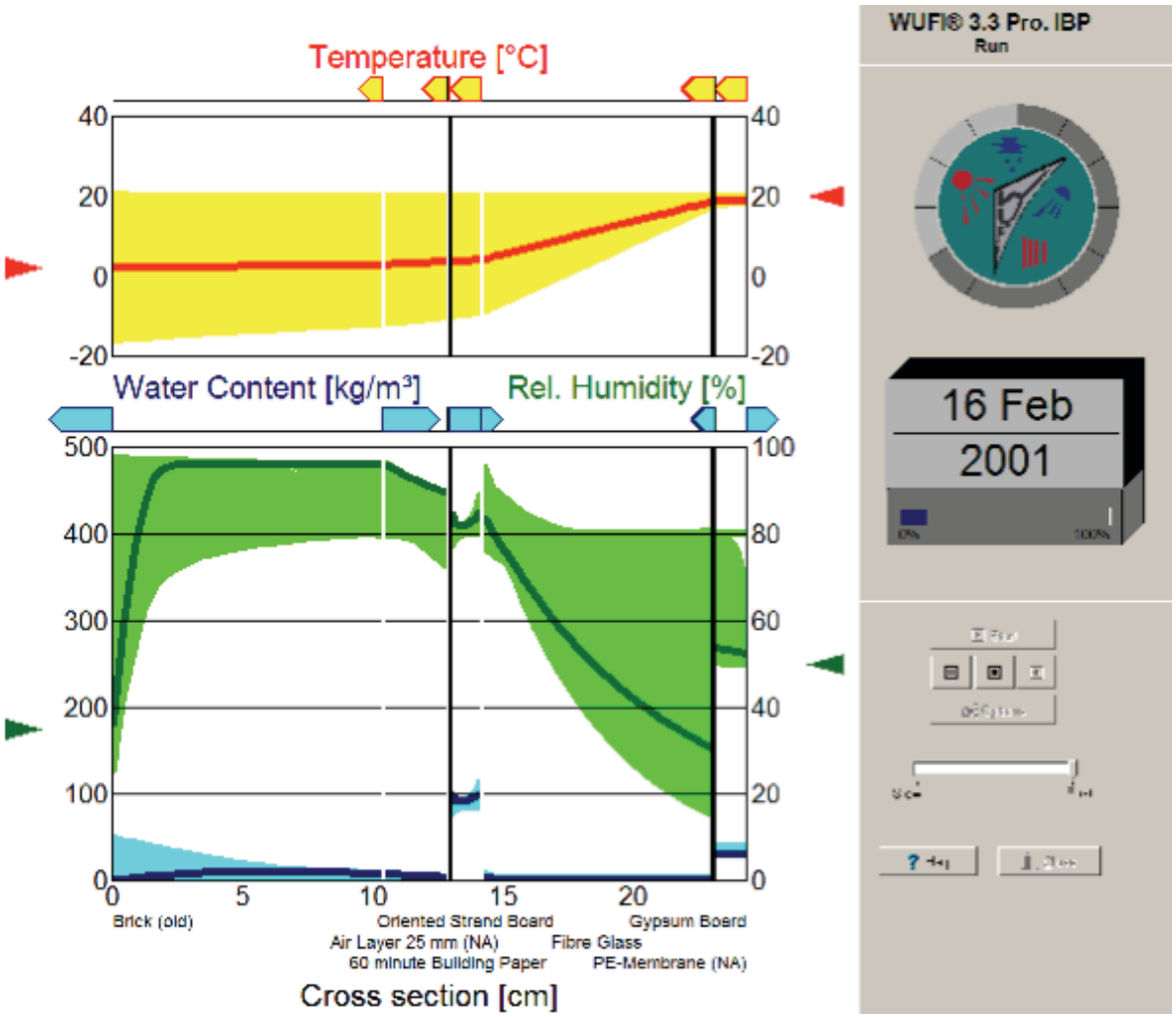
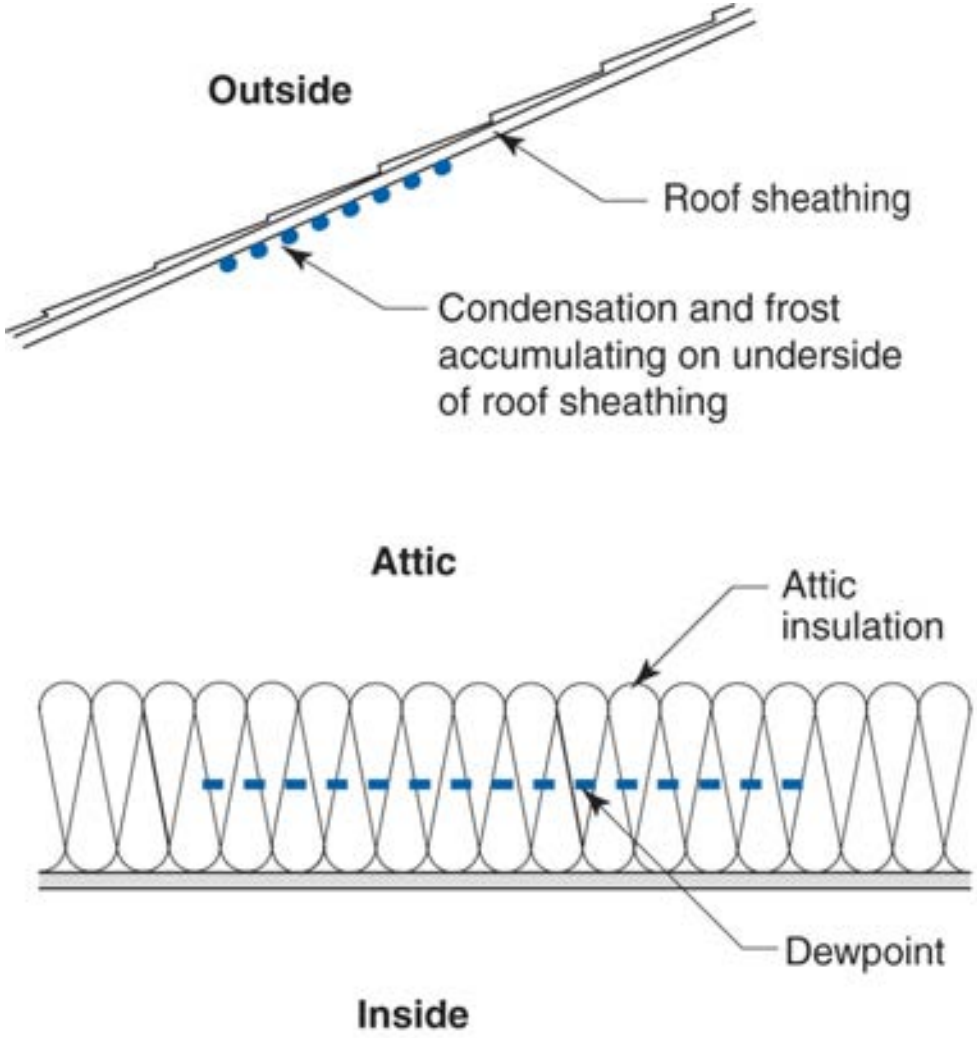
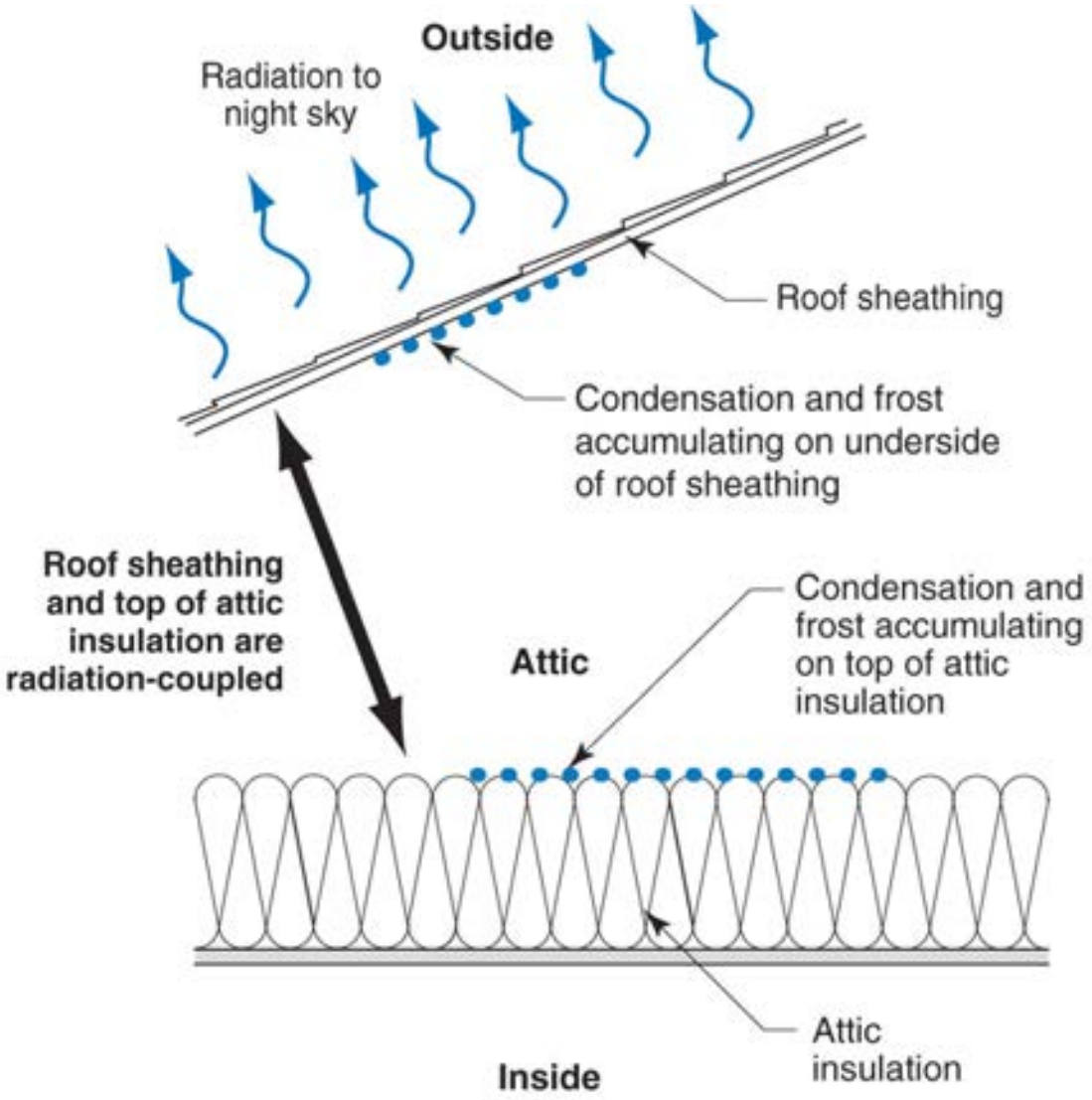
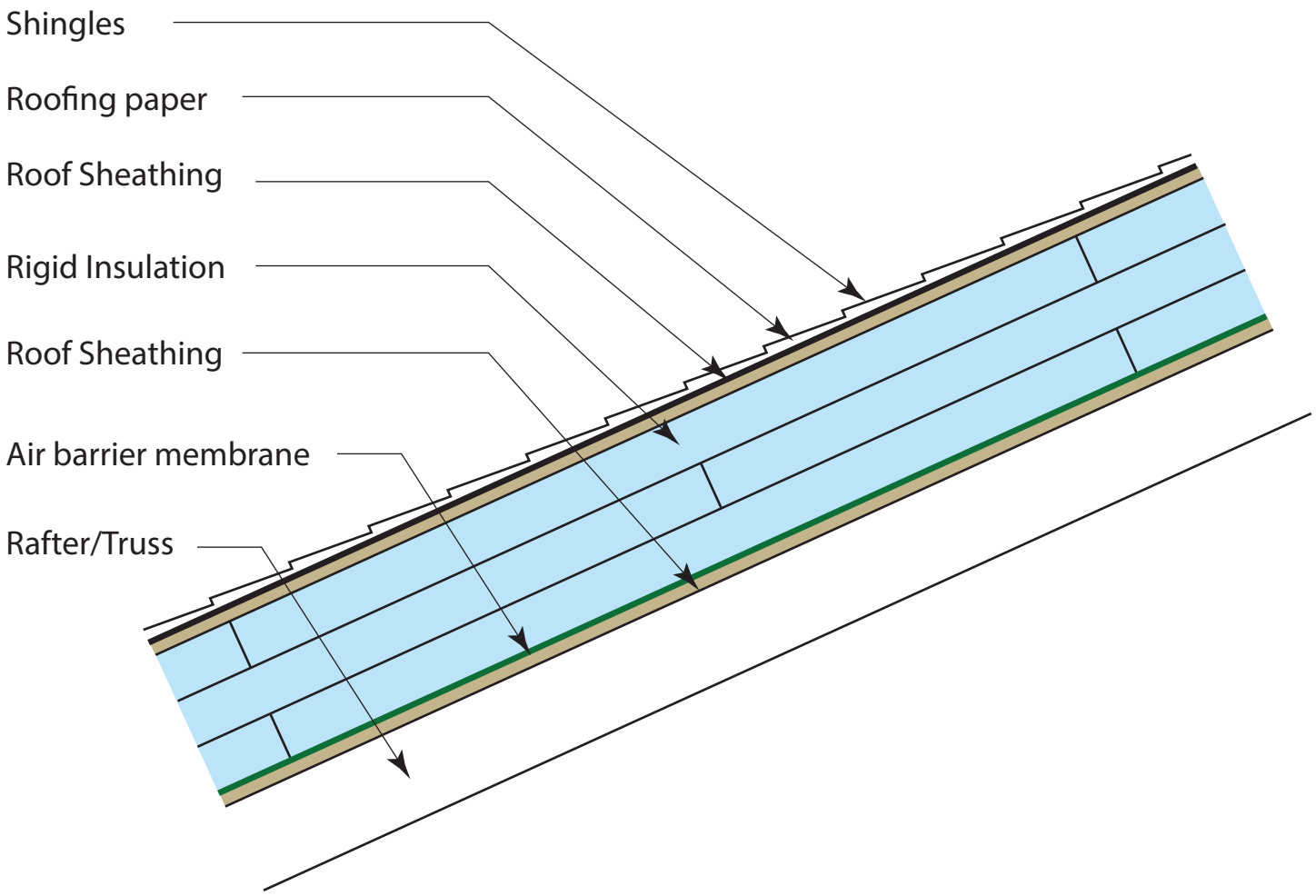


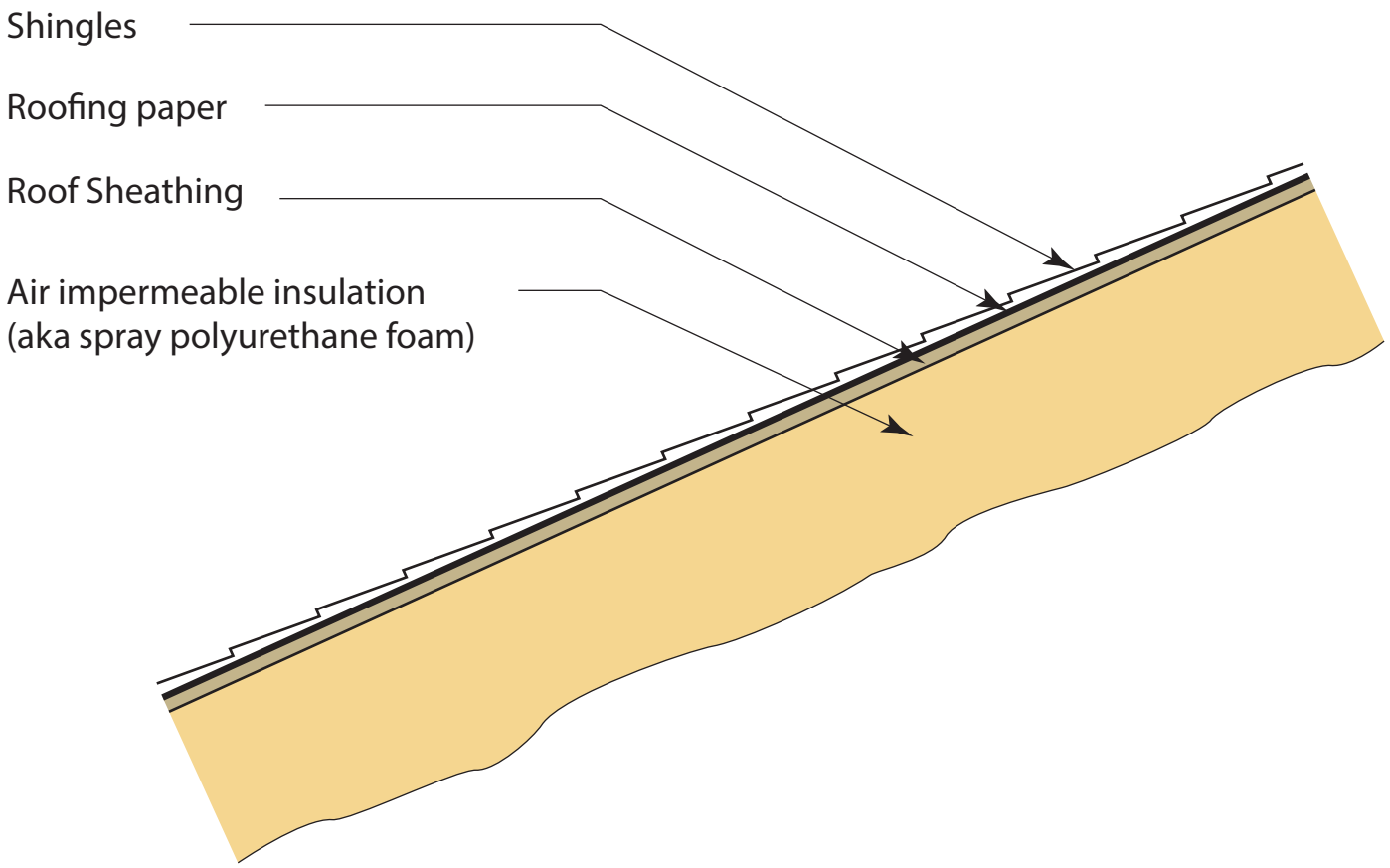
Figure 8-7. Outside vapour pressure, saturated vapour pressure and inside vapour pressure for Winnipeg.

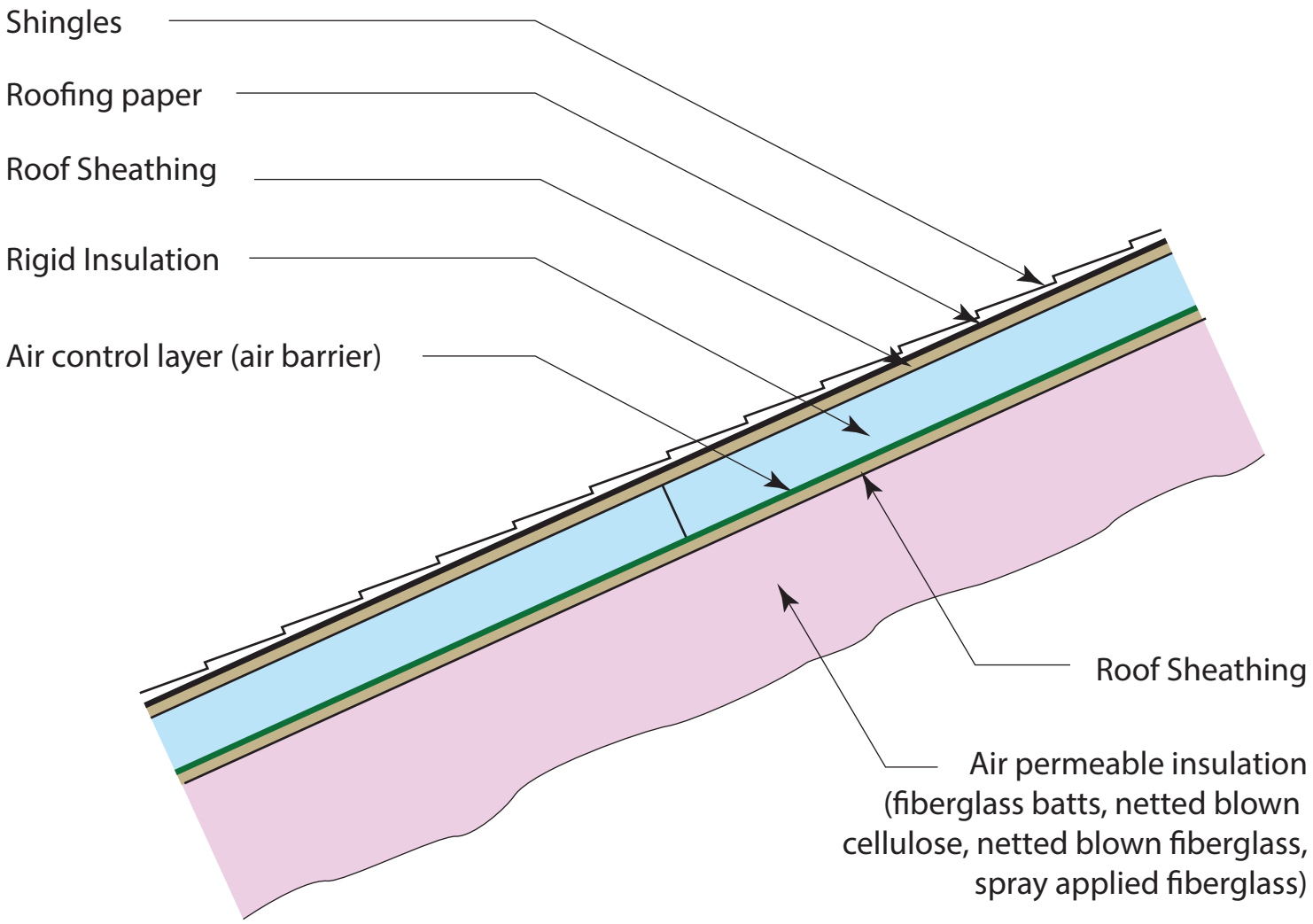

Temperature [°C]
40
20
0
-20
Water Content [kg/m³]
Rel. Humidity [%]
500
400
300
200
100
0
100
80
60
40
20
0
0
5
10
15
20
Brick (old)
Air Layer 25 mm (NA)
60 minute Building Paper
Oriented Strand Board
Fibre Glass
PE-Membrane (NA)
Gypsum Board
Cross section [cm]
WUFI® 3.3 Pro. IBP
Run
16 Feb
2001

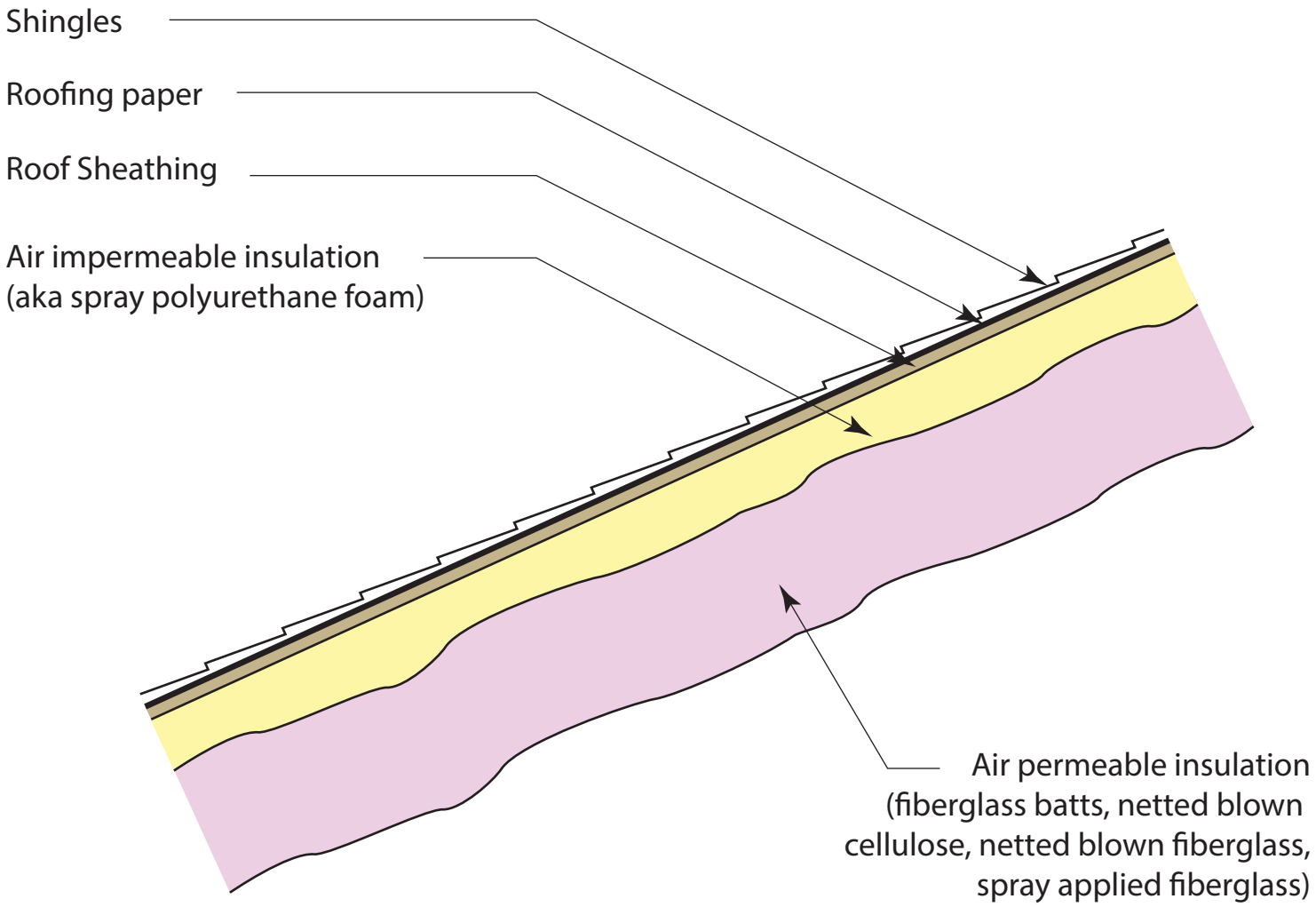

Outside
Roof sheathing
Condensation and frost
accumulating on underside
of roof sheathing
Attic
Attic
insulation
Dewpoint
Inside

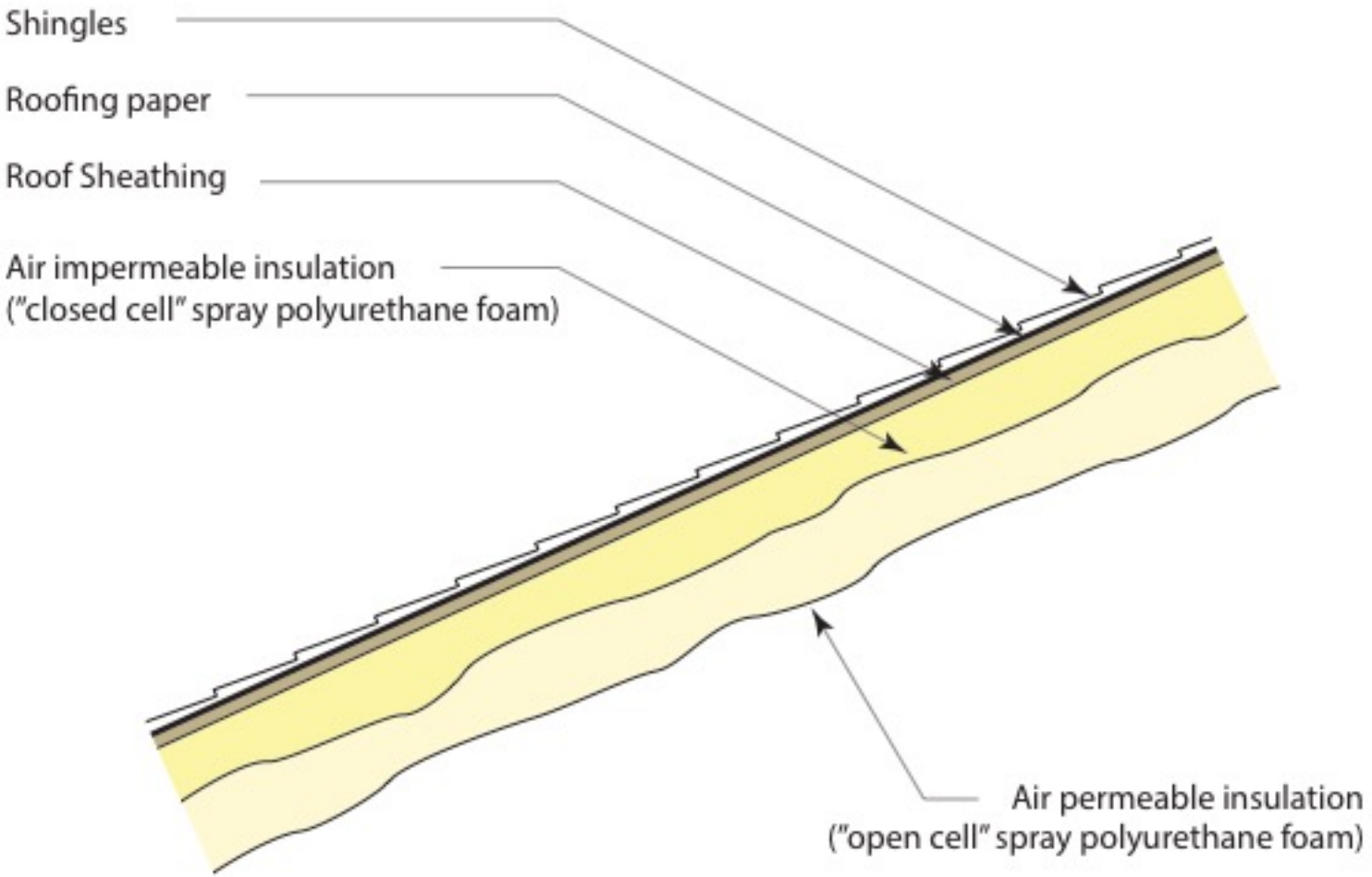

Outside
Radiation to night sky
Roof sheathing
Condensation and frost accumulating on underside of roof sheathing
Roof sheathing and top of attic insulation are radiation-coupled
Attic
Condensation and frost accumulating on top of attic insulation
Attic insulation
Inside

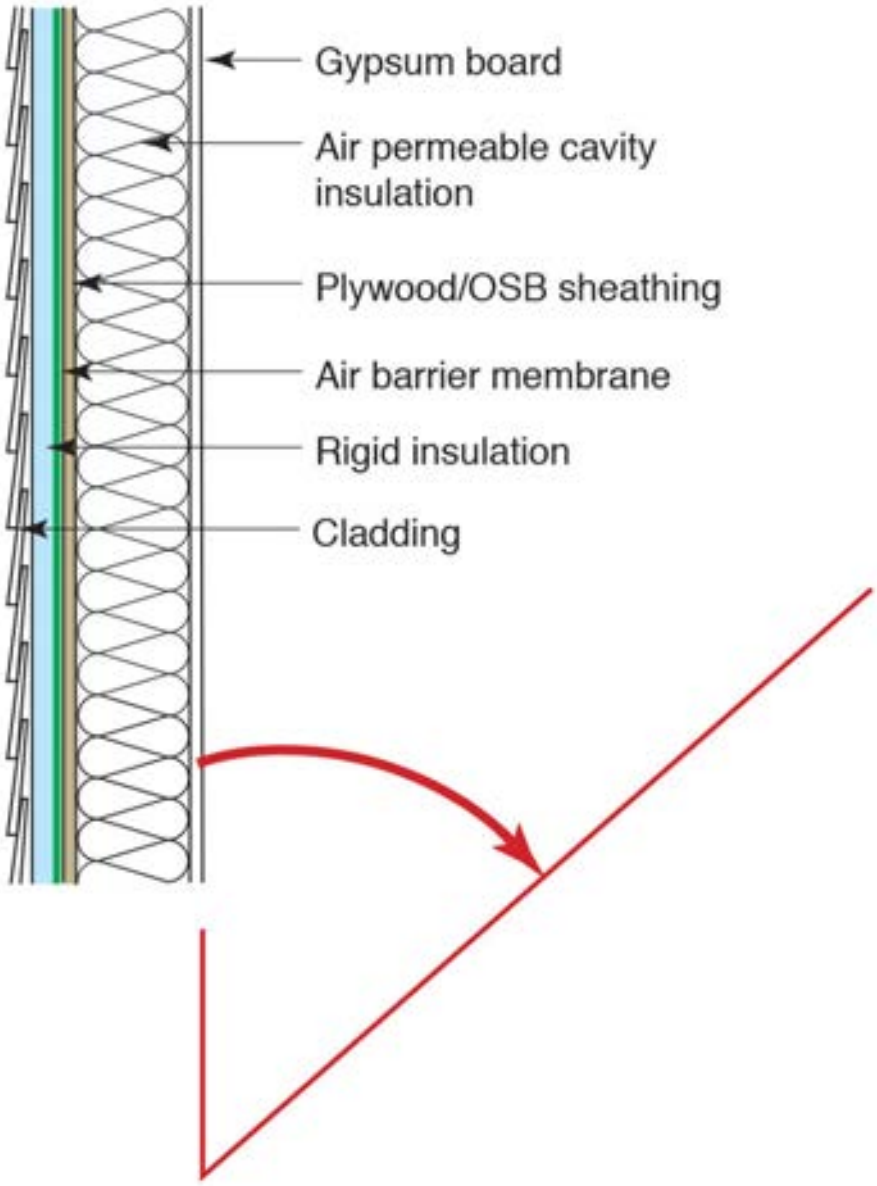

Shingles
Roofing paper
Roof Sheathing
Rigid Insulation
Roof Sheathing
Air barrier membrane
Rafter/Truss

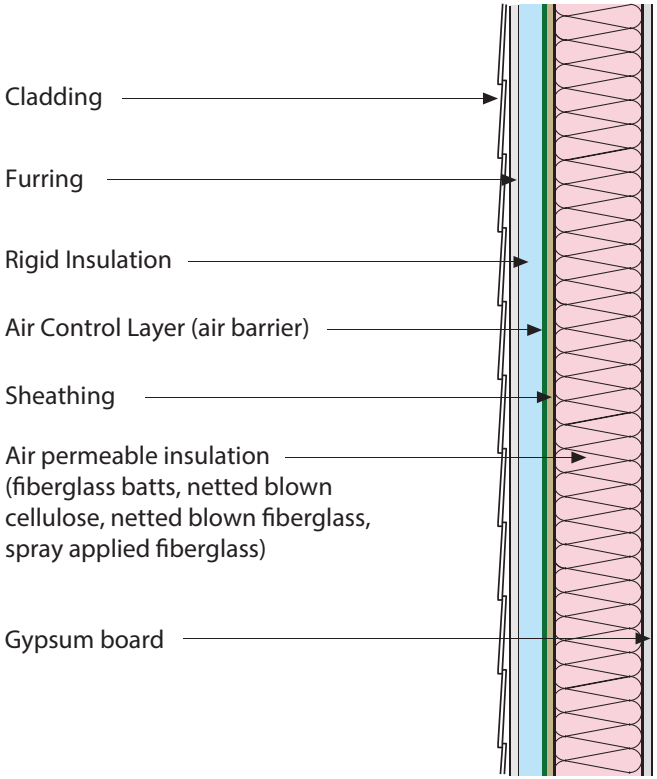

Shingles
Roofing paper
Roof Sheathing
Air impermeable insulation
(aka spray polyurethane foam)

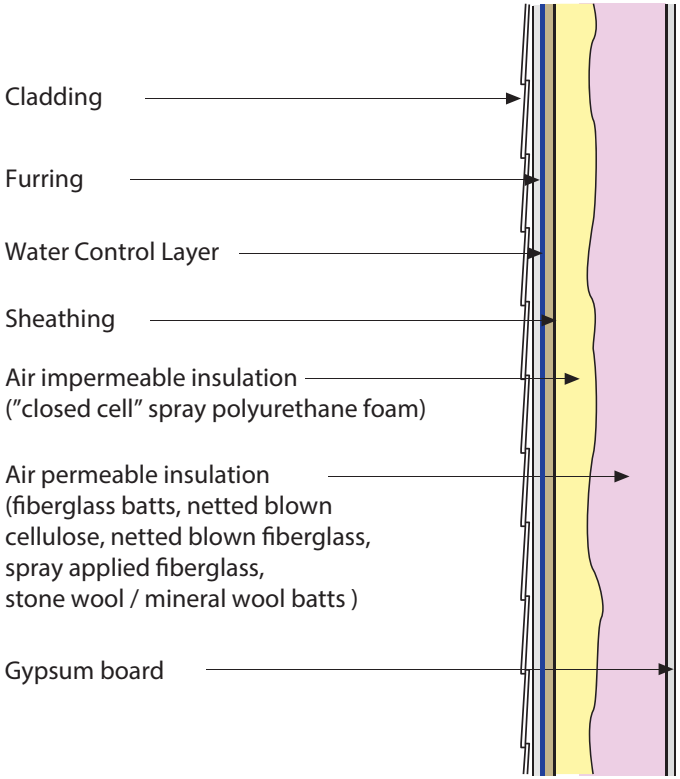

Shingles
Roofing paper
Roof Sheathing
Rigid Insulation
Air control layer (air barrier)
Roof Sheathing
Air permeable insulation
(fiberglass batts, netted blown
cellulose, netted blown fiberglass,
spray applied fiberglass)


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)


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


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

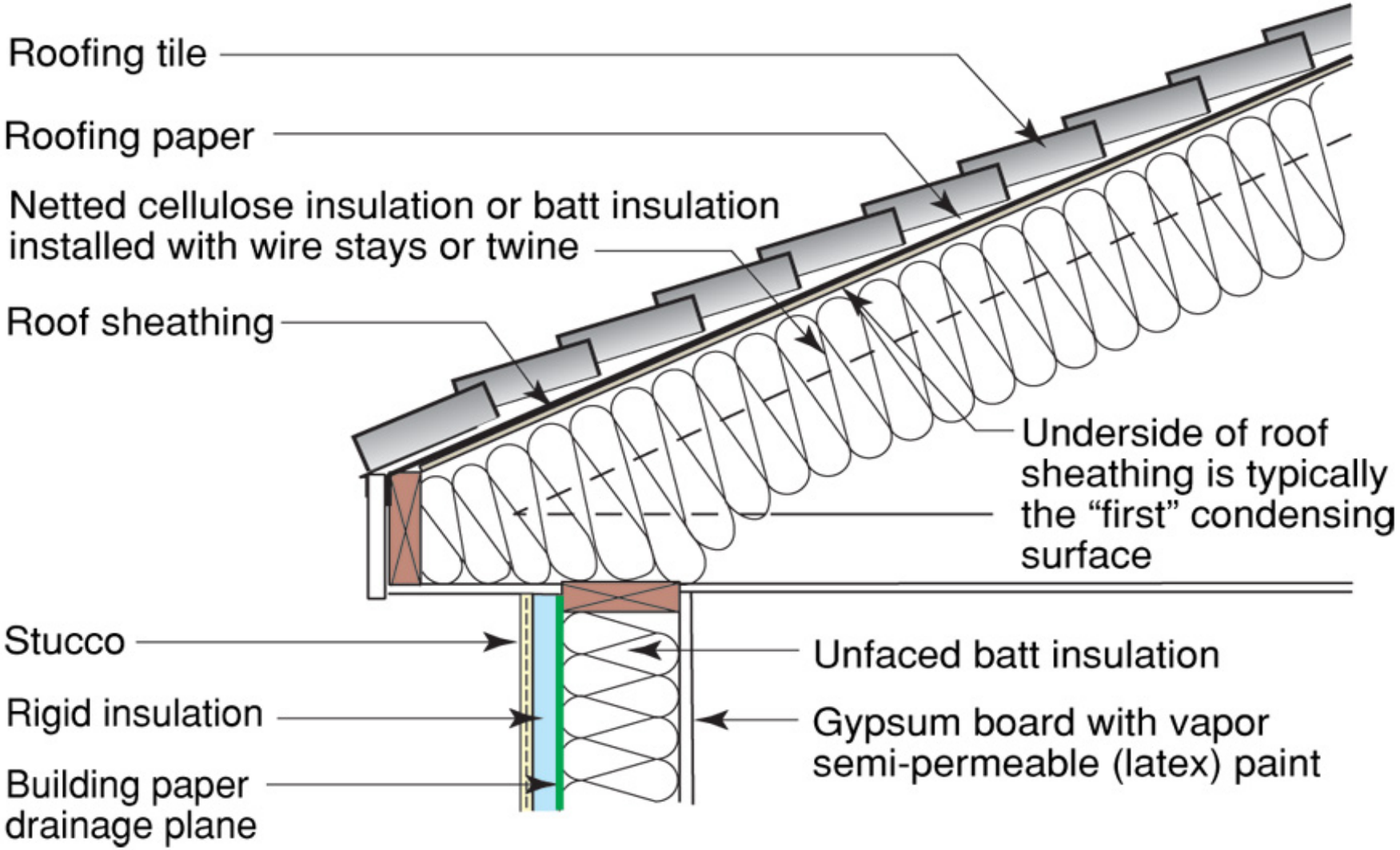
Insulation for Condensation Control*

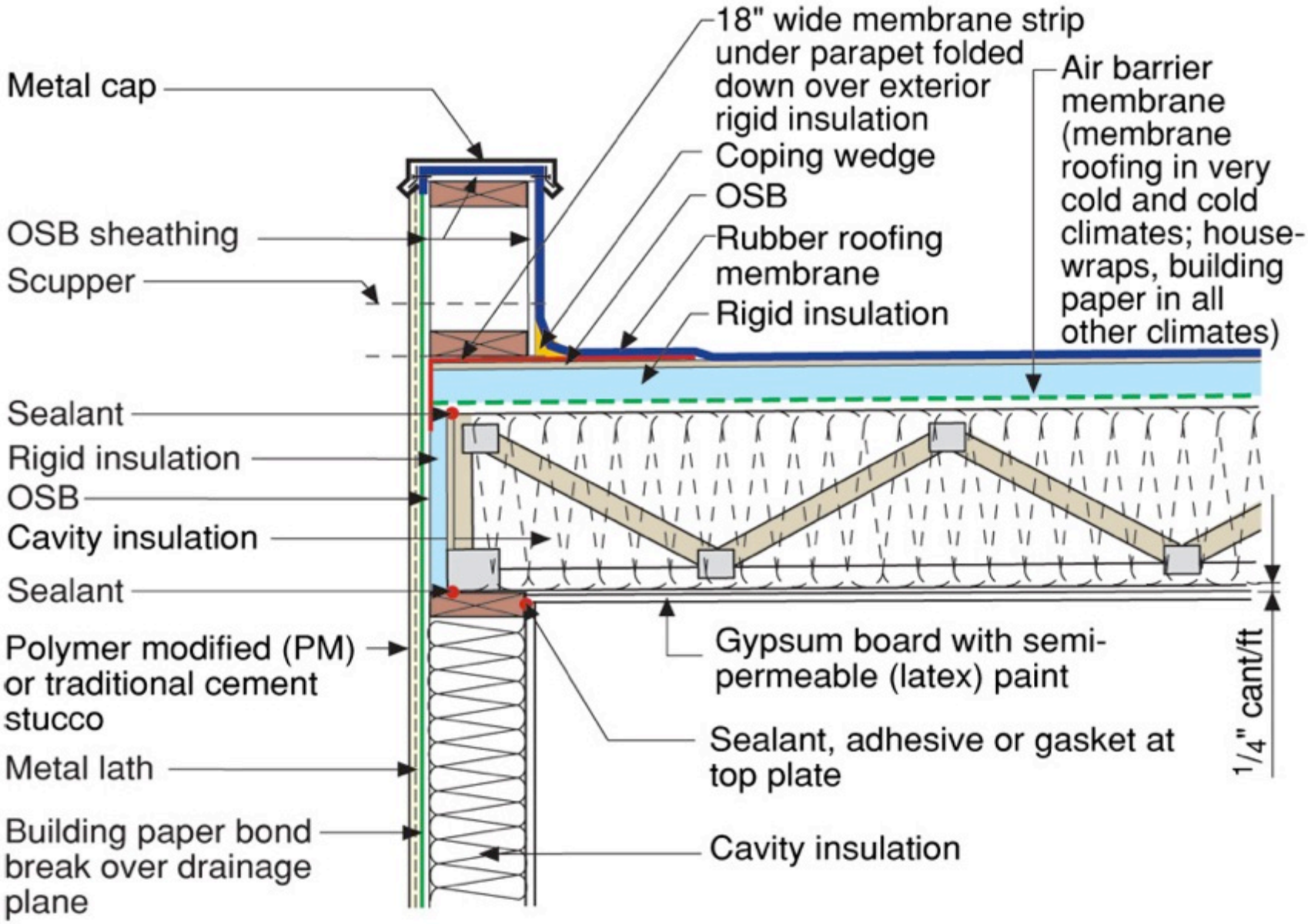
Climate Zone	Rigid Board or Air Impermeable Insulation	Code Required R-Value	Ratio of Rigid Board Insulation or Air Impermeable R-Value to Total Insulation R-Value
1,2,3	R-5	R-38	10%
4C	R-10	R-49	20%
4A, 4B	R-15	R-49	30%
5	R-20	R-49	40%
6	R-25	R-49	50%
7	R-30	R-49	60%
8	R-35	R-49	70%

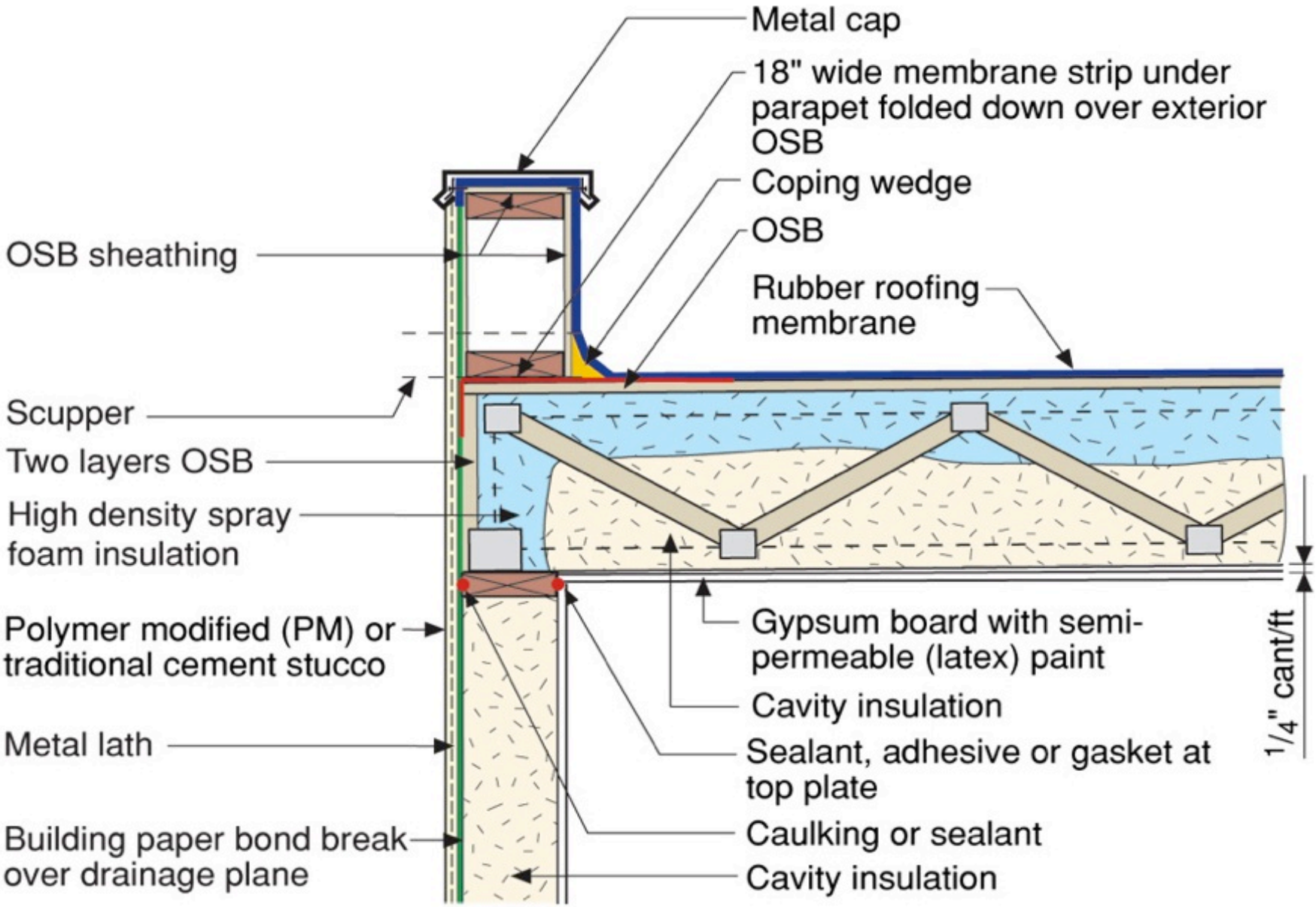
*Adapted from Table R 806.5 2015 International Residential Code

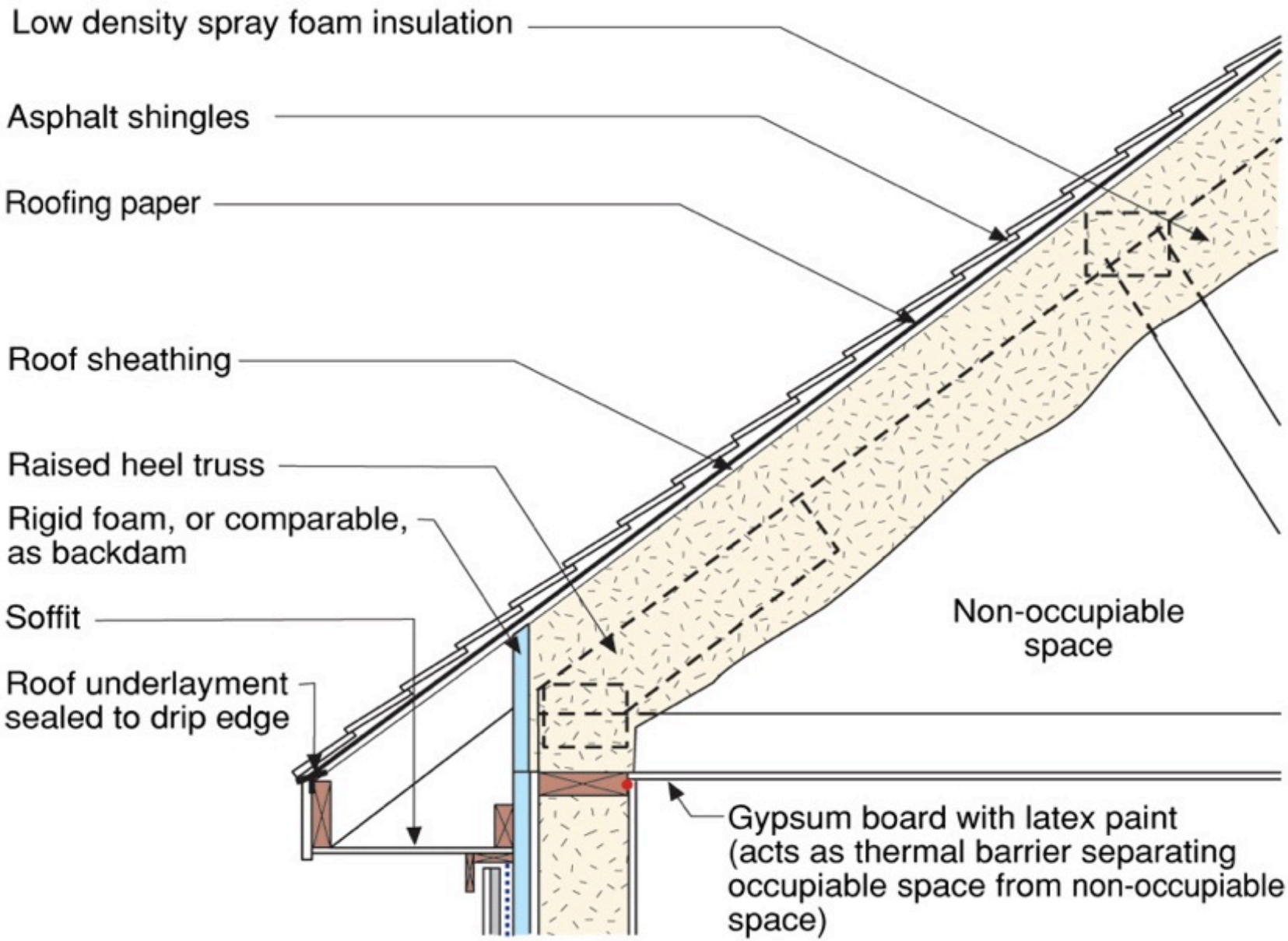
Table 1

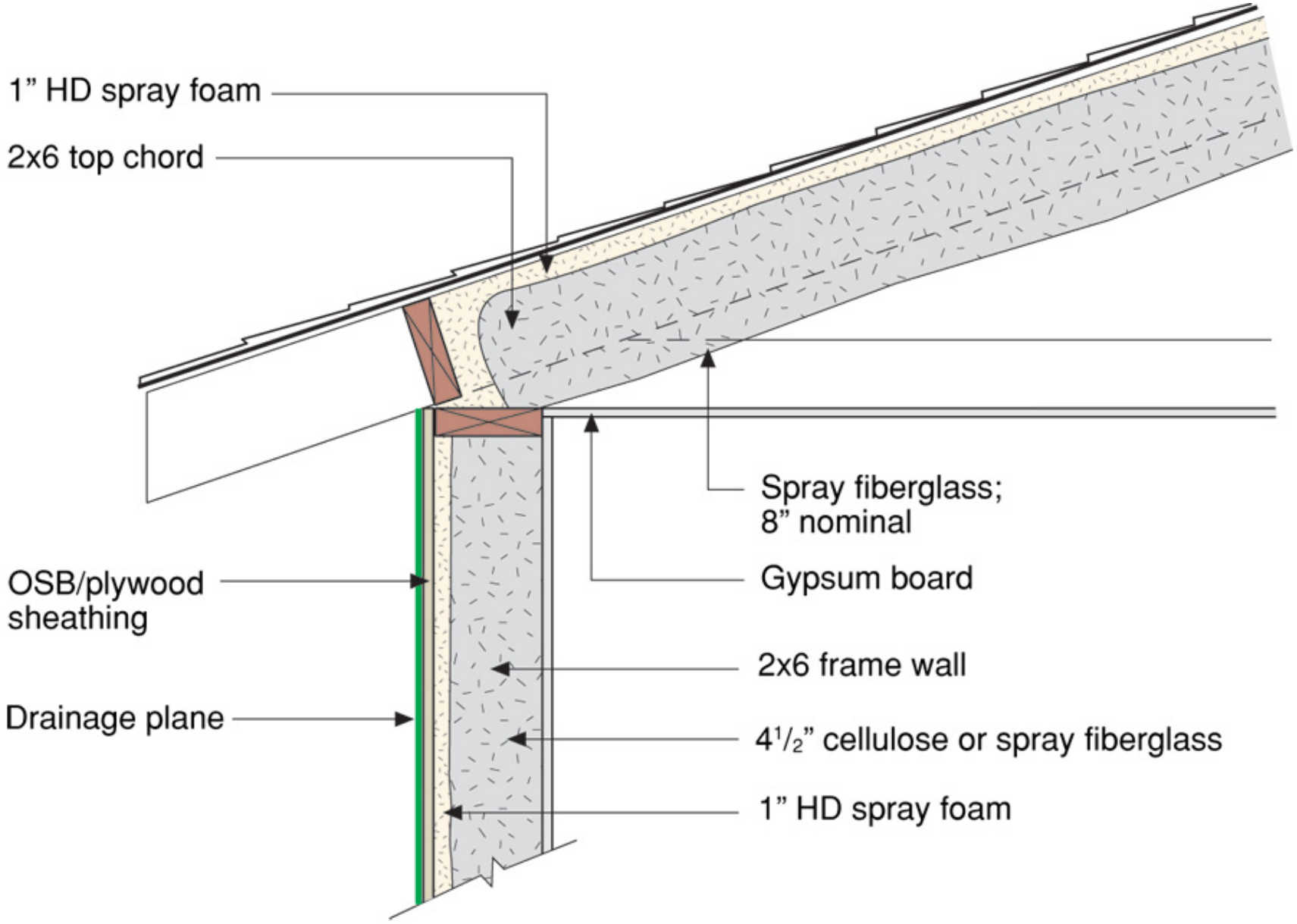

FOAMULAR
OWENS CORNING

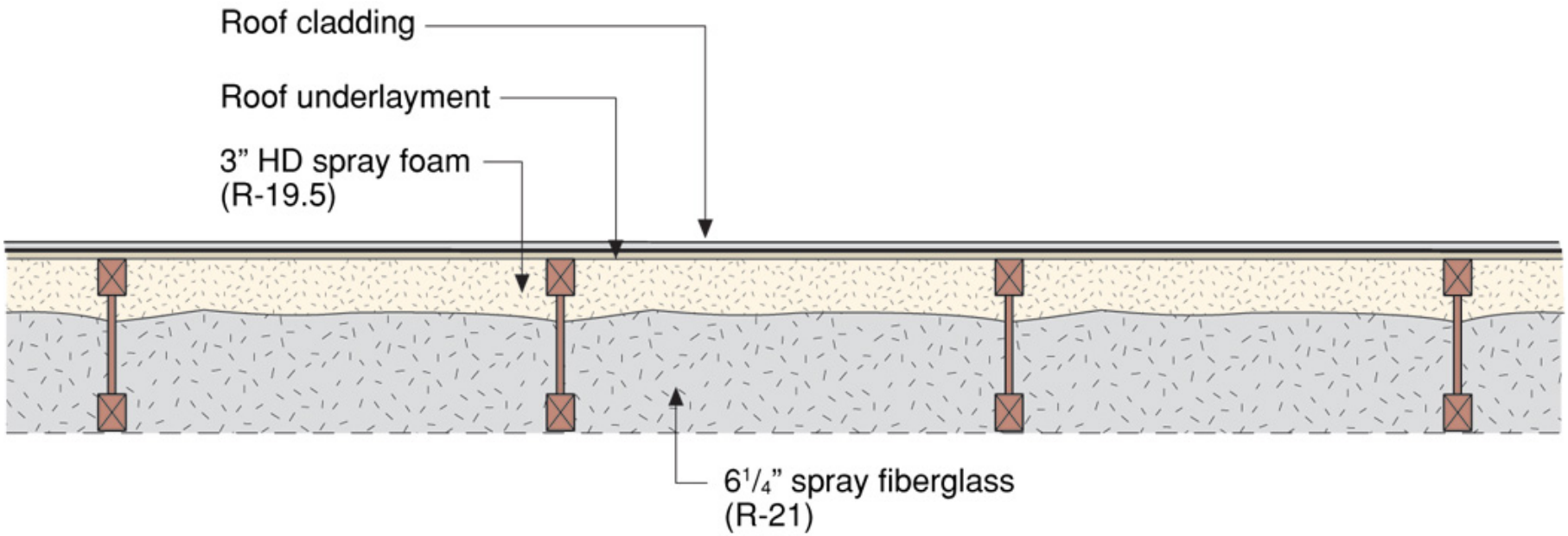

Roofing tile
Roofing paper
Netted cellulose insulation or batt insulation installed with wire stays or twine
Roof sheathing
Underside of roof sheathing is typically the “first” condensing surface
Stucco
Rigid insulation
Building paper drainage plane
Unfaced batt insulation
Gypsum board with vapor semi-permeable (latex) paint


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

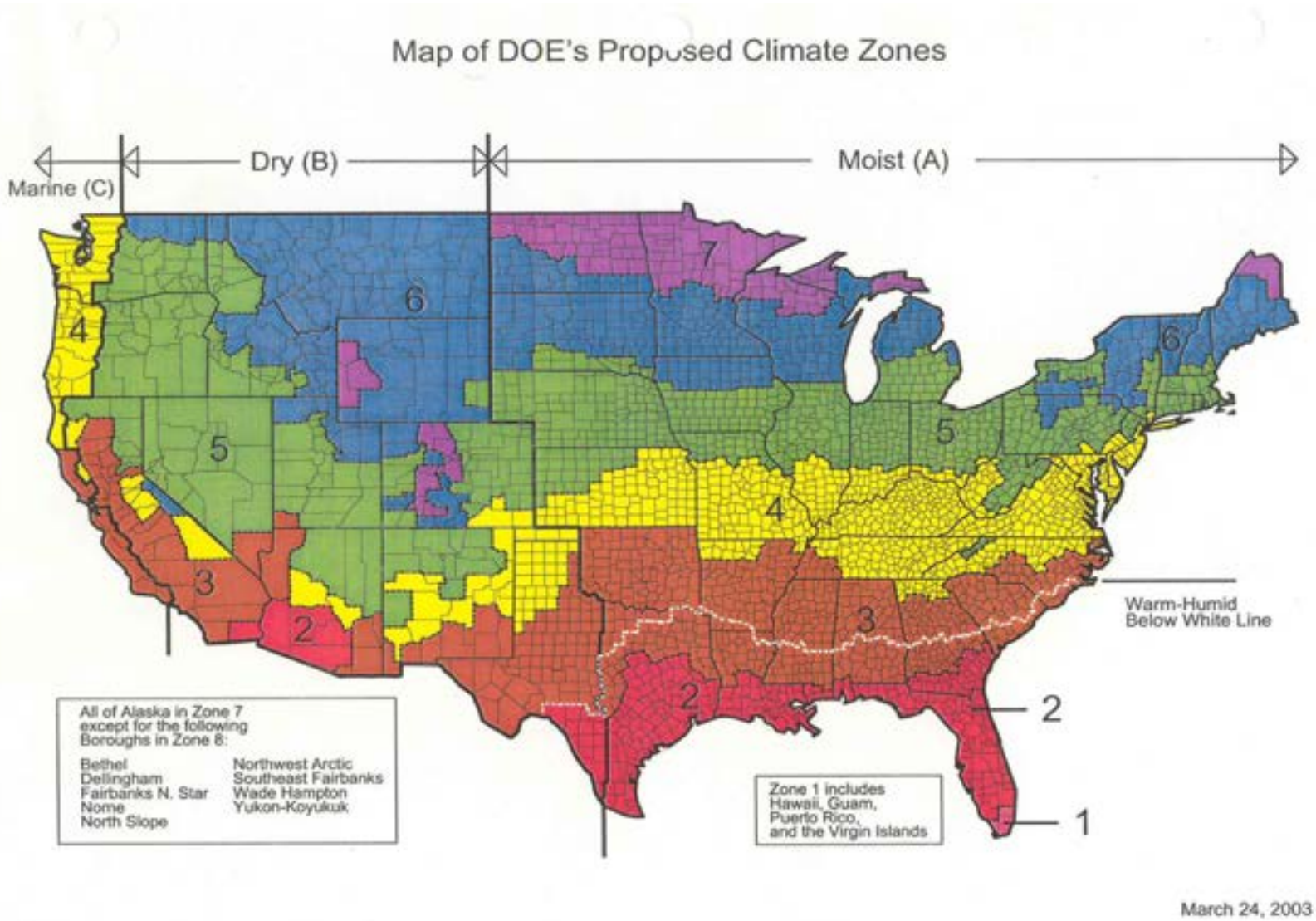

Low density spray foam insulation
Asphalt shingles
Roofing paper
Roof sheathing
Raised heel truss
Rigid foam, or comparable, as backdam
Soffit
Roof underlayment sealed to drip edge
Non-occupiable space
Gypsum board with latex paint (acts as thermal barrier separating occupiable space from non-occupiable space)


1” HD spray foam
2x6 top chord
Spray fiberglass;
8” nominal
Gypsum board
OSB/plywood
sheathing
2x6 frame wall
Drainage plane
4 1/2” cellulose or spray fiberglass
1” HD spray foam

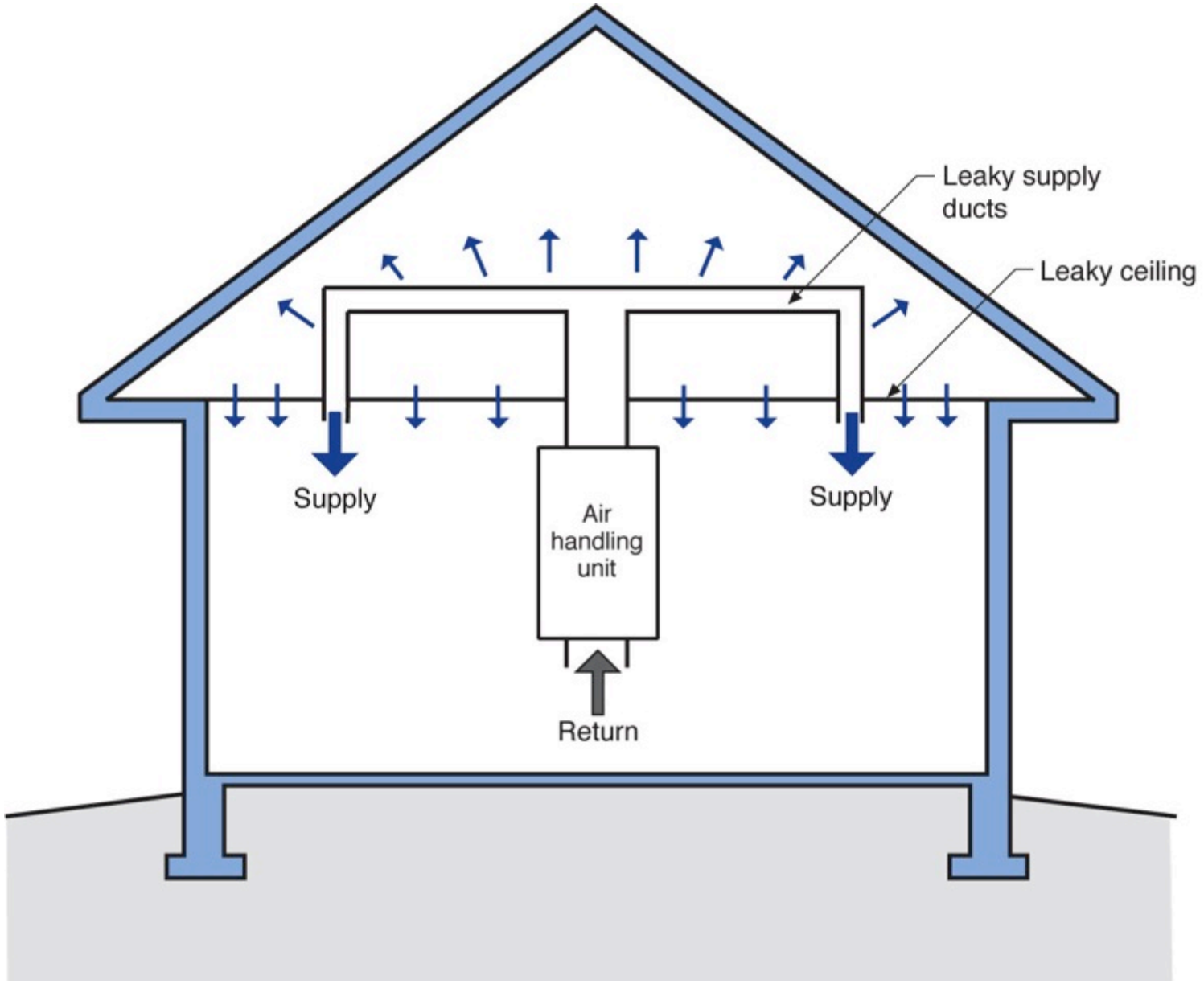

Roof cladding
Roof underlayment
3” HD spray foam
(R-19.5)
6¼” spray fiberglass
(R-21)


GRACE
Ice & Water Shield
TRI-FLEX 30
APR 20 2004


APR 20 2004


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

Conditioned Attics Not Unvented Attics


Leaky supply ducts
Leaky ceiling
Supply
Supply
Air handling unit
Return

Conditioned Attics Not Unvented Attics

Need Supply Air

Conditioned Attics Not Unvented Attics

Need Supply Air

50 cfm/1000 ft2 of Attic

Hygric Buoyancy

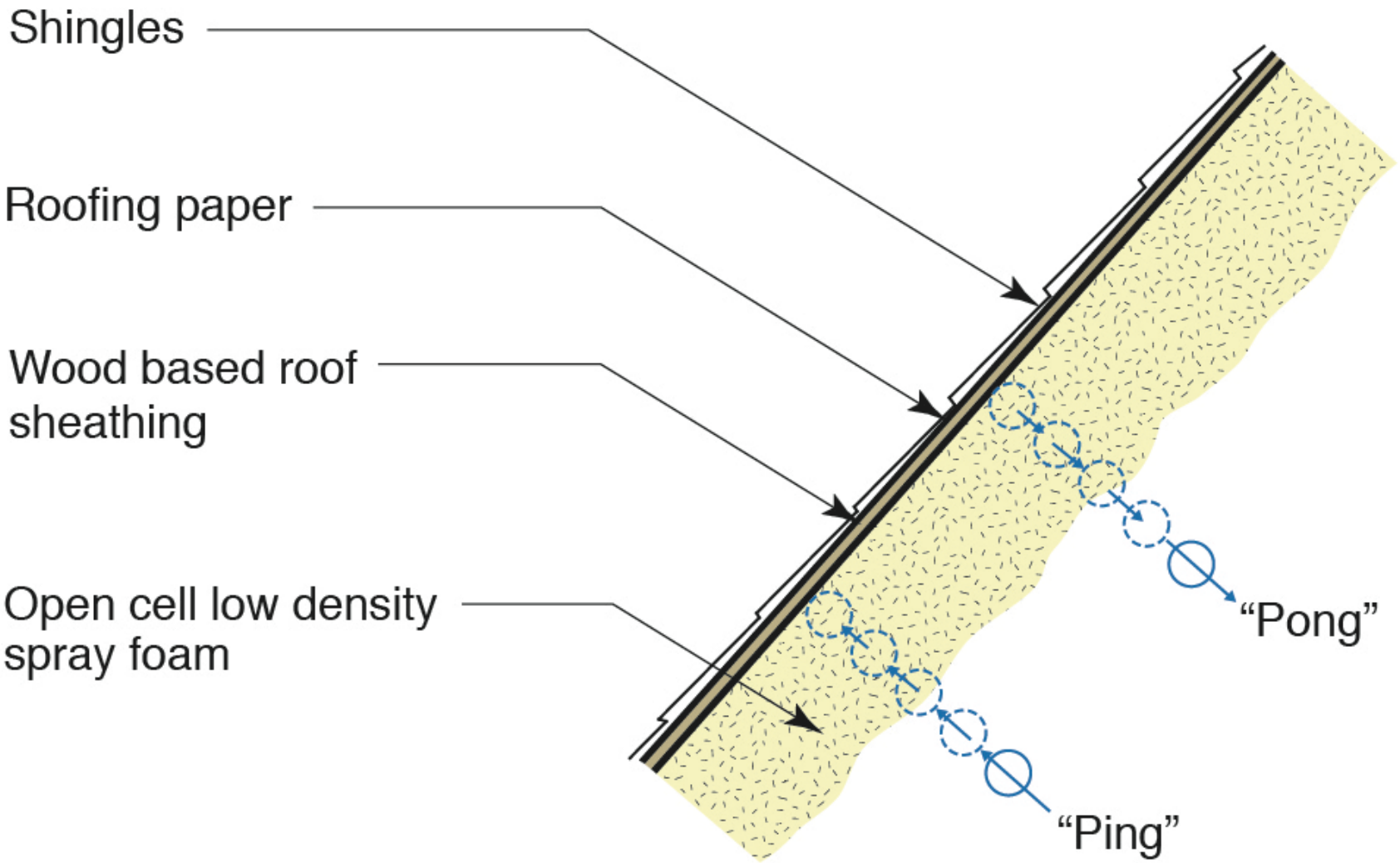
Components in Dry Air	Volume Ratio compared to Dry Air	Molecular Mass - *M* *(kg/kmol)*	Molecular Mass in Air
Oxygen	0.2095	32.00	6.704
Nitrogen	0.7809	28.02	21.88
Carbon Dioxide	0.0003	44.01	0.013
Hydrogen	0.0000005	2.02	0
Argon	0.00933	39.94	0.373
Neon	0.000018	20.18	0
Helium	0.000005	4.00	0
Krypton	0.000001	83.8	0
Xenon	$0.09\ 10^{-6}$	131.29	0
Total Molecular Mass of Air			28.97

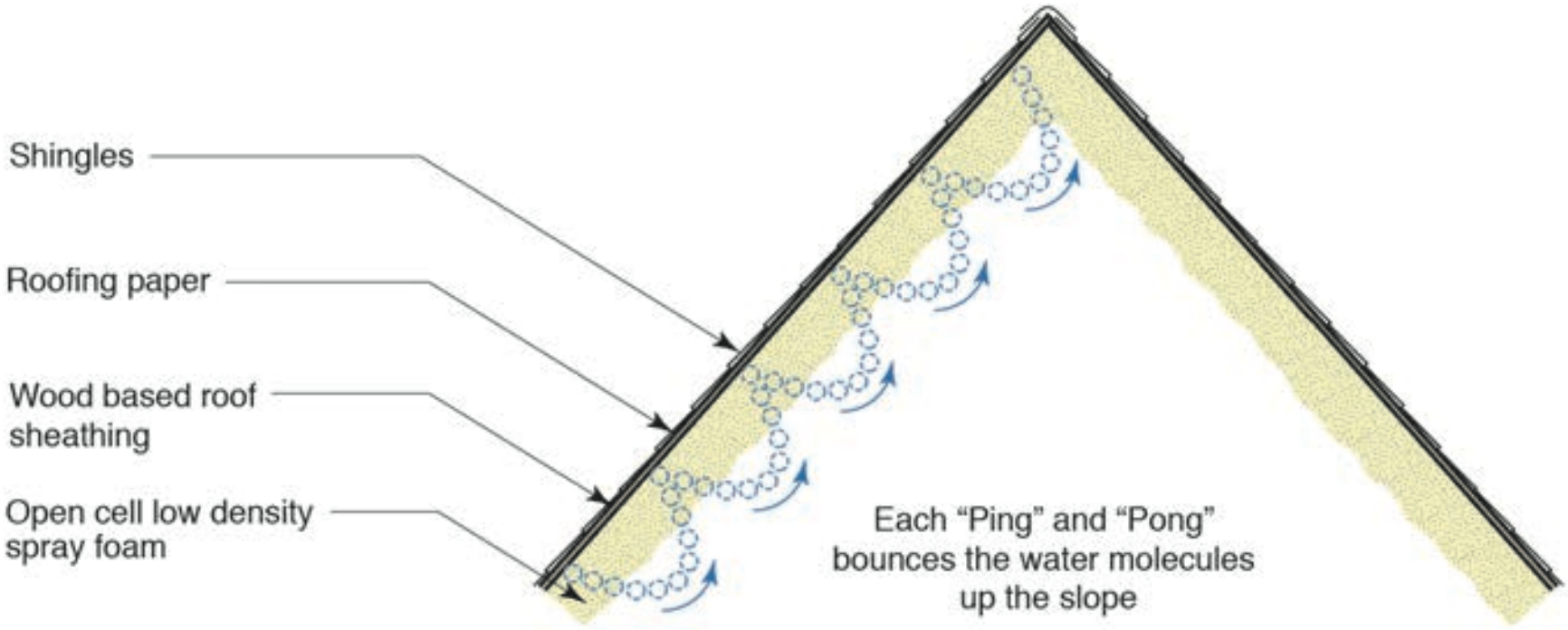
Components in Dry Air	Volume Ratio compared to Dry Air	Molecular Mass - *M* *(kg/kmol)*	Molecular Mass in Air
Oxygen	0.2095	32.00	6.704
Nitrogen	0.7809	28.02	21.88
Carbon Dioxide	0.0003	44.01	0.013
Hydrogen	0.0000005	2.02	0
Argon	0.00933	39.94	0.373
Neon	0.000018	20.18	0
Helium	0.000005	4.00	0
Krypton	0.000001	83.8	0
Xenon	$0.09\ 10^{-6}$	131.29	0
Total Molecular Mass of Air			28.97

Note Water Vapor (H_2O) is 18

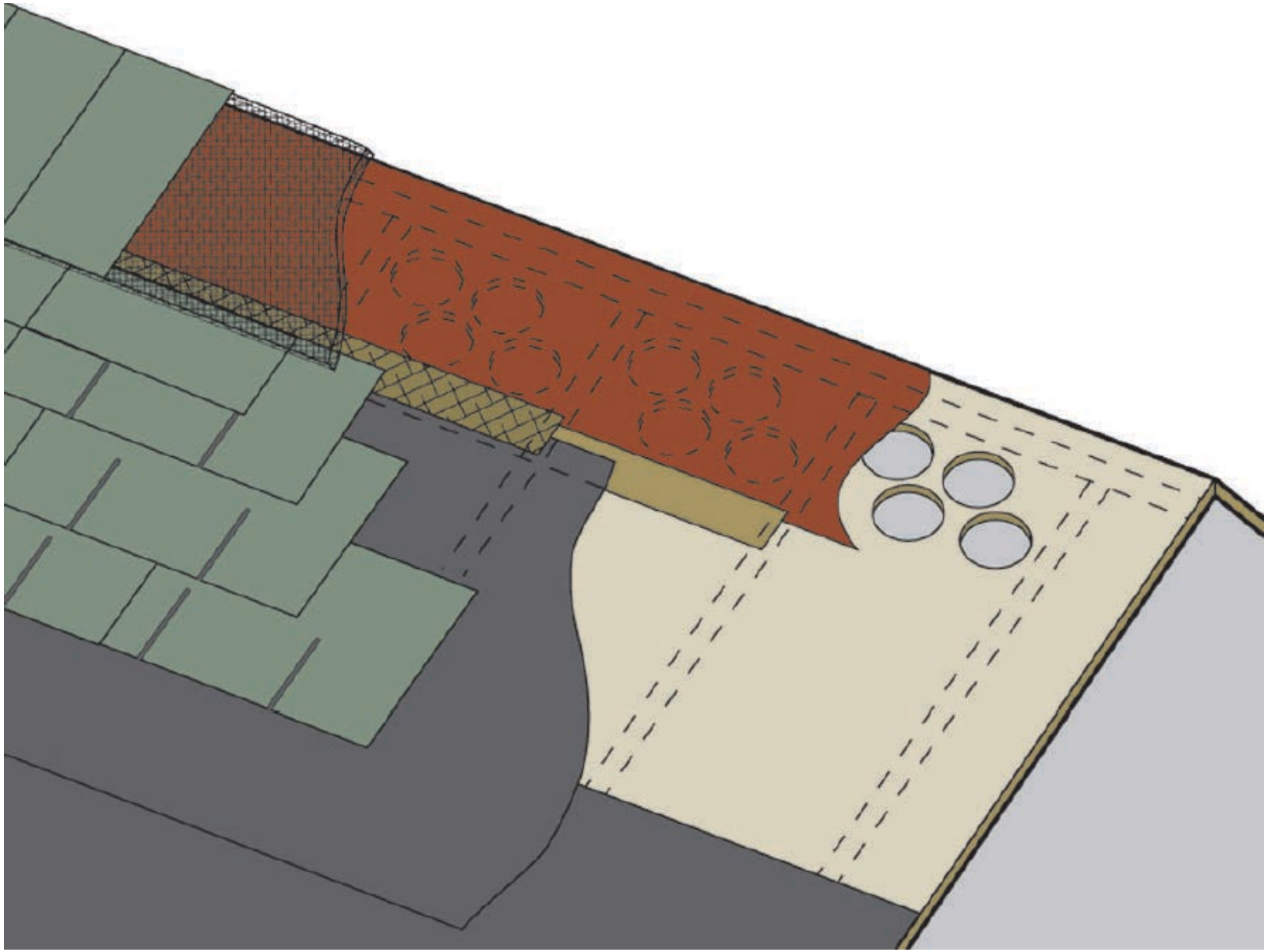
Dry Air is 29

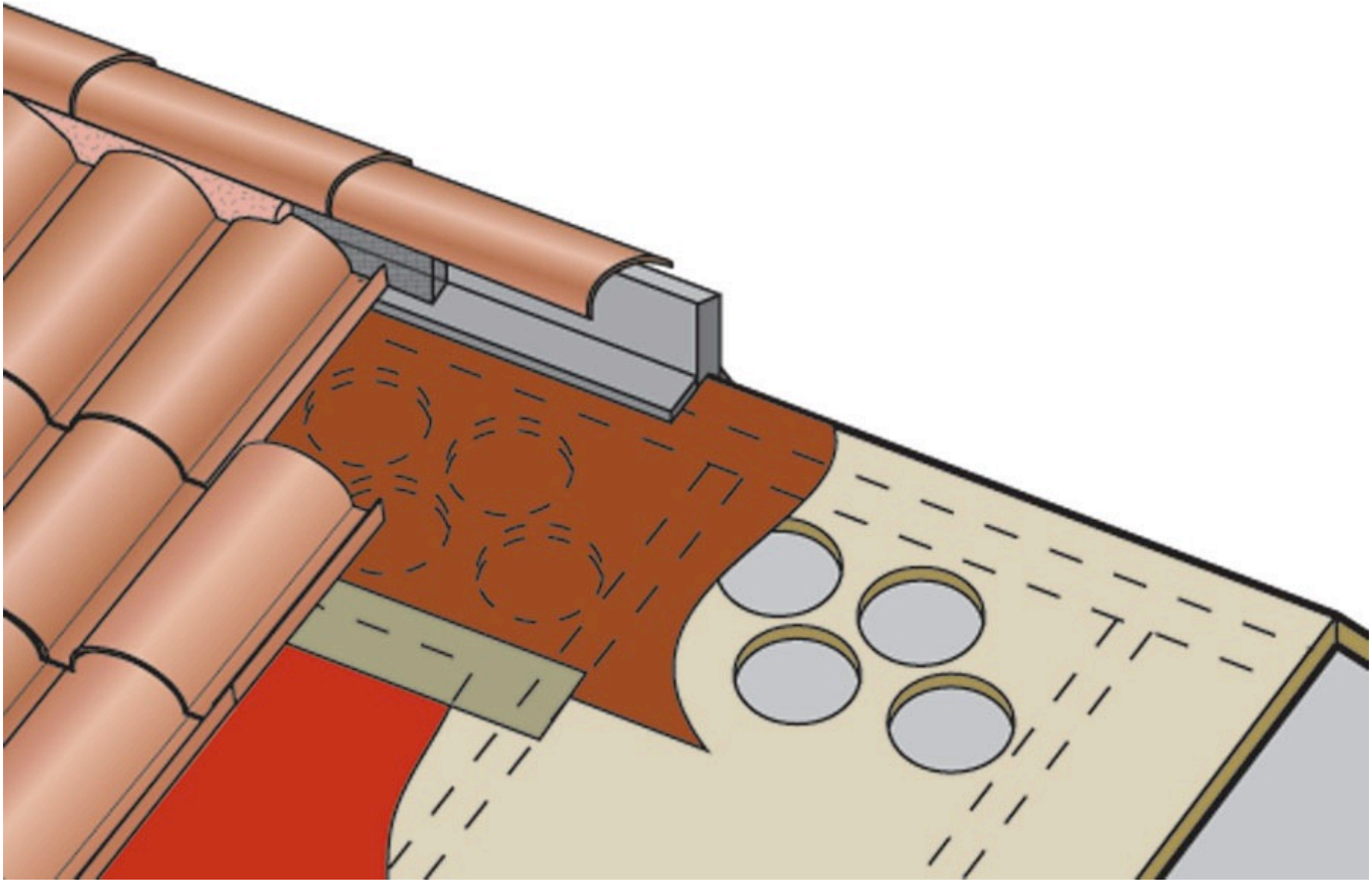

Dual In-Duct
Psychrometer
Fieldpiece
SDP2

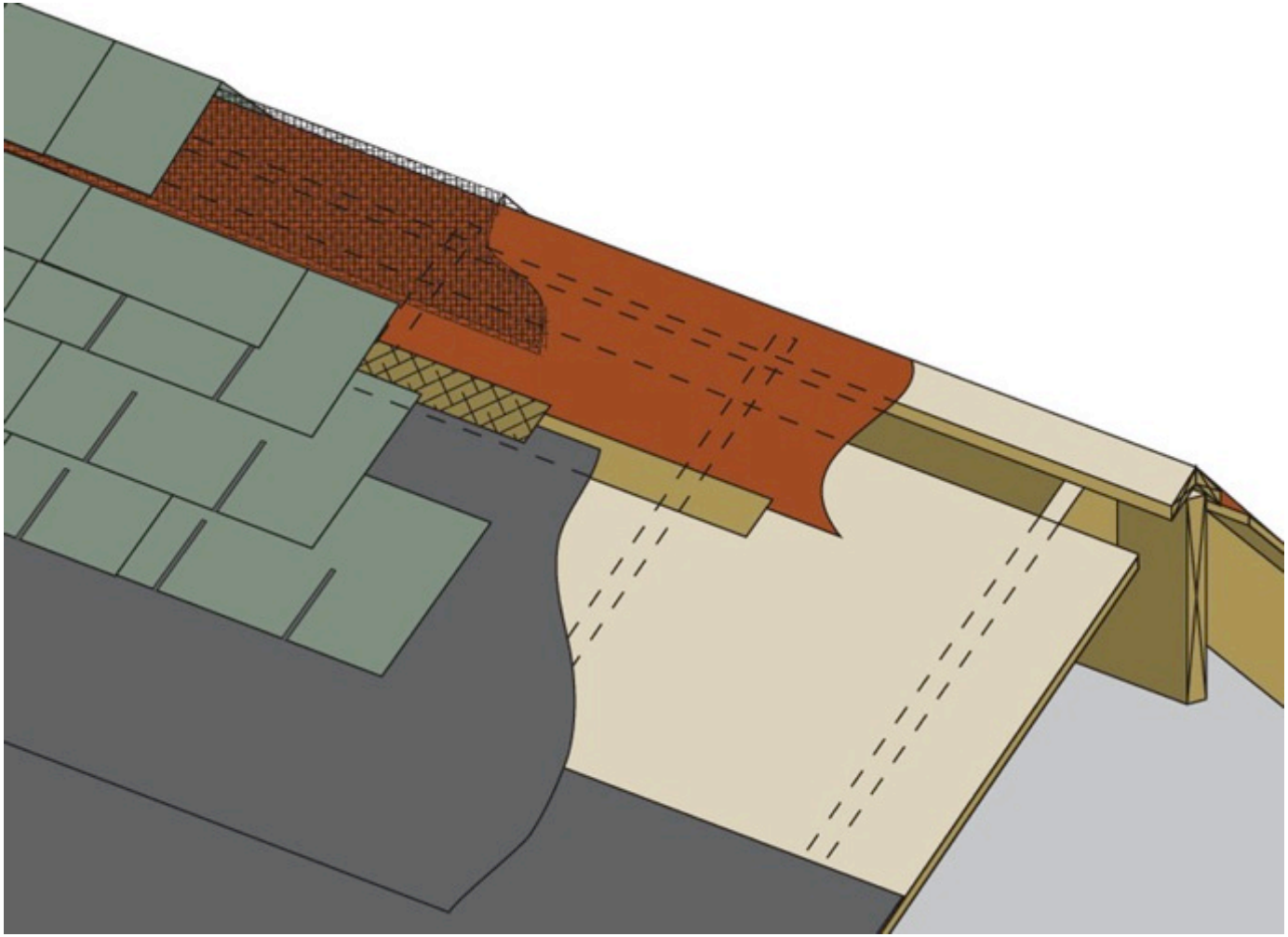

Shingles
Roofing paper
Wood based roof sheathing
Open cell low density spray foam
"Pong"
"Ping"

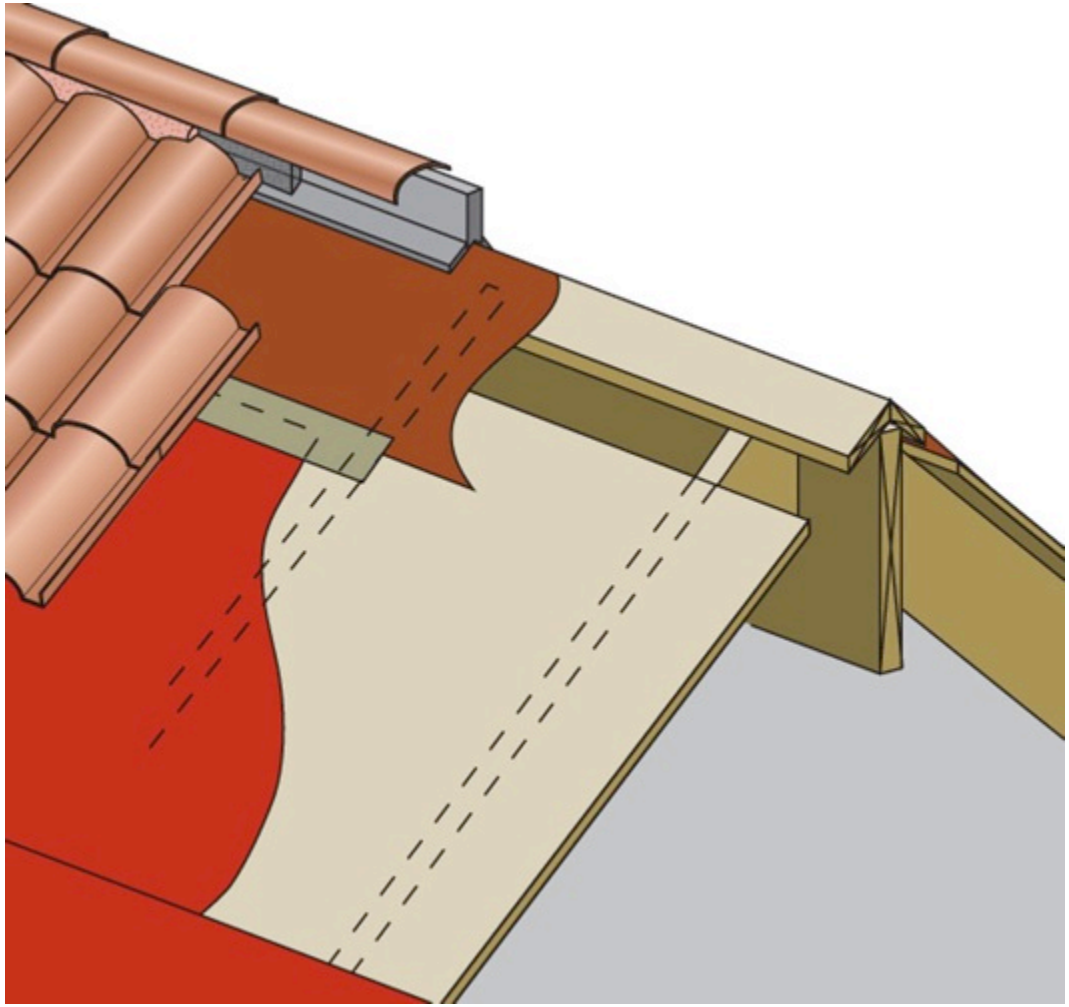

Shingles
Roofing paper
Wood based roof sheathing
Open cell low density spray foam
Each "Ping" and "Pong" bounces the water molecules up the slope


R-30
PROPINK
High Performance
Attic System
OWENS CORNING
R-30
PROPINK
High Performance
Attic System










R-30
R-30


3M


DELTA
DELTA
DELTA

Code Change

R806.5 Unvented attic and unvented attic enclosed rafter assemblies.

- vapor diffusion port
- port area 1:600 of the ceiling area
- vapor permeance greater than 20 perms
- roof slope greater than 3:12
- insulation under the roof deck or at the ceiling
- air supply 50 cfm/1000 ft2 ceiling area when insulation installed directly under the roof deck
- Climate Zones 1, 2 and 3

Vapor Diffusion Port: A passageway for conveying water vapor from an unvented attic to the atmosphere.

Sweating Ducts

Sweating Ducts

Light Colored Roofs

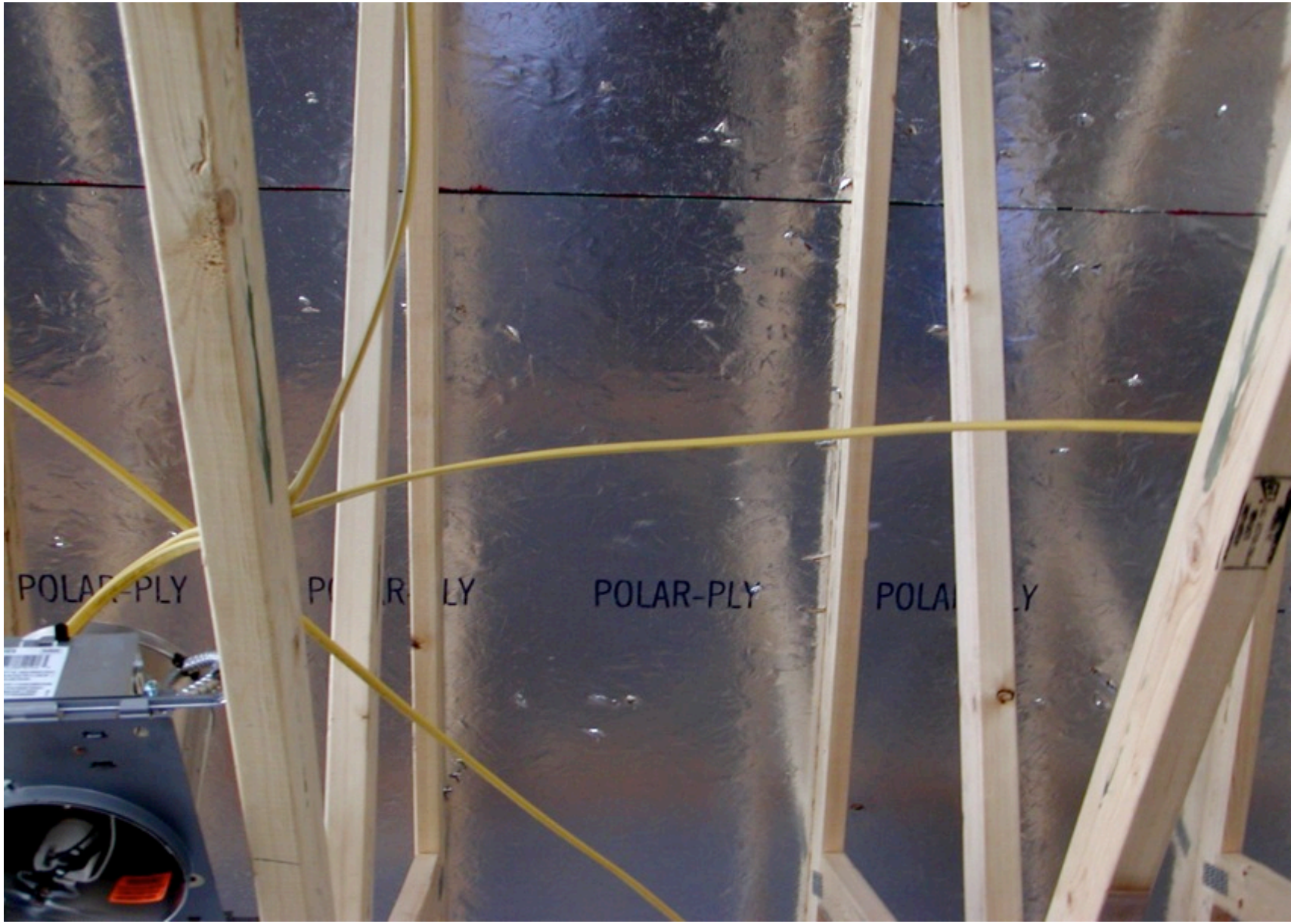
Cool Roofs

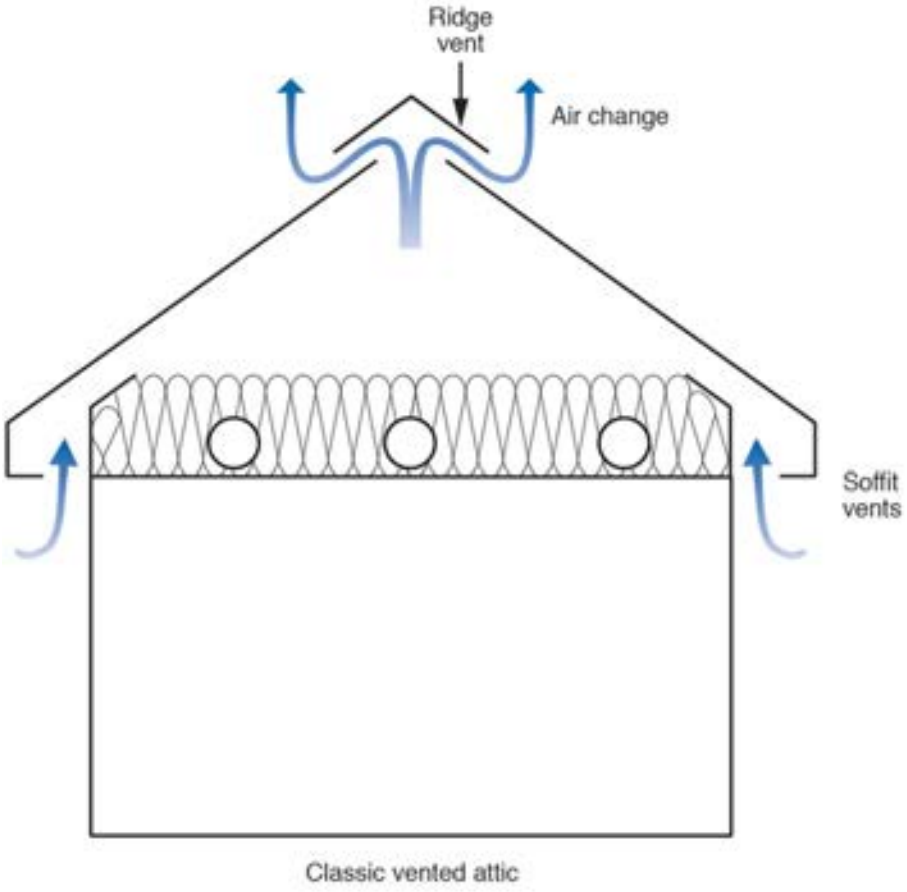
Radiant Barriers

ACCA Manual J, S and D

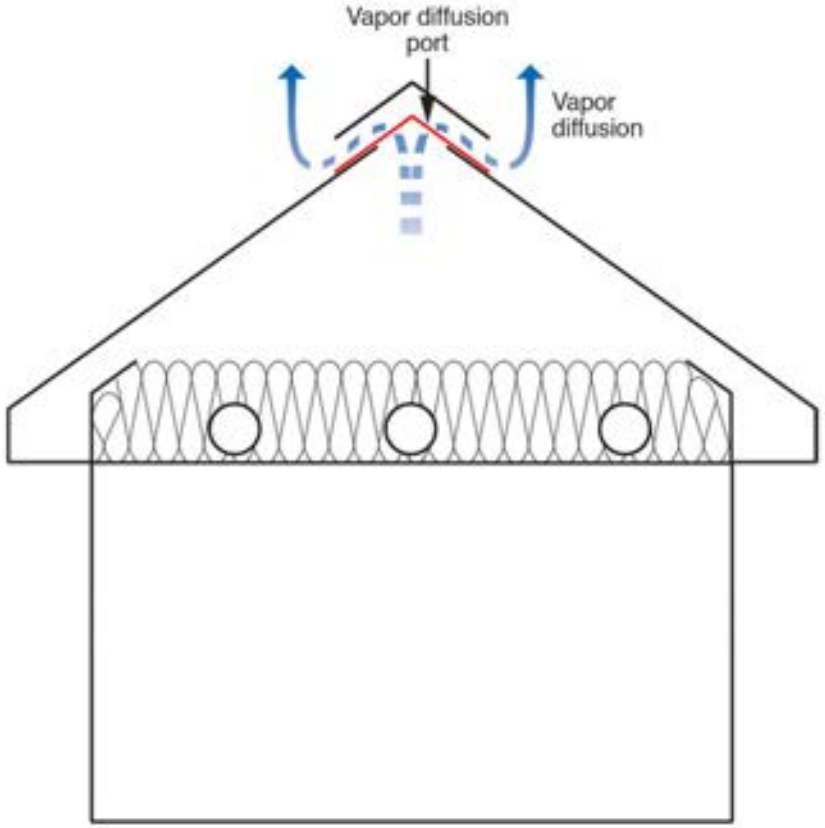
ASHRAE 62.2

Ductwork Attic Dehumidification System


POLAR-PLY
POLAR-PLY

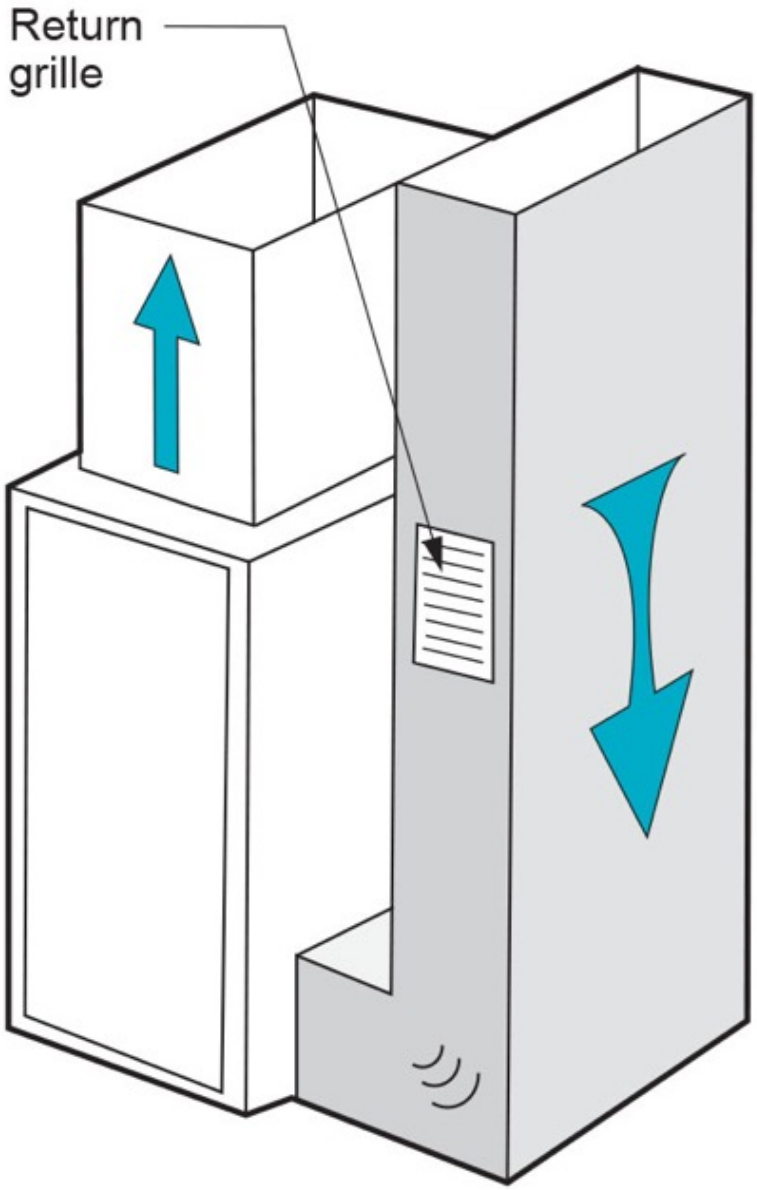


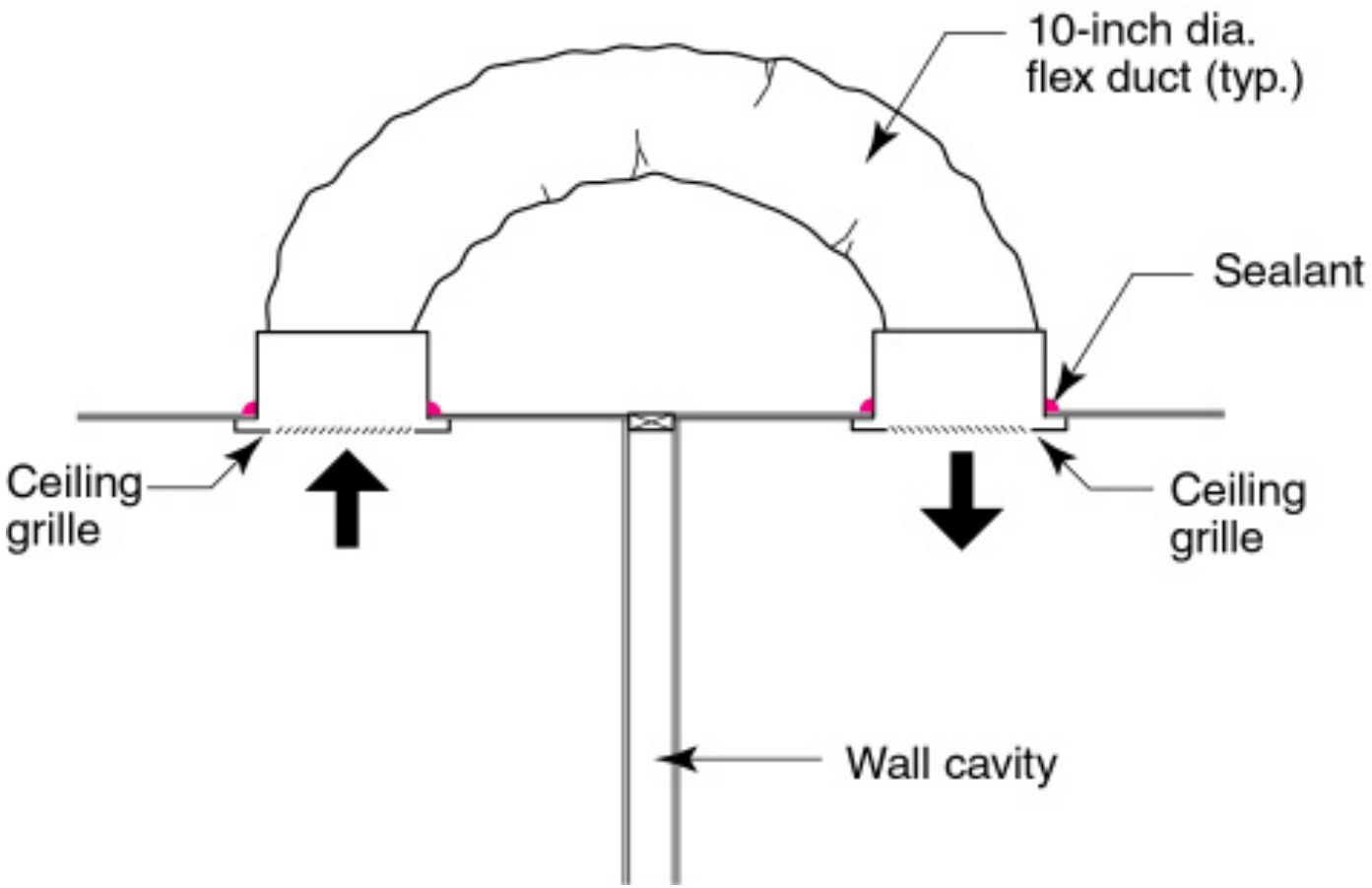
Classic vented attic

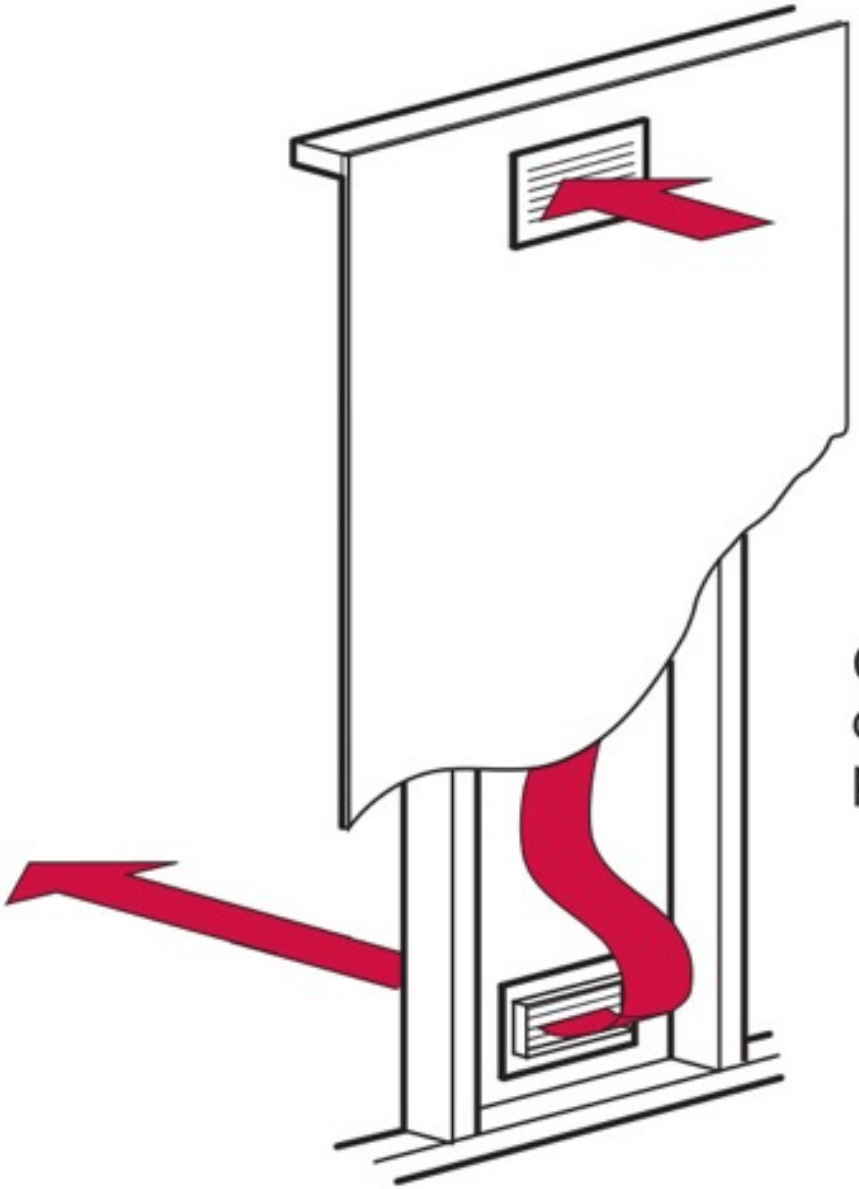


Unvented attic with vapor diffusion port

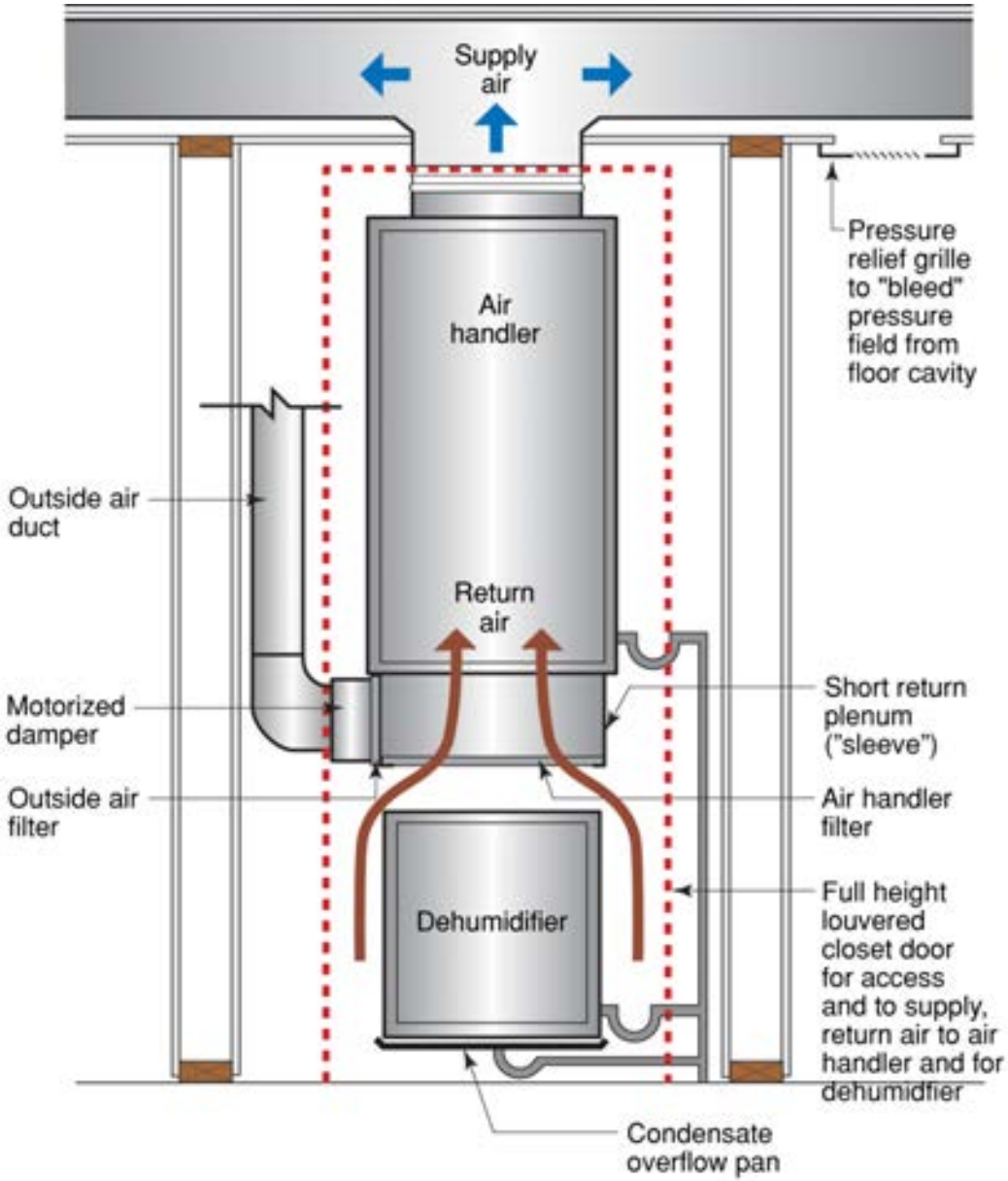

09/14
AF 100
1818-FX

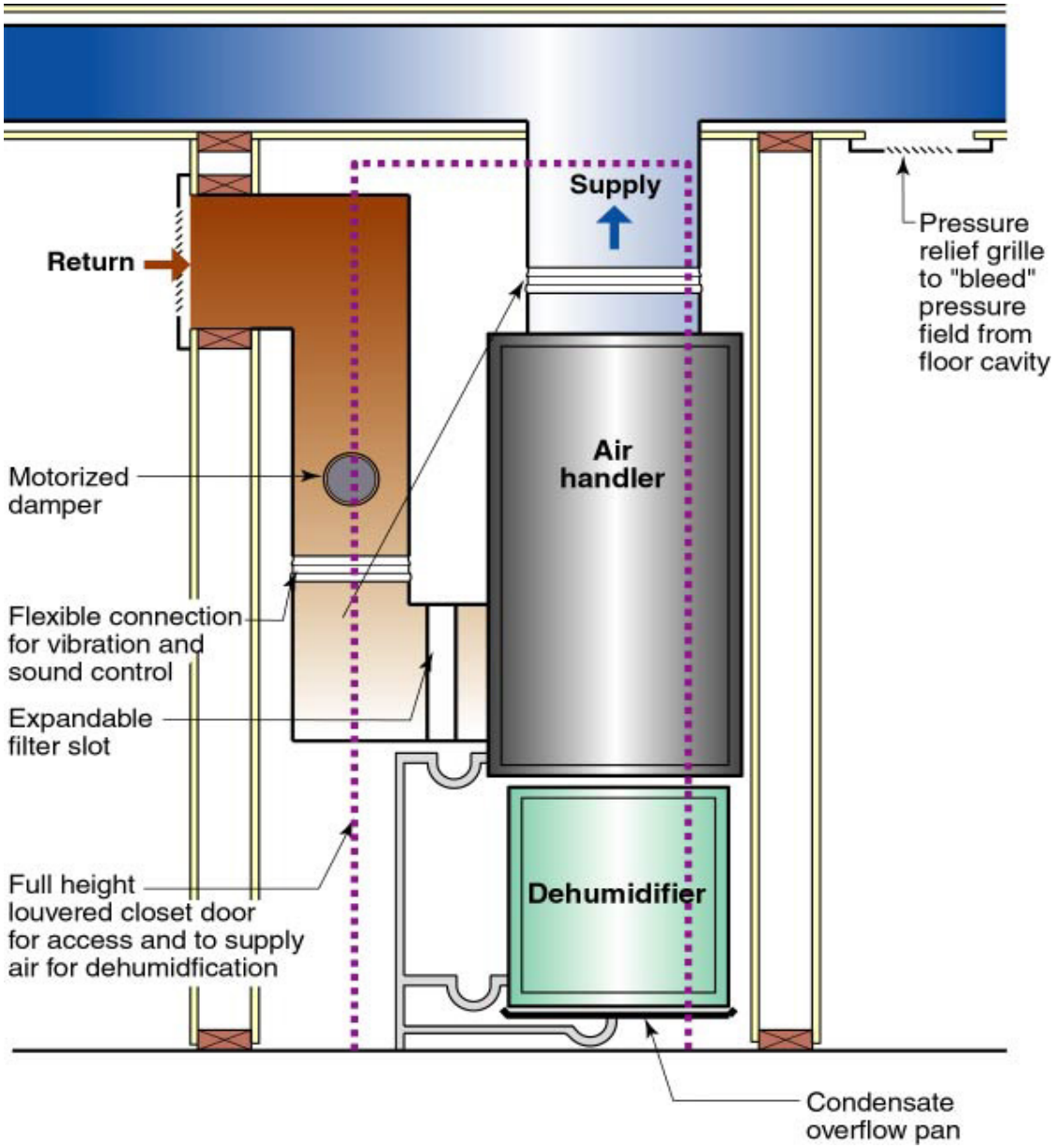

Return
grille

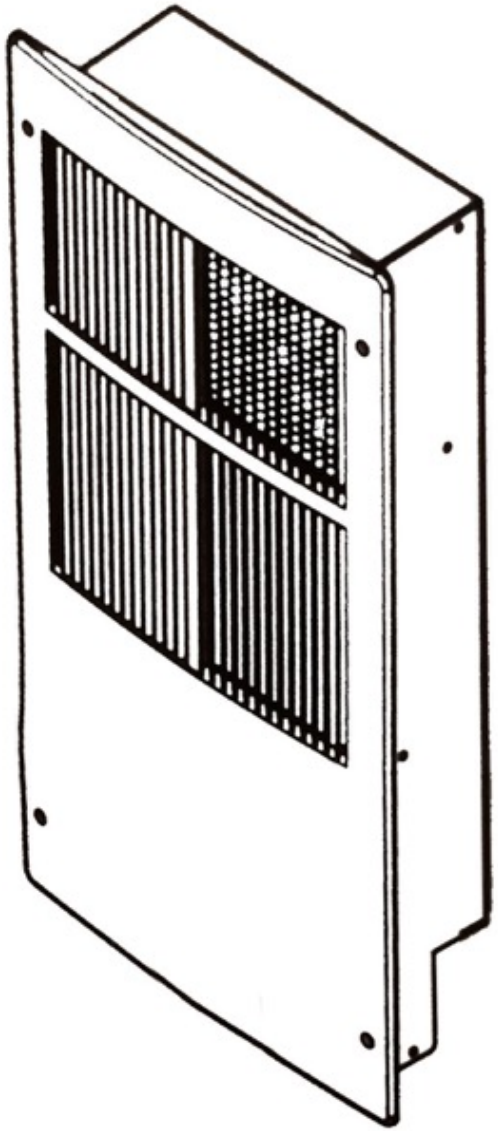

10-inch dia.
flex duct (typ.)
Sealant
Ceiling
grille
Ceiling
grille
Wall cavity



Cavity is sealed tight, drywall glued to studs and plates on both sides


Supply air
Air handler
Pressure relief grille to "bleed" pressure field from floor cavity
Outside air duct
Return air
Motorized damper
Short return plenum ("sleeve")
Outside air filter
Air handler filter
Dehumidifier
Full height louvered closet door for access and to supply, return air to air handler and for dehumidfier
Condensate overflow pan


Supply
Return
Pressure relief grille to "bleed" pressure field from floor cavity
Air handler
Motorized damper
Flexible connection for vibration and sound control
Expandable filter slot
Full height louvered closet door for access and to supply air for dehumidfication
Dehumidifier
Condensate overflow pan



ASHRAE Standard 62.2

0.03 cfm/ft2 plus 7.5 cfm/occupant

IRC/IMC

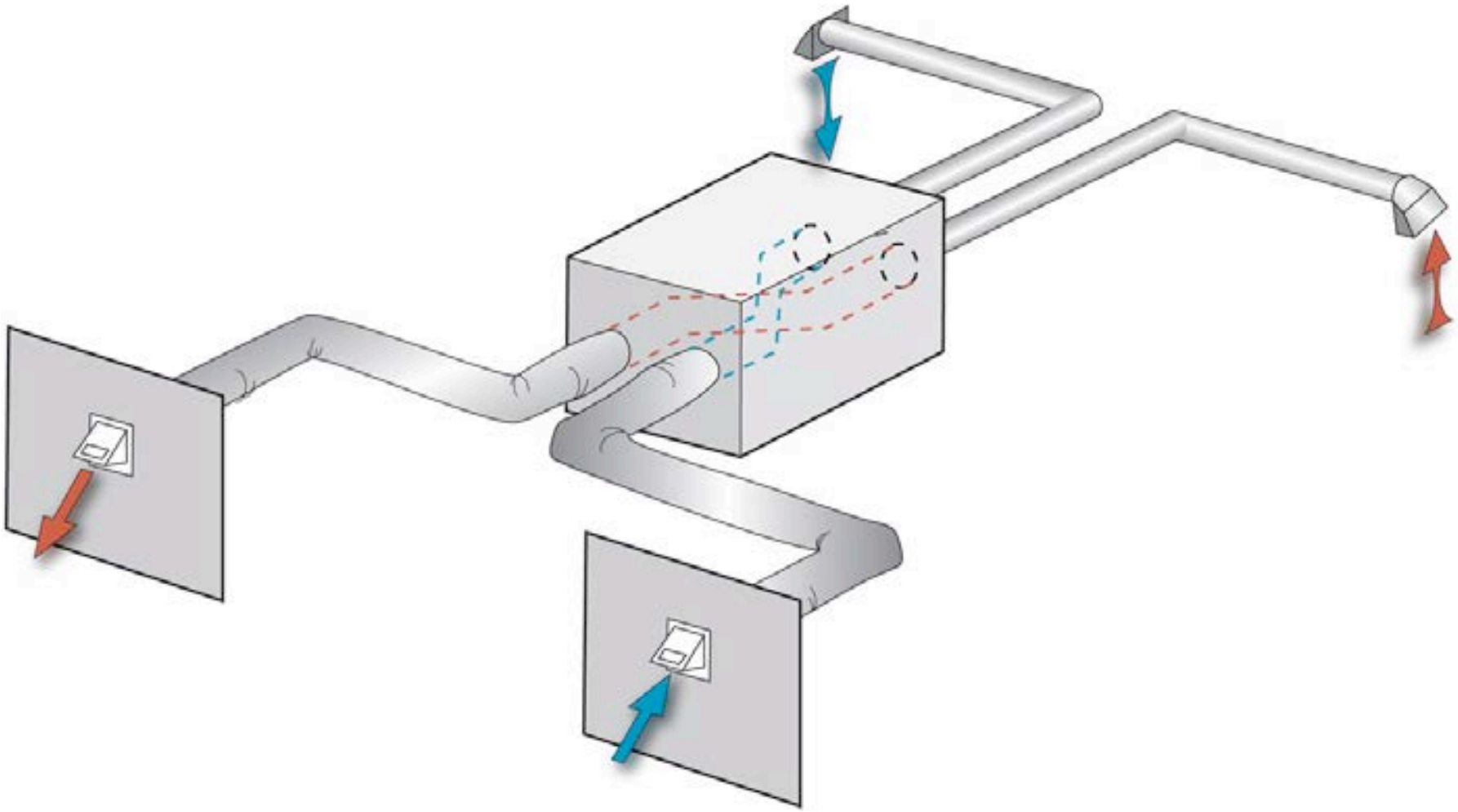
0.01 cfm/ft2 plus 7.5 cfm/occupant

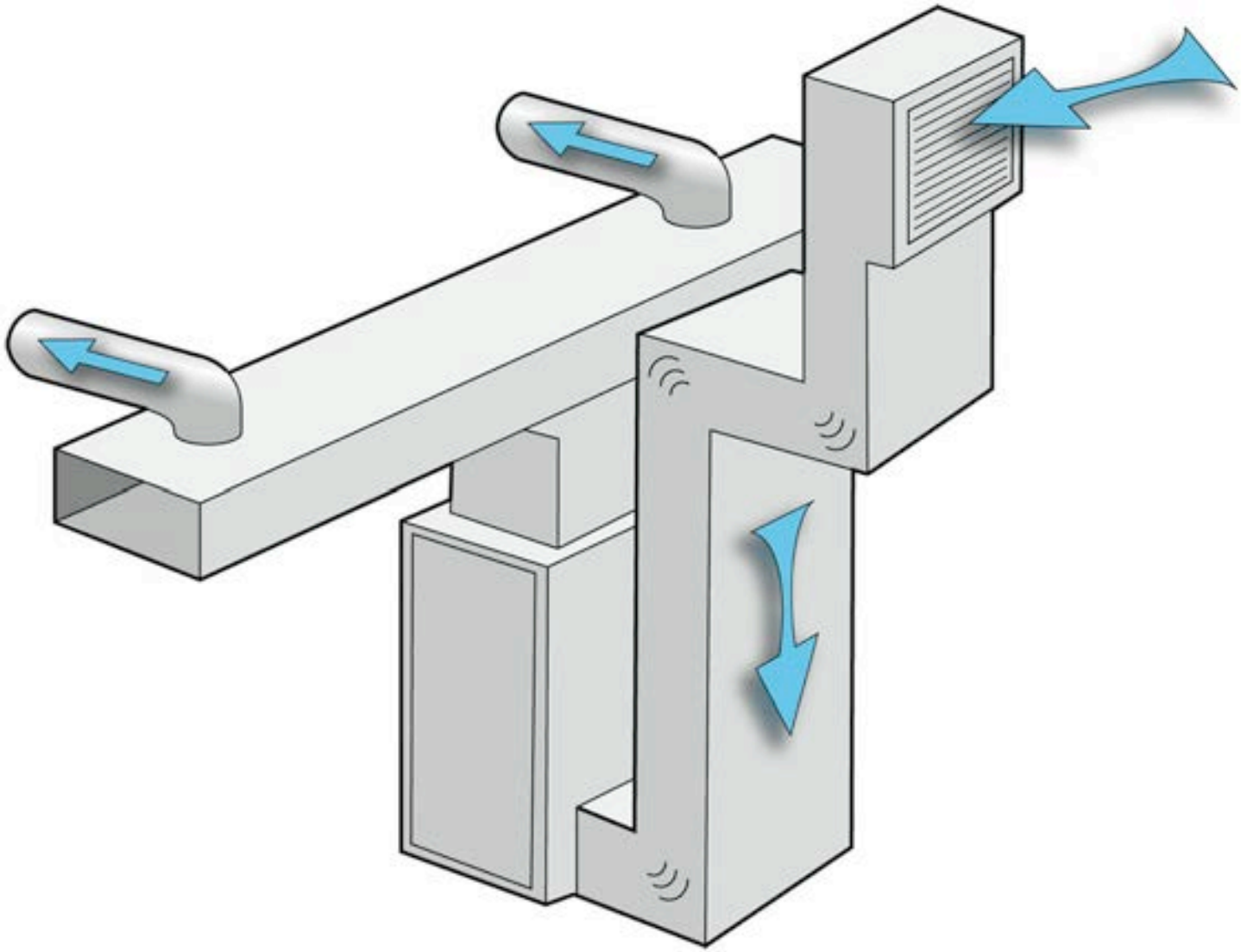
30 percent credit for balanced/distributed

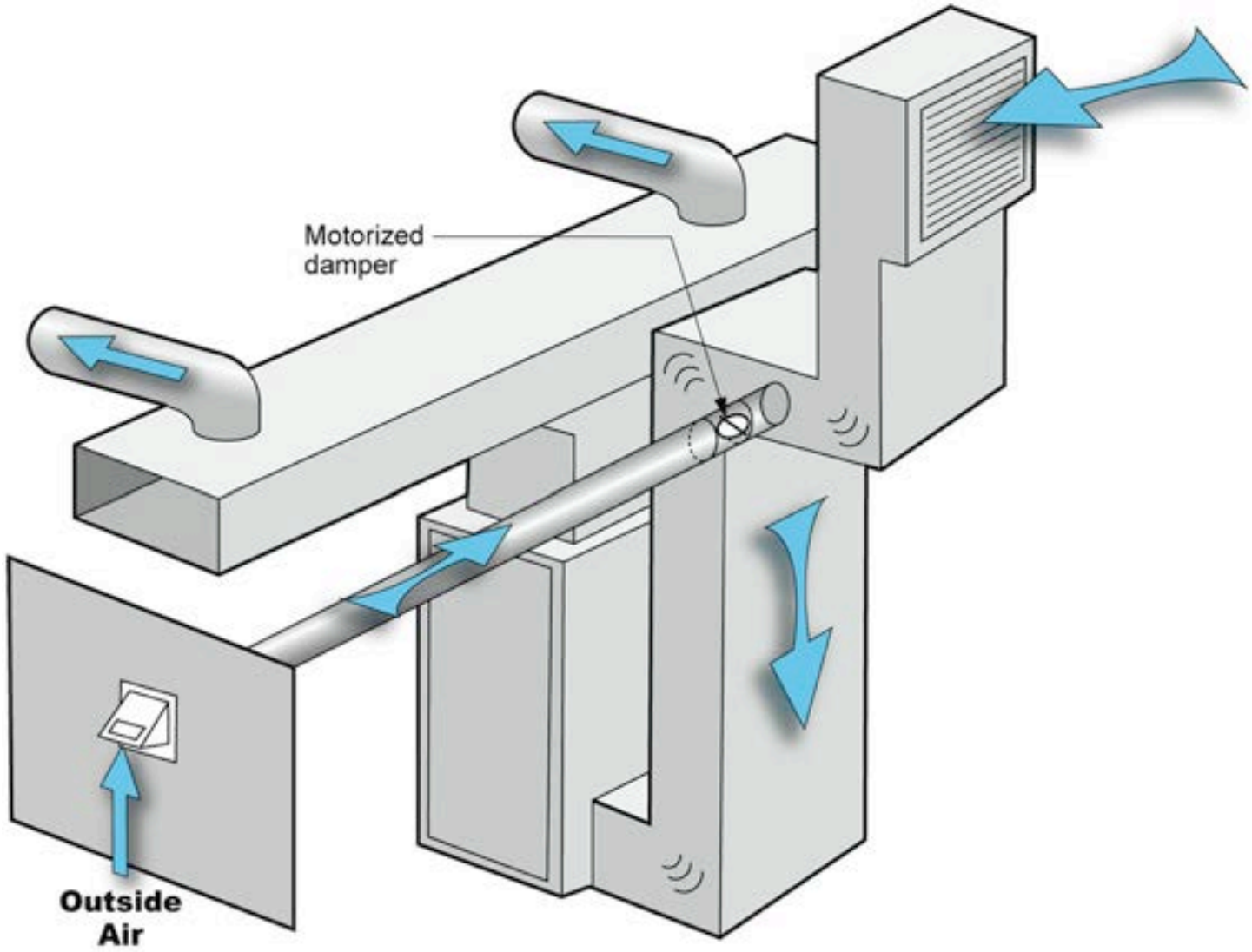
2500 ft2 3 bedroom (occupancy 4)

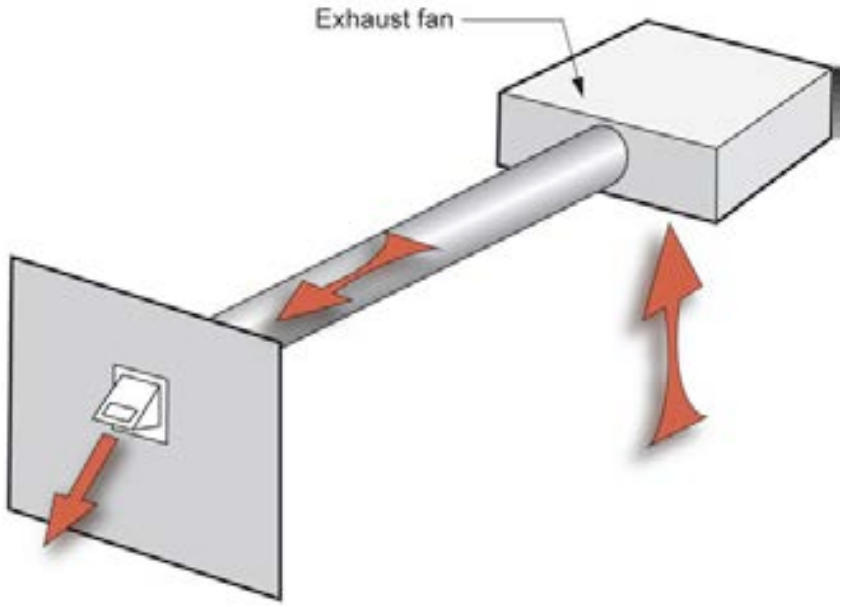
ASHRAE 75 cfm + 30 cfm = 105 cfm

IRC/IMC 25 cfm + 30 cfm = 55 cfm (or 38.5 cfm)






Motorized
damper
Outside
Air


Exhaust fan