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

Building Science

Roofs

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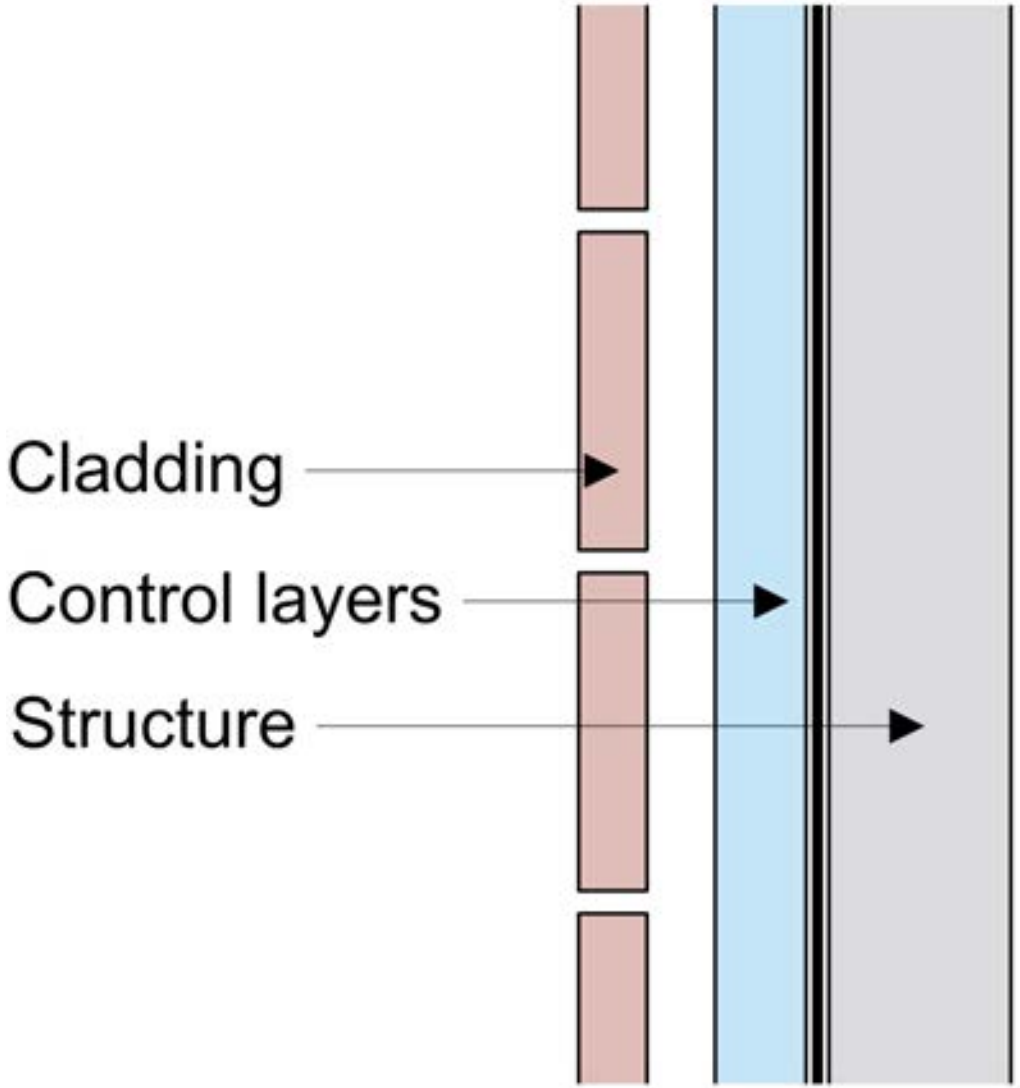
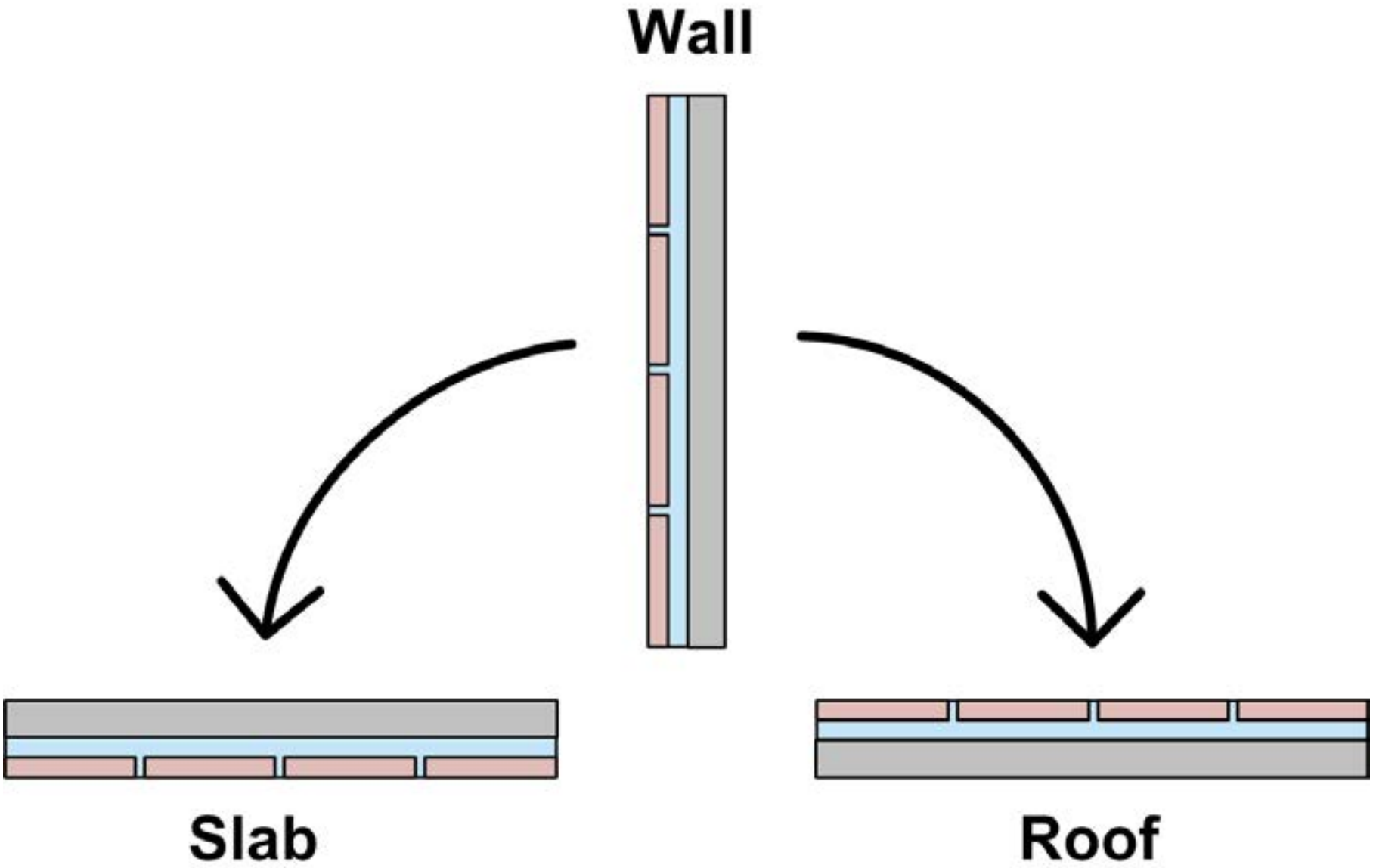
Water Control Layer

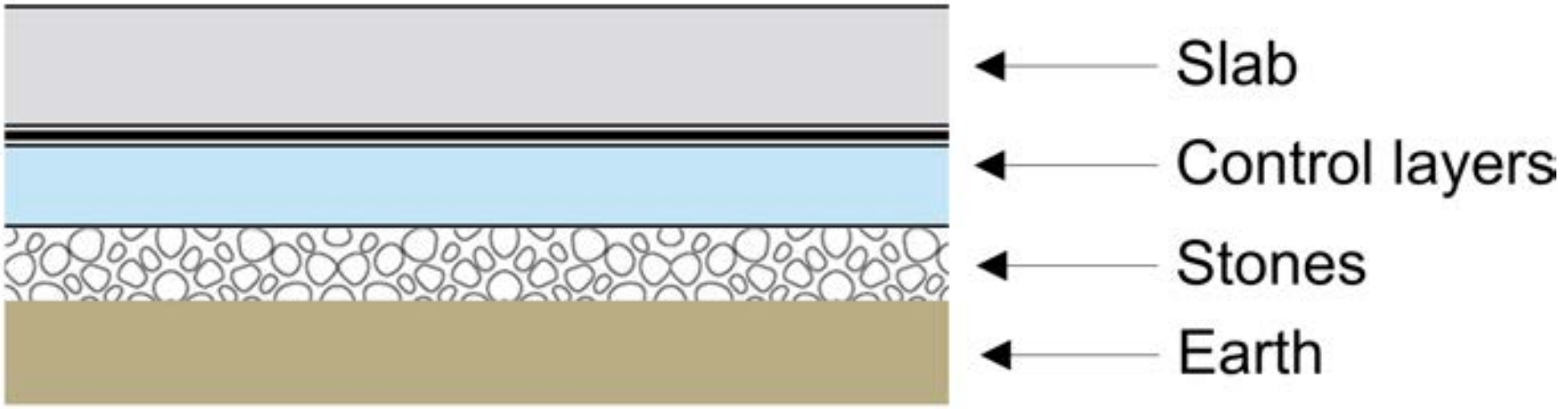
Air Control Layer

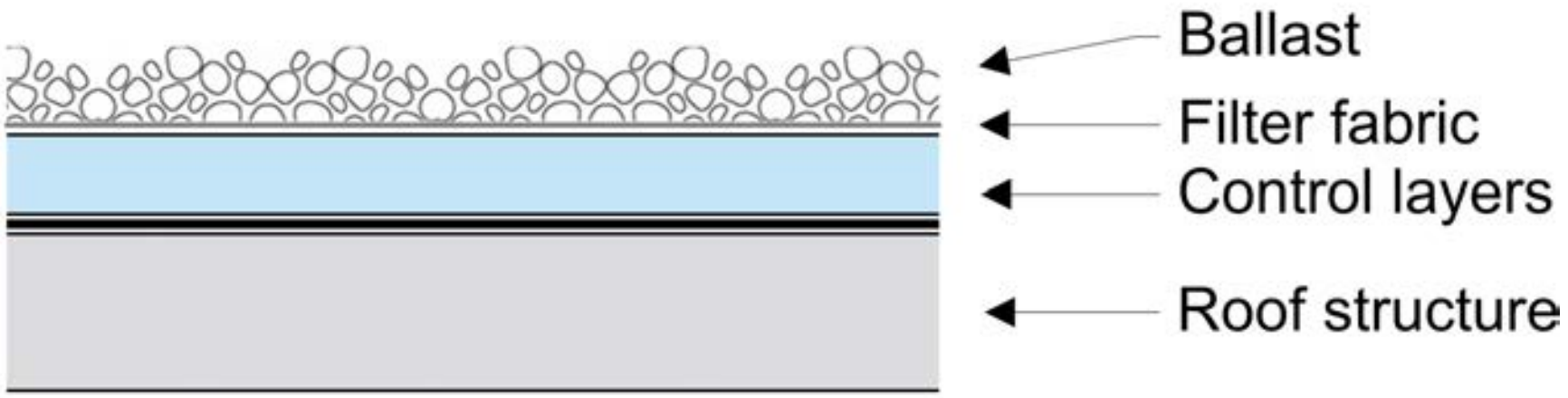
Vapor Control Layer

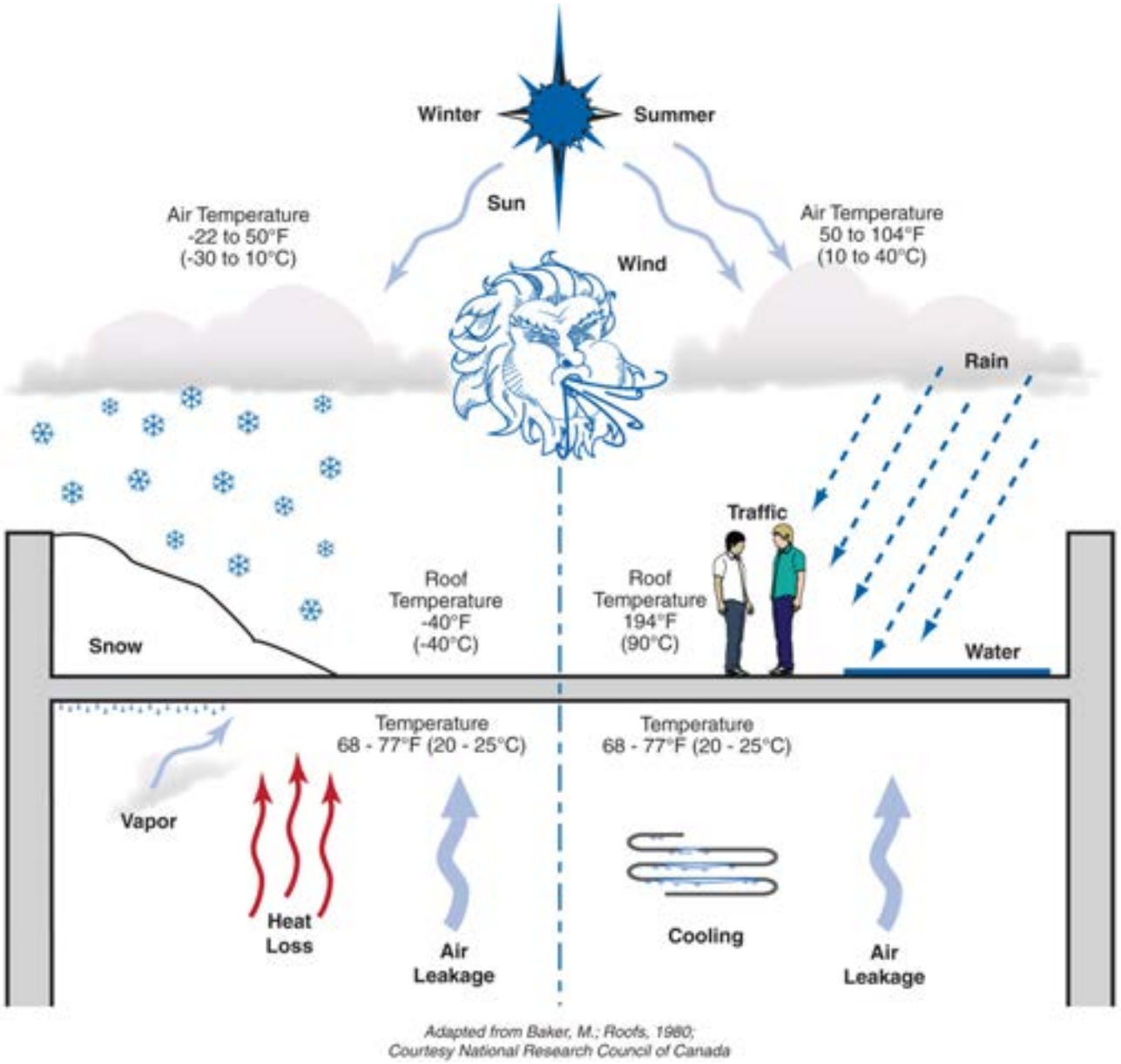
Thermal Control Layer


Cladding
Control layers
Structure

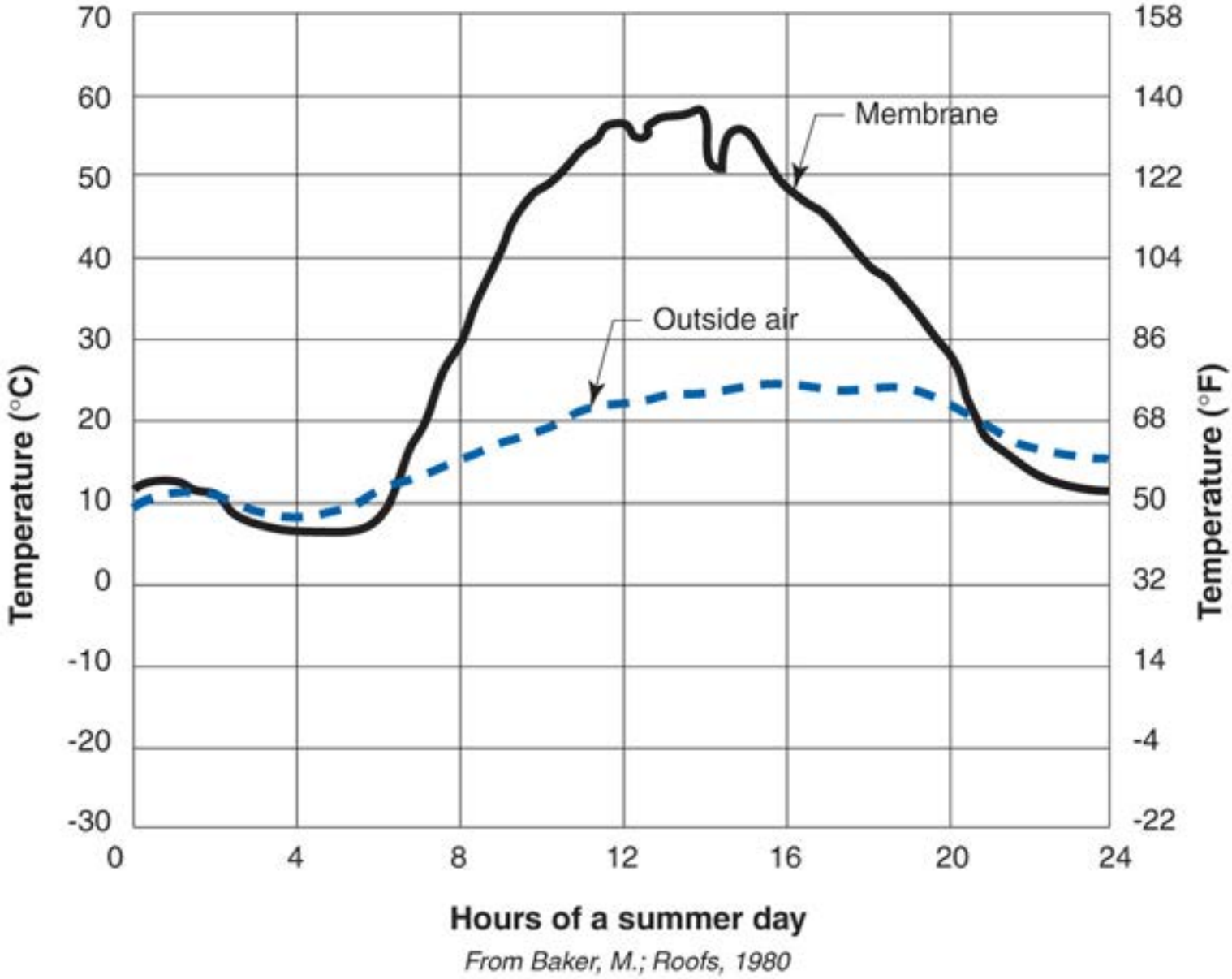

Wall
Slab
Roof

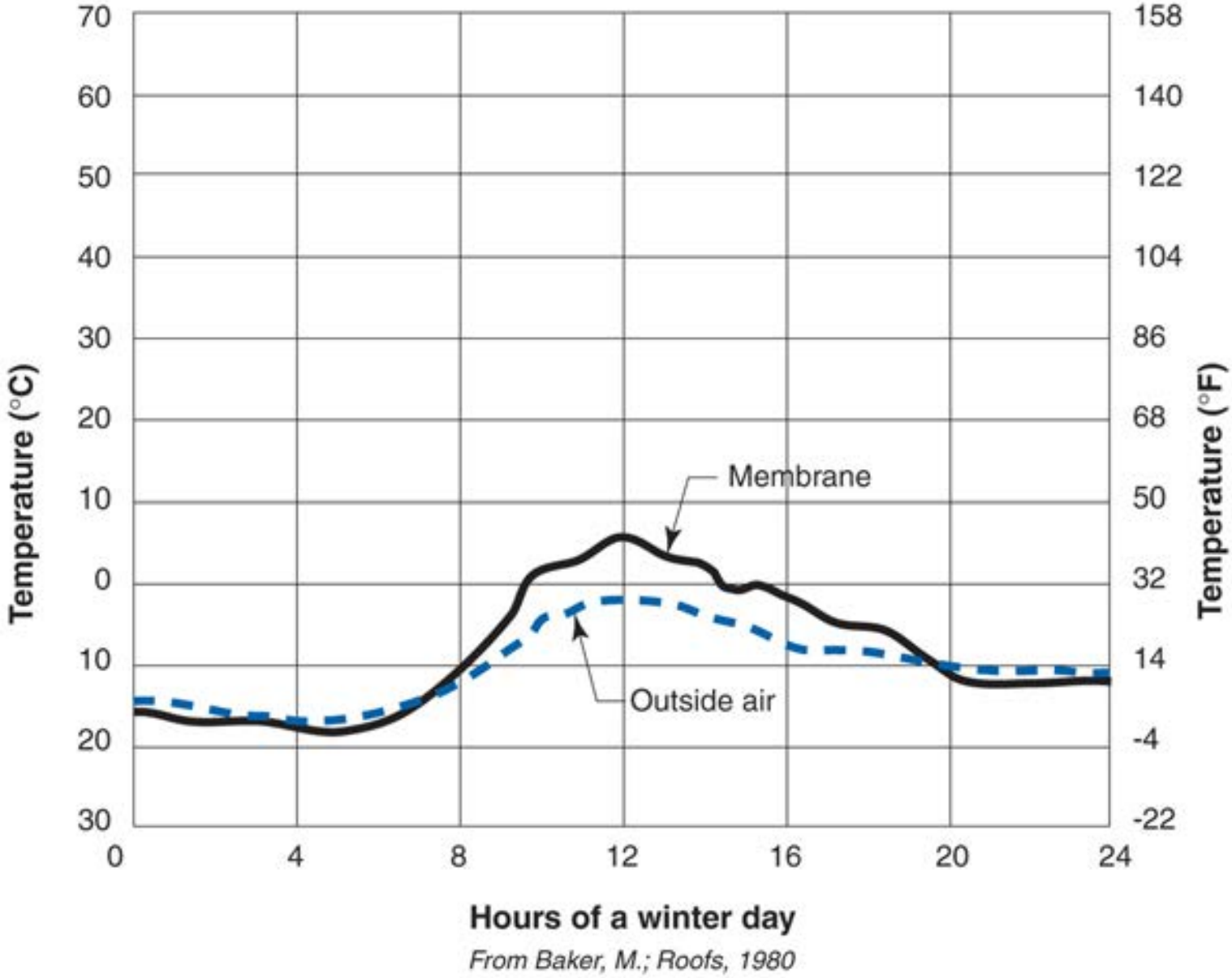

Slab
Control layers
Stones
Earth

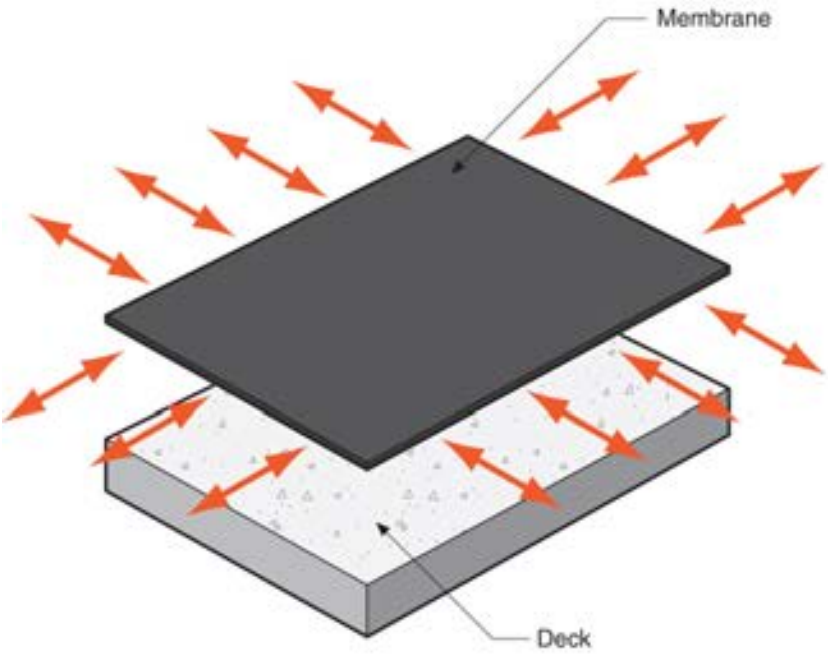

Ballast
Filter fabric
Control layers
Roof structure

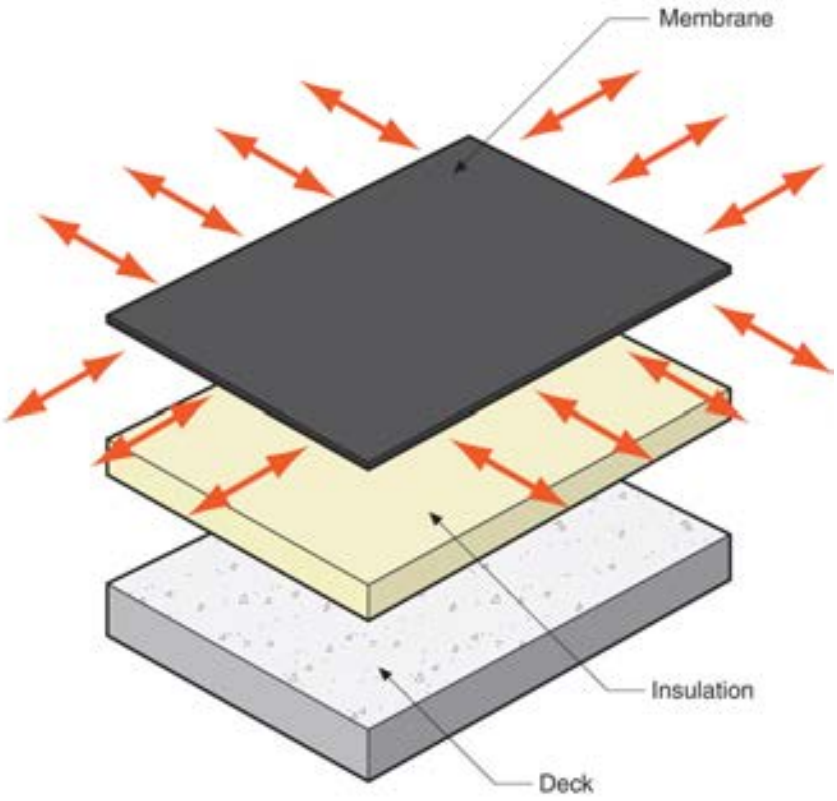


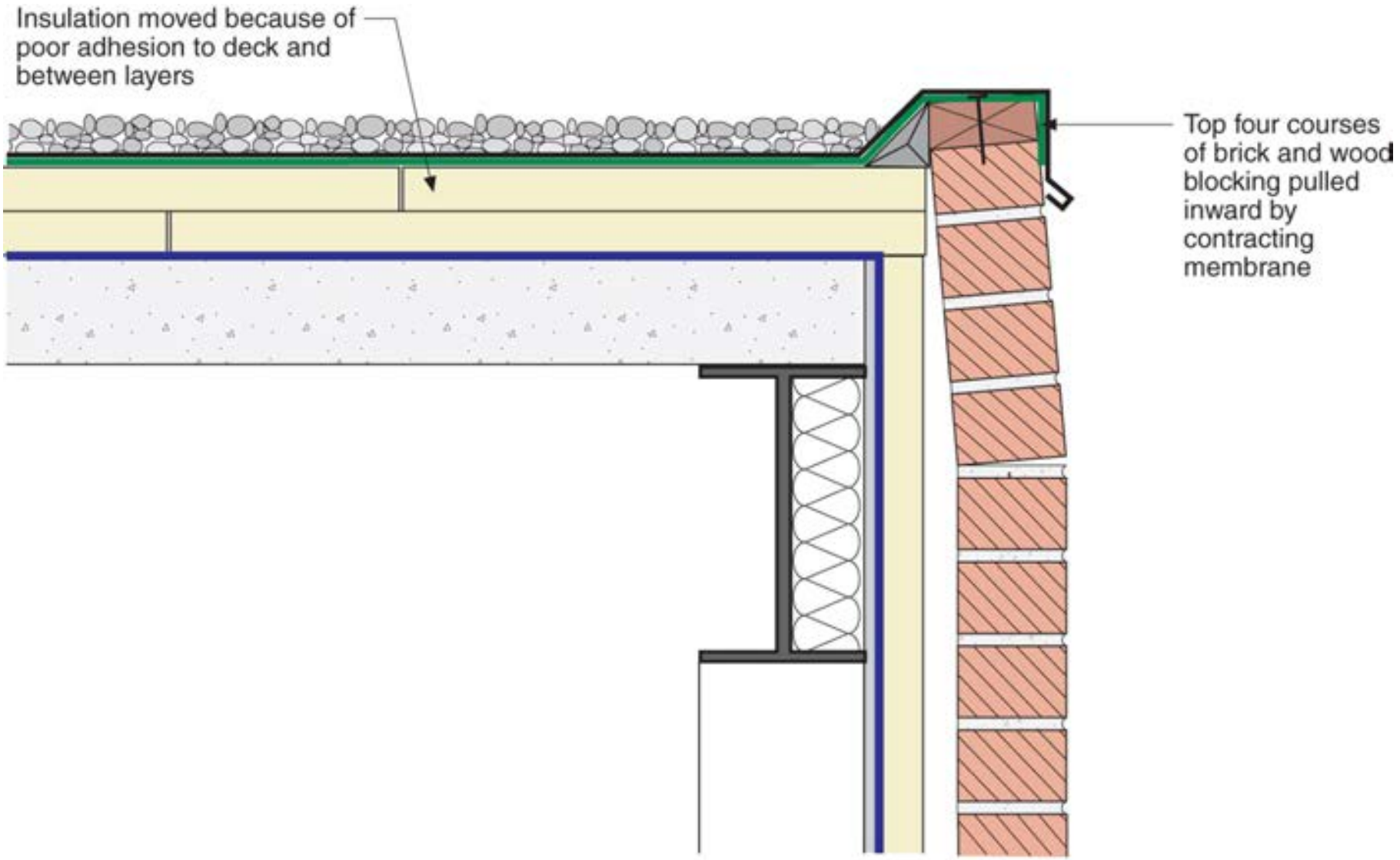
Adapted from Baker, M.; Roofs, 1980;
Courtesy National Research Council of Canada


70
60
50
40
30
20
10
0
-10
-20
-30
158
140
122
104
86
68
50
32
14
-4
-22
0
4
8
12
16
20
24
Membrane
Outside air
Temperature (°C)
Temperature (°F)
Hours of a summer day
From Baker, M.; Roofs, 1980

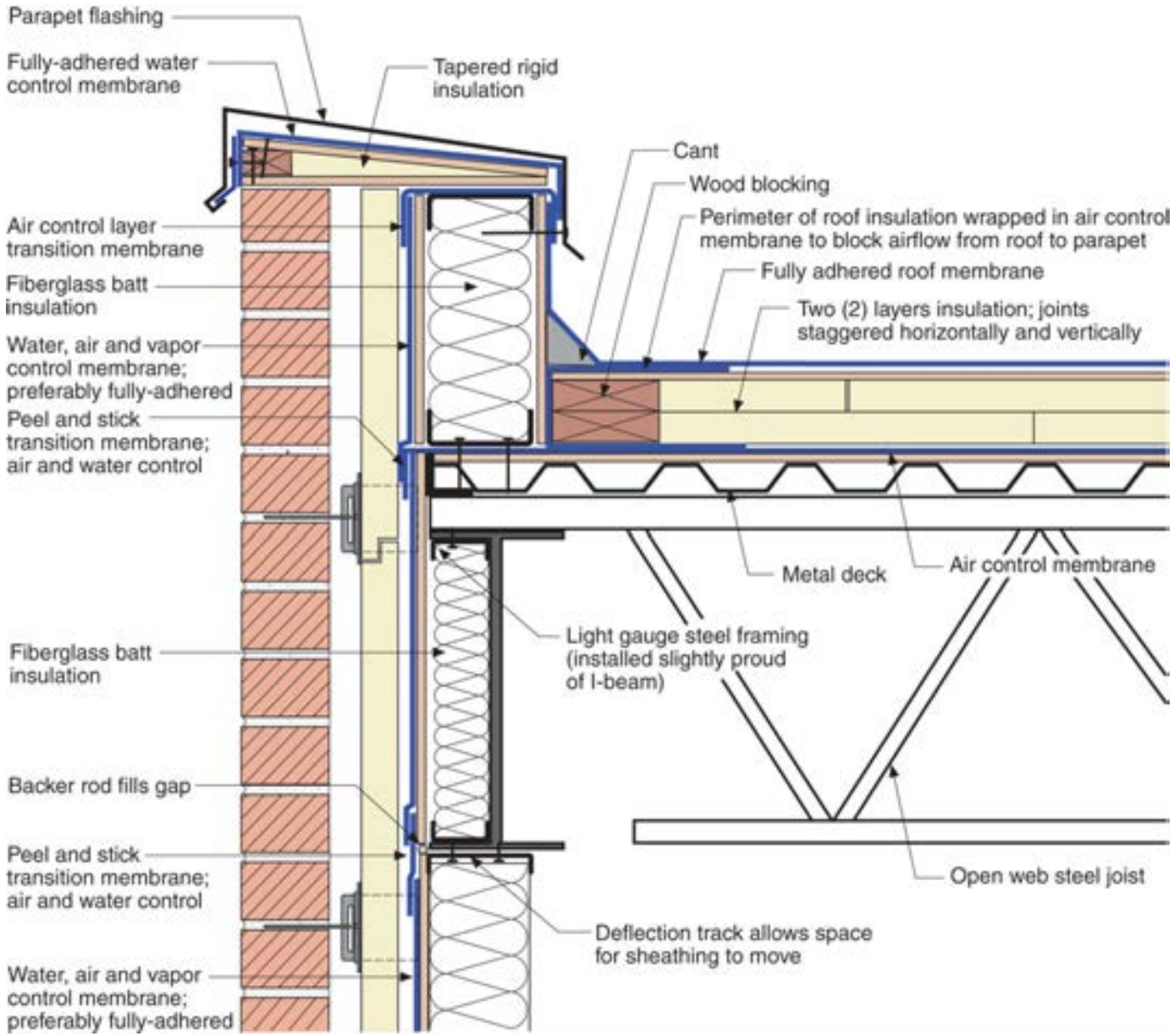

70
60
50
40
30
20
10
0
10
20
30
158
140
122
104
86
68
50
32
14
-4
-22
0
4
8
12
16
20
24
Temperature (°C)
Temperature (°F)
Membrane
Outside air
Hours of a winter day
From Baker, M.; Roofs, 1980

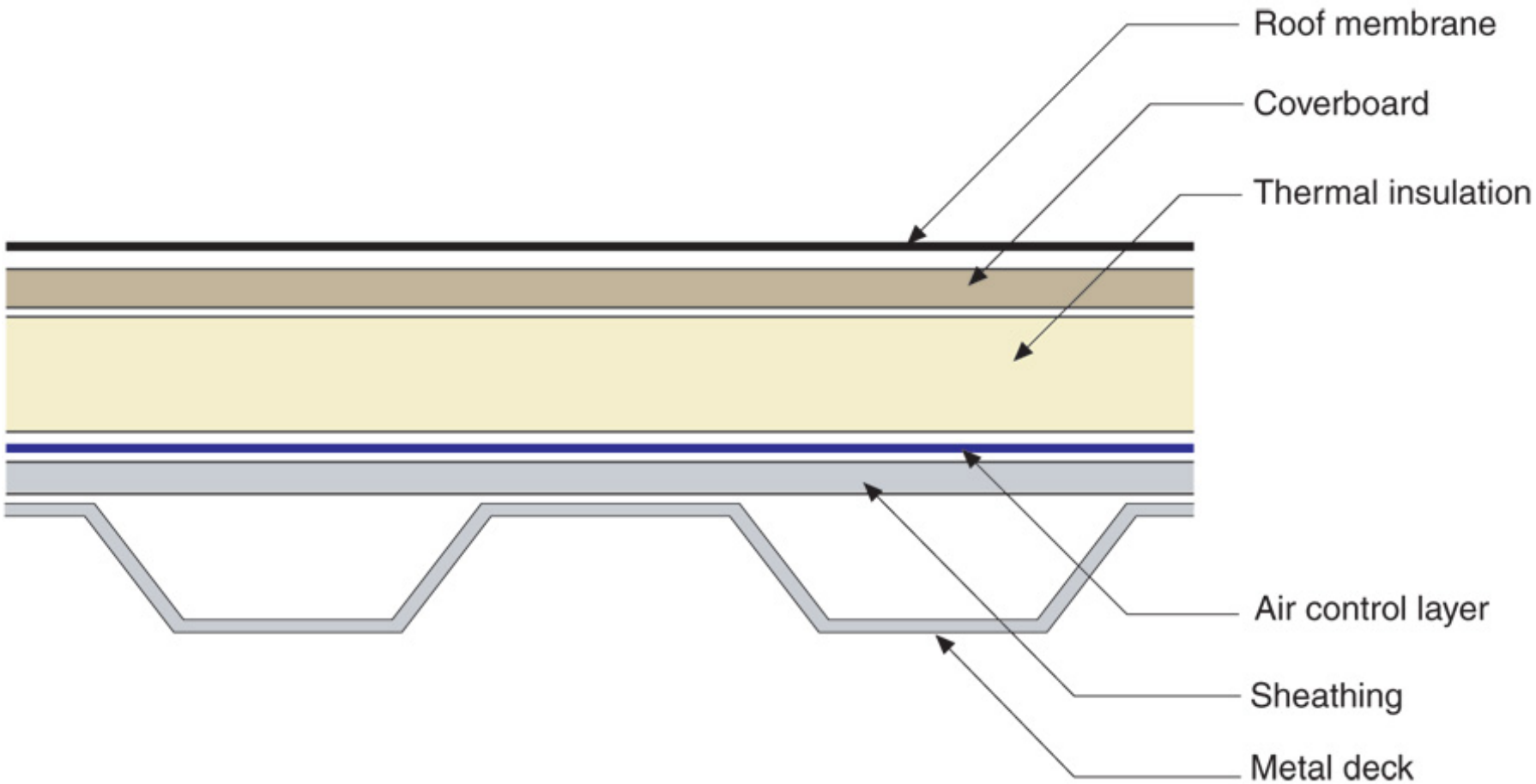

Membrane
Deck

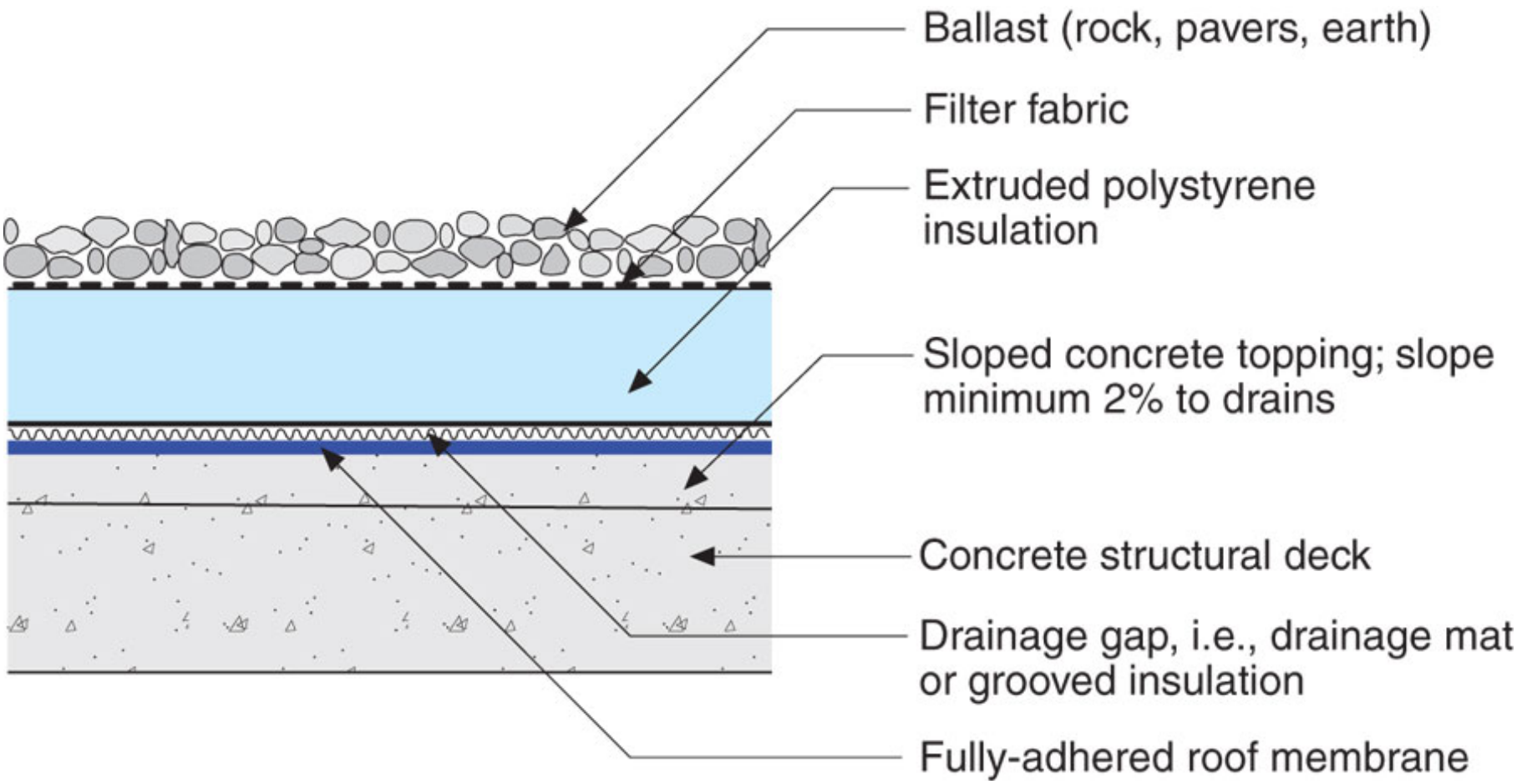

Membrane
Insulation
Deck

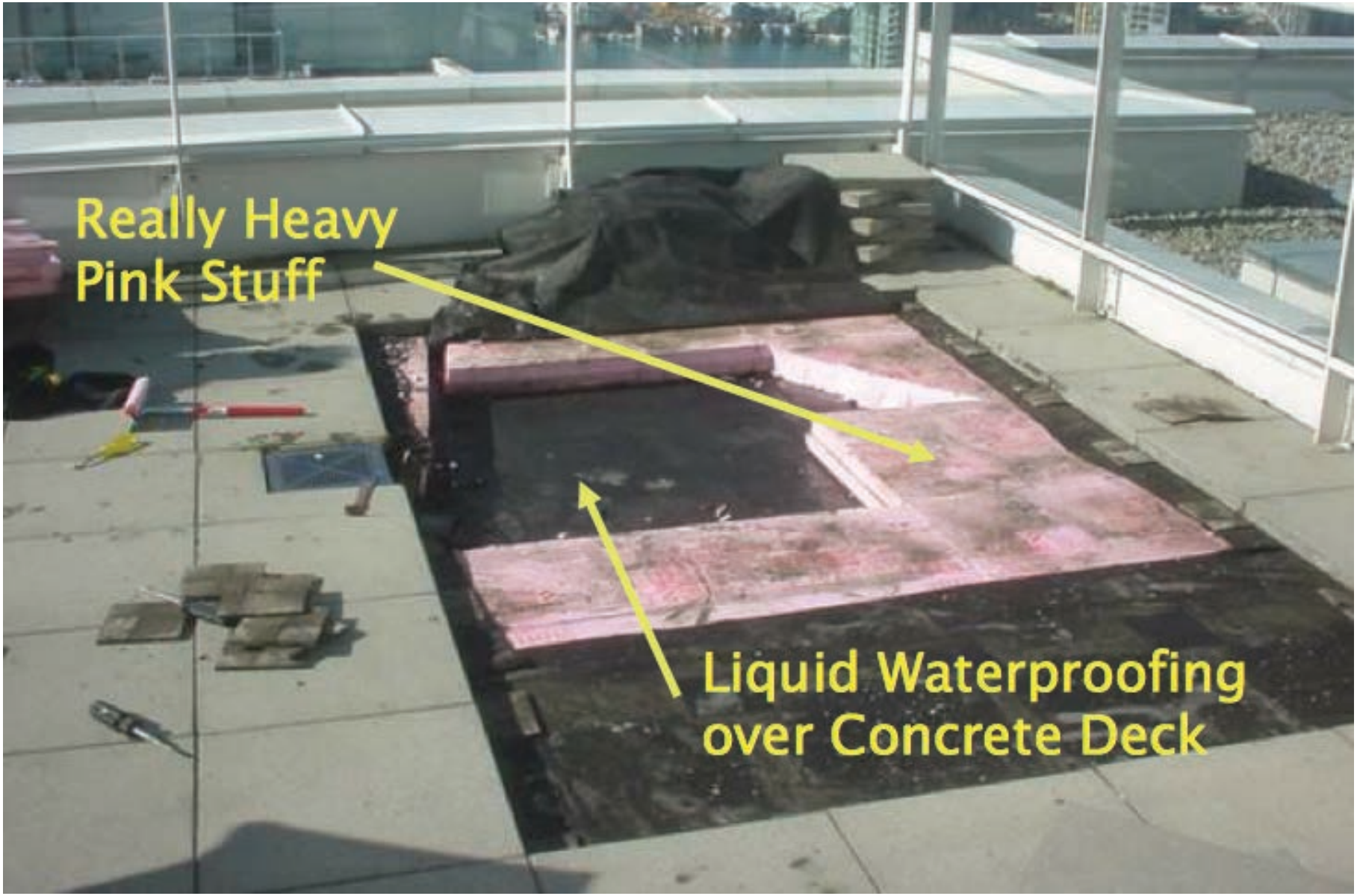


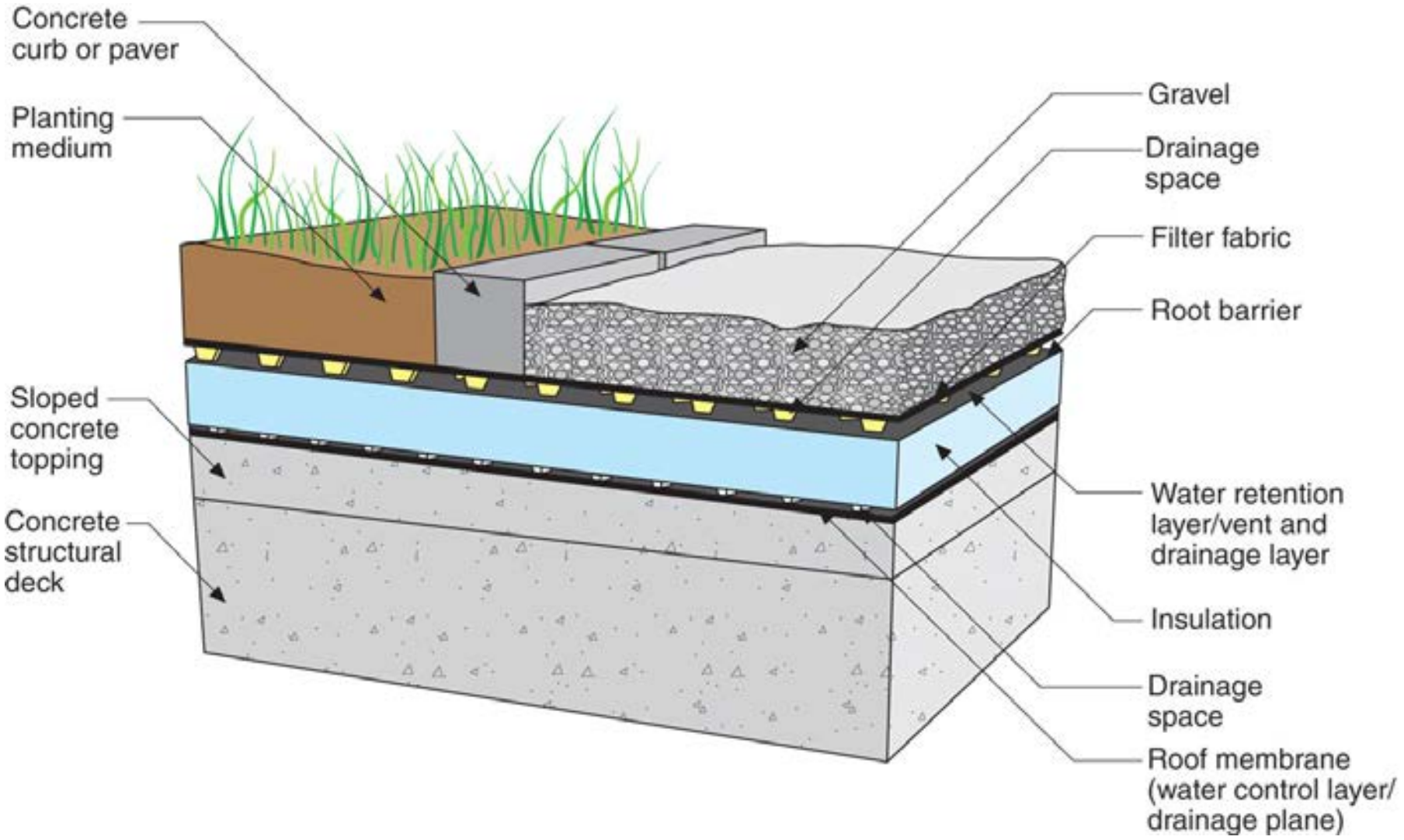
Adapted from Baker, M.; Roofs, 1980;
Courtesy National Research Council of Canada

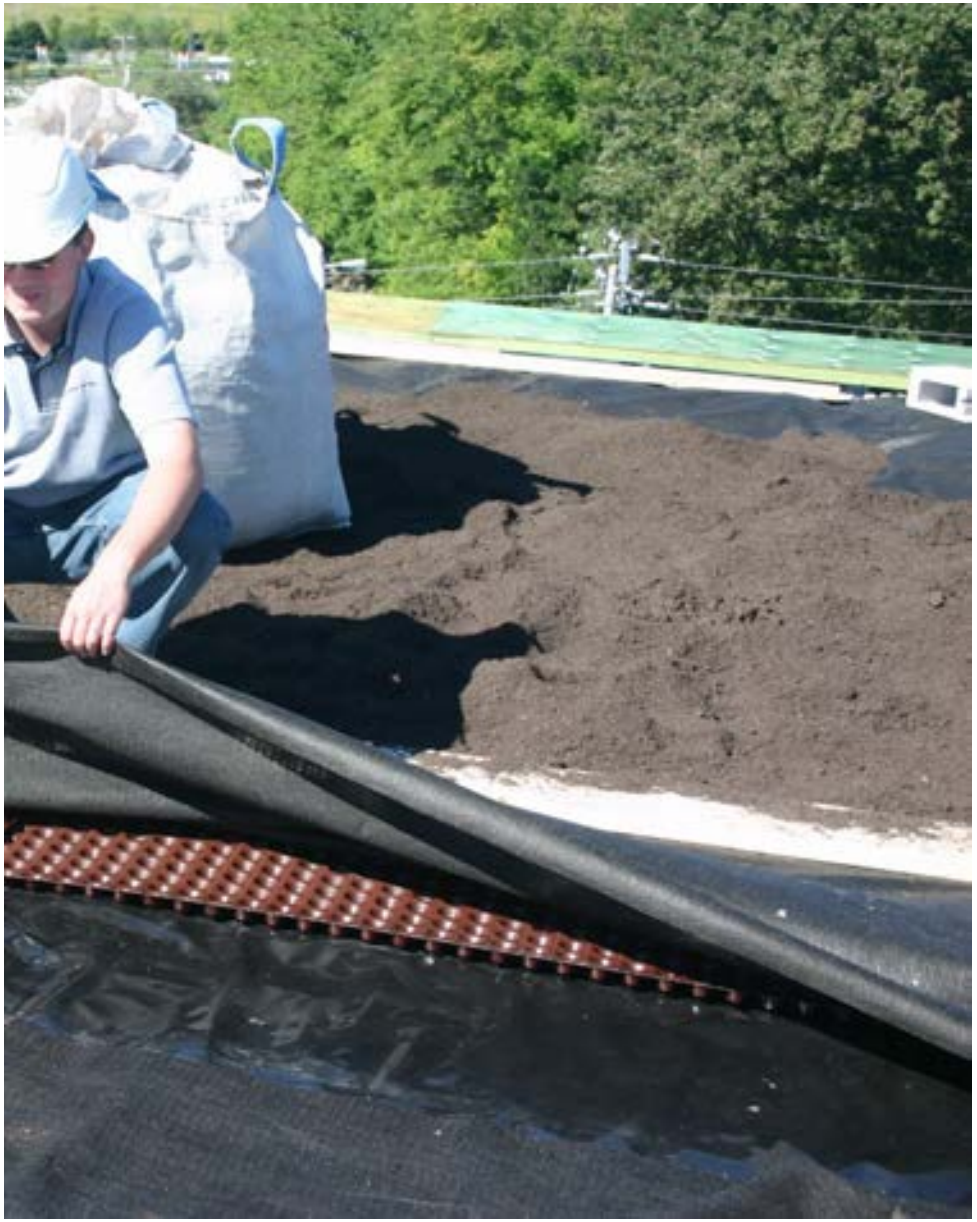

Parapet flashing
Fully-adhered water control membrane
Tapered rigid insulation
Cant
Wood blocking
Perimeter of roof insulation wrapped in air control membrane to block airflow from roof to parapet
Fully adhered roof membrane
Two (2) layers insulation; joints staggered horizontally and vertically
Air control layer transition membrane
Fiberglass batt insulation
Water, air and vapor control membrane; preferably fully-adhered
Peel and stick transition membrane; air and water control
Metal deck
Air control membrane
Light gauge steel framing (installed slightly proud of I-beam)
Fiberglass batt insulation
Backer rod fills gap
Peel and stick transition membrane; air and water control
Open web steel joist
Deflection track allows space for sheathing to move
Water, air and vapor control membrane; preferably fully-adhered

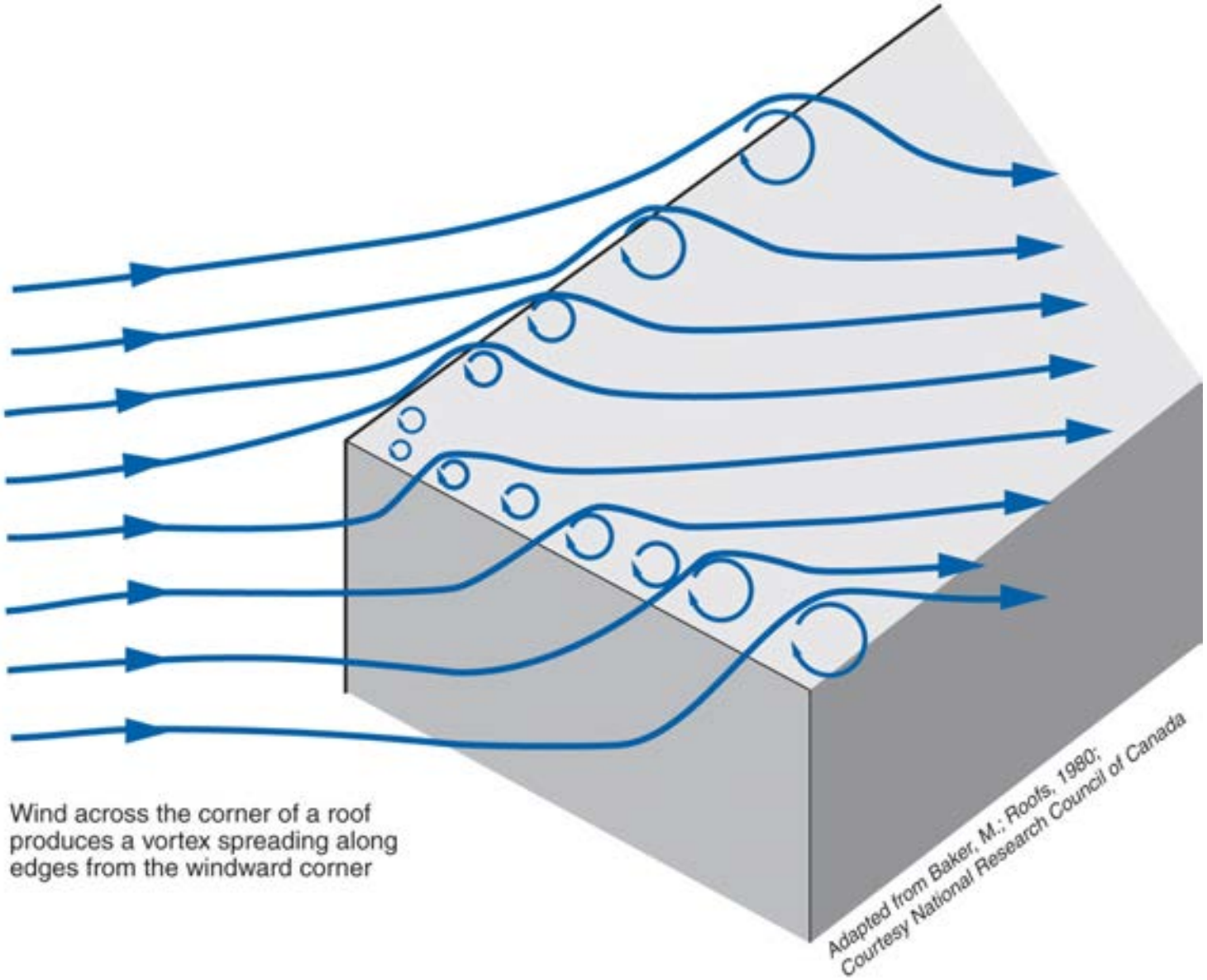

Roof membrane
Coverboard
Thermal insulation
Air control layer
Sheathing
Metal deck


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


Really Heavy
Pink Stuff
Liquid Waterproofing
over Concrete Deck

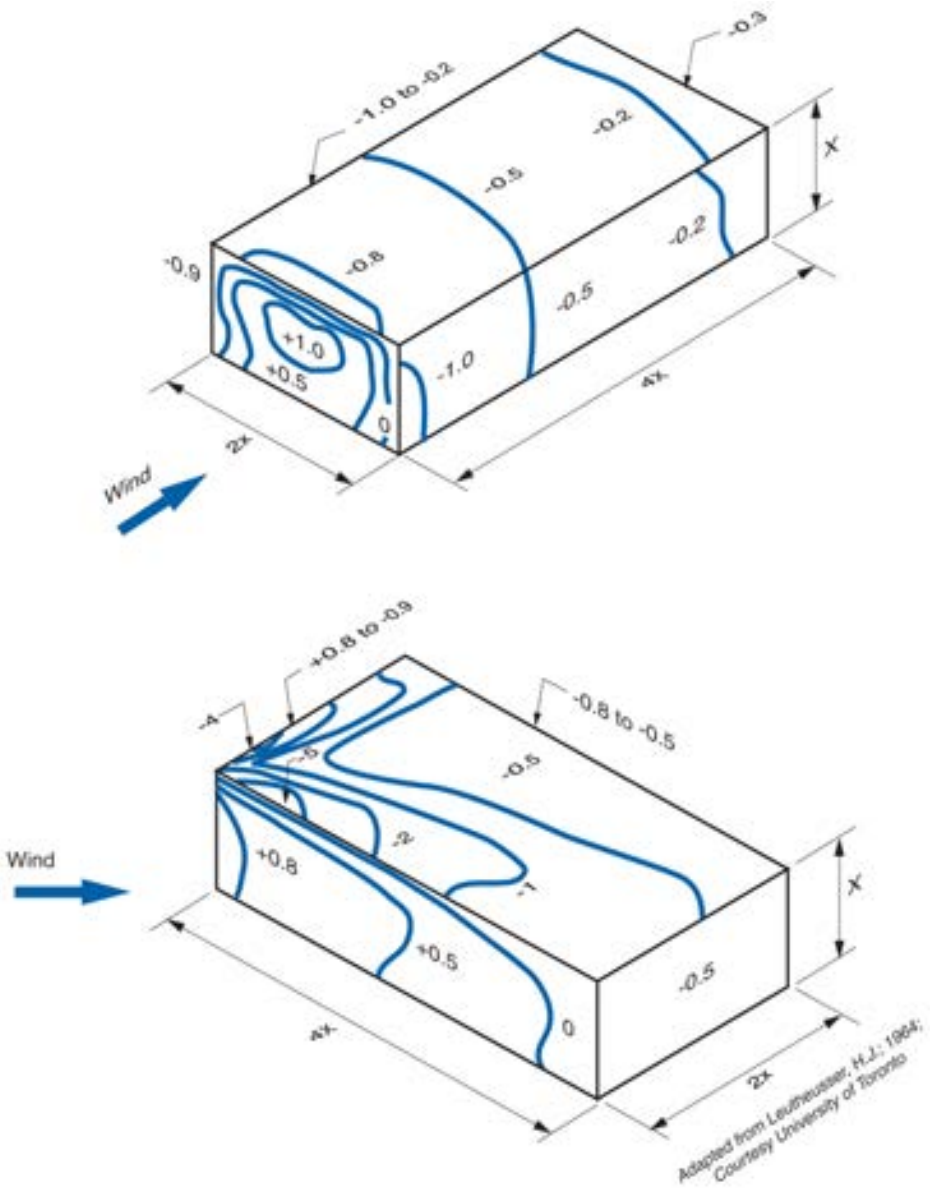

Concrete curb or paver
Planting medium
Sloped concrete topping
Concrete structural deck
Gravel
Drainage space
Filter fabric
Root barrier
Water retention layer/vent and drainage layer
Insulation
Drainage space
Roof membrane (water control layer/ drainage plane)

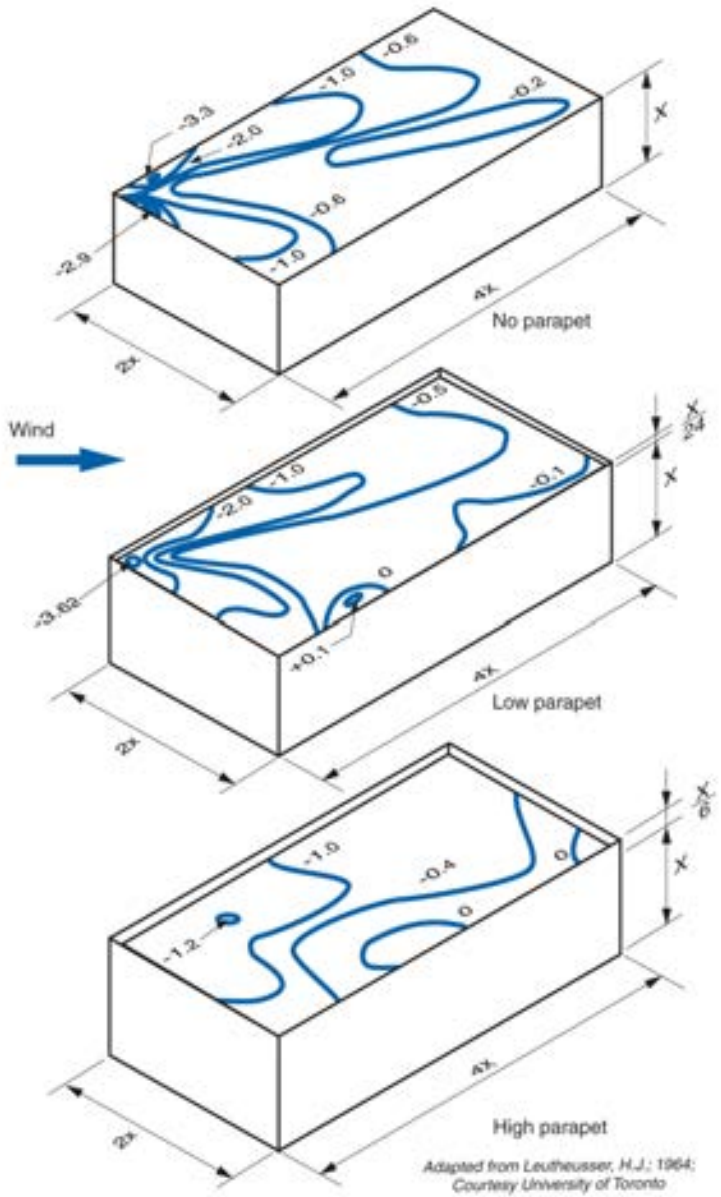


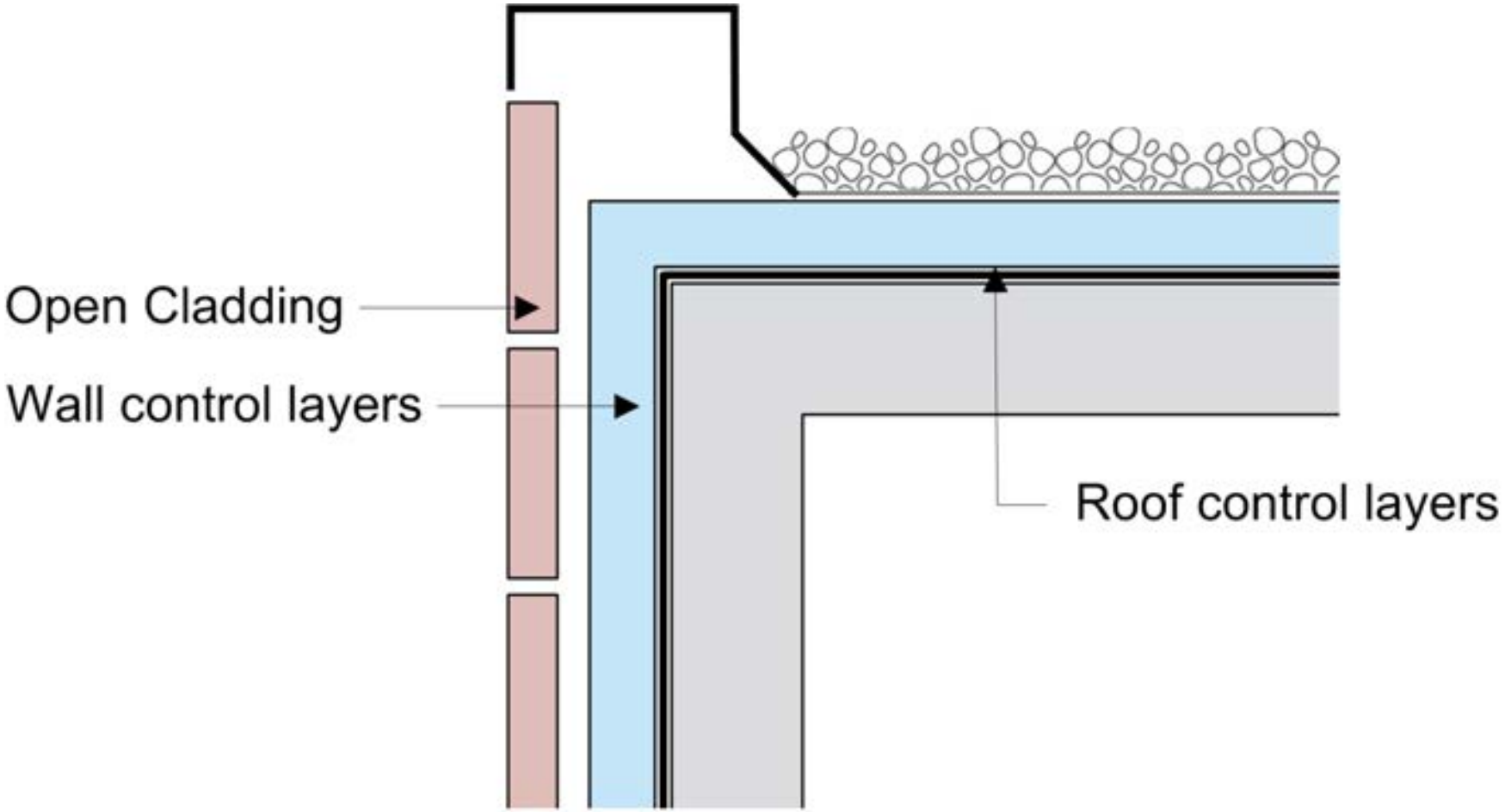


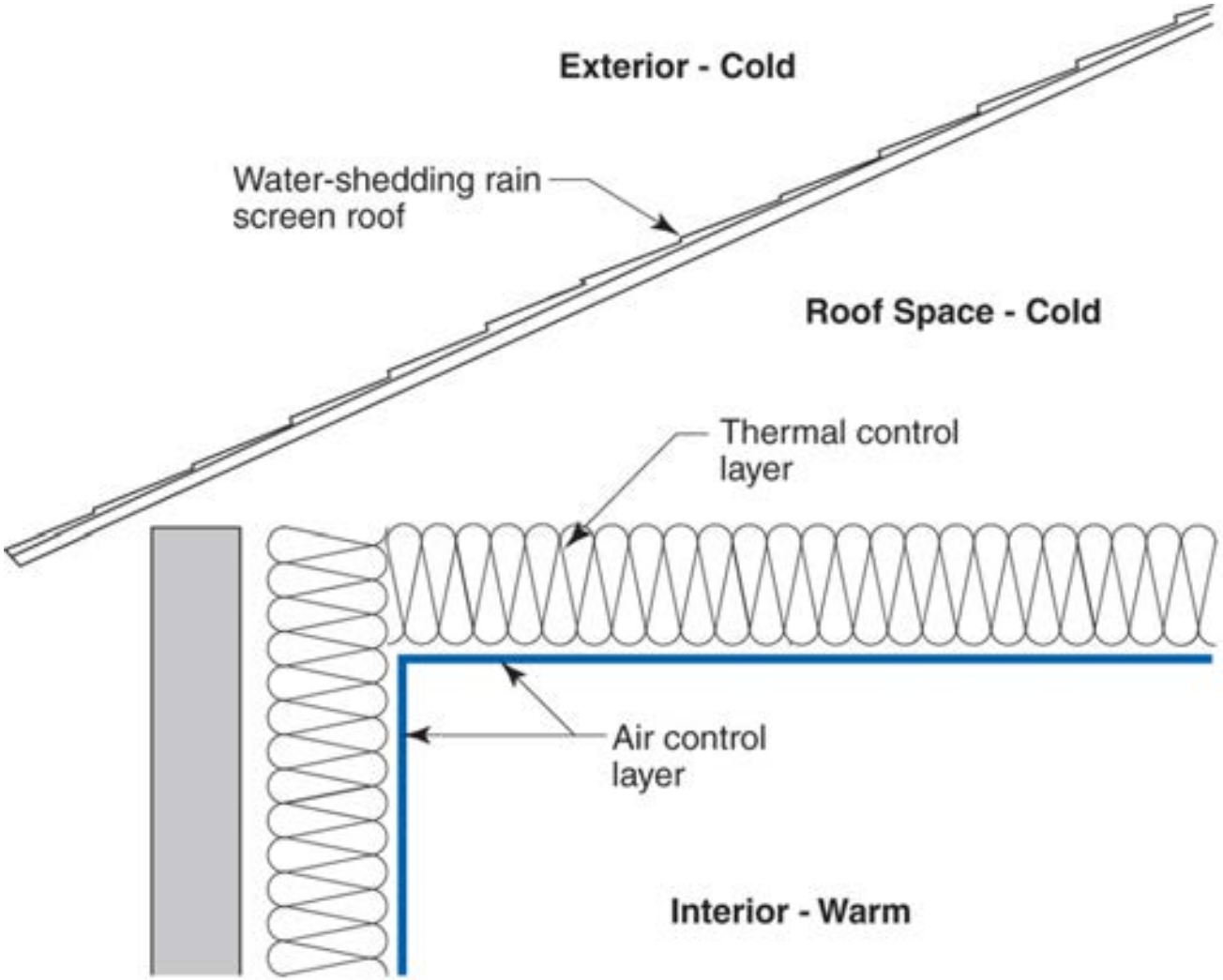
Wind across the corner of a roof produces a vortex spreading along edges from the windward corner

Adapted from Baker, M.; Roofs, 1980; Courtesy National Research Council of Canada

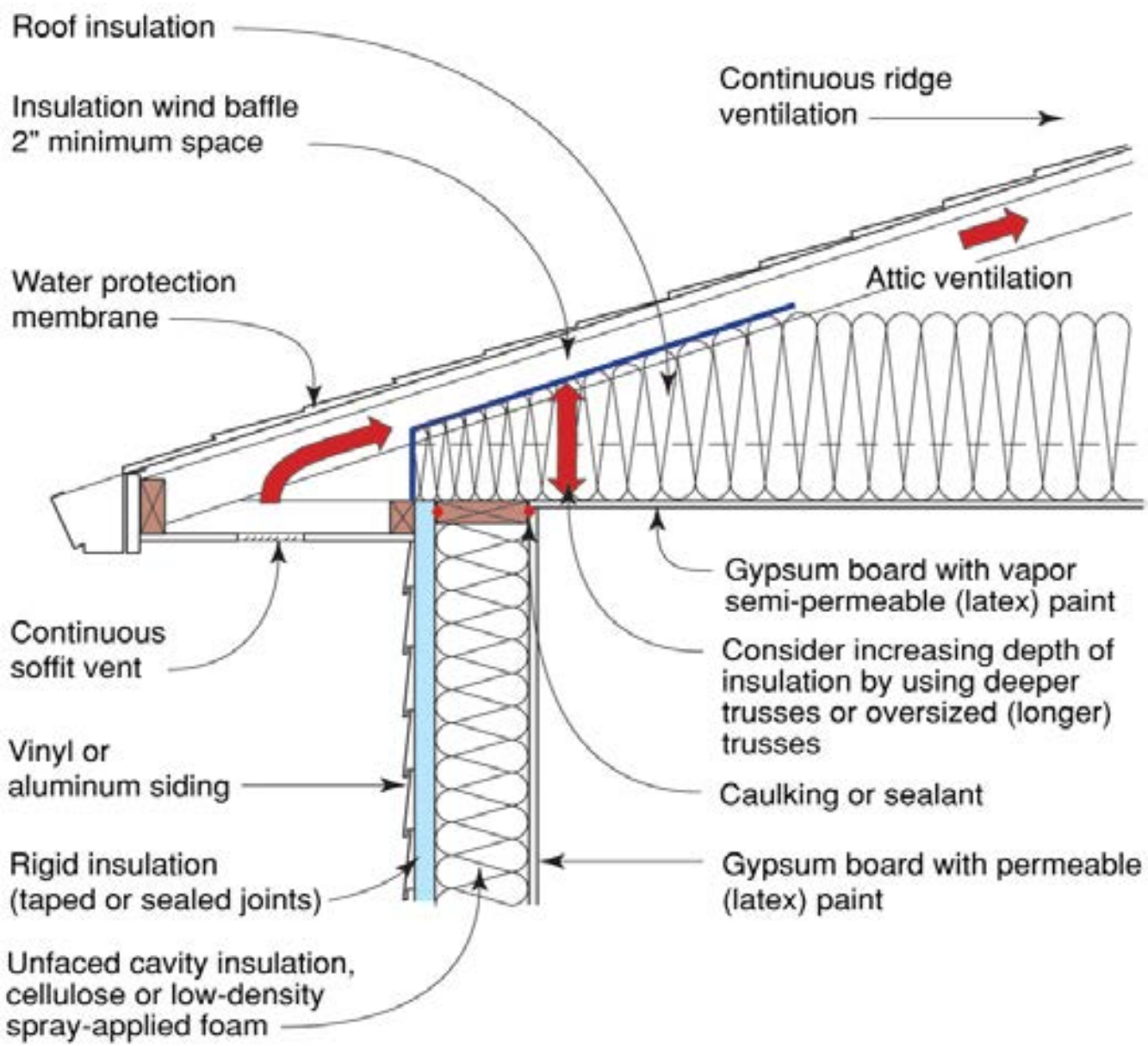

-1.0 to -0.2
-0.5
-0.2
+0.9
-0.8
+1.0
+0.5
0
-1.0
-0.5
-0.2
X
2x
4x
Wind
+0.8 to -0.9
-0.8 to -0.5
-4
-2
-0.5
+0.8
-2
-1
+0.5
0
-0.5
X
4x
2x
Wind
Adapted from Leutheusser, H.J.; 1964; Courtesy University of Toronto

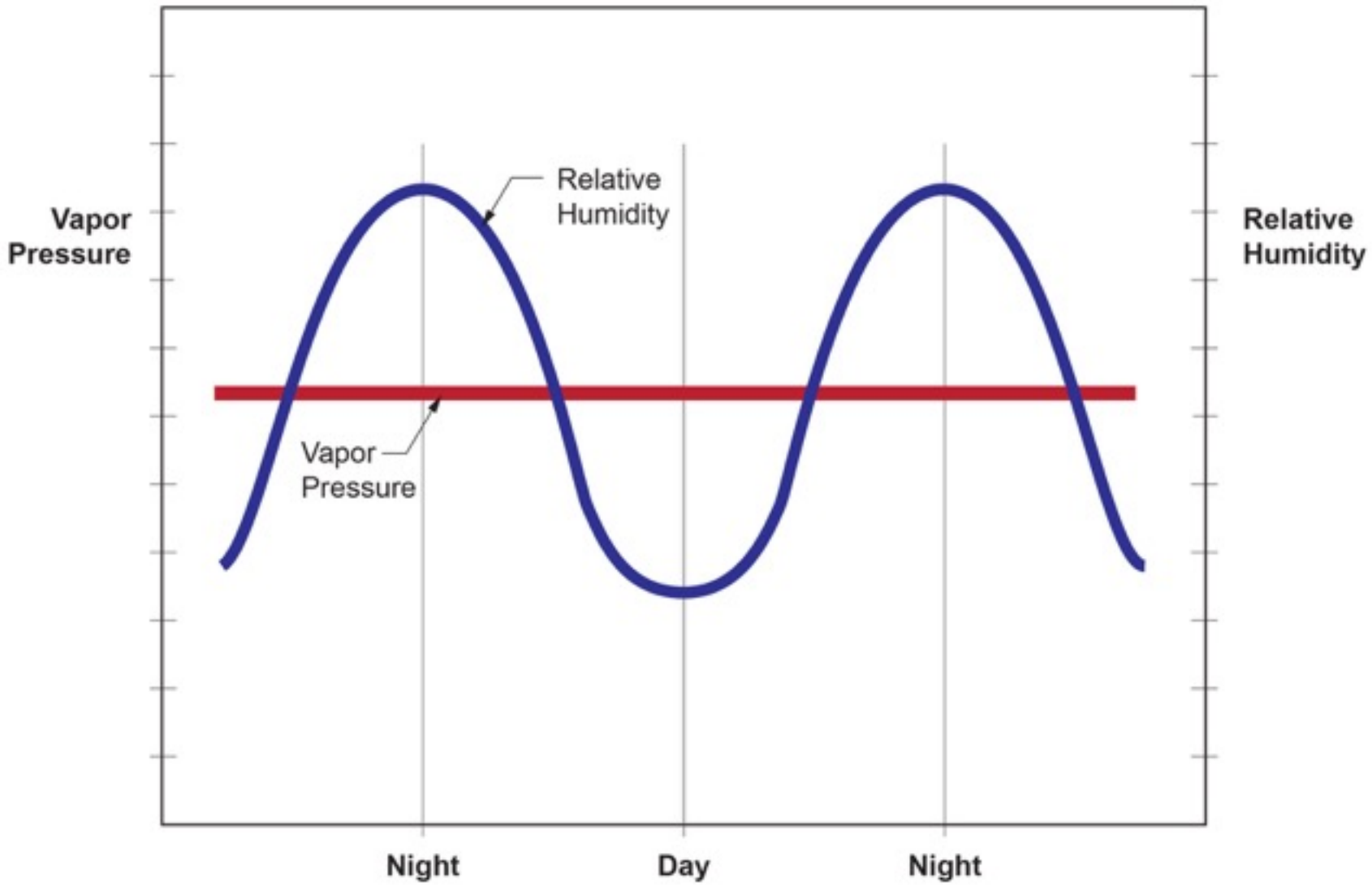

-0.6
-1.0
-0.2
-3.5
-2.0
-0.6
-2.9
-1.0
X
4X
2X
No parapet
Wind
-0.5
-1.0
-0.1
-2.0
0
-3.62
+0.1
X/4
X
4X
2X
Low parapet
-1.0
-0.4
0
0
-1.2
X/8
X
4X
2X
High parapet
Adapted from Leutheusser, H.J.; 1964;
Courtesy University of Toronto

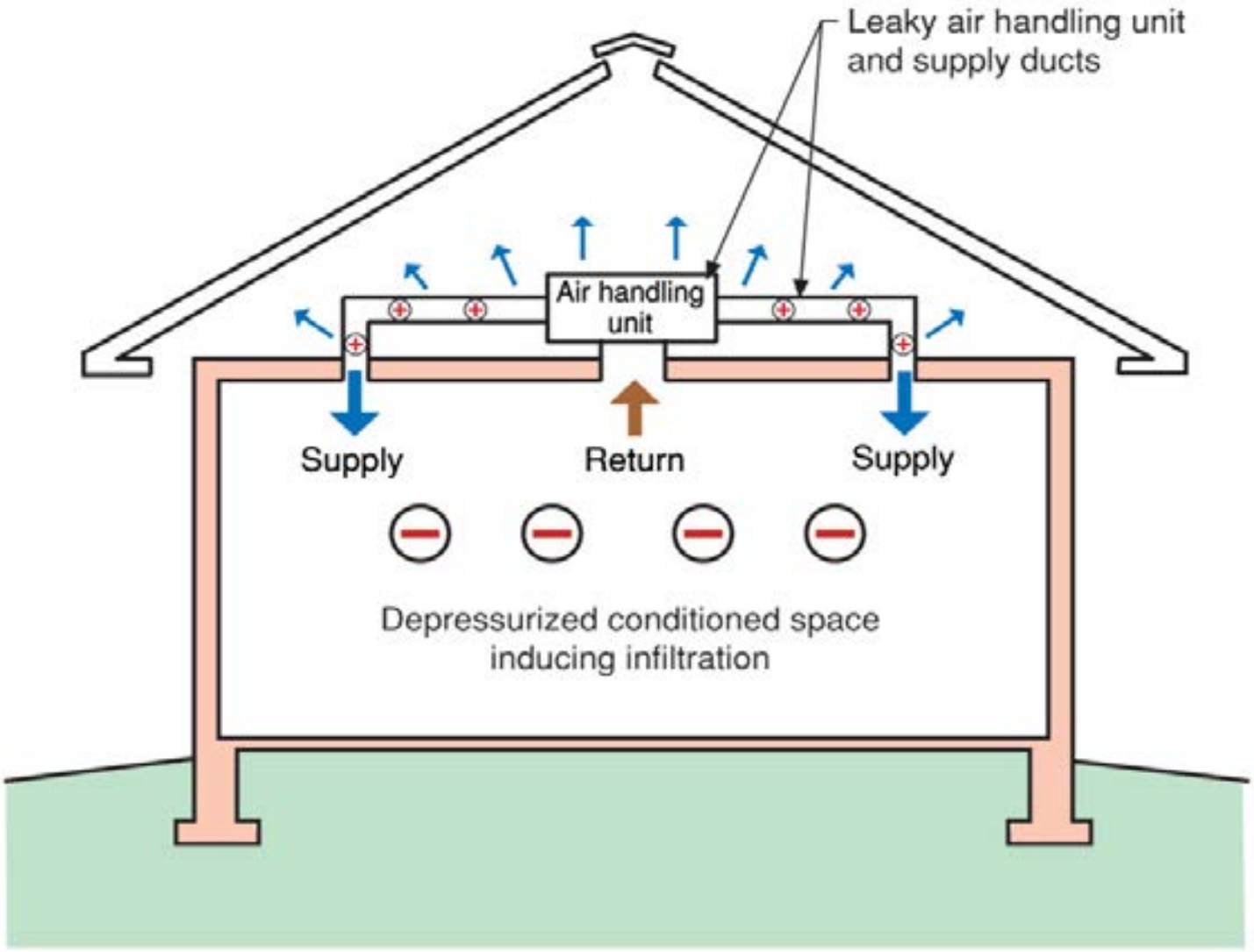

Open Cladding
Wall control layers
Roof control layers



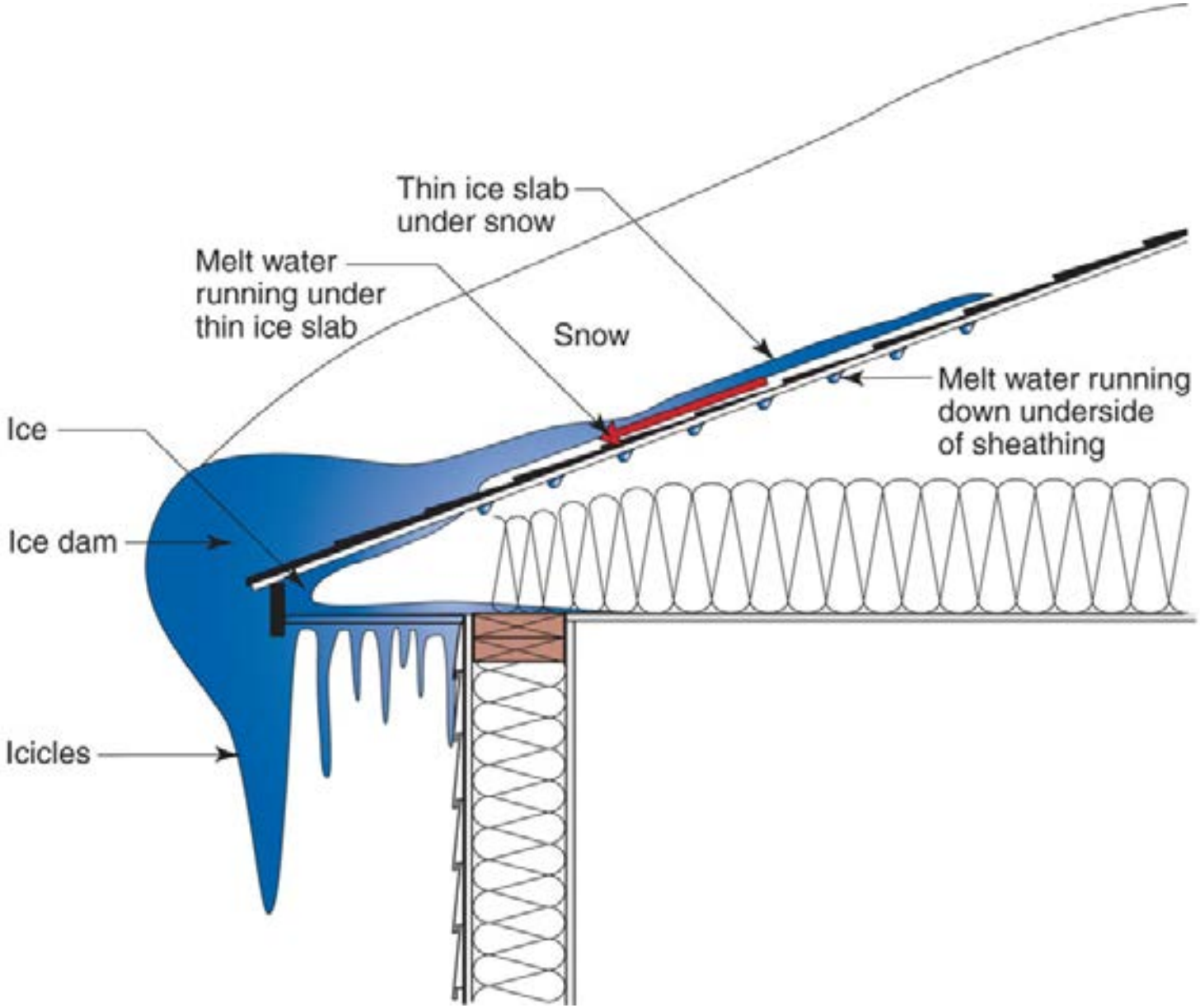
From Baker, M.; Roofs, 1980


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


Vapor Pressure
Relative Humidity
Relative Humidity
Vapor Pressure
Night
Day
Night

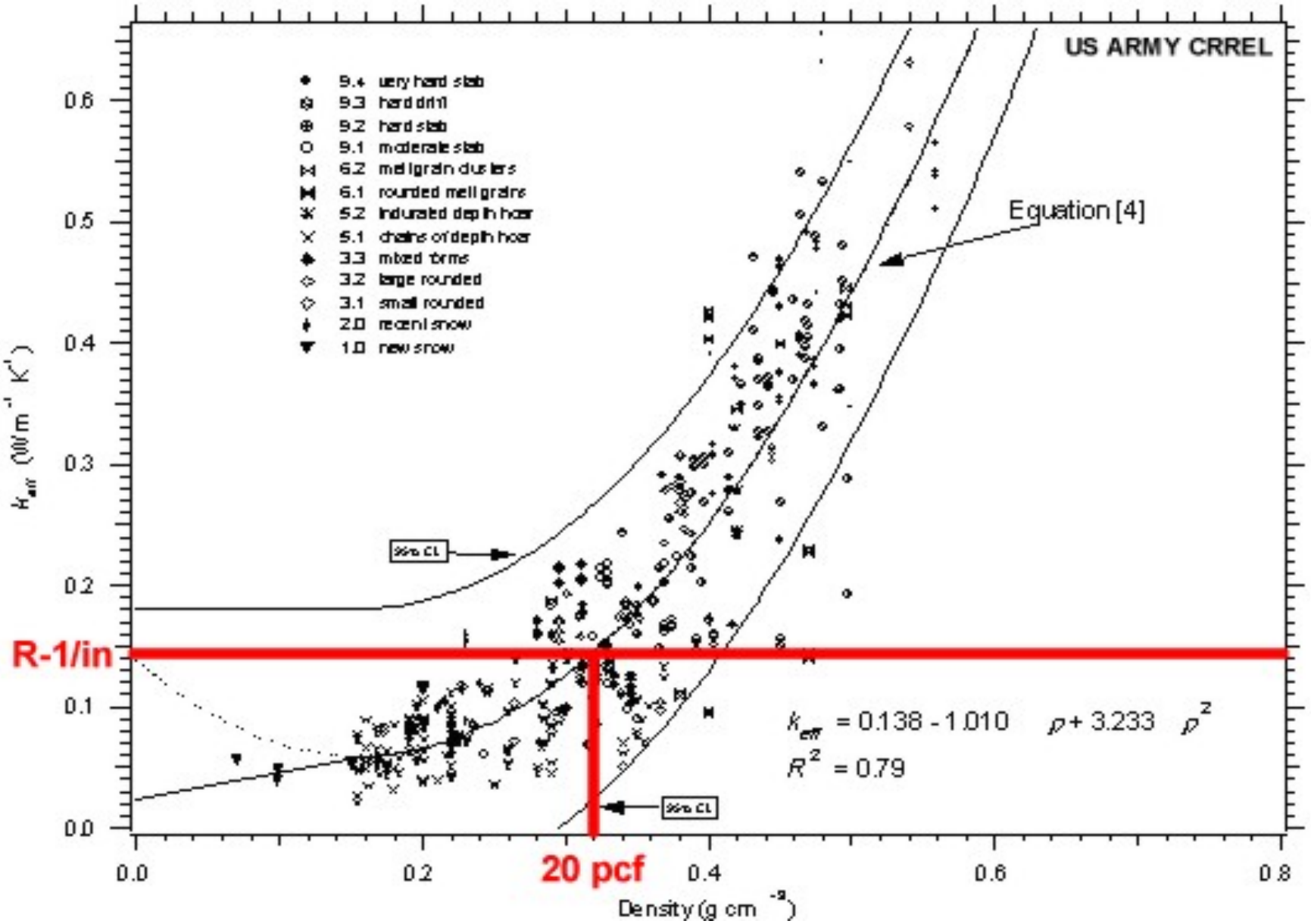


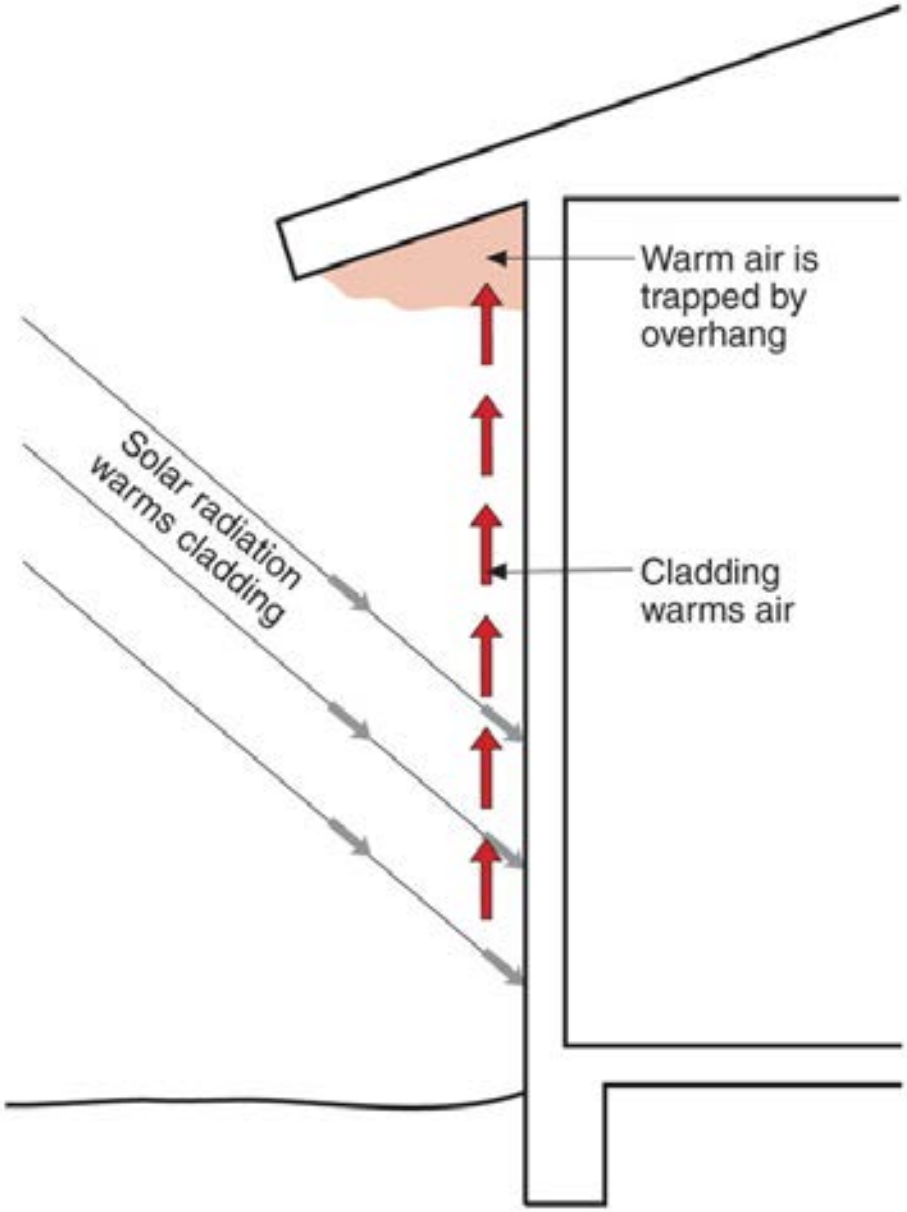
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.


Thin ice slab
under snow
Melt water
running under
thin ice slab
Snow
Melt water running
down underside
of sheathing
Ice
Ice dam
Icicles

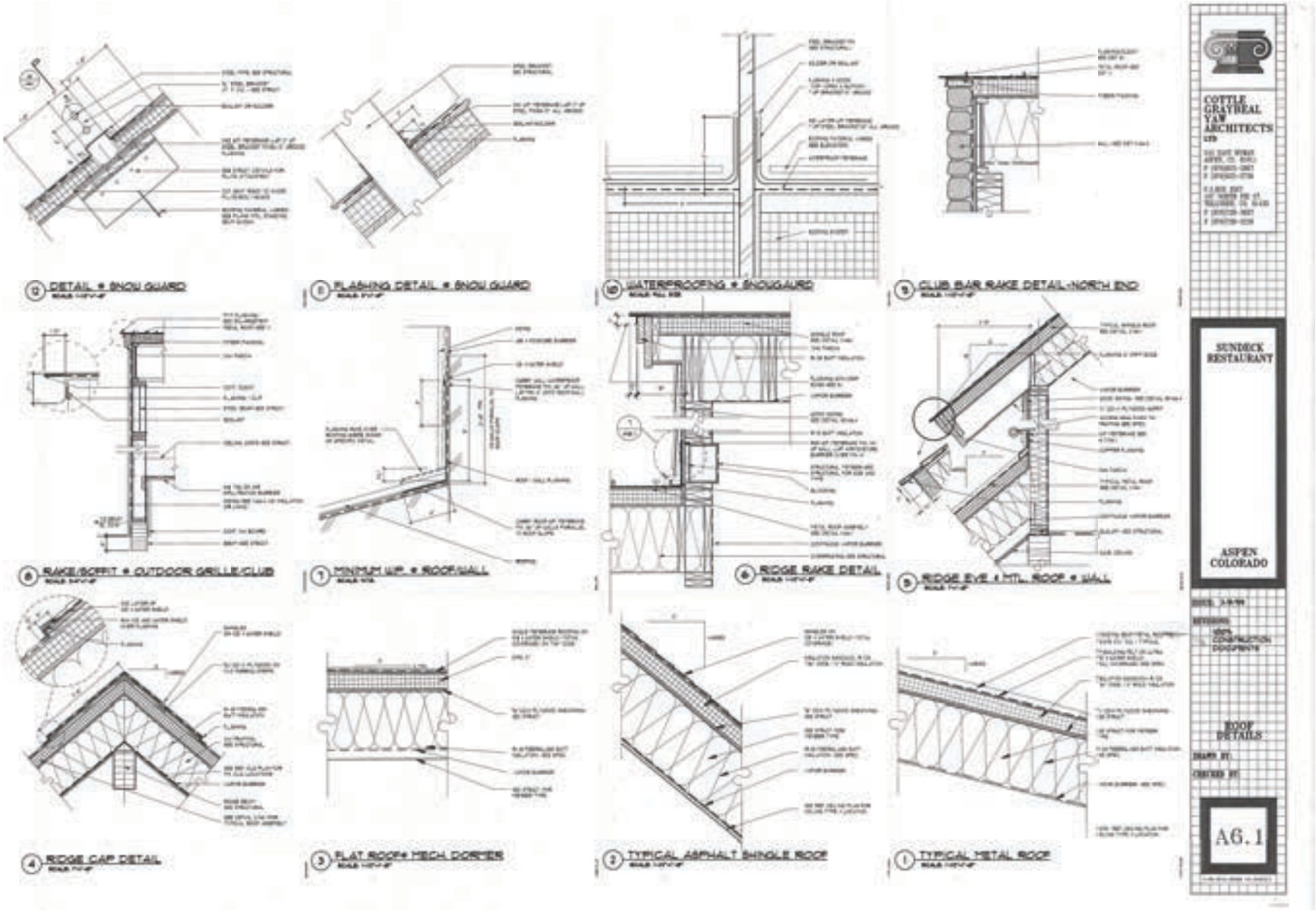

021

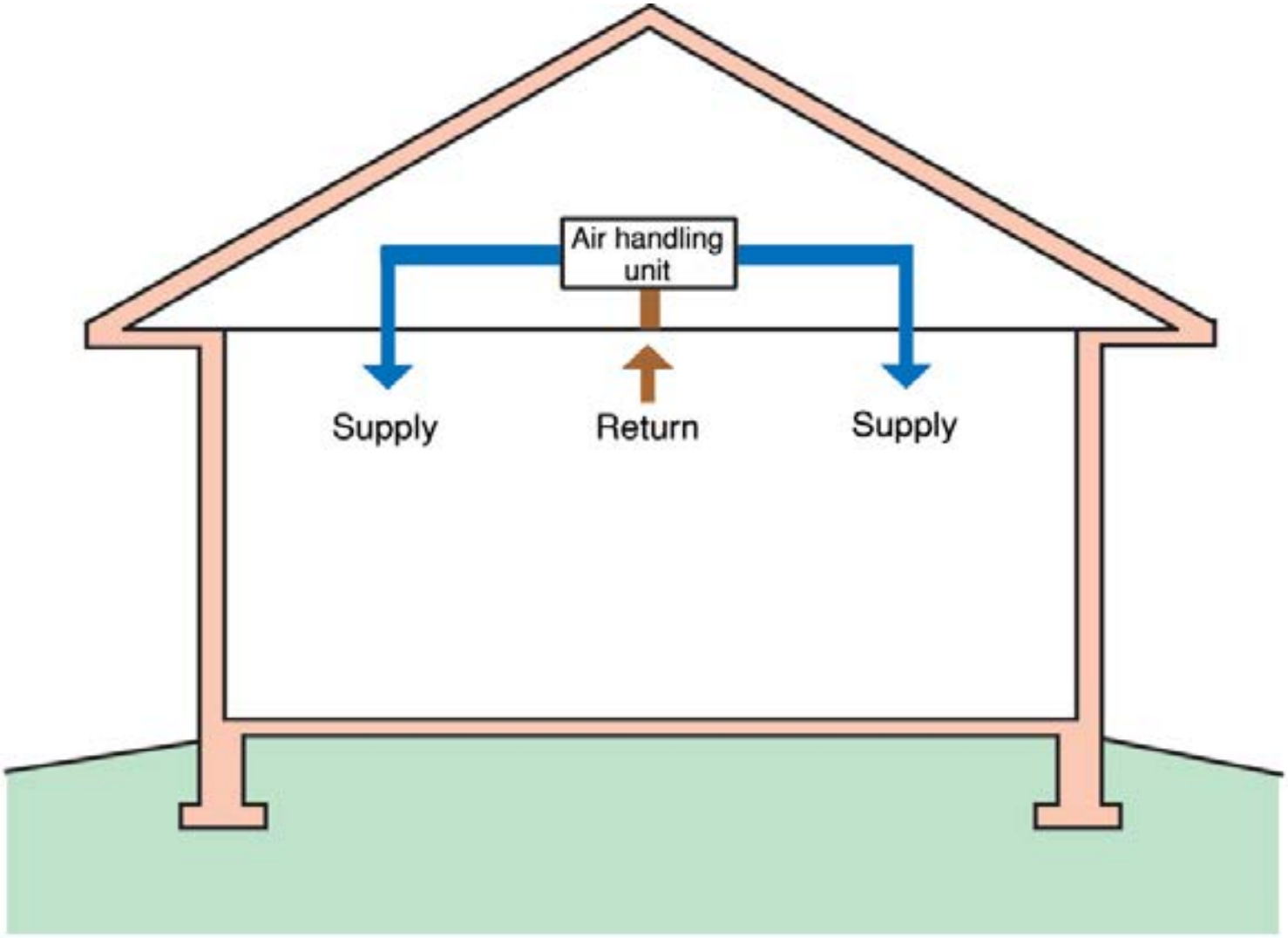

WESTFORD REAL ESTATE


US ARMY CRREL
9.4 very hard slab
9.3 hard drift
9.2 hard slab
9.1 moderate slab
6.2 melt grain clusters
6.1 rounded melt grains
5.2 indurated depth hoar
5.1 chains of depth hoar
3.3 mixed forms
3.2 large rounded
3.1 small rounded
2.0 recent snow
1.0 new snow
Eguation [4]
95% CL
95% CL
R-1/in
20 pcf
k_{eff} = 0.138 - 1.010 ρ + 3.233 ρ^2
R^2 = 0.79
k_{eff} (W m^{-1} K^{-1})
Density (g cm^{-3})
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.0
0.2
0.4
0.6
0.8

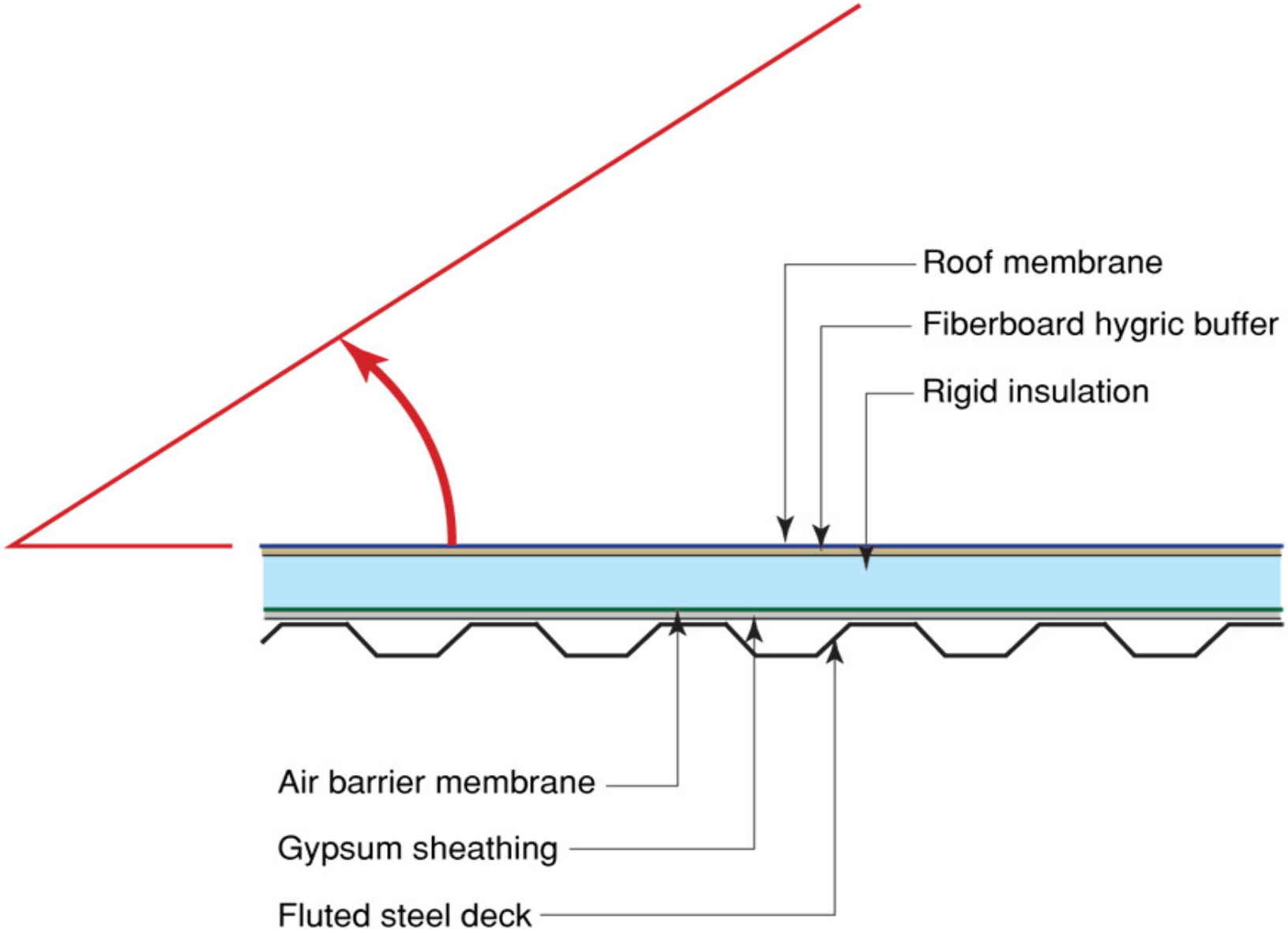

Warm air is trapped by overhang
Solar radiation warms cladding
Cladding warms air

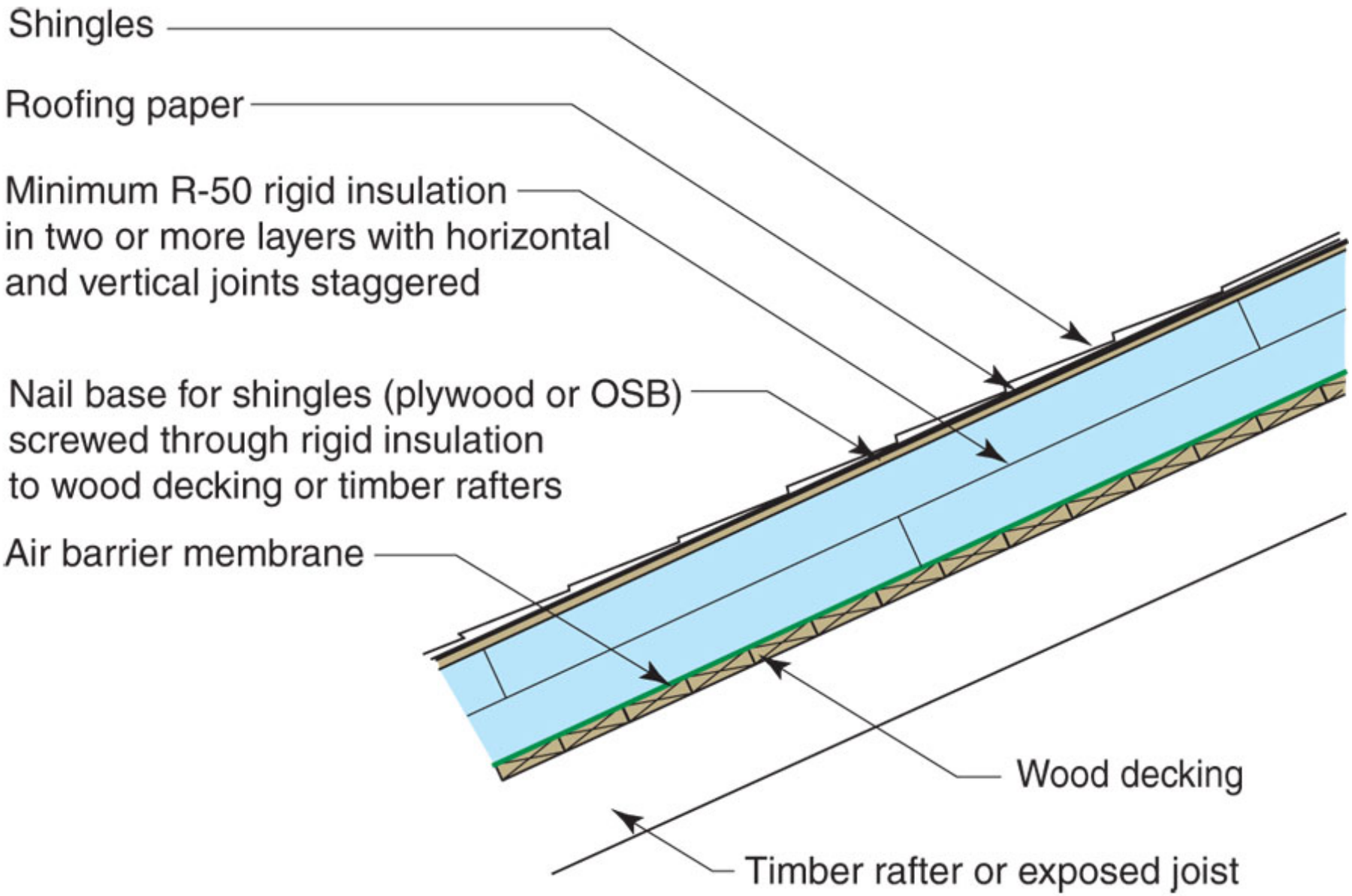

KEEP OUT

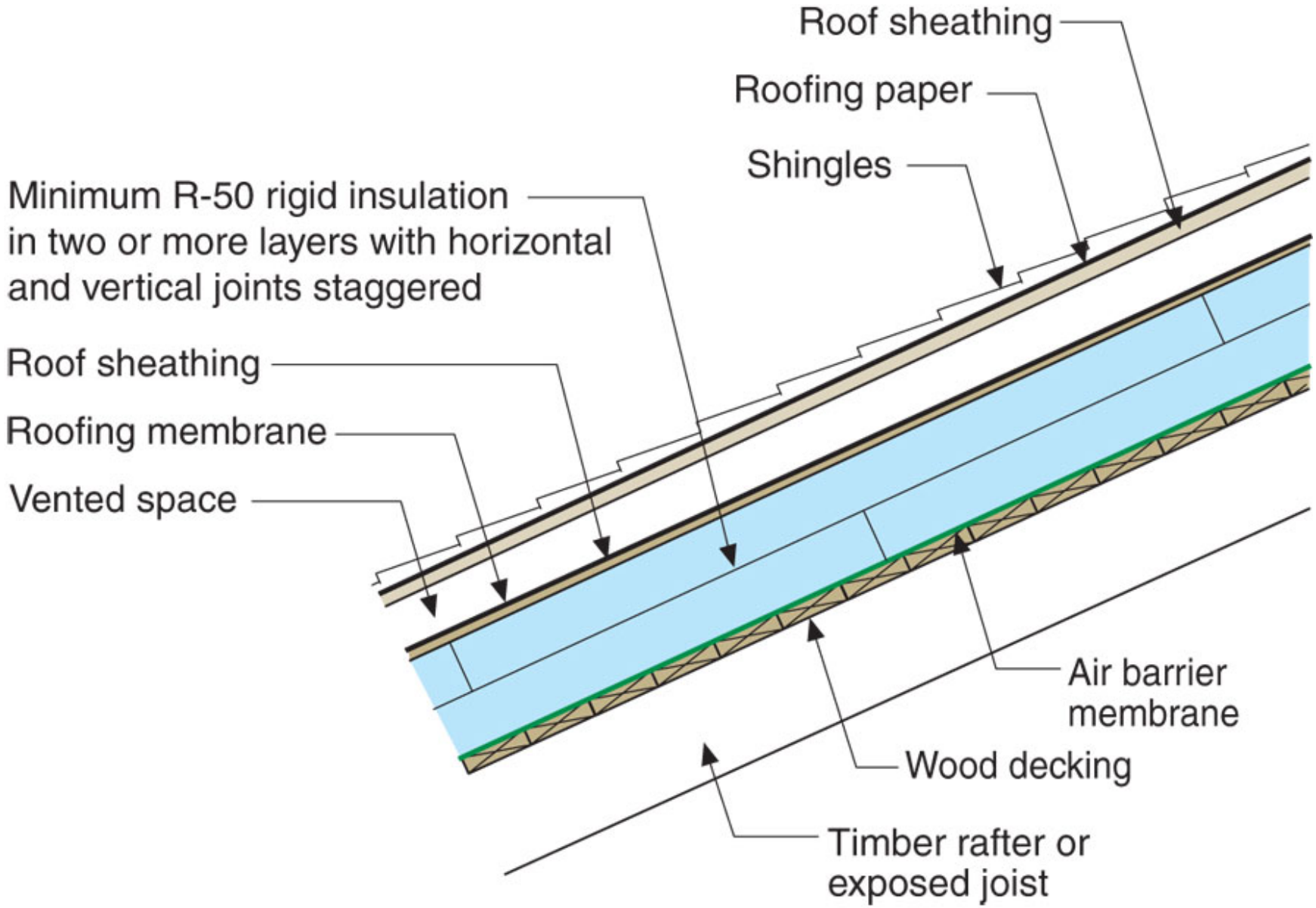

DETAIL @ SNOW GUARD
FLASHING DETAIL @ SNOW GUARD
WATERPROOFING @ SNOWGUARD
CLUB BAR RAKE DETAIL-NORTH END
RAKE/SOFFIT @ OUTDOOR GRILLE/CLUB
MINIMUM WP @ ROOF/WALL
RIDGE RAKE DETAIL
RIDGE EVE @ MTL. ROOF @ WALL
RIDGE CAP DETAIL
FLAT ROOF@ MECH DORMER
TYPICAL ASPHALT SHINGLE ROOF
TYPICAL METAL ROOF
COTTLE GRAYBEAL YAW ARCHITECTS
SUNDECK RESTAURANT
ASPEN COLORADO
ROOF DETAILS
A6.1

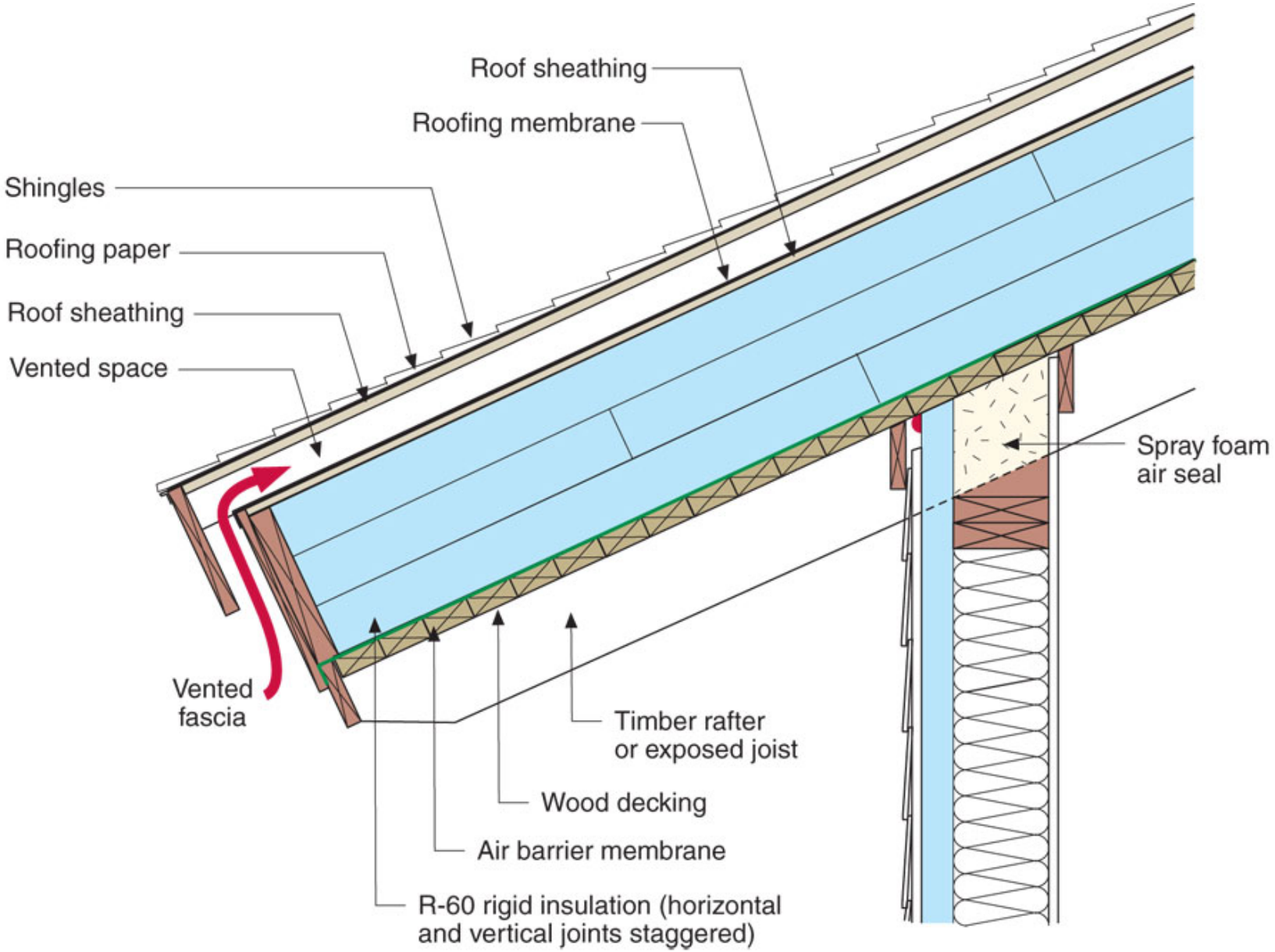


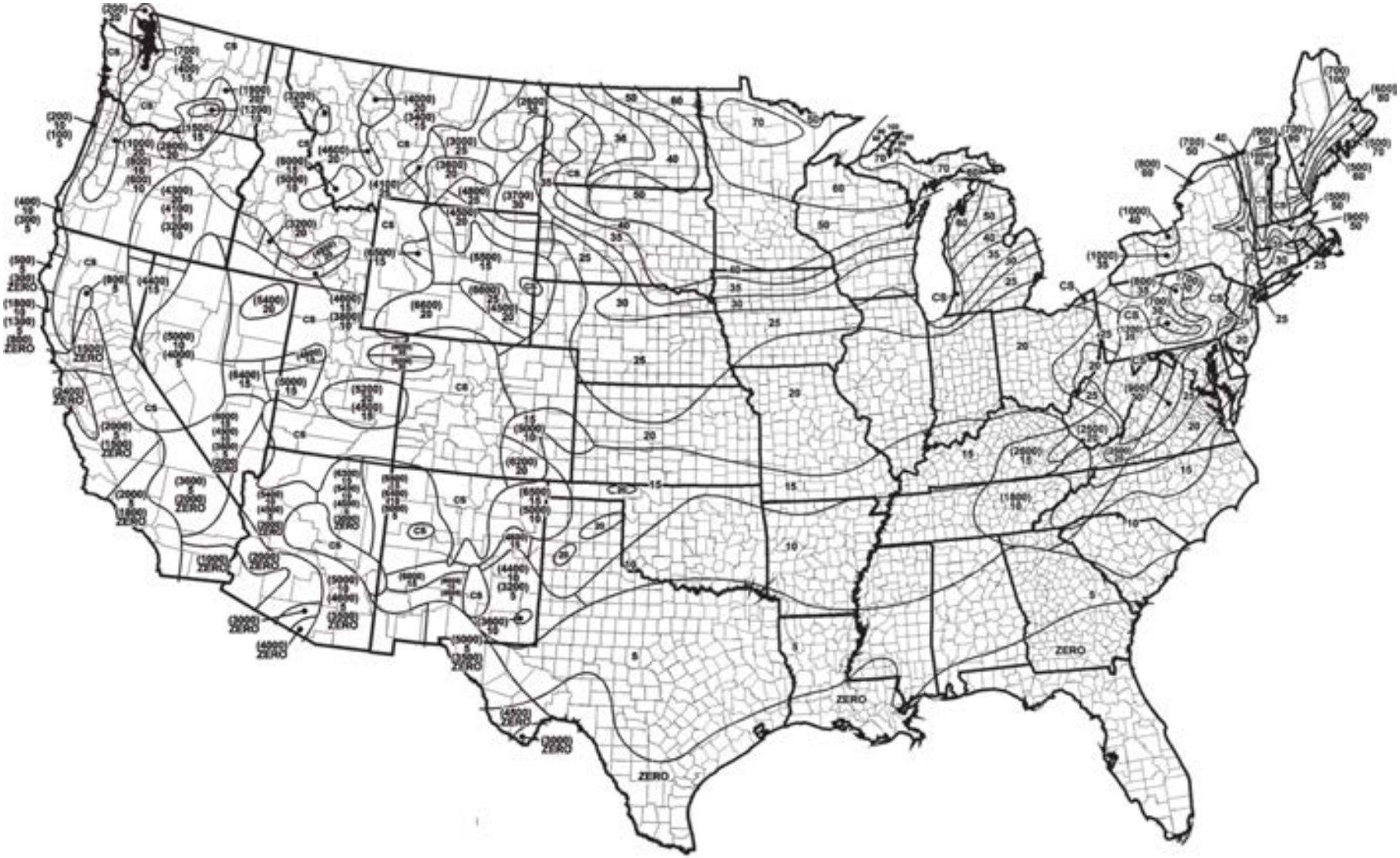
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.


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

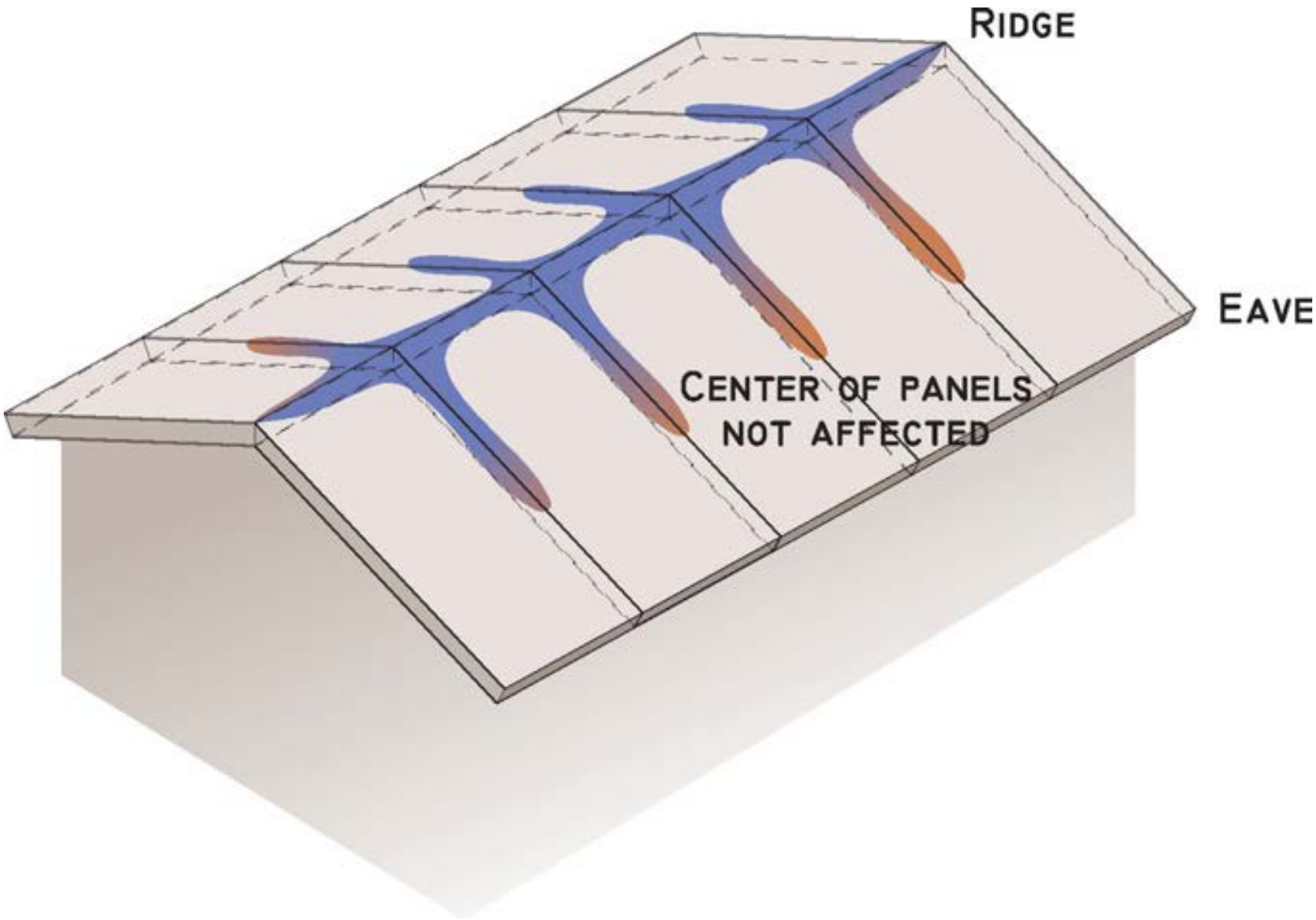

Shingles
Roofing paper
Minimum R-50 rigid insulation
in two or more layers with horizontal
and vertical joints staggered
Nail base for shingles (plywood or OSB)
screwed through rigid insulation
to wood decking or timber rafters
Air barrier membrane
Wood decking
Timber rafter or exposed joist

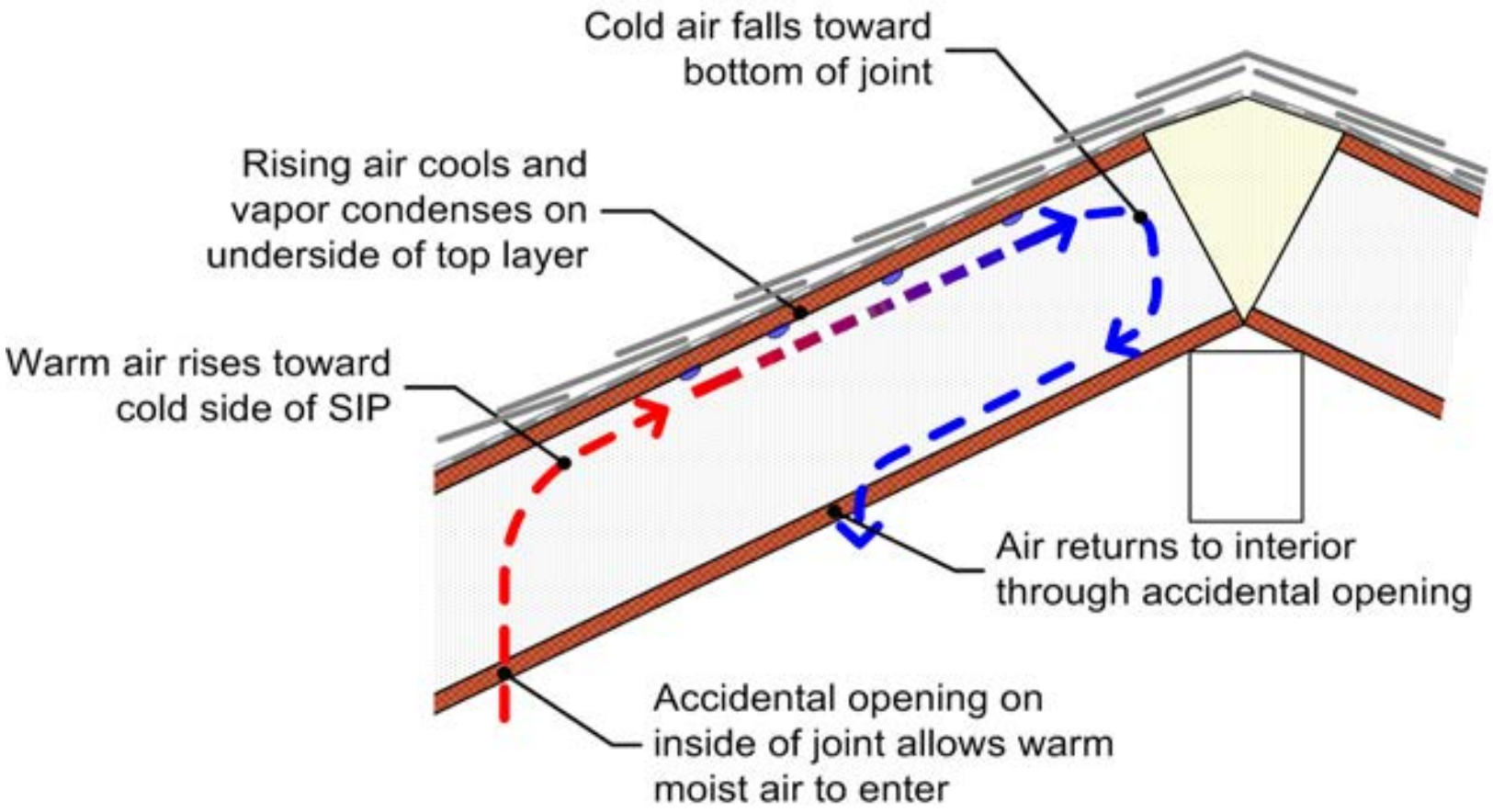

Roof sheathing
Roofing paper
Shingles
Minimum R-50 rigid insulation
in two or more layers with horizontal
and vertical joints staggered
Roof sheathing
Roofing membrane
Vented space
Air barrier
membrane
Wood decking
Timber rafter or
exposed joist

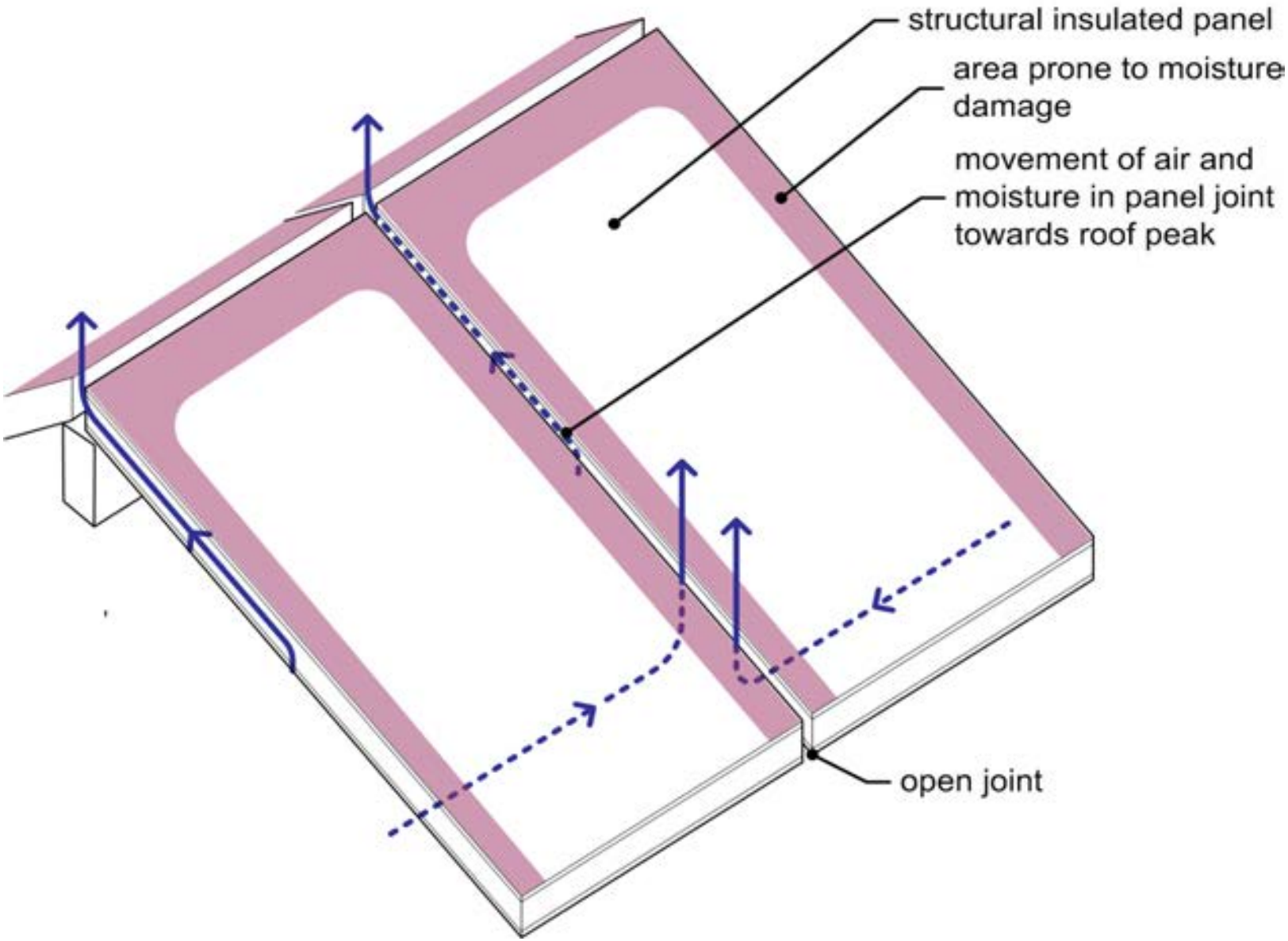

Roof sheathing
Roofing membrane
Shingles
Roofing paper
Roof sheathing
Vented space
Spray foam
air seal
Vented
fascia
Timber rafter
or exposed joist
Wood decking
Air barrier membrane
R-60 rigid insulation (horizontal
and vertical joints staggered)

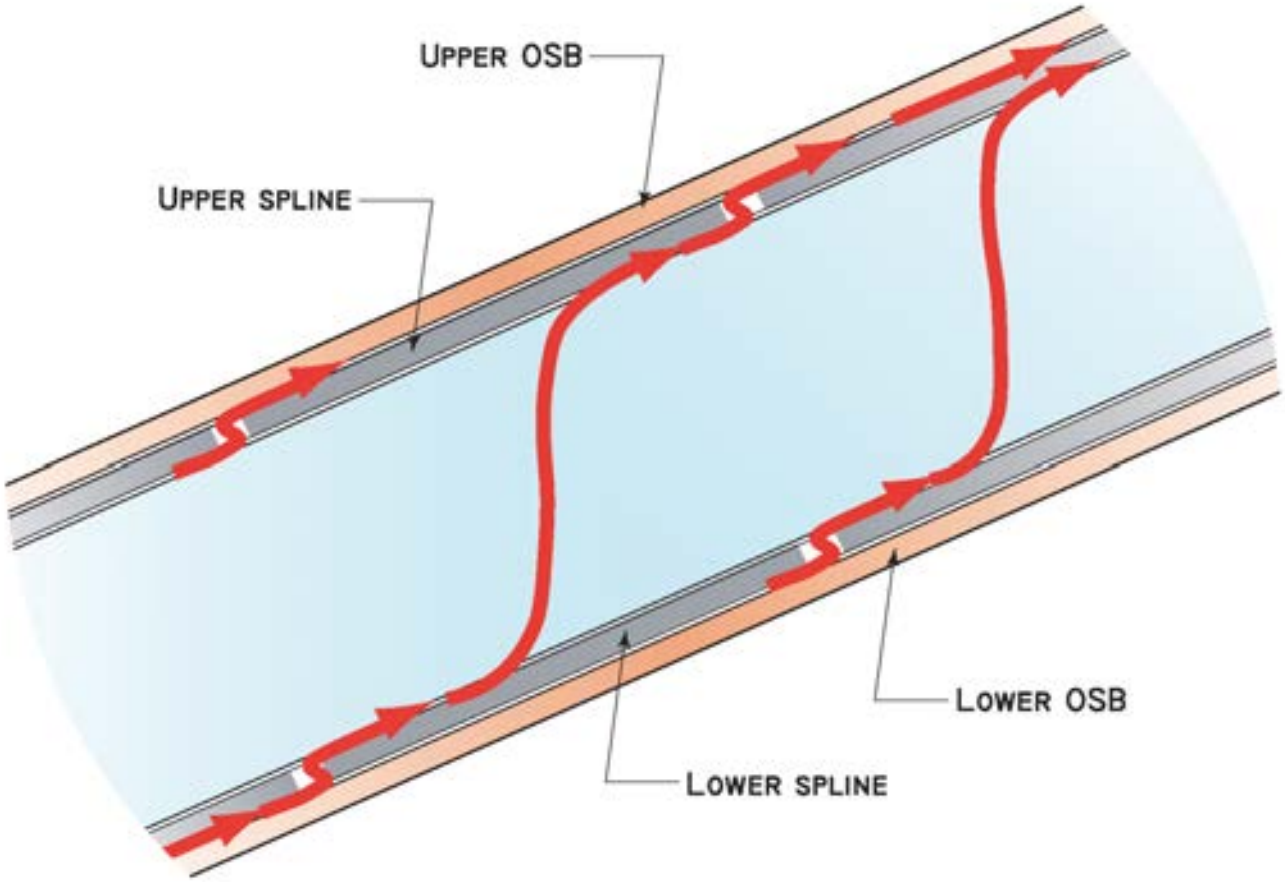

ZERO
ZERO
ZERO
ZERO


8/22/01 09:32


RIDGE
EAVE
CENTER OF PANELS
NOT AFFECTED


Cold air falls toward bottom of joint
Rising air cools and vapor condenses on underside of top layer
Warm air rises toward cold side of SIP
Air returns to interior through accidental opening
Accidental opening on inside of joint allows warm moist air to enter


structural insulated panel
area prone to moisture damage
movement of air and moisture in panel joint towards roof peak
open joint

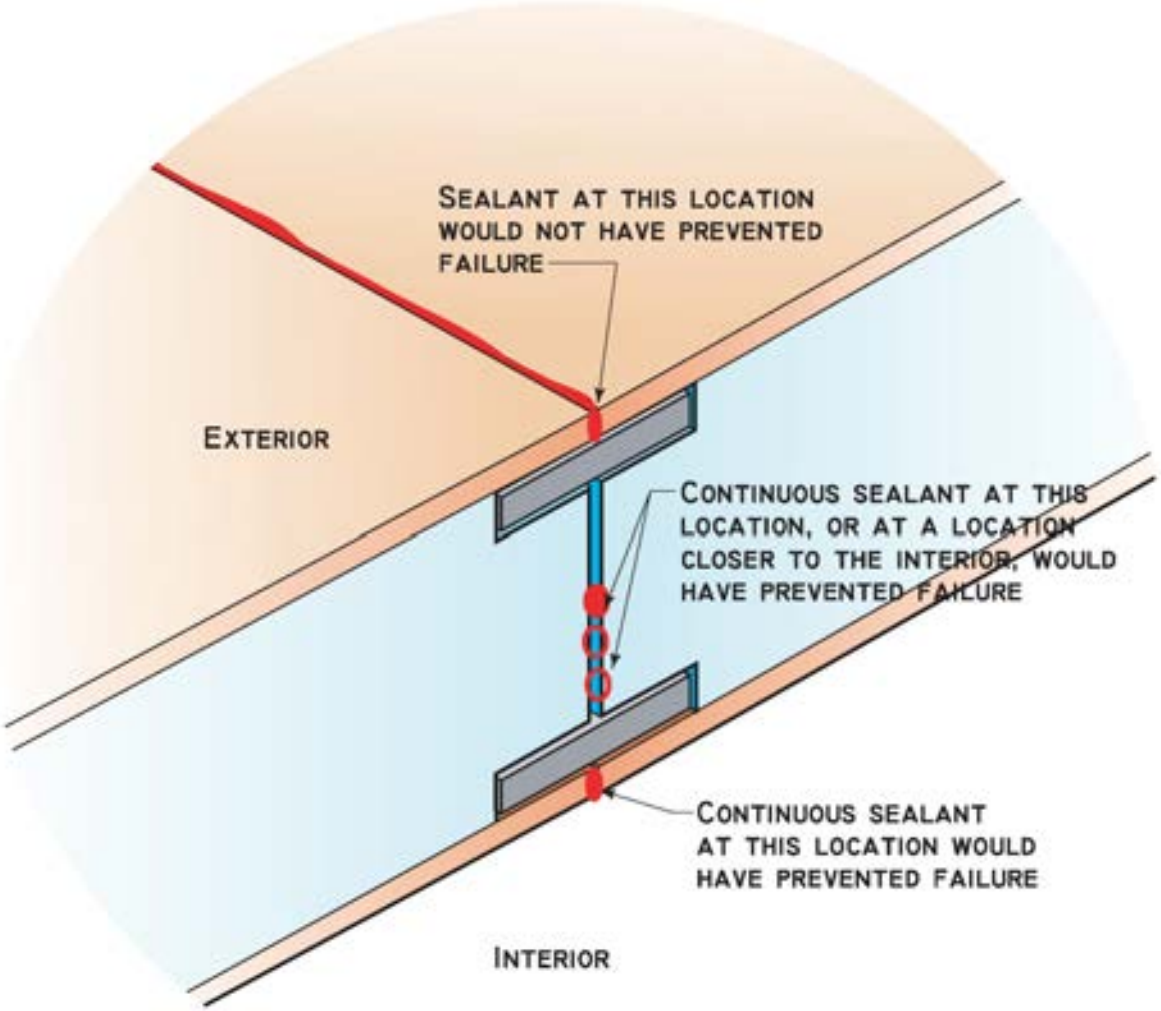

UPPER OSB
UPPER SPLINE
LOWER OSB
LOWER SPLINE

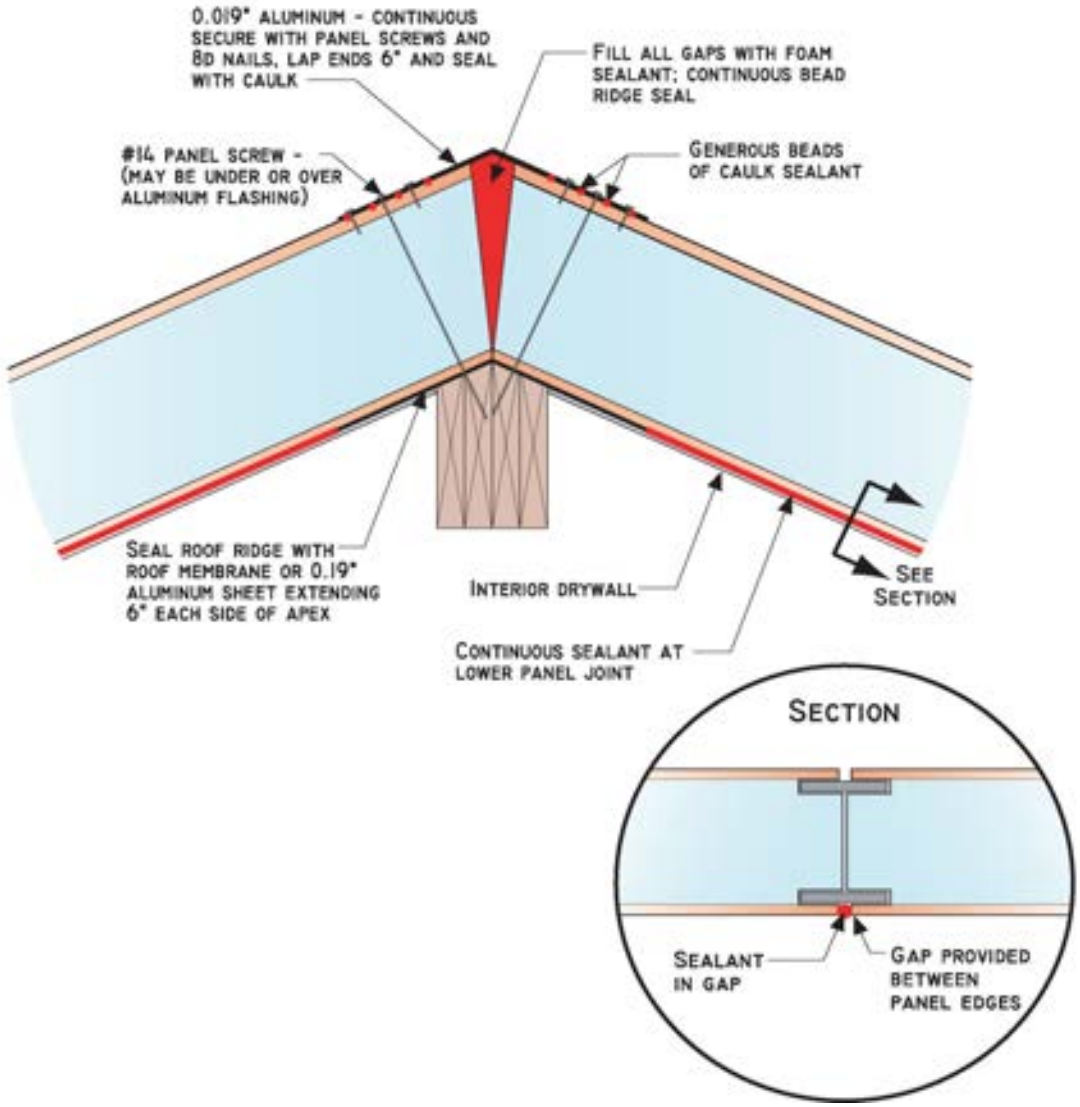

8/22/01 10:13


8/22/01 10:29

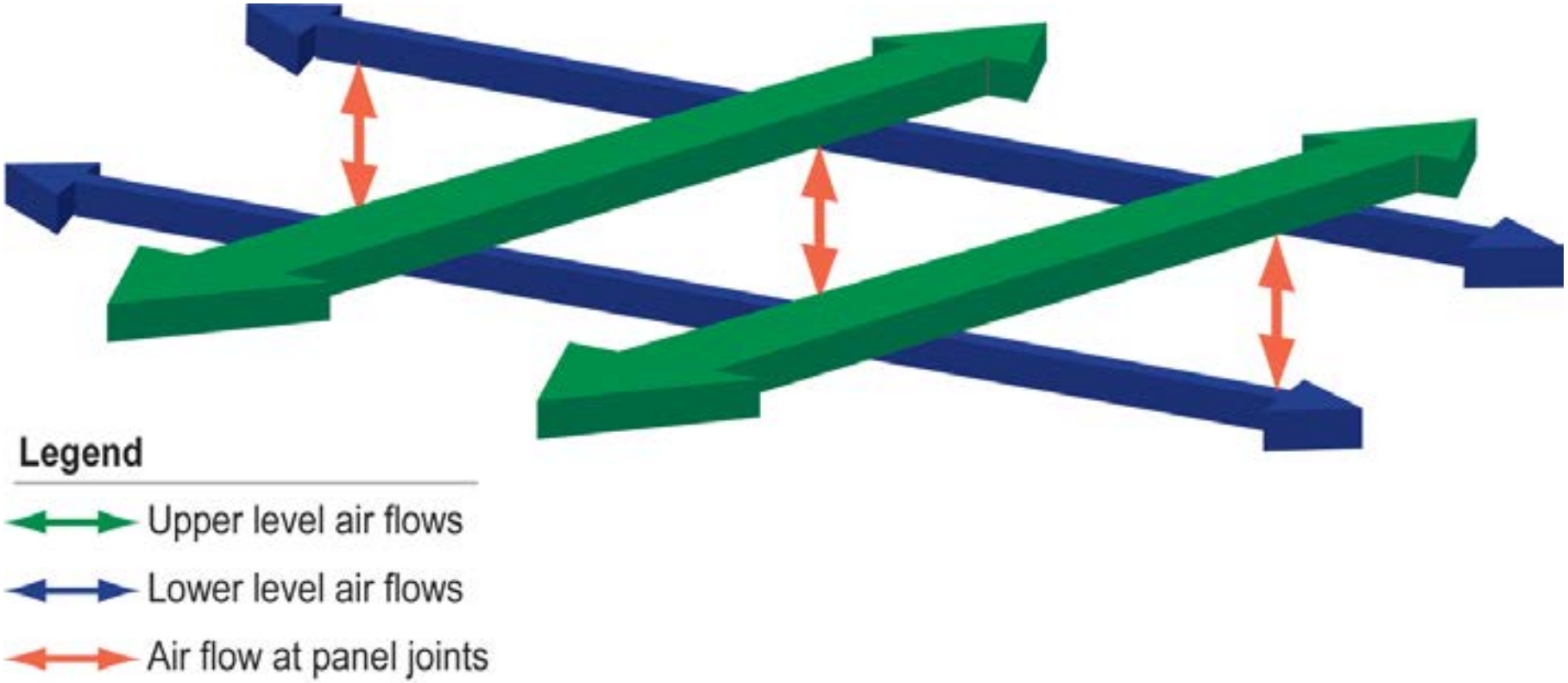

8/22/01 10:30

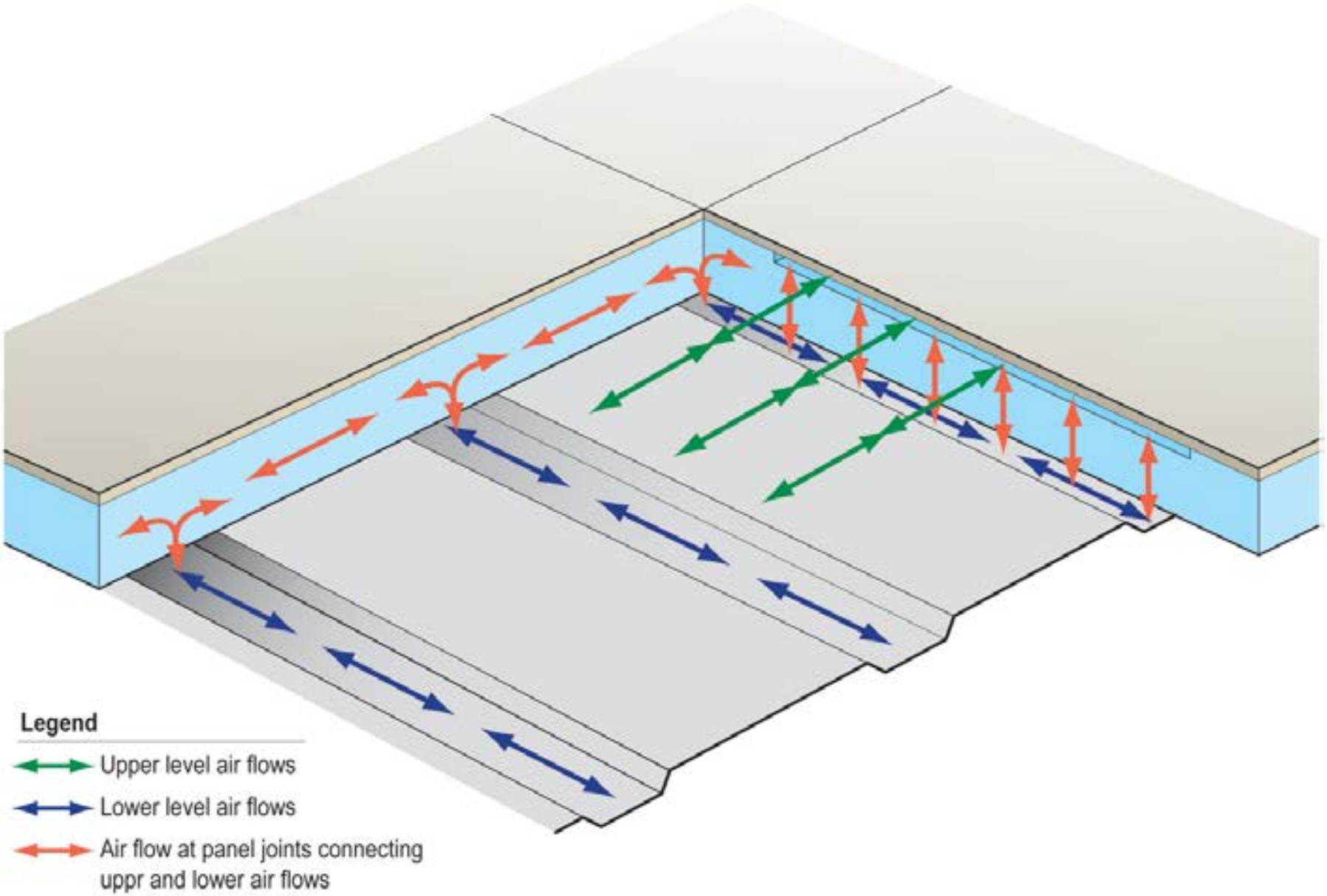

8/17/01 11:43

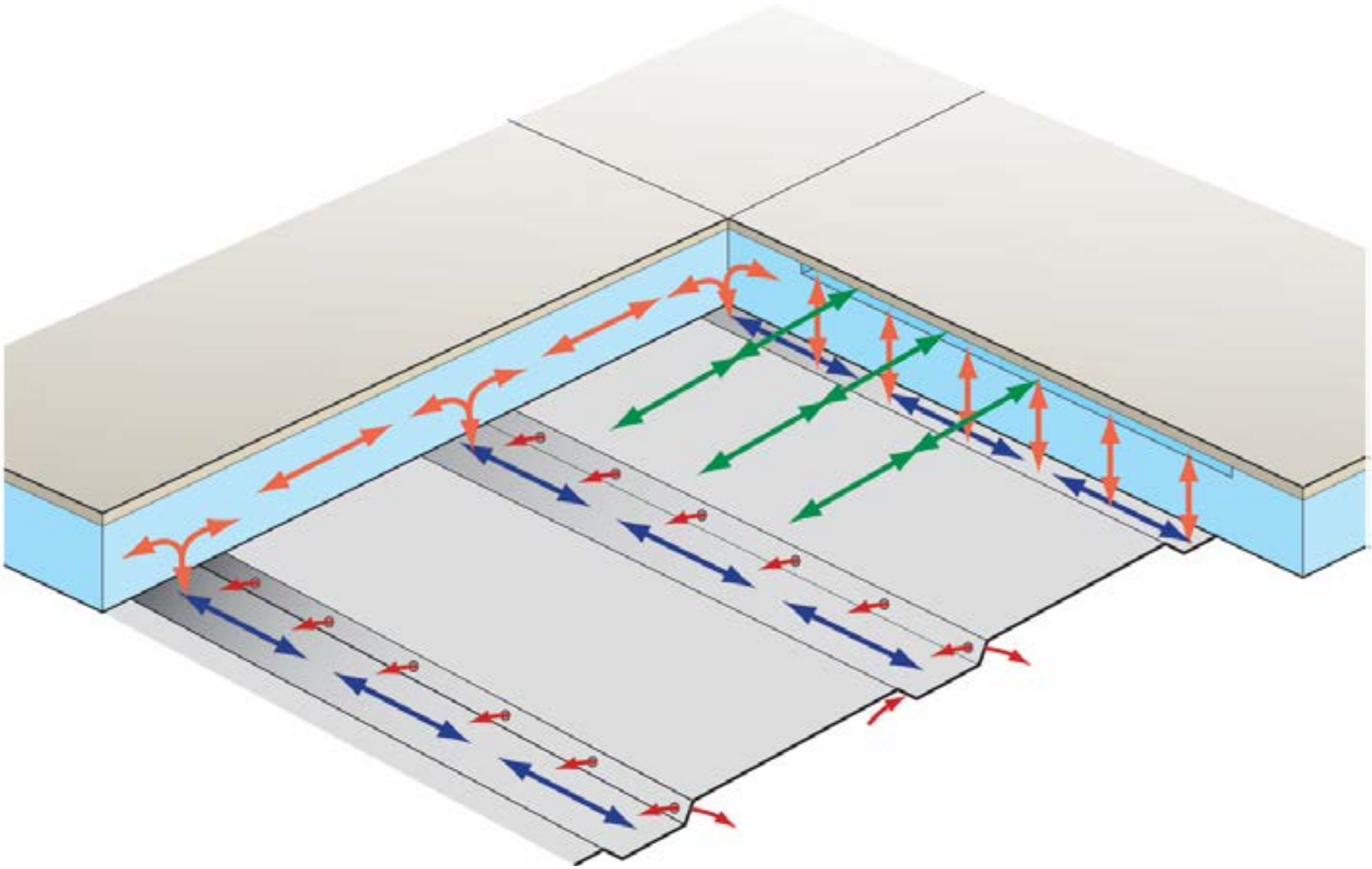

SEALANT AT THIS LOCATION WOULD NOT HAVE PREVENTED FAILURE
EXTERIOR
CONTINUOUS SEALANT AT THIS LOCATION, OR AT A LOCATION CLOSER TO THE INTERIOR, WOULD HAVE PREVENTED FAILURE
CONTINUOUS SEALANT AT THIS LOCATION WOULD HAVE PREVENTED FAILURE
INTERIOR

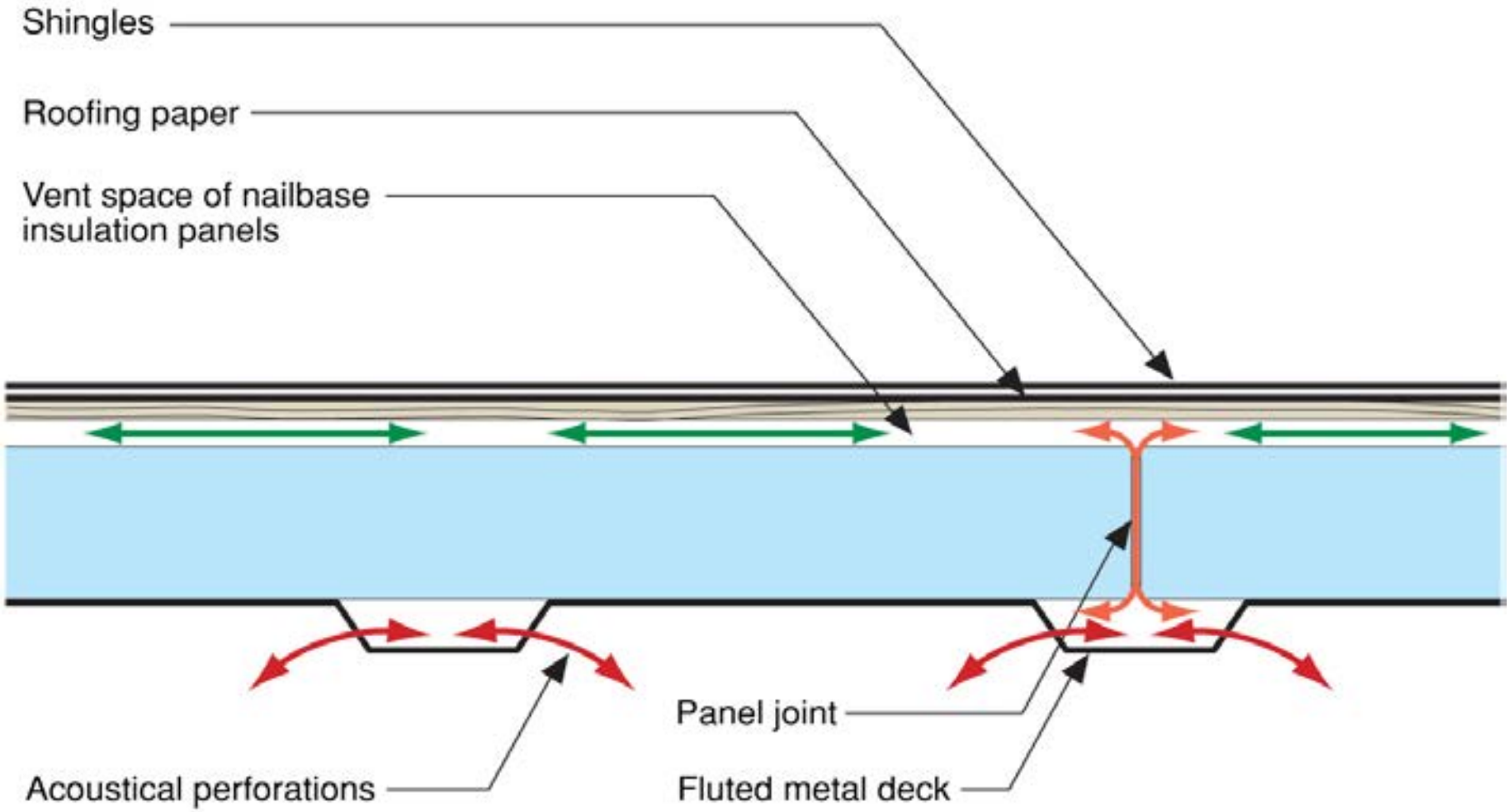

0.019" ALUMINUM - CONTINUOUS SECURE WITH PANEL SCREWS AND 8D NAILS, LAP ENDS 6" AND SEAL WITH CAULK
FILL ALL GAPS WITH FOAM SEALANT; CONTINUOUS BEAD RIDGE SEAL
#14 PANEL SCREW - (MAY BE UNDER OR OVER ALUMINUM FLASHING)
GENEROUS BEADS OF CAULK SEALANT
SEAL ROOF RIDGE WITH ROOF MEMBRANE OR 0.19" ALUMINUM SHEET EXTENDING 6" EACH SIDE OF APEX
INTERIOR DRYWALL
SEE SECTION
CONTINUOUS SEALANT AT LOWER PANEL JOINT
SECTION
SEALANT IN GAP
GAP PROVIDED BETWEEN PANEL EDGES

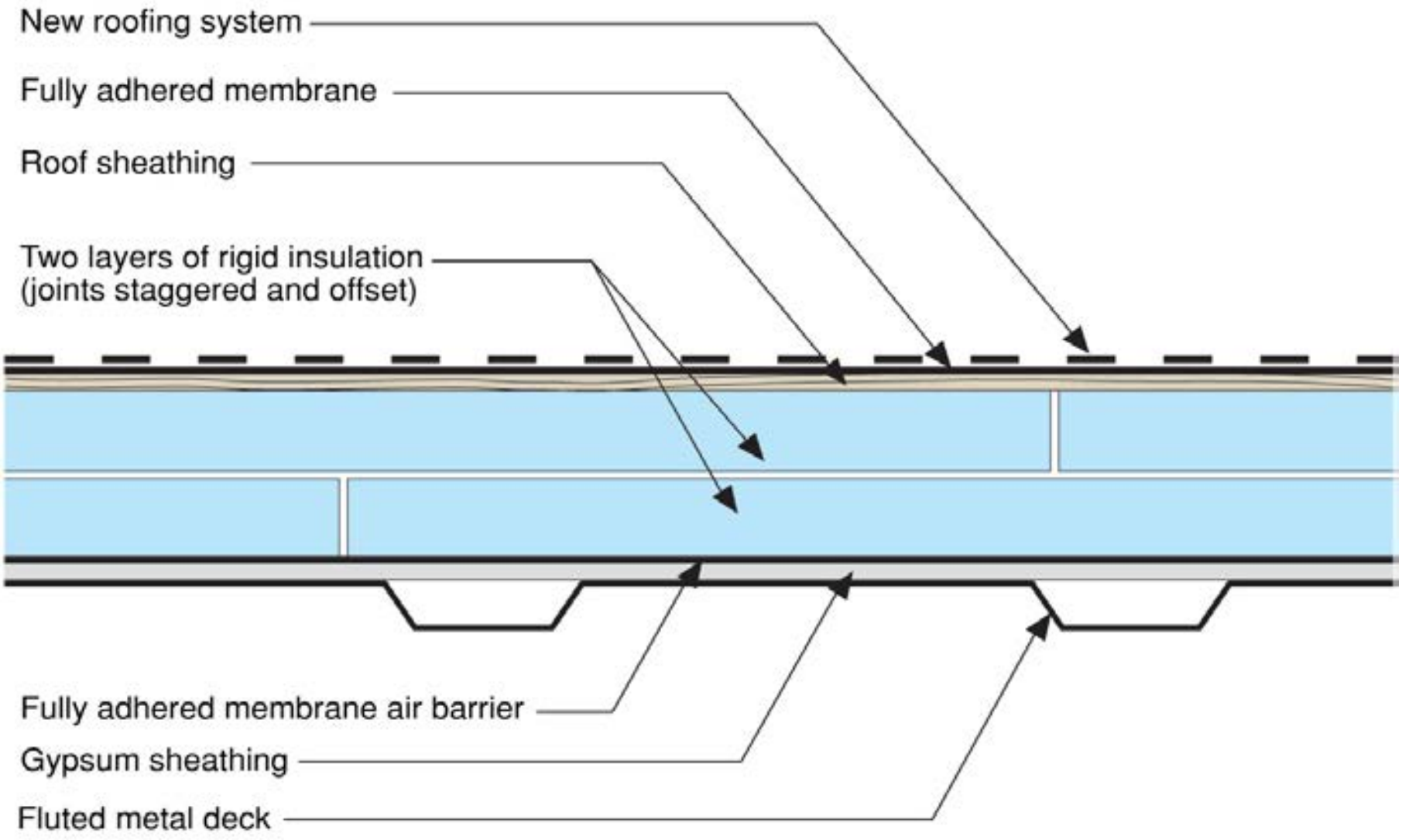

DIET

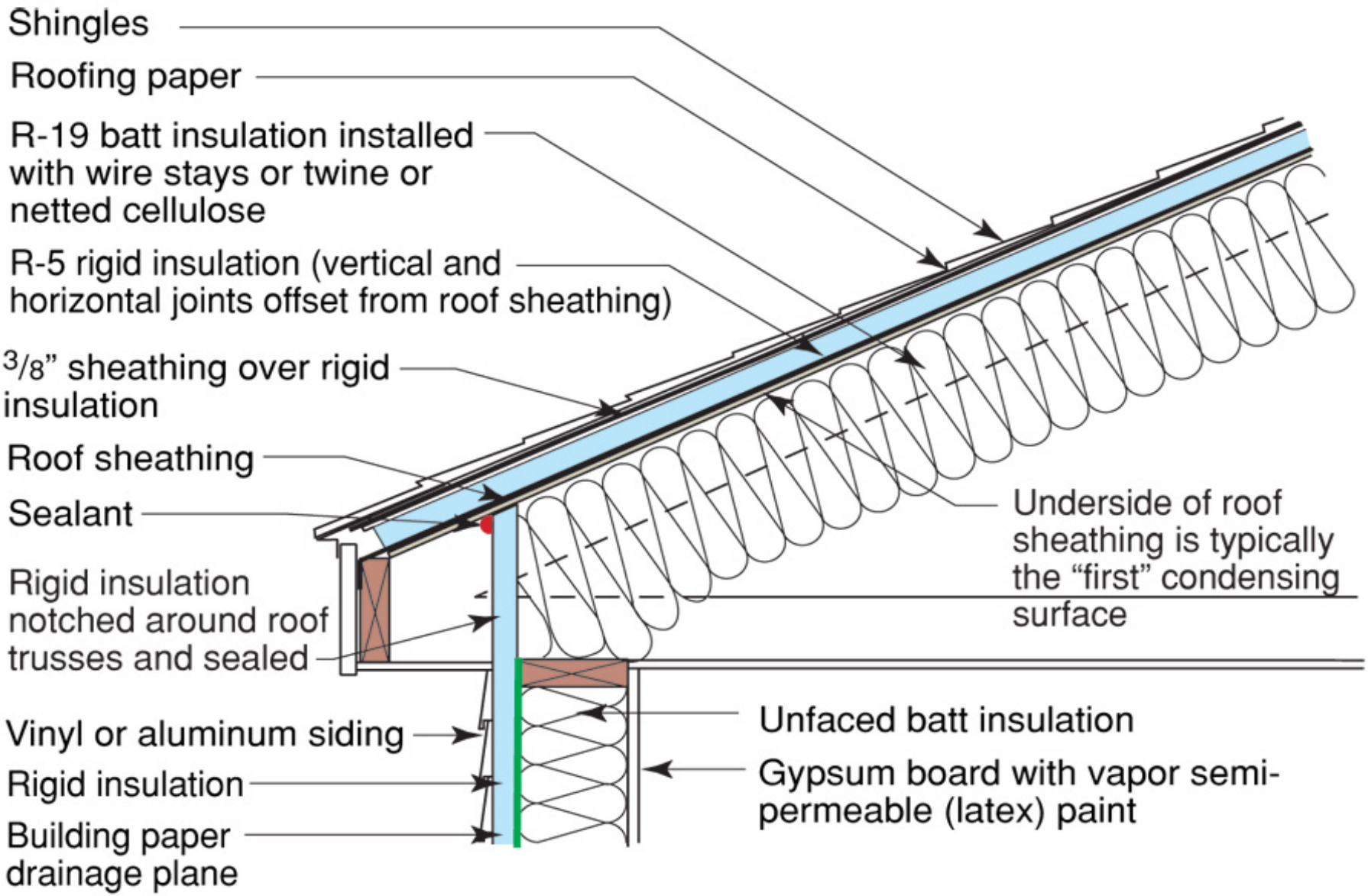

Legend
Upper level air flows
Lower level air flows
Air flow at panel joints

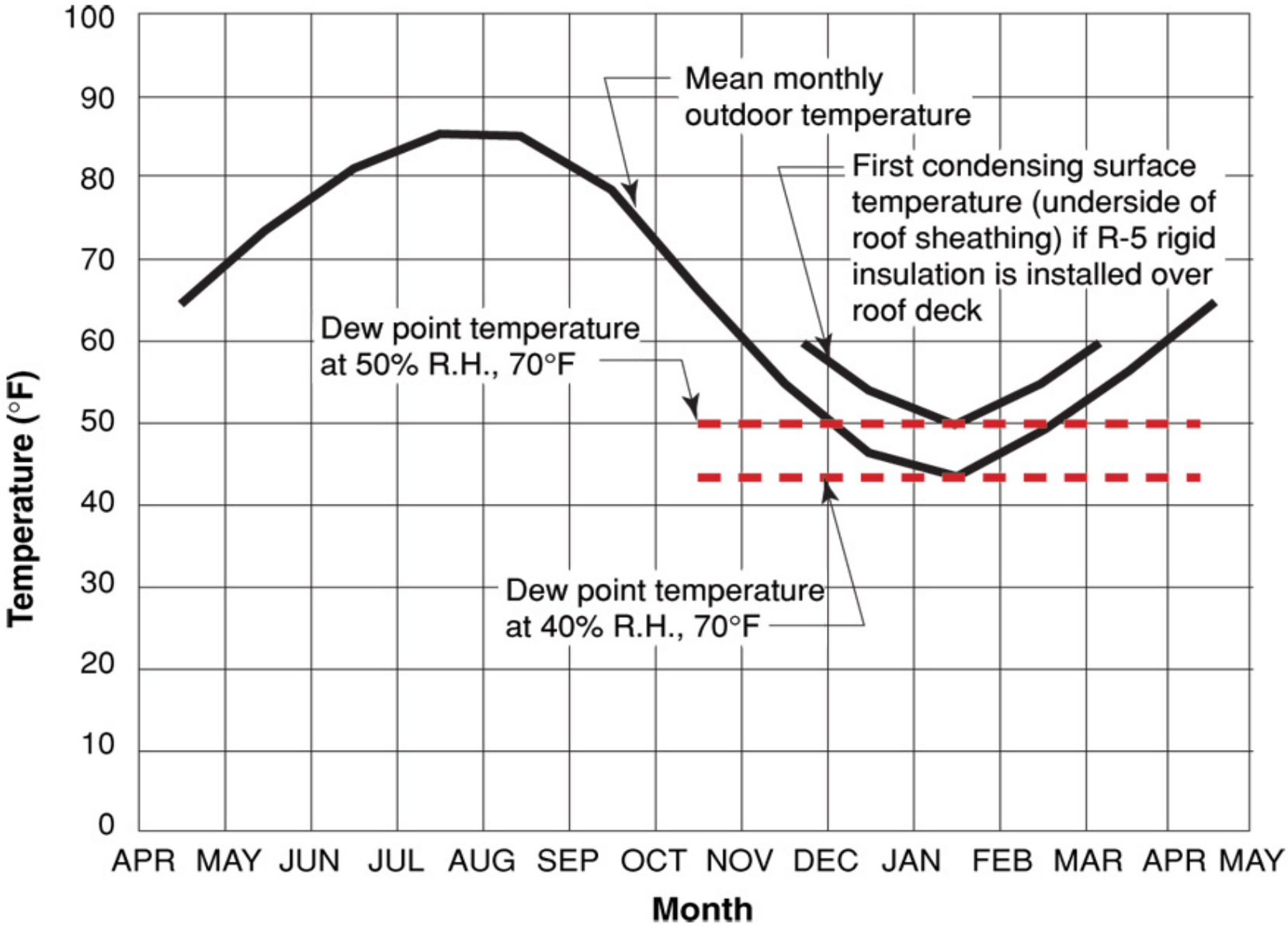

Legend
Upper level air flows
Lower level air flows
Air flow at panel joints connecting
uppr and lower air flows

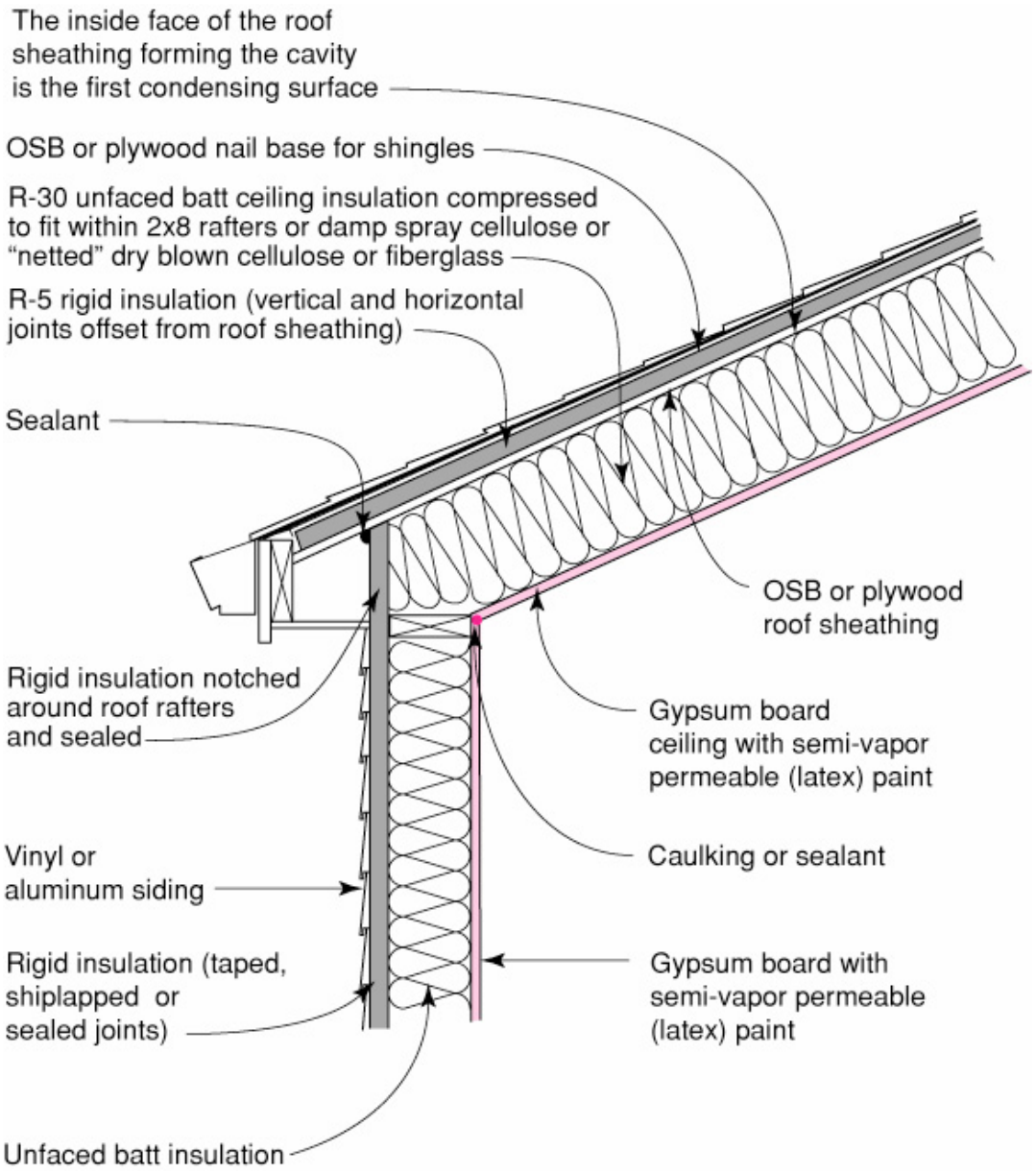


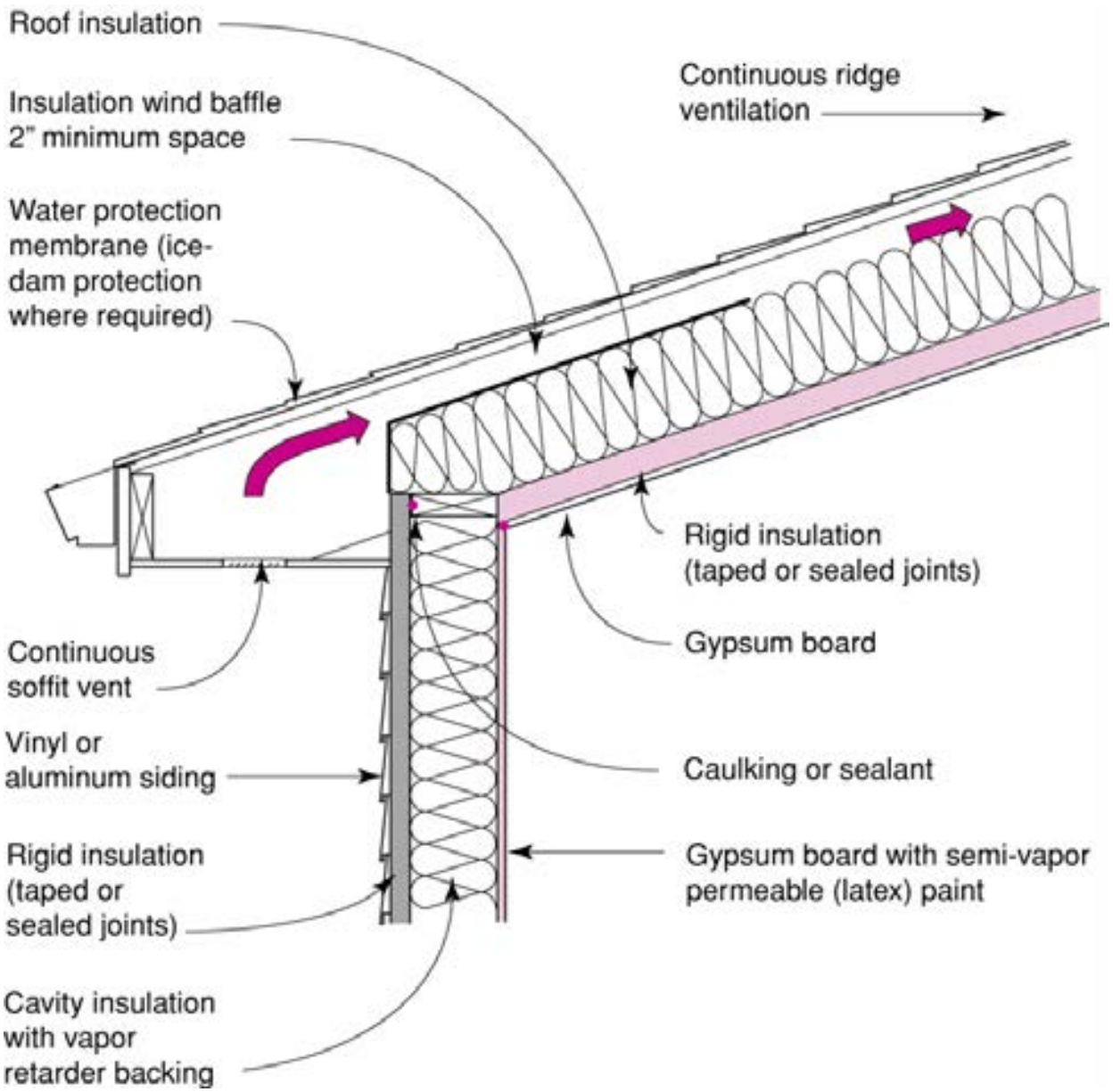

Shingles
Roofing paper
Vent space of nailbase insulation panels
Panel joint
Acoustical perforations
Fluted metal deck

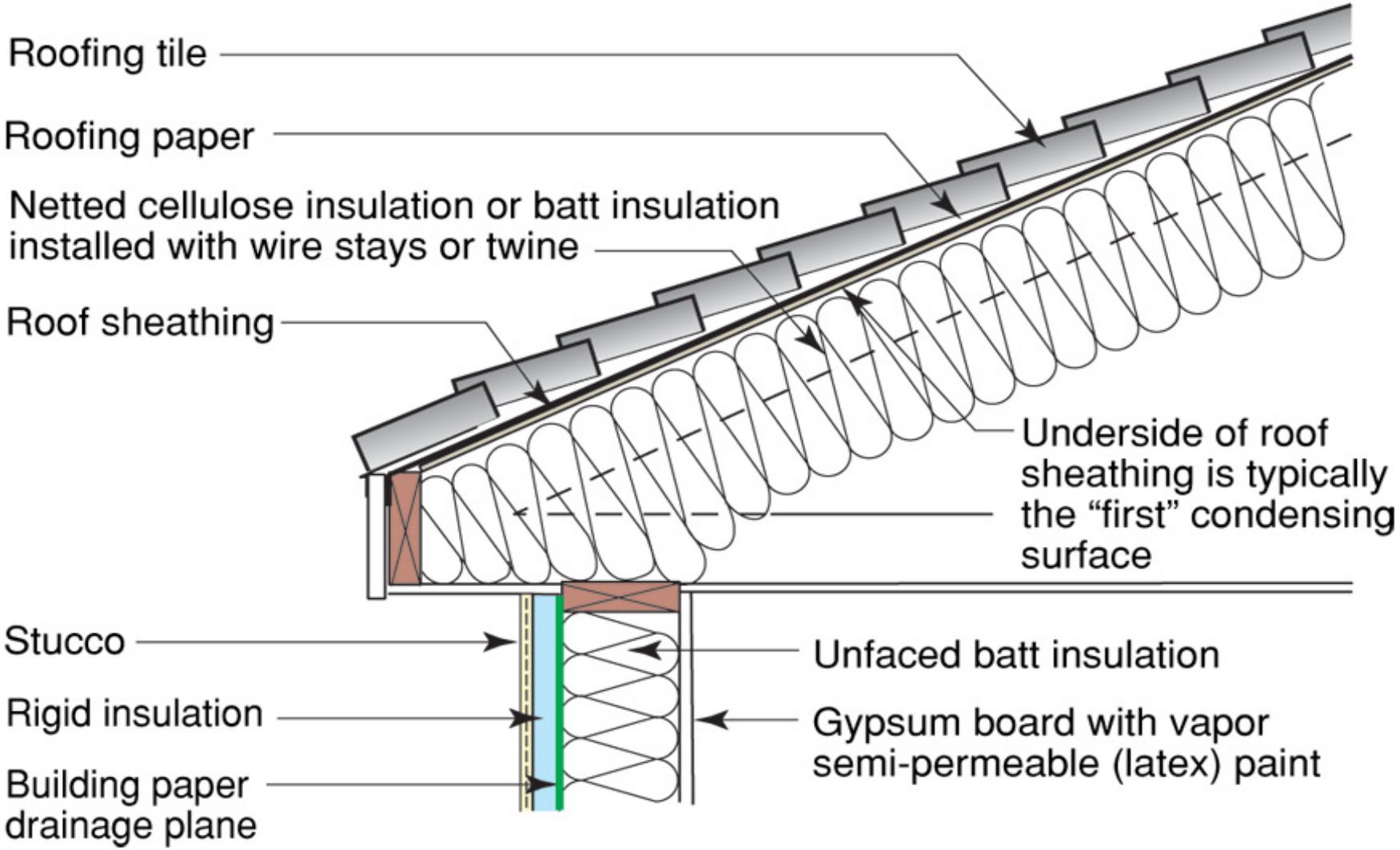

New roofing system
Fully adhered membrane
Roof sheathing
Two layers of rigid insulation
(joints staggered and offset)
Fully adhered membrane air barrier
Gypsum sheathing
Fluted metal deck

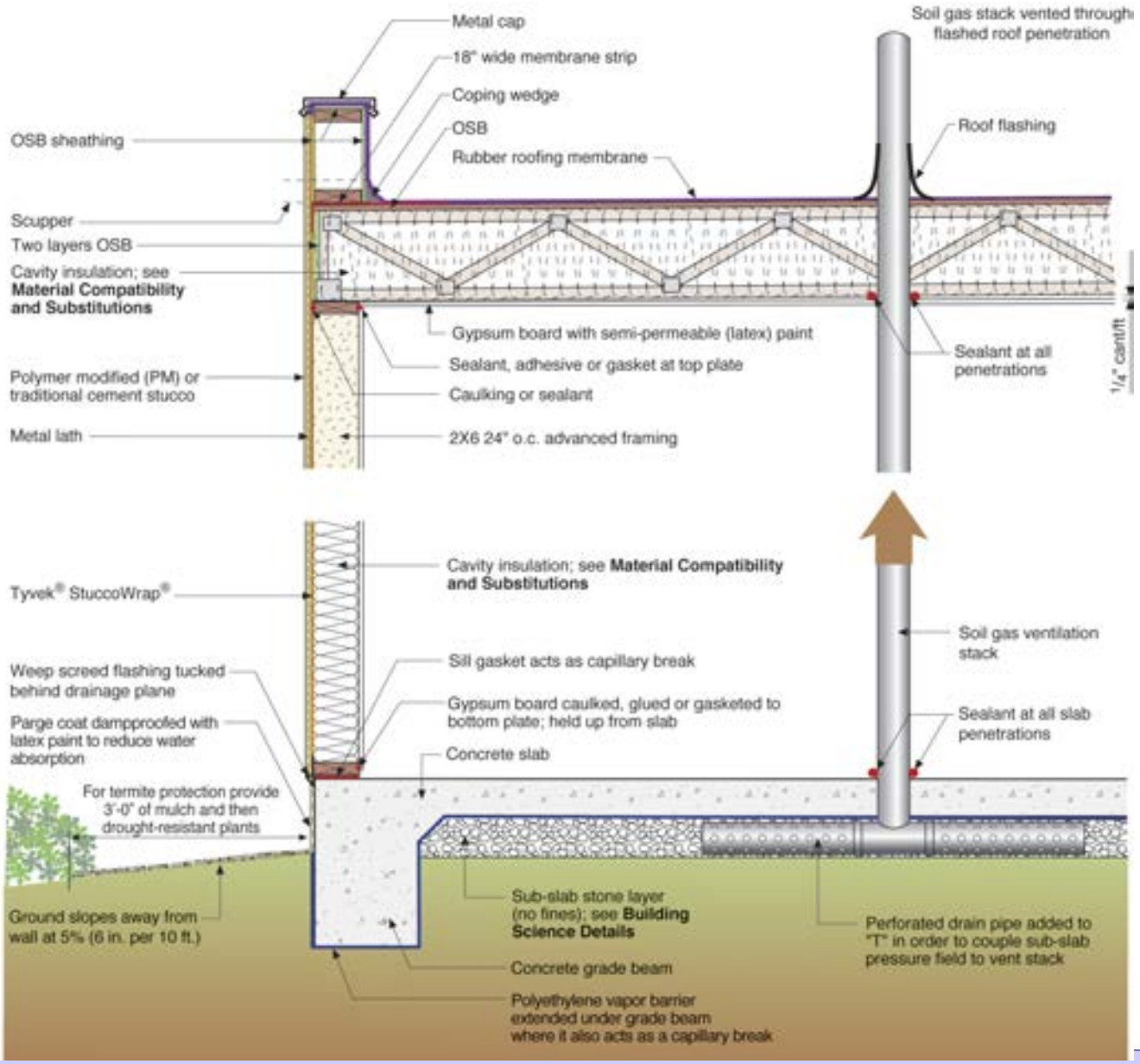

Shingles
Roofing paper
R-19 batt insulation installed with wire stays or twine or netted cellulose
R-5 rigid insulation (vertical and horizontal joints offset from roof sheathing)
3/8" sheathing over rigid insulation
Roof sheathing
Sealant
Rigid insulation notched around roof trusses and sealed
Vinyl or aluminum siding
Rigid insulation
Building paper drainage plane
Underside of roof sheathing is typically the "first" condensing surface
Unfaced batt insulation
Gypsum board with vapor semi-permeable (latex) paint

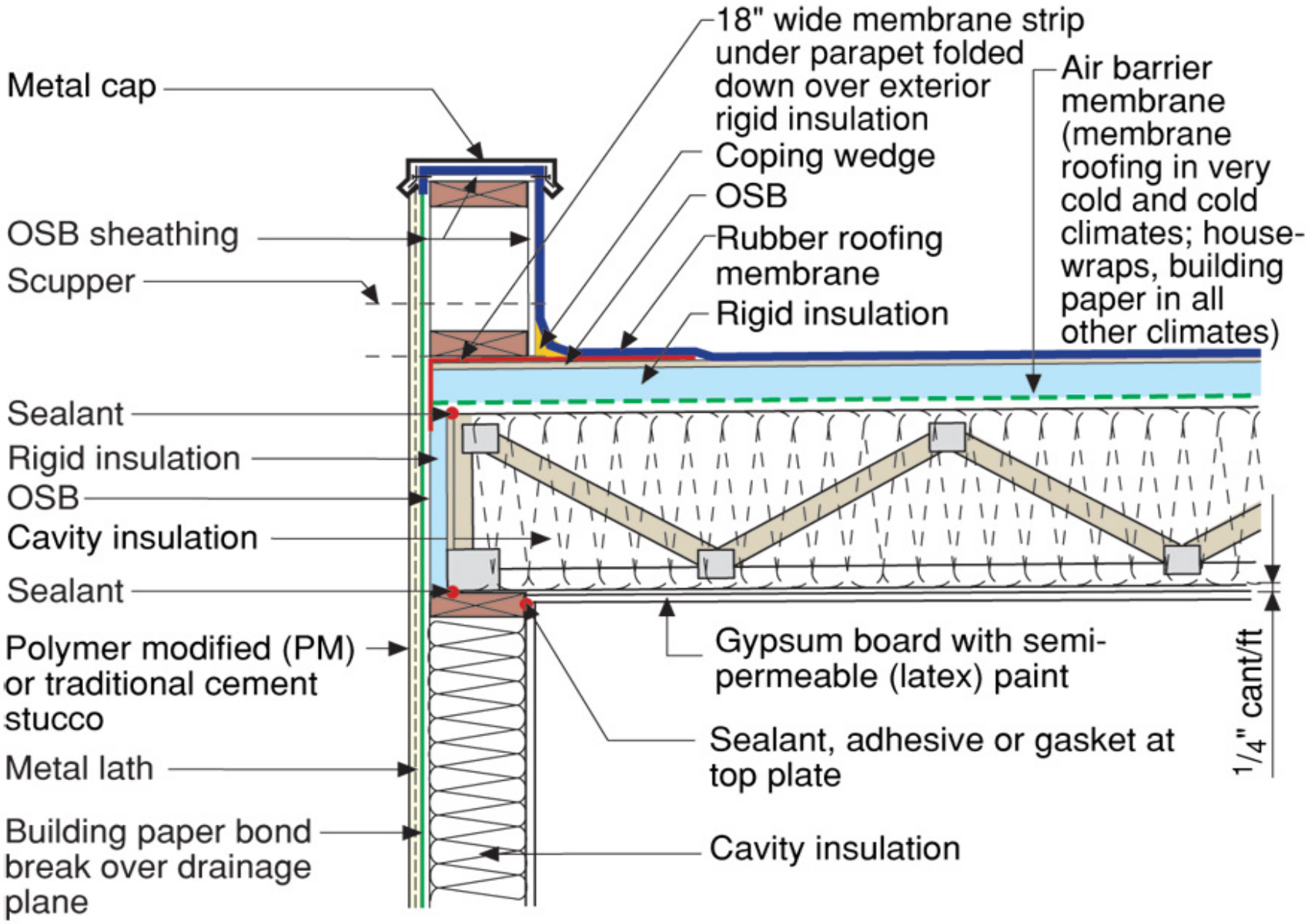

100
90
80
70
60
50
40
30
20
10
0
Temperature (°F)
APR MAY JUN JUL AUG SEP OCT NOV DEC JAN FEB MAR APR MAY
Month
Mean monthly outdoor temperature
First condensing surface temperature (underside of roof sheathing) if R-5 rigid insulation is installed over roof deck
Dew point temperature at 50% R.H., 70°F
Dew point temperature at 40% R.H., 70°F

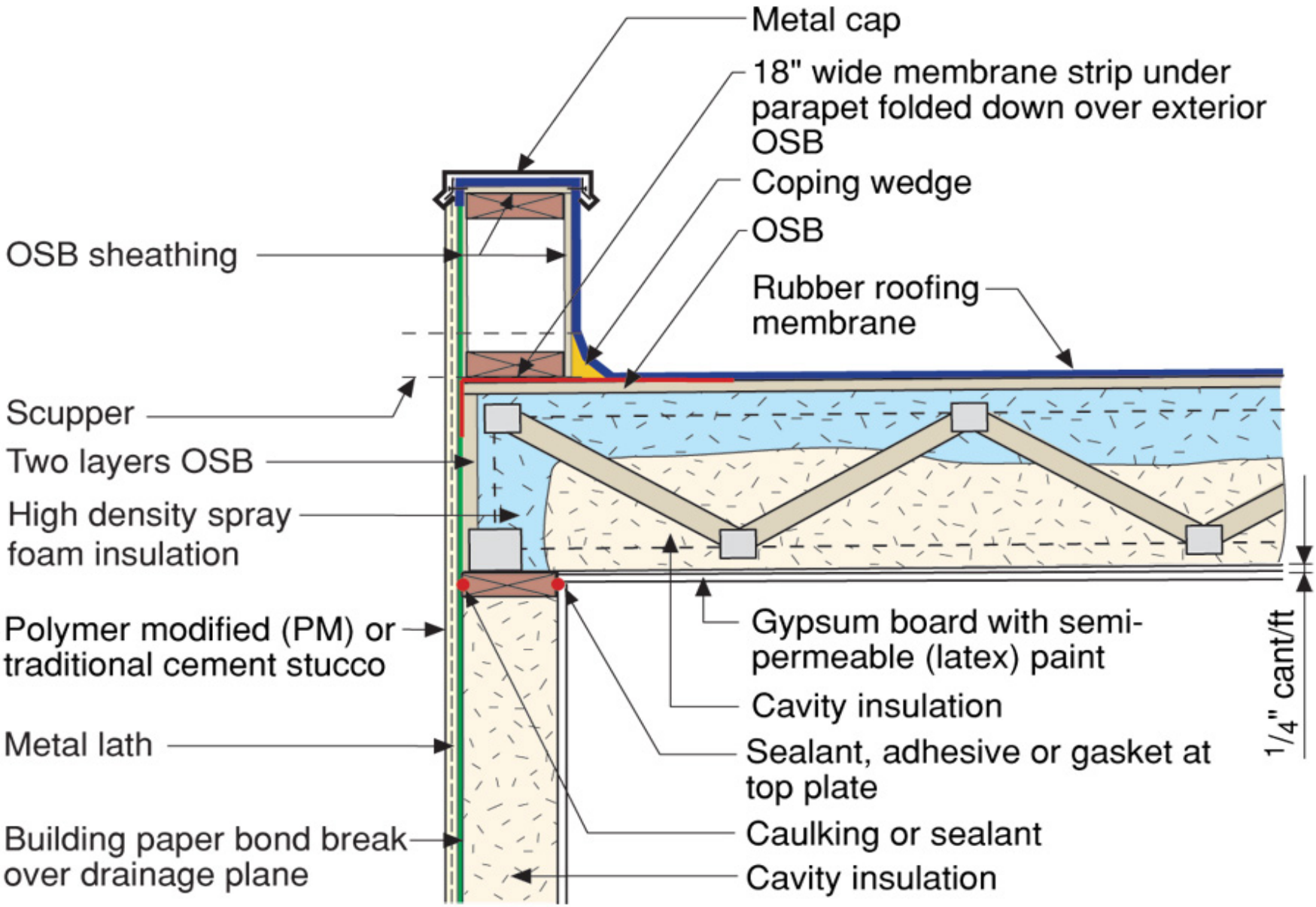

The inside face of the roof sheathing forming the cavity is the first condensing surface
OSB or plywood nail base for shingles
R-30 unfaced batt ceiling insulation compressed to fit within 2x8 rafters or damp spray cellulose or "netted" dry blown cellulose or fiberglass
R-5 rigid insulation (vertical and horizontal joints offset from roof sheathing)
Sealant
OSB or plywood roof sheathing
Rigid insulation notched around roof rafters and sealed
Gypsum board ceiling with semi-vapor permeable (latex) paint
Caulking or sealant
Vinyl or aluminum siding
Rigid insulation (taped, shiplapped or sealed joints)
Gypsum board with semi-vapor permeable (latex) paint
Unfaced batt insulation

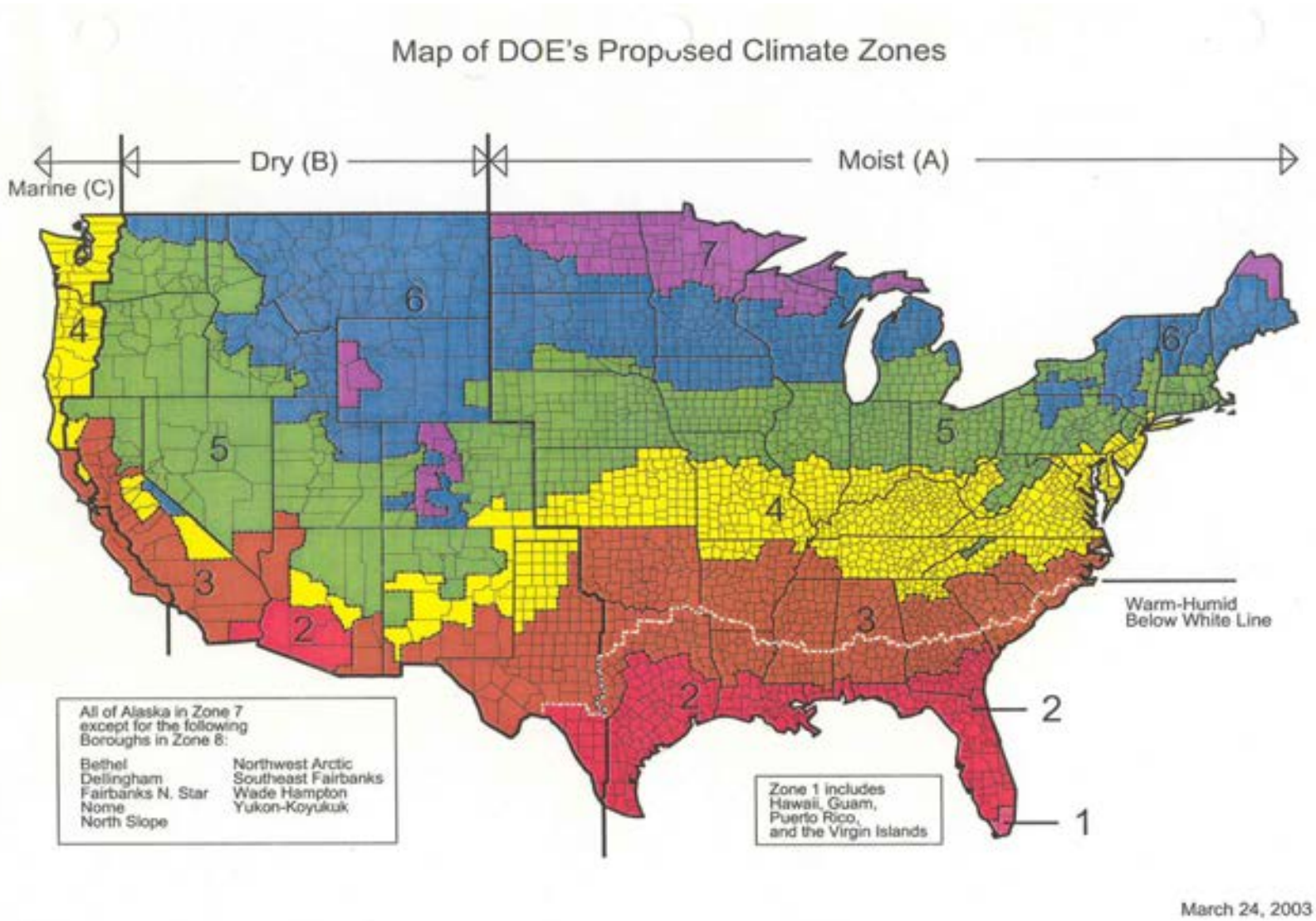

Roof insulation
Insulation wind baffle
2" minimum space
Water protection
membrane (ice-
dam protection
where required)
Continuous ridge
ventilation
Rigid insulation
(taped or sealed joints)
Gypsum board
Continuous
soffit vent
Vinyl or
aluminum siding
Caulking or sealant
Rigid insulation
(taped or
sealed joints)
Gypsum board with semi-vapor
permeable (latex) paint
Cavity insulation
with vapor
retarder backing

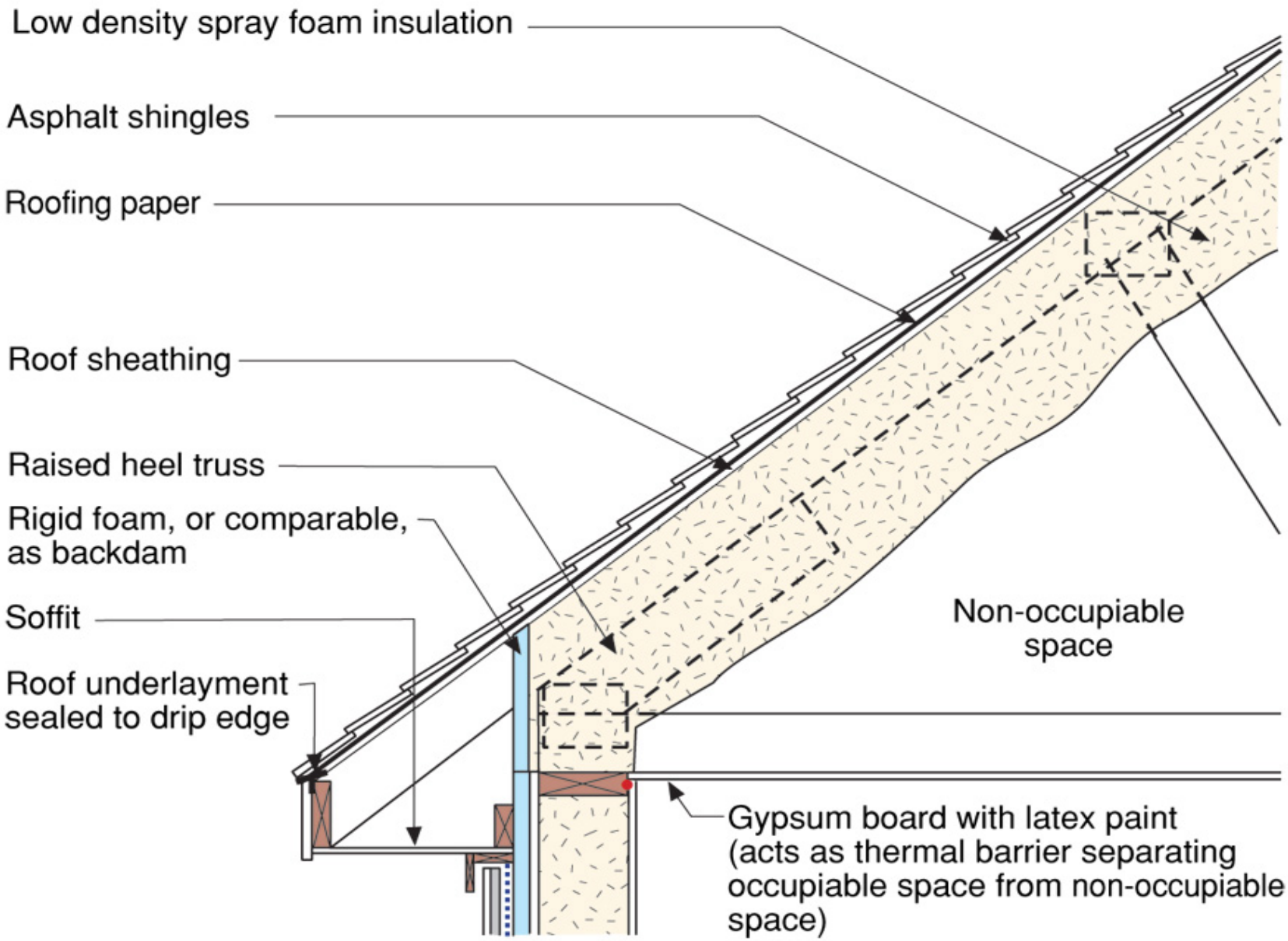

Roofing tile
Roofing paper
Netted cellulose insulation or batt insulation installed with wire stays or twine
Roof sheathing
Underside of roof sheathing is typically the “first” condensing surface
Stucco
Rigid insulation
Building paper drainage plane
Unfaced batt insulation
Gypsum board with vapor semi-permeable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

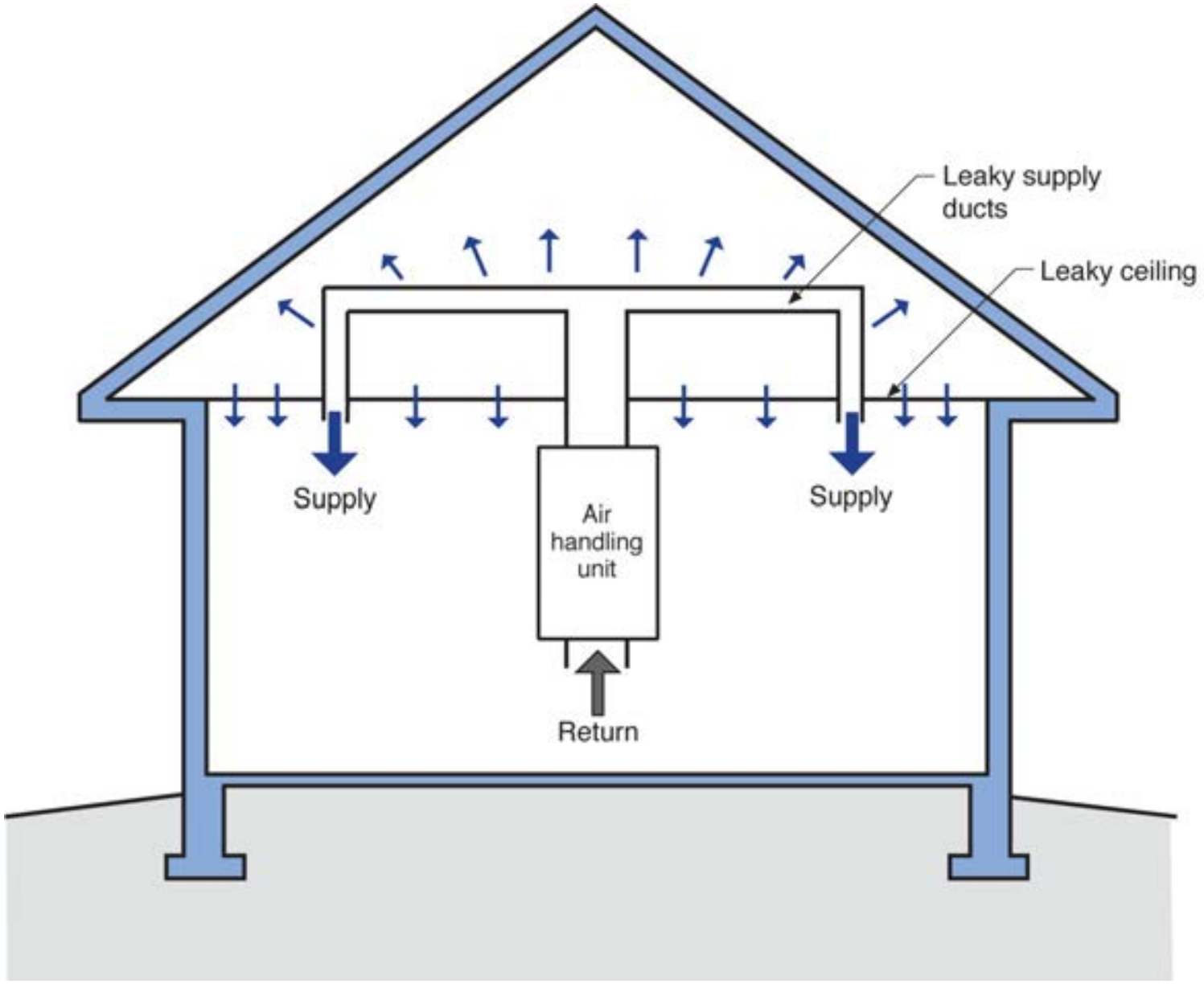

Metal cap
18" wide membrane strip
Coping wedge
OSB
Rubber roofing membrane
Soil gas stack vented through flashed roof penetration
Roof flashing
OSB sheathing
Scupper
Two layers OSB
Cavity insulation; see Material Compatibility and Substitutions
Polymer modified (PM) or traditional cement stucco
Metal lath
Gypsum board with semi-permeable (latex) paint
Sealant, adhesive or gasket at top plate
Caulking or sealant
2X6 24" o.c. advanced framing
Sealant at all penetrations
1/4" cant/ft
Tyvek® StuccoWrap®
Cavity insulation; see Material Compatibility and Substitutions
Soil gas ventilation stack
Weep screed flashing tucked behind drainage plane
Sill gasket acts as capillary break
Parge coat dampproofed with latex paint to reduce water absorption
Gypsum board caulked, glued or gasketed to bottom plate; held up from slab
Sealant at all slab penetrations
Concrete slab
For termite protection provide 3'-0" of mulch and then drought-resistant plants
Ground slopes away from wall at 5% (6 in. per 10 ft.)
Sub-slab stone layer (no fines); see Building Science Details
Perforated drain pipe added to "T" in order to couple sub-slab pressure field to vent stack
Concrete grade beam
Polyethylene vapor barrier extended under grade beam where it also acts as a capillary break


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


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


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)


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
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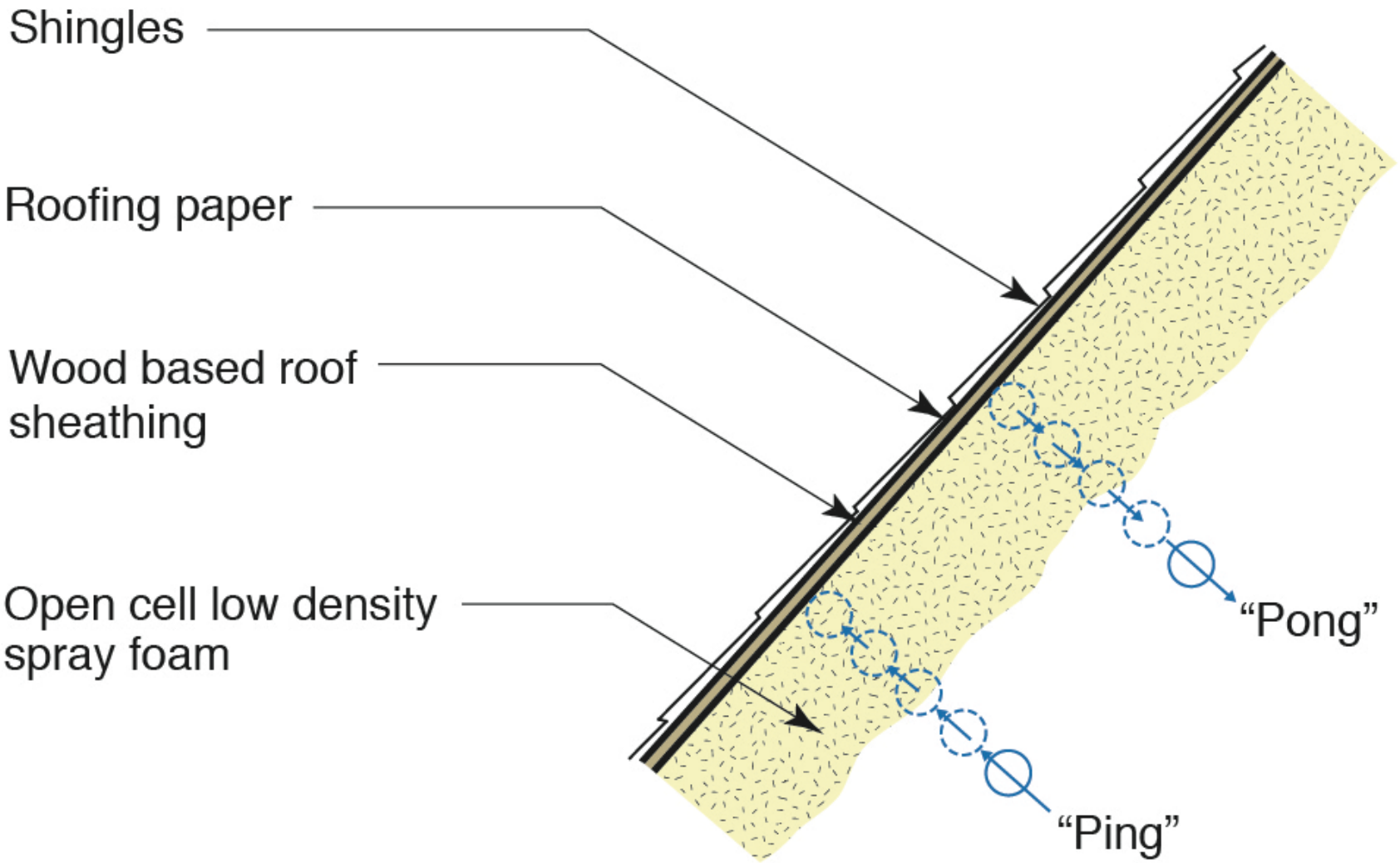
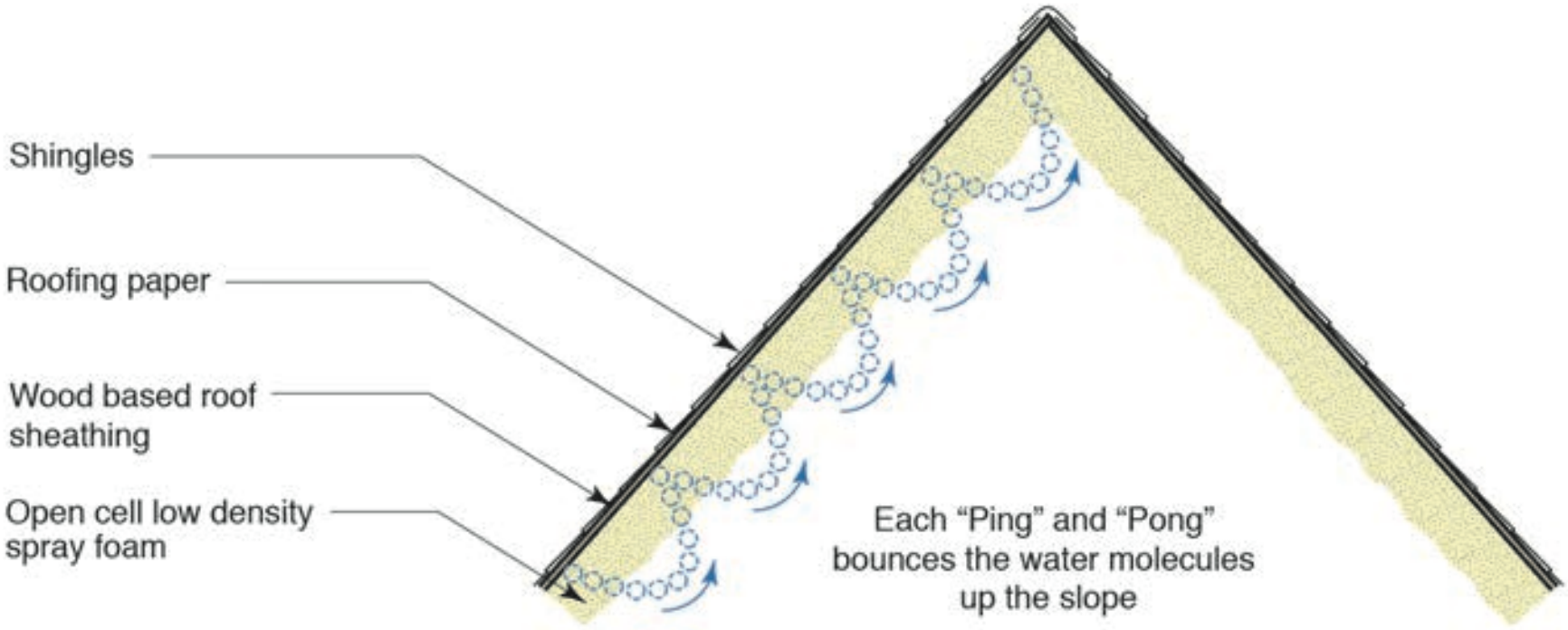
Neon	0.000018	20.18	0
Helium	0.000005	4.00	0
Krypton	0.000001	83.8	0
Xenon	$0.09\ 10^{-6}$	131.29	0
Total Molecular Mass of Air			28.97

Note Water Vapor (H2O) is 18

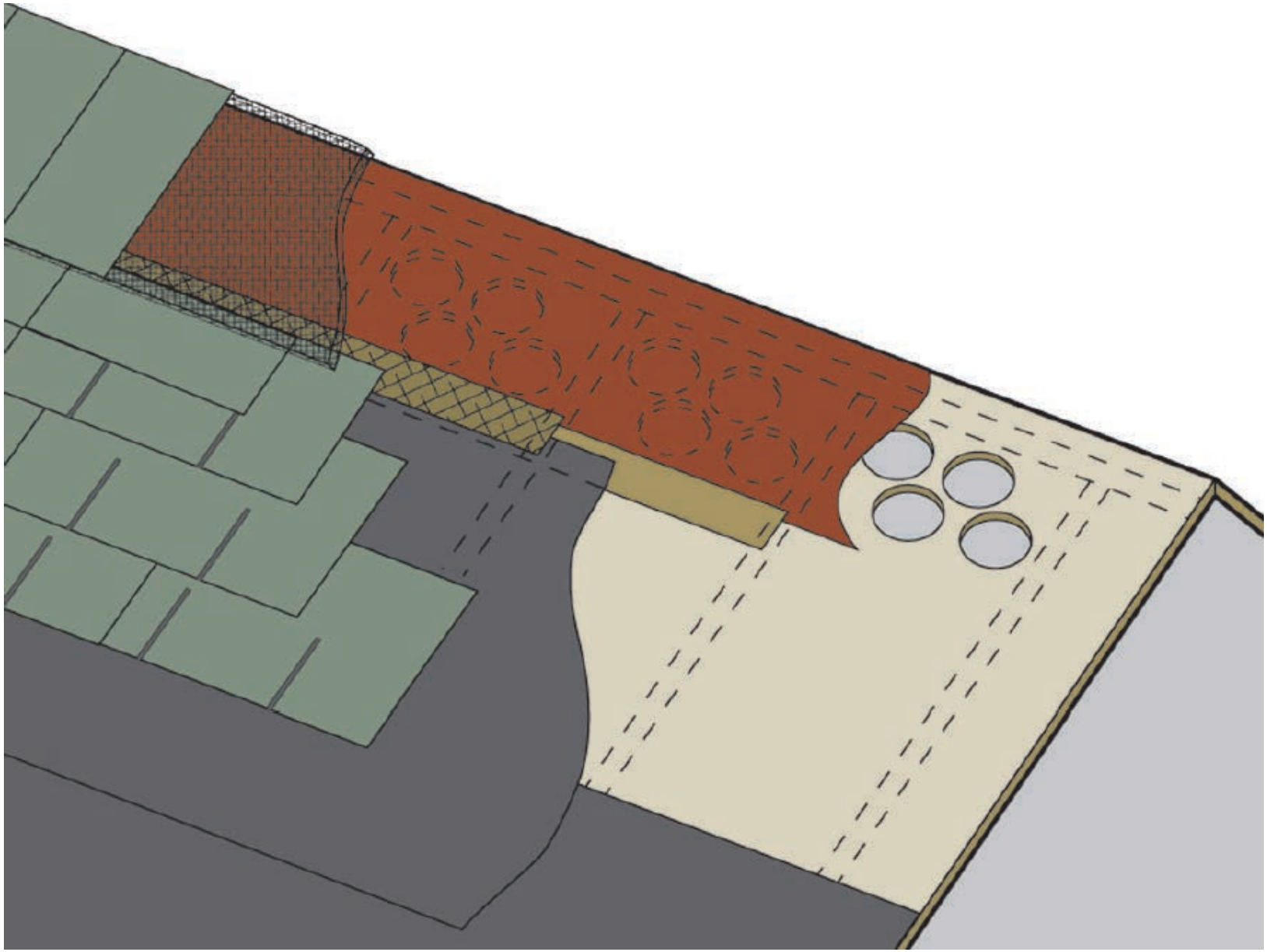
Dry Air is 29

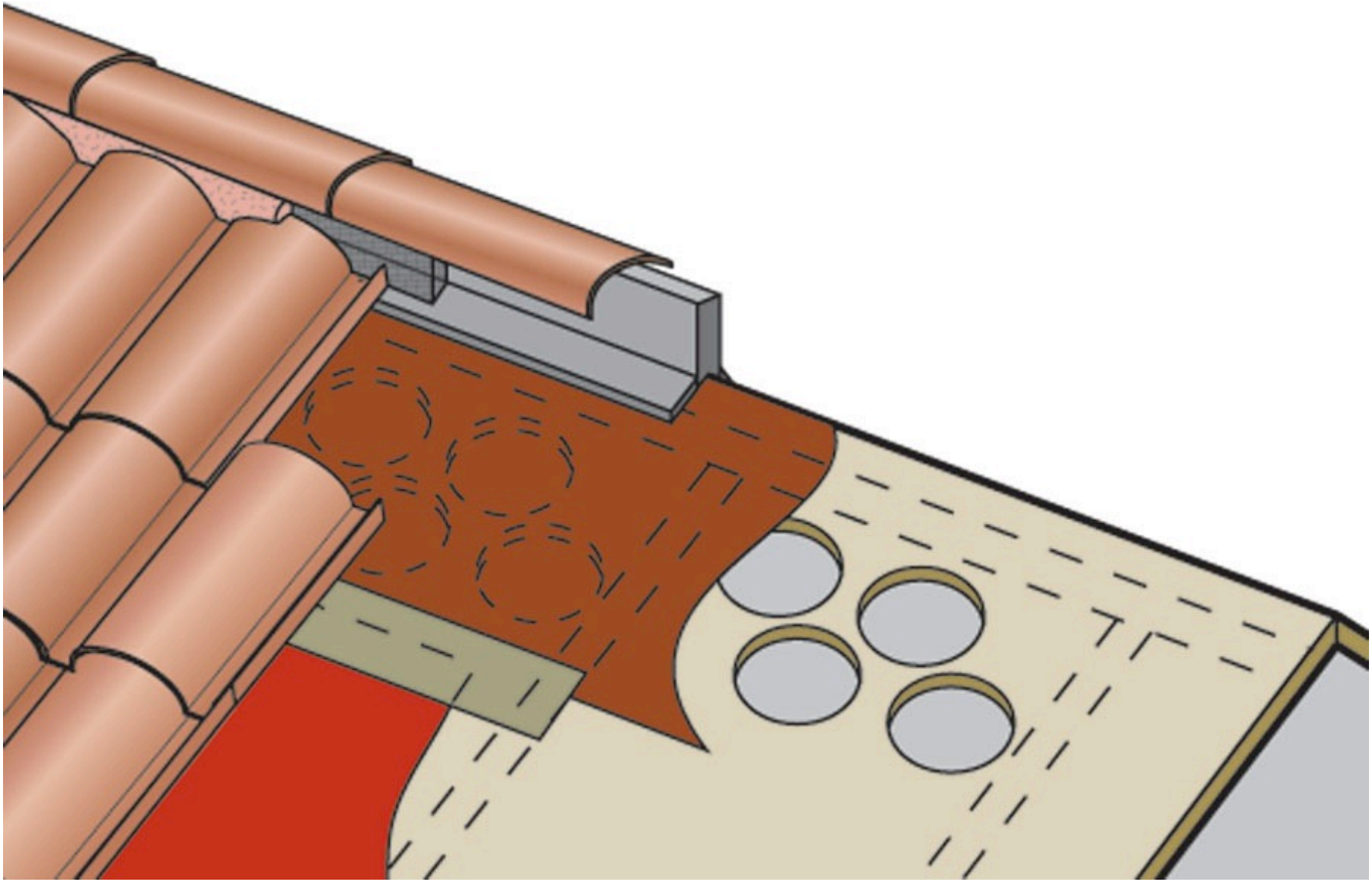

Dual In-Duct
Psychrometer
Fieldpiece
SDP2

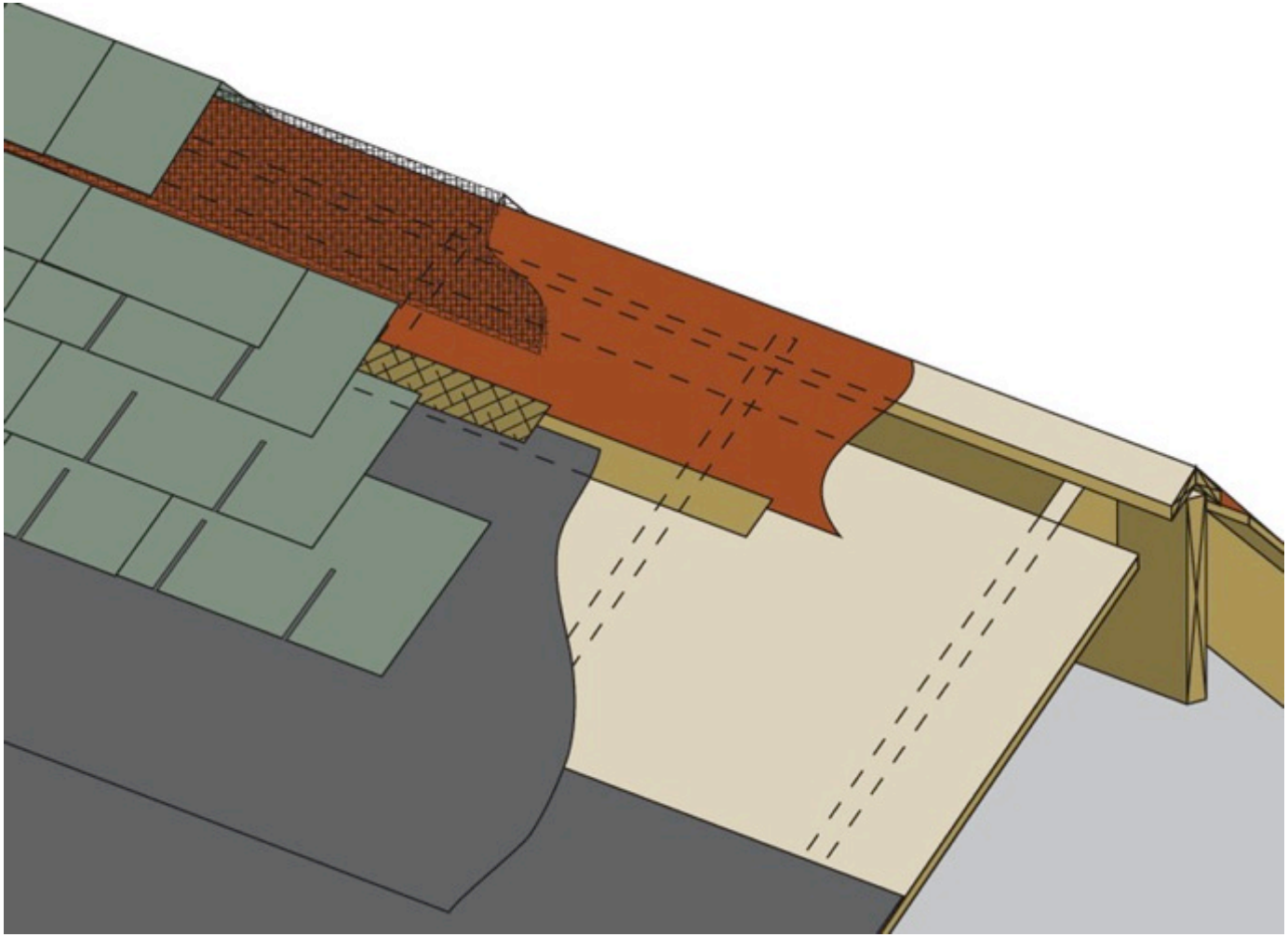

Shingles
Roofing paper
Wood based roof sheathing
Open cell low density spray foam
"Pong"
"Ping"

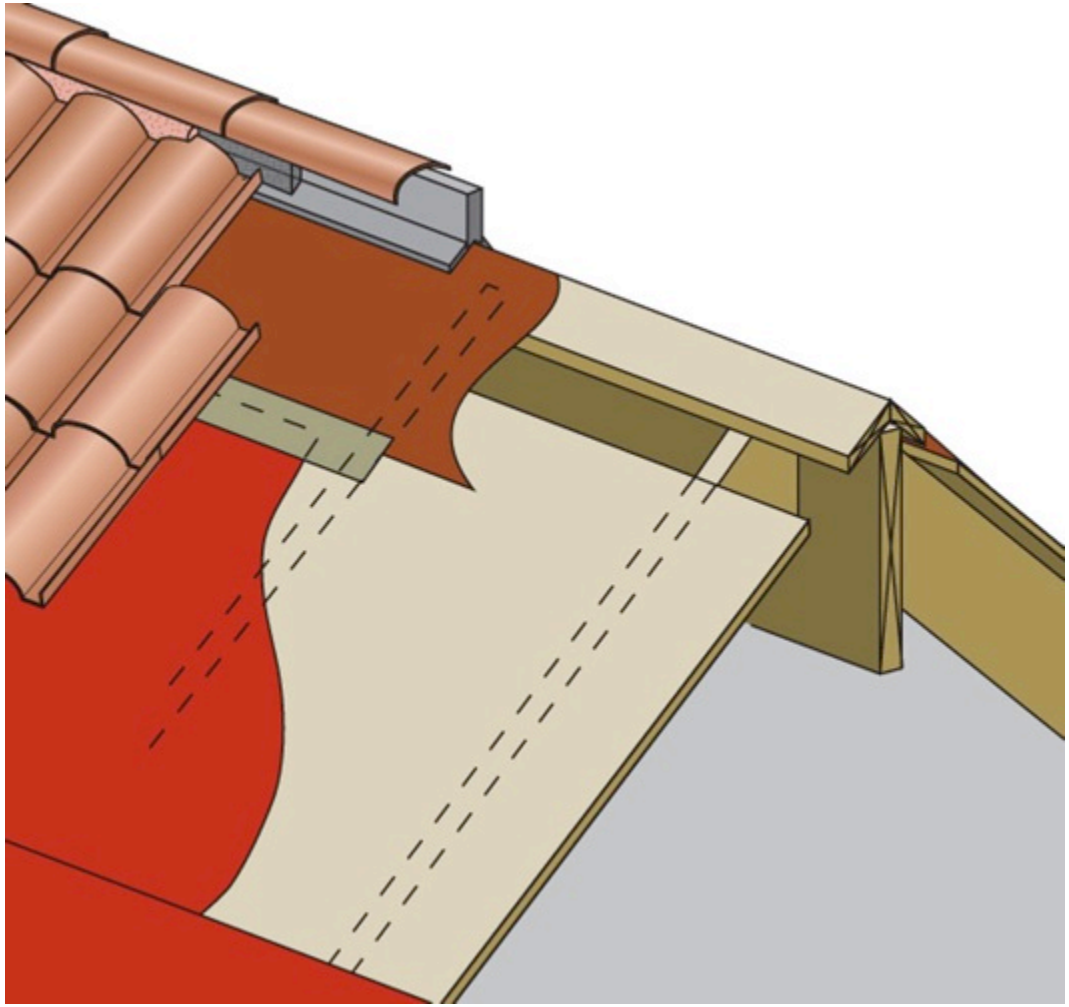

Shingles
Roofing paper
Wood based roof sheathing
Open cell low density spray foam
Each "Ping" and "Pong" bounces the water molecules up the slope


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

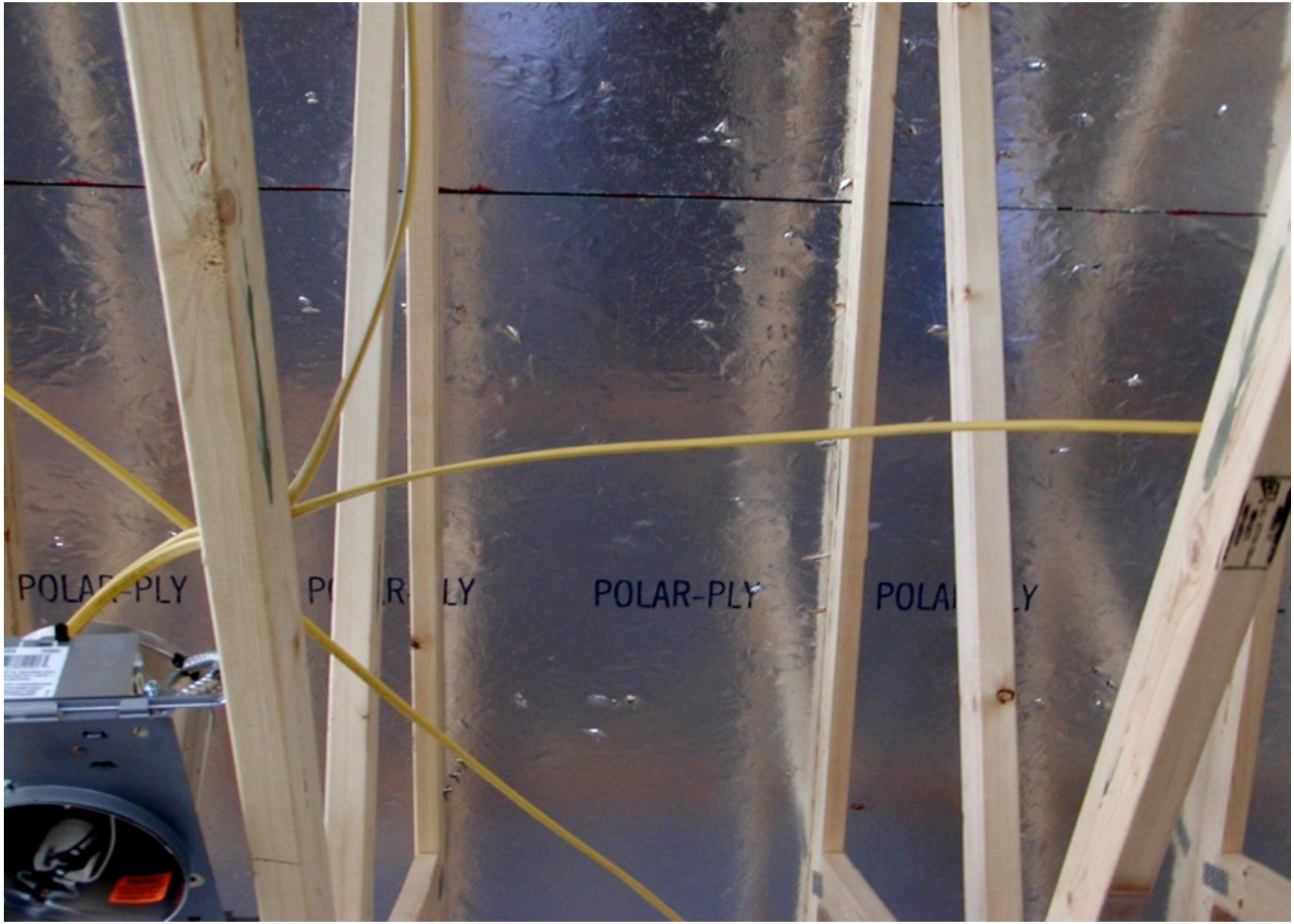
Cool Roofs

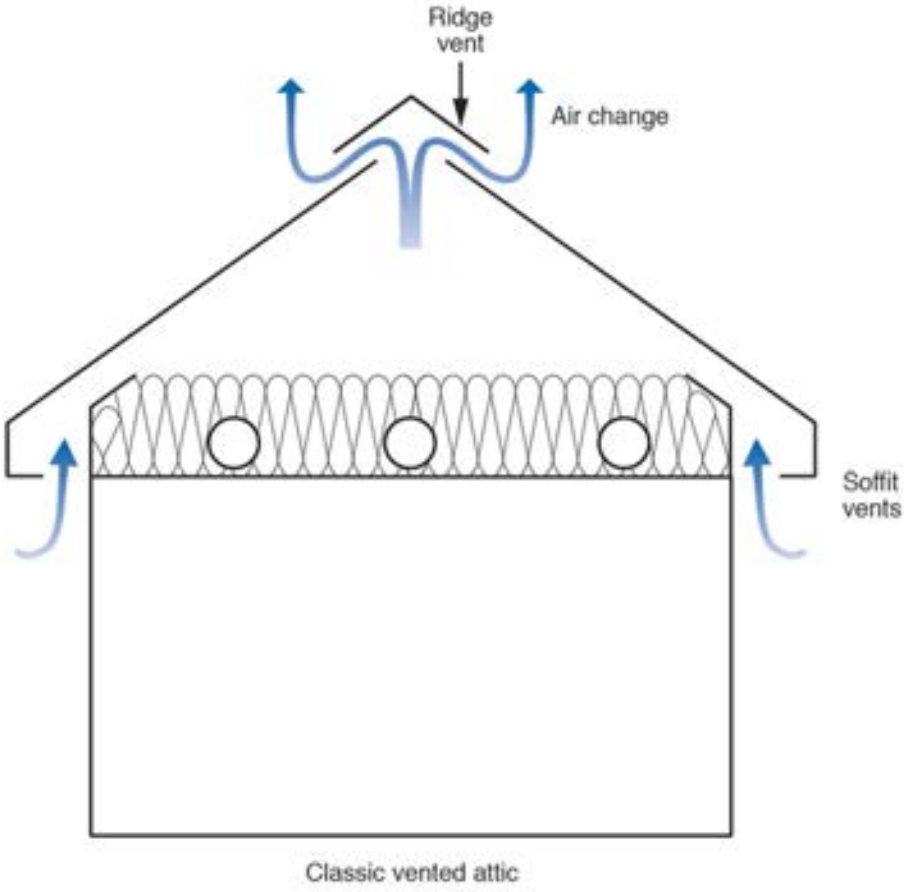
Radiant Barriers

ACCA Manual J, S and D

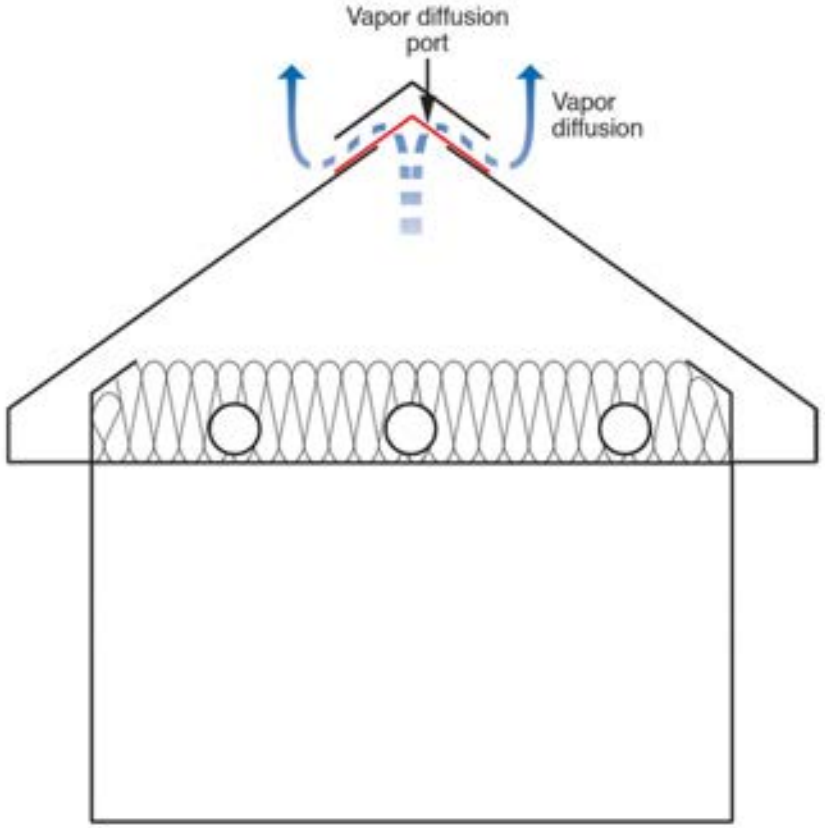
ASHRAE 62.2

Ductwork Attic Dehumidification System


POLAR-PLY
POLAR-PLY



Classic vented attic



Unvented attic with vapor diffusion port


09/14
AF 100
09/14
AF 100