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

Building Science

Adventures In Building Science

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Arrhenius Equation

For Every 10 Degree K Rise

Activation Energy Doubles

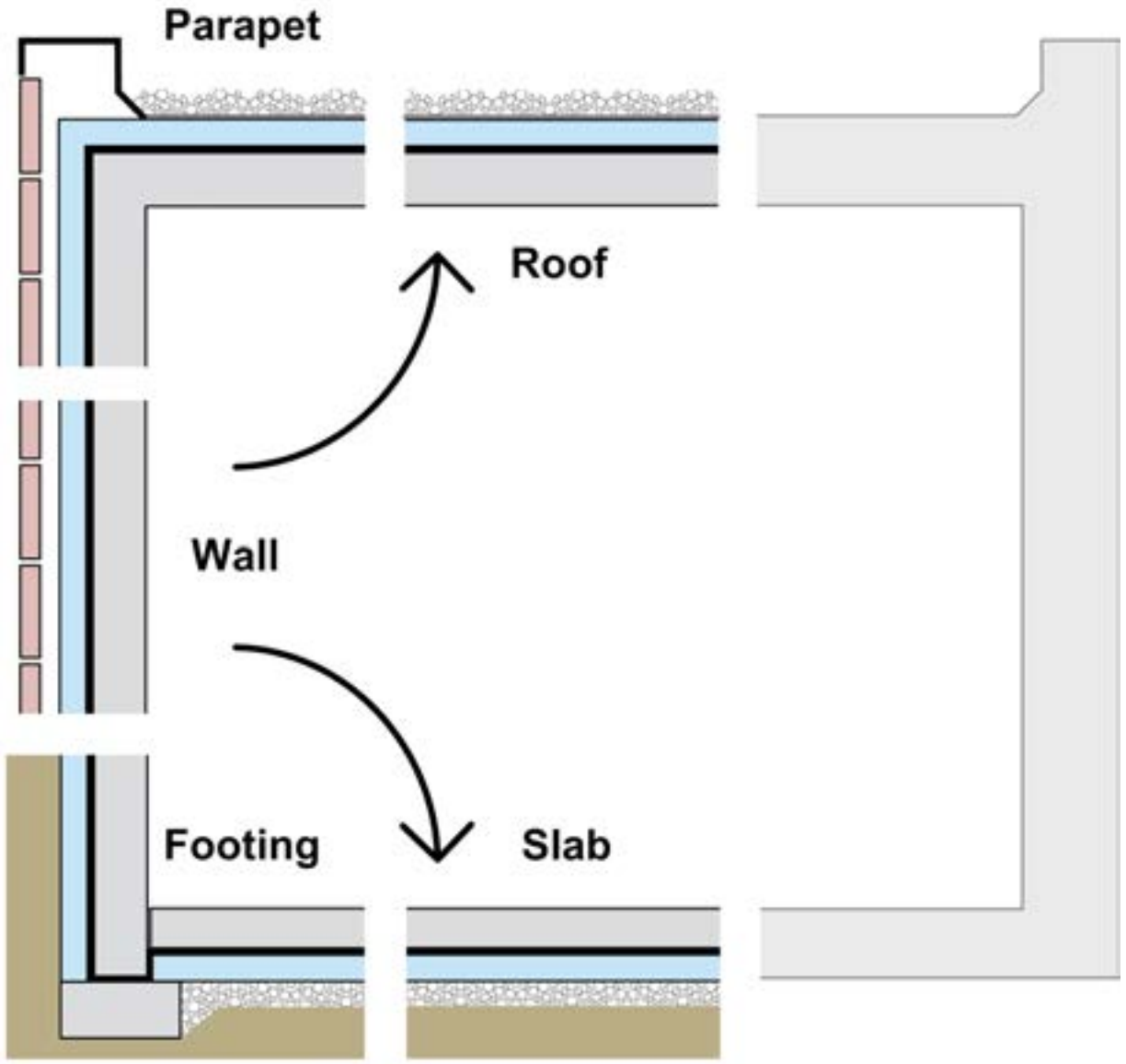
$$k = Ae^{-E_a/(RT)}$$

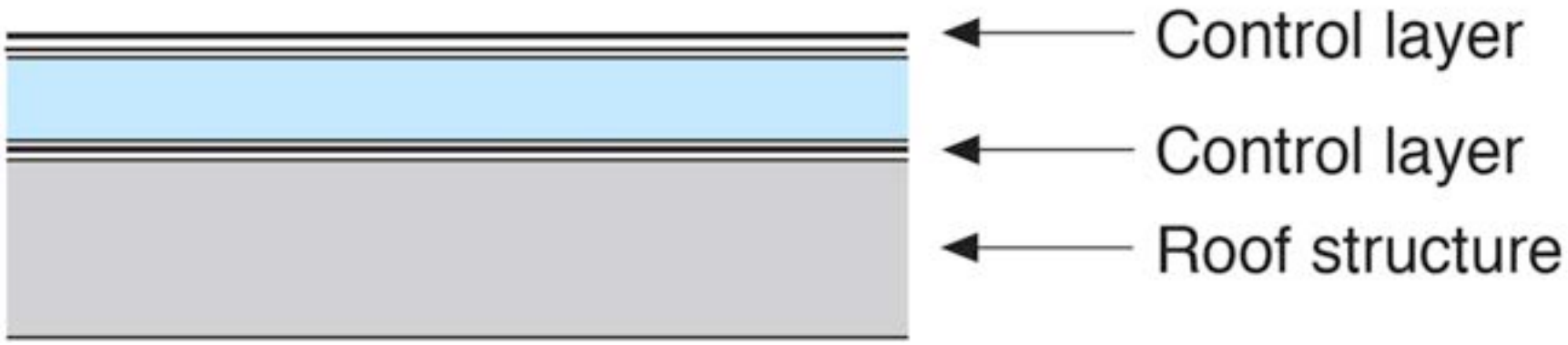
Damage Functions

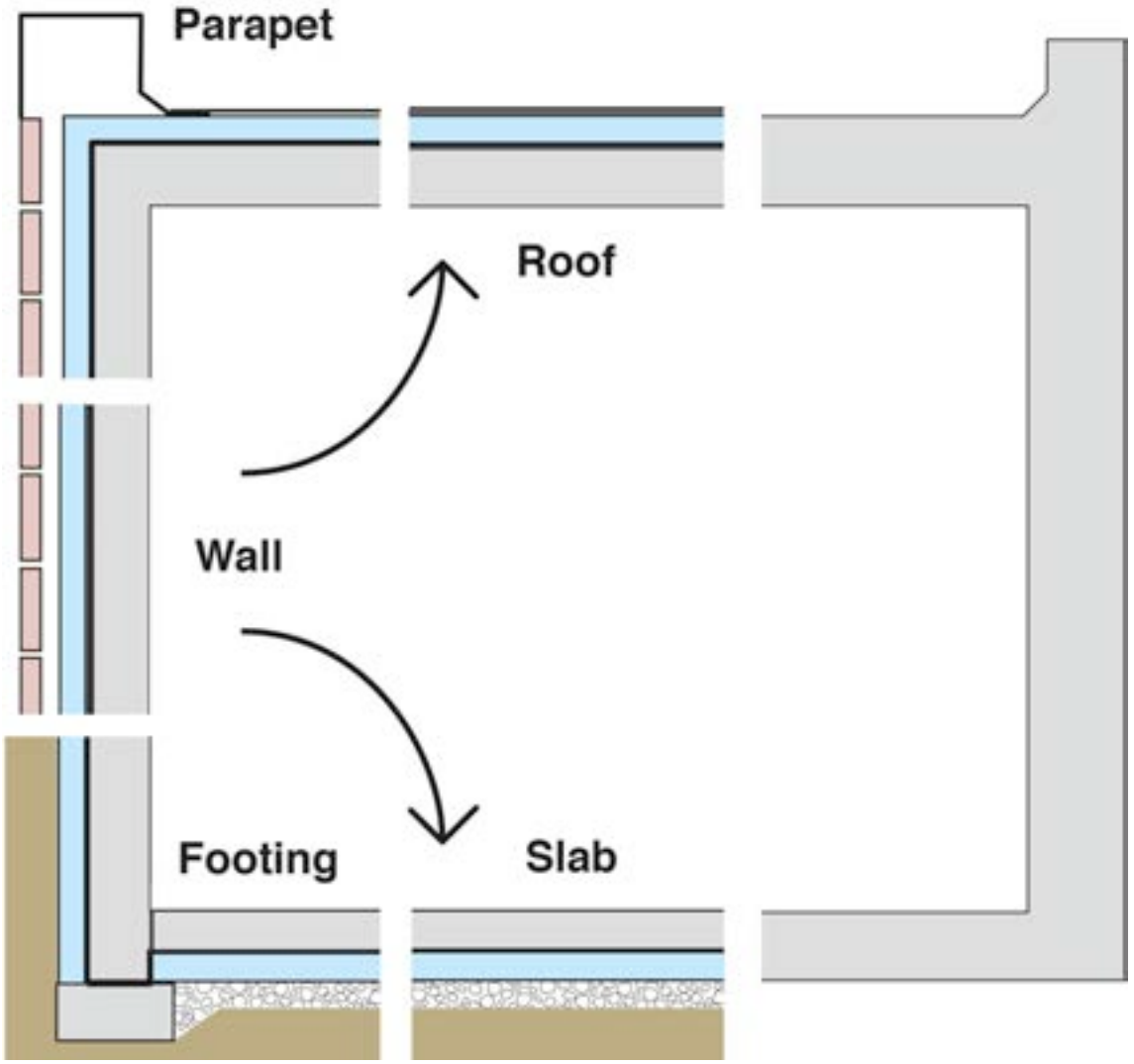
Water

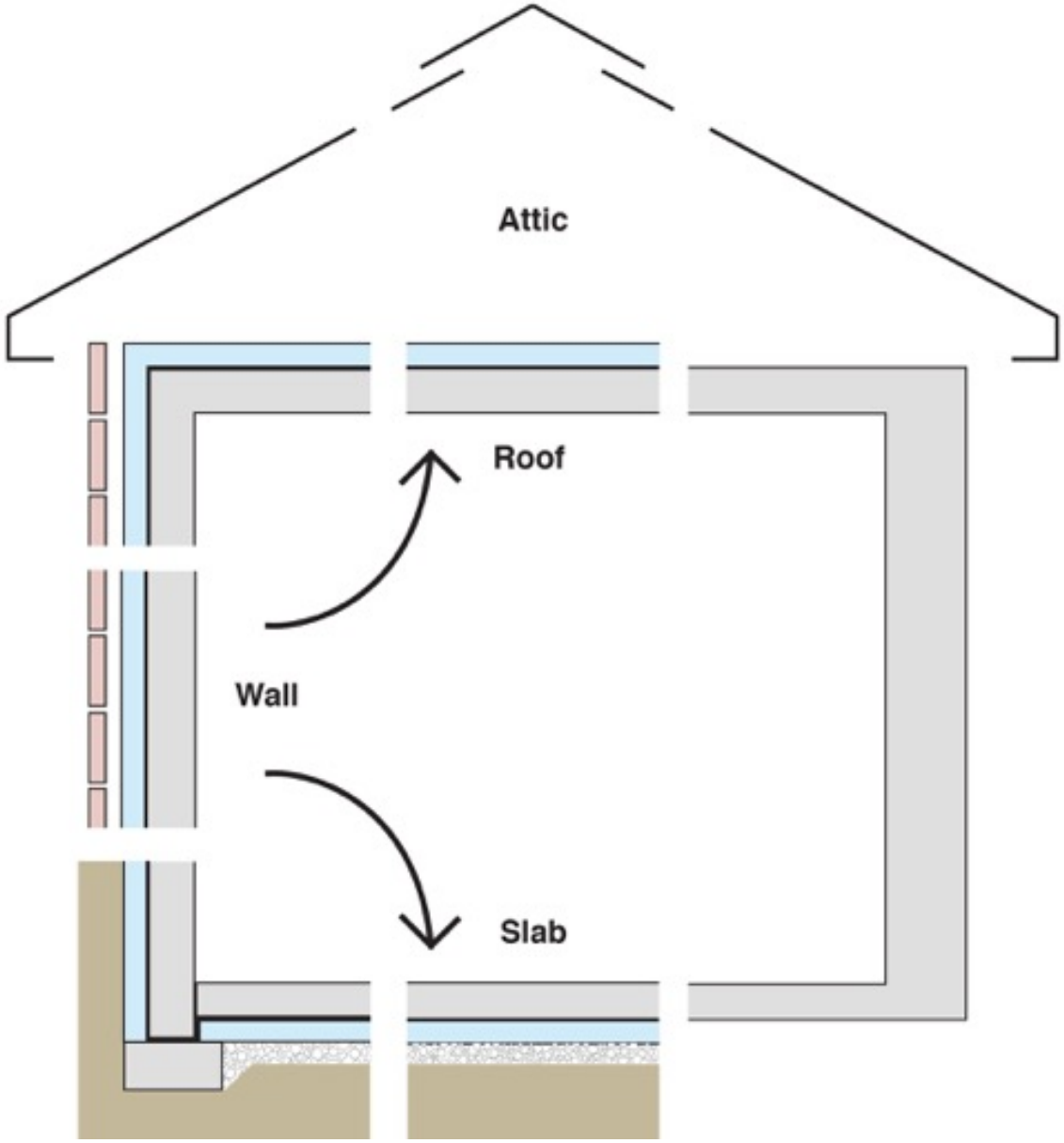
Heat

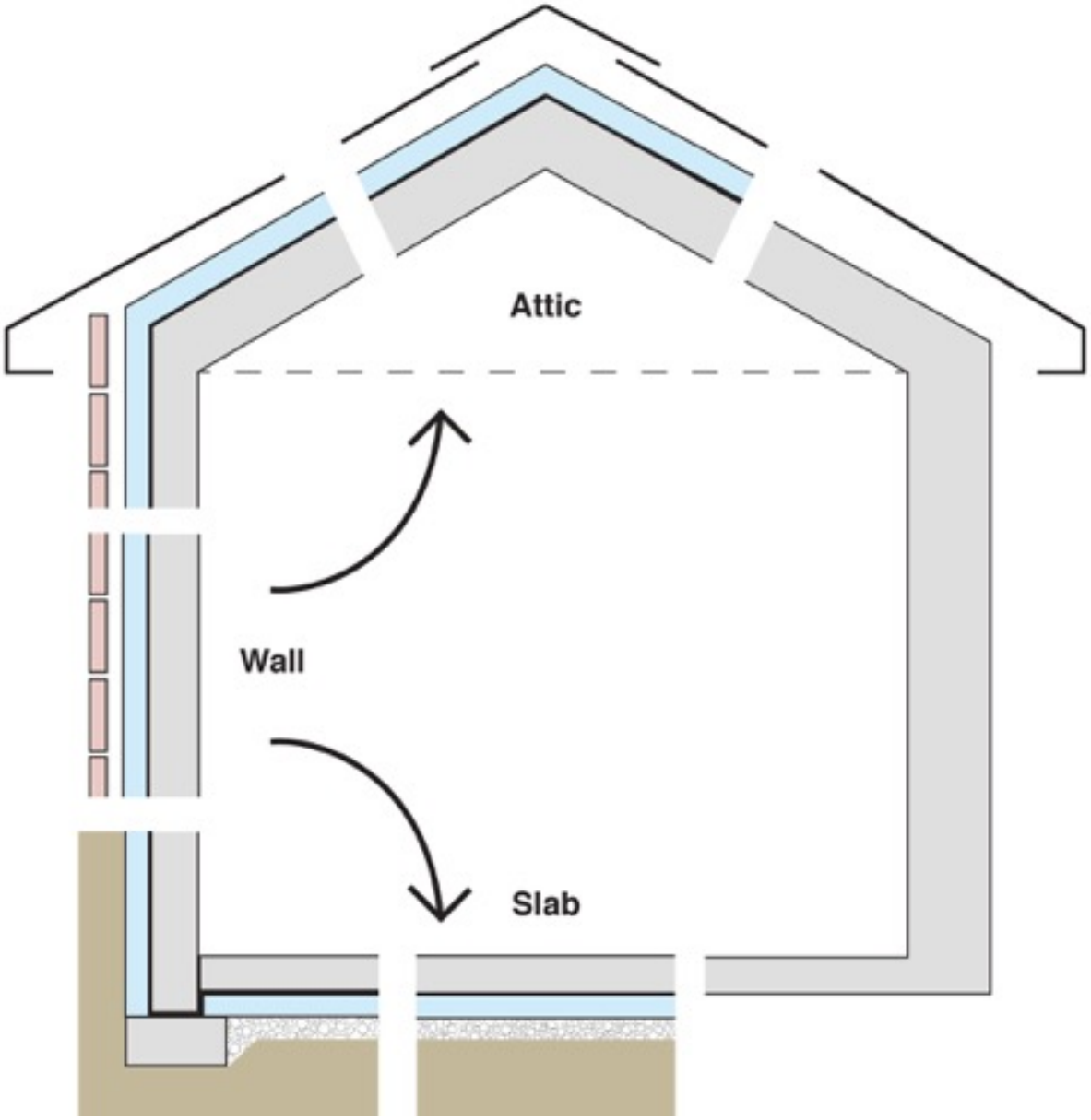
Ultra-violet Radiation

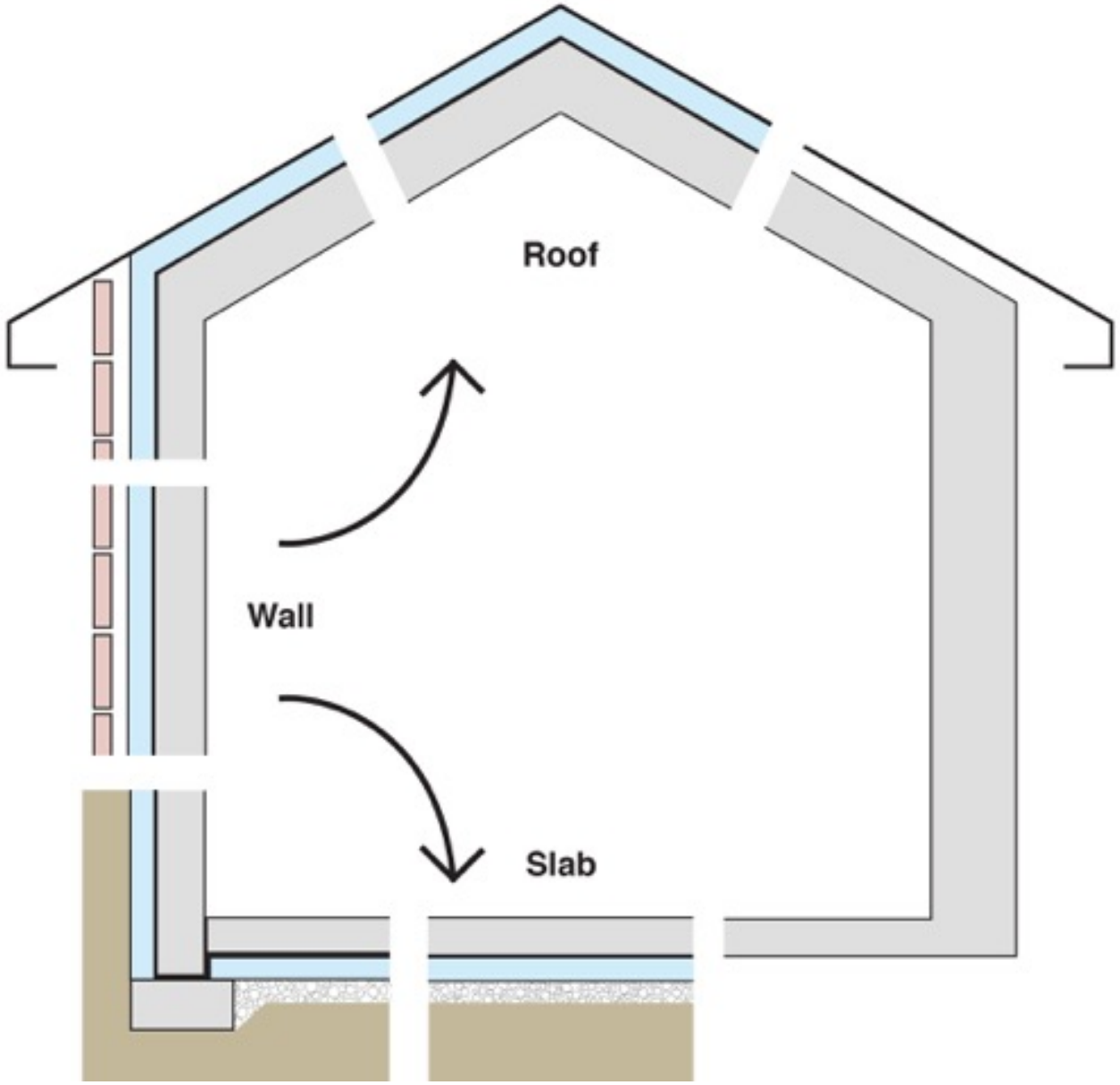

Parapet
Roof
Wall
Footing
Slab

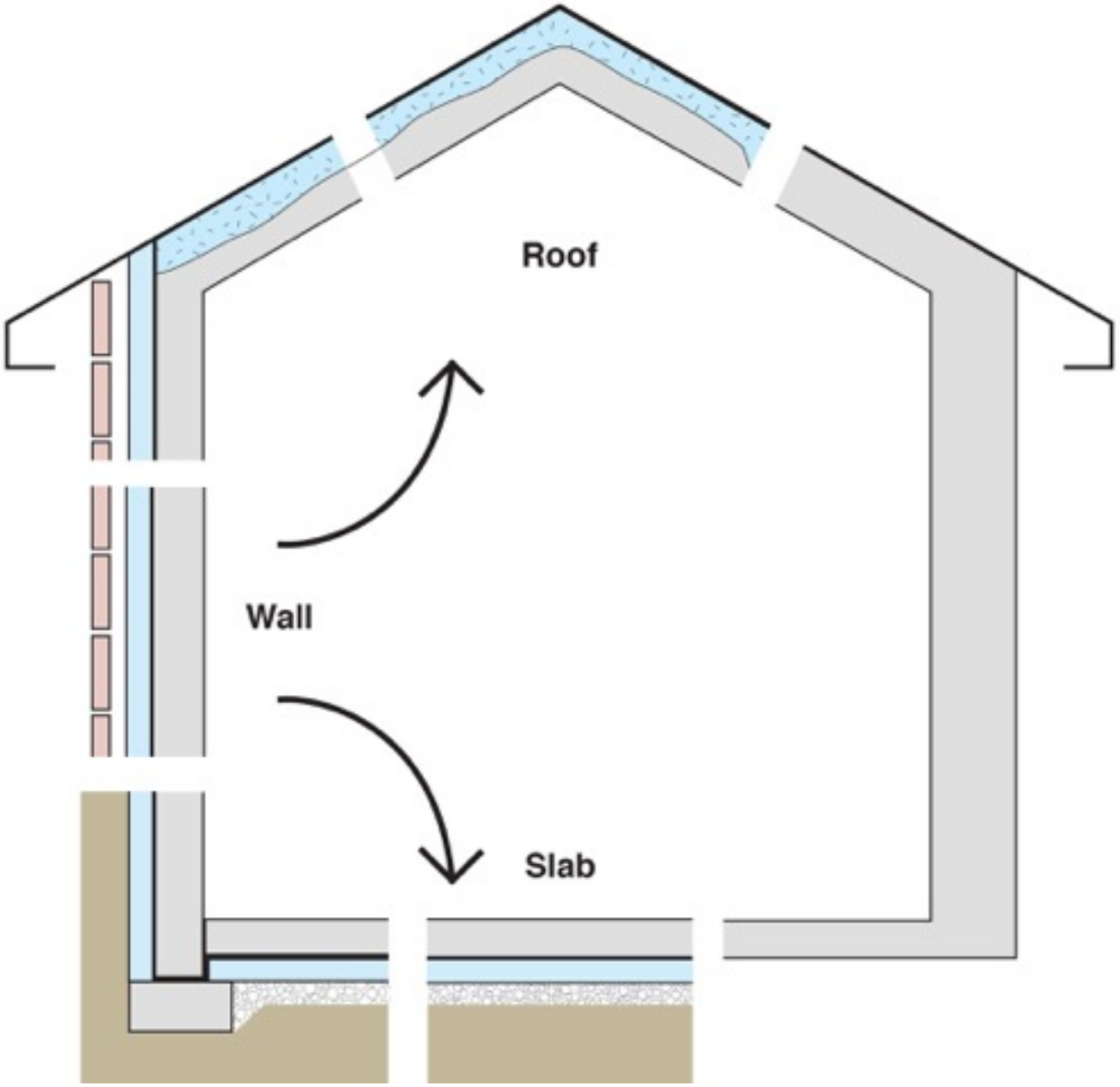

Control layer
Control layer
Roof structure

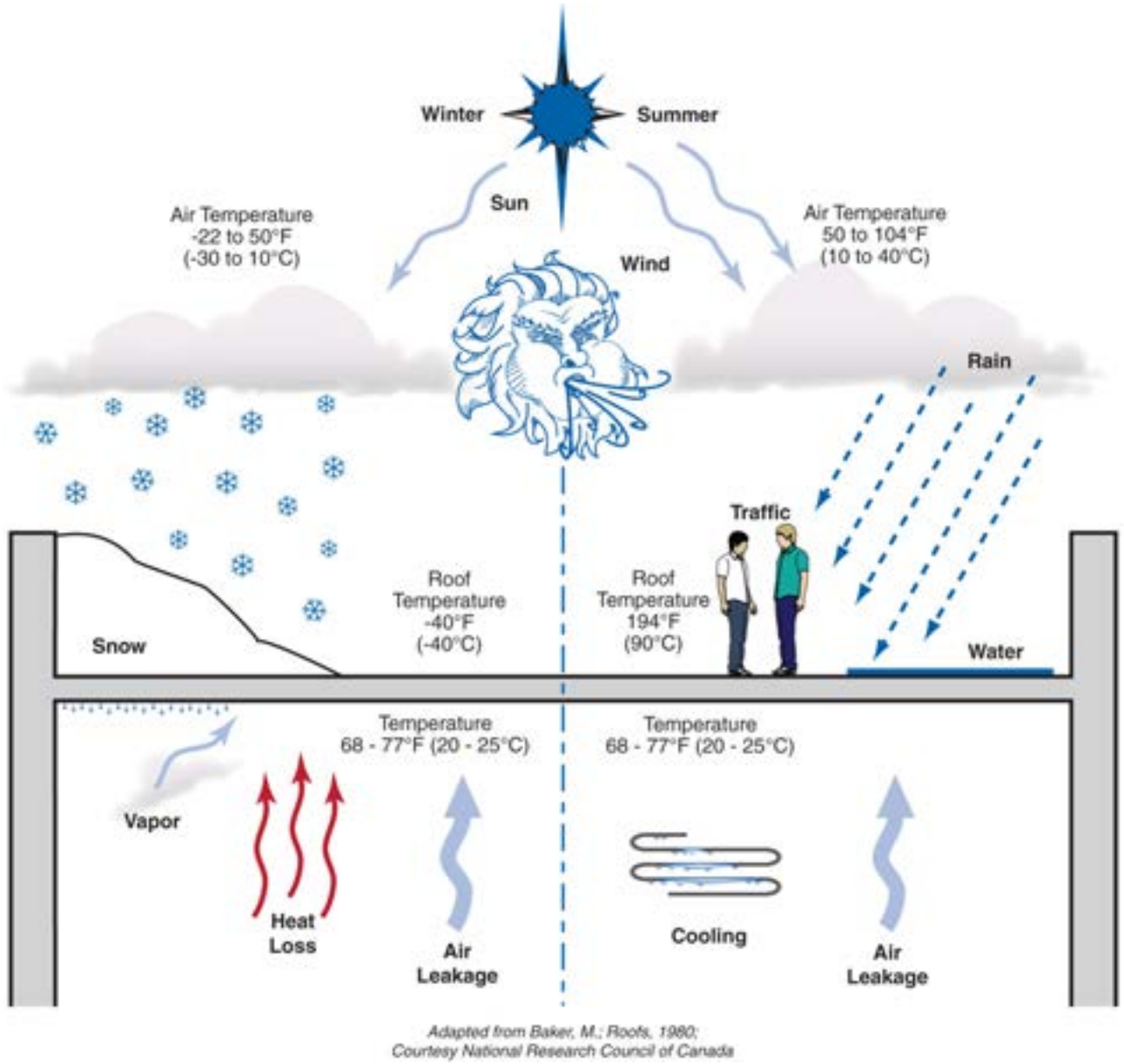

Parapet
Roof
Wall
Footing
Slab


Attic
Roof
Wall
Slab

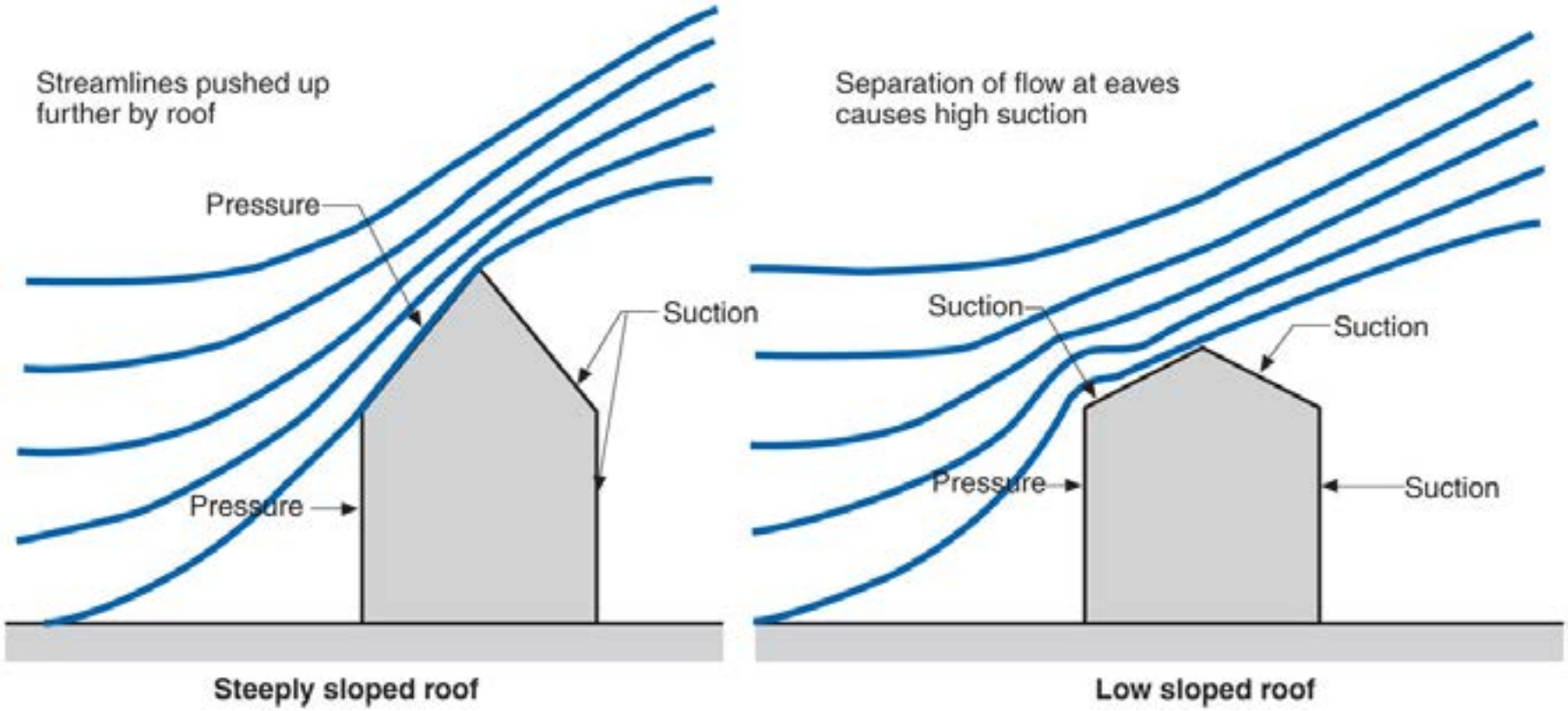

Attic
Wall
Slab

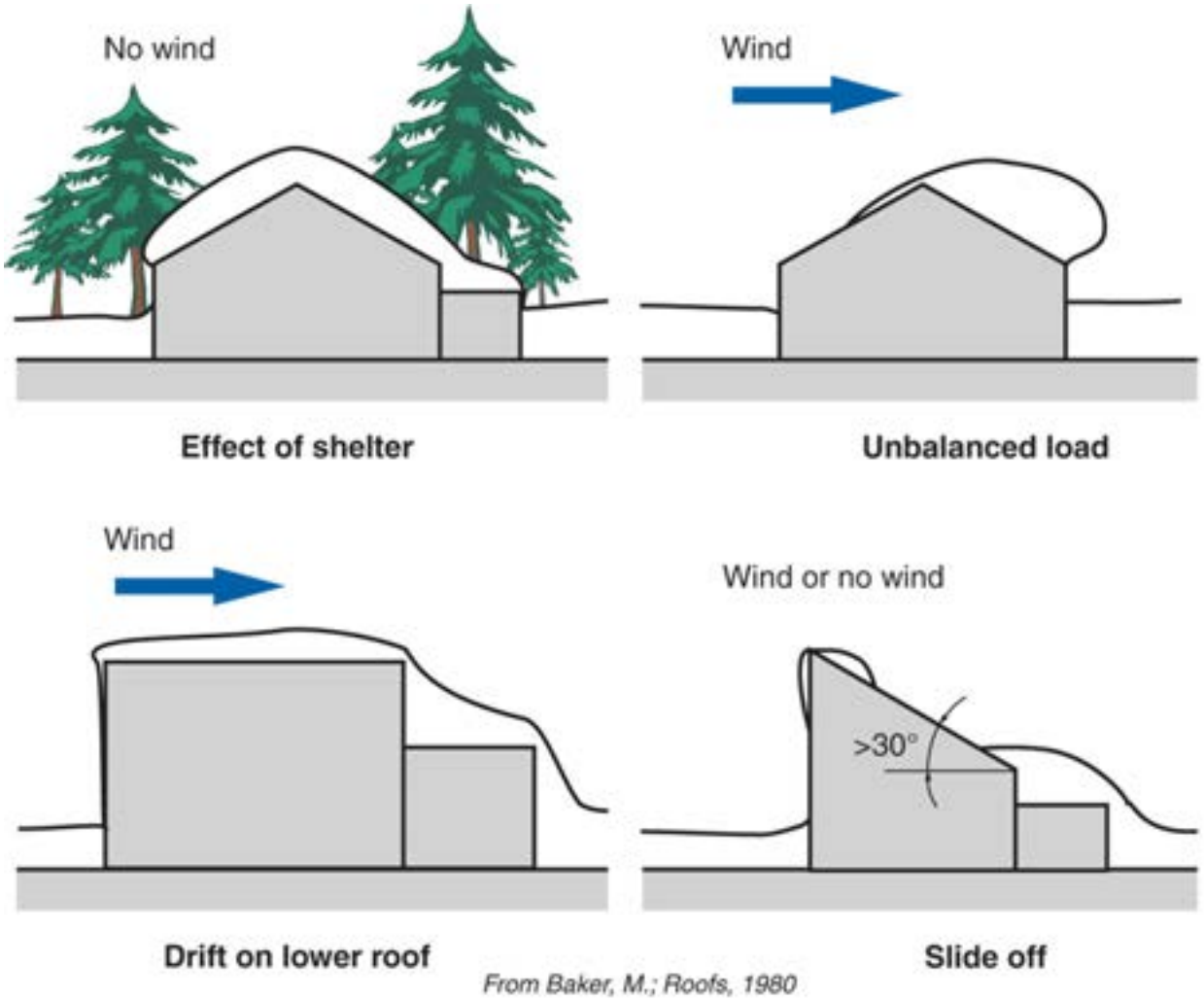

Roof
Wall
Slab

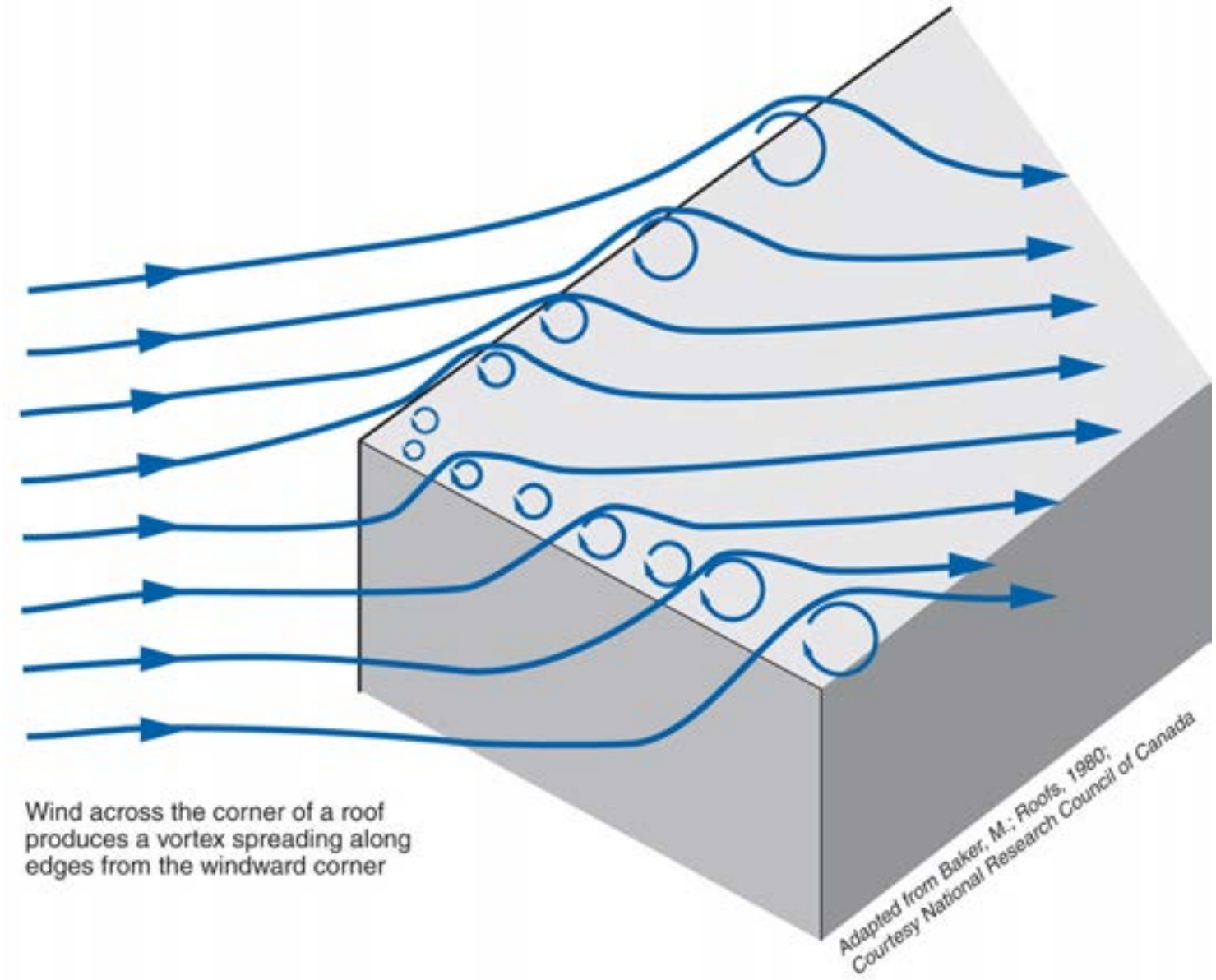

Roof
Wall
Slab



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

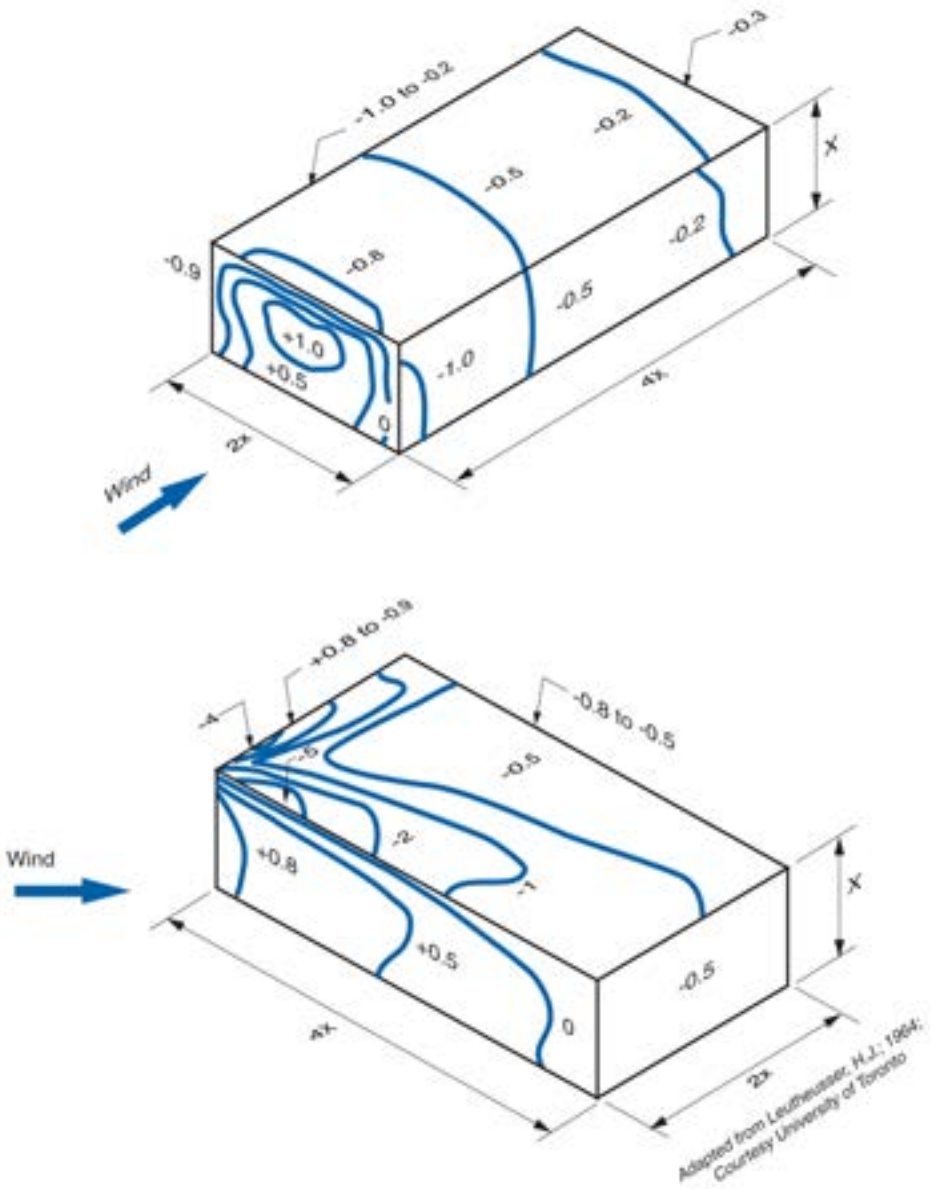

Streamlines pushed up further by roof
Pressure
Suction
Pressure
Steeply sloped roof
Separation of flow at eaves causes high suction
Suction
Suction
Pressure
Suction
Low sloped roof

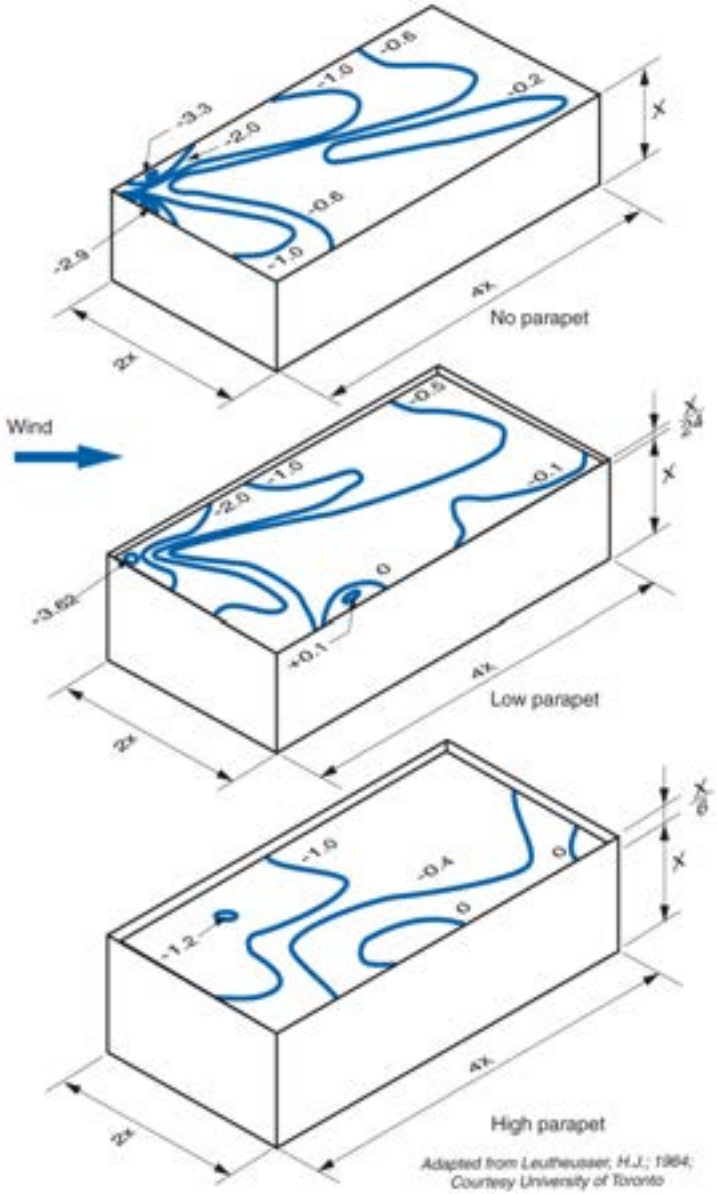

No wind
Wind
Effect of shelter
Unbalanced load
Wind
Wind or no wind
>30°
Drift on lower roof
Slide off
From Baker, M.; Roofs, 1980

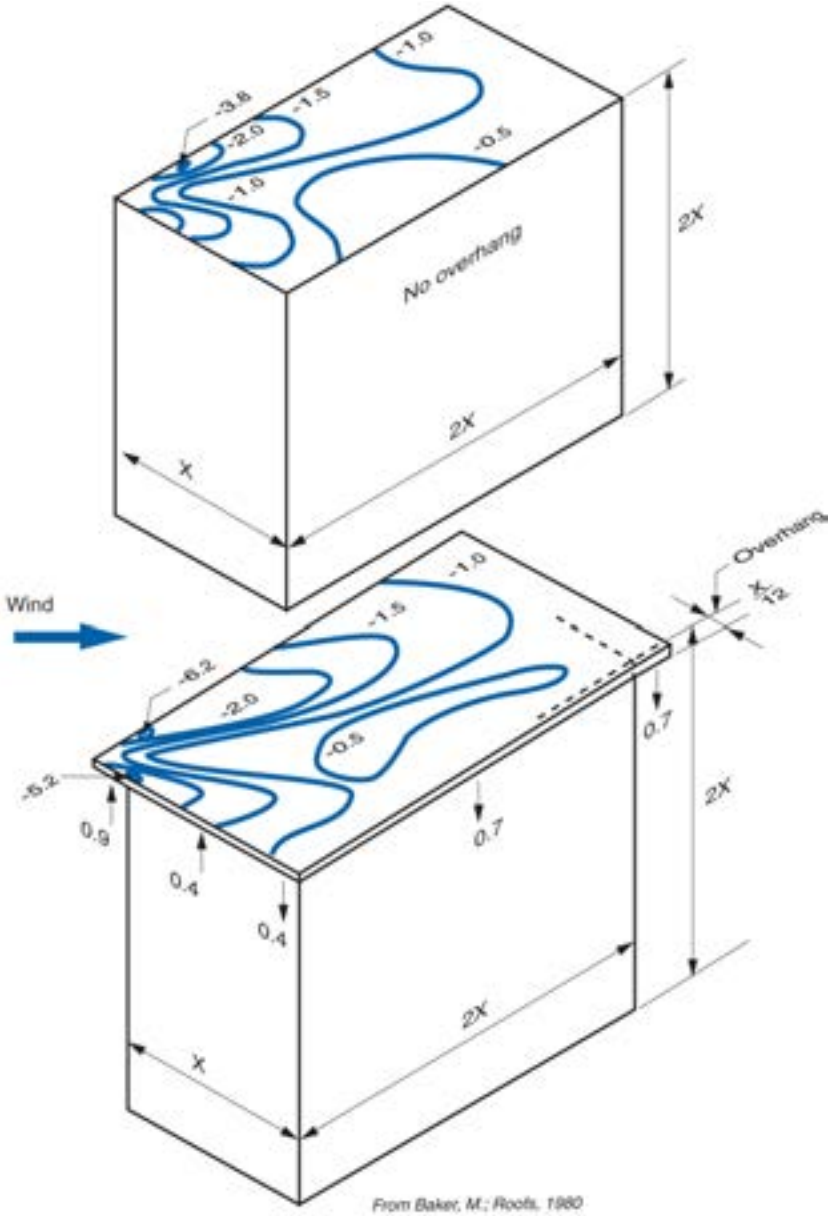


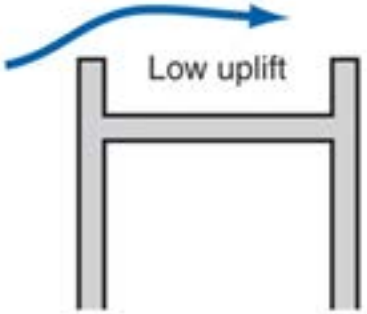
Wind across the corner of a roof produces a vortex spreading along edges from the windward corner

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

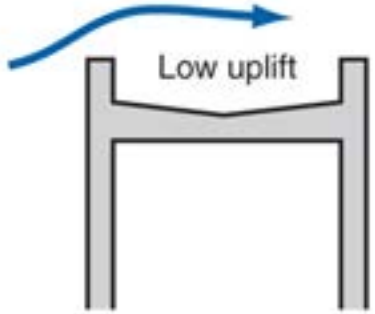

-1.0 to -0.2
-0.2
-0.5
-0.9
-0.8
+1.0
+0.5
0
-1.0
-0.5
-0.2
X
2x
4x
Wind
+0.8 to +0.9
-0.8 to -0.5
-0.5
+0.8
-2
-1
+0.5
0
-0.5
X
4x
2x
Wind
Adapted from Leutheusser, H.J.; 1964;
Courtesy University of Toronto


-0.6
-1.0
-0.2
-3.3
-2.0
-0.6
-2.9
-1.0
X
4X
2X
No parapet
Wind
-0.5
-1.5
-0.1
-2.0
0
-3.62
+0.1
X/2
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

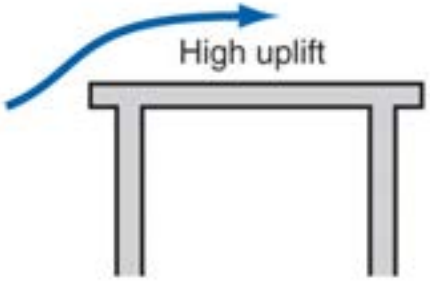

-3.8
-2.0
-1.5
-1.0
-0.5
-1.0
No overhang
2X
X
2X
Overhang
X/2
Wind
-1.0
-1.5
-0.2
-2.0
-0.5
-0.2
0.9
0.4
0.4
0.7
0.7
2X
X
2X
From Baker, M.; Roofs, 1980



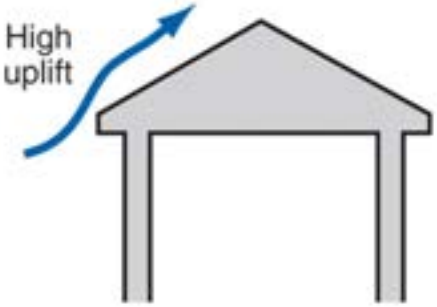
Flat roof with parapets
blow-off hazard: low
slippage hazard: low



Sloped roof with parapets
blow-off hazard: low
slippage hazard: medium

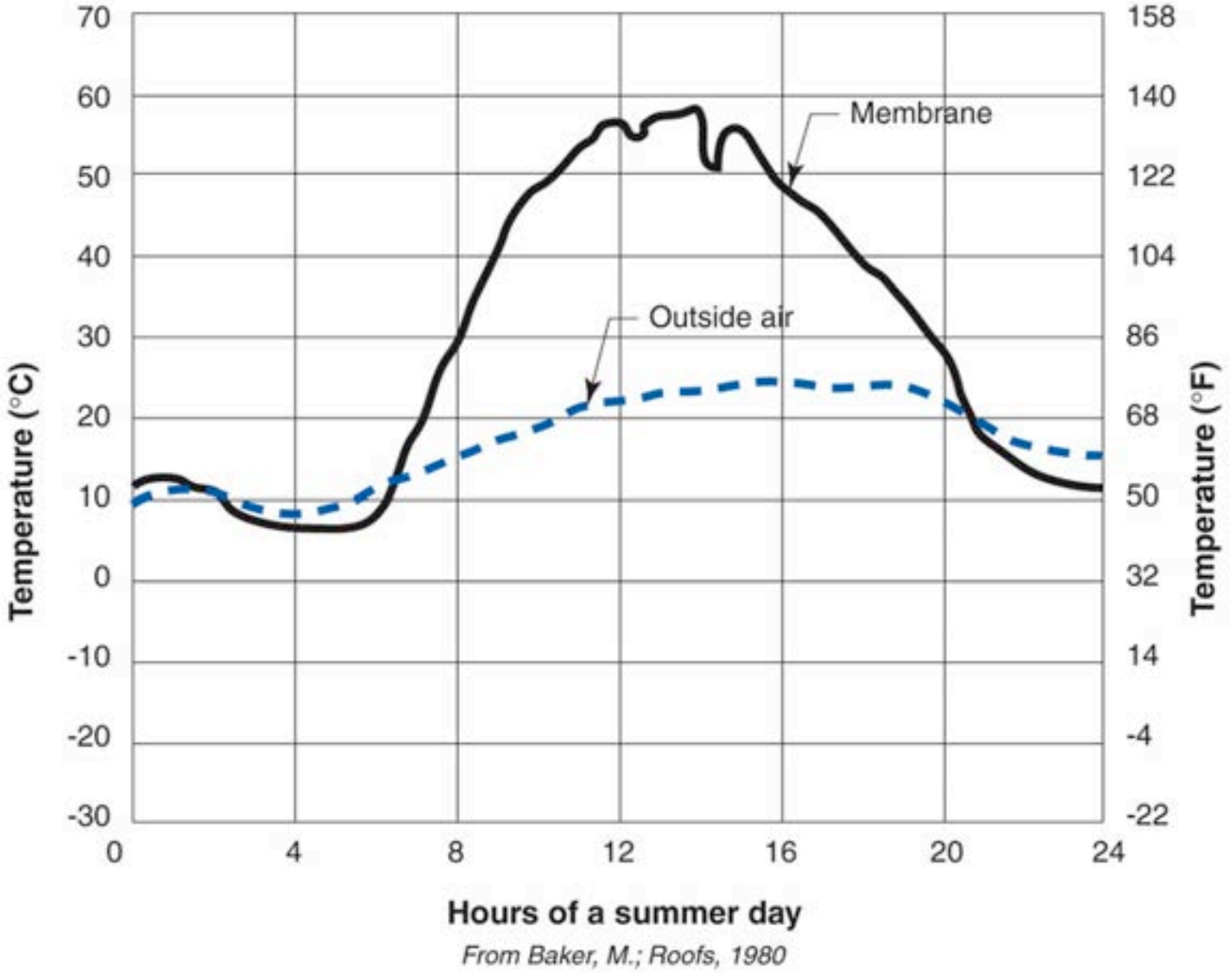


Flat roof or overhang
blow off hazard: high
slippage hazard: low

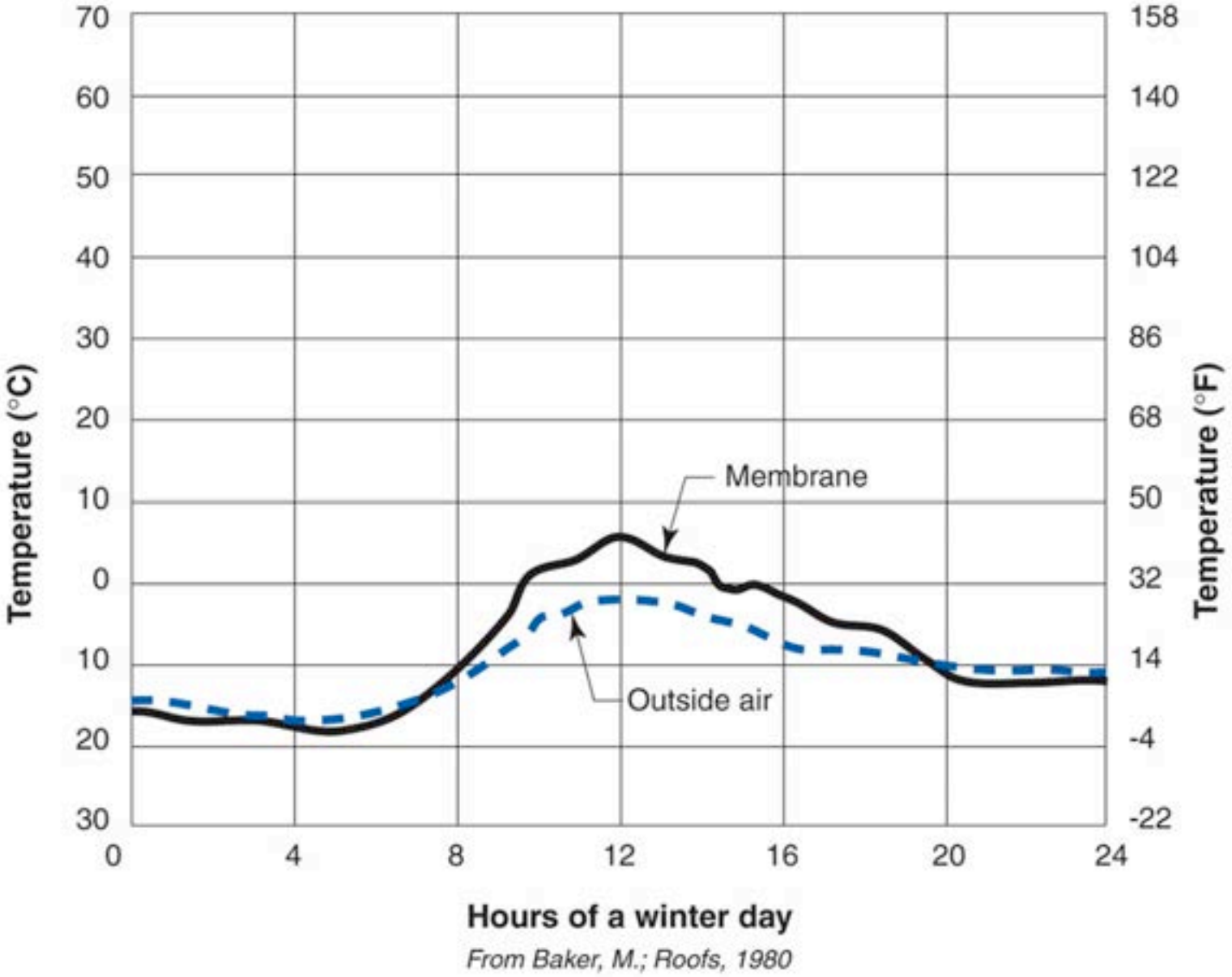


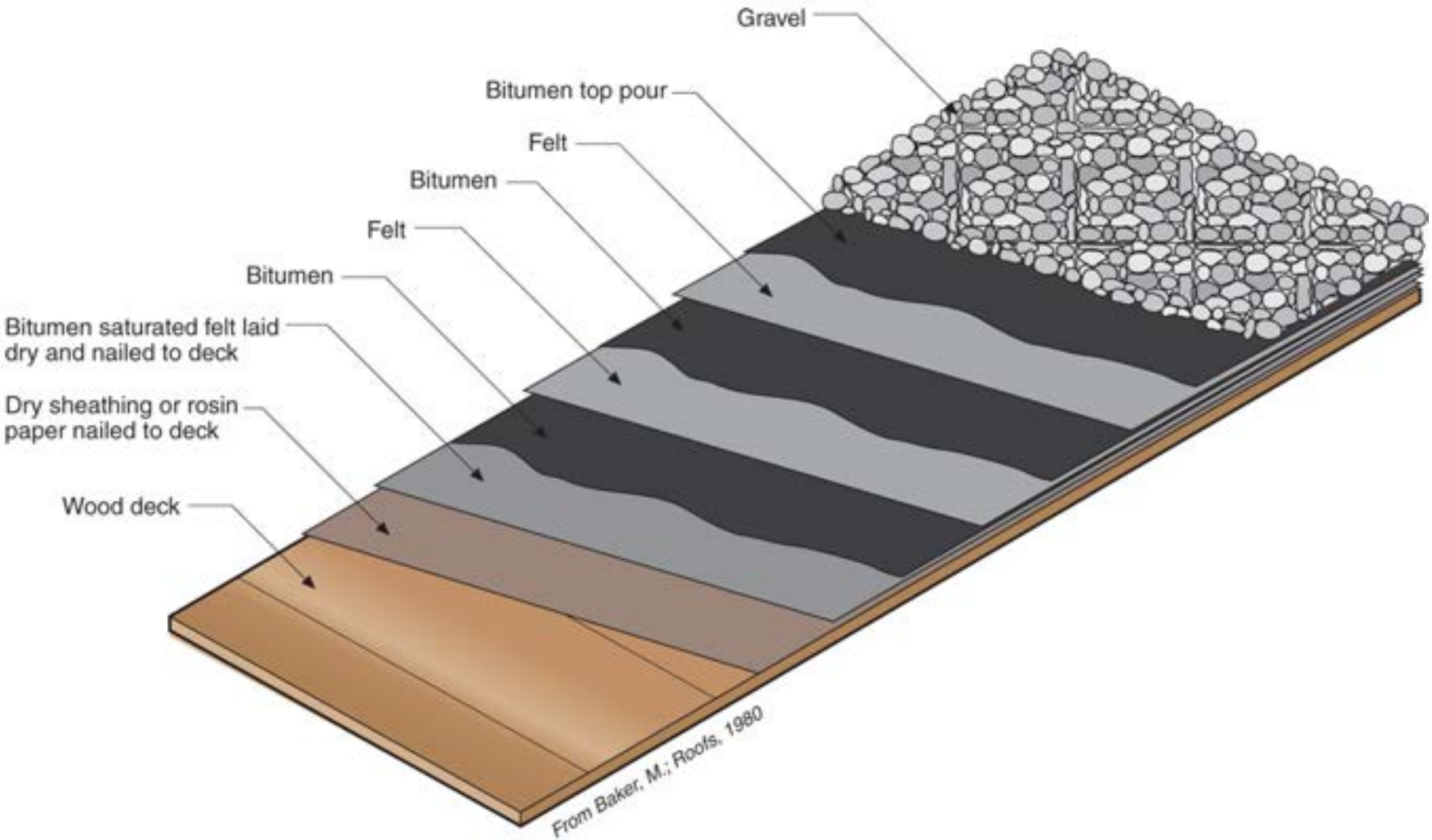
Outward sloping roof
blow-off hazard: high
slippage hazard: high

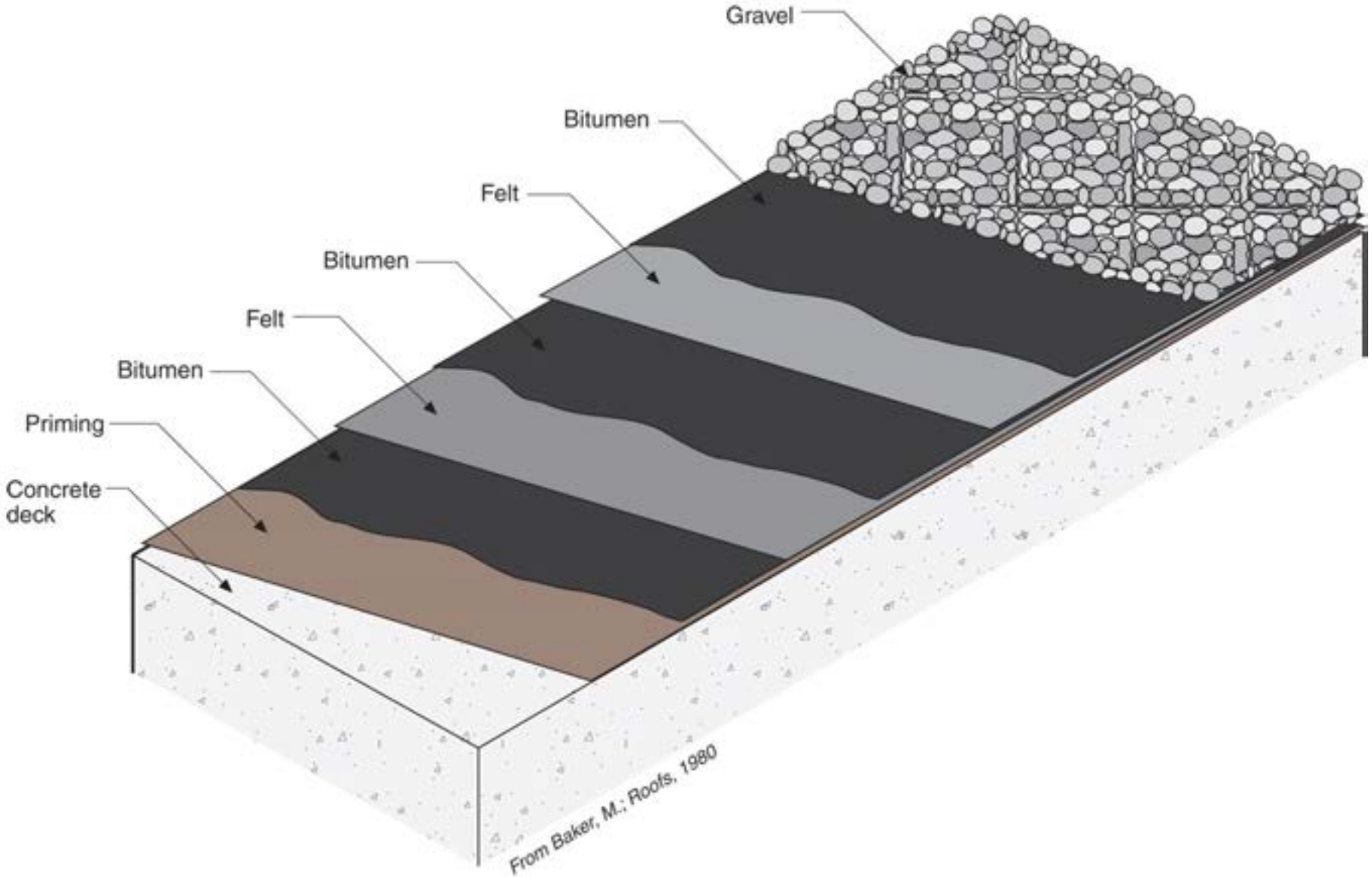
From Baker, M.; Roofs, 1980

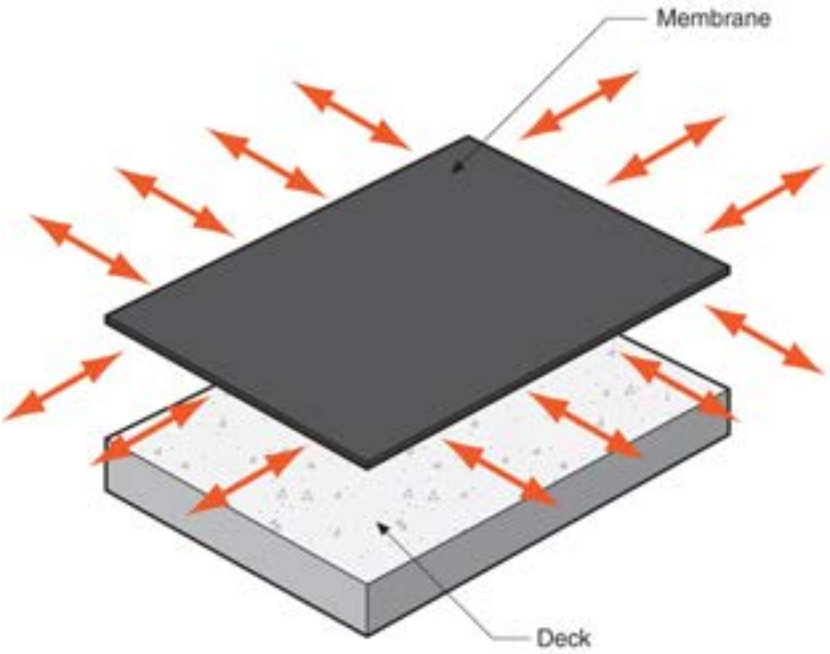


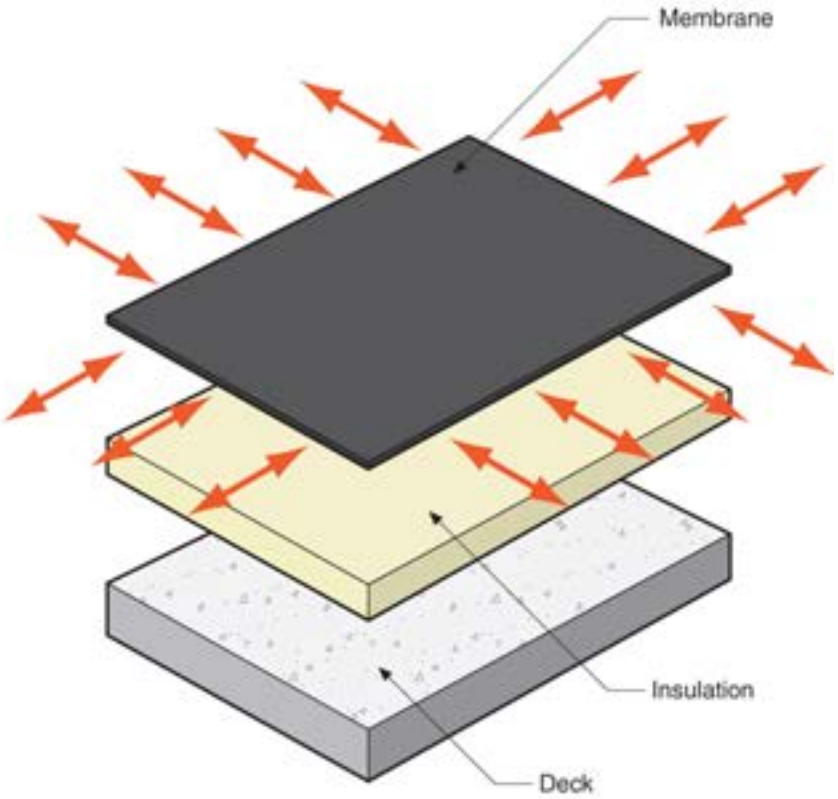
From Baker, M.; Roofs, 1980

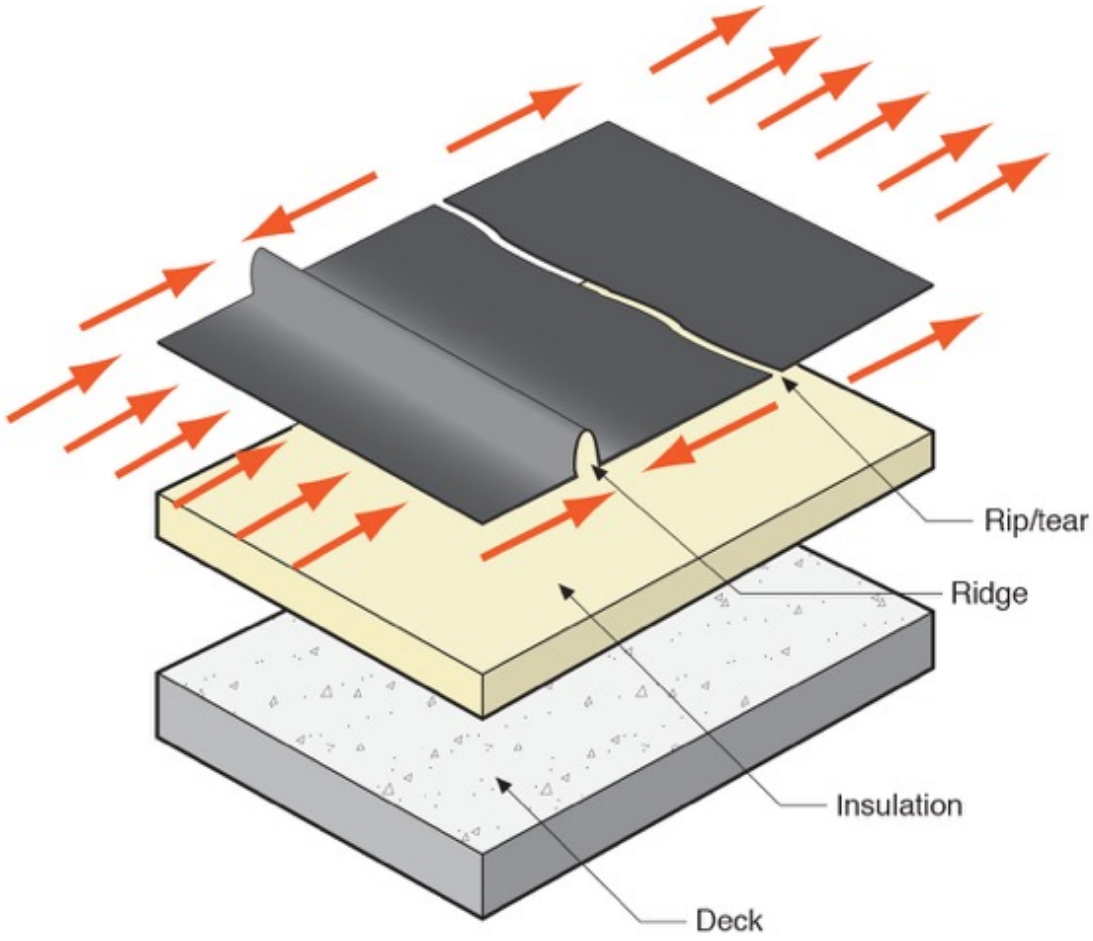

70
60
50
40
30
20
10
0
10
20
30
158
140
122
104
86
68
50
32
14
-4
-22
Temperature (°C)
Temperature (°F)
Membrane
Outside air
0
4
8
12
16
20
24
Hours of a winter day
From Baker, M.; Roofs, 1980

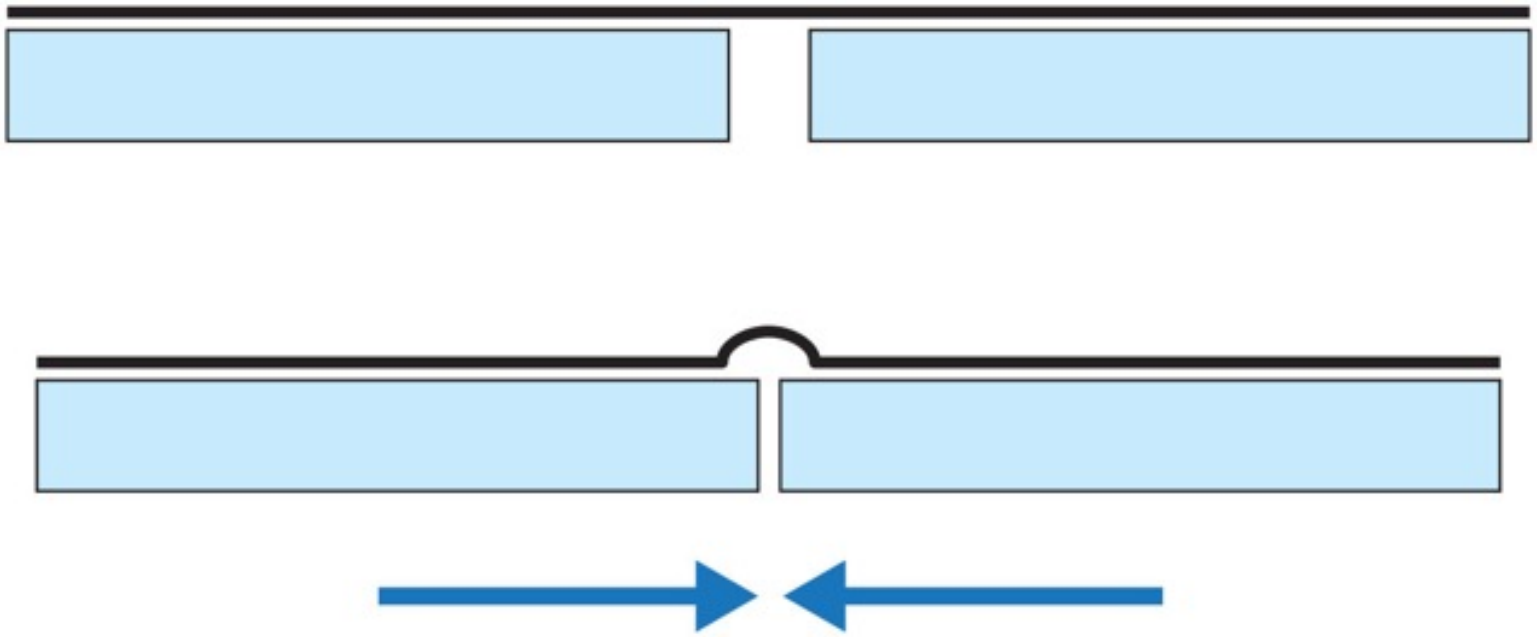

Gravel
Bitumen top pour
Felt
Bitumen
Felt
Bitumen
Bitumen saturated felt laid dry and nailed to deck
Dry sheathing or rosin paper nailed to deck
Wood deck
From Baker, M.; Roofs, 1980

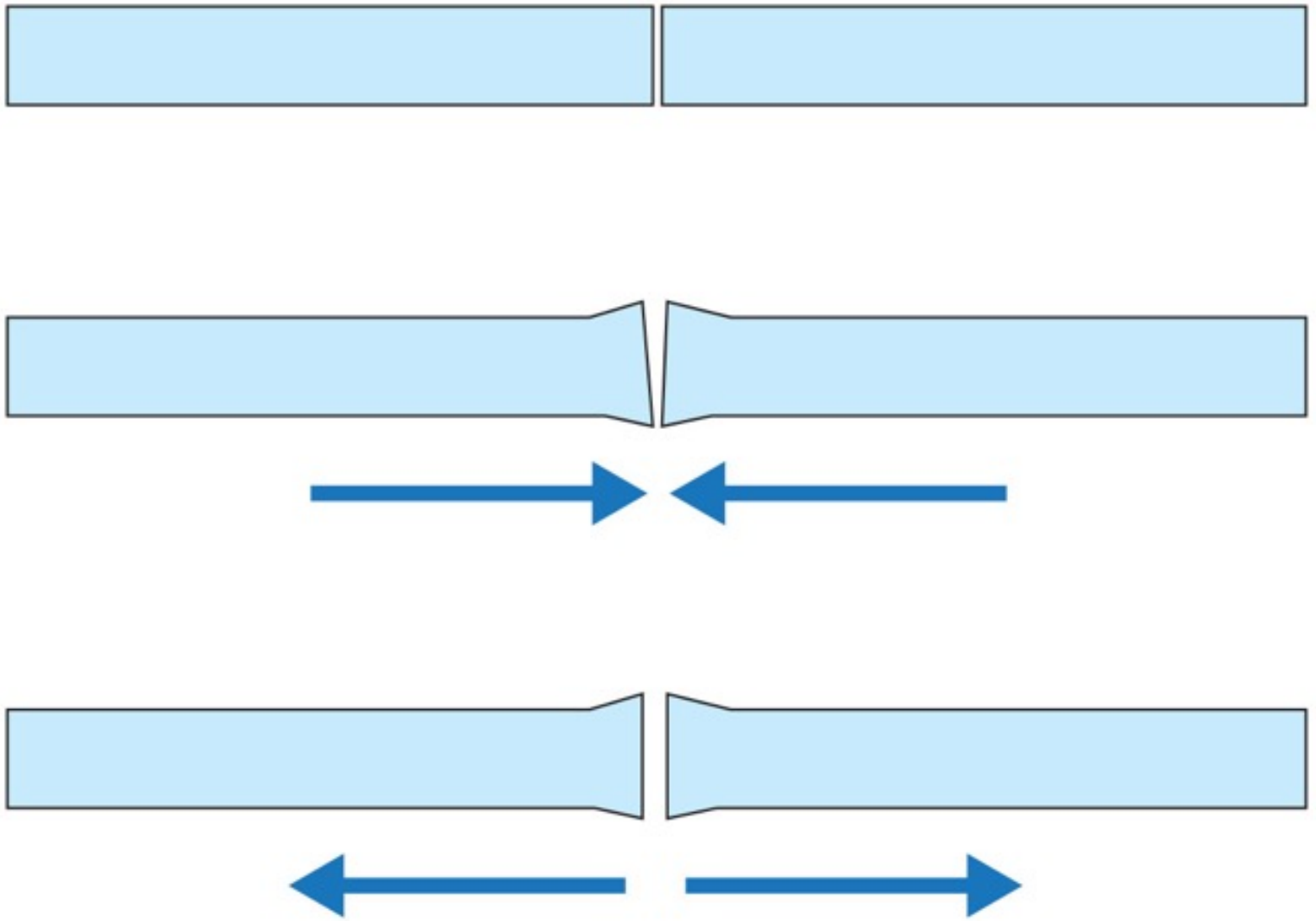

Gravel
Bitumen
Felt
Bitumen
Felt
Bitumen
Priming
Concrete deck
From Baker, M.; Roofs, 1980

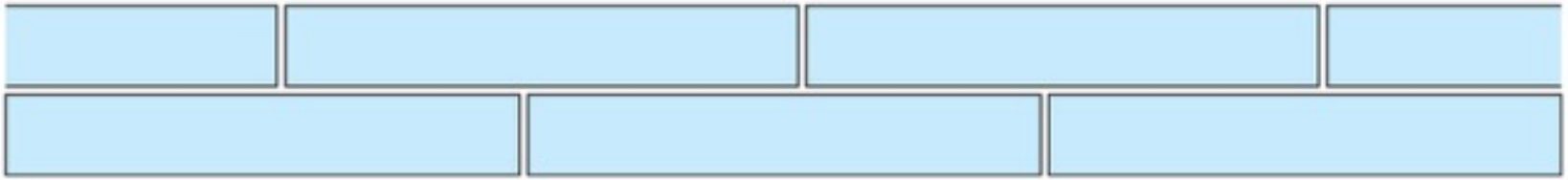

Membrane
Deck

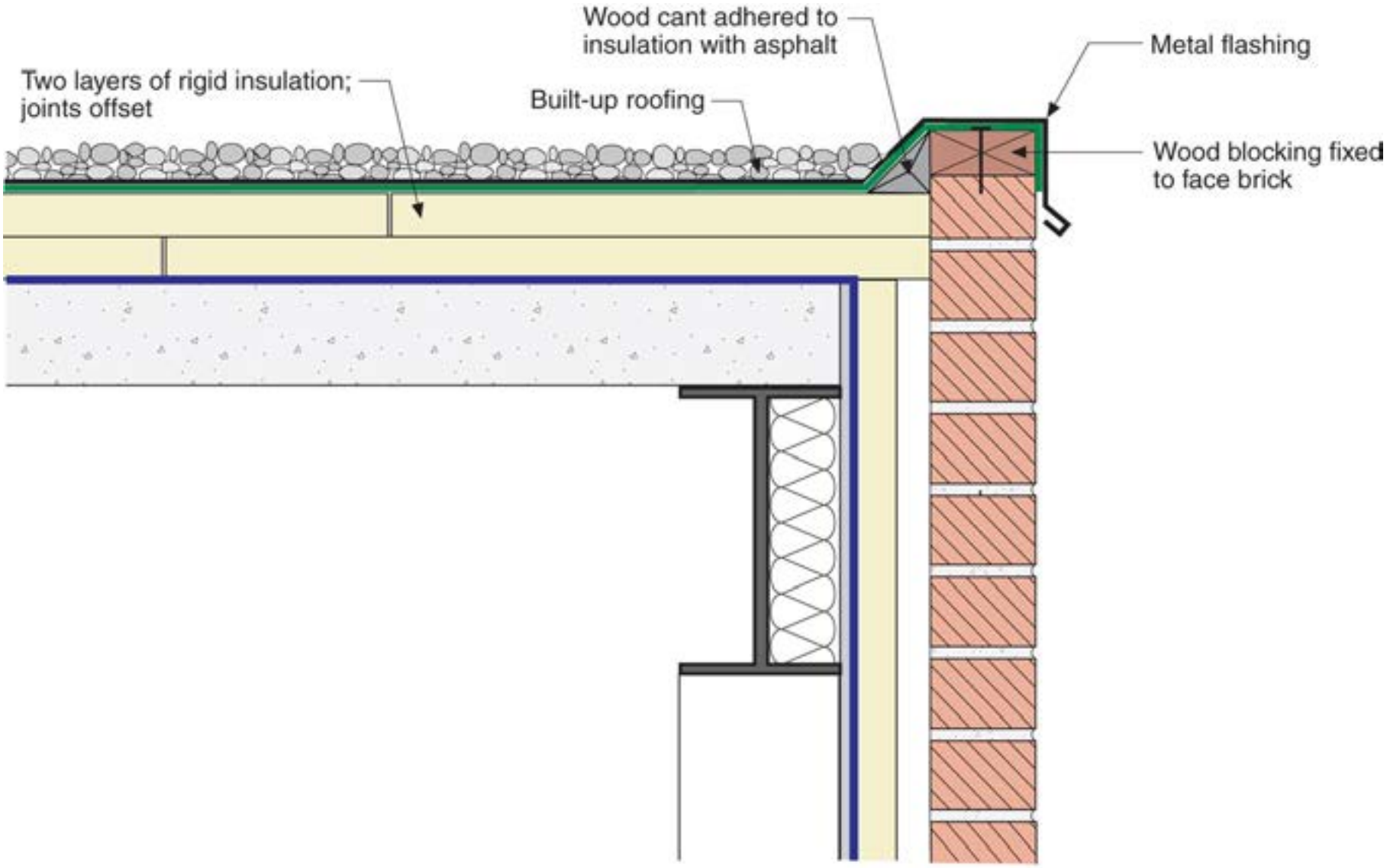

Membrane
Insulation
Deck


Rip/tear
Ridge
Insulation
Deck

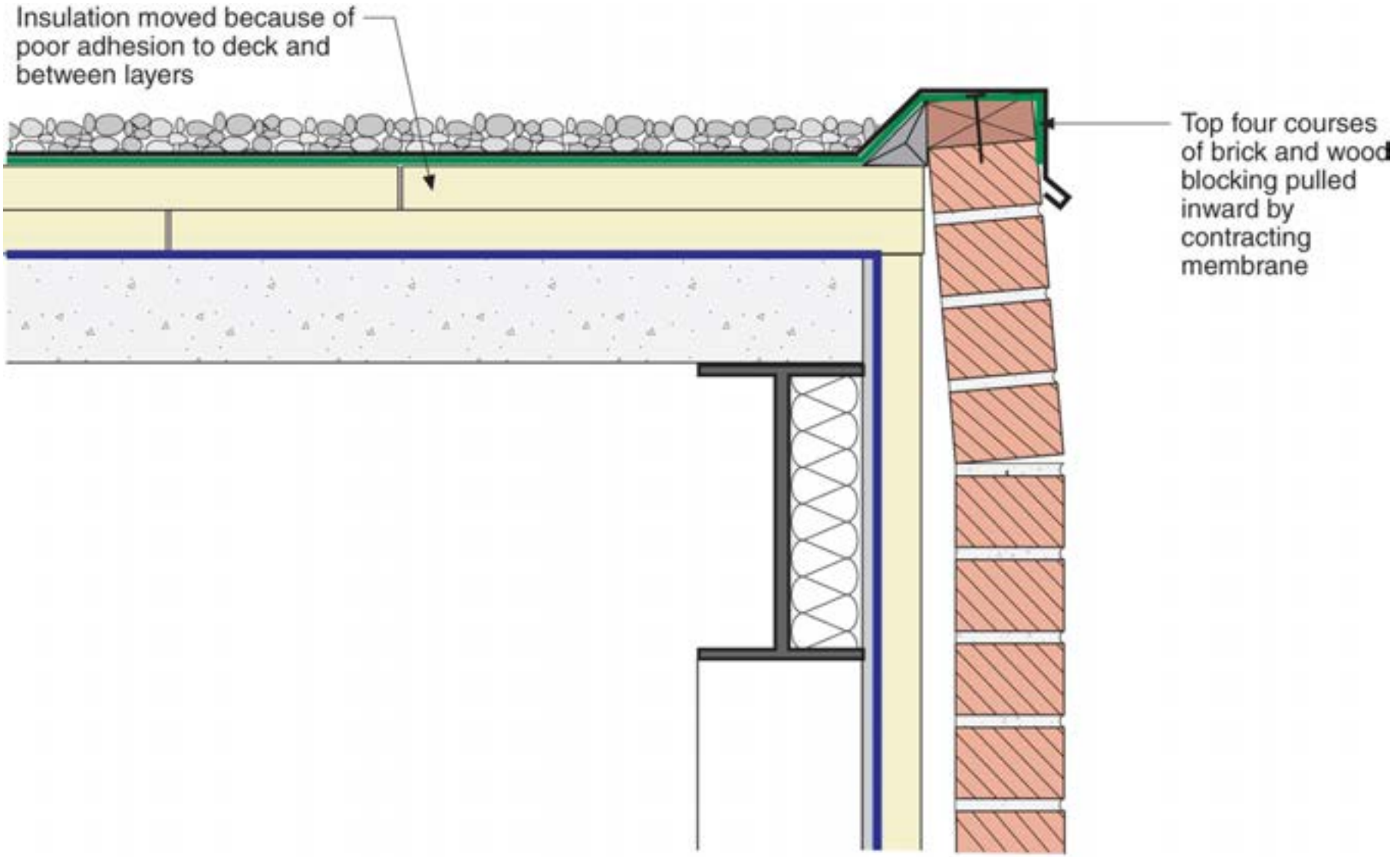




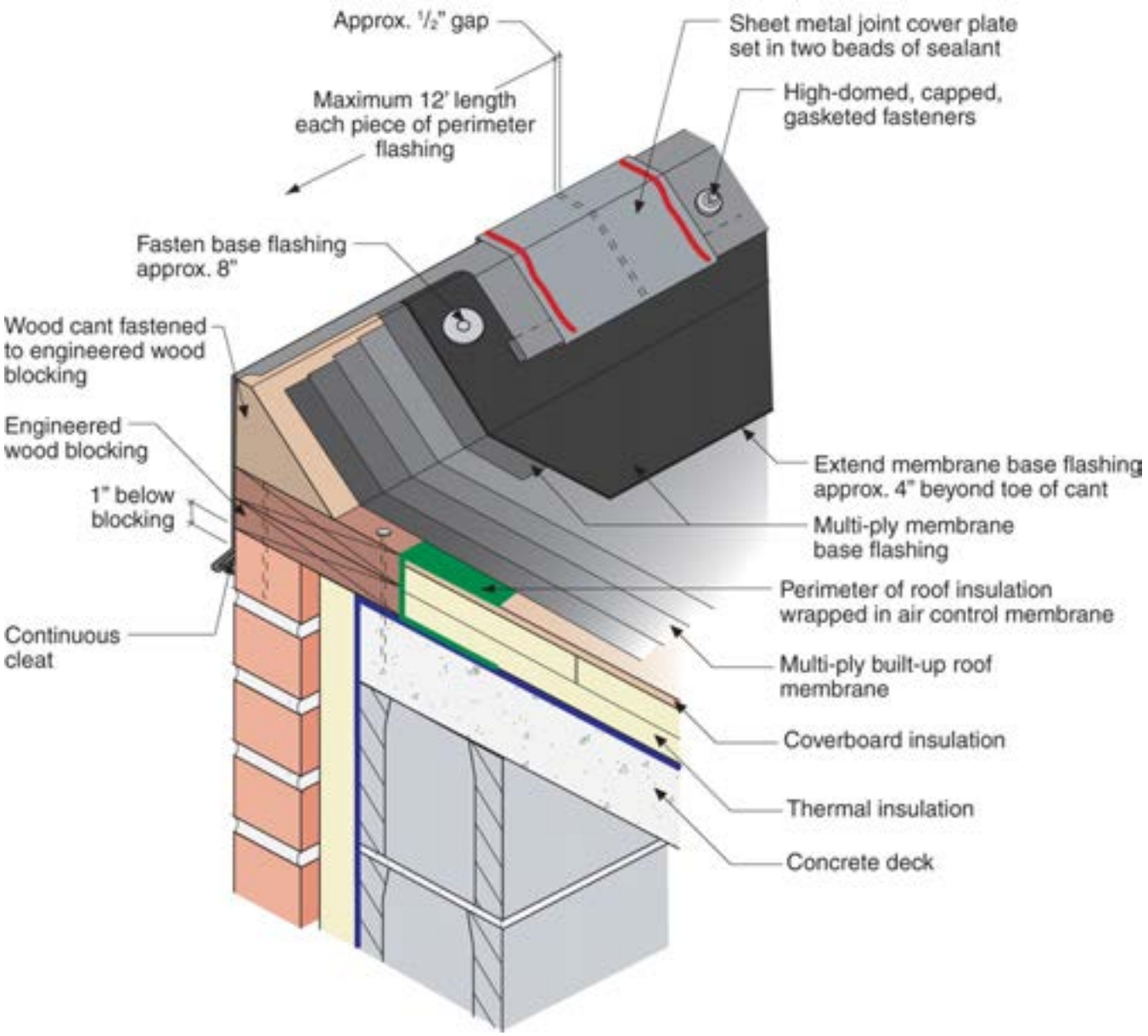


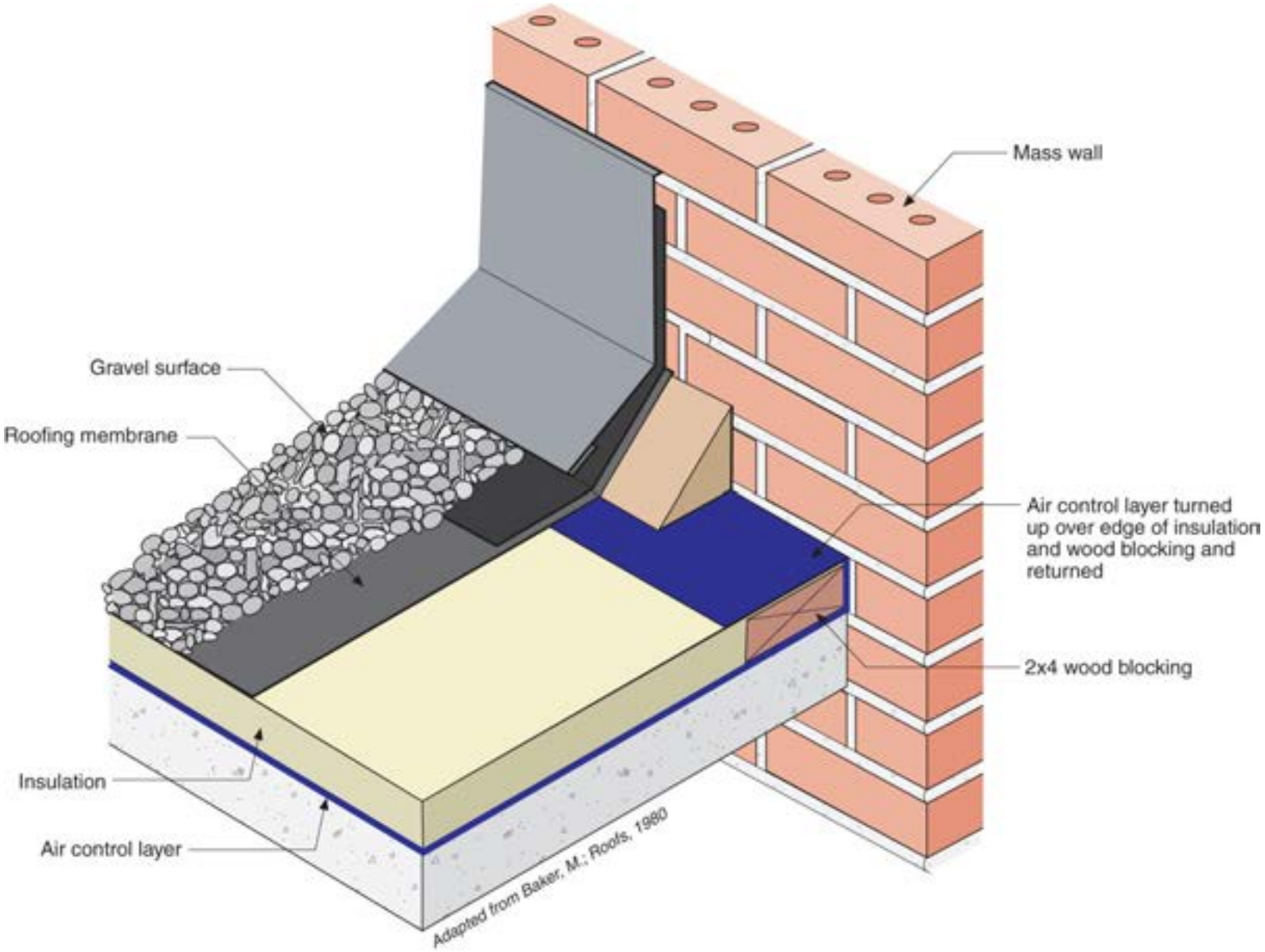


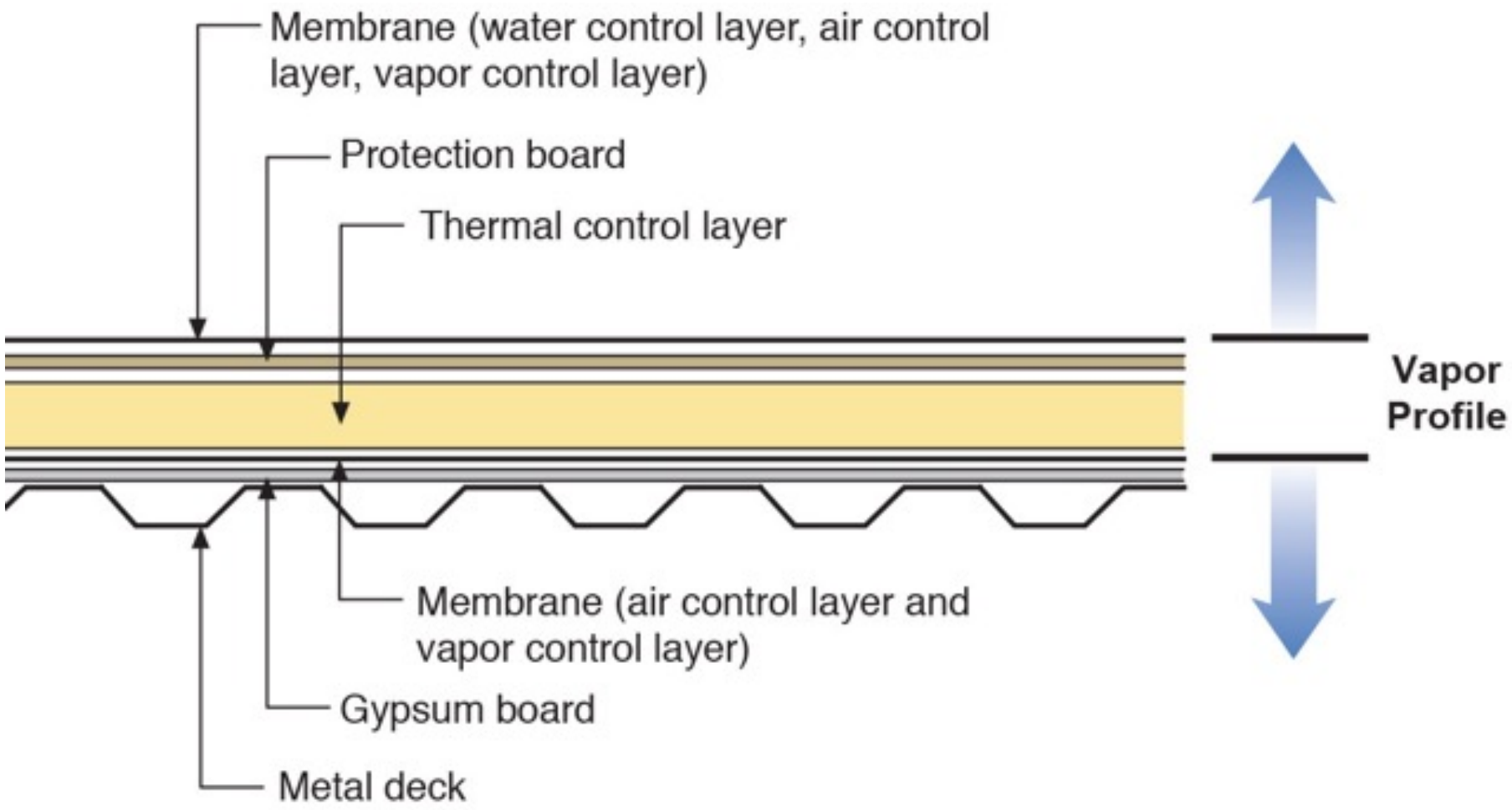
Adapted from Baker, M.; Roofs, 1980

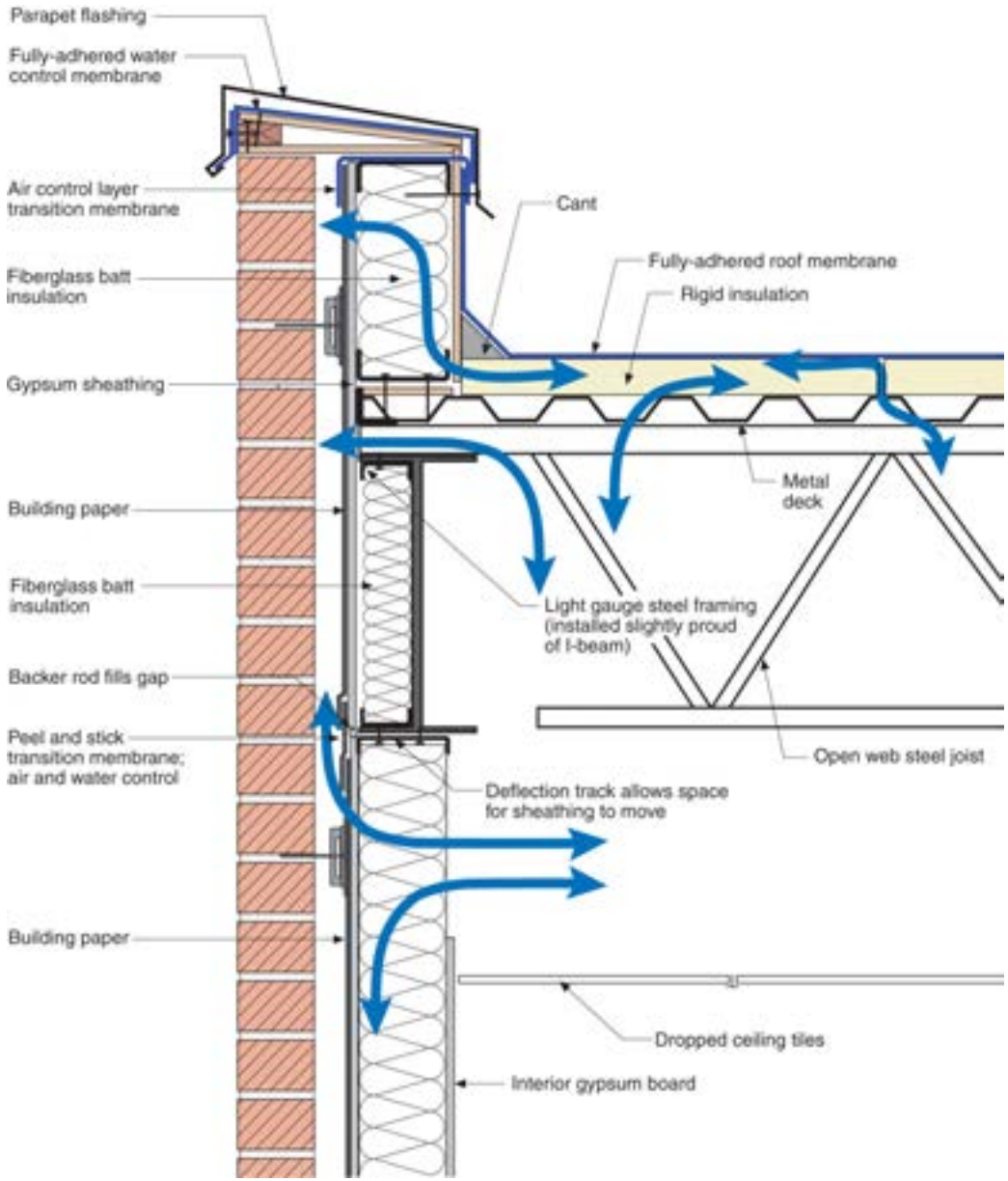


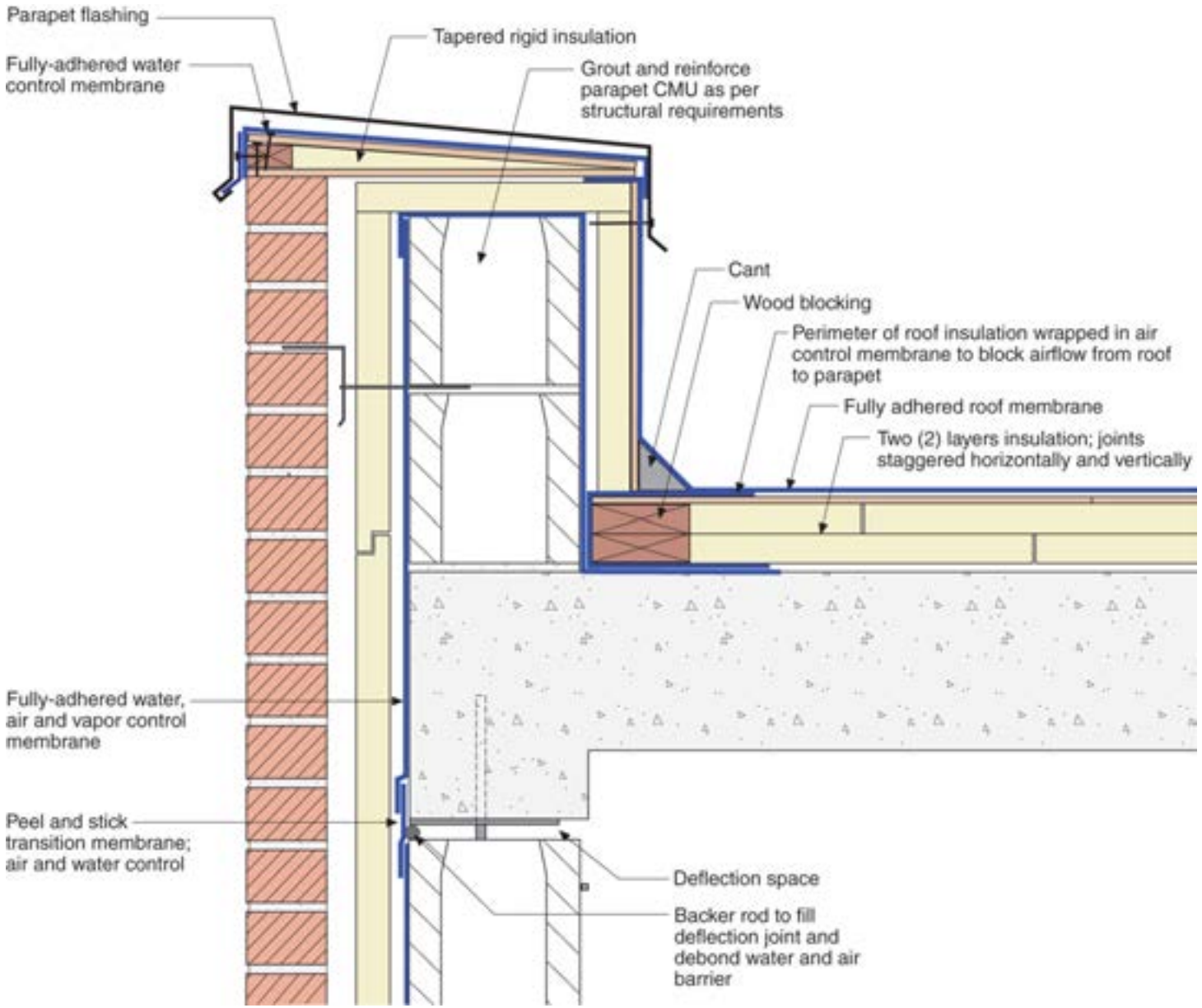
Adapted from Baker, M.; Roofs, 1980;
Courtesy National Research Council of Canada

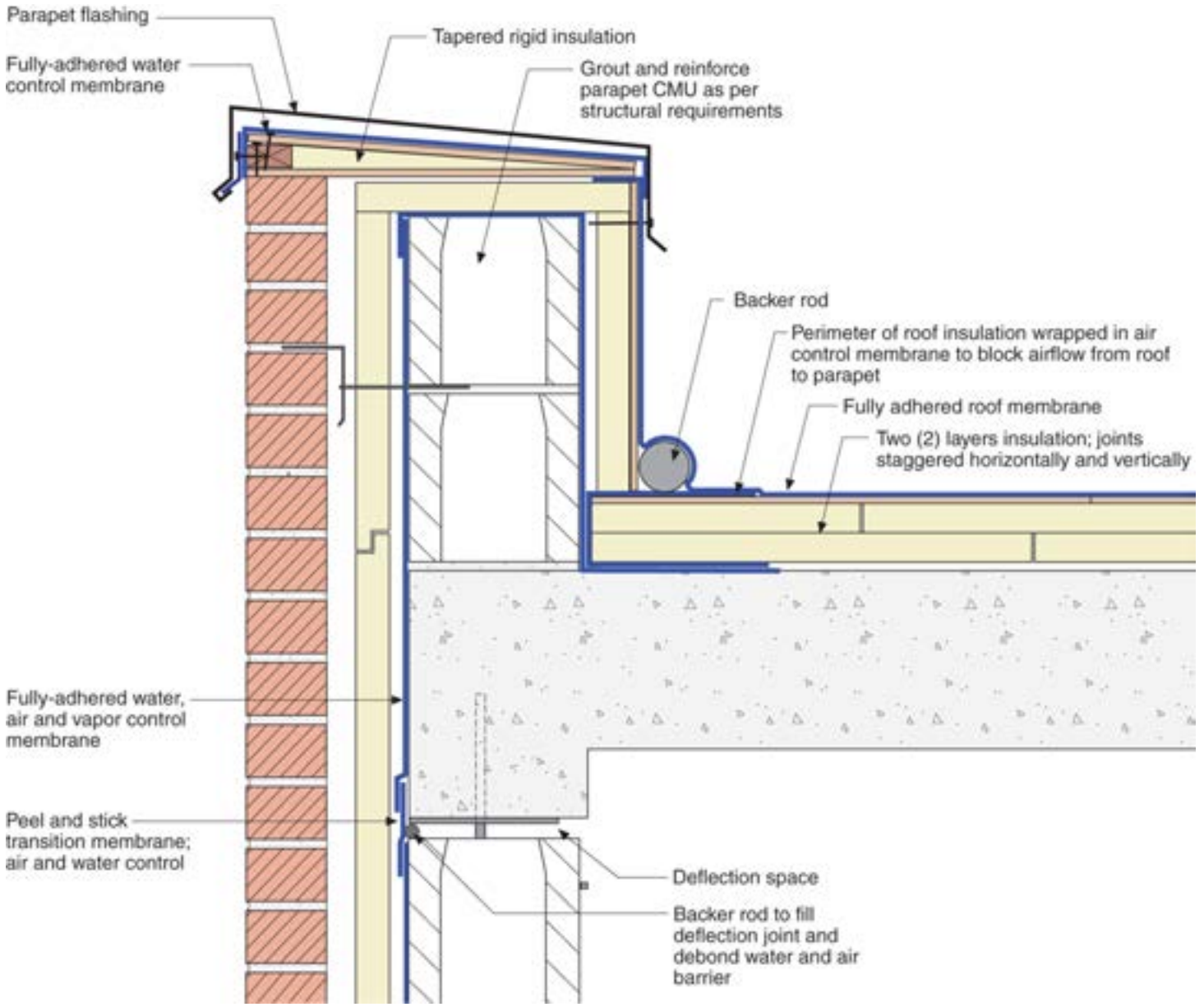

Approx. ½" gap
Maximum 12' length each piece of perimeter flashing
Sheet metal joint cover plate set in two beads of sealant
High-domed, capped, gasketed fasteners
Fasten base flashing approx. 8"
Wood cant fastened to engineered wood blocking
Engineered wood blocking
1" below blocking
Continuous cleat
Extend membrane base flashing approx. 4" beyond toe of cant
Multi-ply membrane base flashing
Perimeter of roof insulation wrapped in air control membrane
Multi-ply built-up roof membrane
Coverboard insulation
Thermal insulation
Concrete deck

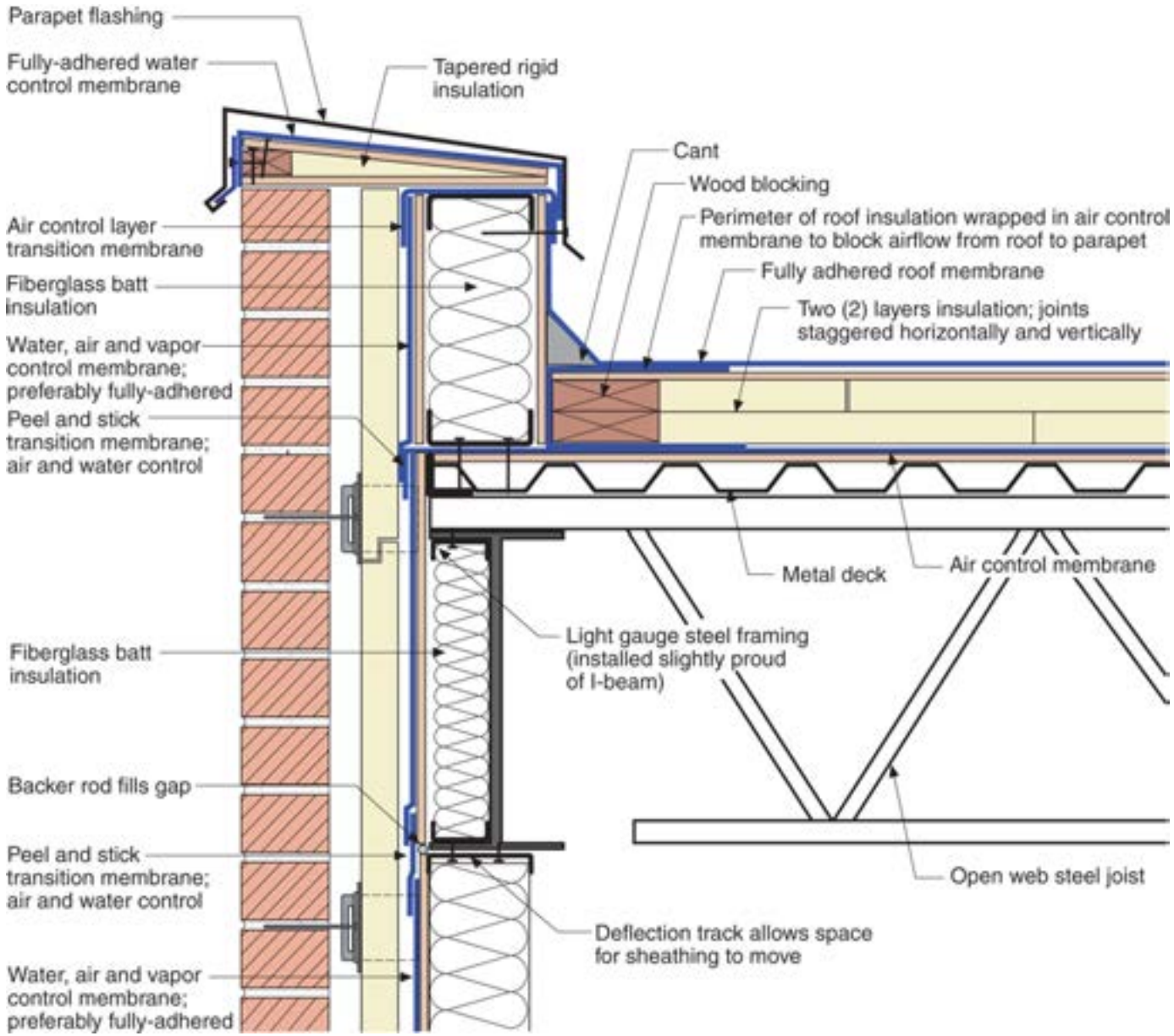

Mass wall
Gravel surface
Roofing membrane
Air control layer turned up over edge of insulation and wood blocking and returned
2x4 wood blocking
Insulation
Air control layer
Adapted from Baker, M.; Roofs, 1980

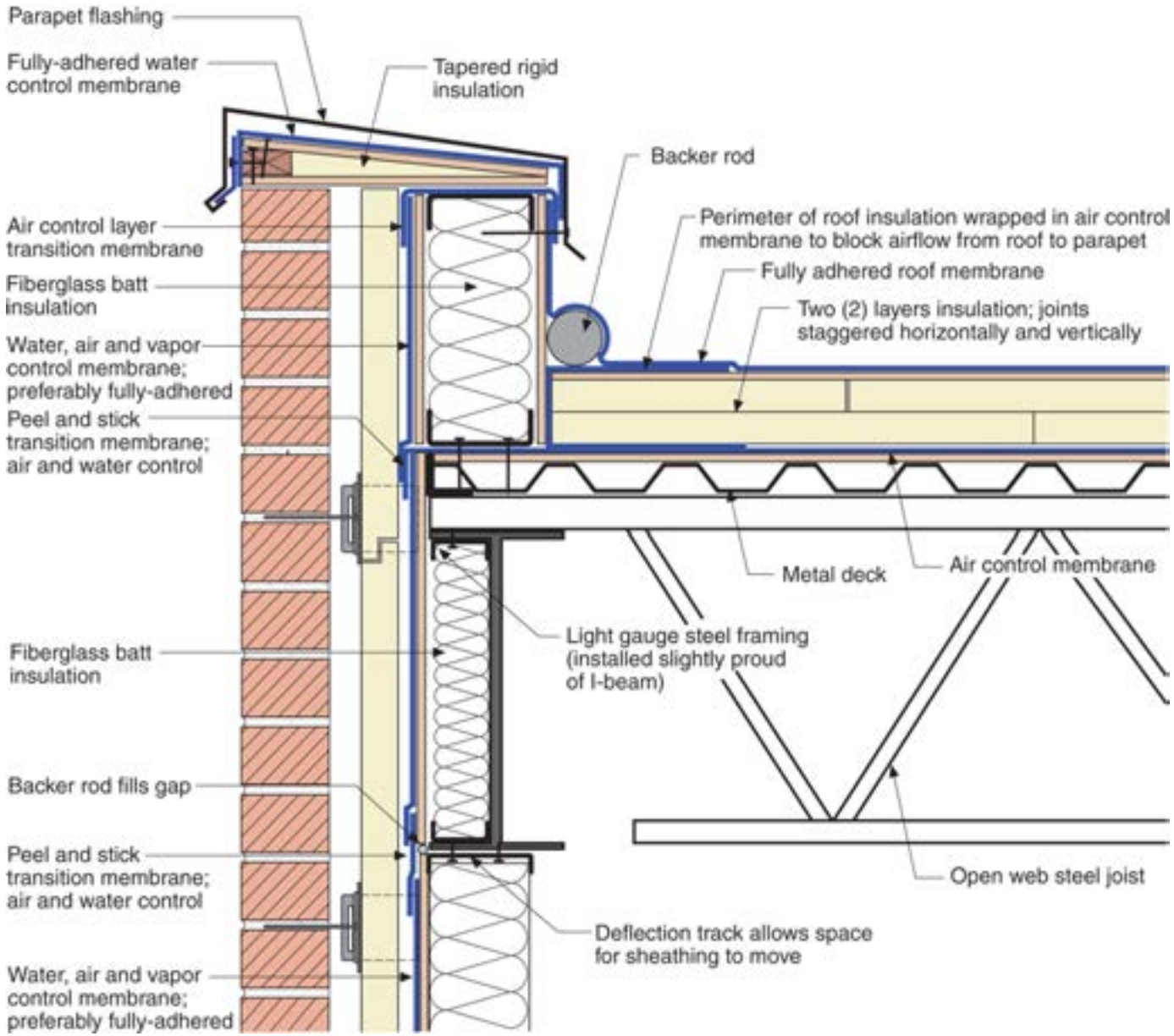

Membrane (water control layer, air control layer, vapor control layer)
Protection board
Thermal control layer
Vapor Profile
Membrane (air control layer and vapor control layer)
Gypsum board
Metal deck

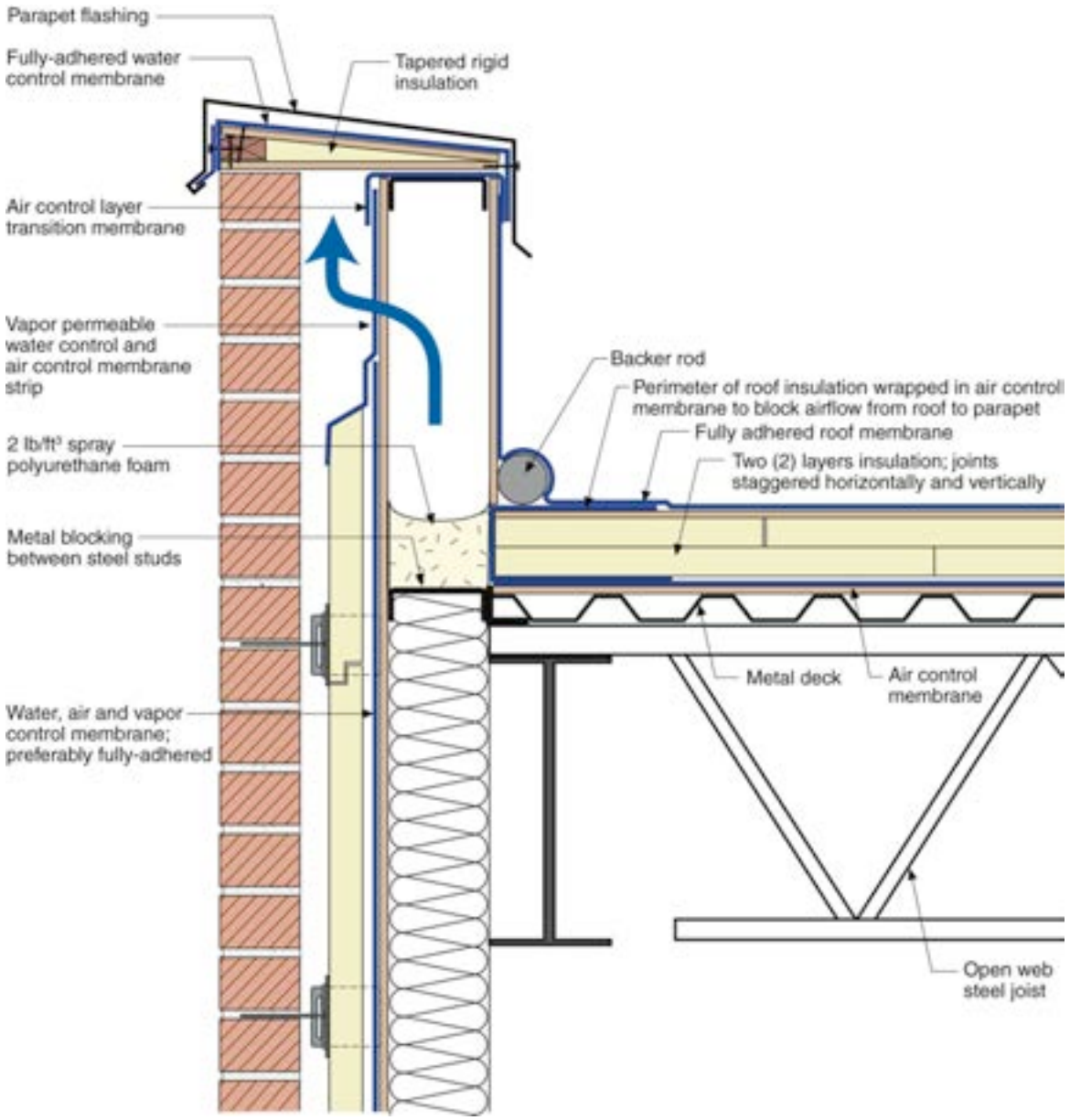

Parapet flashing
Fully-adhered water control membrane
Air control layer transition membrane
Fiberglass batt insulation
Gypsum sheathing
Building paper
Fiberglass batt insulation
Backer rod fills gap
Peel and stick transition membrane; air and water control
Building paper
Cant
Fully-adhered roof membrane
Rigid insulation
Metal deck
Light gauge steel framing (installed slightly proud of I-beam)
Open web steel joist
Deflection track allows space for sheathing to move
Dropped ceiling tiles
Interior gypsum board

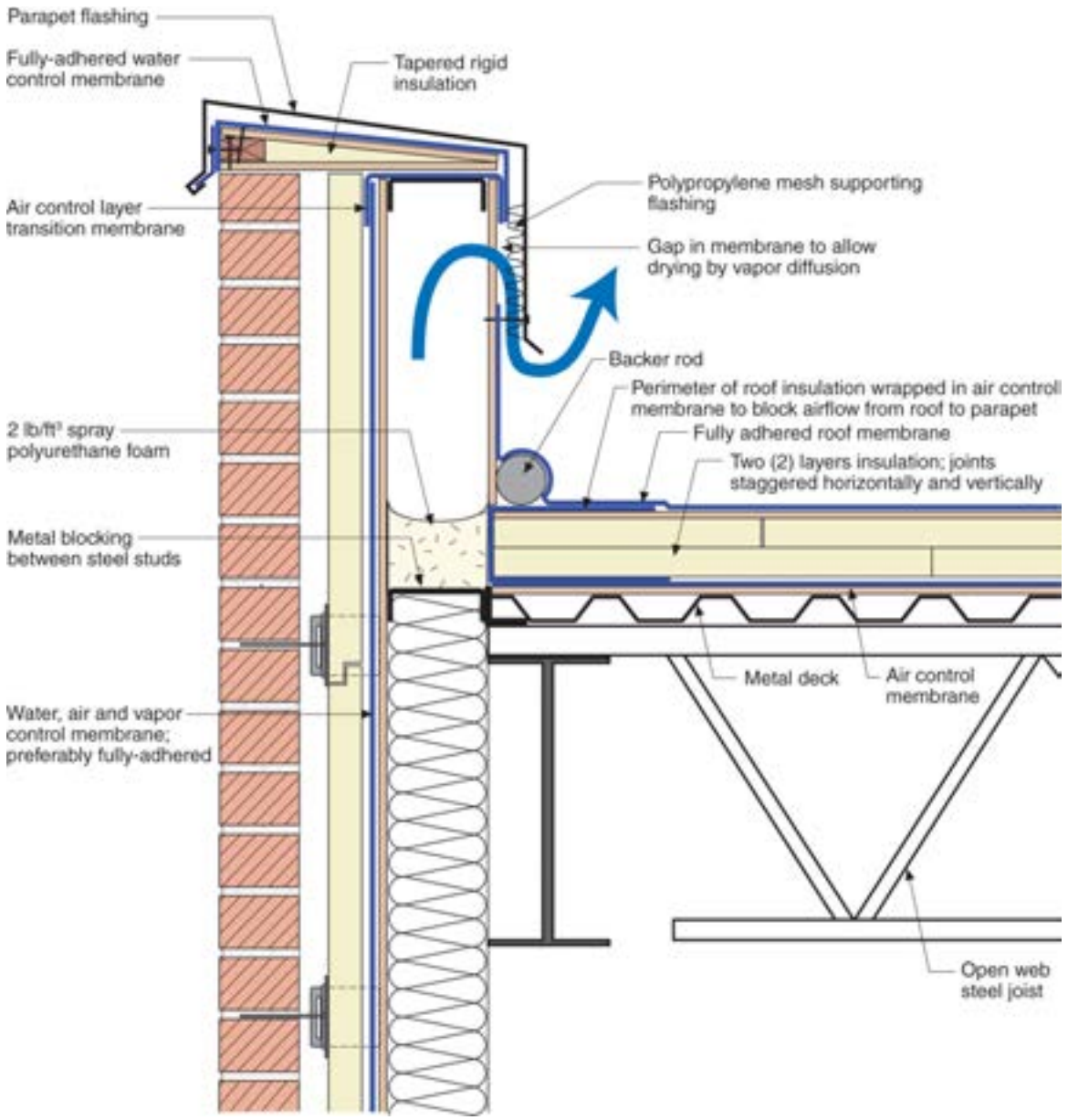

Parapet flashing
Fully-adhered water control membrane
Tapered rigid insulation
Grout and reinforce parapet CMU as per structural requirements
Cant
Wood blocking
Perimeter of roof insulation wrapped in air control membrane to block airflow from roof to parapet
Fully adhered roof membrane
Two (2) layers insulation; joints staggered horizontally and vertically
Fully-adhered water, air and vapor control membrane
Peel and stick transition membrane; air and water control
Deflection space
Backer rod to fill deflection joint and debond water and air barrier

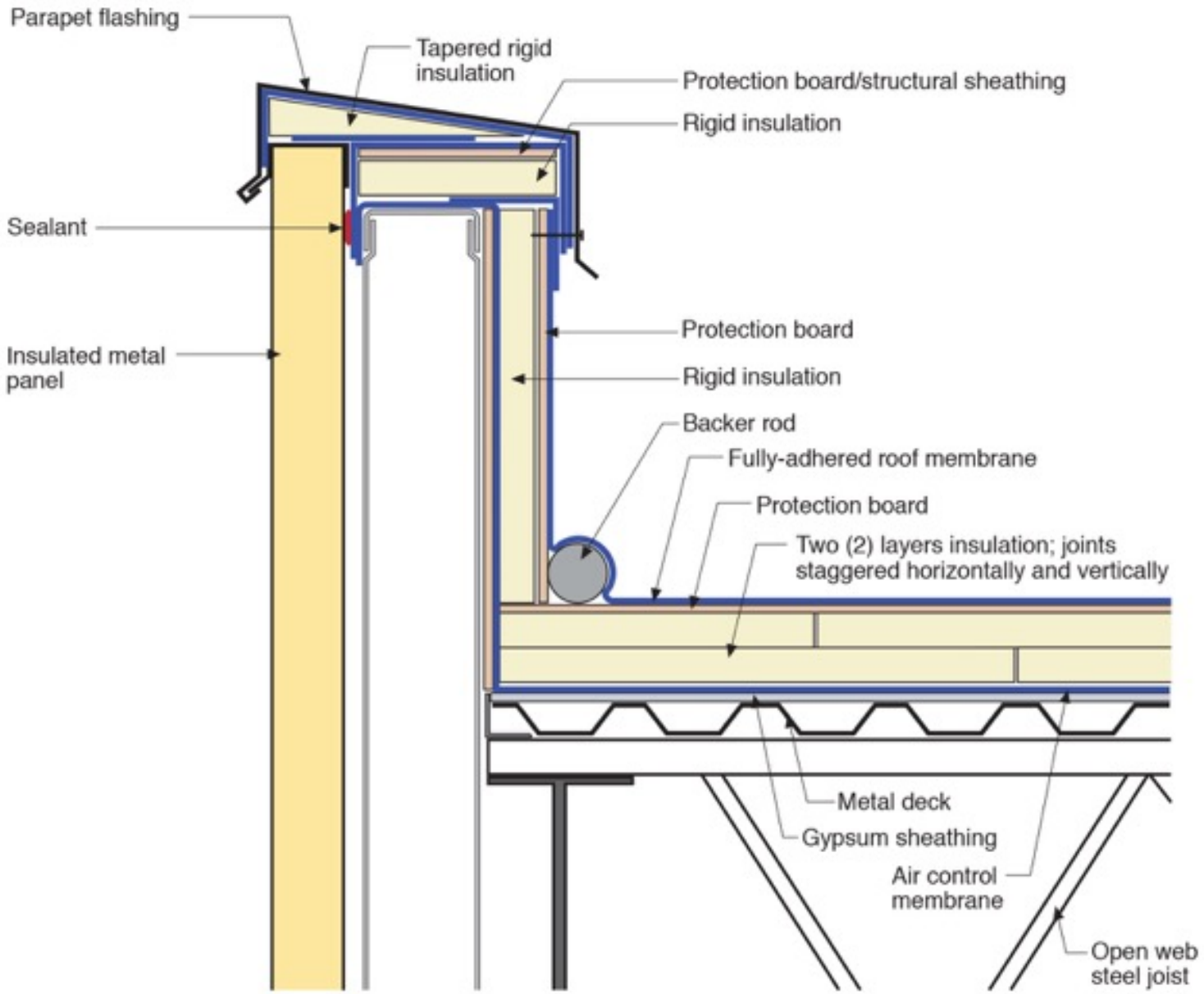

Parapet flashing
Fully-adhered water control membrane
Tapered rigid insulation
Grout and reinforce parapet CMU as per structural requirements
Backer rod
Perimeter of roof insulation wrapped in air control membrane to block airflow from roof to parapet
Fully adhered roof membrane
Two (2) layers insulation; joints staggered horizontally and vertically
Fully-adhered water, air and vapor control membrane
Peel and stick transition membrane; air and water control
Deflection space
Backer rod to fill deflection joint and debond water and air barrier

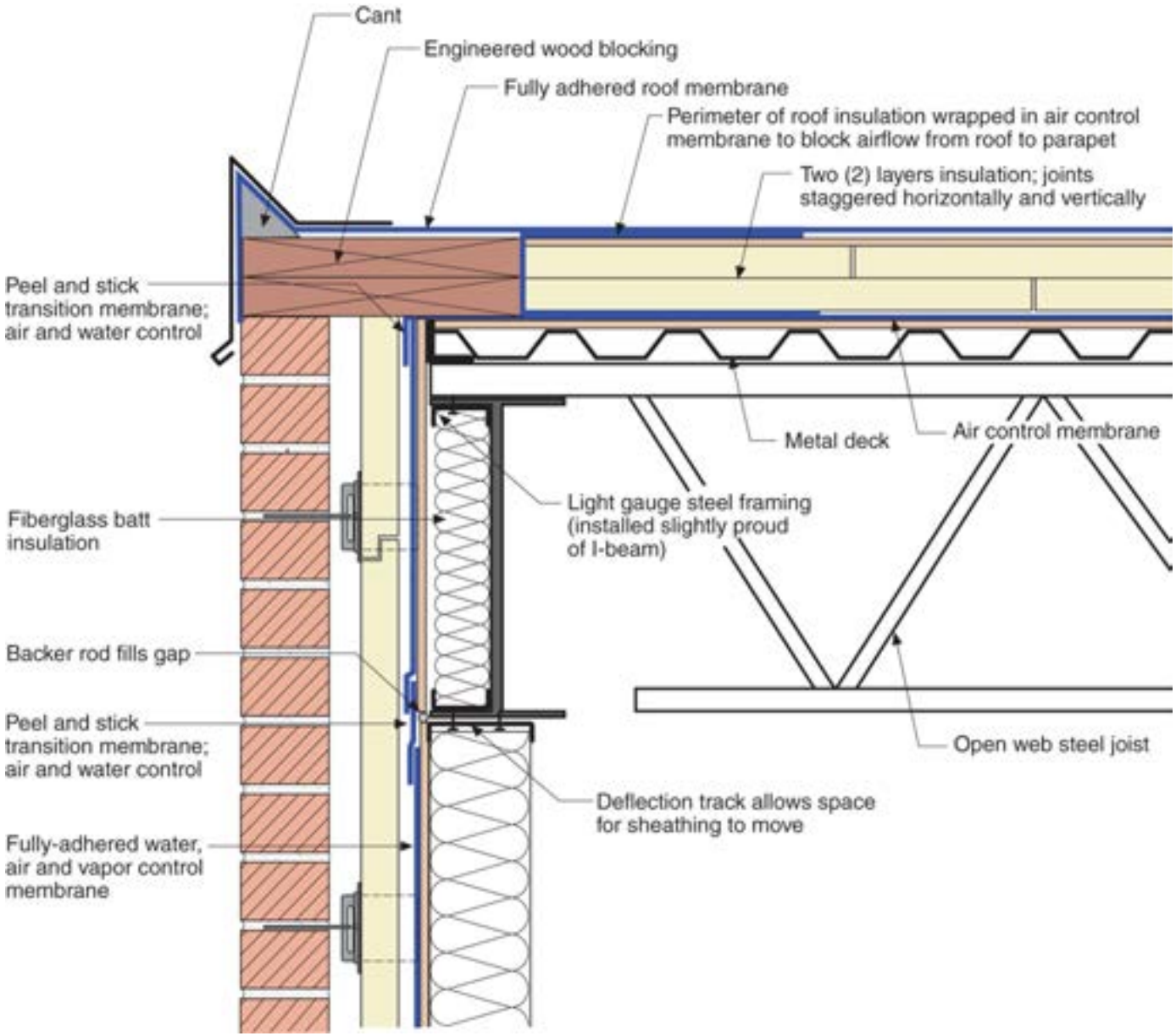

Parapet flashing
Fully-adhered water control membrane
Tapered rigid insulation
Cant
Wood blocking
Perimeter of roof insulation wrapped in air control membrane to block airflow from roof to parapet
Fully adhered roof membrane
Two (2) layers insulation; joints staggered horizontally and vertically
Air 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

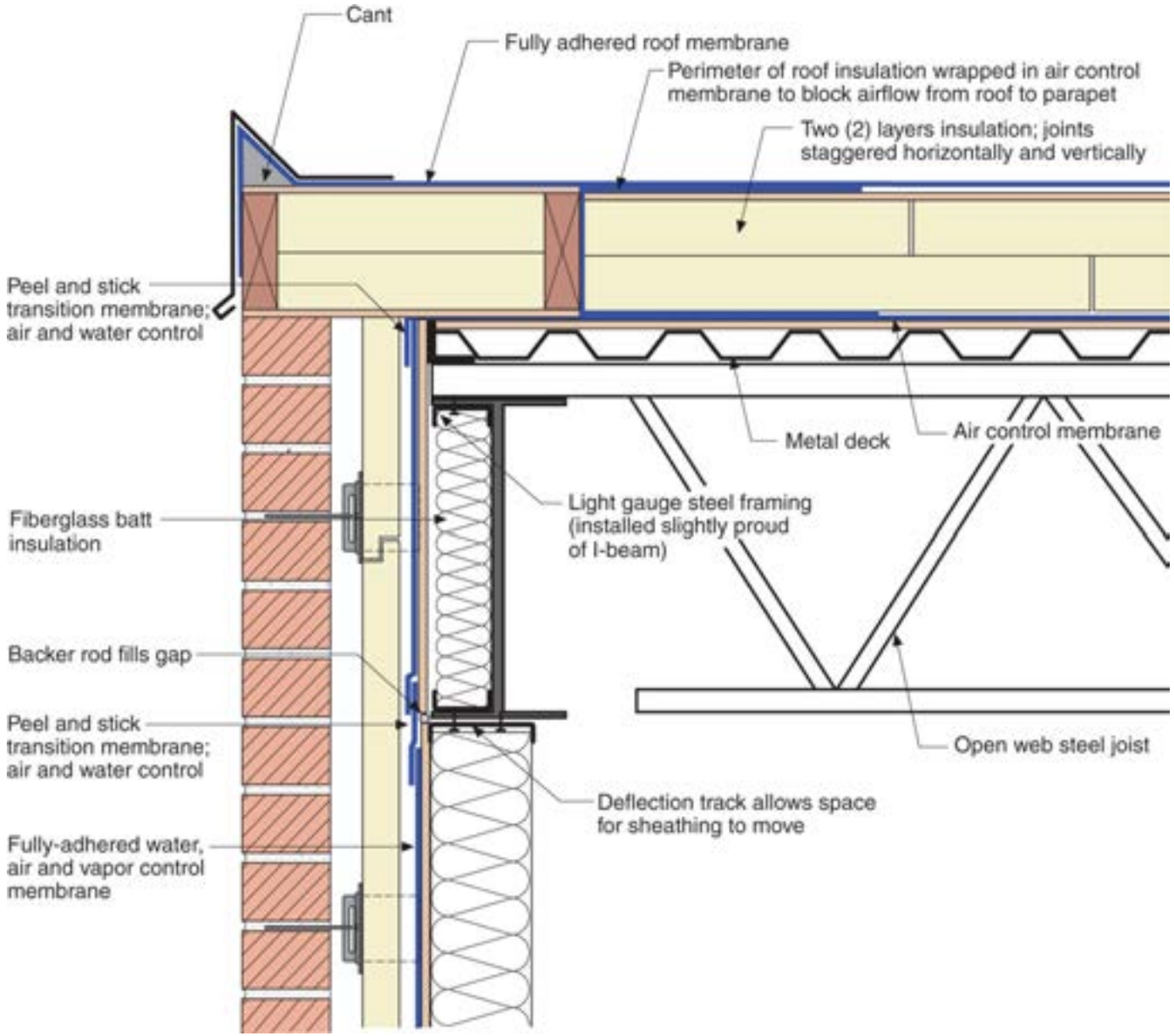

Parapet flashing
Fully-adhered water control membrane
Tapered rigid insulation
Backer rod
Air control layer transition membrane
Perimeter of roof insulation wrapped in air control membrane to block airflow from roof to parapet
Fiberglass batt insulation
Fully adhered roof membrane
Two (2) layers insulation; joints staggered horizontally and vertically
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


Parapet flashing
Fully-adhered water control membrane
Tapered rigid insulation
Air control layer transition membrane
Vapor permeable water control and air control membrane strip
2 lb/ft³ spray polyurethane foam
Metal blocking between steel studs
Water, air and vapor control membrane; preferably fully-adhered
Backer rod
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
Metal deck
Air control membrane
Open web steel joist


Parapet flashing
Fully-adhered water control membrane
Tapered rigid insulation
Air control layer transition membrane
Polypropylene mesh supporting flashing
Gap in membrane to allow drying by vapor diffusion
Backer rod
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
2 lb/ft³ spray polyurethane foam
Metal blocking between steel studs
Metal deck
Air control membrane
Water, air and vapor control membrane; preferably fully-adhered
Open web steel joist


Parapet flashing
Tapered rigid insulation
Protection board/structural sheathing
Rigid insulation
Sealant
Insulated metal panel
Protection board
Rigid insulation
Backer rod
Fully-adhered roof membrane
Protection board
Two (2) layers insulation; joints staggered horizontally and vertically
Metal deck
Gypsum sheathing
Air control membrane
Open web steel joist


Cant
Engineered wood blocking
Fully adhered roof membrane
Perimeter of roof insulation wrapped in air control membrane to block airflow from roof to parapet
Two (2) layers insulation; joints staggered horizontally and vertically
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
Fully-adhered water, air and vapor control membrane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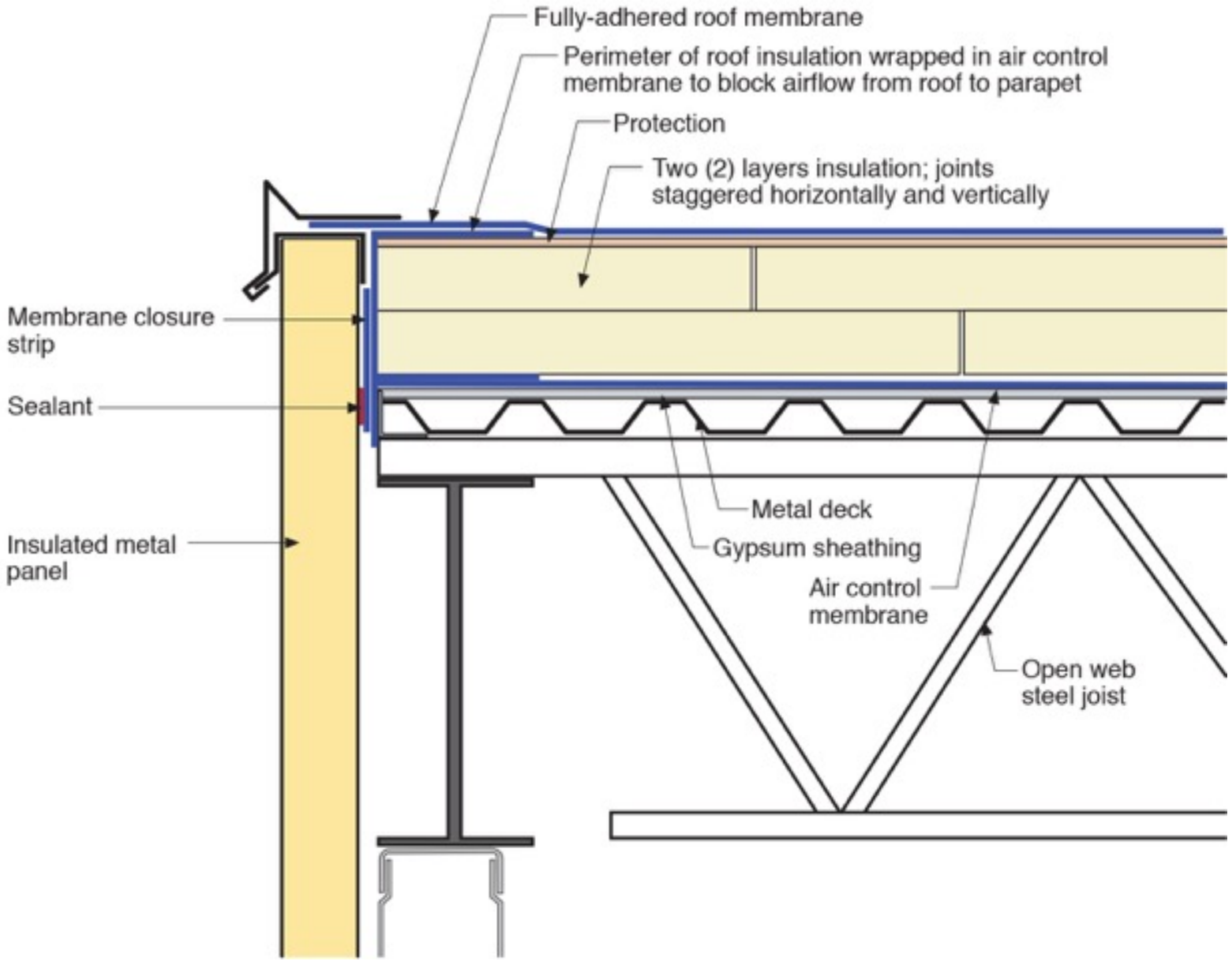

Fully-adhered roof membrane
Perimeter of roof insulation wrapped in air control membrane to block airflow from roof to parapet
Protection
Two (2) layers insulation; joints staggered horizontally and vertically
Membrane closure strip
Sealant
Insulated metal panel
Metal deck
Gypsum sheathing
Air control membrane
Open web steel joist

It’s a Case of Black or White

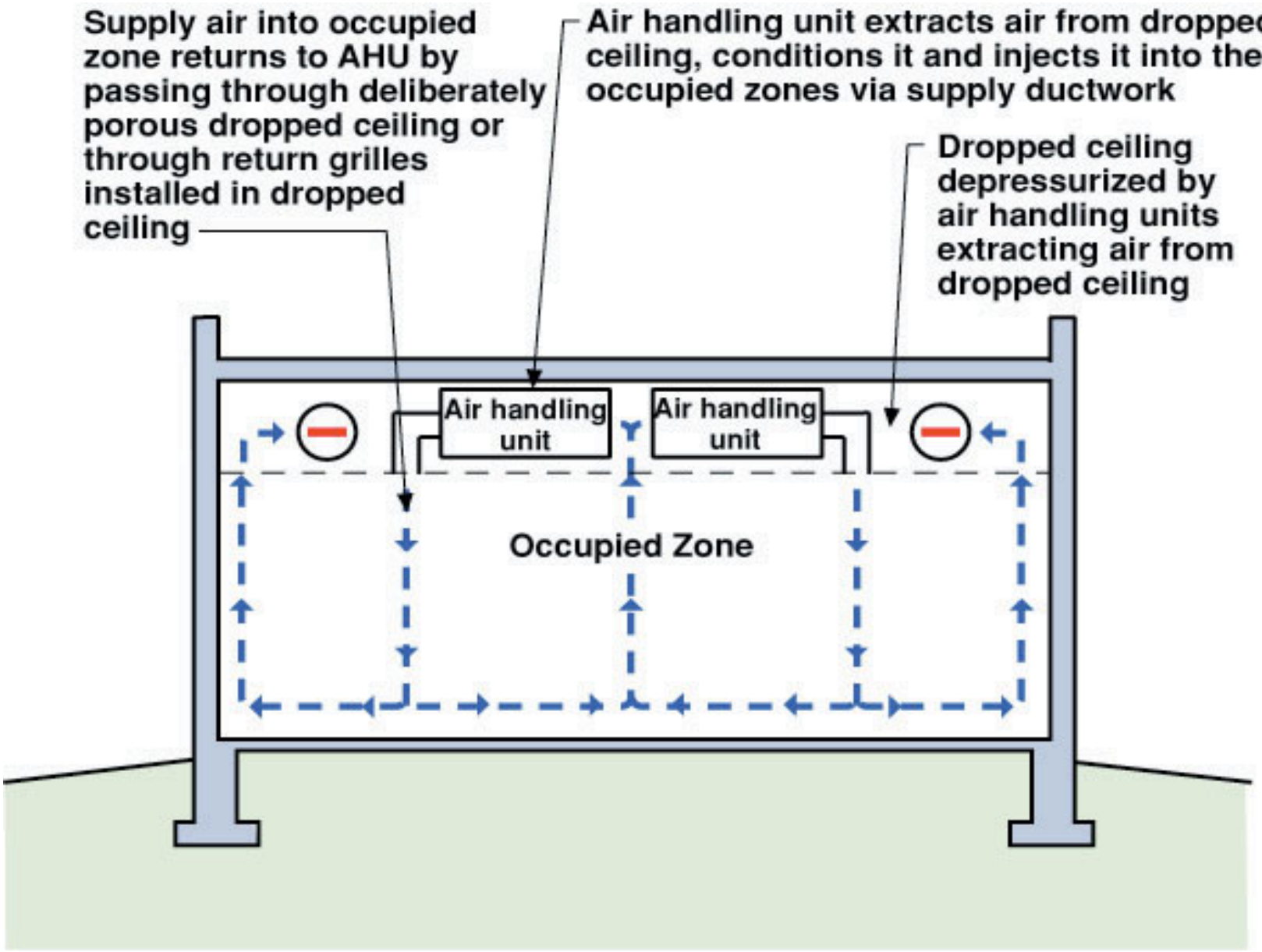
It’s a Case of Black or White

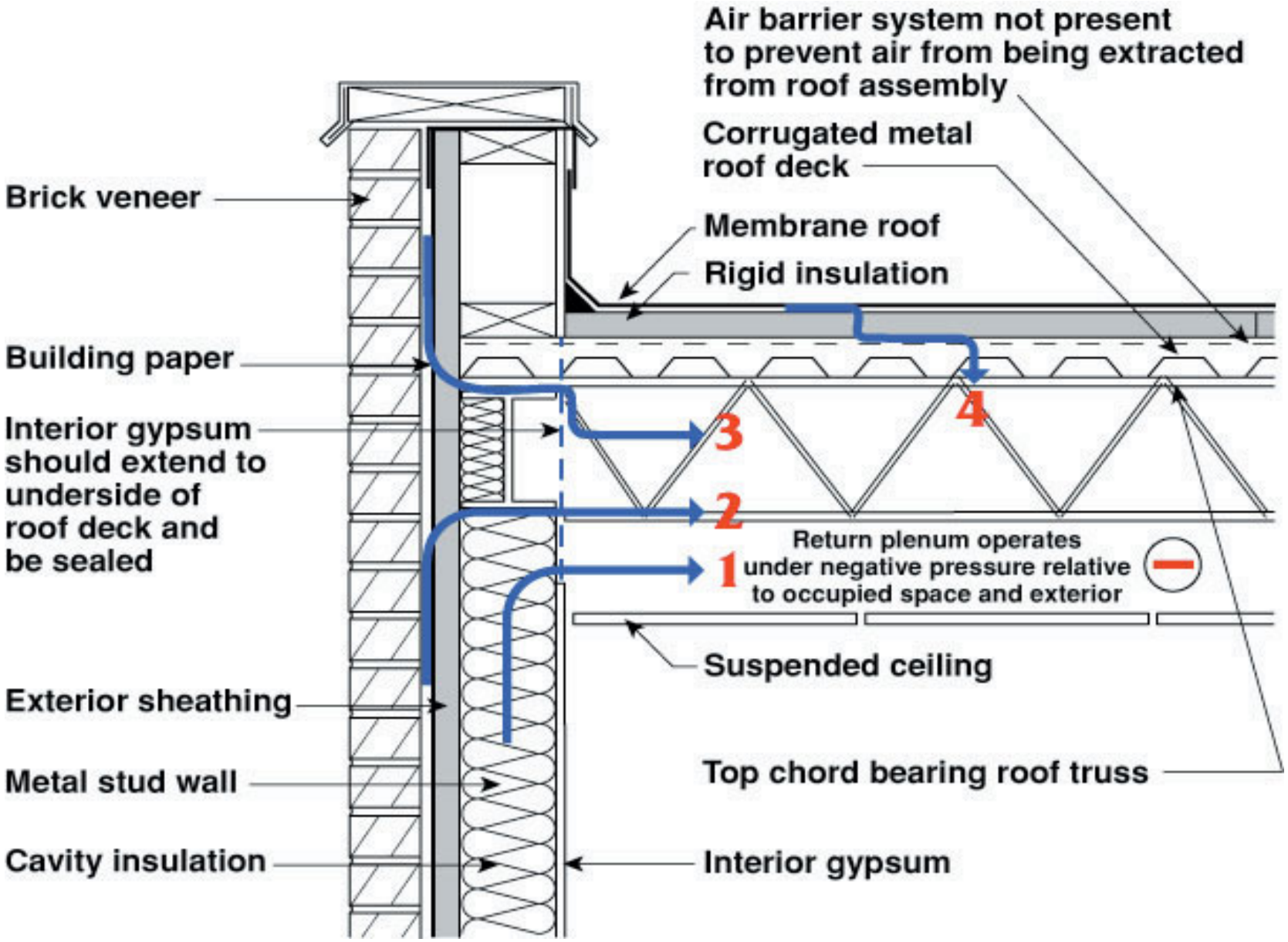
Arrhenius

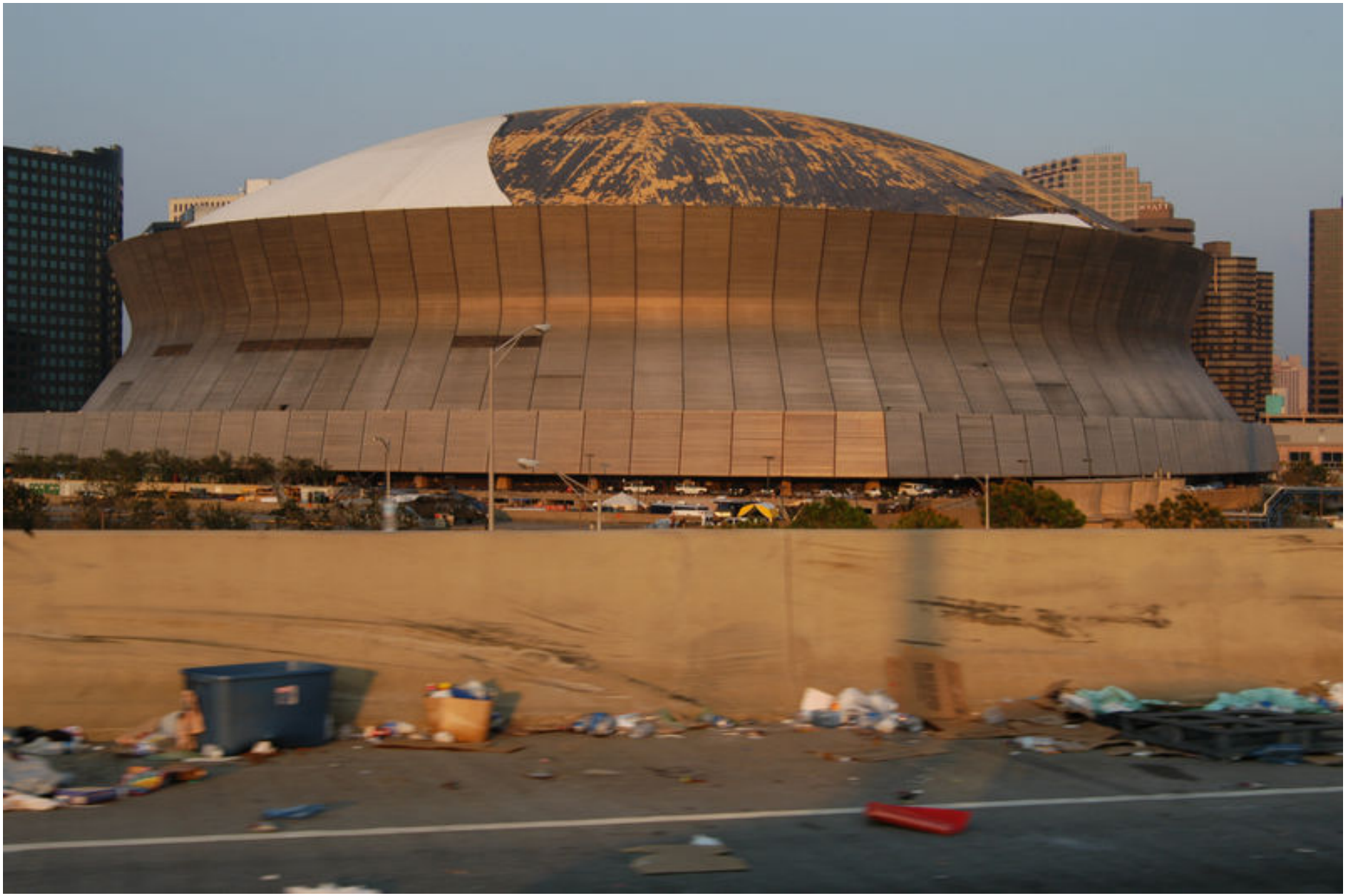
It’s a Case of Black or White

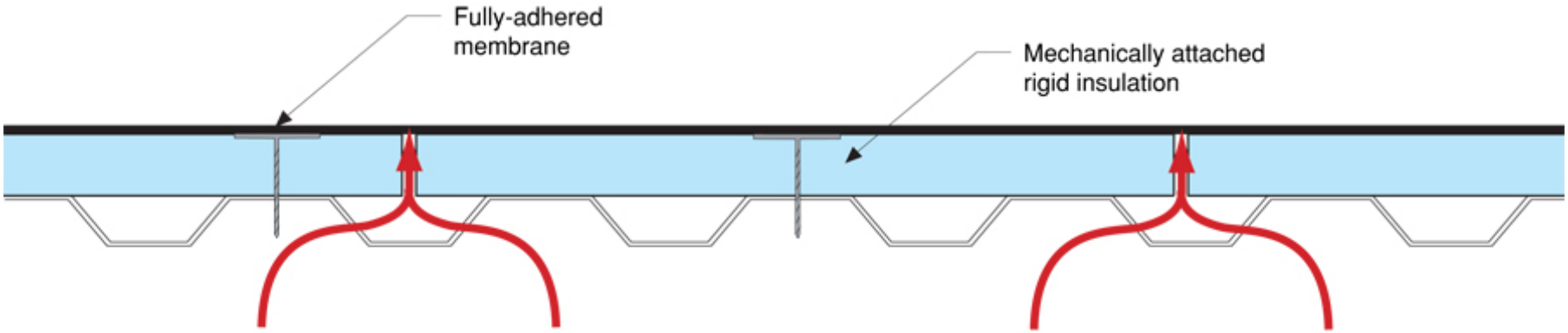
Arrhenius

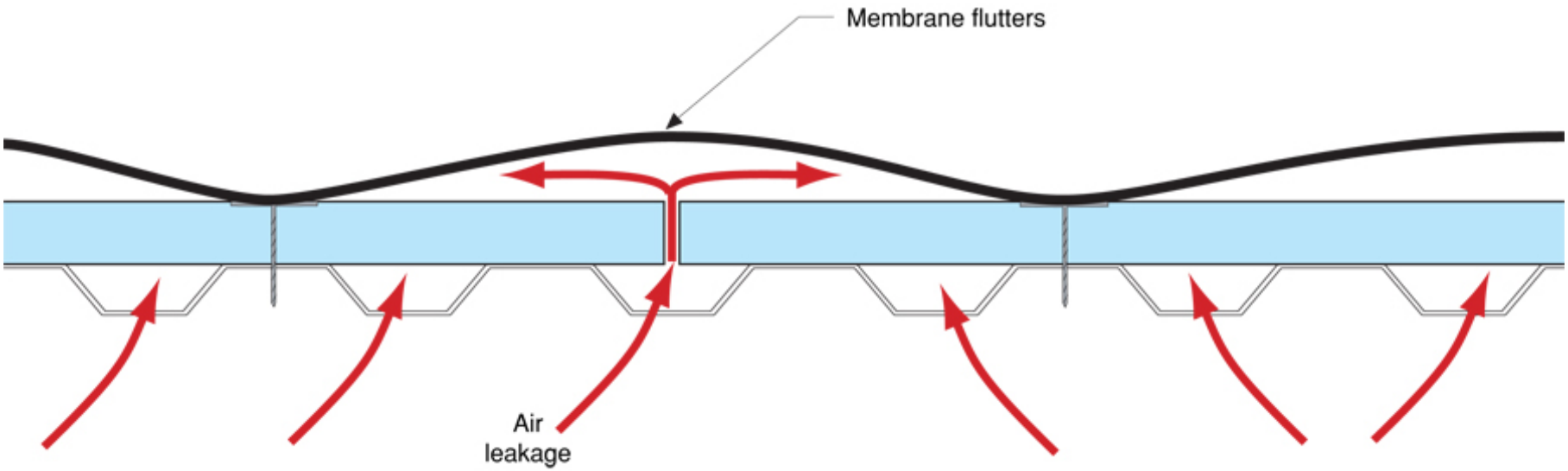
Every 10 degrees C – double the “badness”

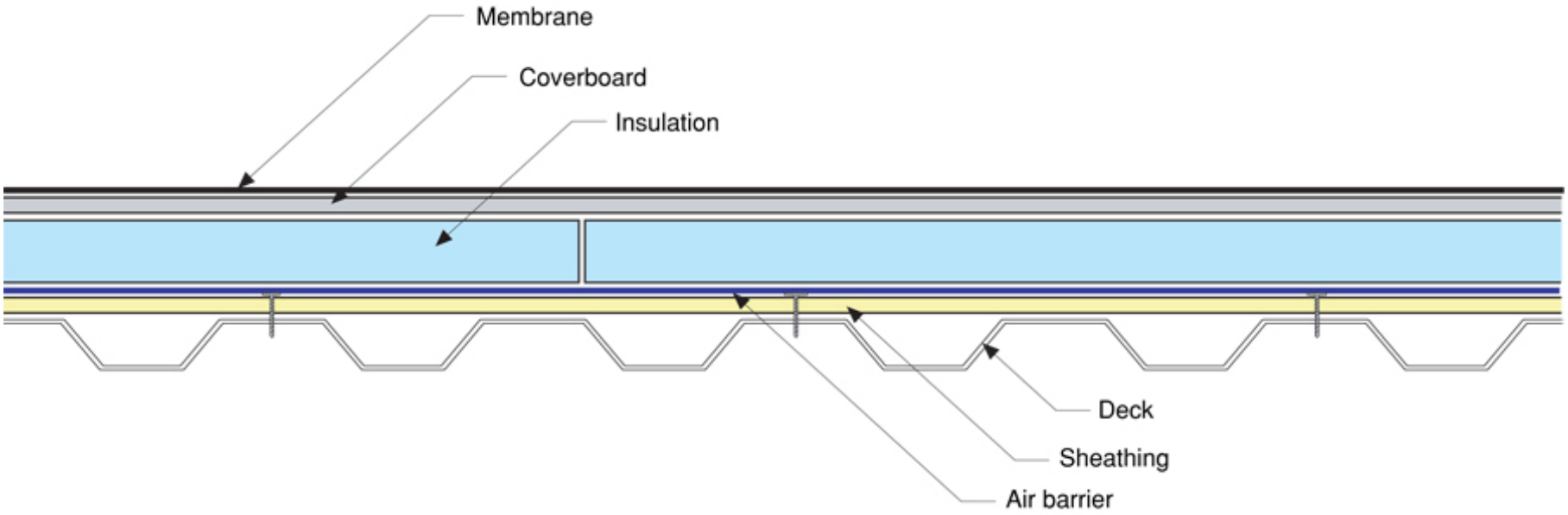

Supply air into occupied zone returns to AHU by passing through deliberately porous dropped ceiling or through return grilles installed in dropped ceiling
Air handling unit extracts air from dropped ceiling, conditions it and injects it into the occupied zones via supply ductwork
Dropped ceiling depressurized by air handling units extracting air from dropped ceiling
Air handling unit
Air handling unit
Occupied Zone

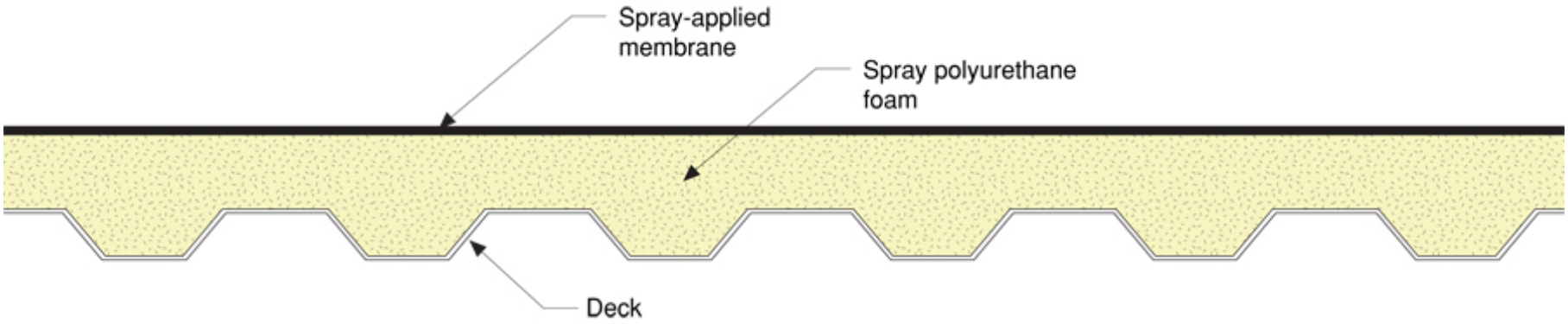

Air barrier system not present to prevent air from being extracted from roof assembly
Corrugated metal roof deck
Membrane roof
Rigid insulation
Brick veneer
Building paper
Interior gypsum should extend to underside of roof deck and be sealed
3
4
2
1
Return plenum operates under negative pressure relative to occupied space and exterior
Suspended ceiling
Exterior sheathing
Metal stud wall
Cavity insulation
Top chord bearing roof truss
Interior gypsum

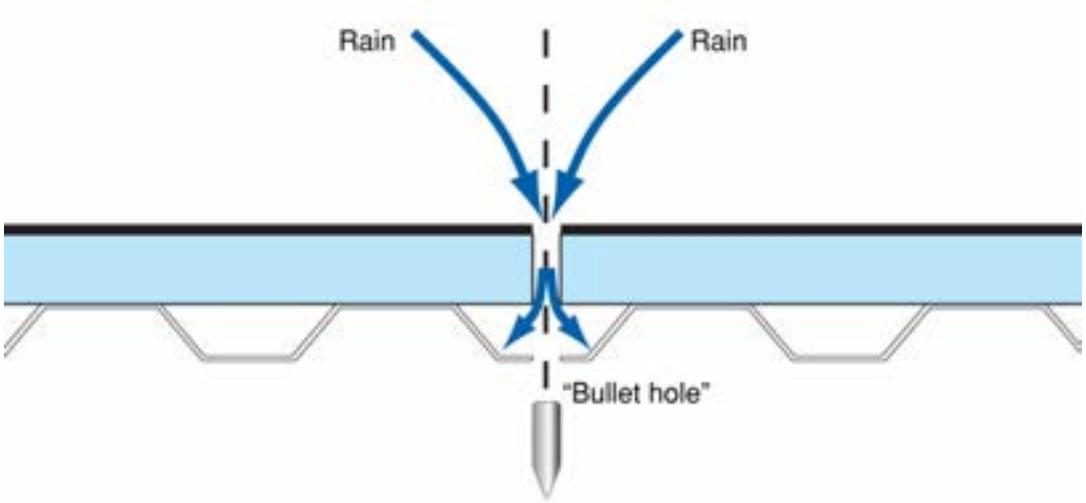


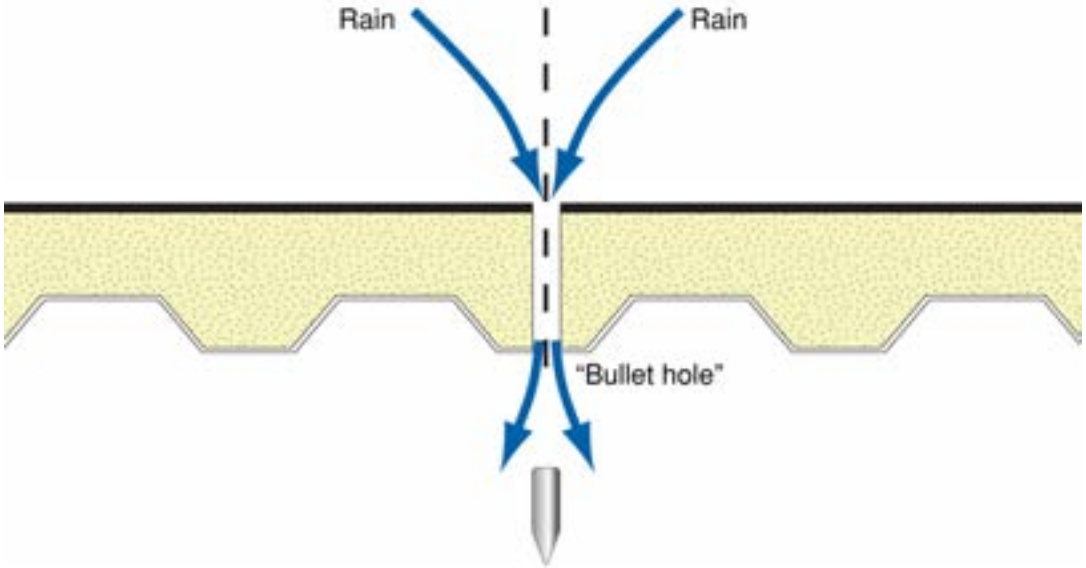

Fully-adhered
membrane
Mechanically attached
rigid insulation

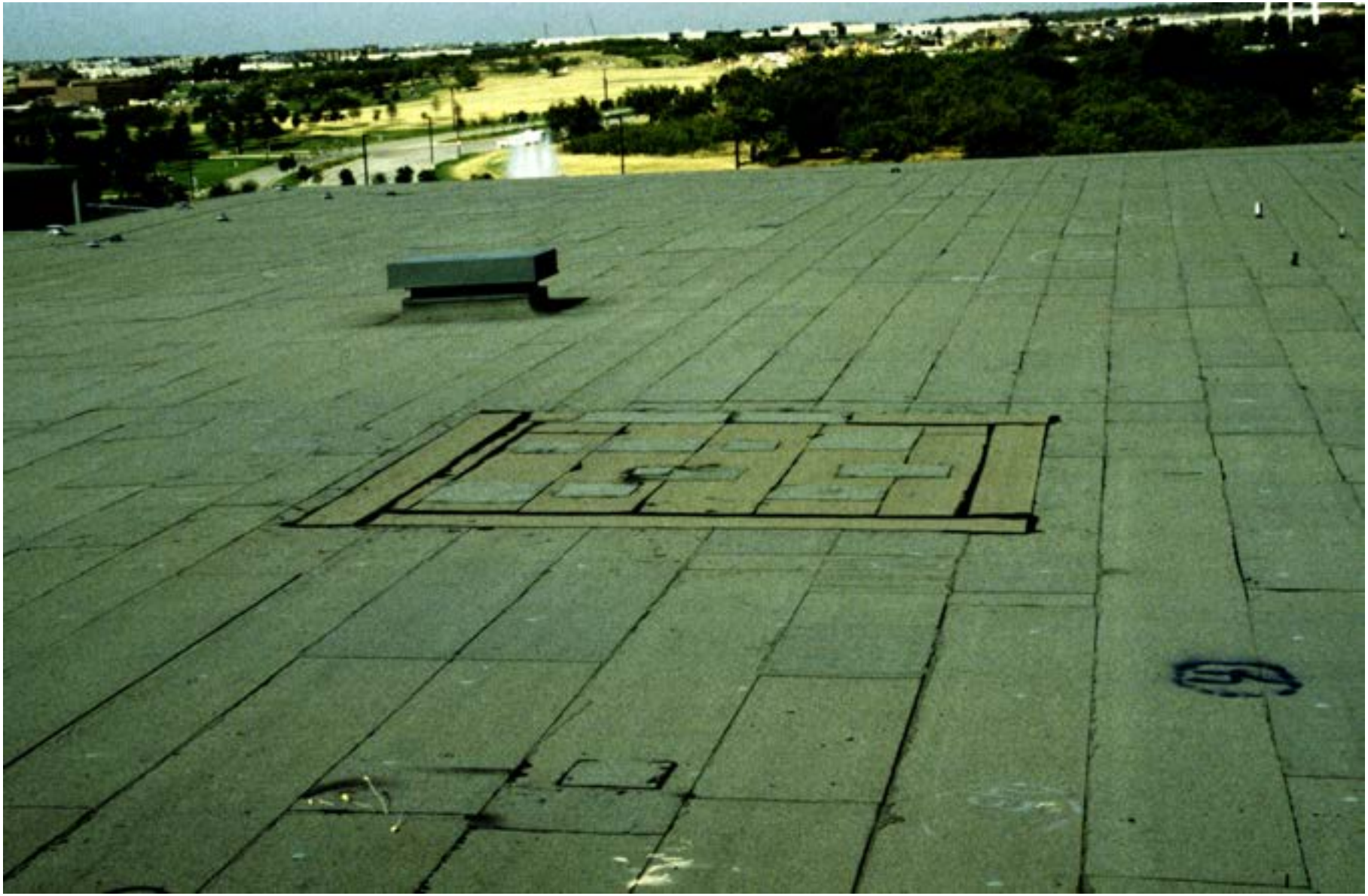

Membrane flutters
Air
leakage

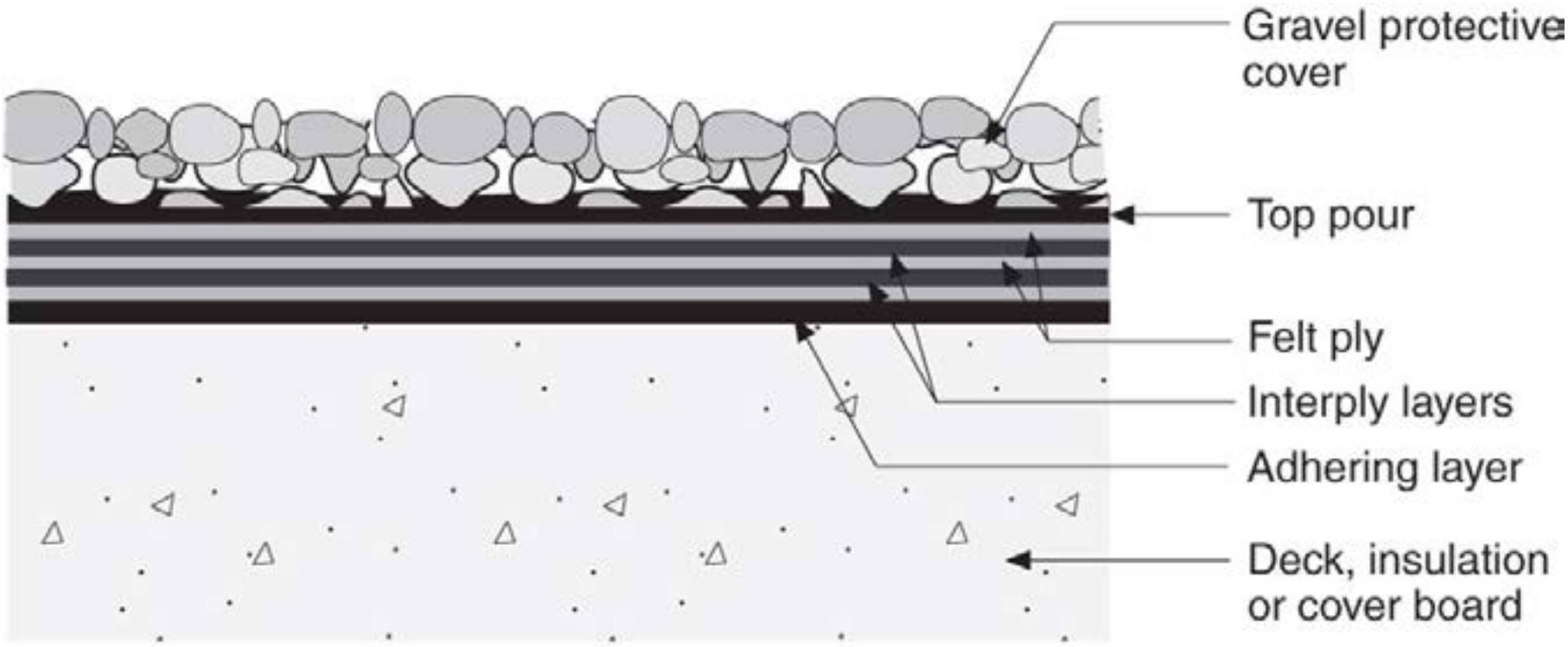

Membrane
Coverboard
Insulation
Deck
Sheathing
Air barrier


Spray-applied
membrane
Spray polyurethane
foam
Deck

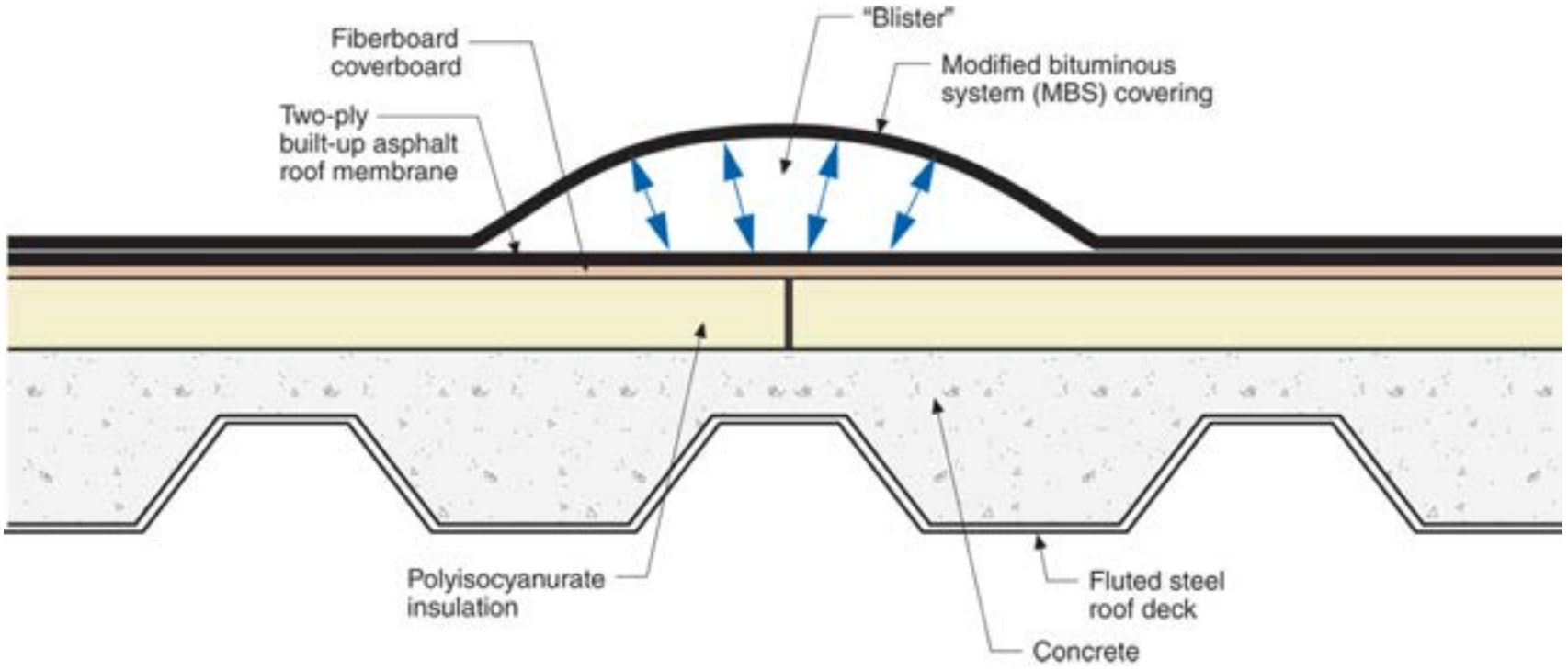

Rain
Rain
"Bullet hole"

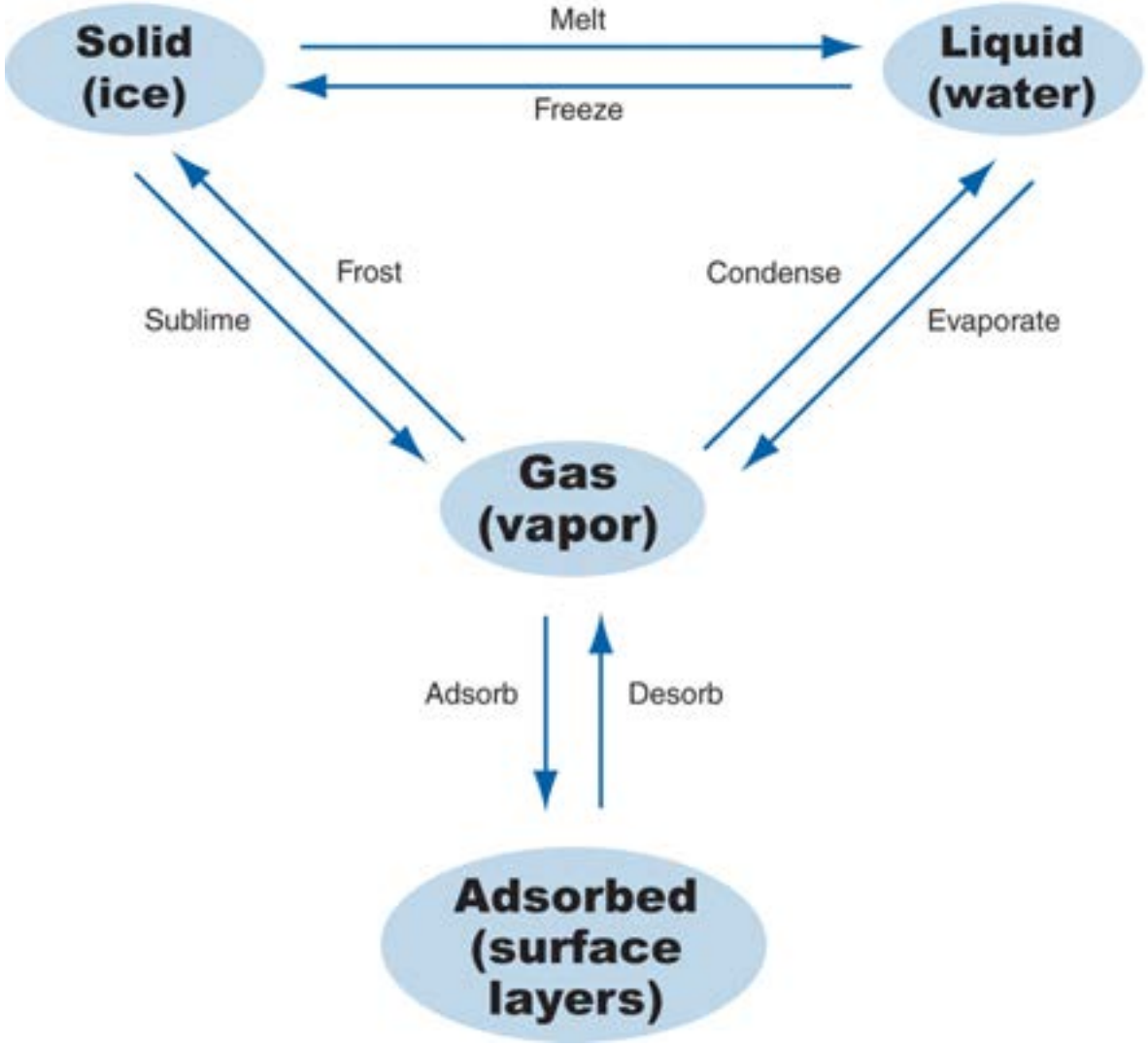

Rain
Rain
"Bullet hole"





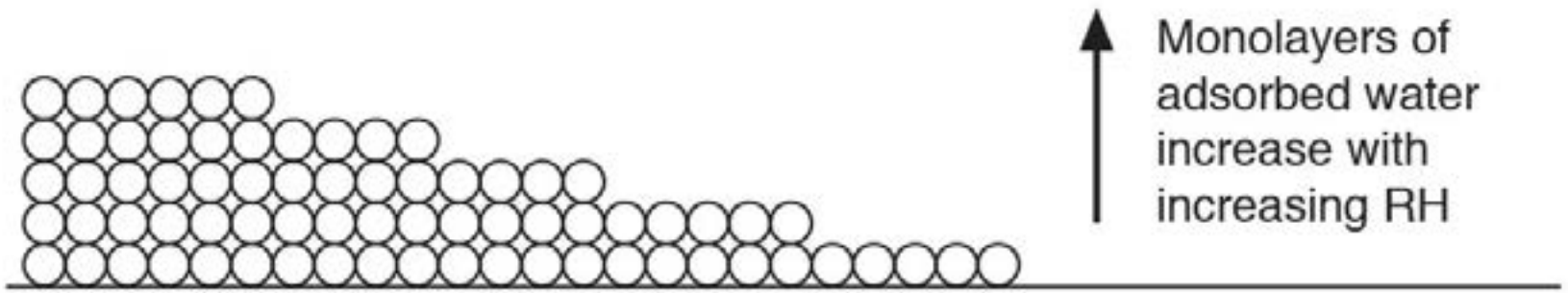
From Baker, M.; Roofs, 1980

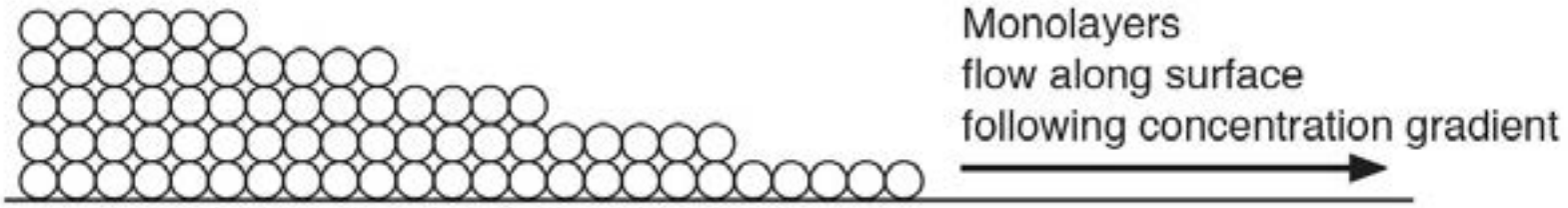

"Blister"
Fiberboard coverboard
Modified bituminous system (MBS) covering
Two-ply built-up asphalt roof membrane
Polyisocyanurate insulation
Fluted steel roof deck
Concrete

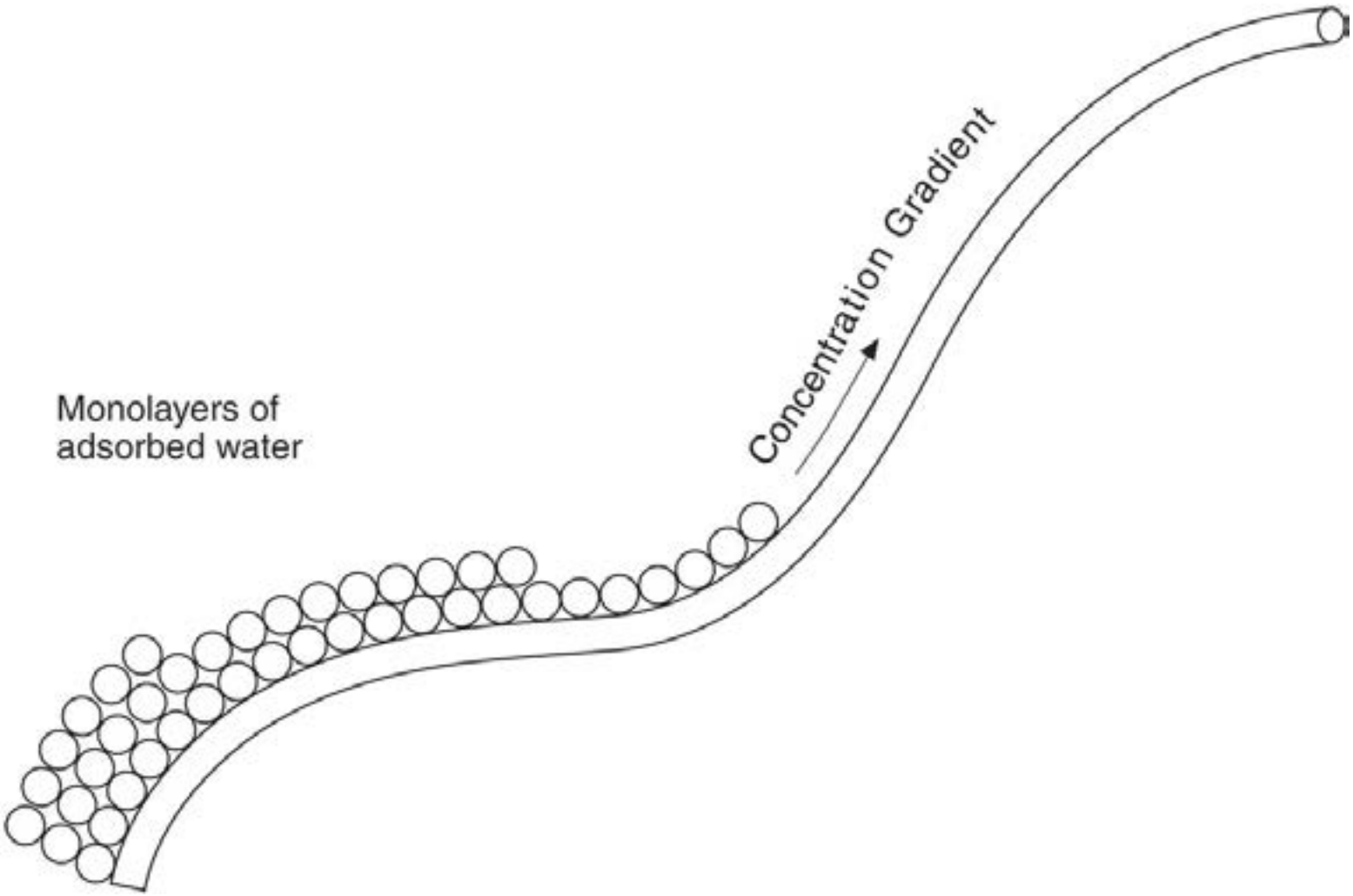

Solid (ice)
Melt
Freeze
Liquid (water)
Frost
Sublime
Condense
Evaporate
Gas (vapor)
Adsorb
Desorb
Adsorbed (surface layers)

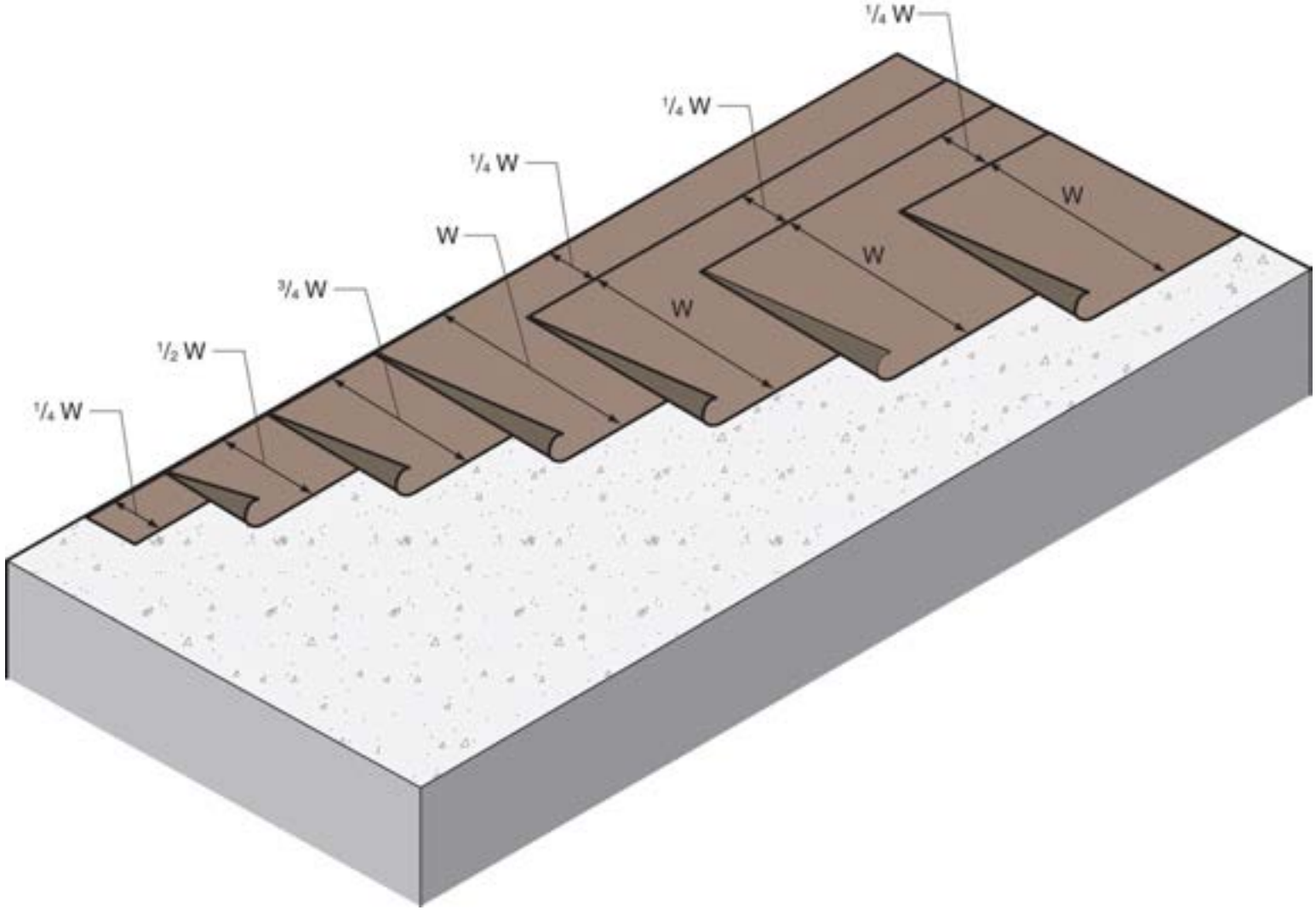
Moisture Transport in Porous Media

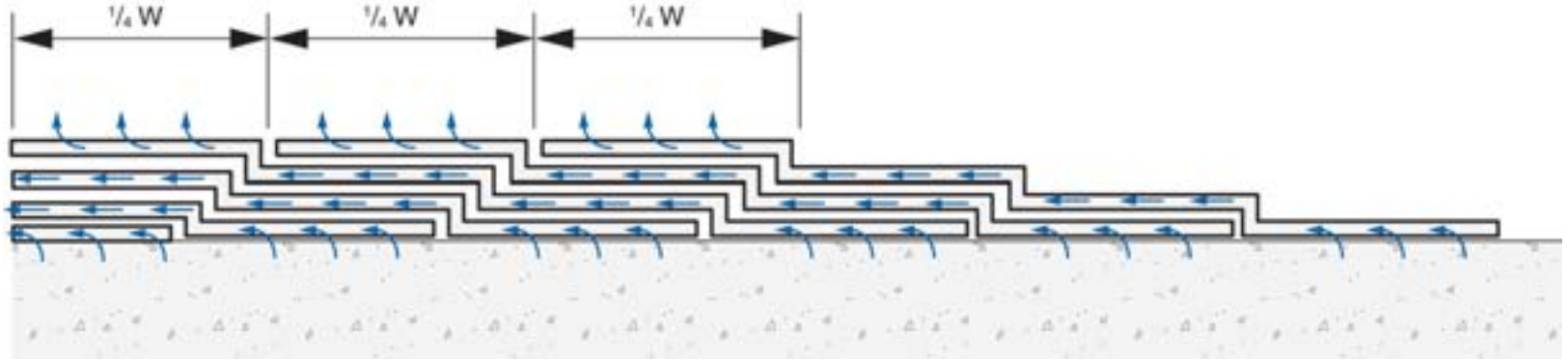
Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration

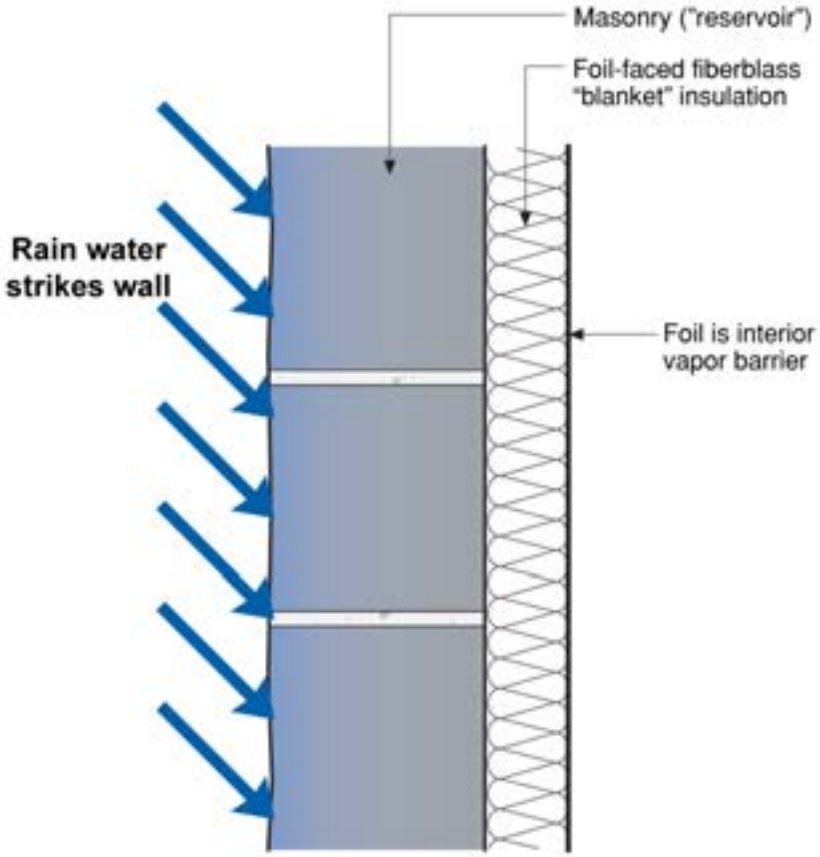

Monolayers of
adsorbed water
increase with
increasing RH


Monolayers
flow along surface
following concentration gradient


Monolayers of
adsorbed water
Concentration Gradient

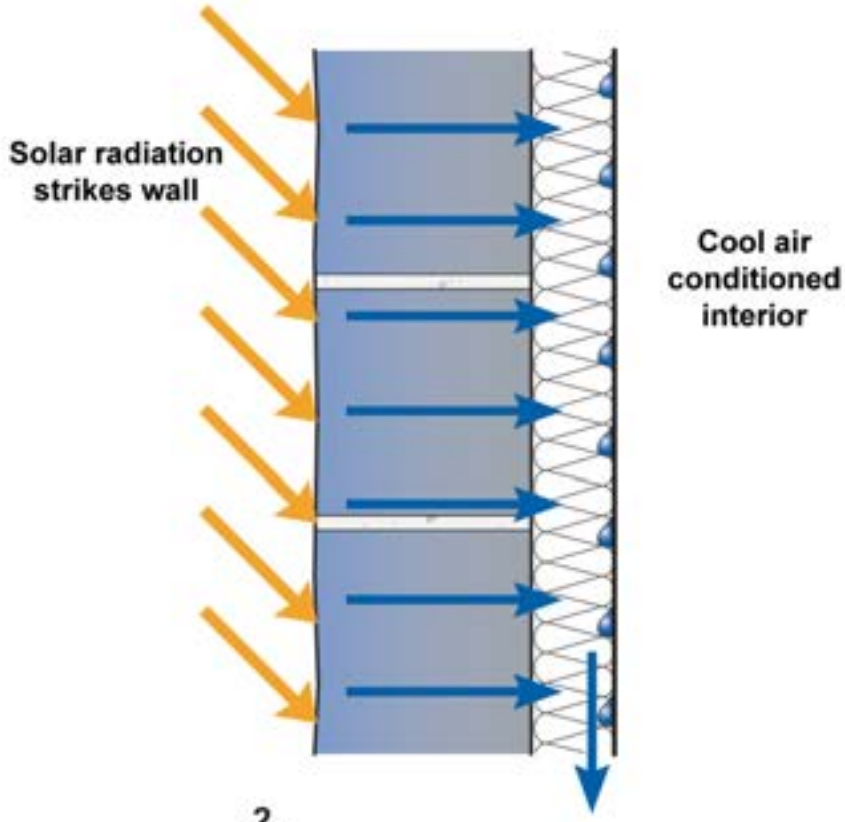

¼ W
¼ W
¼ W
W
¾ W
½ W
¼ W
W
W
W


¼ W
¼ W
¼ W



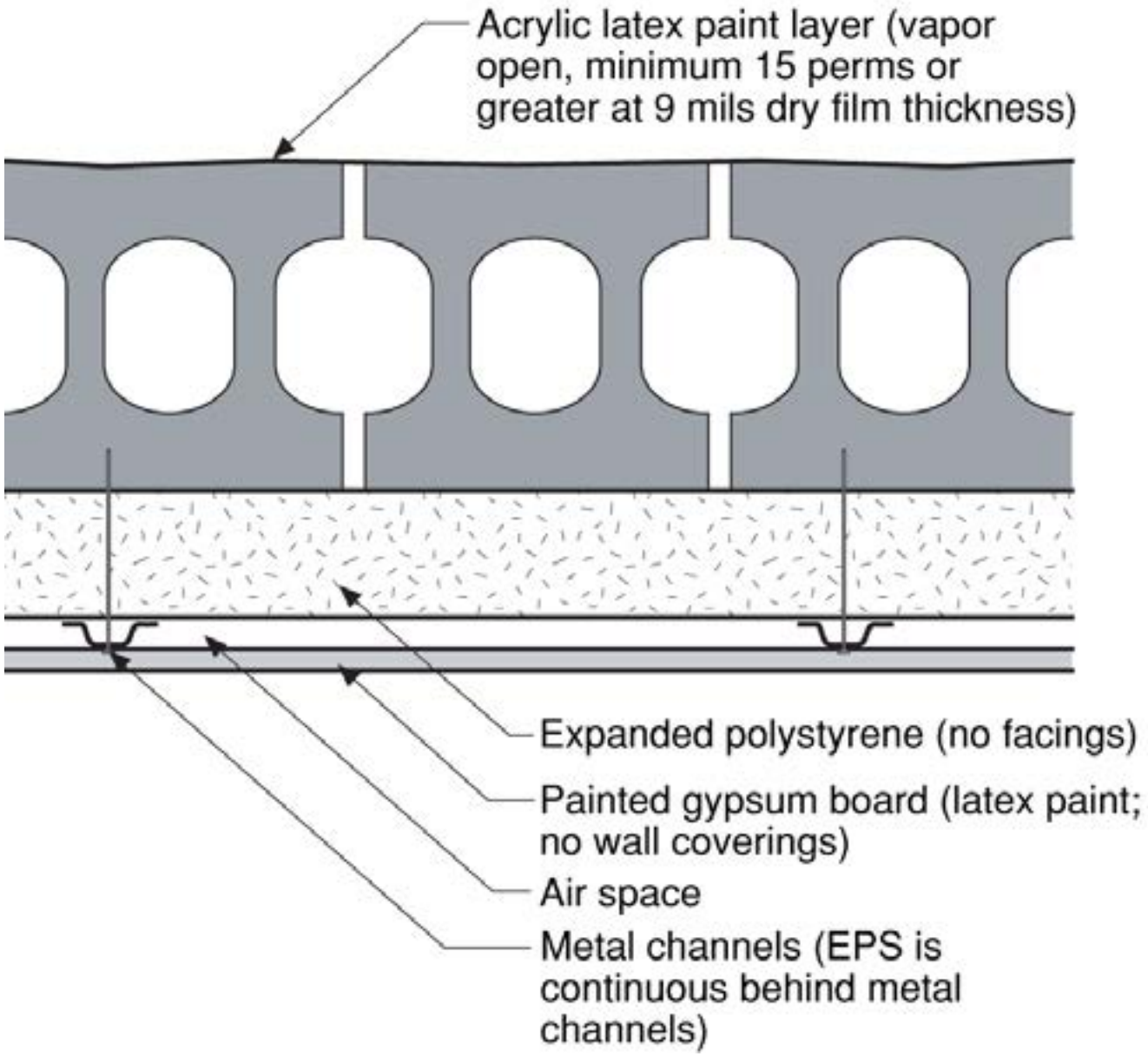
1.

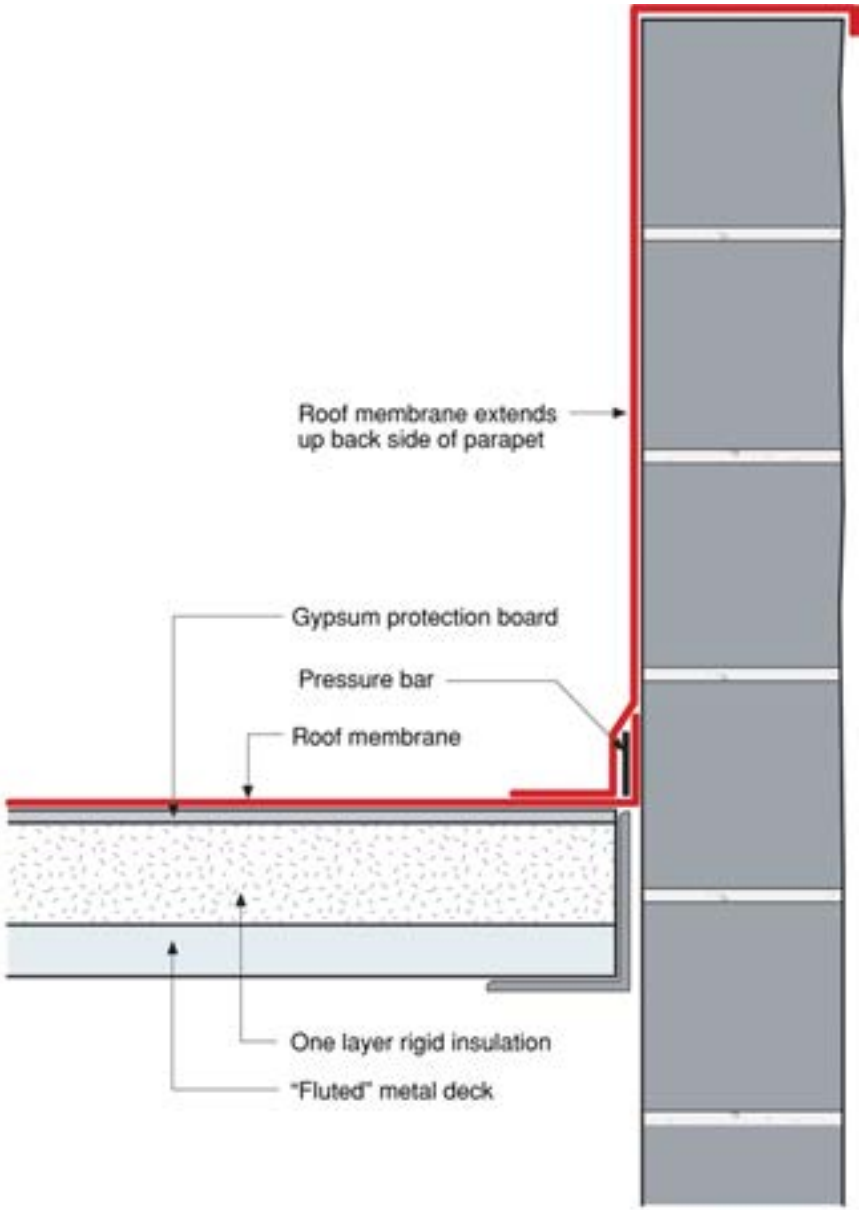
- Rain water is deposited on exterior face of masonry
- Rain water enters masonry through paint layer

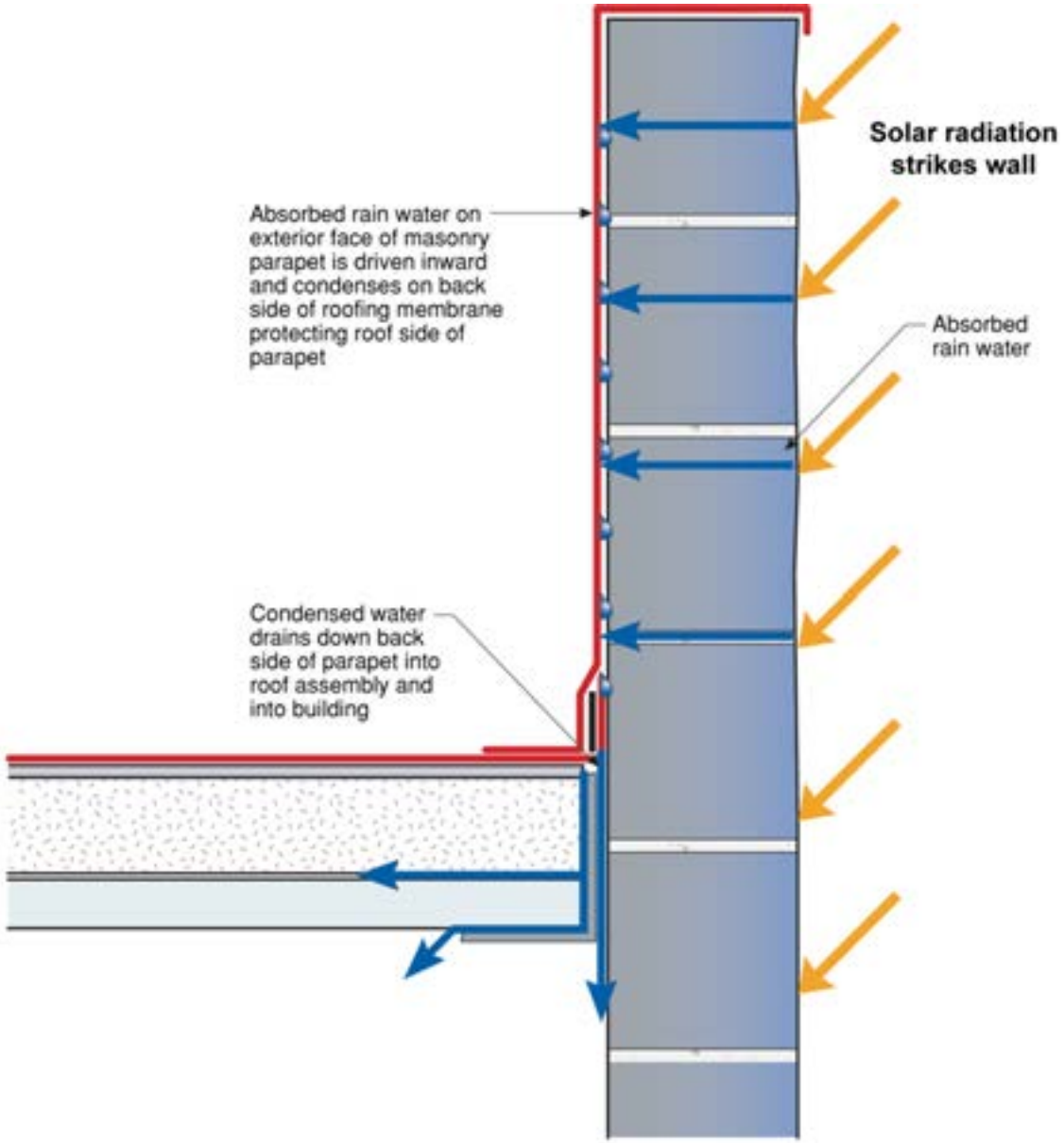


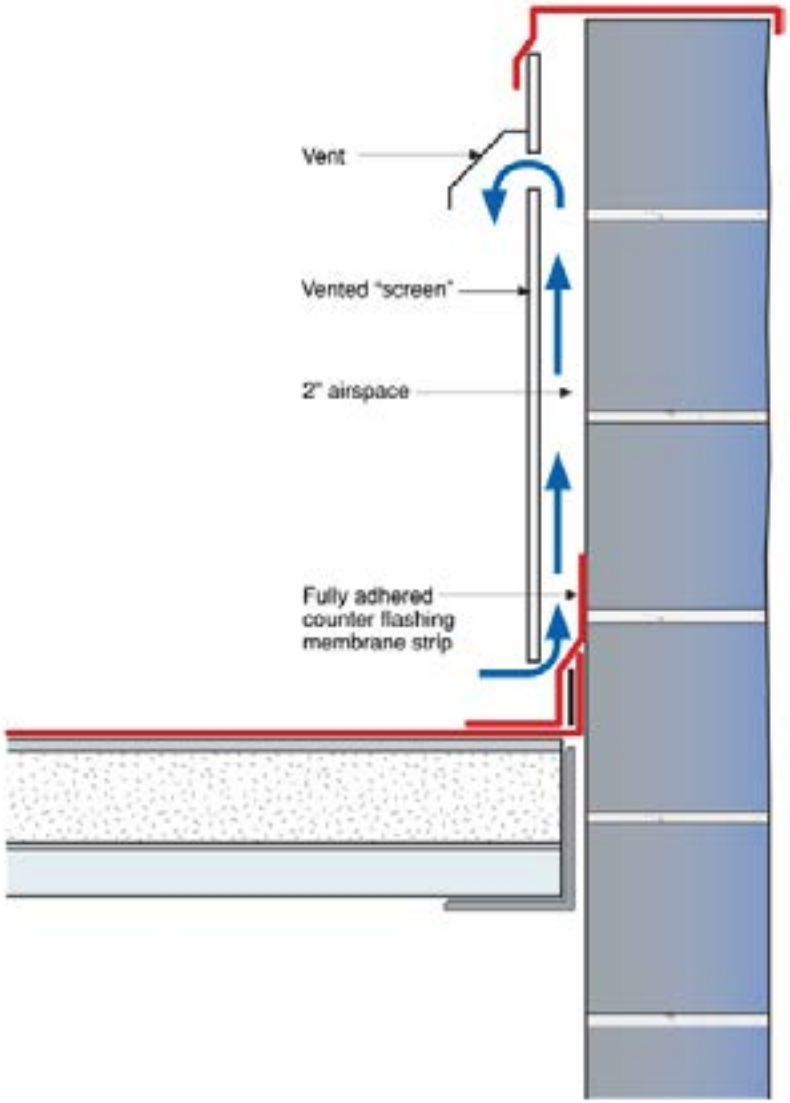
2.

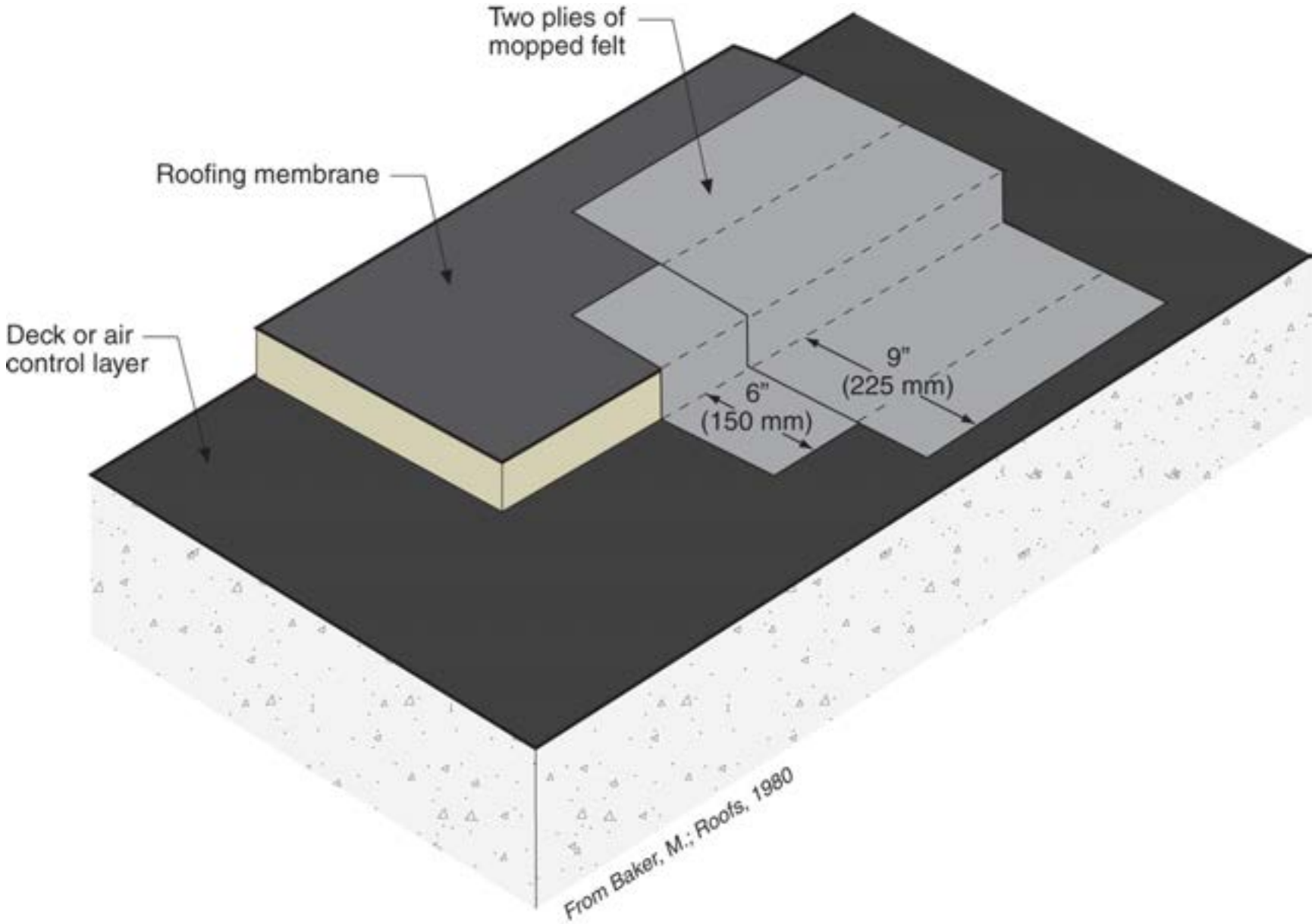
- Solar radiation heats exterior while A/C cools interior
- Moisture is driven inward, condenses on foil vapor barrier and runs down wall

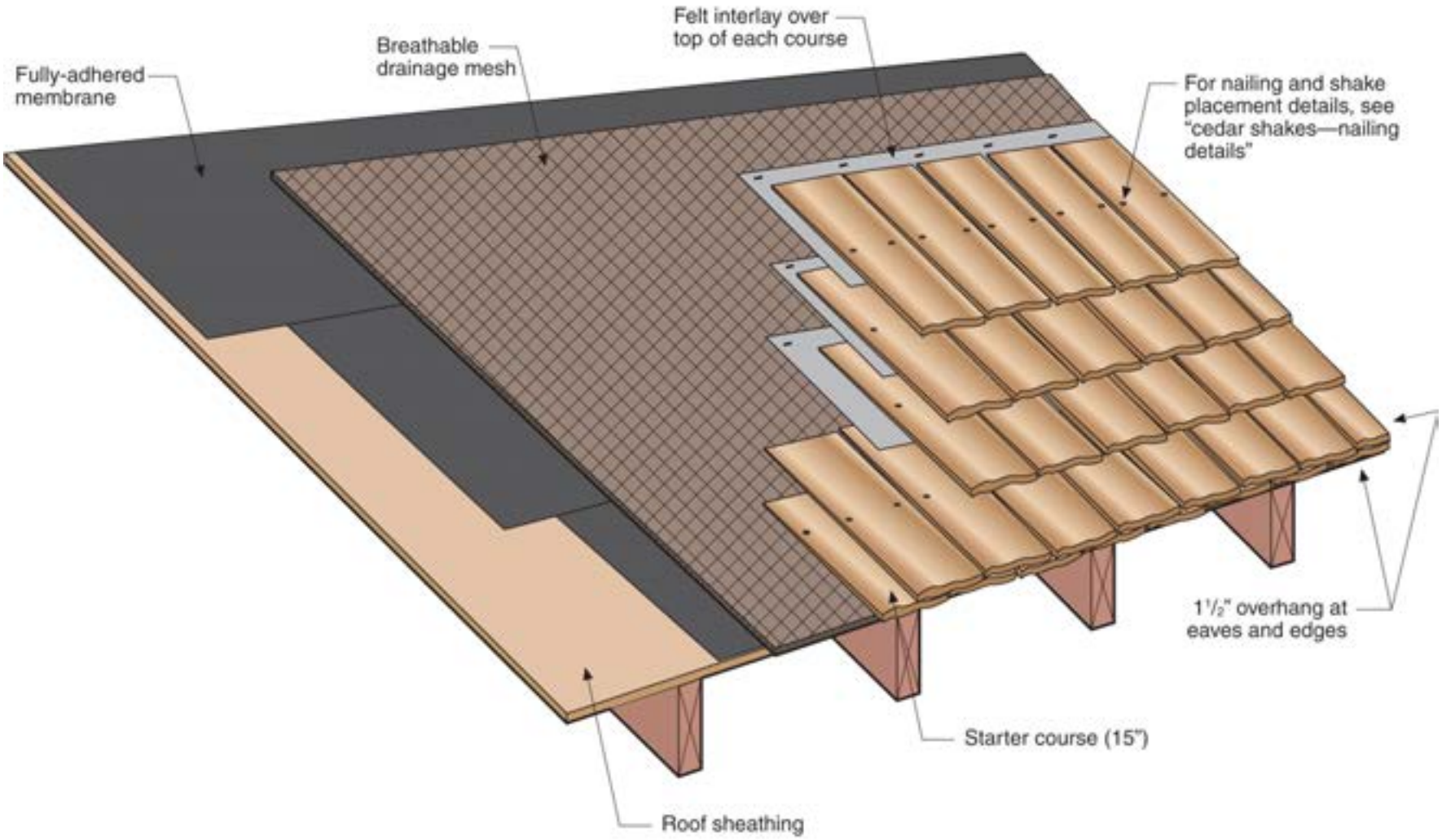

Acrylic latex paint layer (vapor open, minimum 15 perms or greater at 9 mils dry film thickness)
Expanded polystyrene (no facings)
Painted gypsum board (latex paint; no wall coverings)
Air space
Metal channels (EPS is continuous behind metal channels)

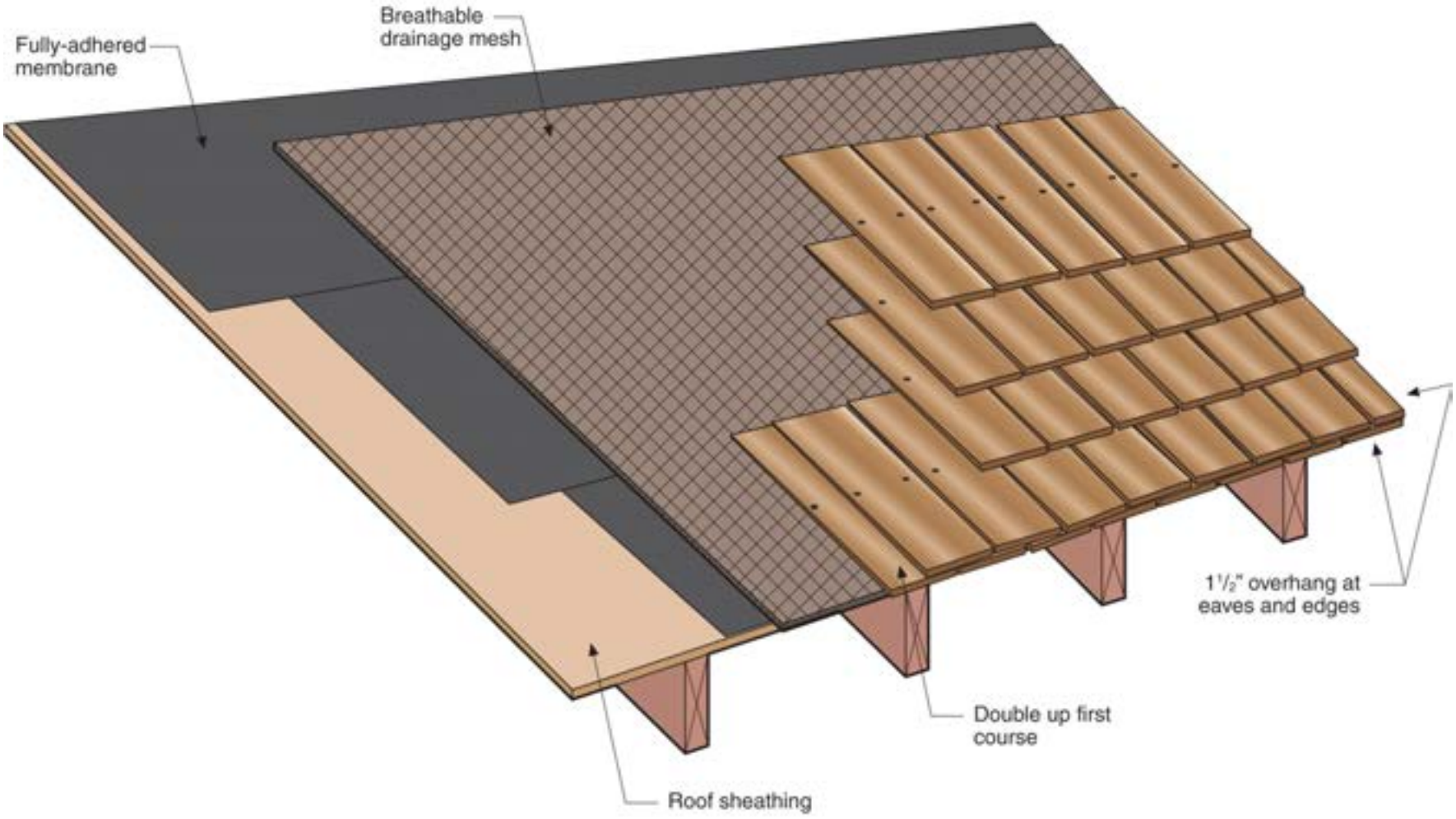

Roof membrane extends
up back side of parapet
Gypsum protection board
Pressure bar
Roof membrane
One layer rigid insulation
"Fluted" metal deck

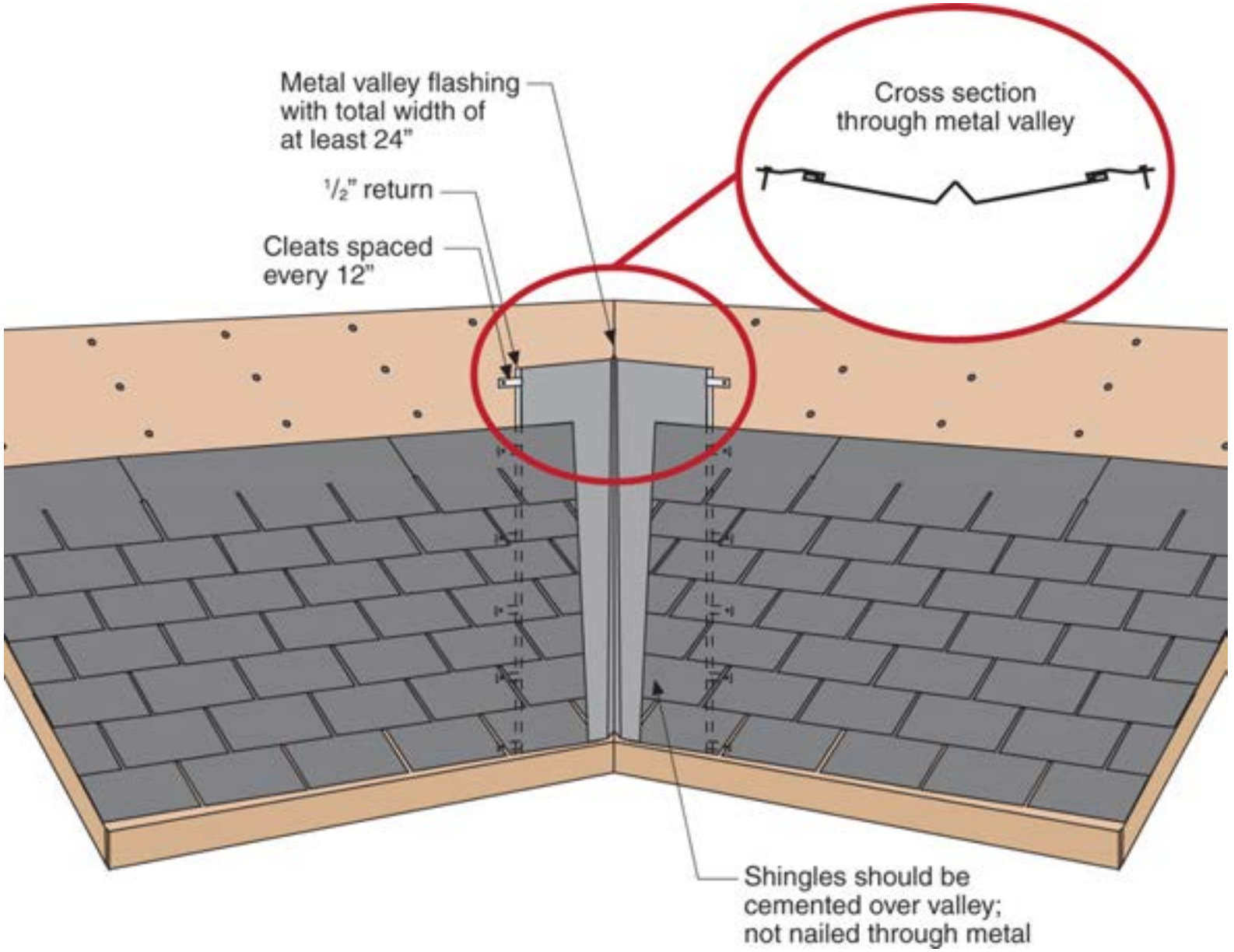

Solar radiation strikes wall
Absorbed rain water on exterior face of masonry parapet is driven inward and condenses on back side of roofing membrane protecting roof side of parapet
Absorbed rain water
Condensed water drains down back side of parapet into roof assembly and into building

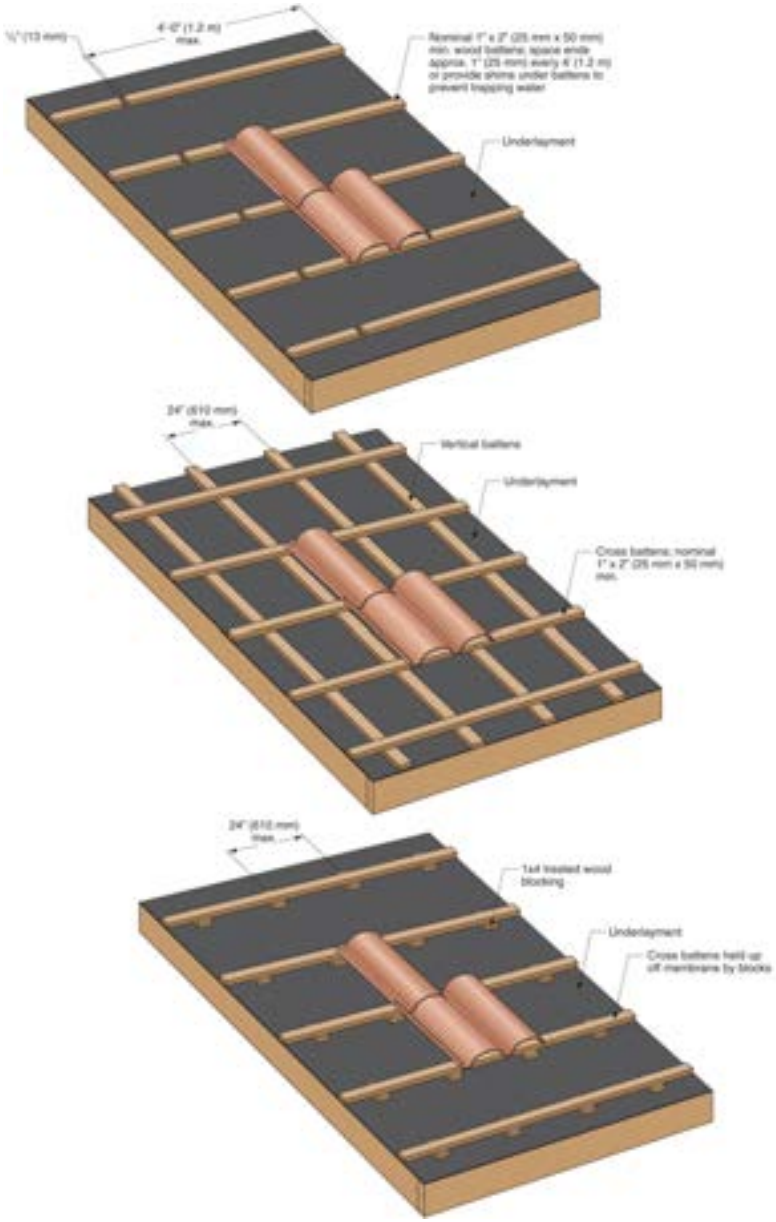

Vent
Vented "screen"
2" airspace
Fully adhered
counter flashing
membrane strip


Two plies of
mopped felt
Roofing membrane
Deck or air
control layer
9"
(225 mm)
6"
(150 mm)
From Baker, M.; Roofs, 1980

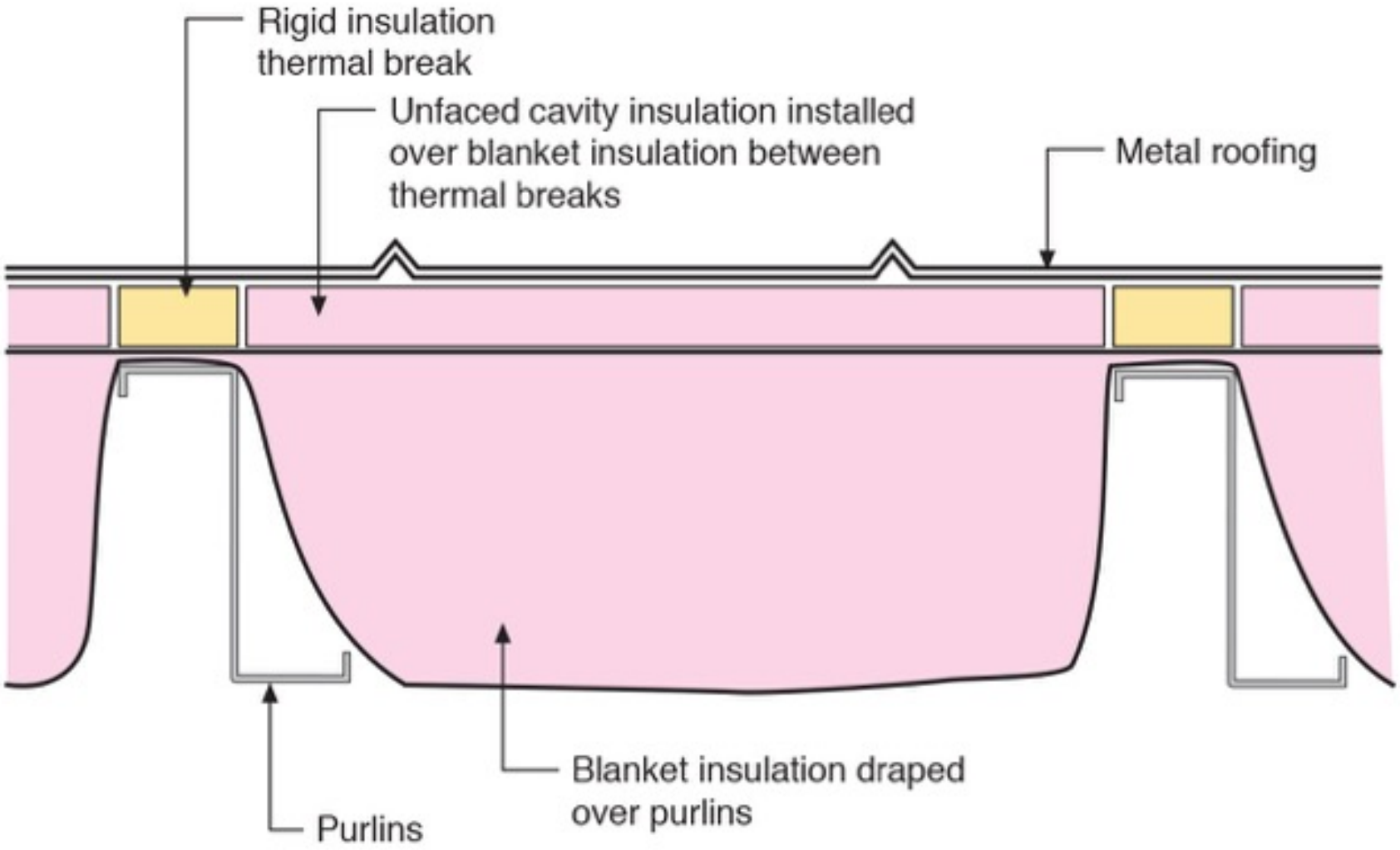

Felt interlay over top of each course
Breathable drainage mesh
Fully-adhered membrane
For nailing and shake placement details, see "cedar shakes—nailing details"
1½" overhang at eaves and edges
Starter course (15")
Roof sheathing


Fully-adhered membrane
Breathable drainage mesh
1½" overhang at eaves and edges
Double up first course
Roof sheathing

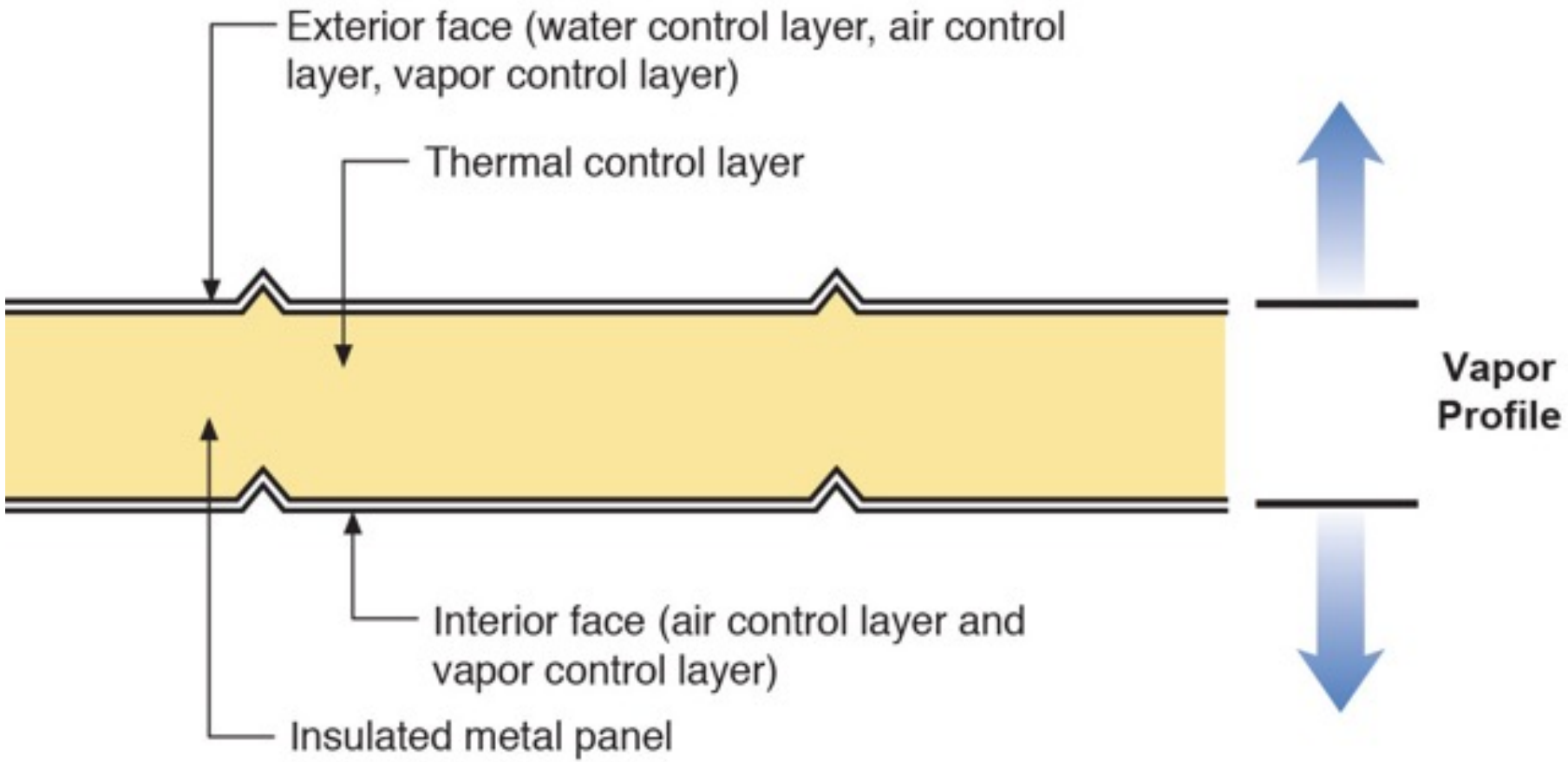

Metal valley flashing with total width of at least 24"
½" return
Cleats spaced every 12"
Cross section through metal valley
Shingles should be cemented over valley; not nailed through metal

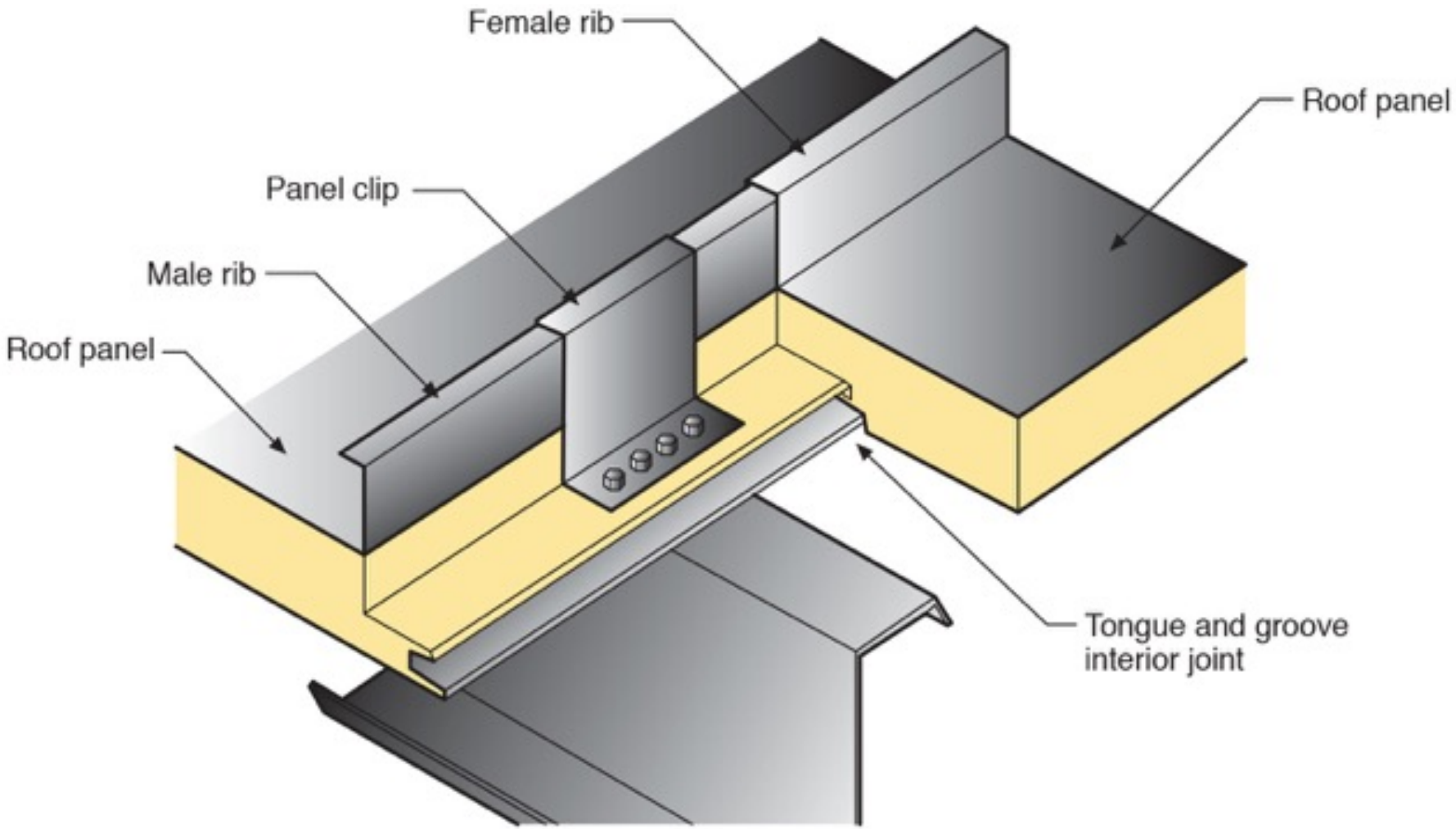

½" (13 mm)
4'-0" (1.2 m) max.
Nominal 1" x 2" (25 mm x 50 mm) min. wood battens; space ends approx. 1" (25 mm) every 4' (1.2 m) or provide shims under battens to prevent trapping water
Underlayment
24" (610 mm) max.
Vertical battens
Underlayment
Cross battens; nominal 1" x 2" (25 mm x 50 mm) min.
24" (610 mm) max.
1x4 treated wood blocking
Underlayment
Cross battens held up off membrane by blocks


PARKING

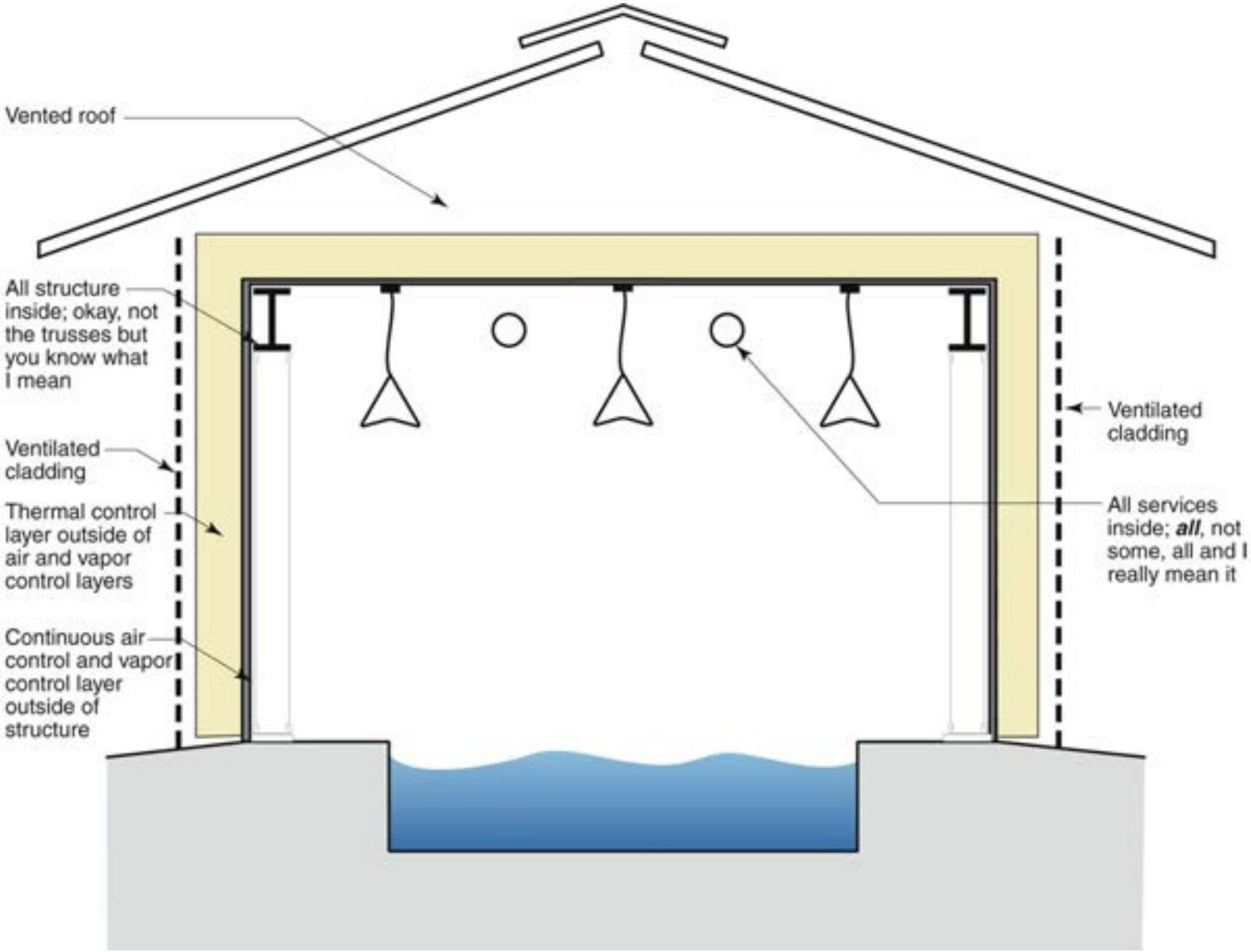


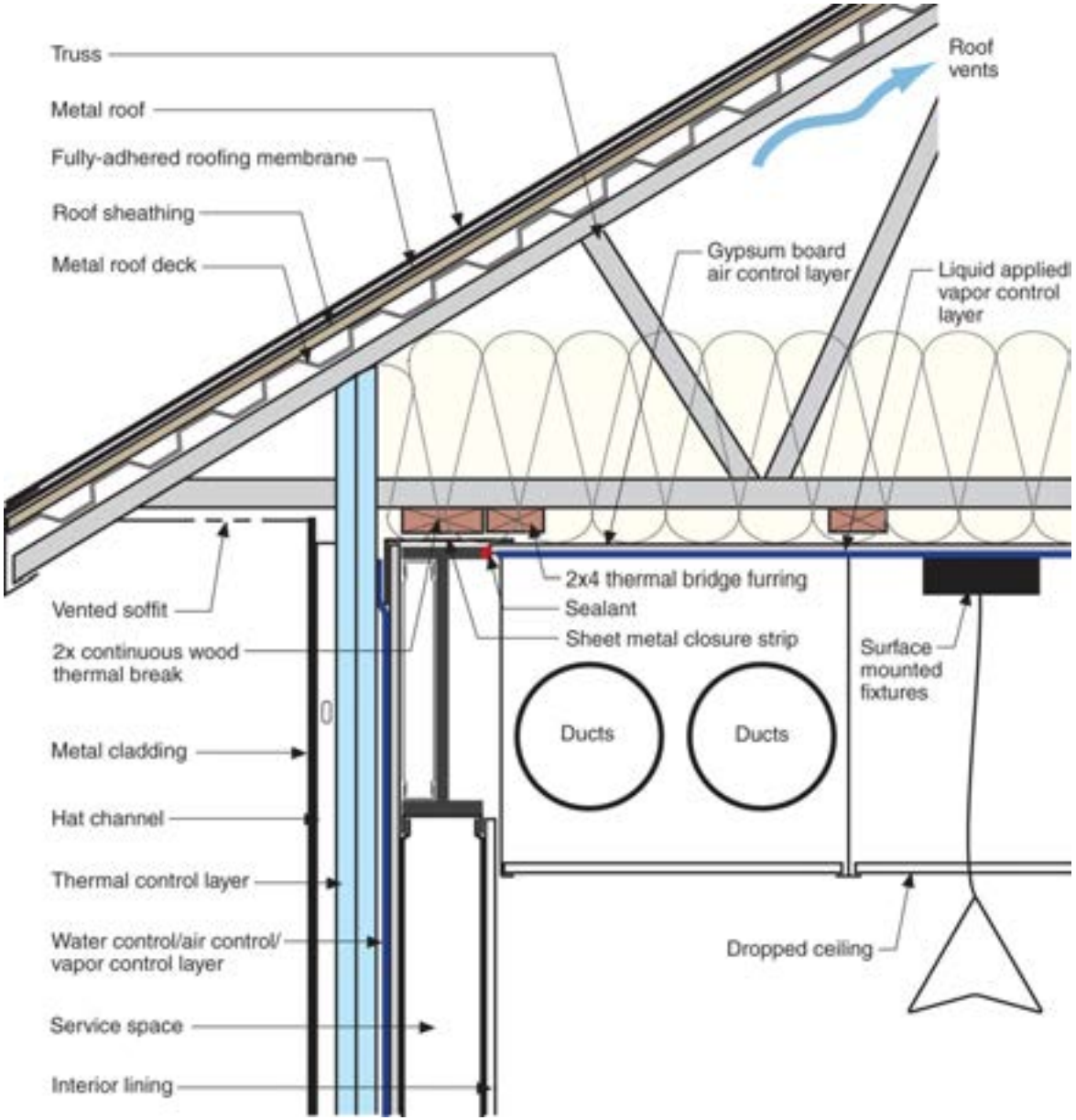
Blanket Insulation Purlin Roof System

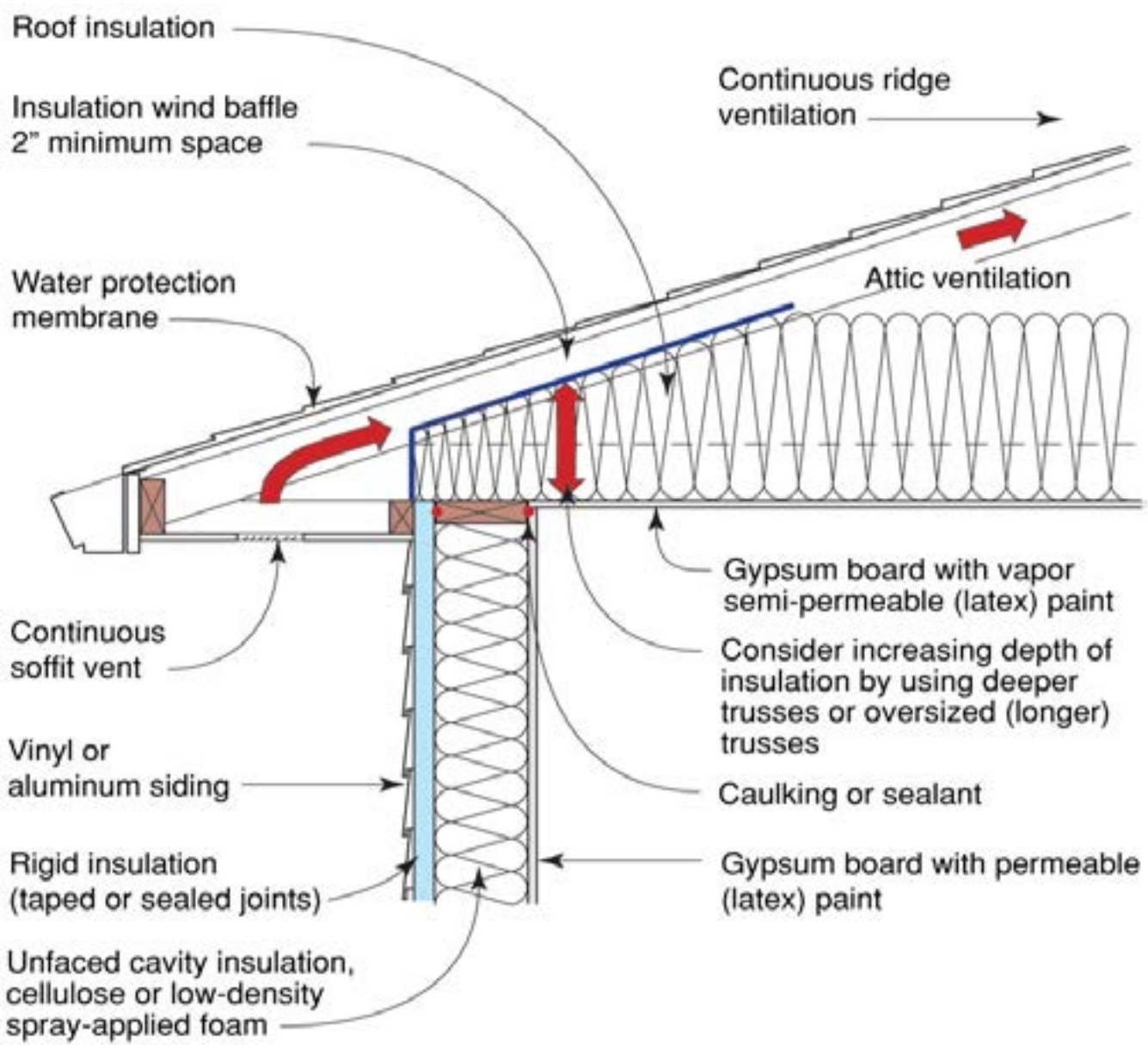

Exterior face (water control layer, air control layer, vapor control layer)
Thermal control layer
Vapor Profile
Interior face (air control layer and vapor control layer)
Insulated metal panel

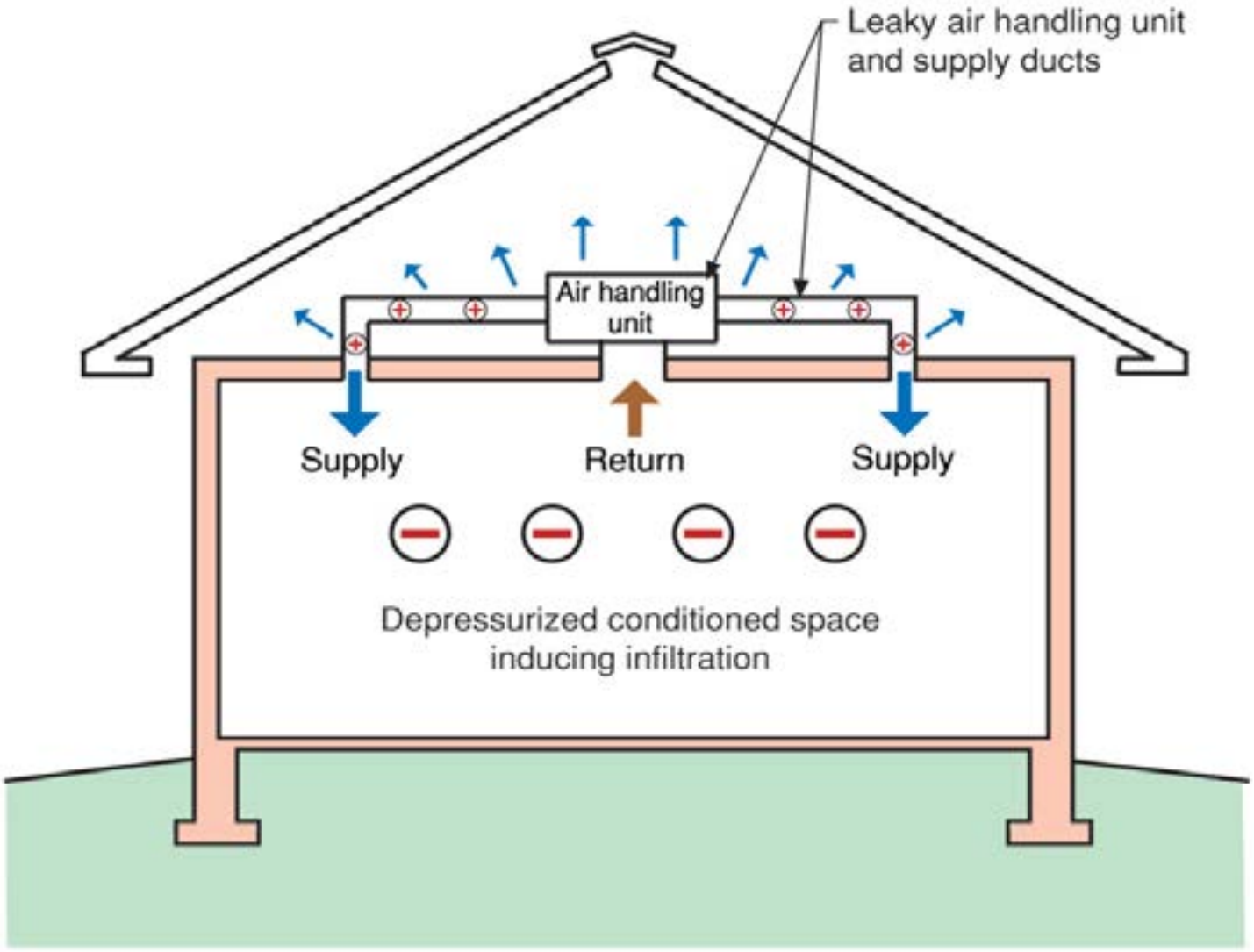

Female rib
Roof panel
Panel clip
Male rib
Roof panel
Tongue and groove
interior joint


NO DIVING
3'-6"

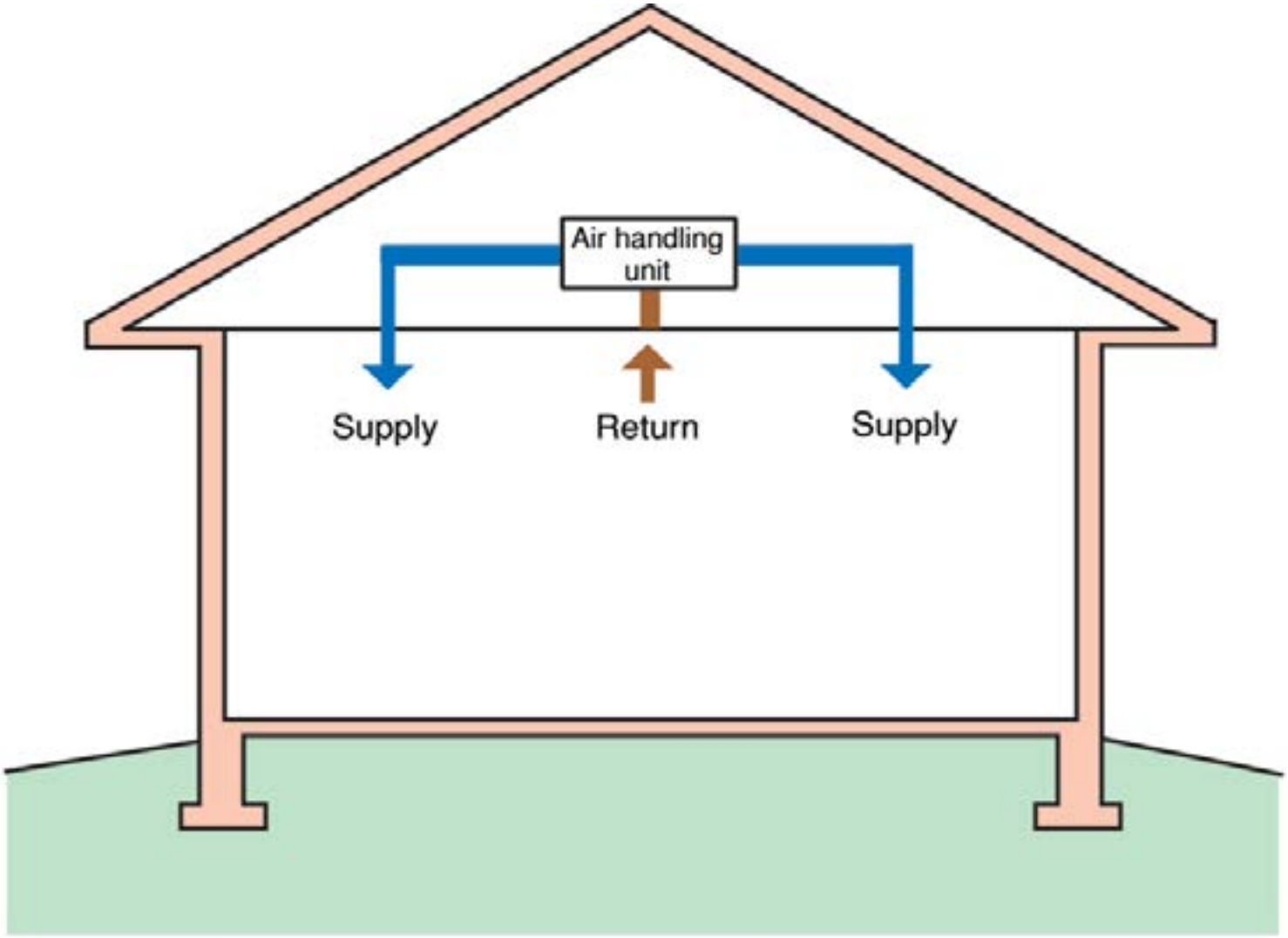

Vented roof
All structure inside; okay, not the trusses but you know what I mean
Ventilated cladding
Thermal control layer outside of air and vapor control layers
Continuous air control and vapor control layer outside of structure
Ventilated cladding
All services inside; *all*, not some, all and I really mean it


Truss
Metal roof
Fully-adhered roofing membrane
Roof sheathing
Metal roof deck
Roof vents
Gypsum board air control layer
Liquid applied vapor control layer
Vented soffit
2x continuous wood thermal break
2x4 thermal bridge furring
Sealant
Sheet metal closure strip
Surface mounted fixtures
Ducts
Ducts
Metal cladding
Hat channel
Thermal control layer
Water control/air control/ vapor control layer
Service space
Interior lining
Dropped ceiling

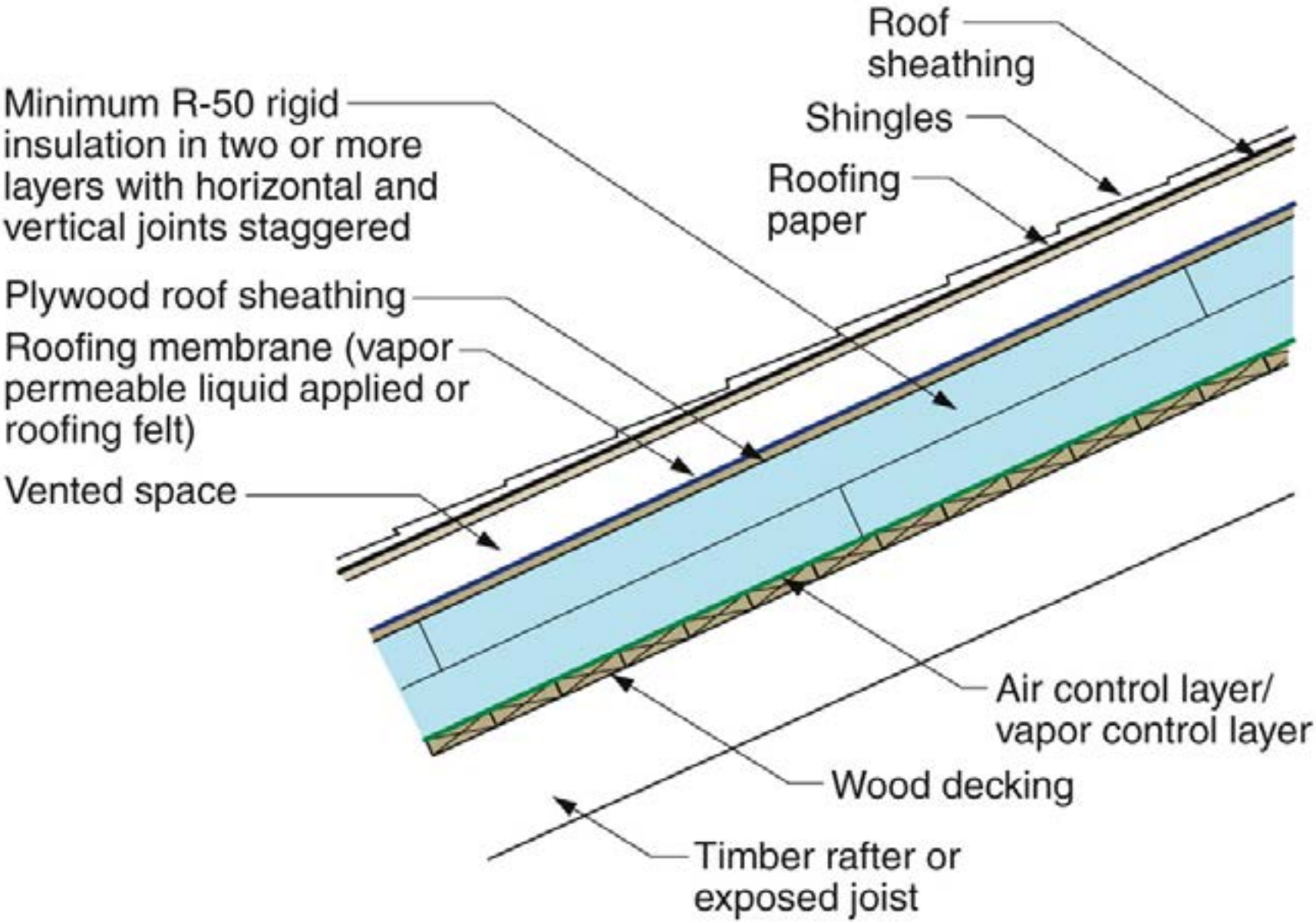

Roof insulation
Insulation wind baffle
2" minimum space
Continuous ridge
ventilation
Water protection
membrane
Attic ventilation
Gypsum board with vapor
semi-permeable (latex) paint
Consider increasing depth of
insulation by using deeper
trusses or oversized (longer)
trusses
Continuous
soffit vent
Vinyl 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

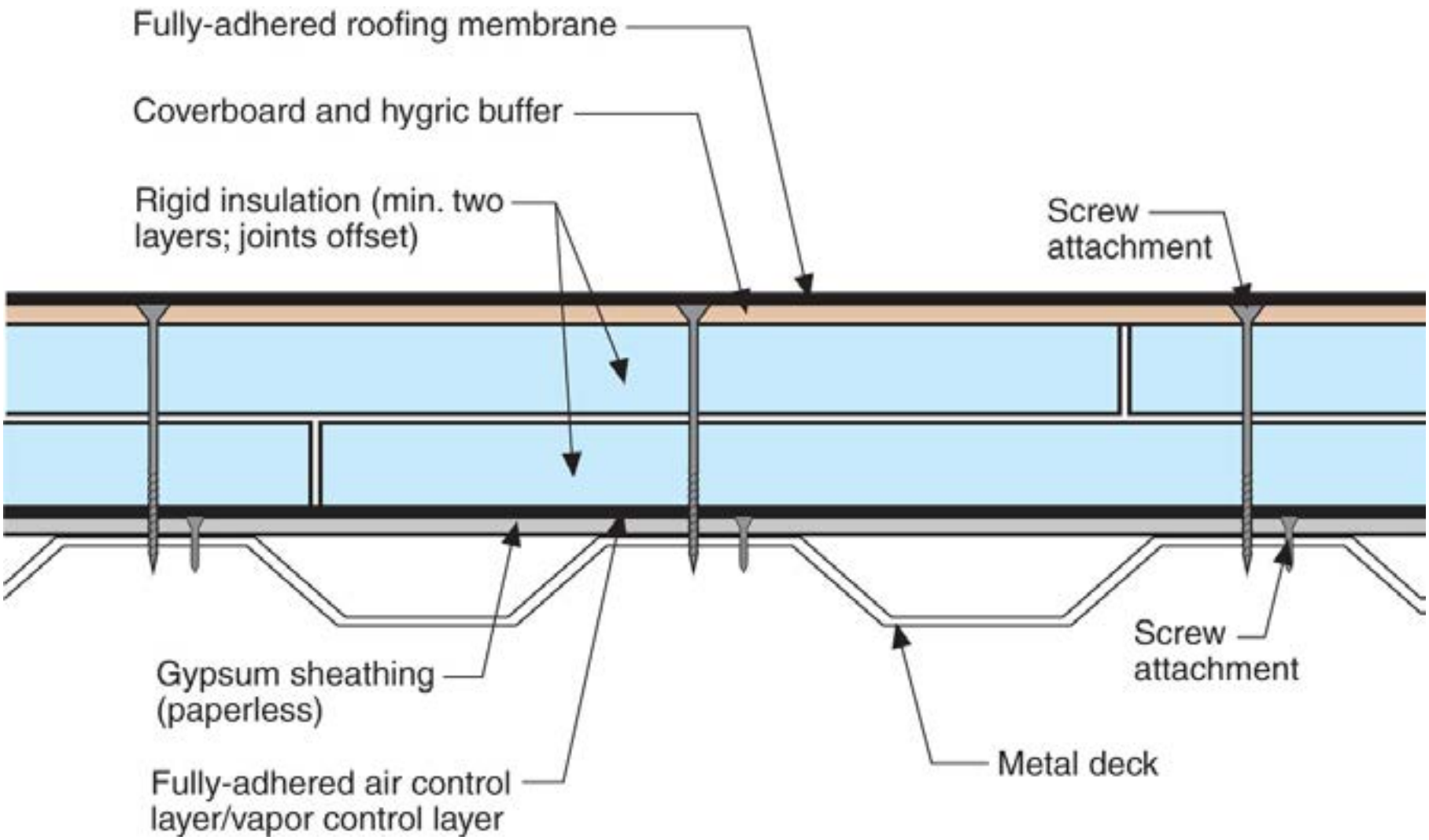


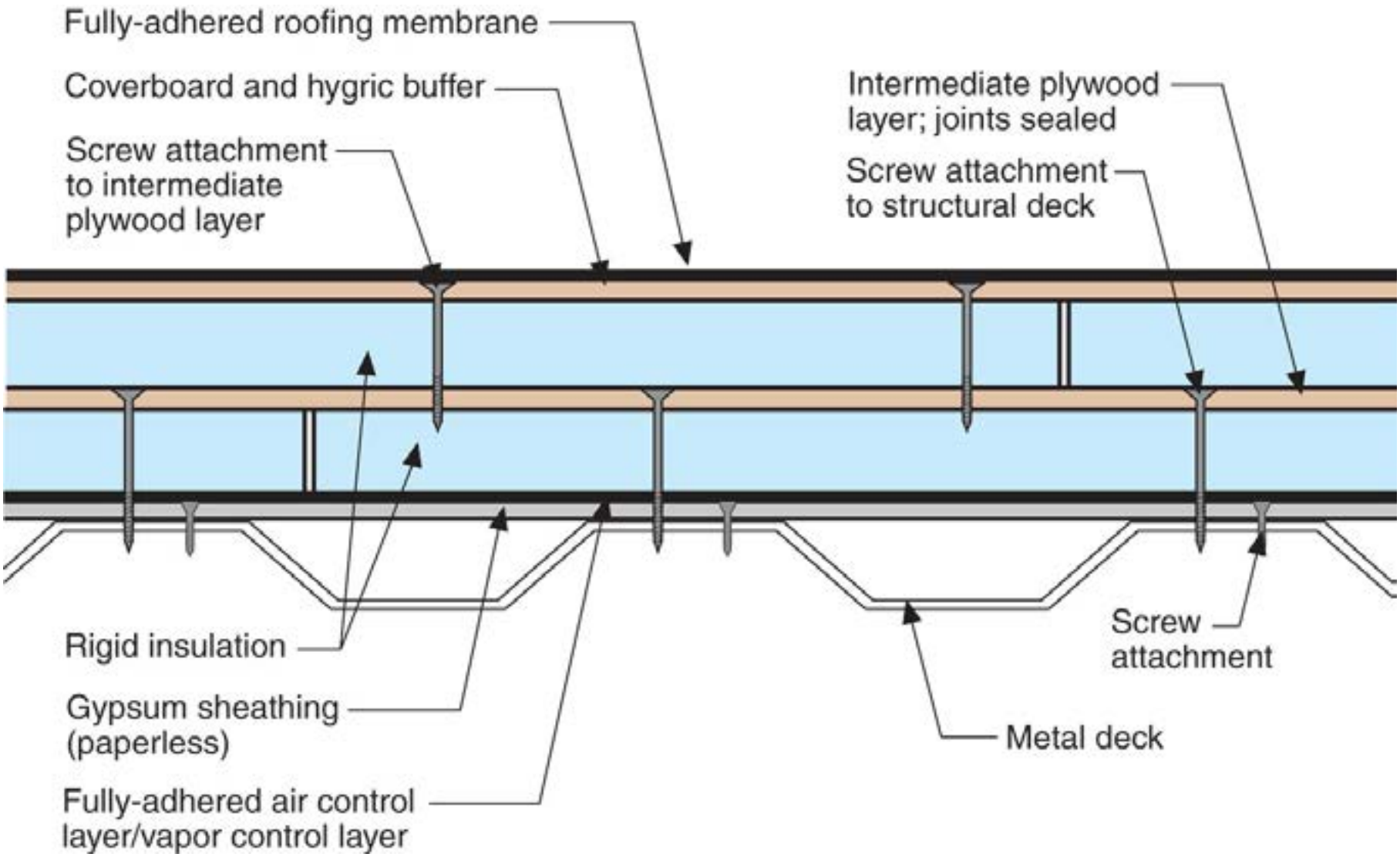
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

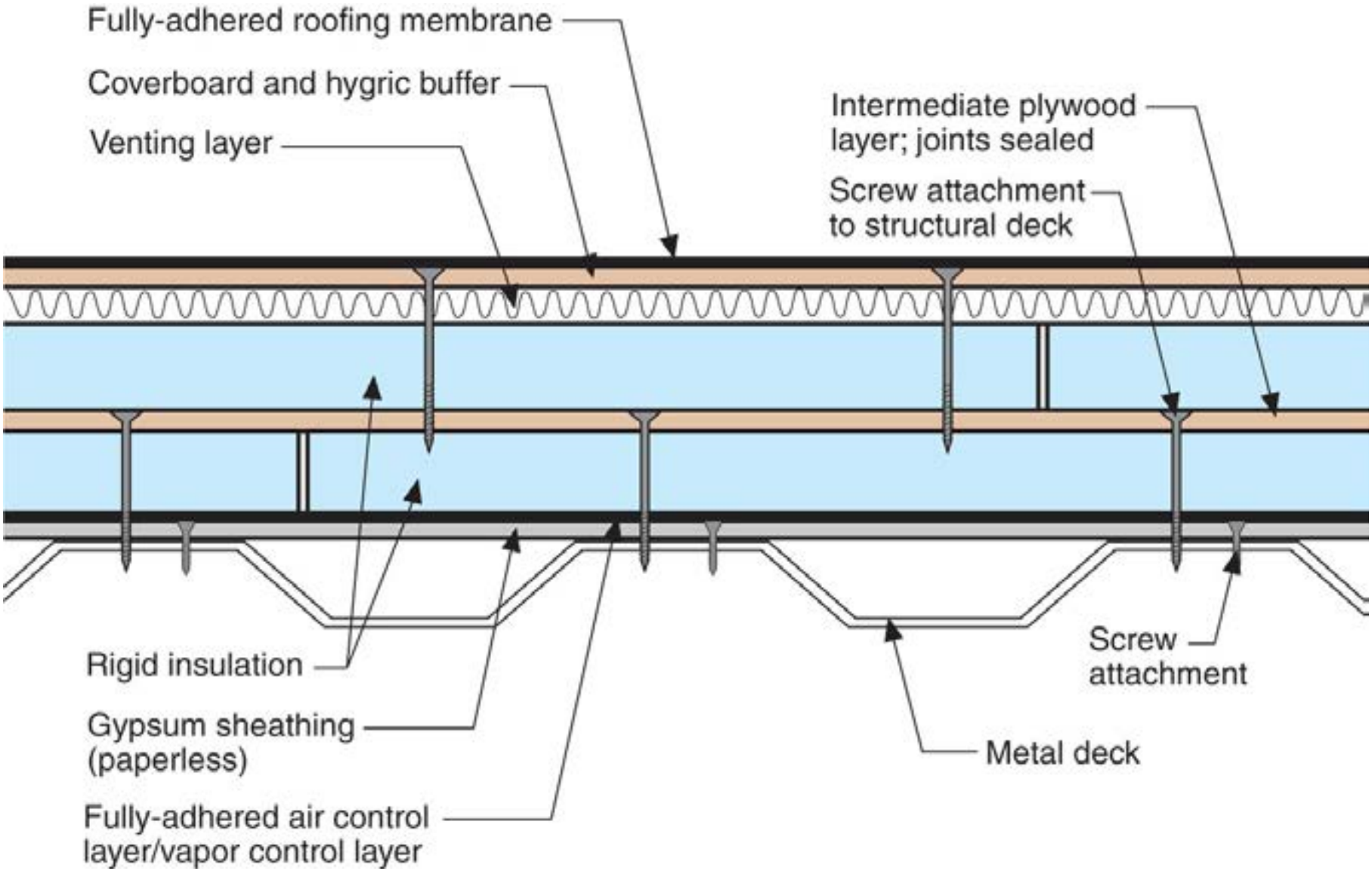


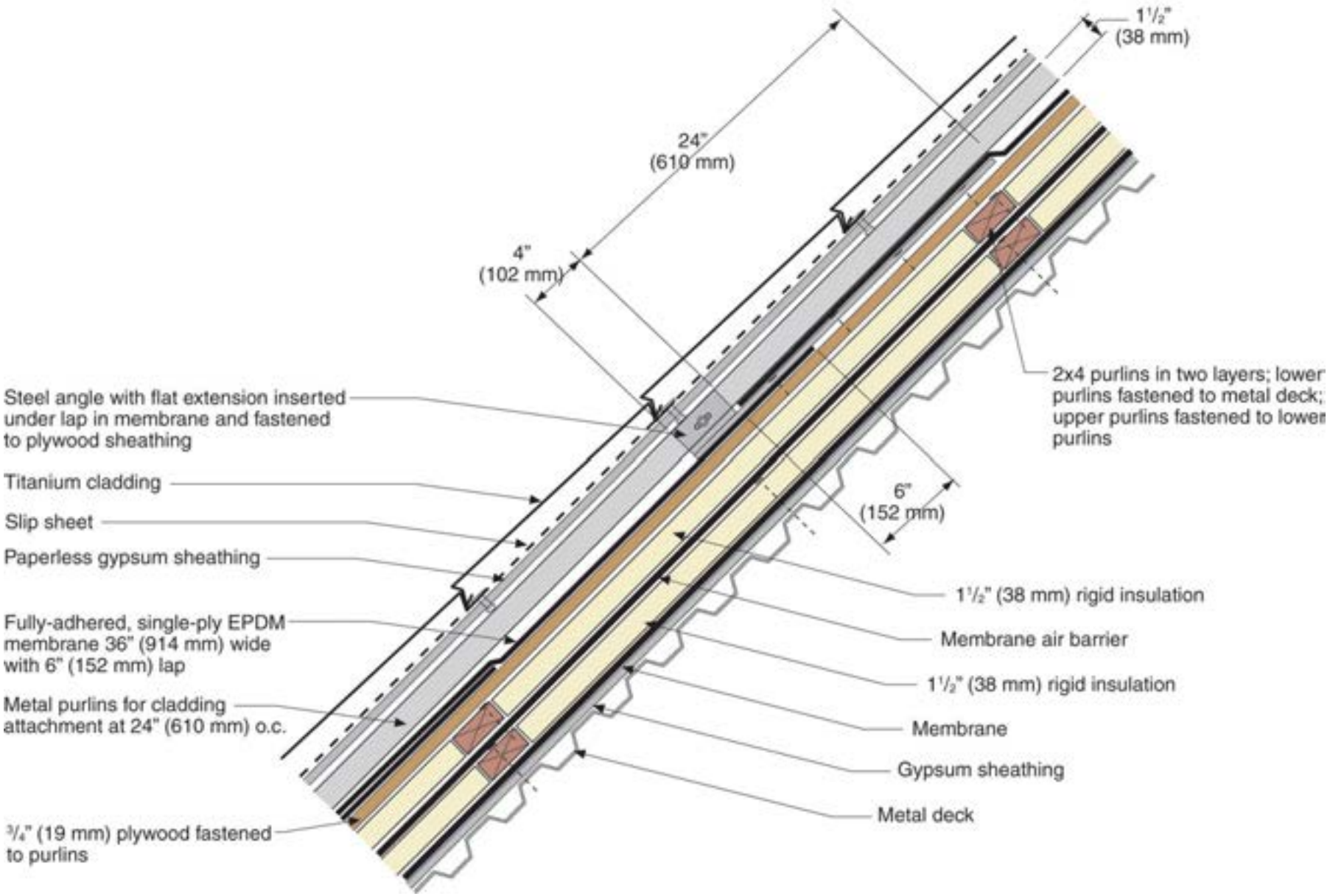
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

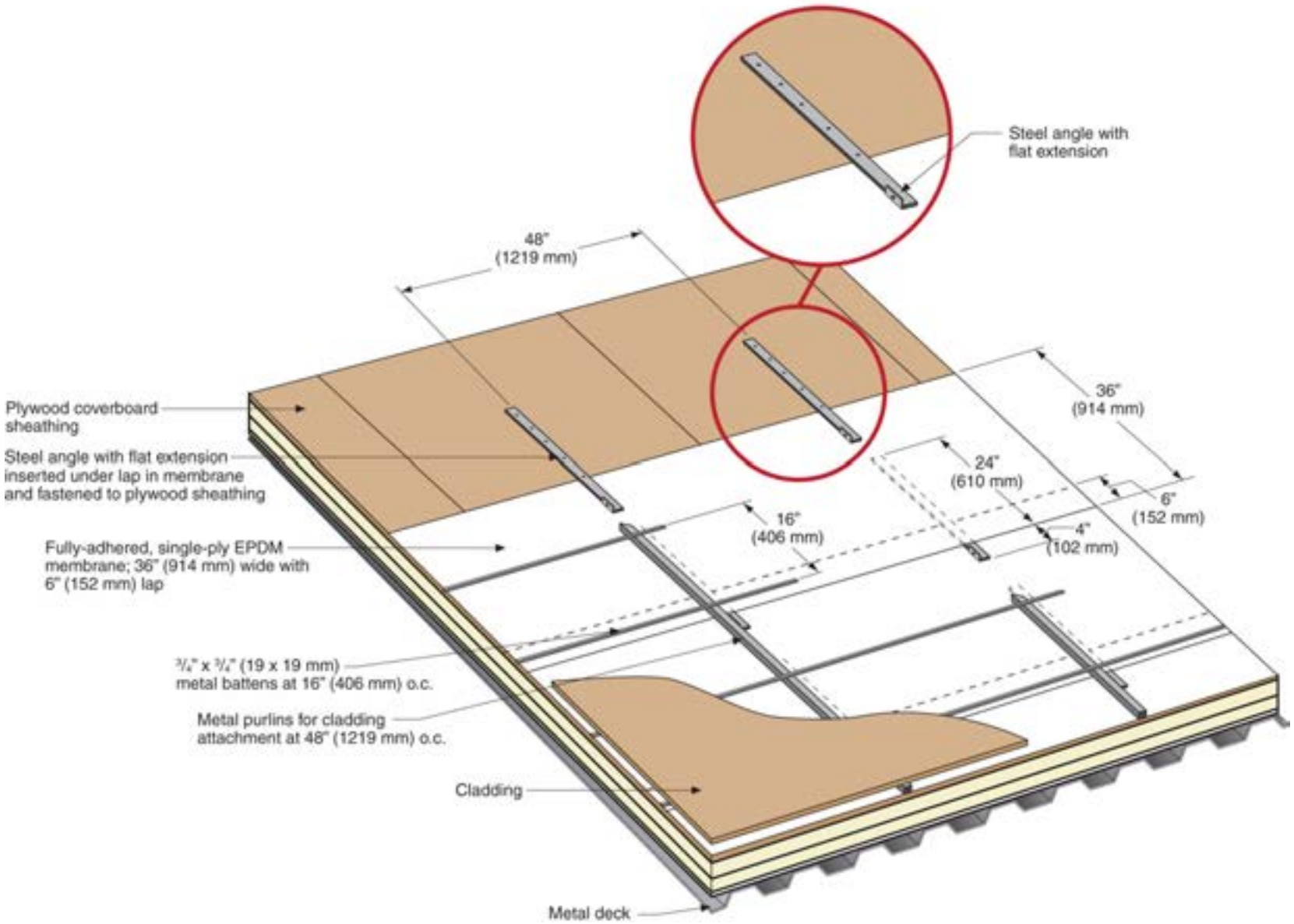

Roof sheathing
Shingles
Roofing paper
Minimum R-50 rigid insulation in two or more layers with horizontal and vertical joints staggered
Plywood roof sheathing
Roofing membrane (vapor permeable liquid applied or roofing felt)
Vented space
Air control layer/ vapor control layer
Wood decking
Timber rafter or exposed joist


Fully-adhered roofing membrane
Coverboard and hygric buffer
Rigid insulation (min. two layers; joints offset)
Screw attachment
Gypsum sheathing (paperless)
Fully-adhered air control layer/vapor control layer
Screw attachment
Metal deck


Fully-adhered roofing membrane
Coverboard and hygric buffer
Screw attachment to intermediate plywood layer
Intermediate plywood layer; joints sealed
Screw attachment to structural deck
Rigid insulation
Gypsum sheathing (paperless)
Fully-adhered air control layer/vapor control layer
Screw attachment
Metal deck


Fully-adhered roofing membrane
Coverboard and hygric buffer
Venting layer
Intermediate plywood layer; joints sealed
Screw attachment to structural deck
Rigid insulation
Gypsum sheathing (paperless)
Fully-adhered air control layer/vapor control layer
Screw attachment
Metal deck


1½" (38 mm)
24" (610 mm)
4" (102 mm)
6" (152 mm)
Steel angle with flat extension inserted under lap in membrane and fastened to plywood sheathing
Titanium cladding
Slip sheet
Paperless gypsum sheathing
Fully-adhered, single-ply EPDM membrane 36" (914 mm) wide with 6" (152 mm) lap
Metal purlins for cladding attachment at 24" (610 mm) o.c.
¾" (19 mm) plywood fastened to purlins
2x4 purlins in two layers; lower purlins fastened to metal deck; upper purlins fastened to lower purlins
1½" (38 mm) rigid insulation
Membrane air barrier
1½" (38 mm) rigid insulation
Membrane
Gypsum sheathing
Metal deck


Steel angle with flat extension
48" (1219 mm)
Plywood coverboard sheathing
Steel angle with flat extension inserted under lap in membrane and fastened to plywood sheathing
Fully-adhered, single-ply EPDM membrane; 36" (914 mm) wide with 6" (152 mm) lap
¾" x ¾" (19 x 19 mm) metal battens at 16" (406 mm) o.c.
Metal purlins for cladding attachment at 48" (1219 mm) o.c.
Cladding
Metal deck
36" (914 mm)
24" (610 mm)
16" (406 mm)
6" (152 mm)
4" (102 mm)