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

Building Science

Adventures In Building Science

www.buildingscience.com

Arrhenius Equation

For Every 10 Degree K Rise

Activation Energy Doubles

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

Damage Functions

Water

Heat

Ultra-violet Radiation

2nd Law of Thermodynamics

Heat Flow Is From Warm To Cold

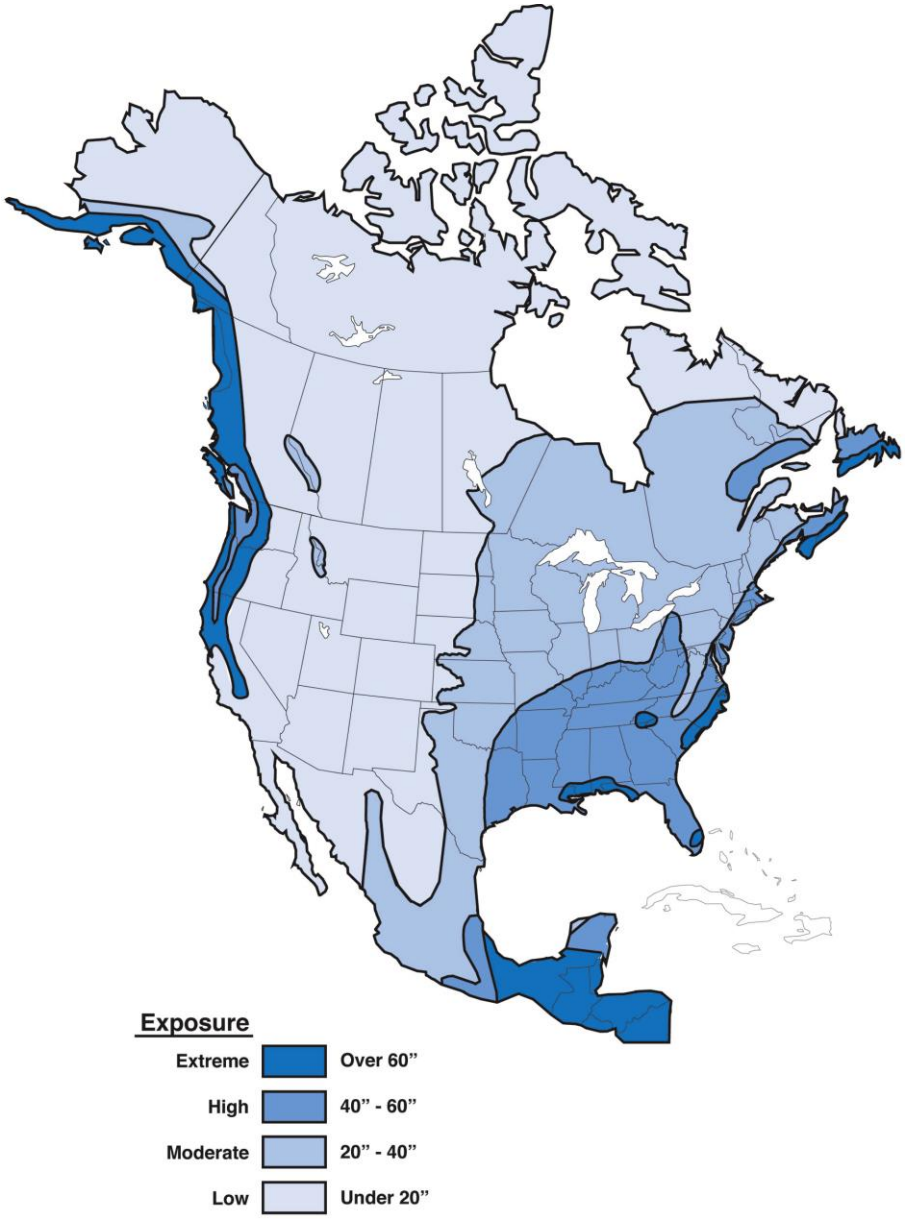
Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

Air Flow Is From A Higher Pressure to a Lower Pressure

Gravity Acts Down


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

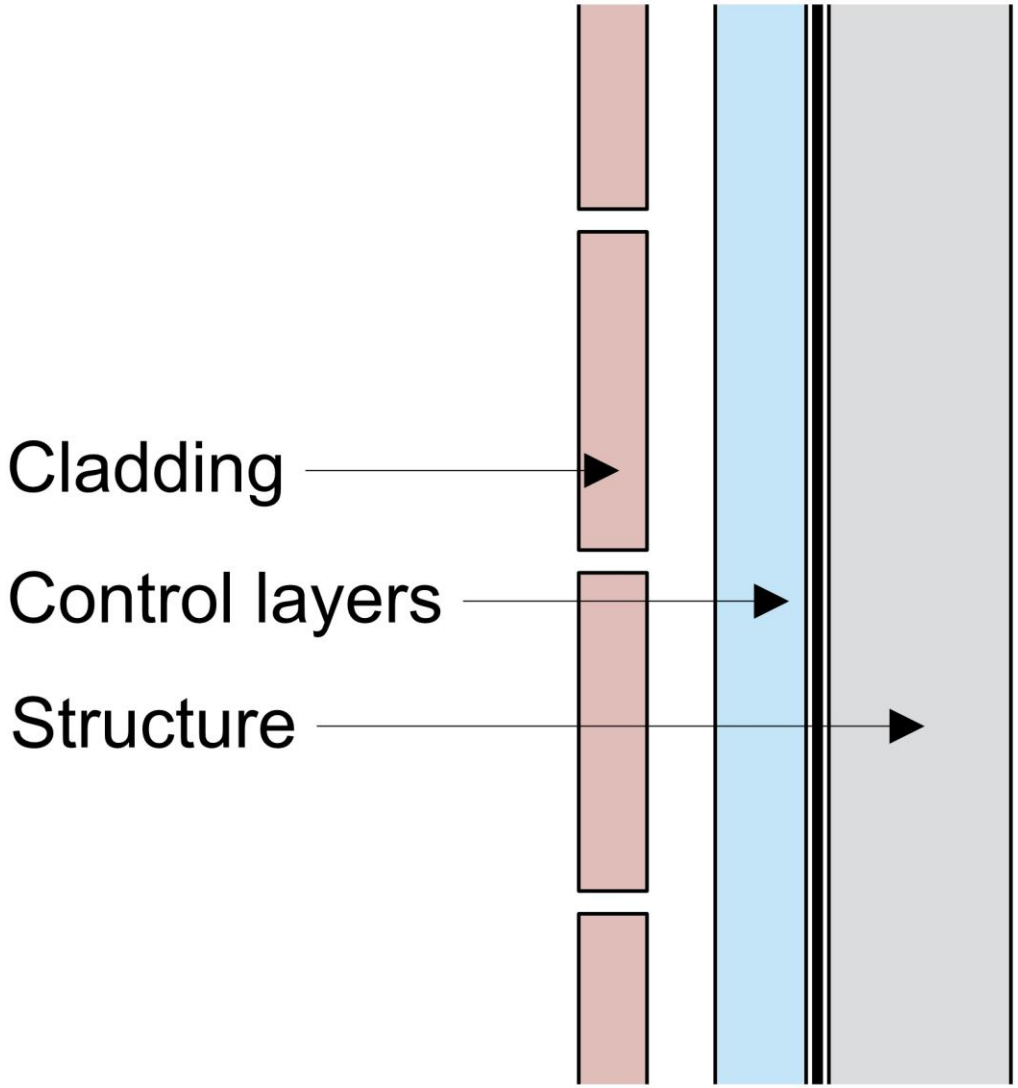

Exposure
Extreme
Over 60”
High
40” - 60”
Moderate
20” - 40”
Low
Under 20”

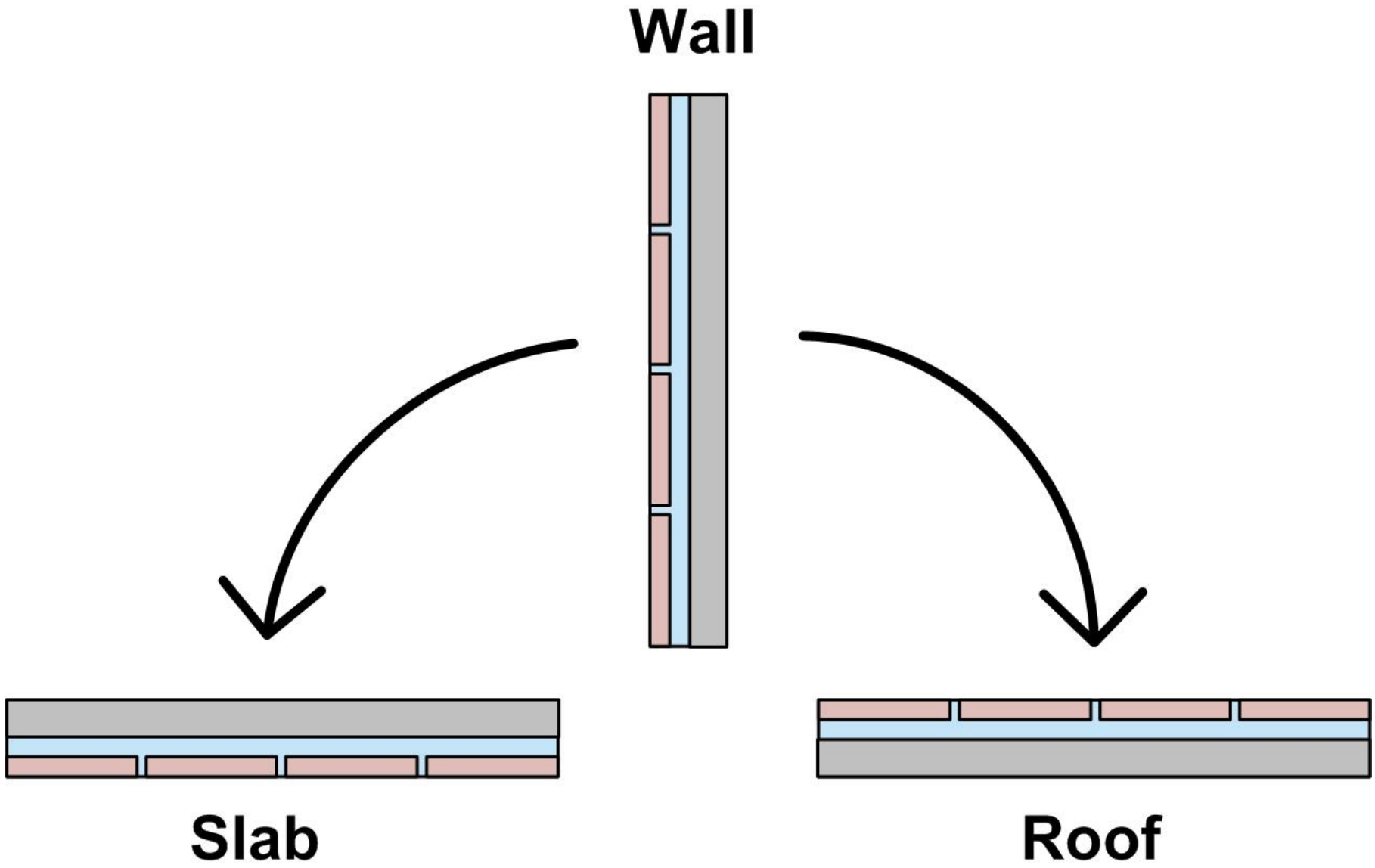
Water Control Layer

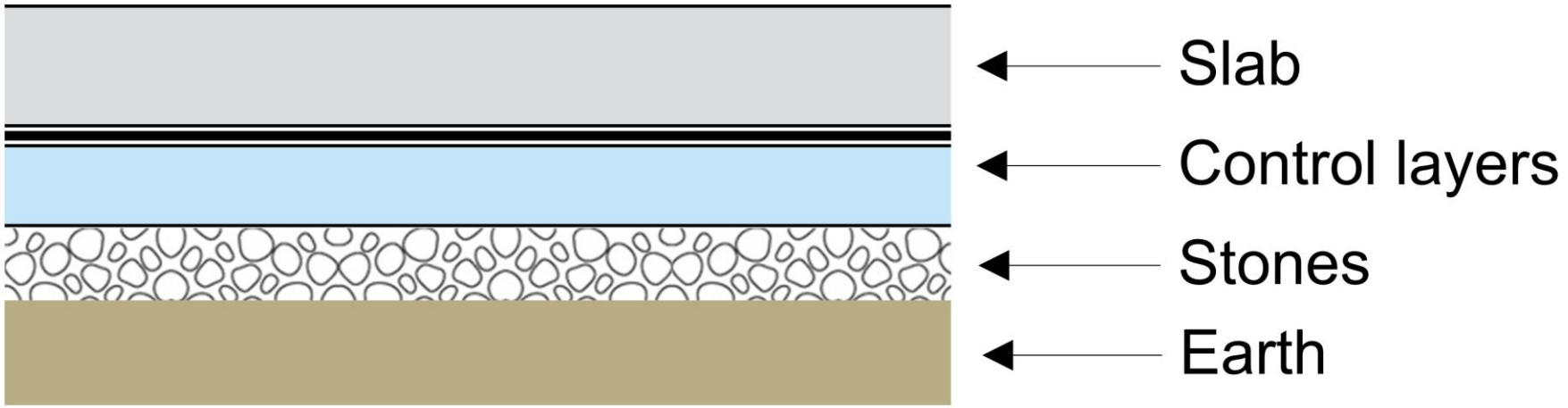
Air Control Layer

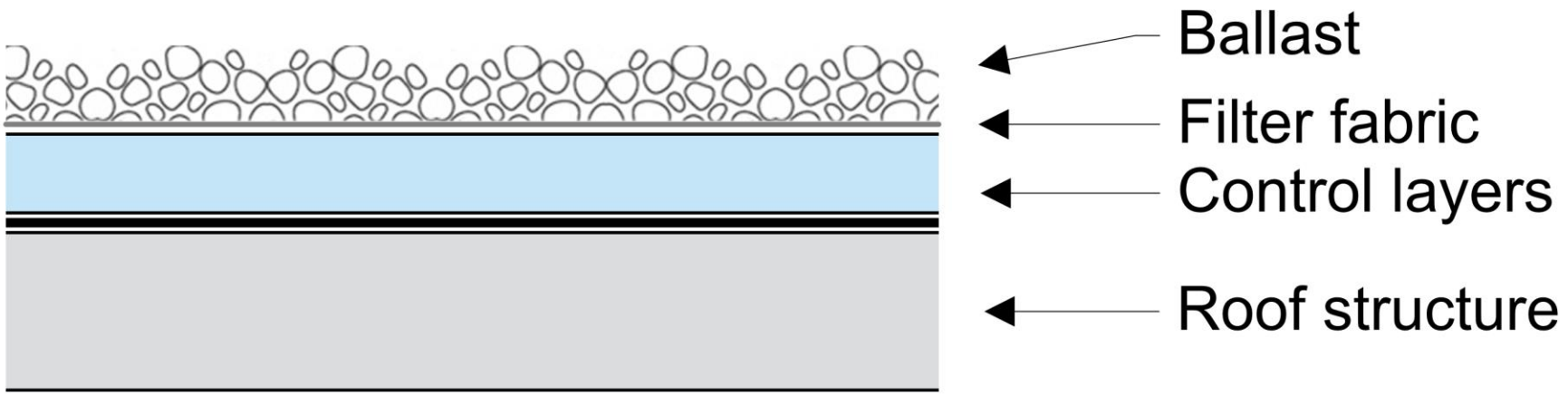
Vapor Control Layer

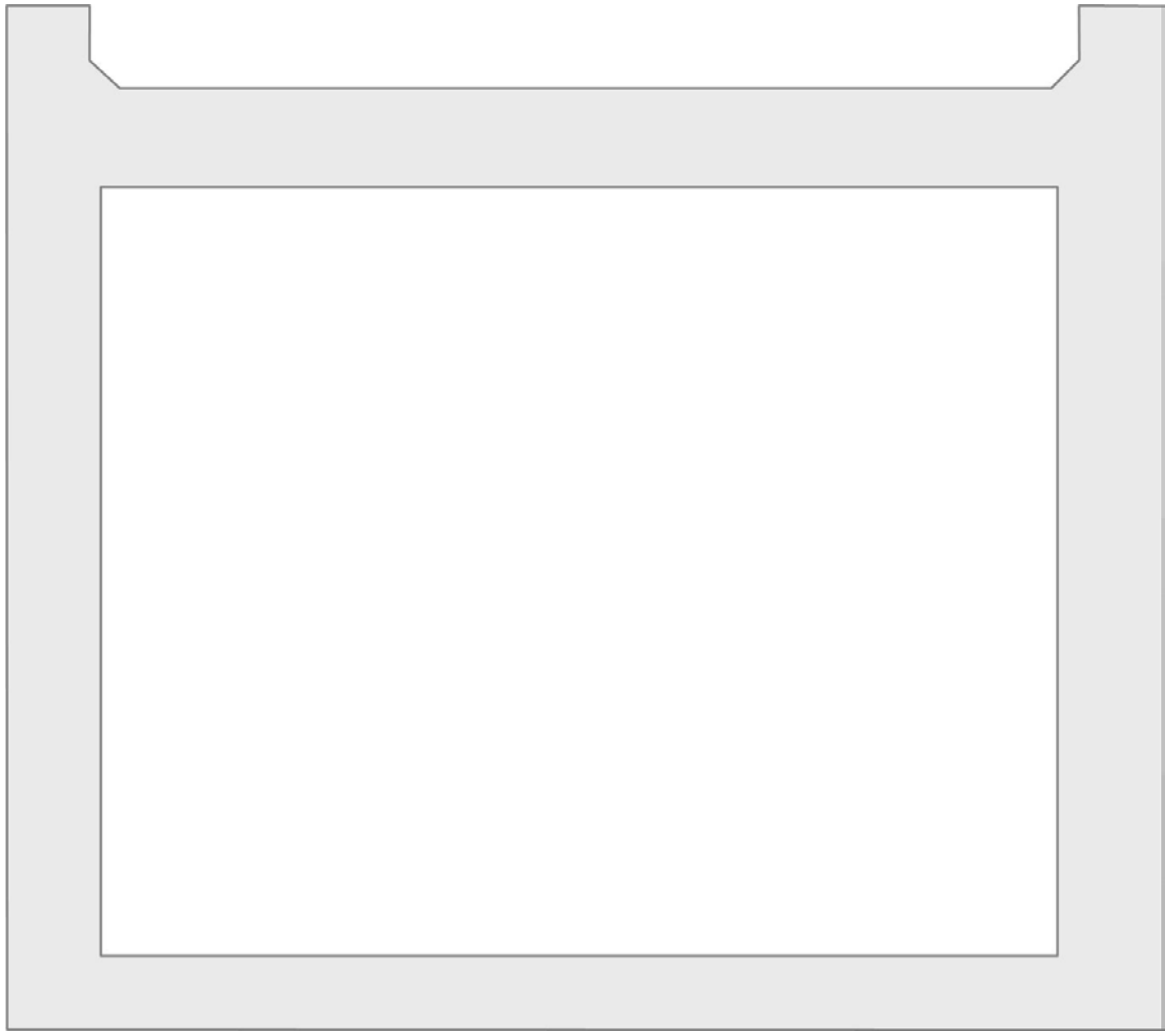
Thermal Control Layer

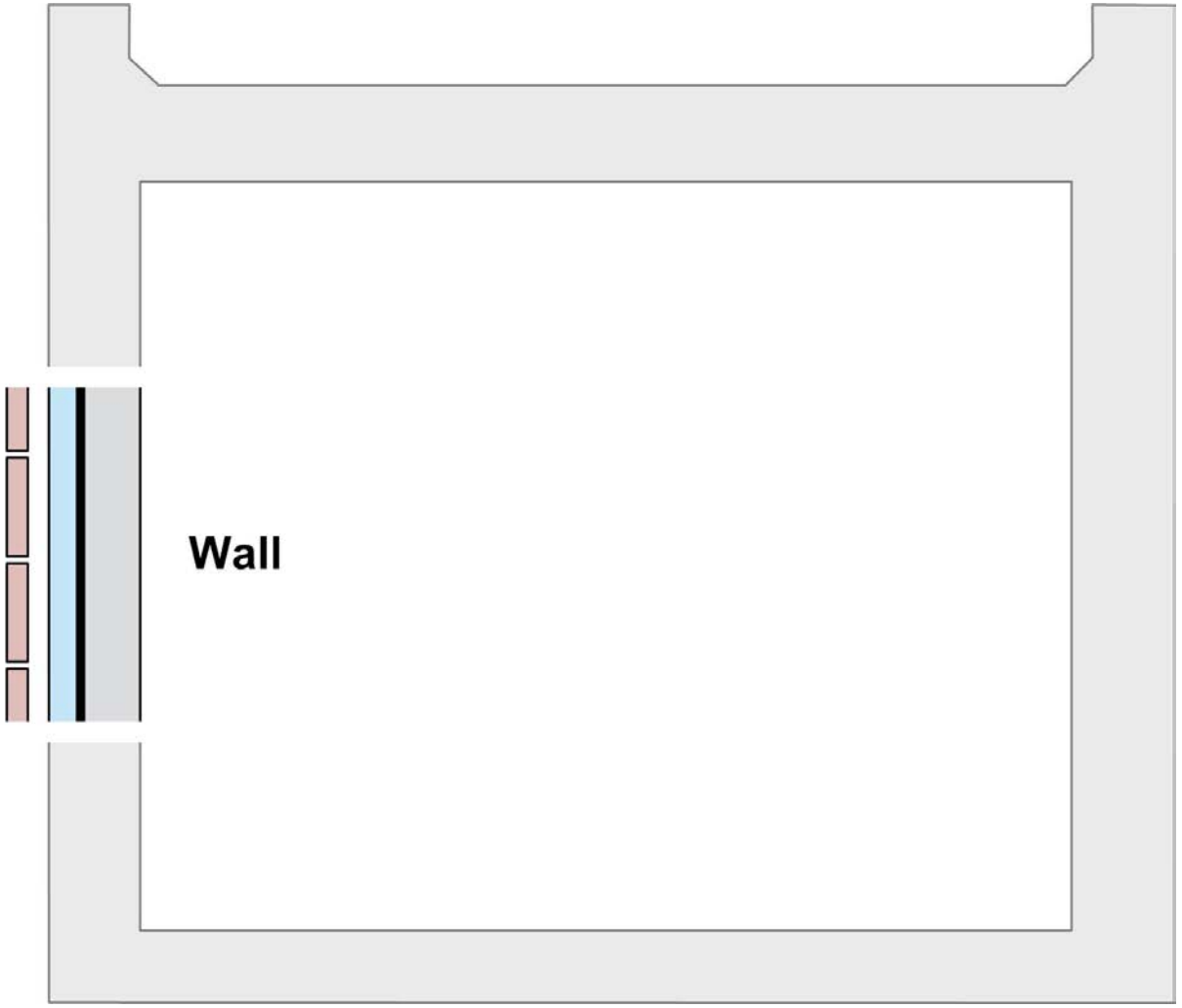

Cladding
Control layers
Structure

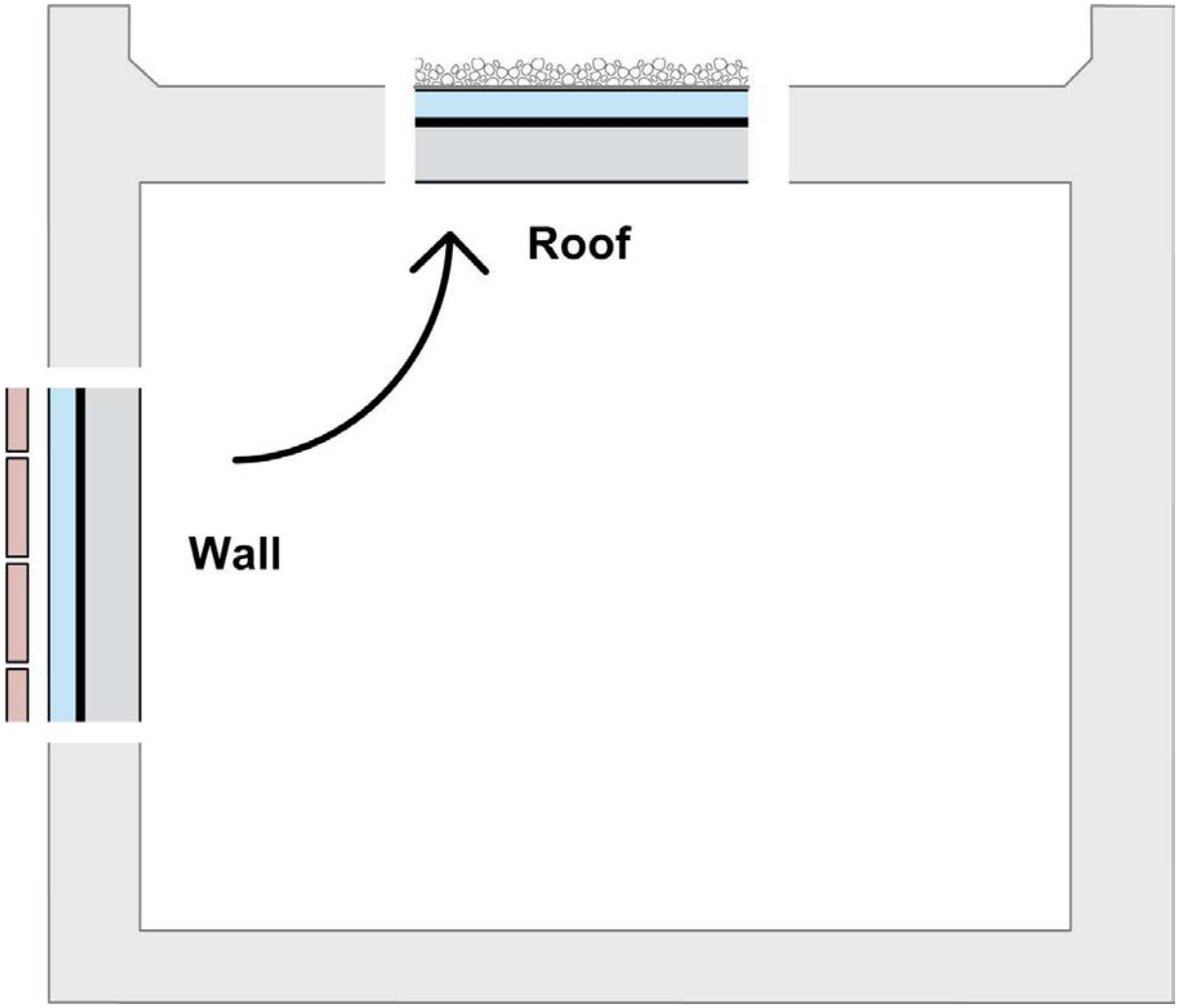

Wall
Slab
Roof

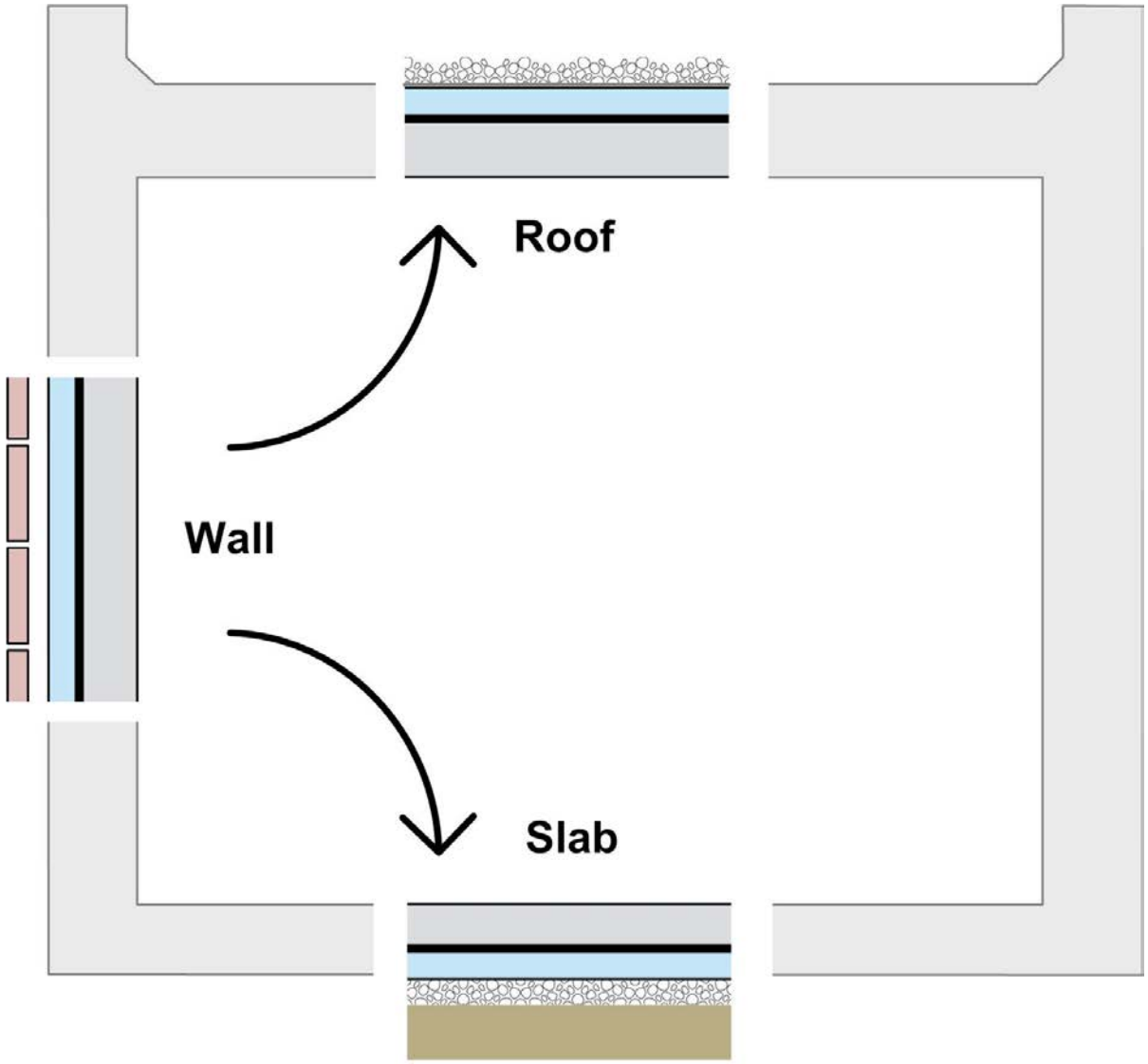

Slab
Control layers
Stones
Earth

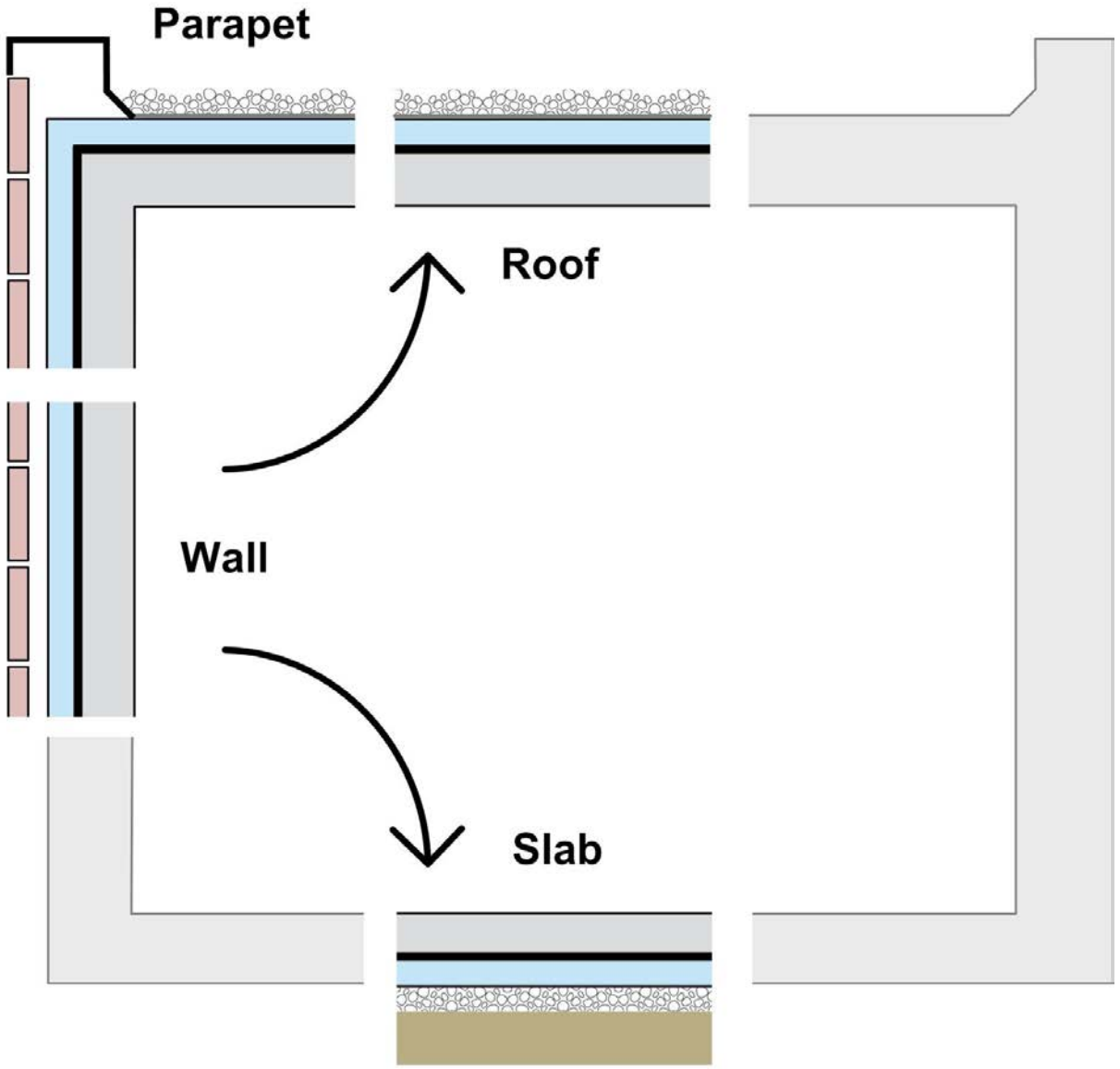

Ballast
Filter fabric
Control layers
Roof structure

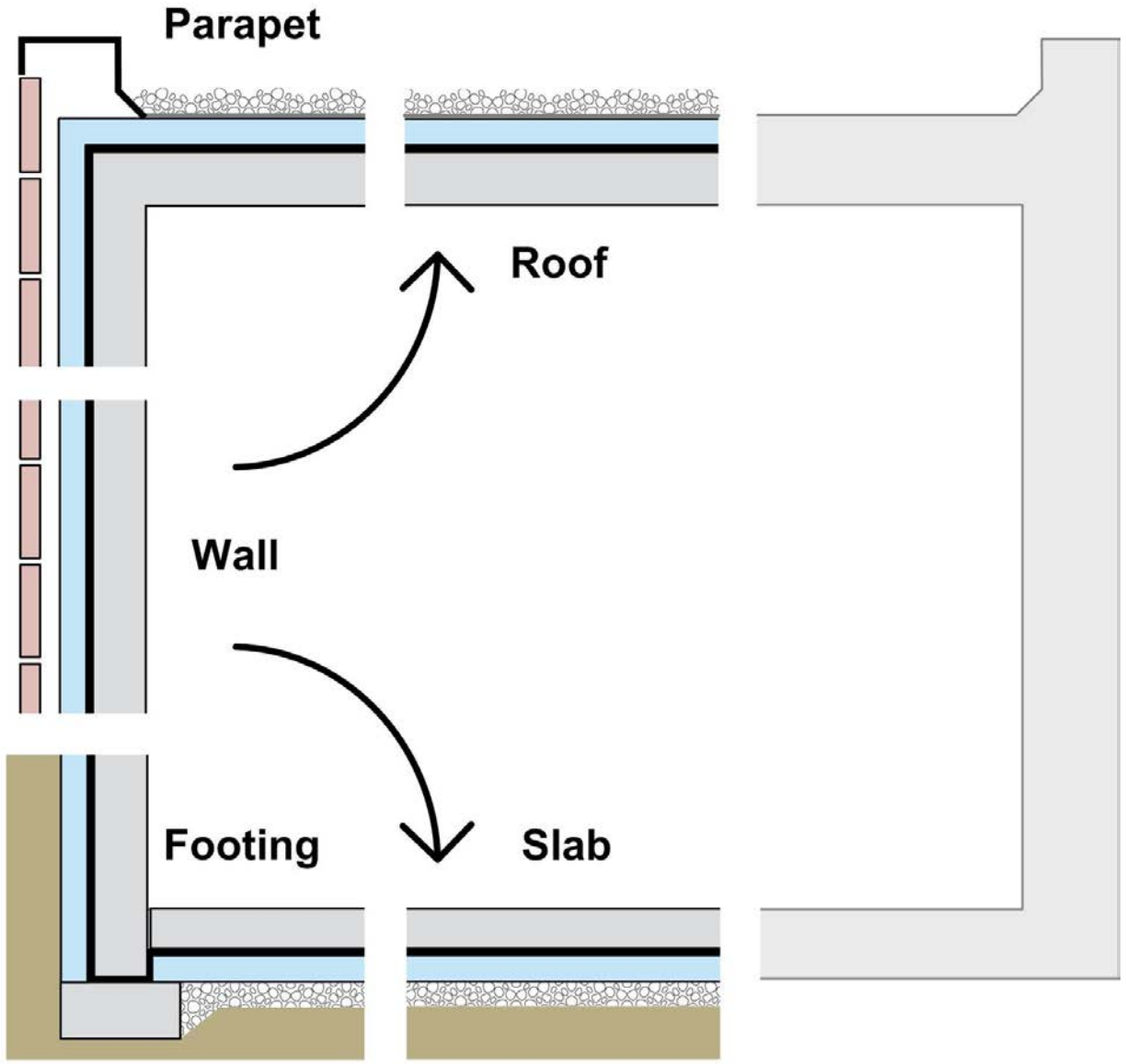


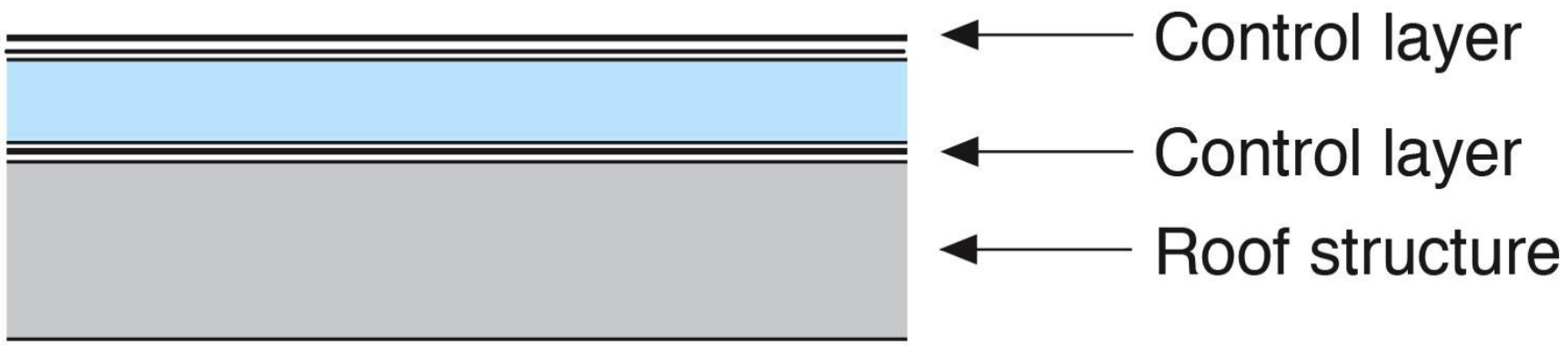

Wall

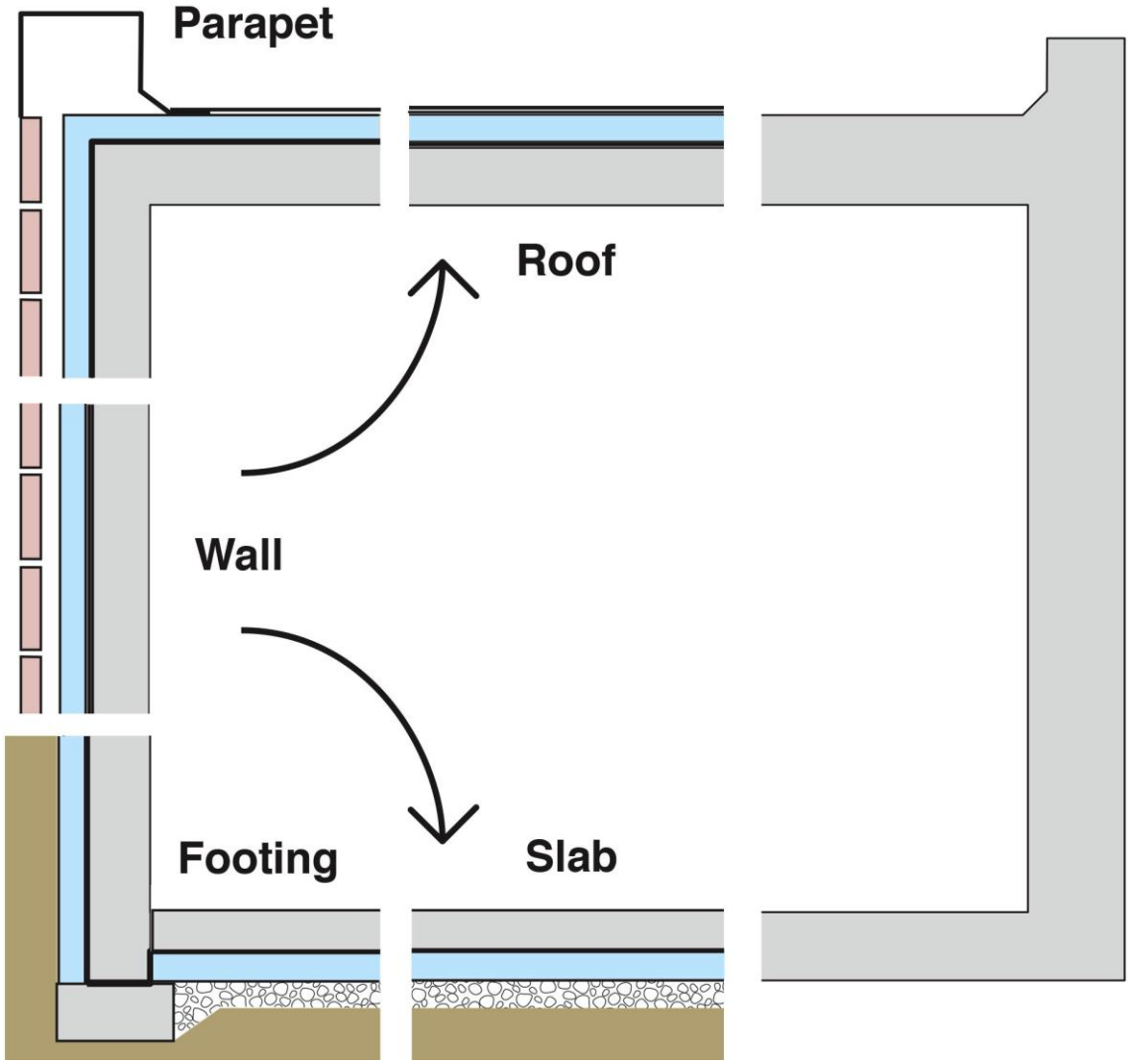

Roof
Wall

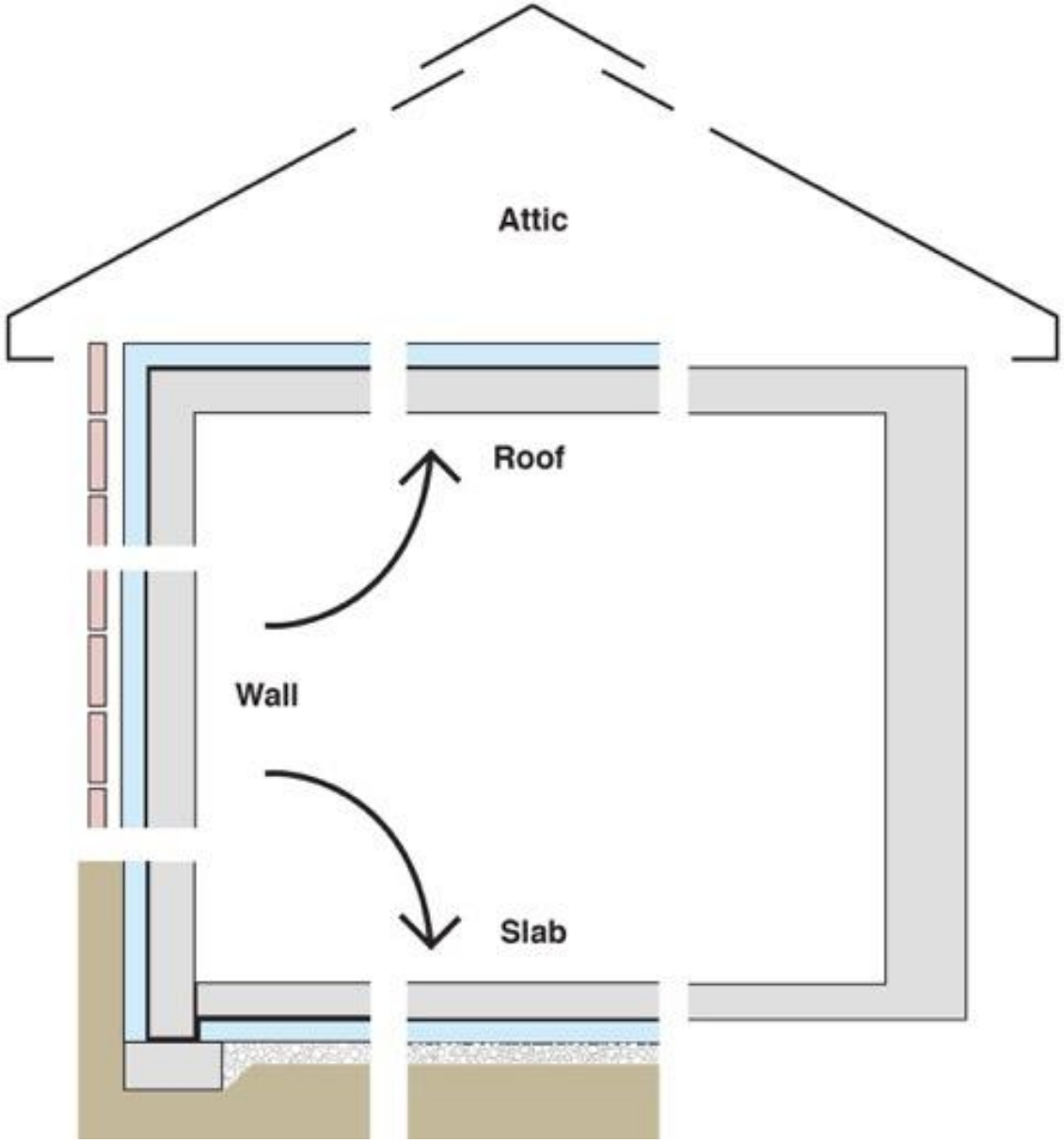

Roof
Wall
Slab

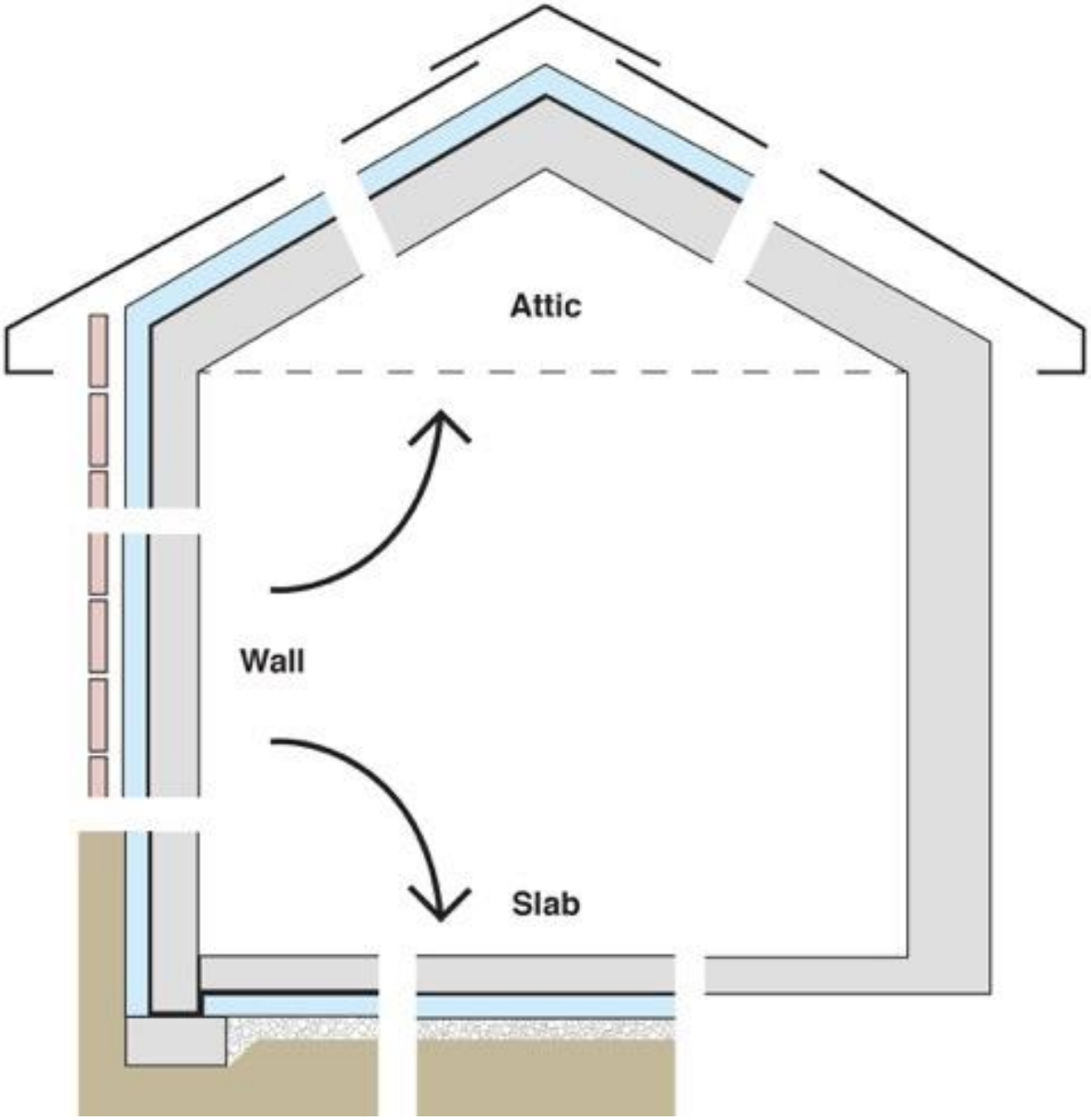

Parapet
Roof
Wall
Slab

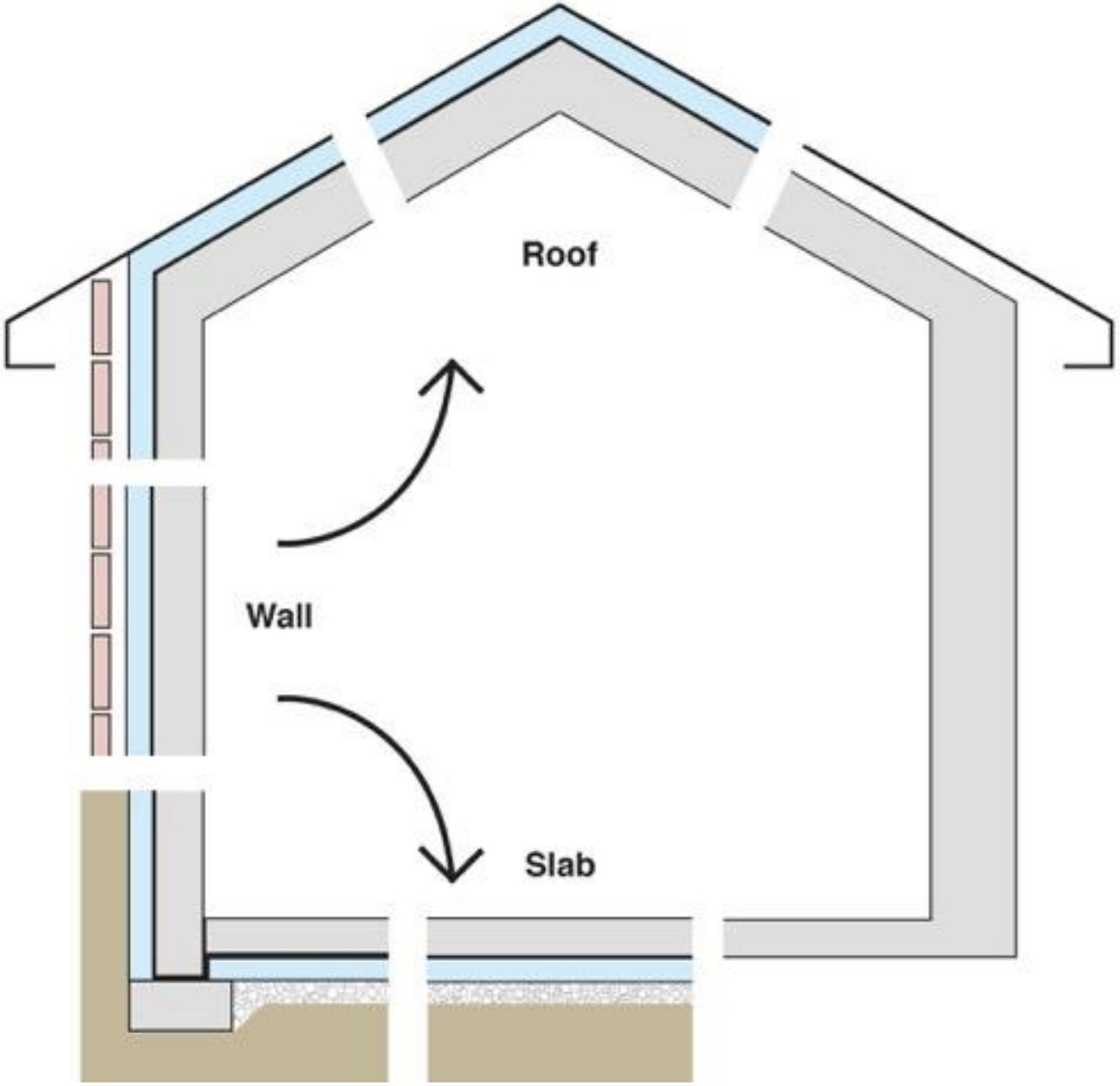

Parapet
Roof
Wall
Footing
Slab

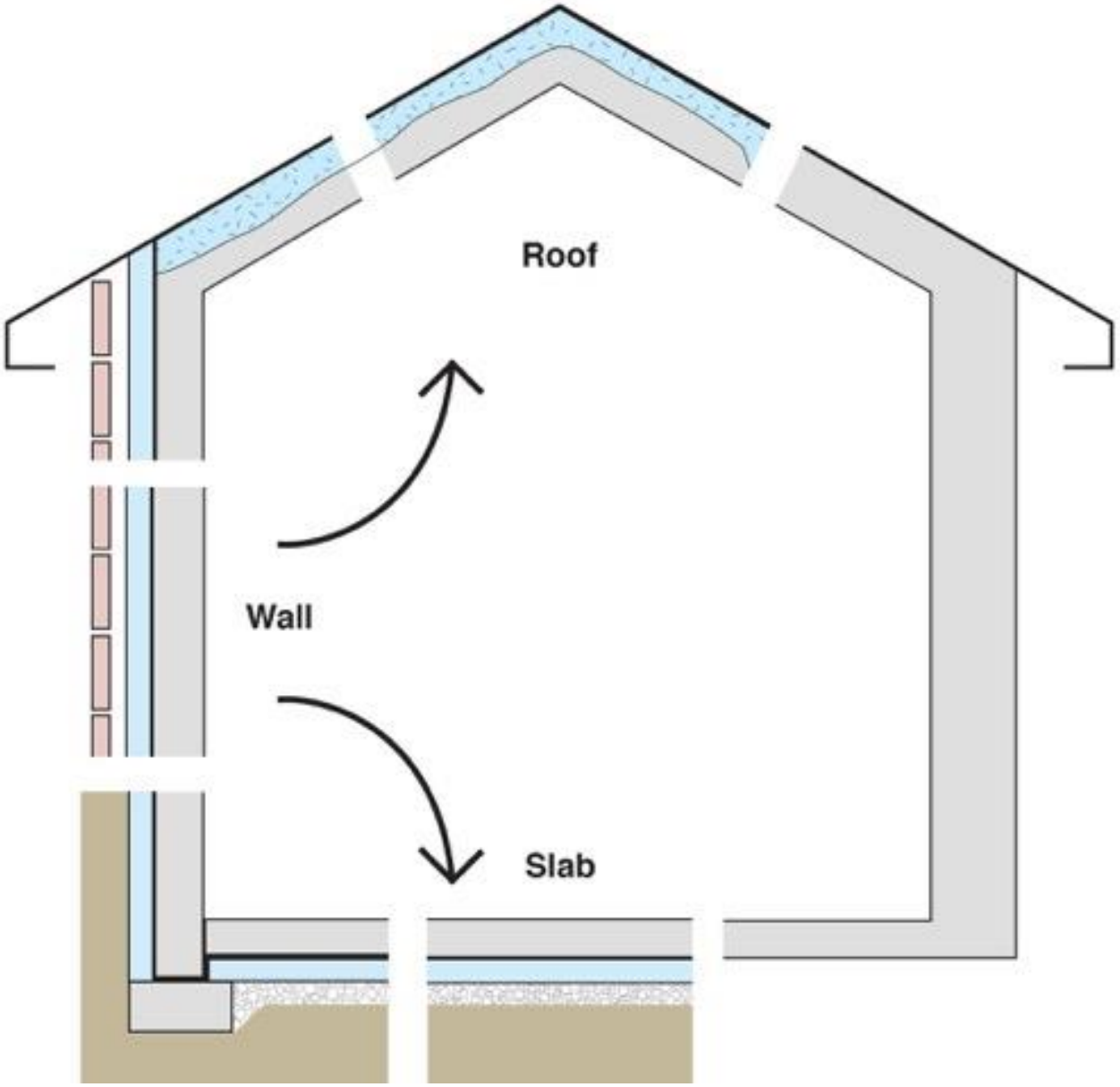

Control layer
Control layer
Roof structure

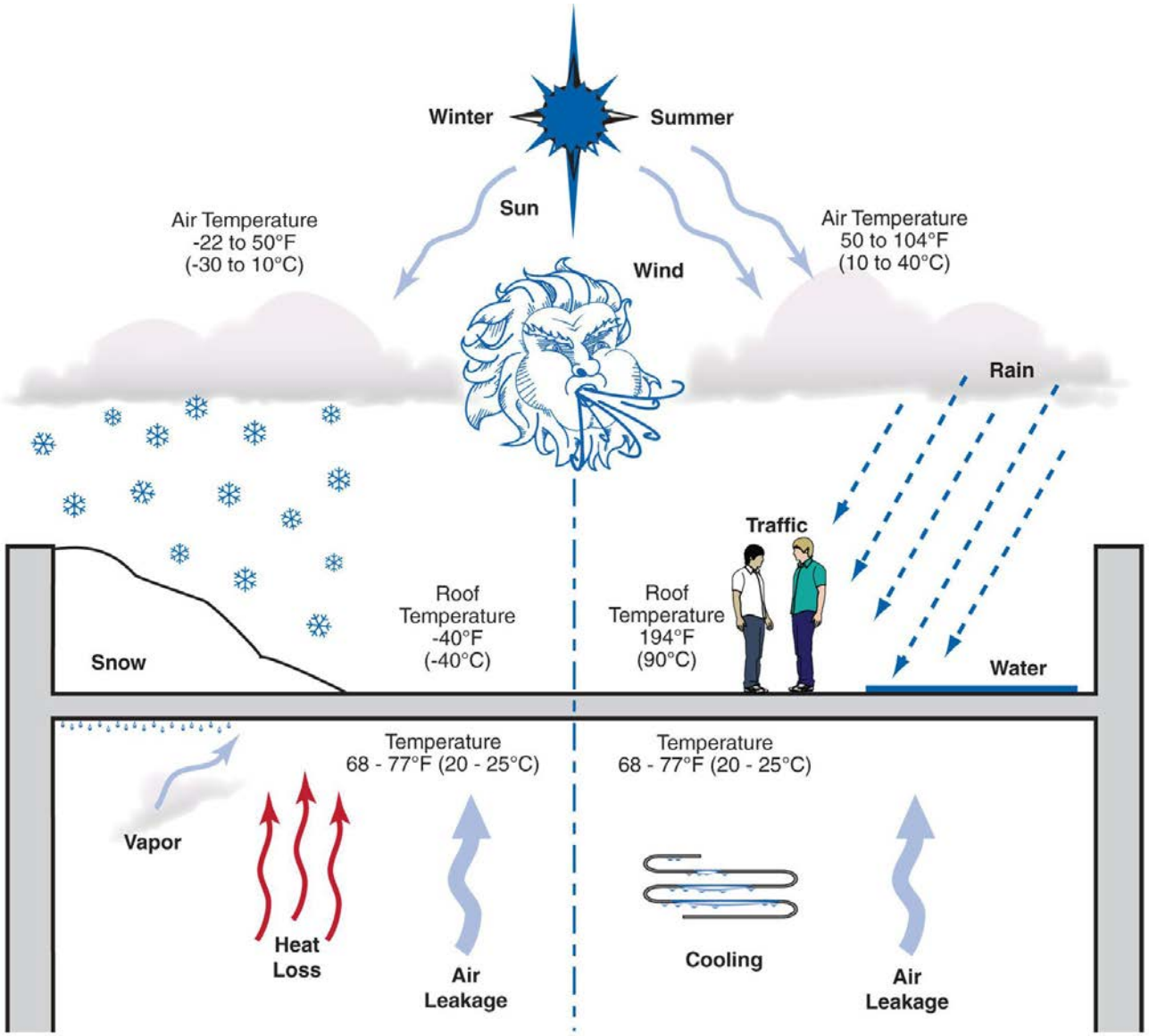

Parapet
Roof
Wall
Footing
Slab


Attic
Roof
Wall
Slab

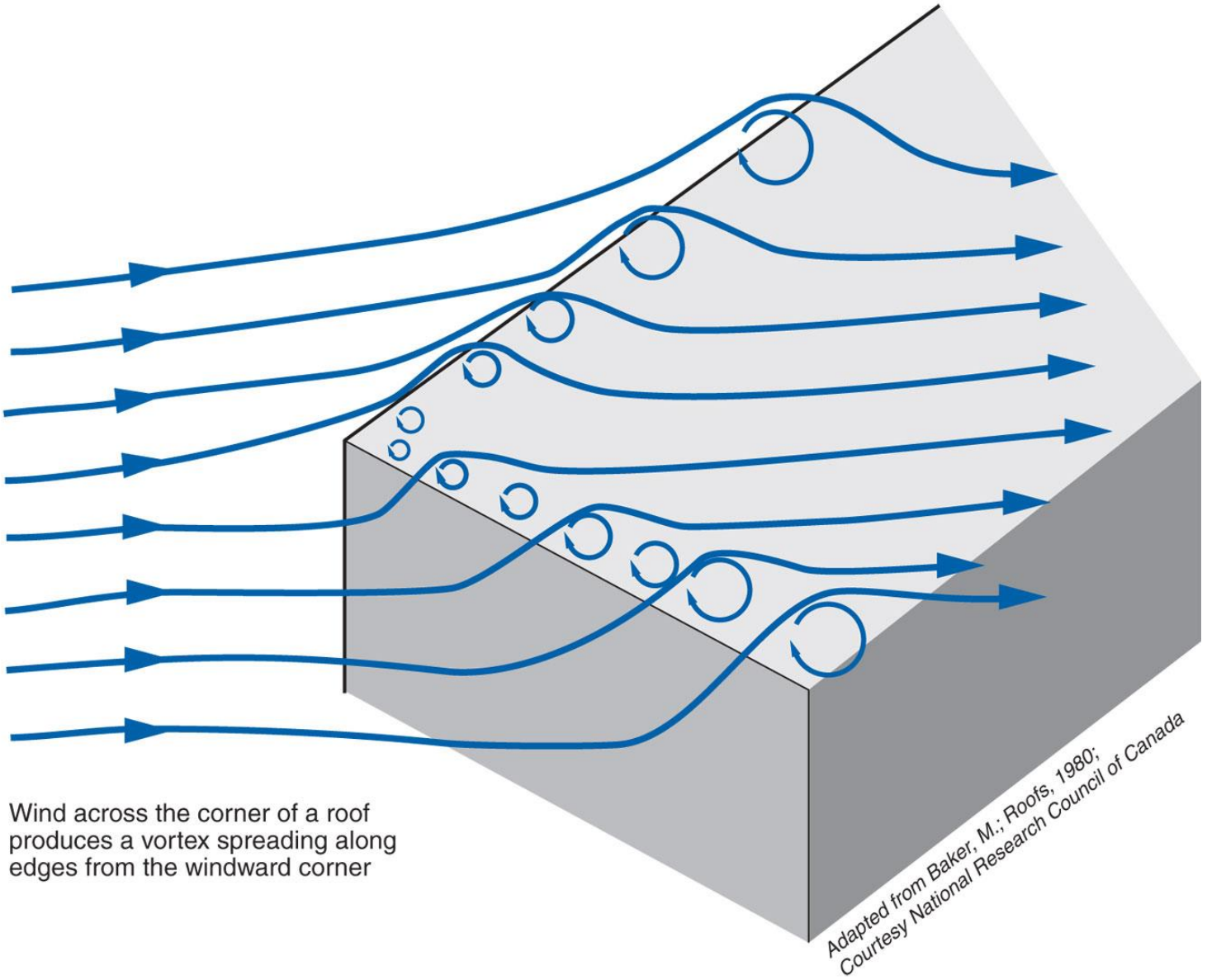

Attic
Wall
Slab


Roof
Wall
Slab


Roof
Wall
Slab

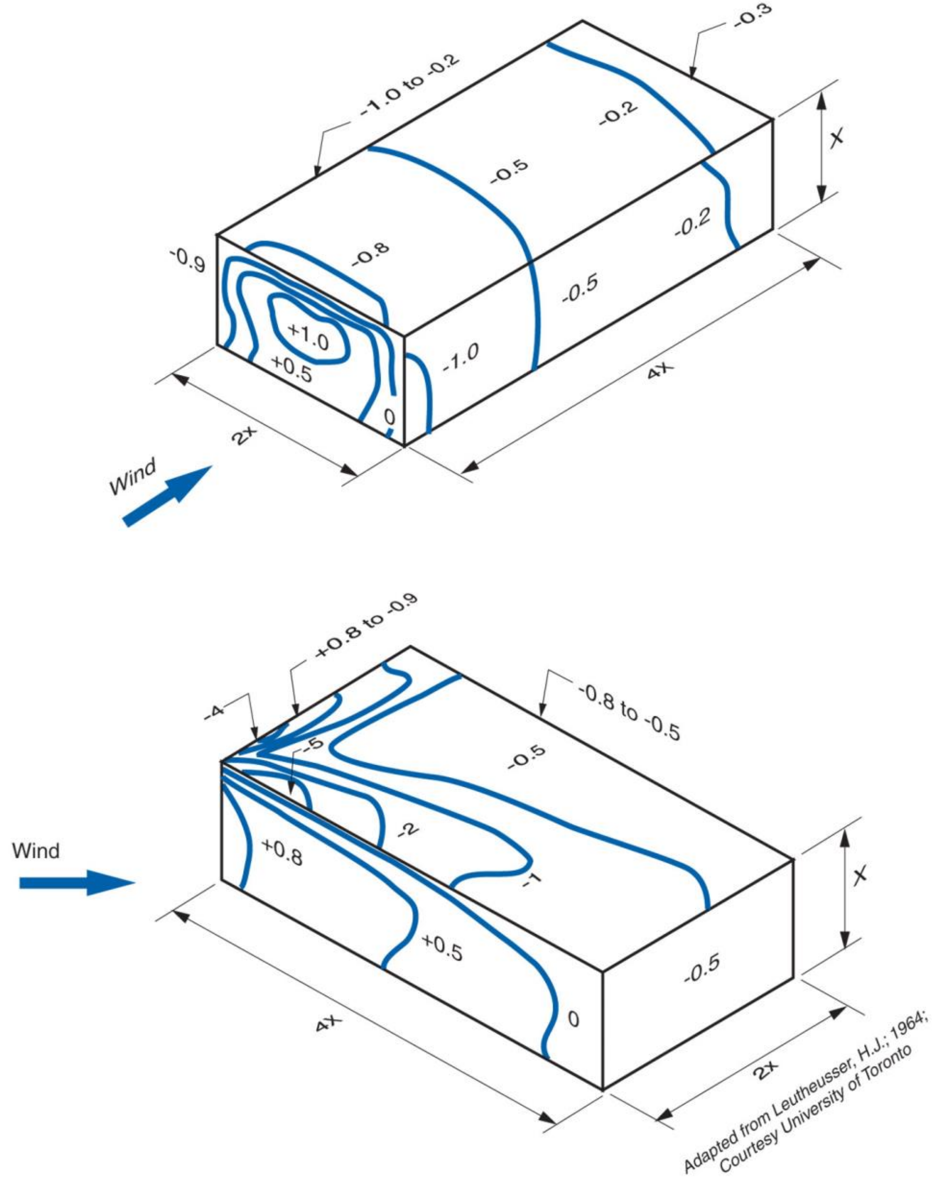


Adapted from Baker, M.; Roofs, 1980;
Courtesy National Research Council of Canada

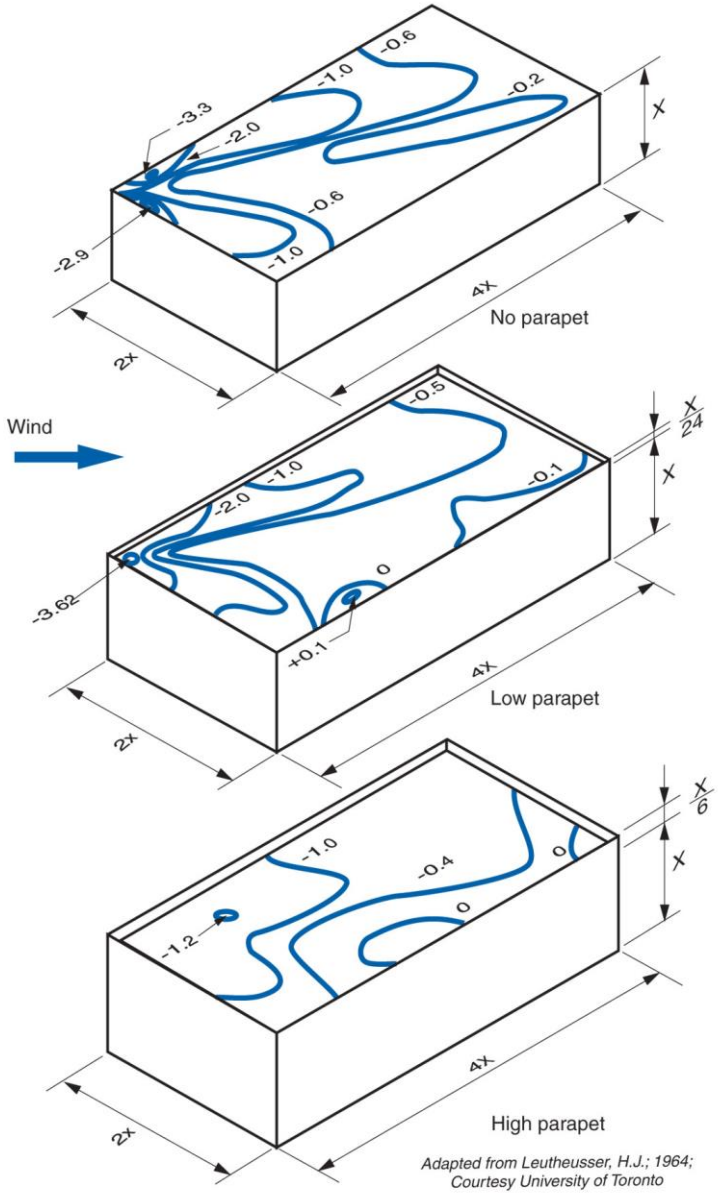


Wind across the corner of a roof produces a vortex spreading along edges from the windward corner

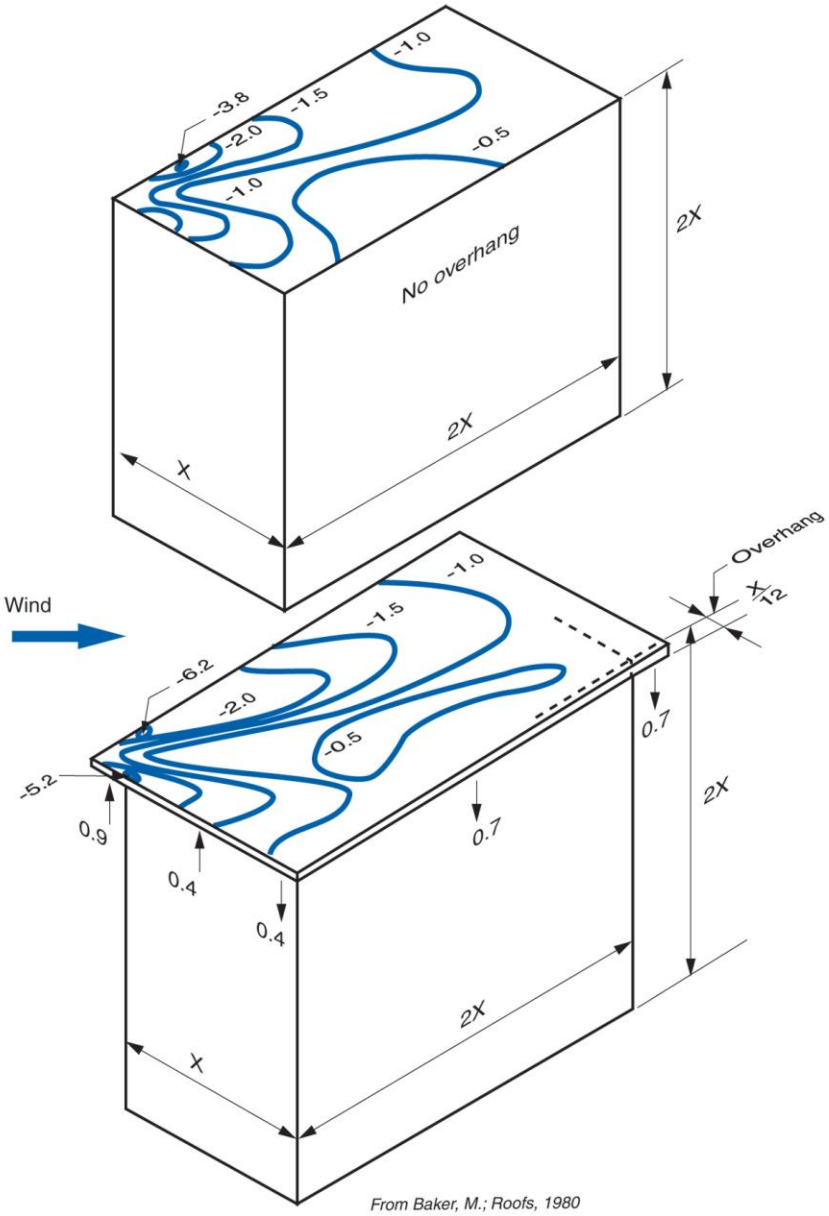
Adapted from Baker, M.; Roofs, 1980; Courtesy National Research Council of Canada



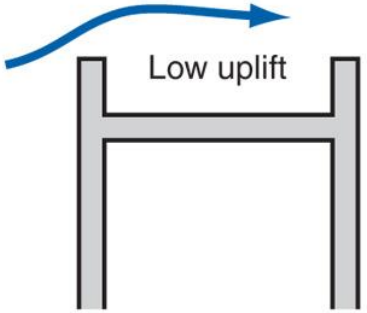
-0.3
-1.0 to -0.2
-0.2
-0.5
-0.2
-0.9
-0.8
+1.0
+0.5
0
-1.0
-0.5
4x
2x
X
Wind
+0.8 to -0.9
-4
-5
-0.8 to -0.5
-0.5
-2
-1
+0.8
+0.5
0
-0.5
Wind
4x
2x
X
Adapted from Leutheusser, H.J.; 1964;
Courtesy University of Toronto



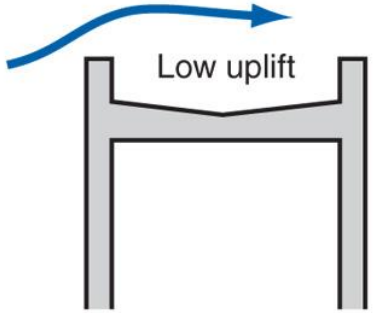
Adapted from Leutheusser, H.J.; 1964; Courtesy University of Toronto



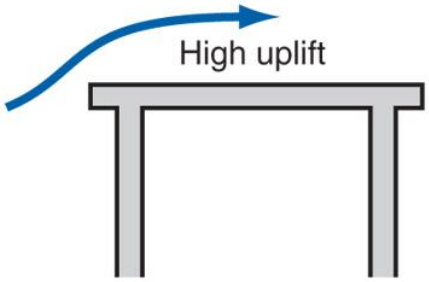
From Baker, M.; Roofs, 1980



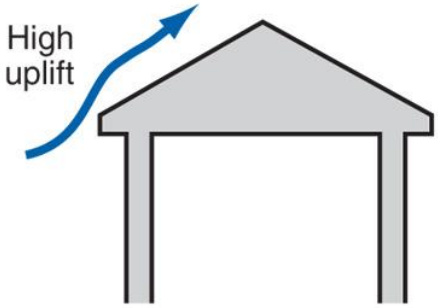
Flat roof with parapets
blow-off hazard: low
slippage hazard: low



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

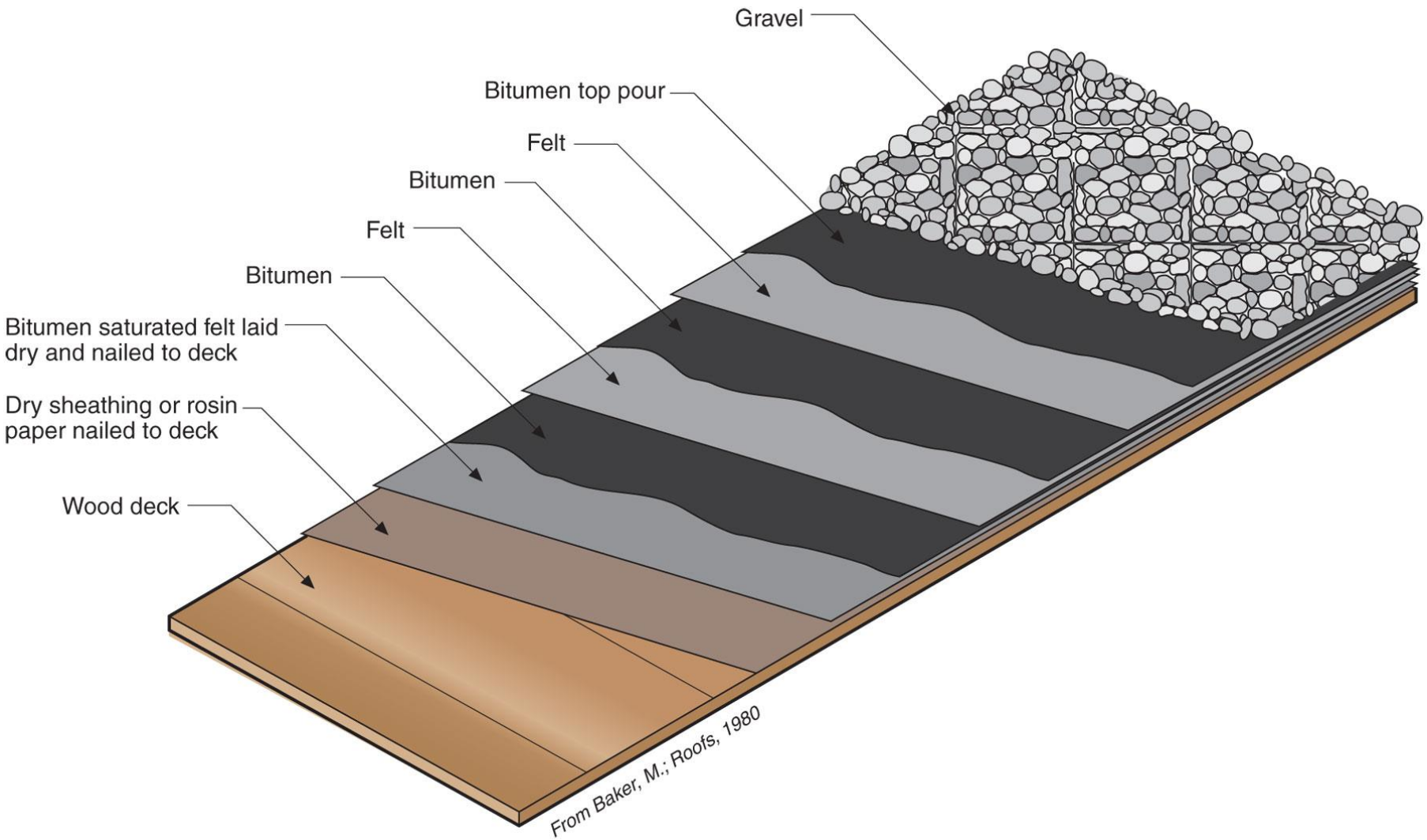


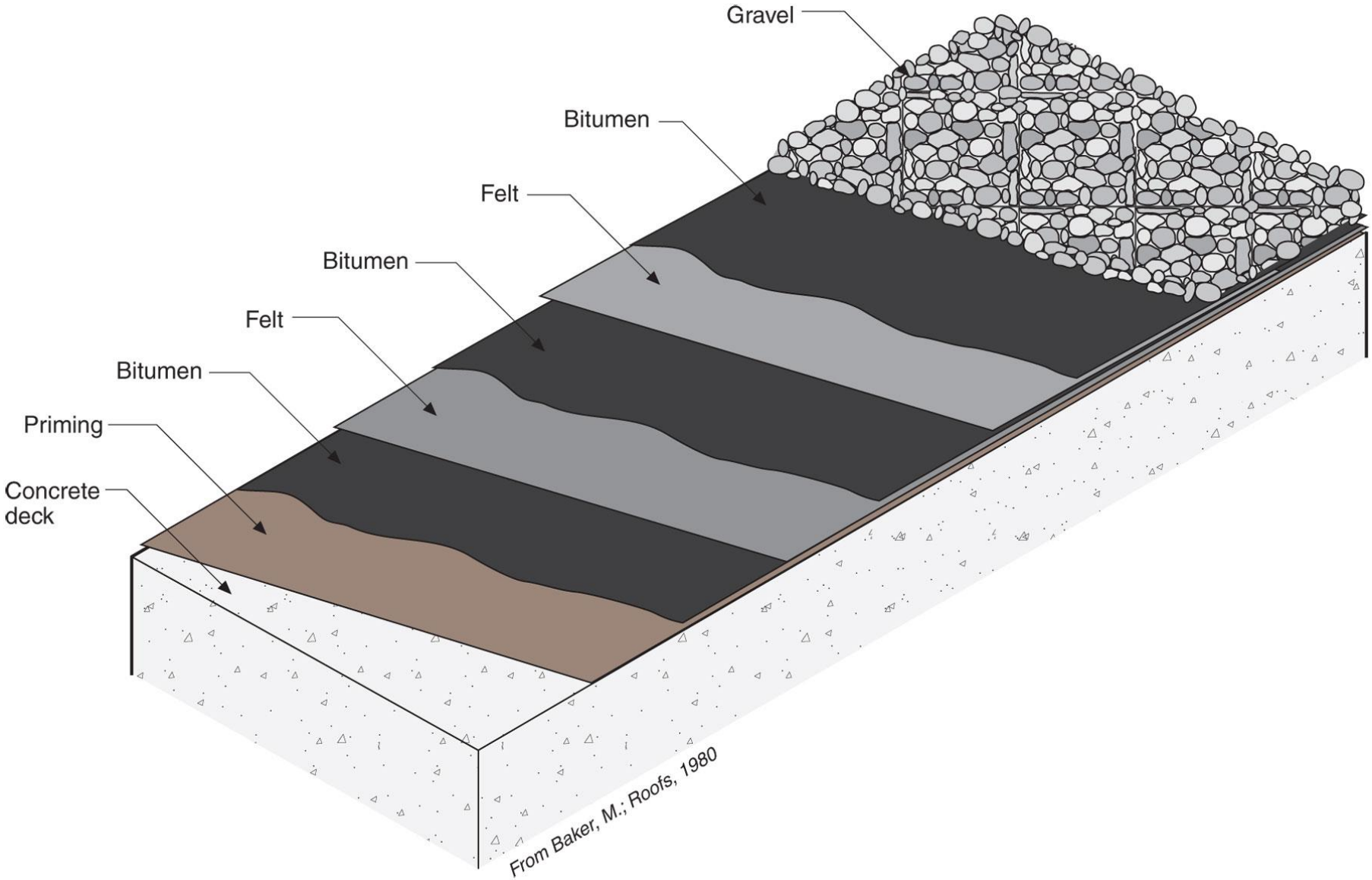
Flat roof or overhang
blow off hazard: high
slippage hazard: low

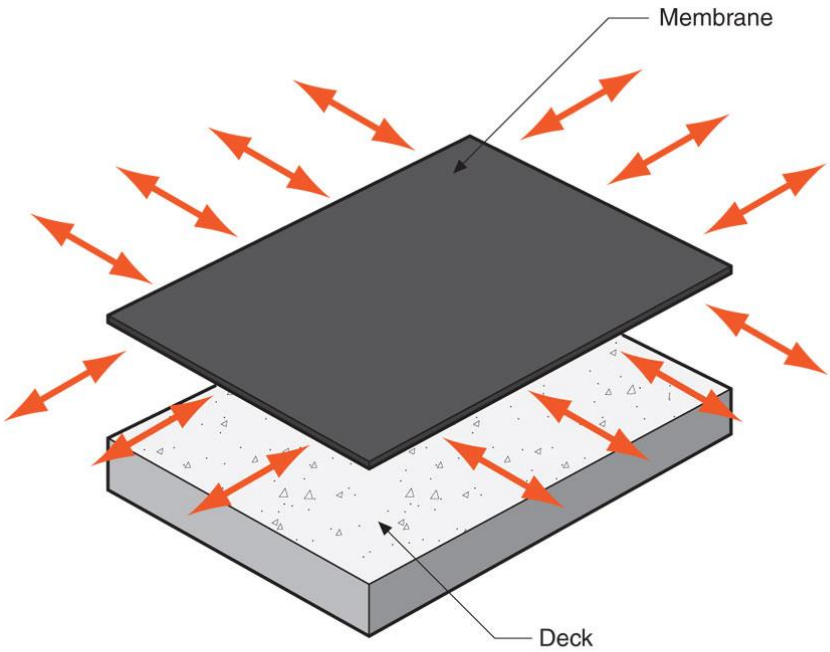


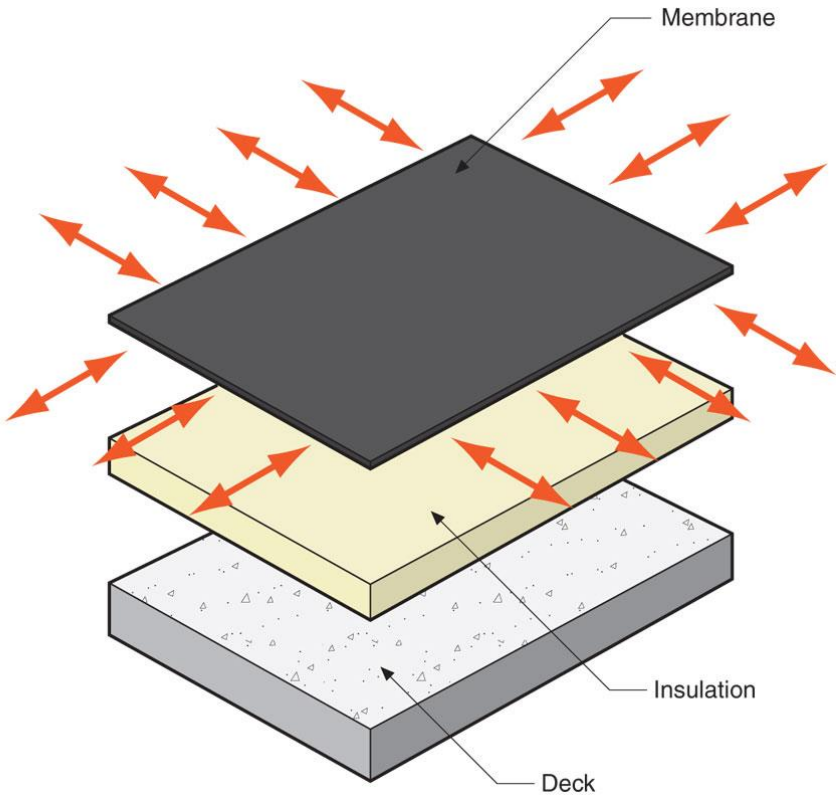
Outward sloping roof
blow-off hazard: high
slippage hazard: high

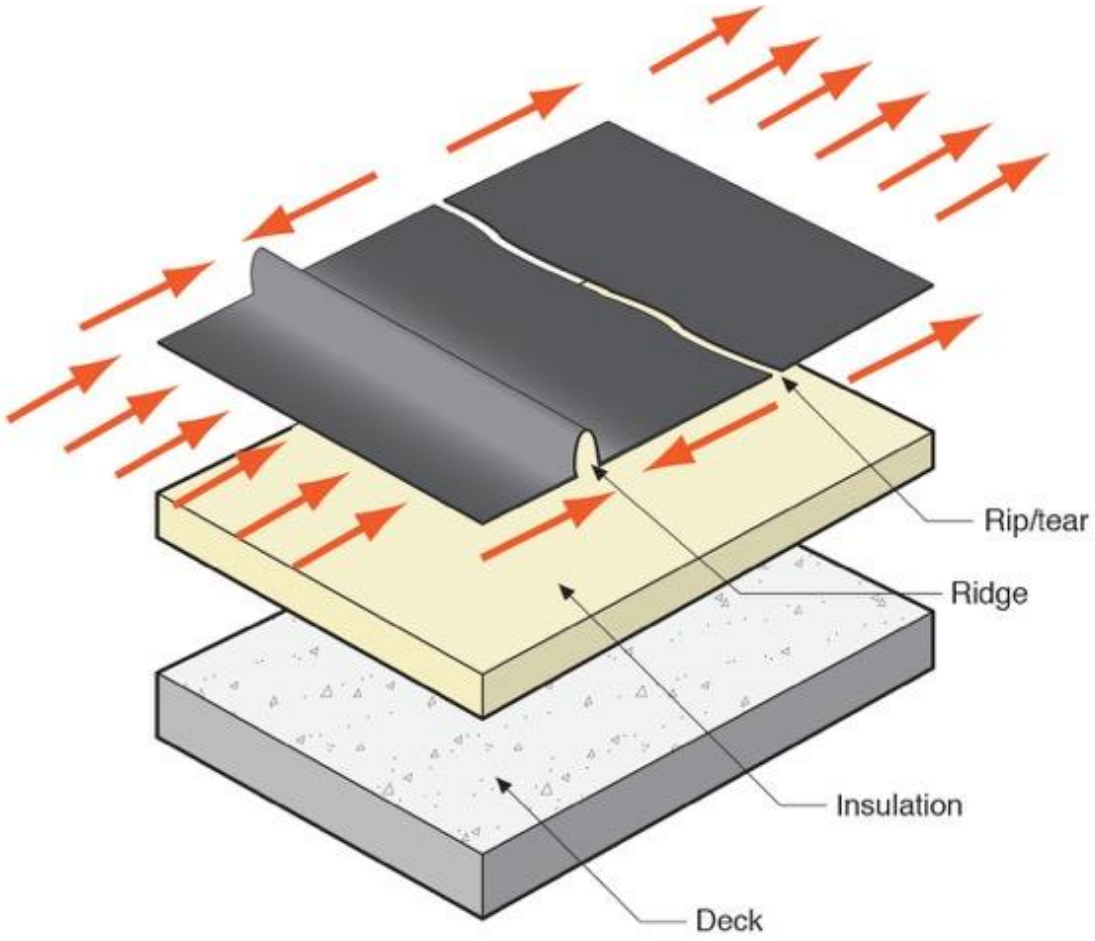
From Baker, M.; Roofs, 1980

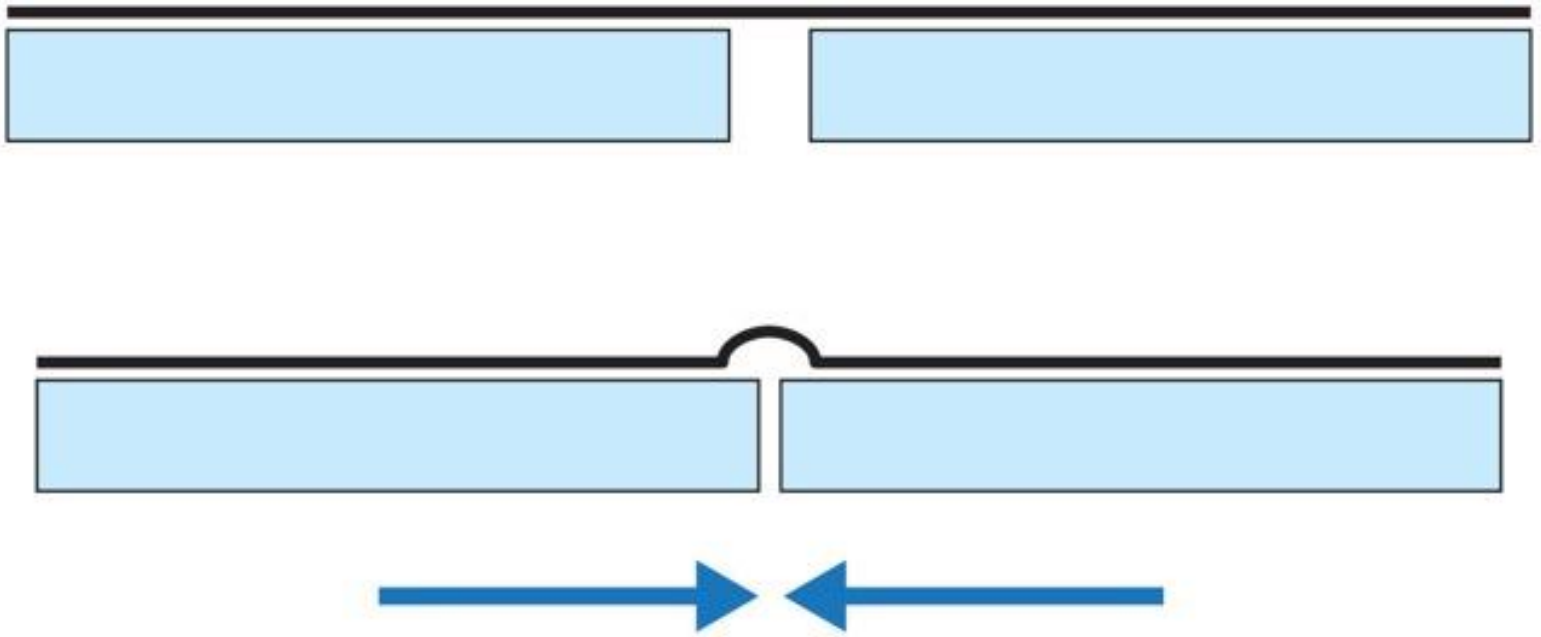

Gravel
Bitumen top pour
Felt
Bitumen
Felt
Bitumen
Bitumen saturated felt laid dry and nailed to deck
Dry sheathing or rosin paper nailed to deck
Wood deck
From Baker, M.; Roofs, 1980

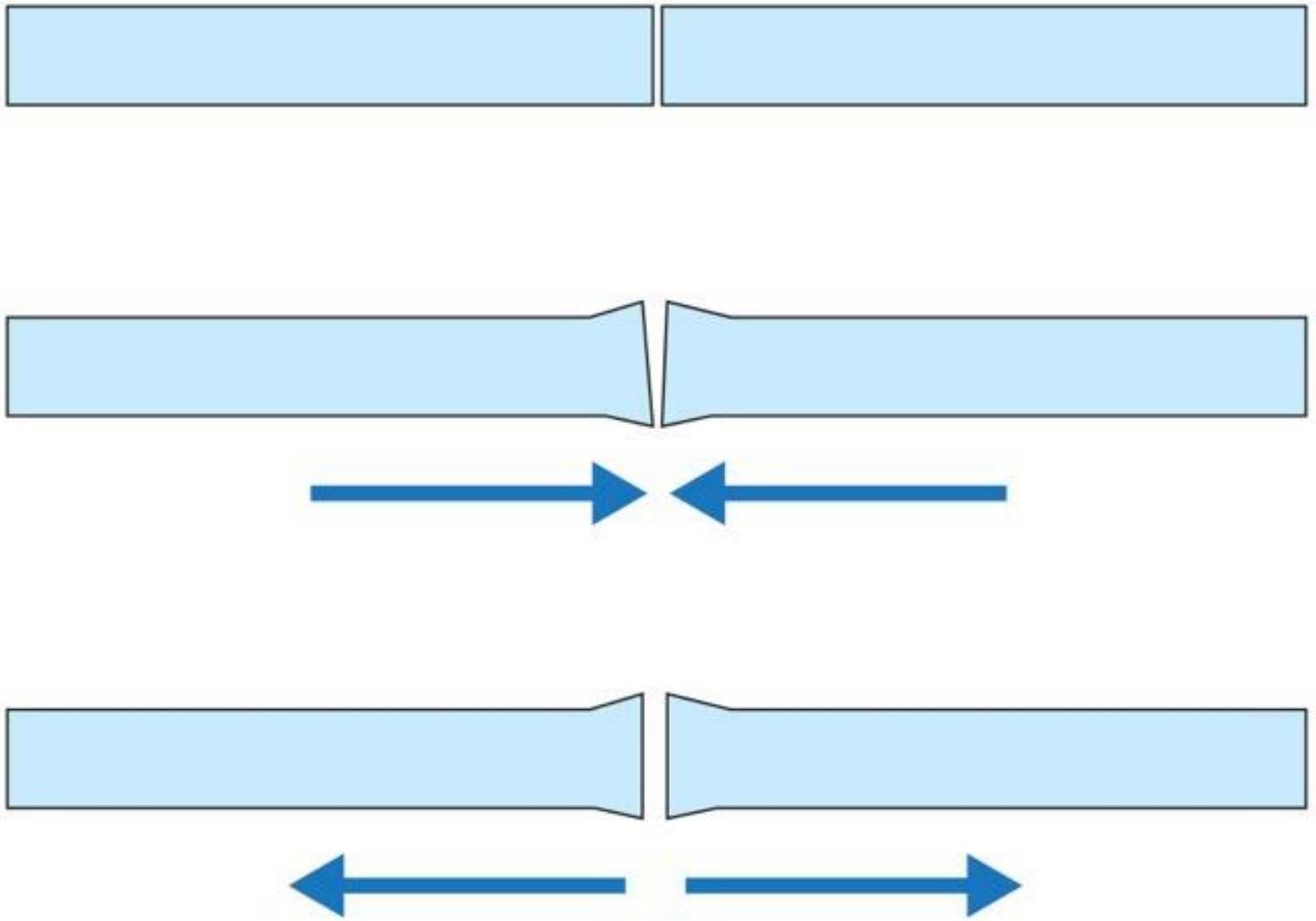

Gravel
Bitumen
Felt
Bitumen
Felt
Bitumen
Priming
Concrete deck
From Baker, M.; Roofs, 1980

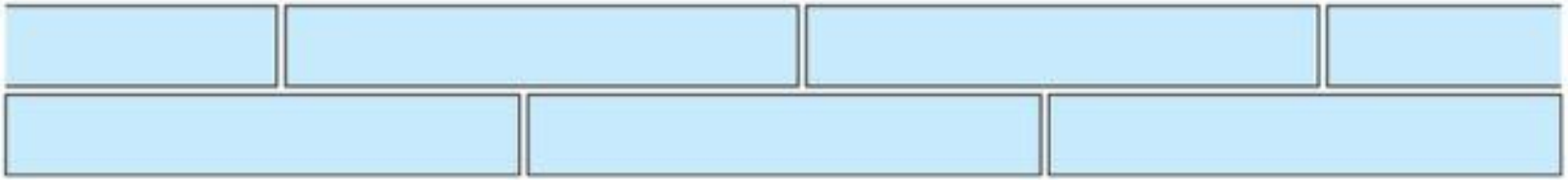

Membrane
Deck

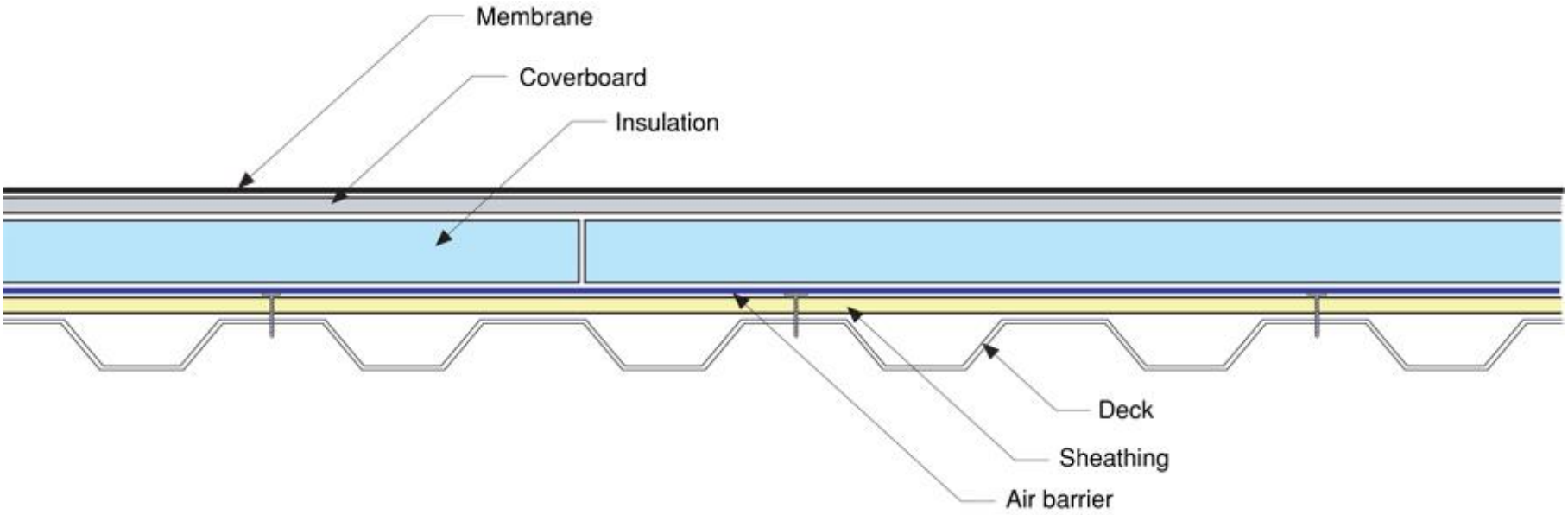

Membrane
Insulation
Deck

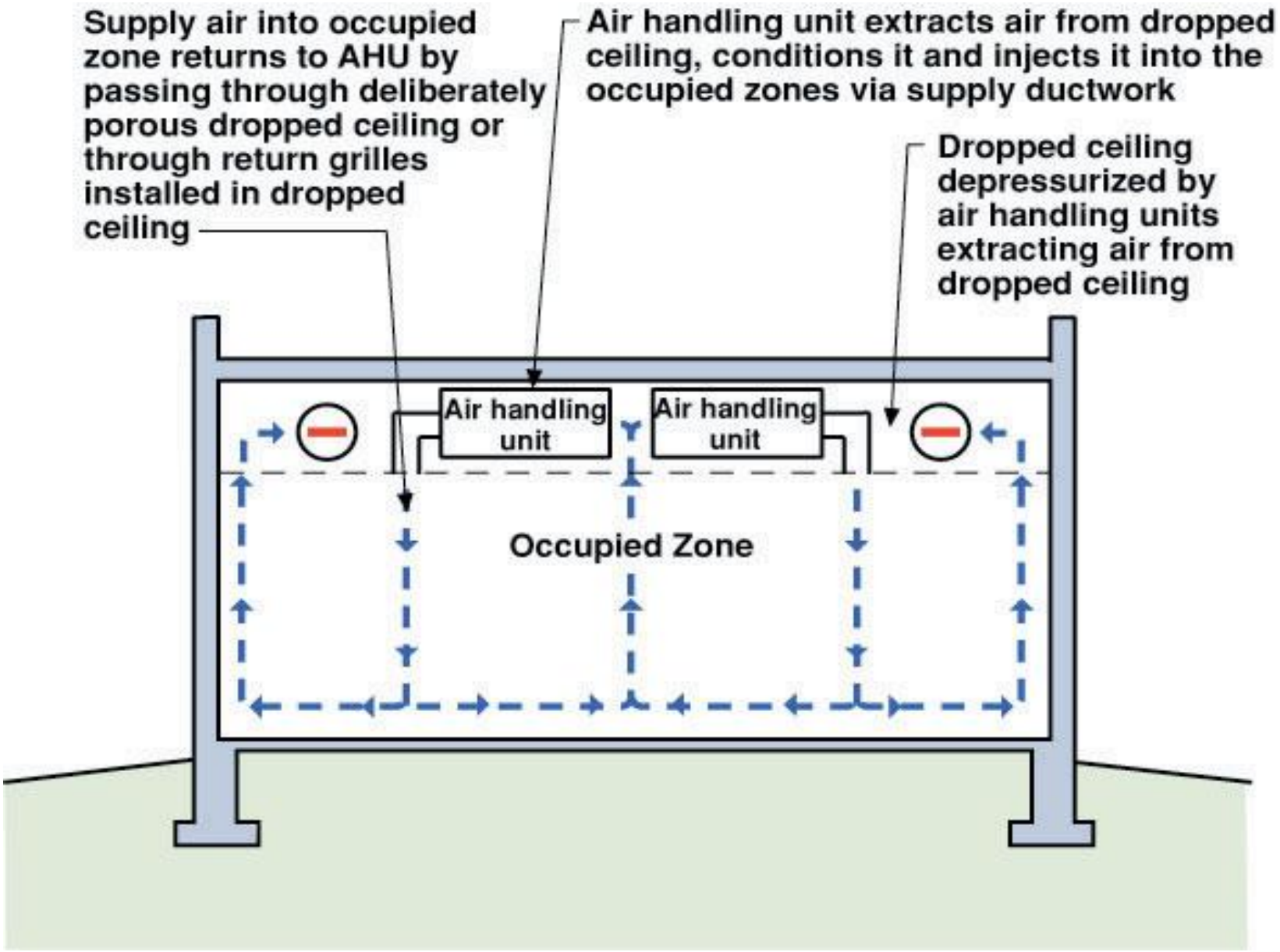

Rip/tear
Ridge
Insulation
Deck

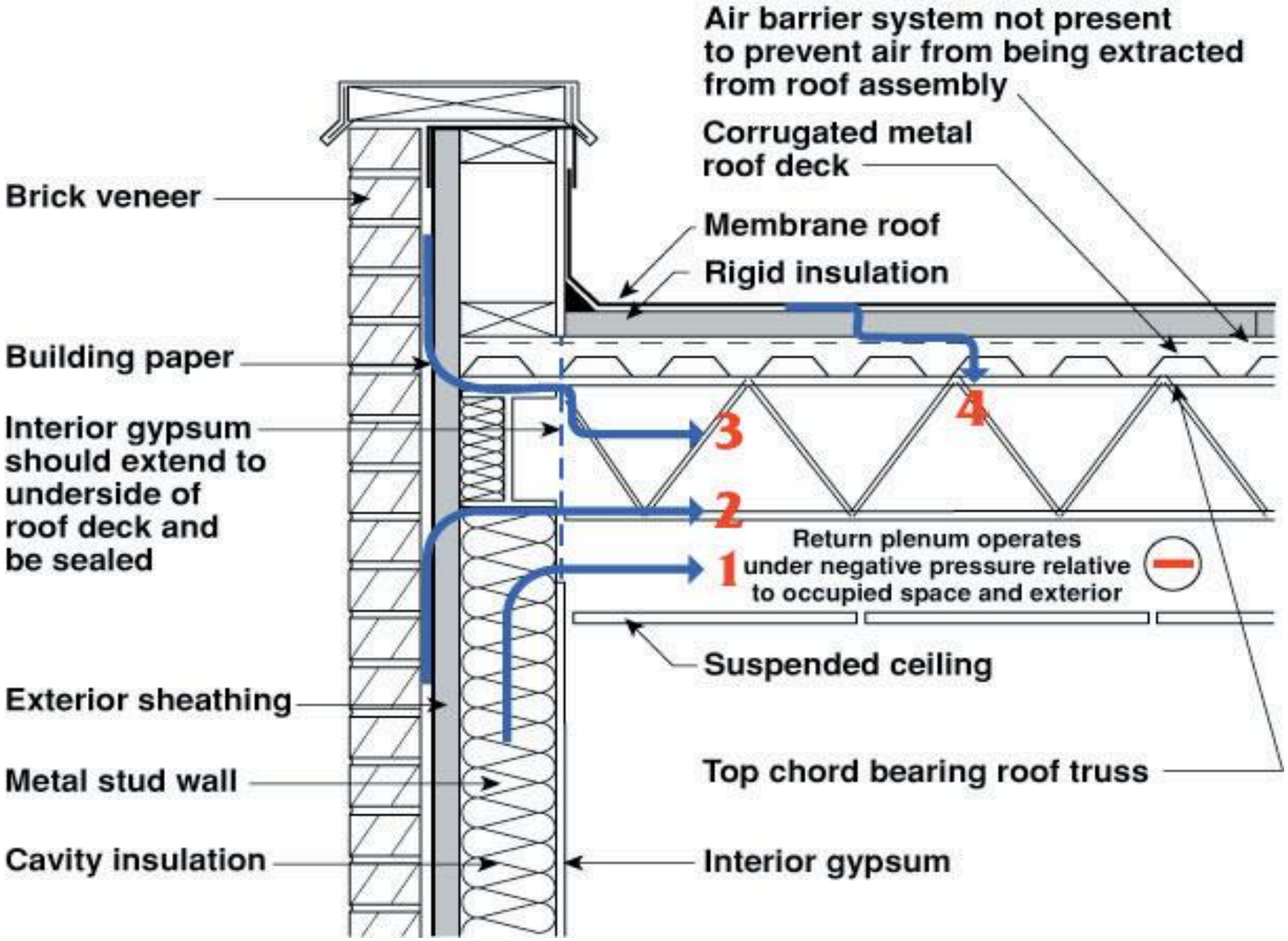


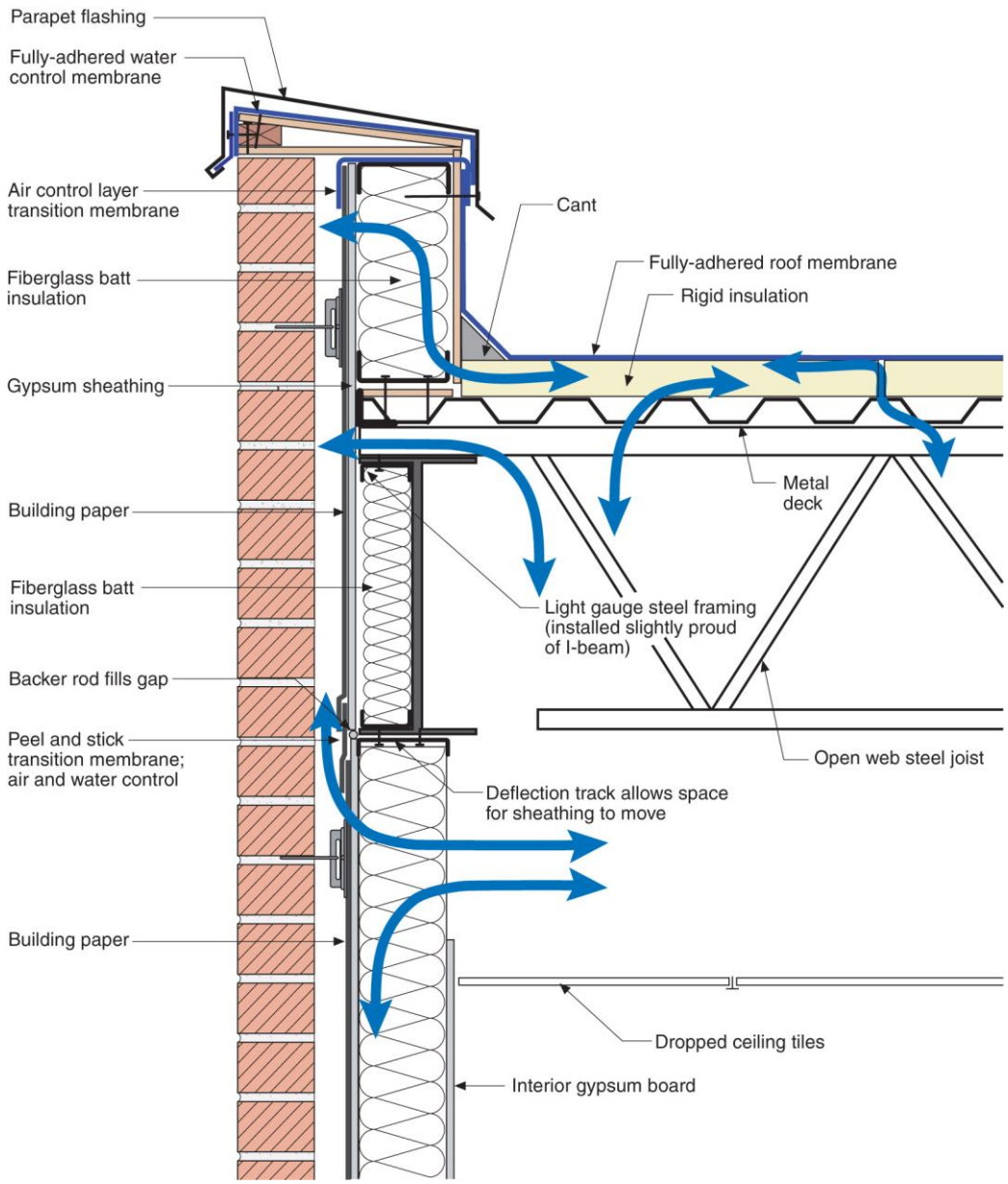


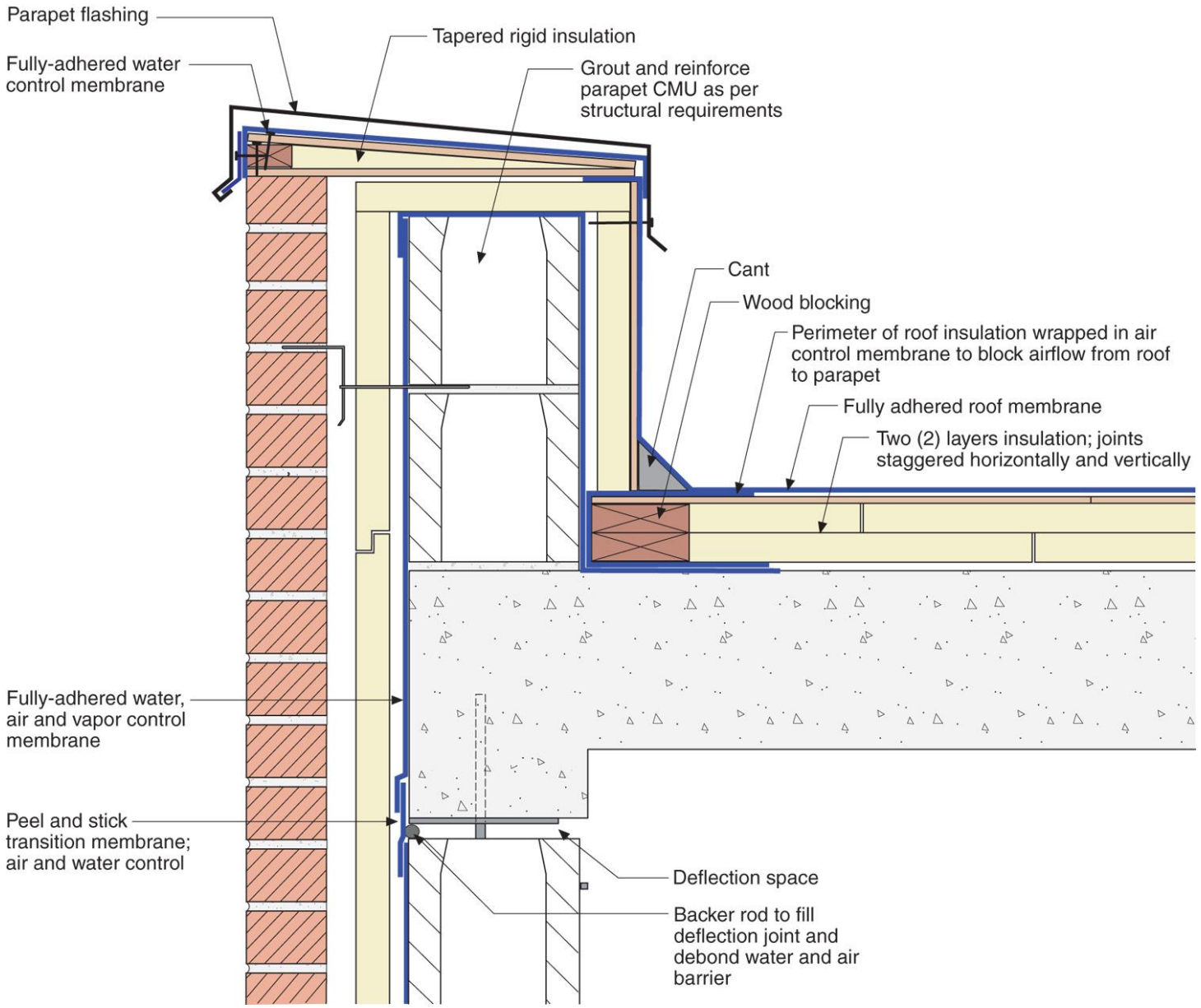


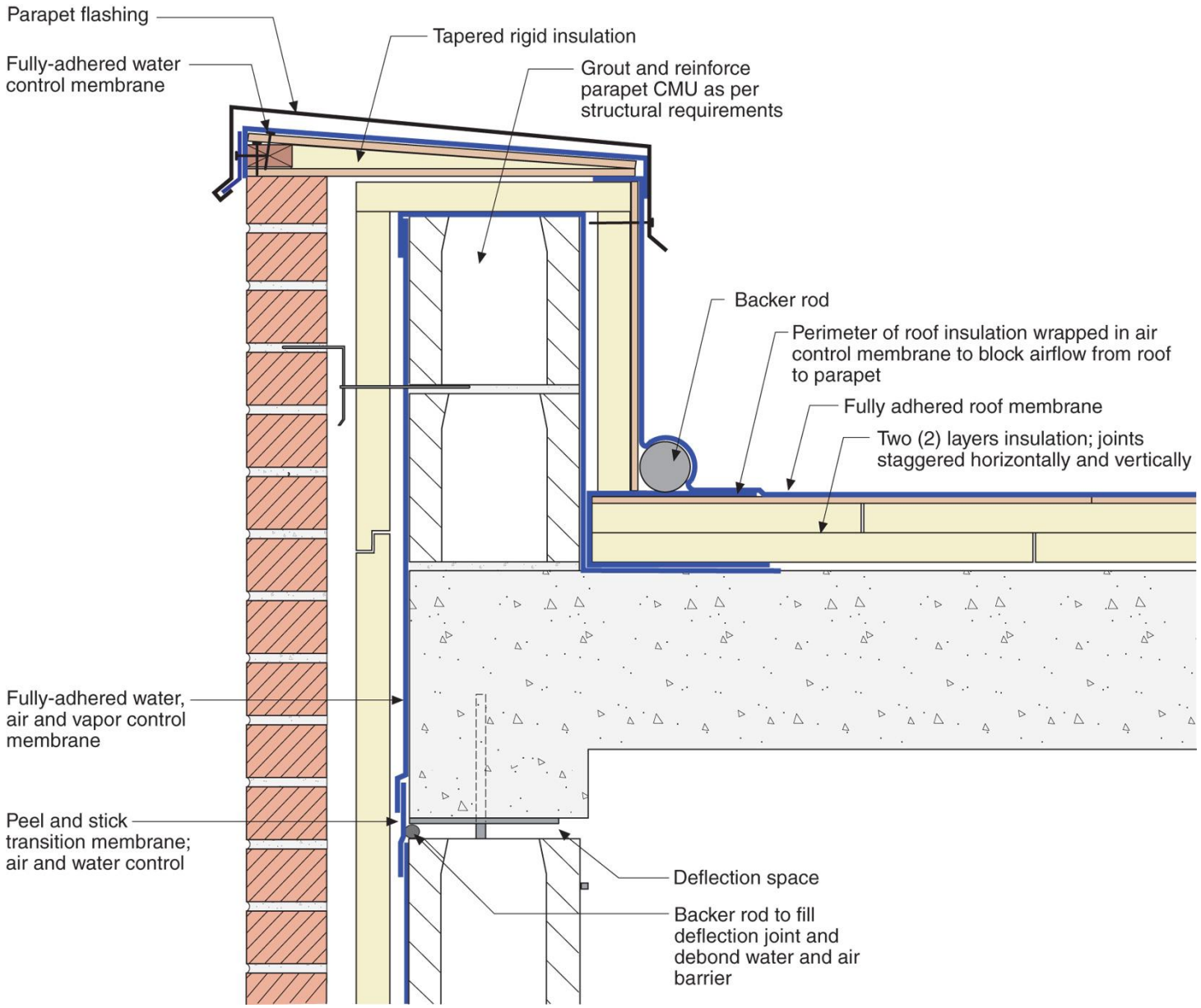

Membrane
Coverboard
Insulation
Deck
Sheathing
Air barrier


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
Top chord bearing roof truss
Metal stud wall
Cavity insulation
Interior gypsum


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
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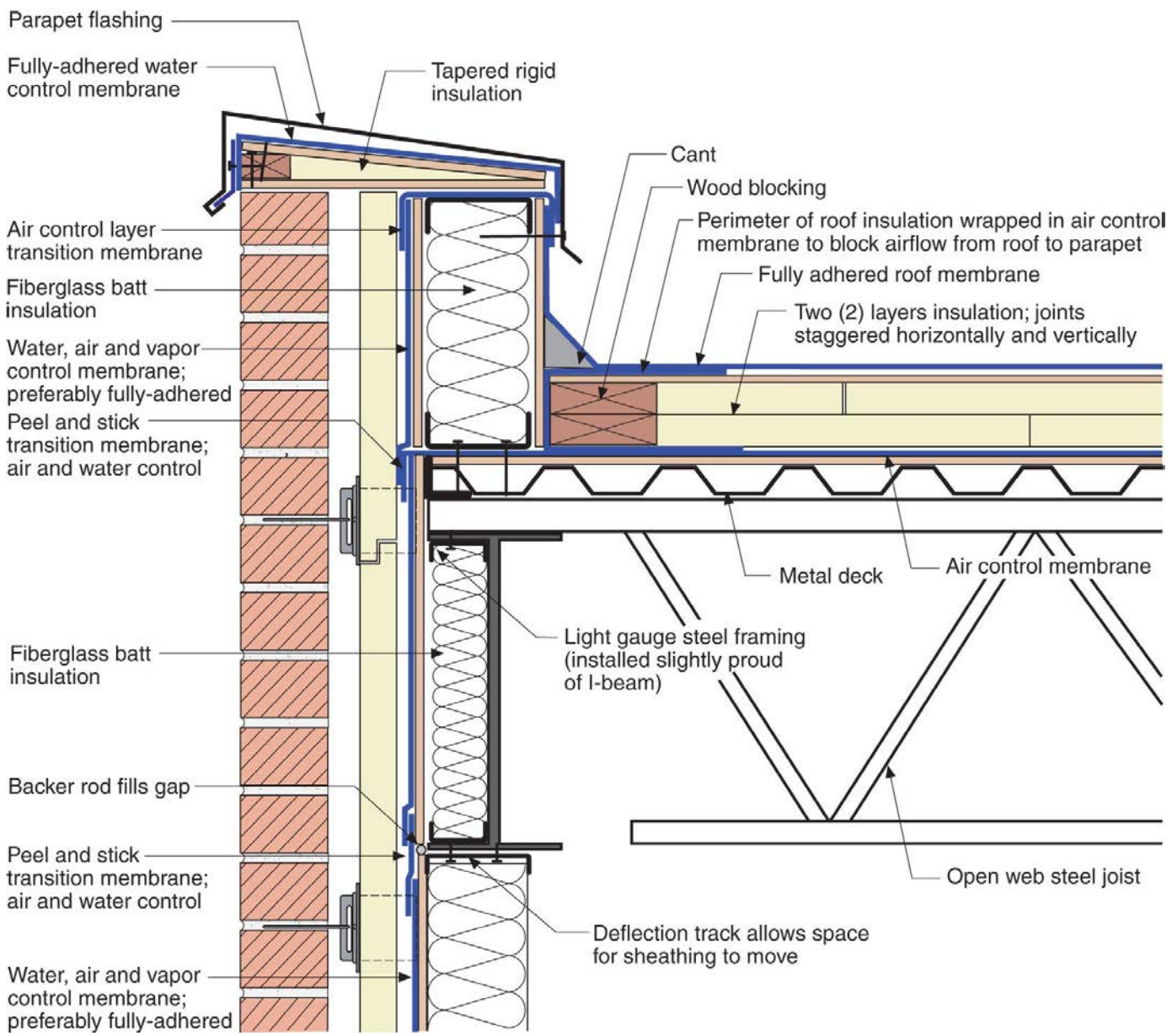
Deflection space
Backer rod to fill deflection joint and debond water and air barrier


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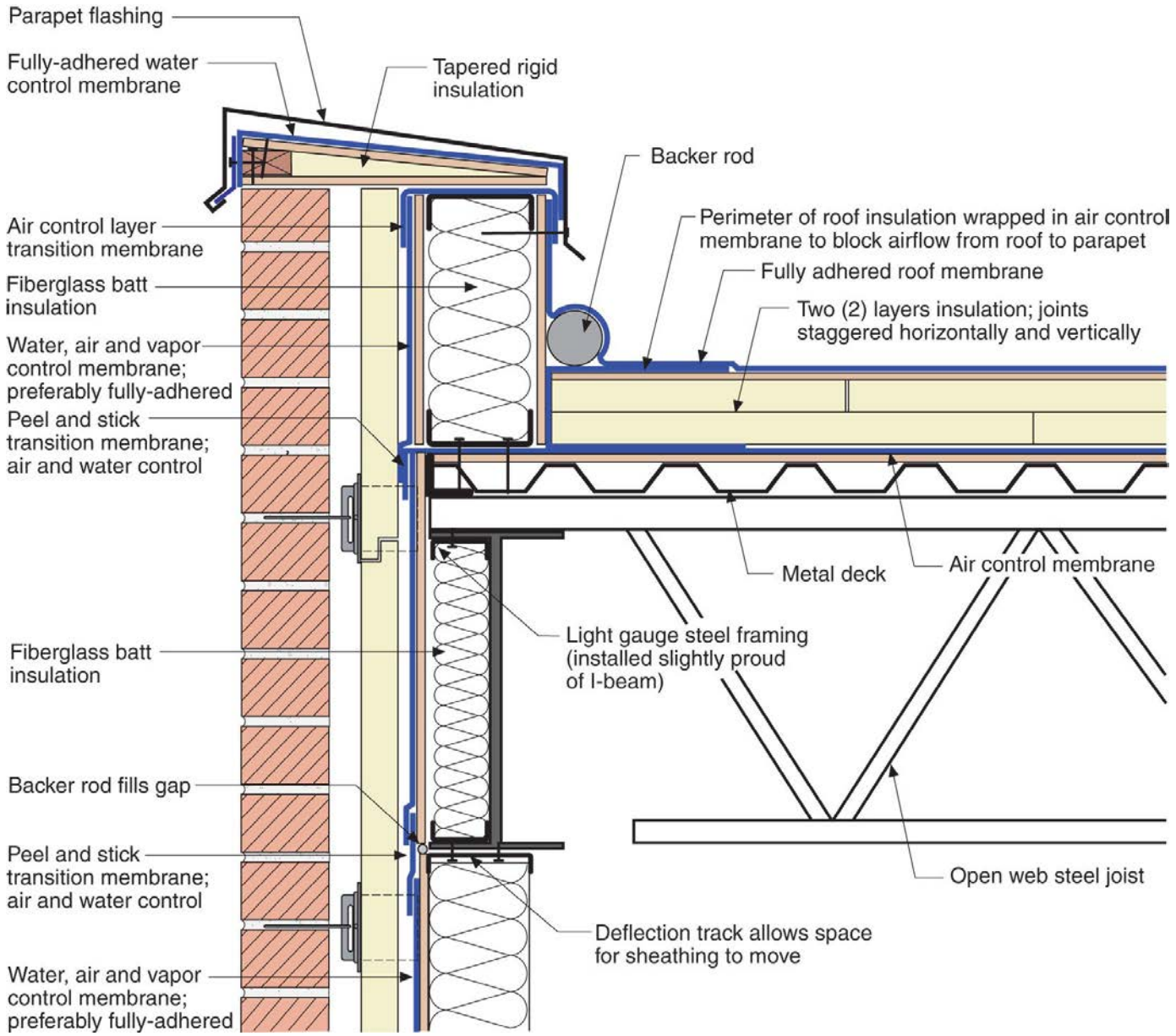
Tapered rigid insulation
Cant
Wood blocking
Perimeter of roof insulation wrapped in air control membrane to block airflow from roof to parapet
Fully adhered roof membrane
Two (2) layers insulation; joints staggered horizontally and vertically
Air control layer transition membrane
Fiberglass batt insulation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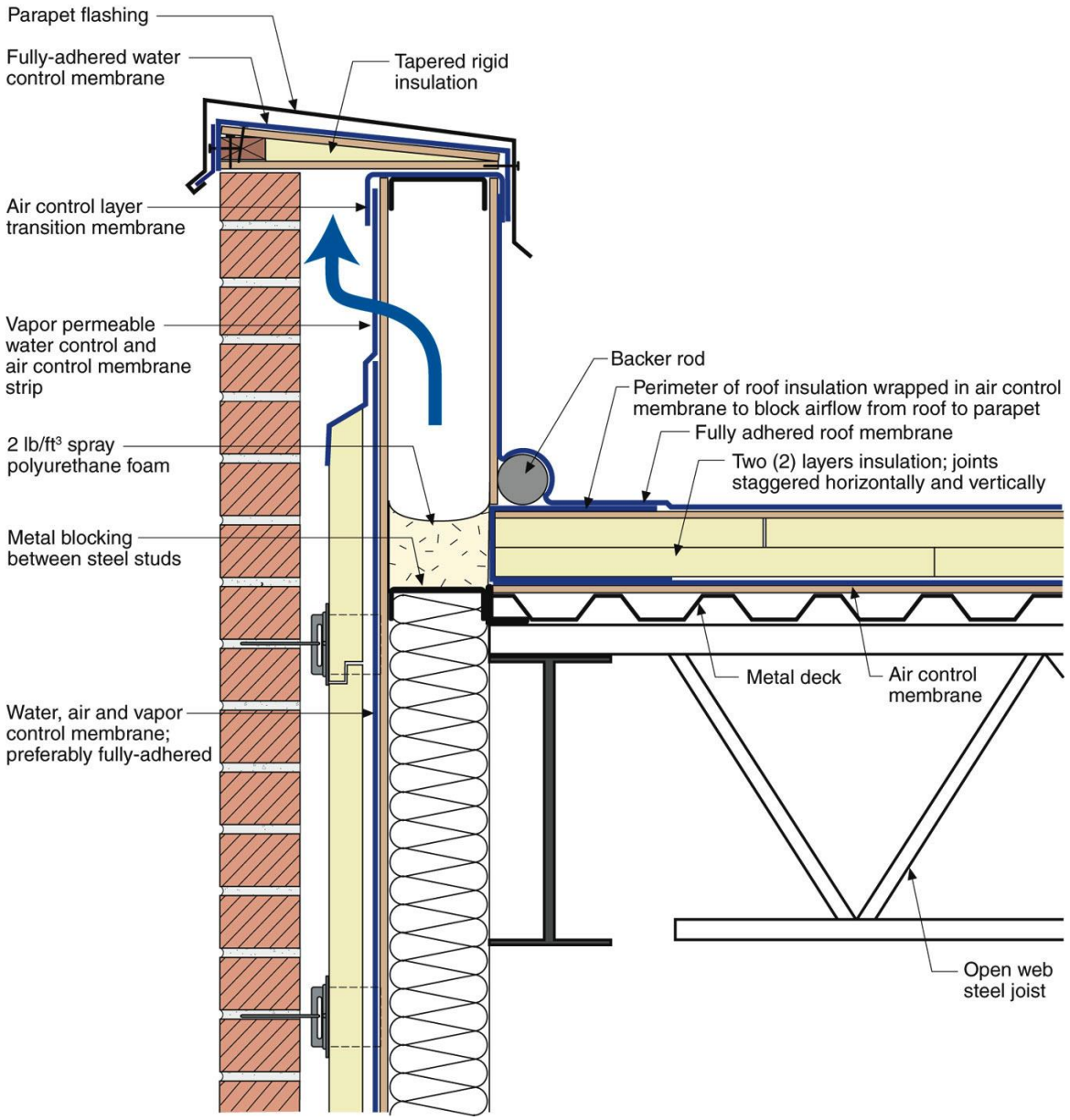
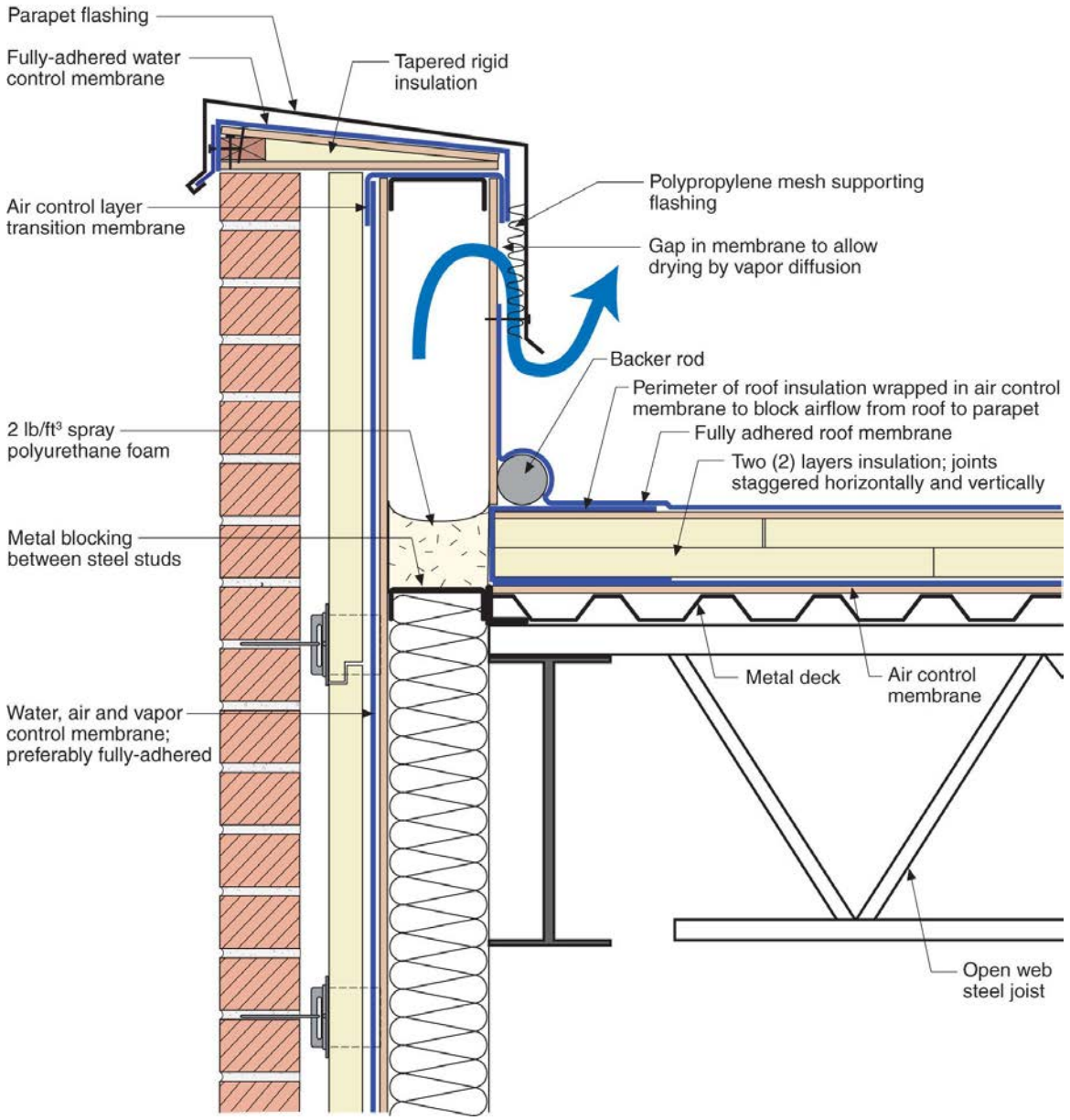
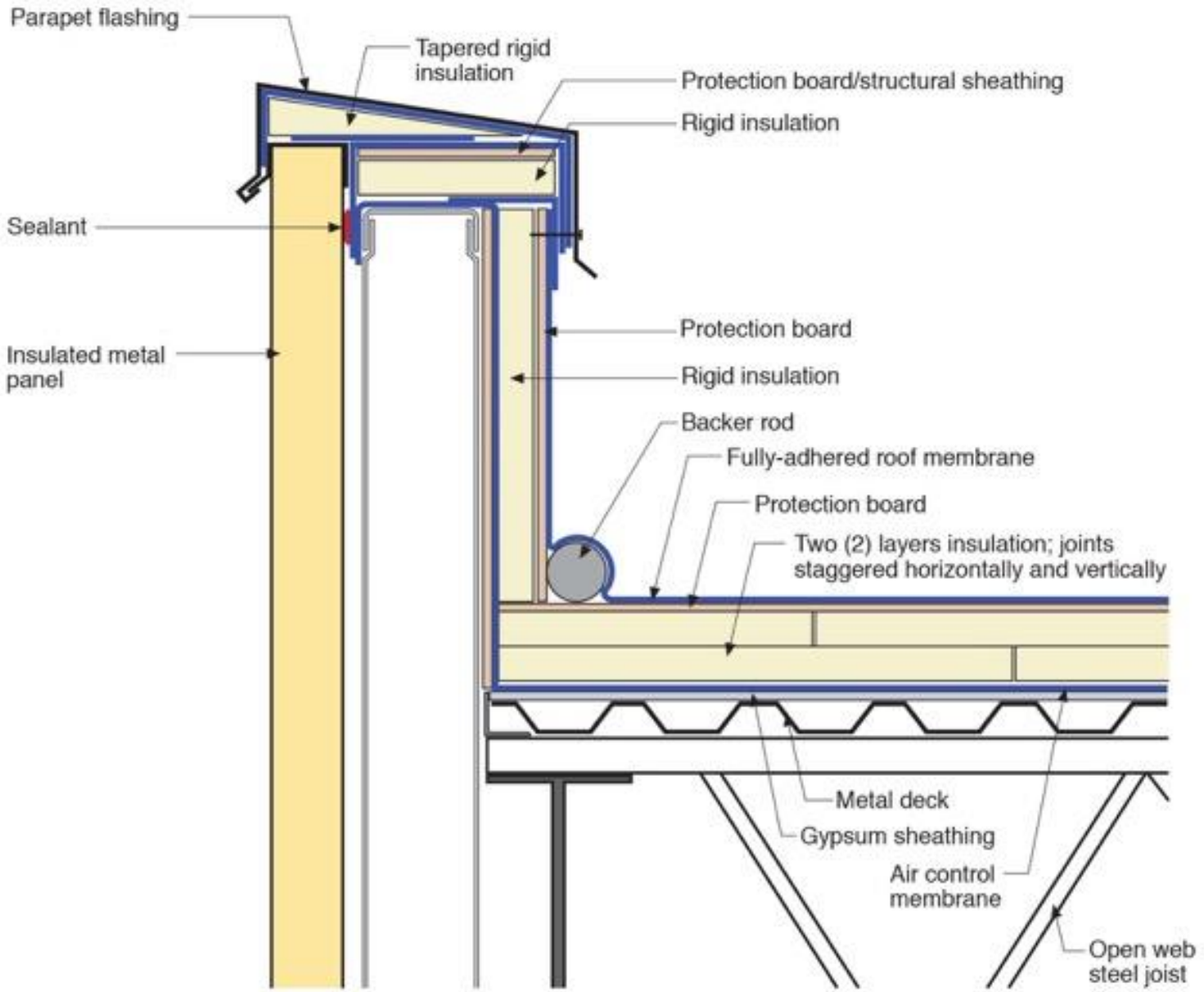
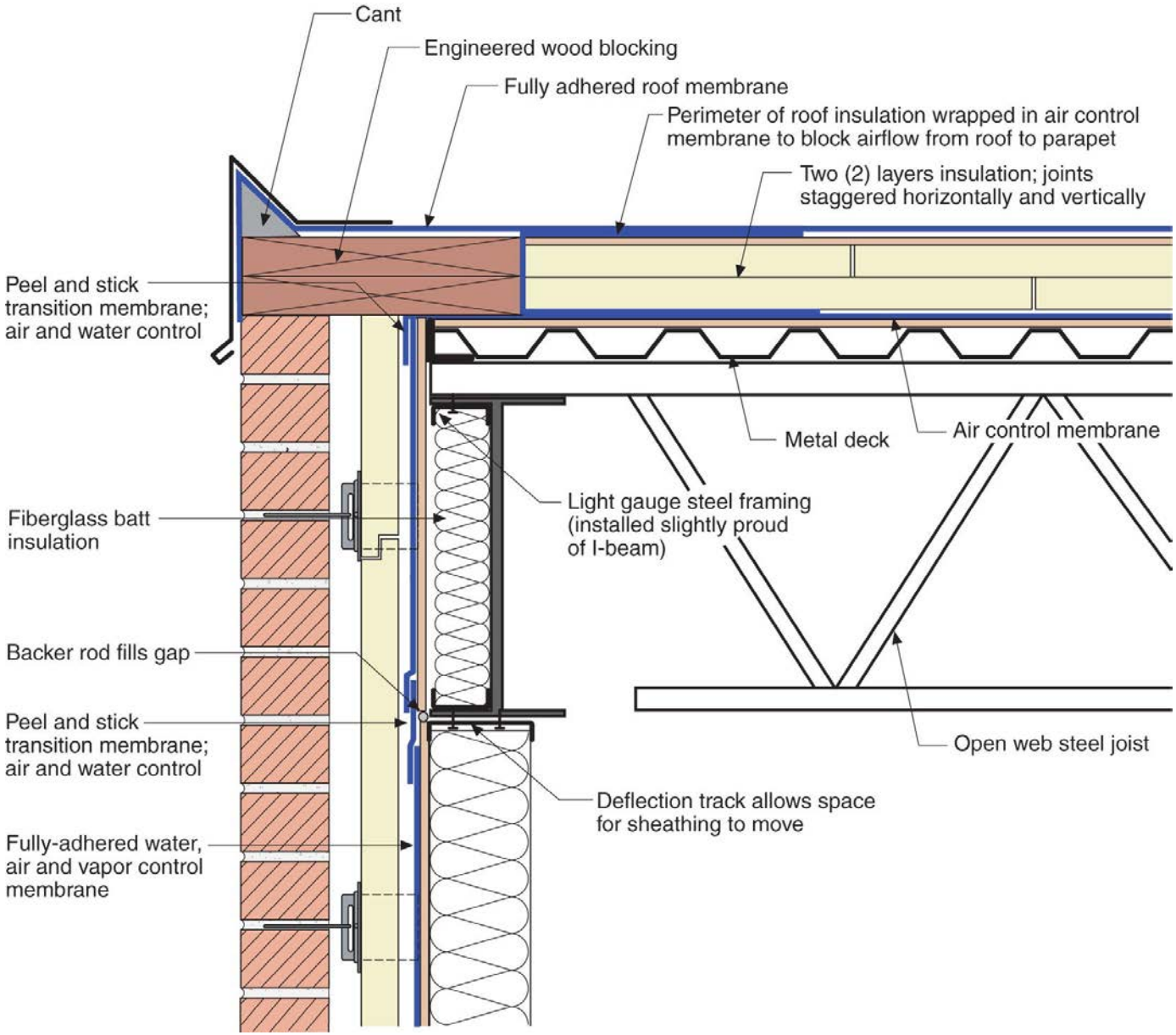
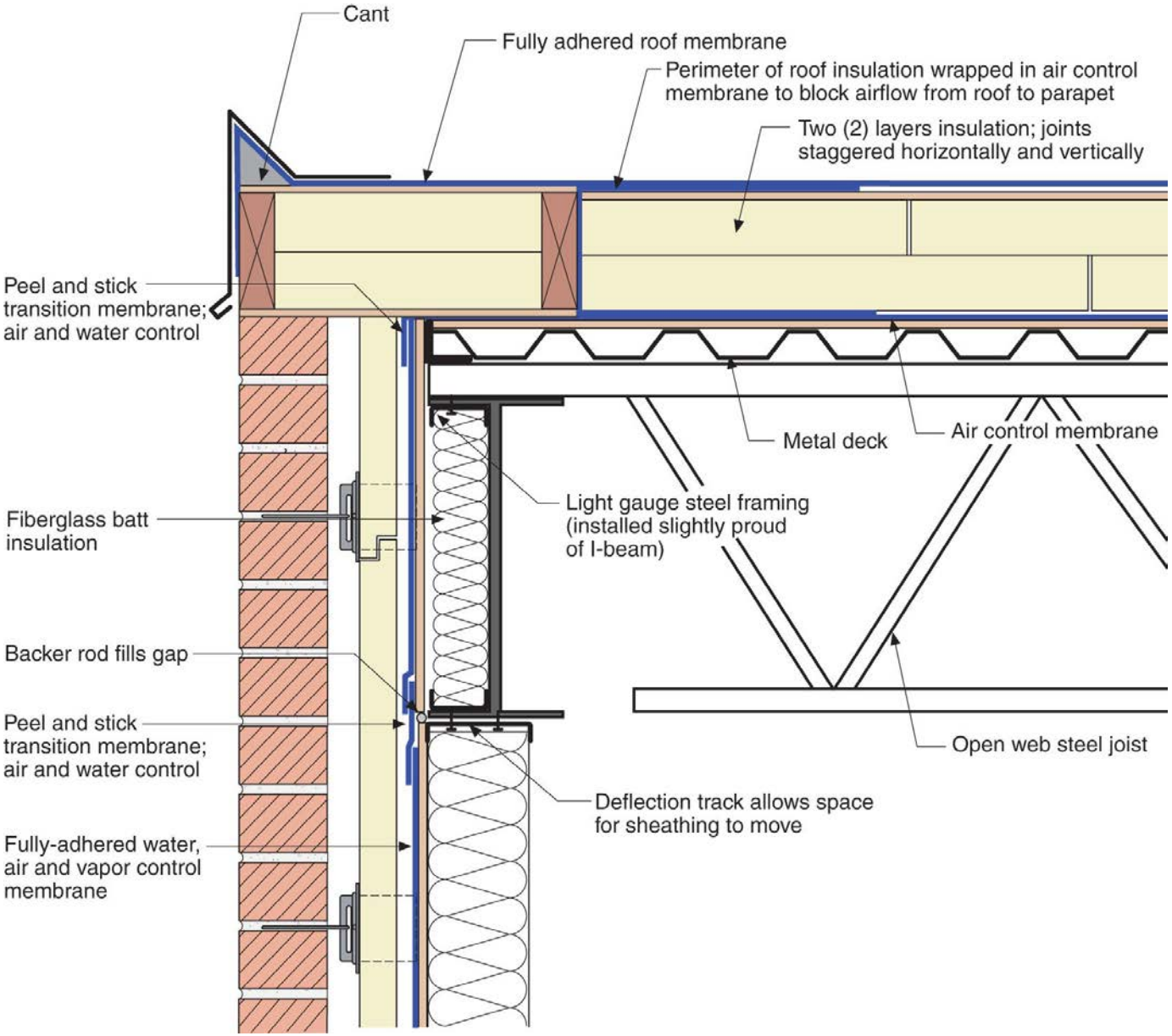
Metal deck
Air control membrane
Light gauge steel framing (installed slightly proud of I-beam)
Fiberglass batt insulation
Backer rod fills gap
Peel and stick transition membrane; air and water control
Open web steel joist
Deflection track allows space for sheathing to move
Water, air and vapor control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

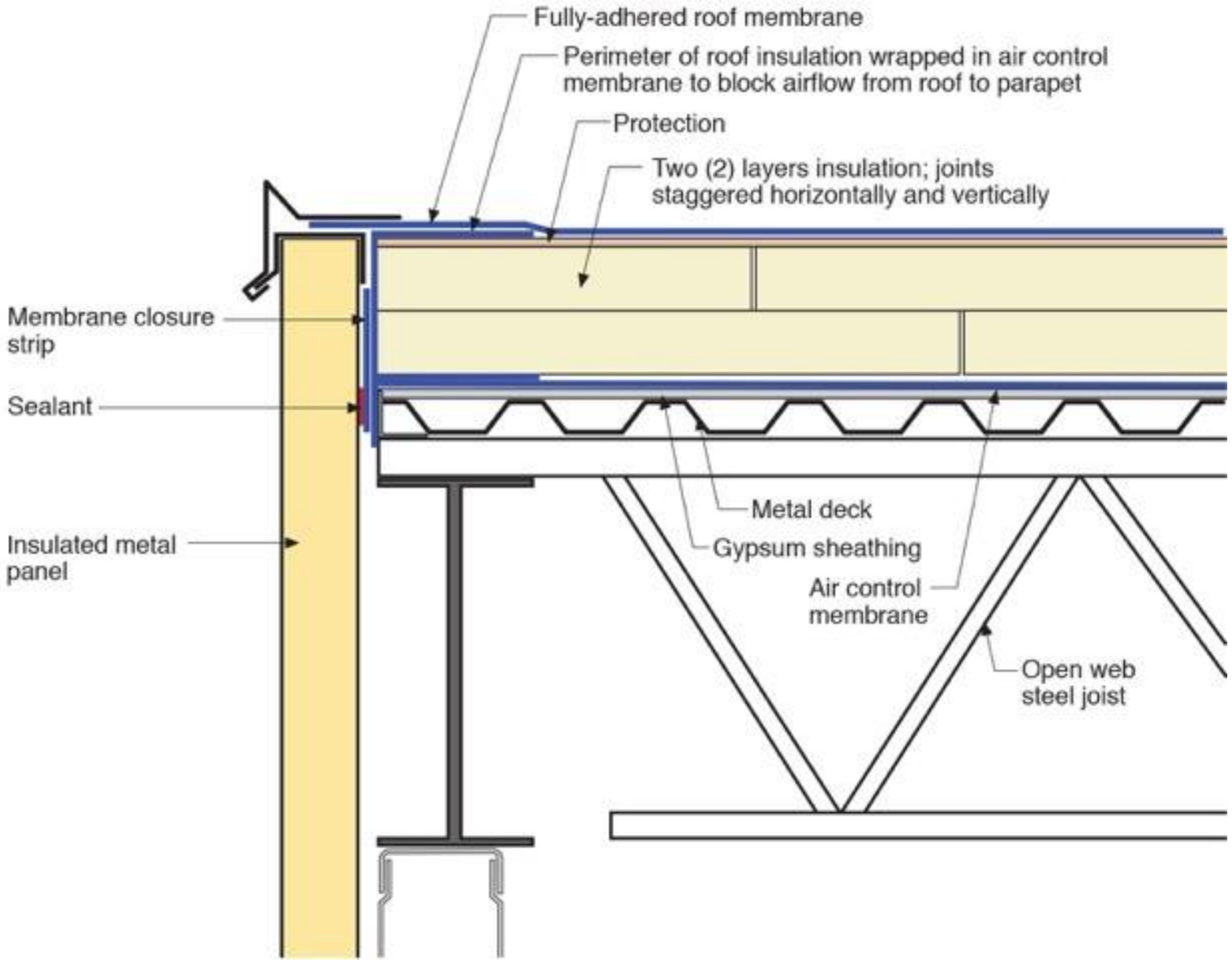

Parapet flashing
Fully-adhered water control membrane
Tapered rigid insulation
Air control layer transition membrane
Vapor permeable water control and air control membrane strip
2 lb/ft³ spray polyurethane foam
Metal blocking between steel studs
Water, air and vapor control membrane; preferably fully-adhered
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
2 lb/ft³ spray polyurethane foam
Fully adhered roof membrane
Two (2) layers insulation; joints staggered horizontally and vertically
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


Cant
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


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

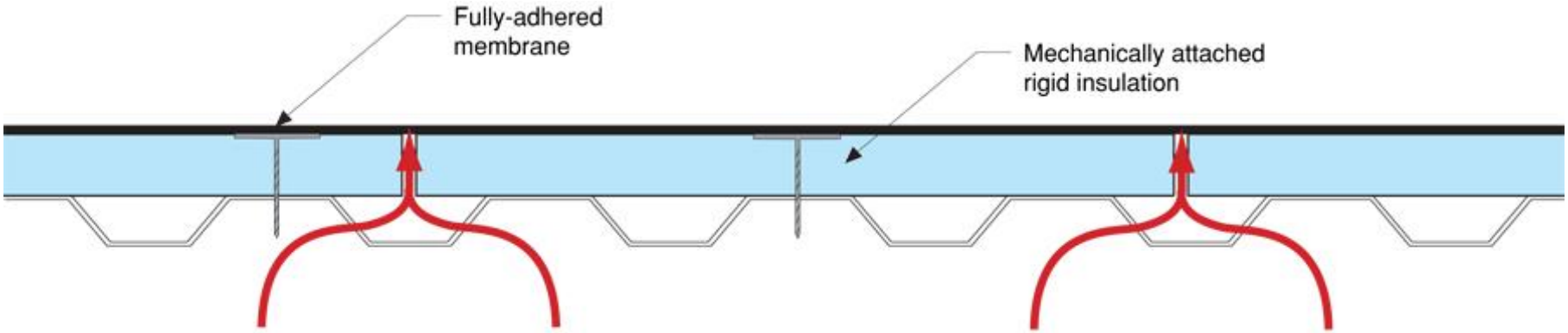
It’s a Case of Black or White

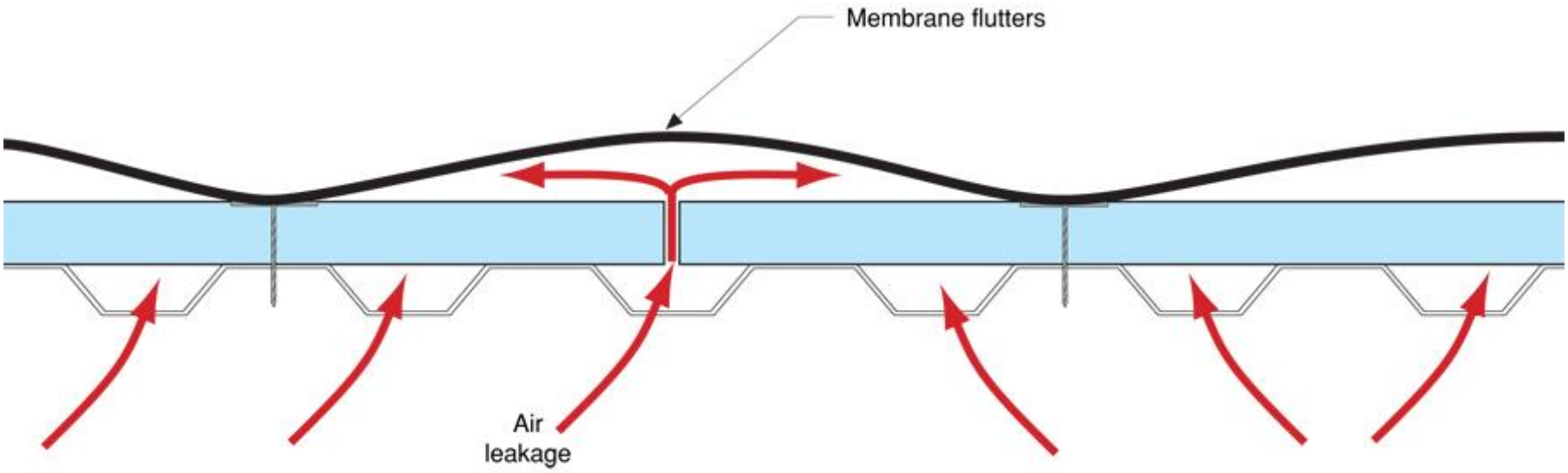
Arrhenius

It’s a Case of Black or White

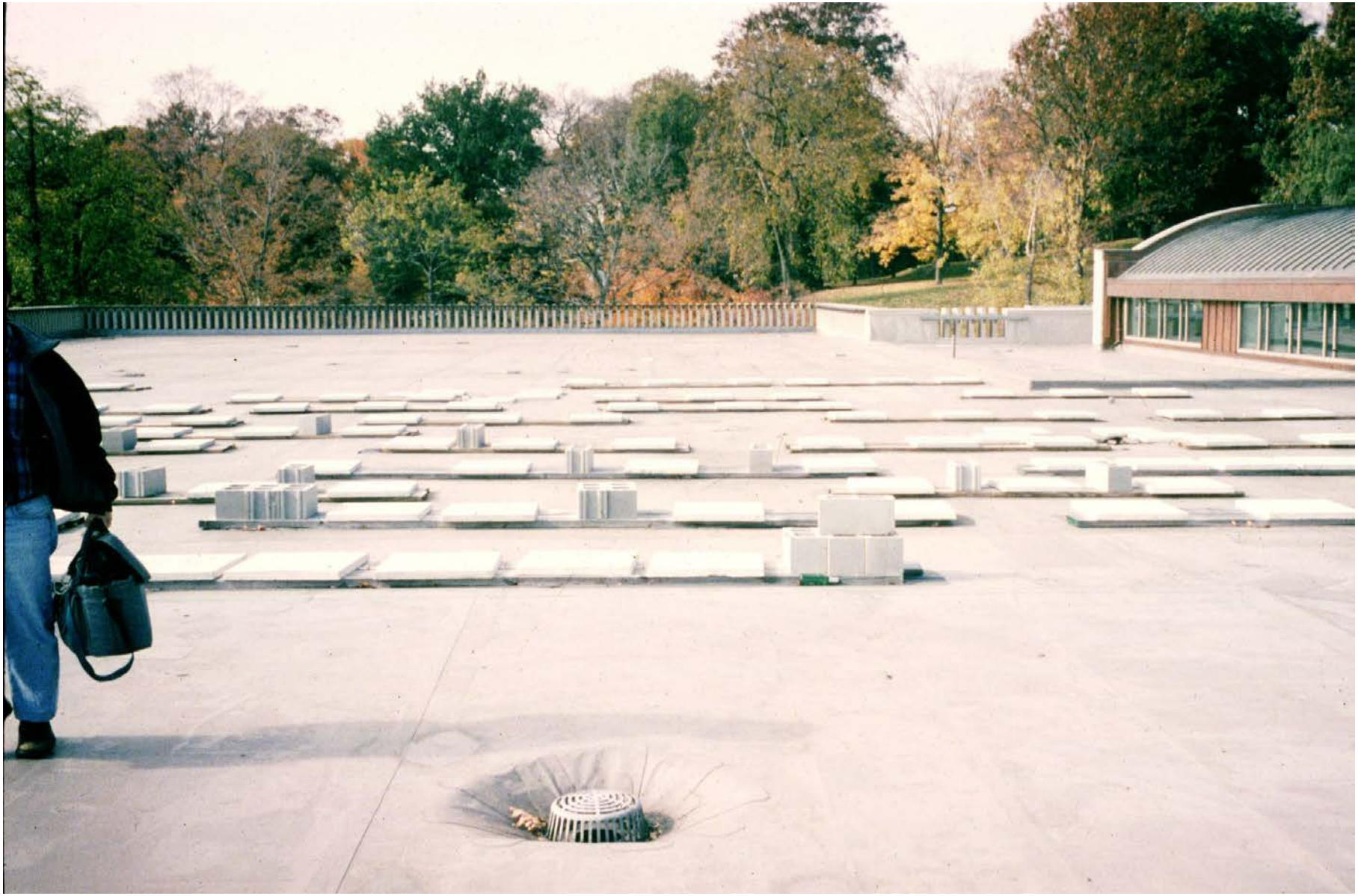
Arrhenius

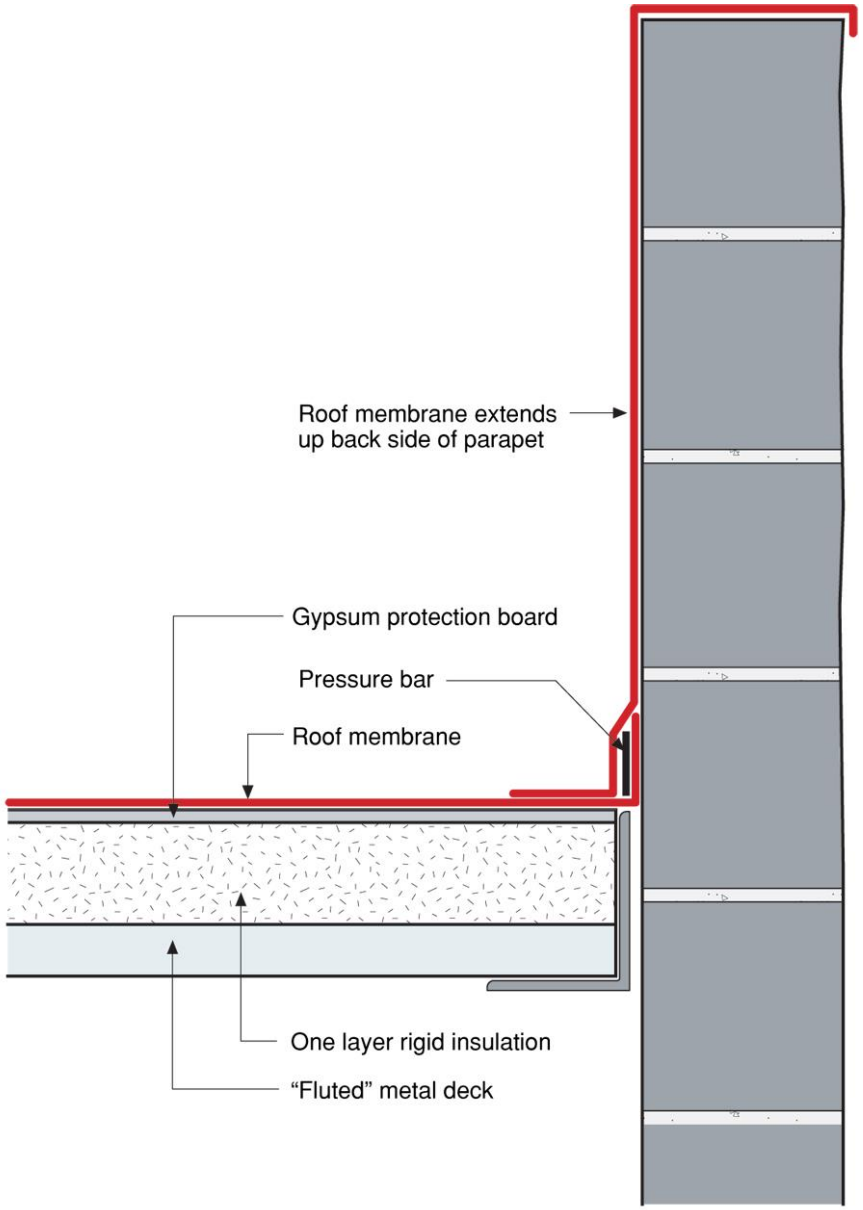
Every 10 degrees C – double the “badness”

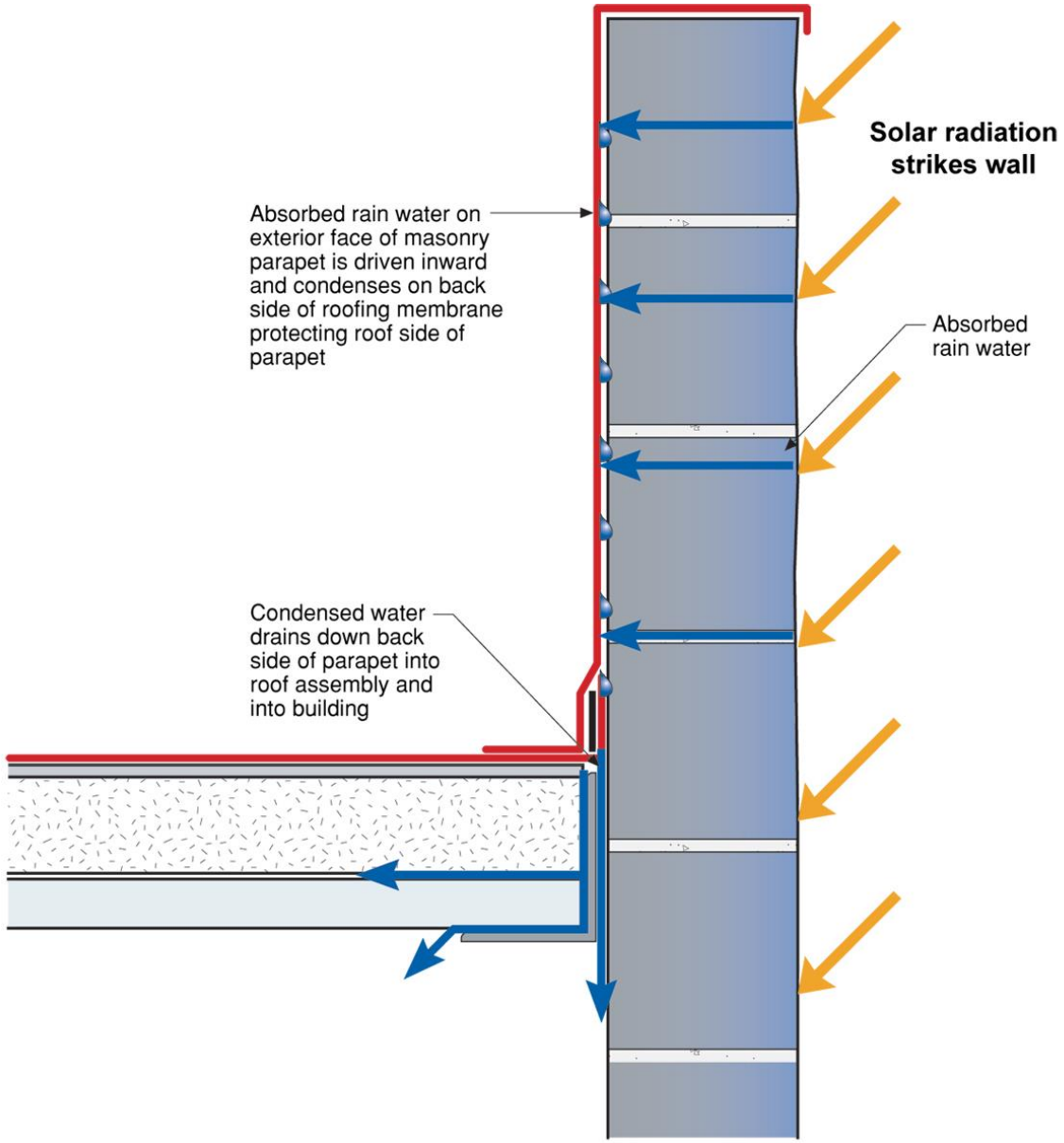

Fully-adhered
membrane
Mechanically attached
rigid insulation

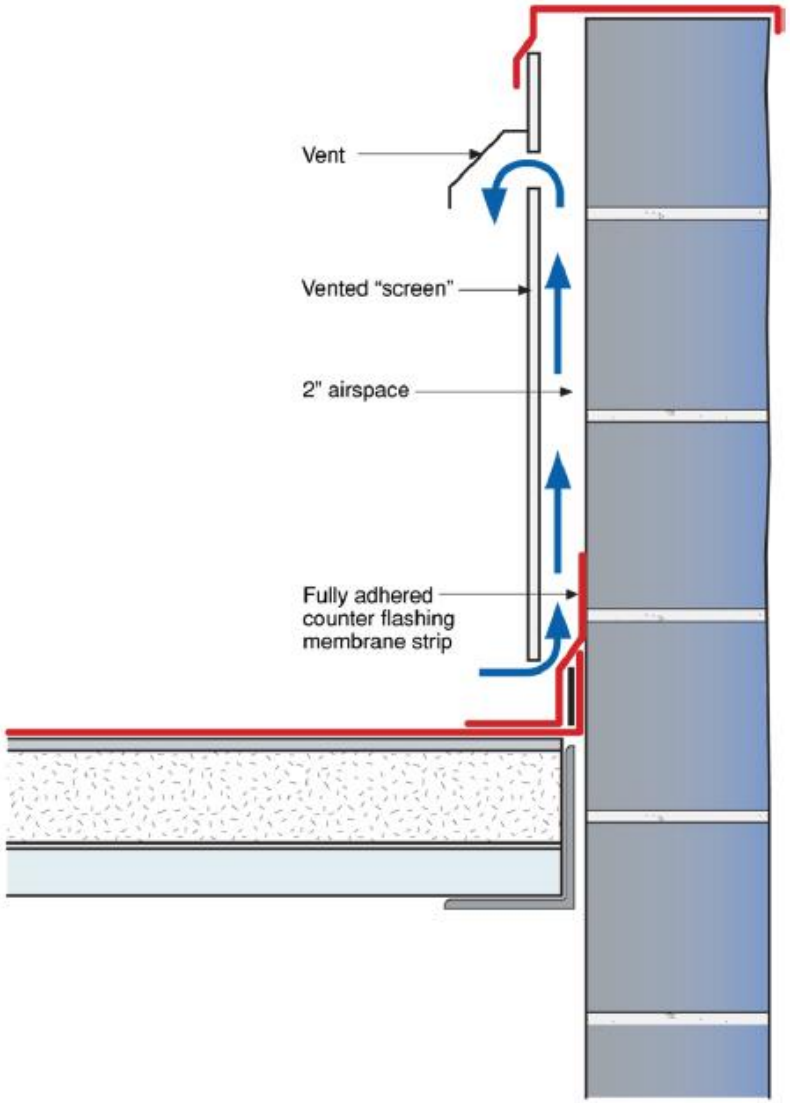

Membrane flutters
Air
leakage

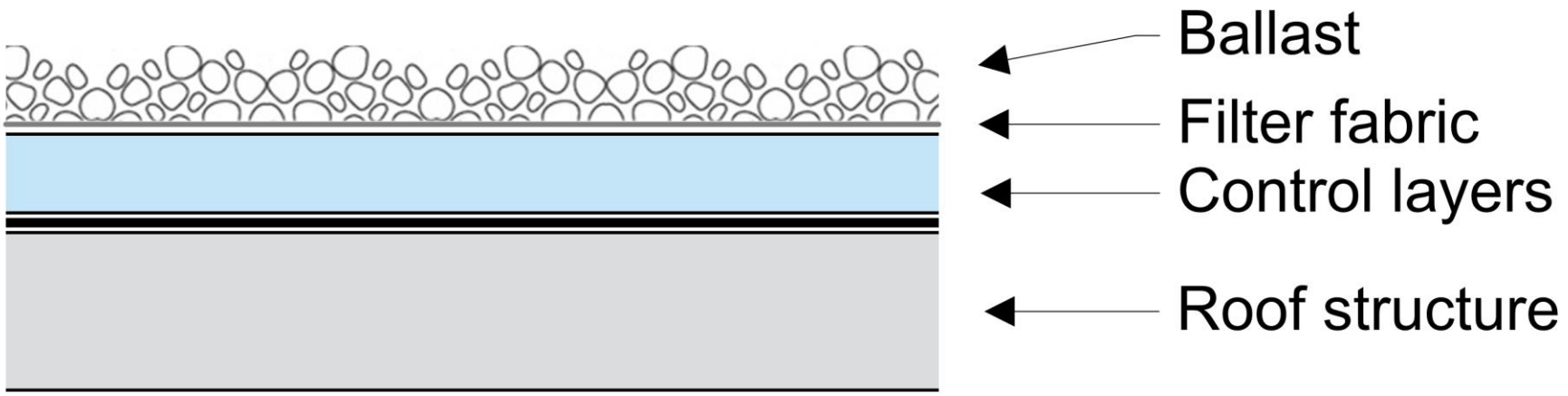

THE TISCH LIBRARY

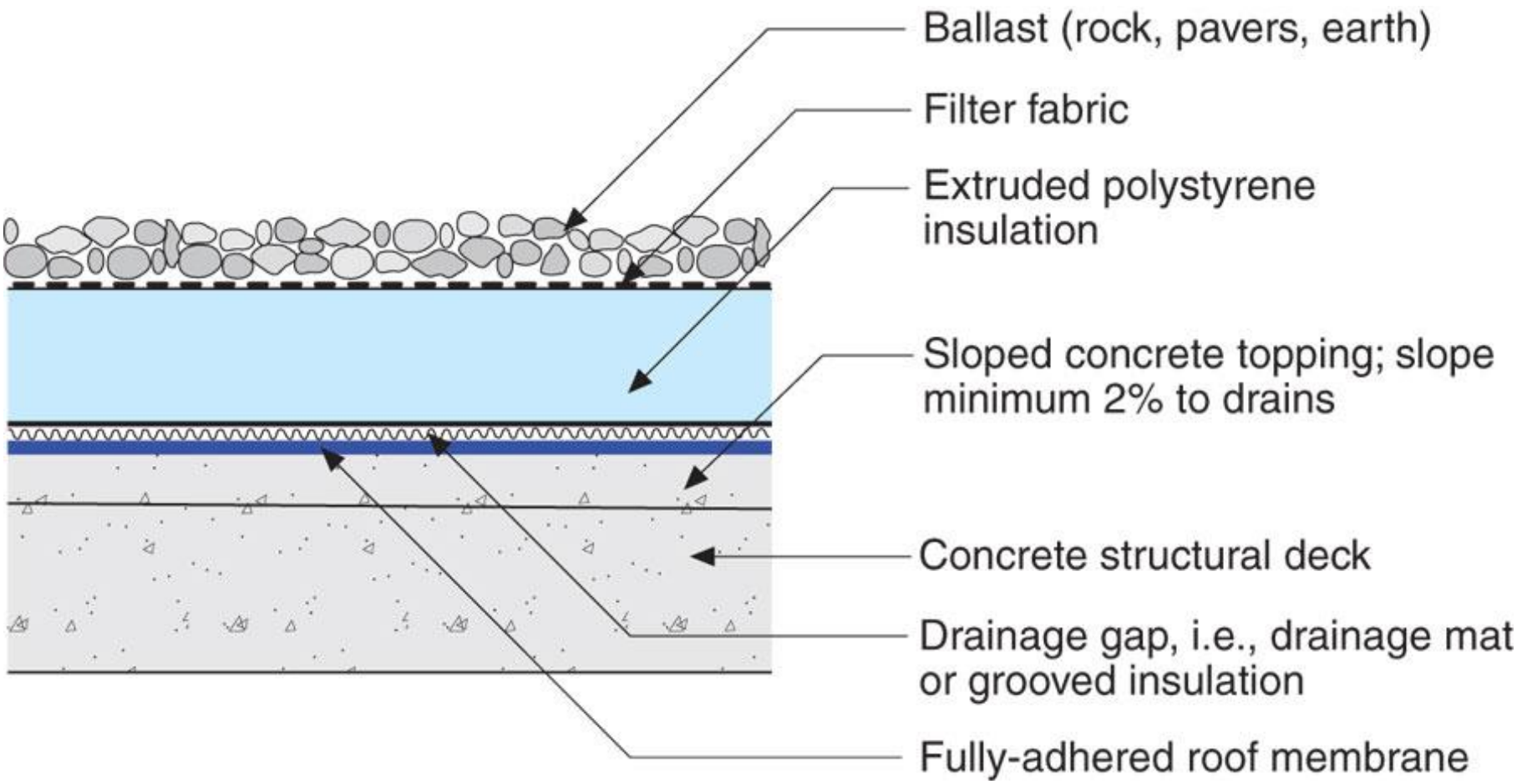


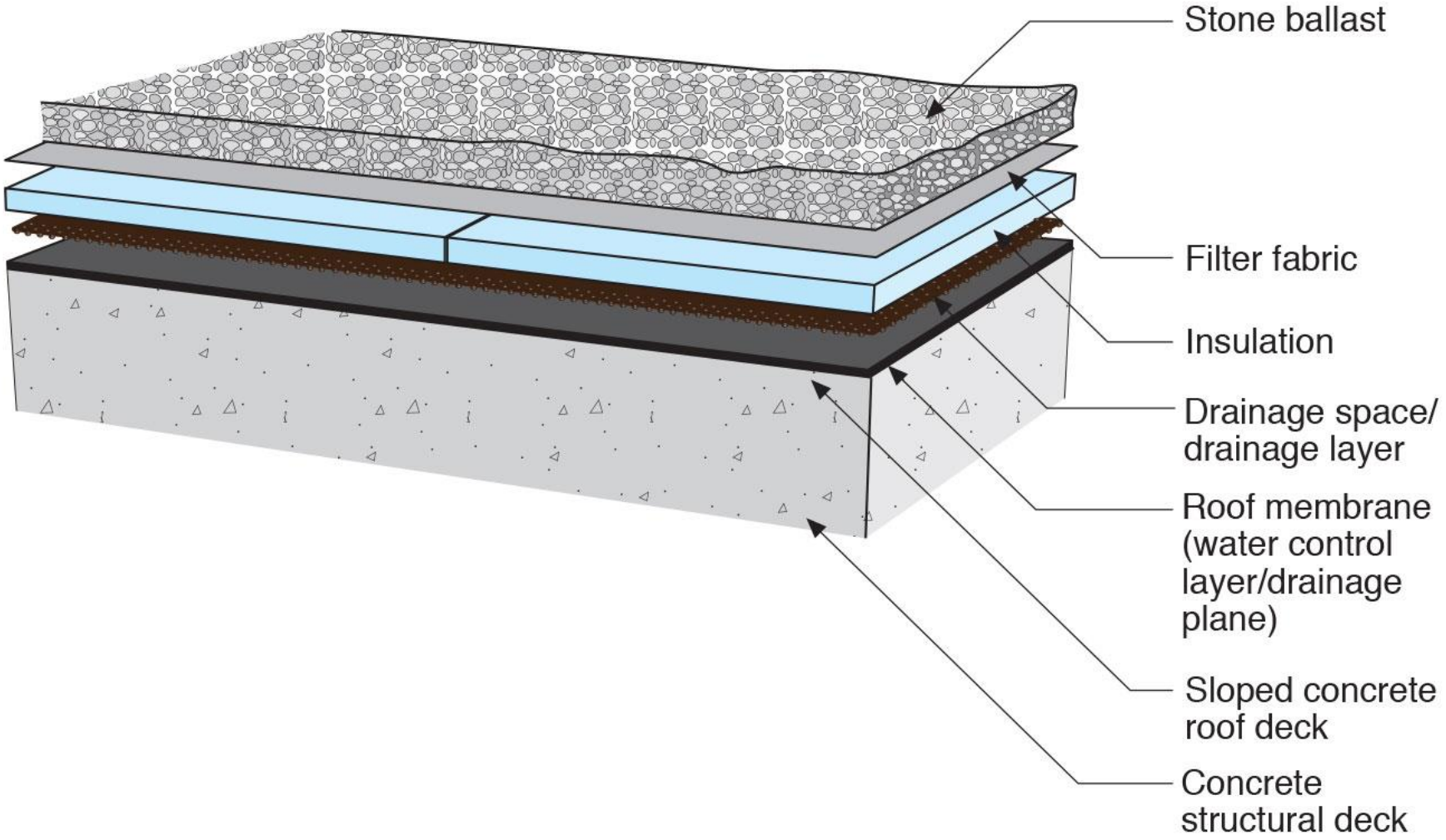

Roof membrane extends
up back side of parapet
Gypsum protection board
Pressure bar
Roof membrane
One layer rigid insulation
“Fluted” metal deck

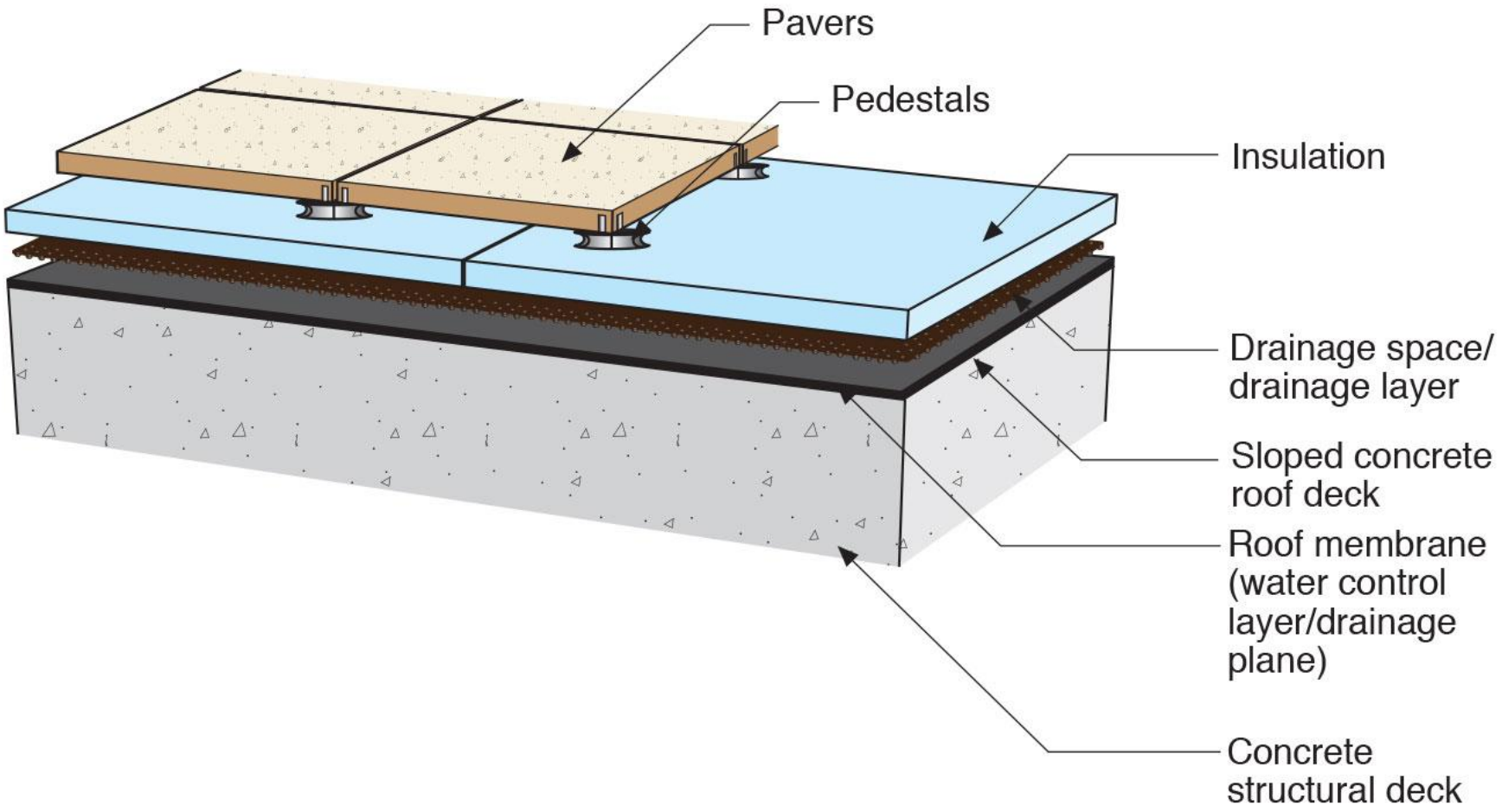

Solar radiation strikes wall
Absorbed rain water on exterior face of masonry parapet is driven inward and condenses on back side of roofing membrane protecting roof side of parapet
Absorbed rain water
Condensed water drains down back side of parapet into roof assembly and into building

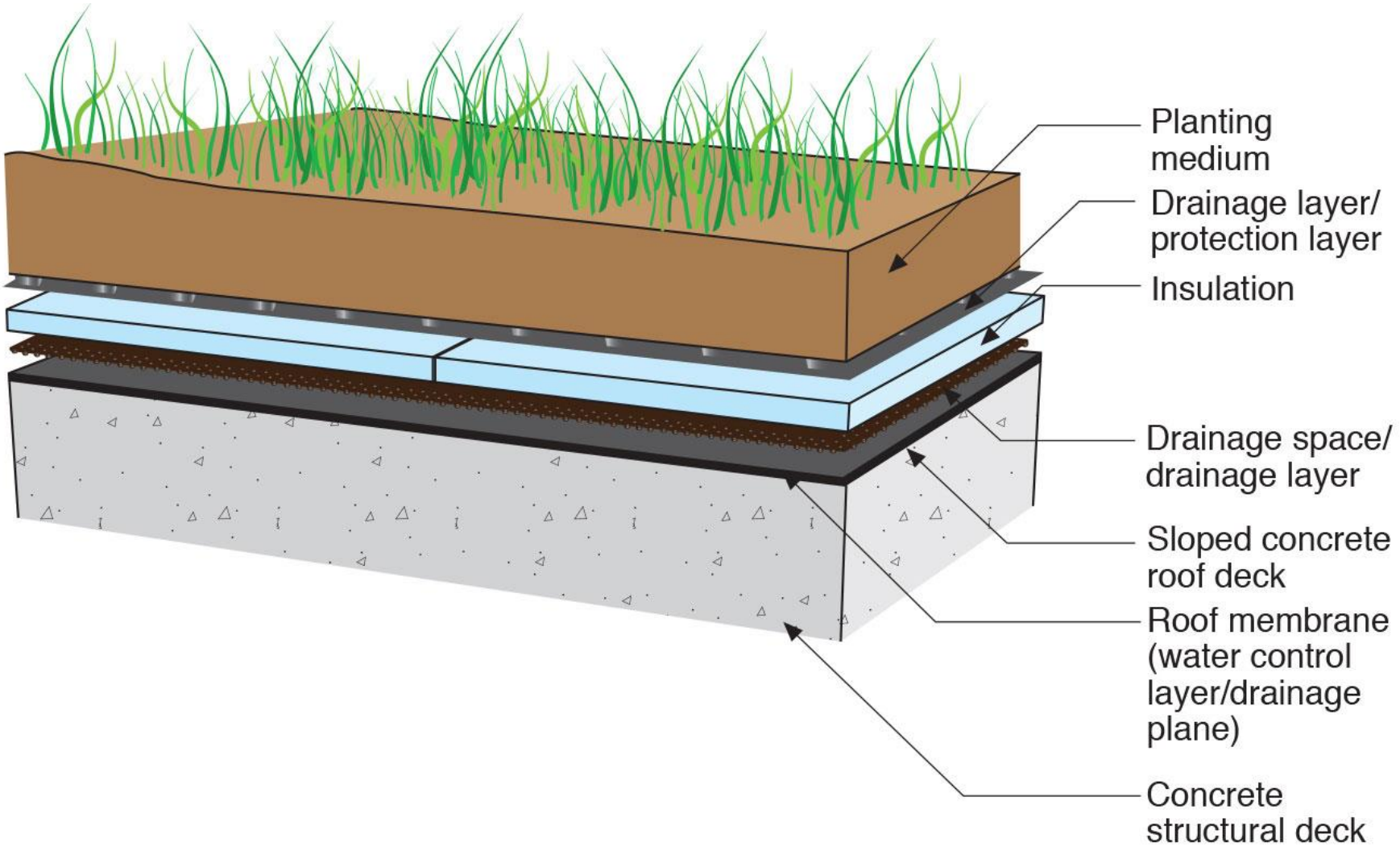

Vent
Vented "screen"
2" airspace
Fully adhered
counter flashing
membrane strip

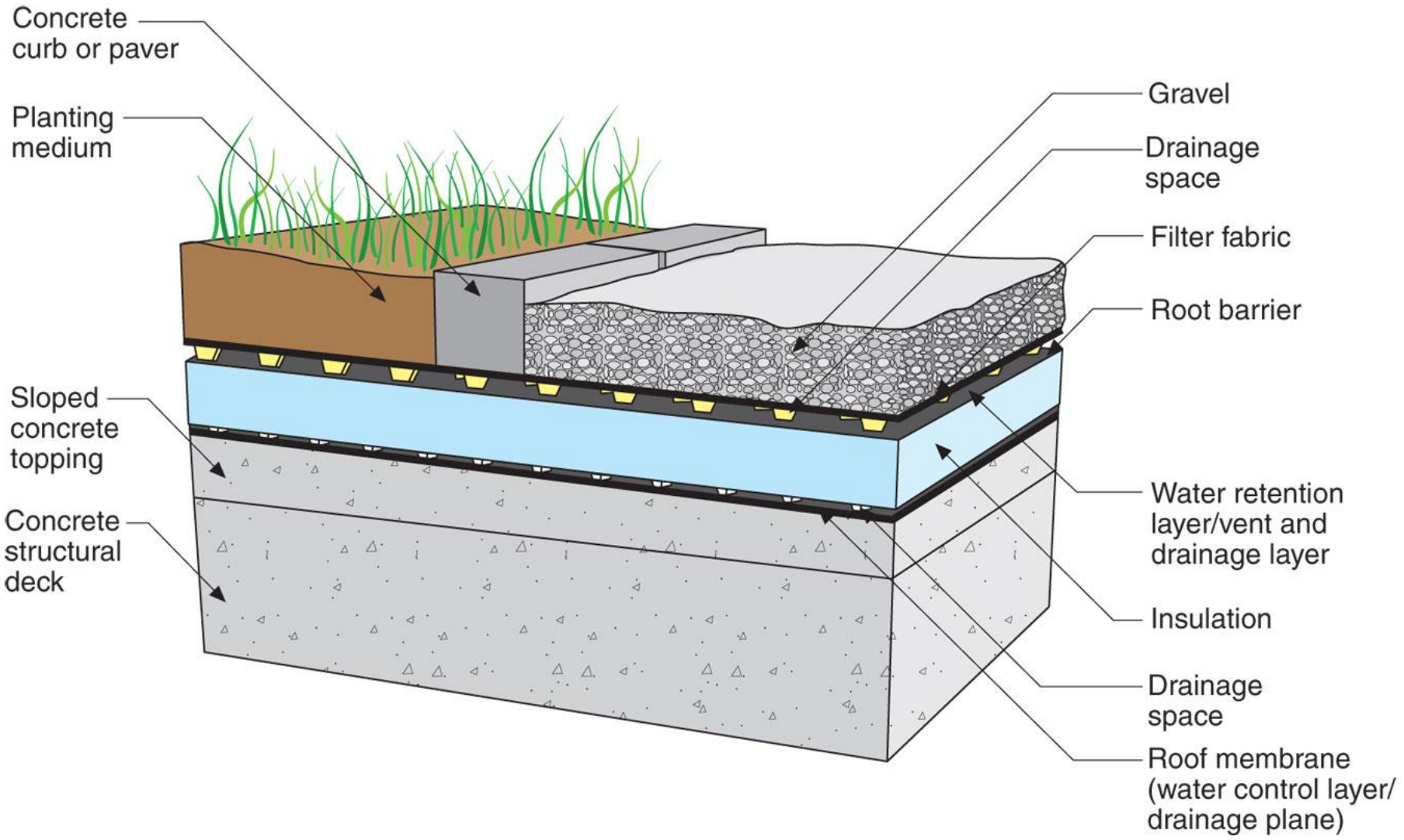

Ballast
Filter fabric
Control layers
Roof structure

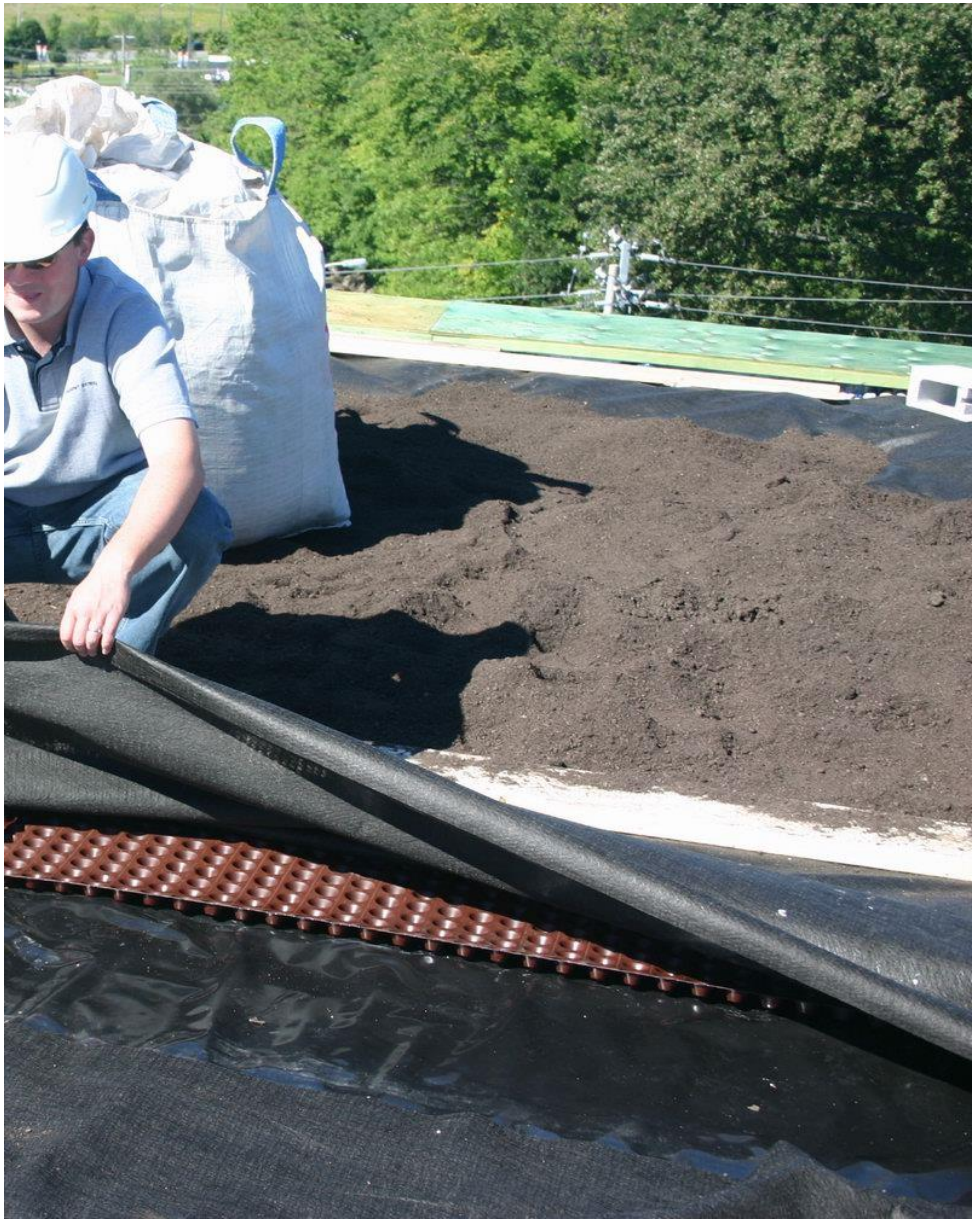

Ballast (rock, pavers, earth)
Filter fabric
Extruded polystyrene insulation
Sloped concrete topping; slope minimum 2% to drains
Concrete structural deck
Drainage gap, i.e., drainage mat or grooved insulation
Fully-adhered roof membrane


Stone ballast
Filter fabric
Insulation
Drainage space/
drainage layer
Roof membrane
(water control
layer/drainage
plane)
Sloped concrete
roof deck
Concrete
structural deck

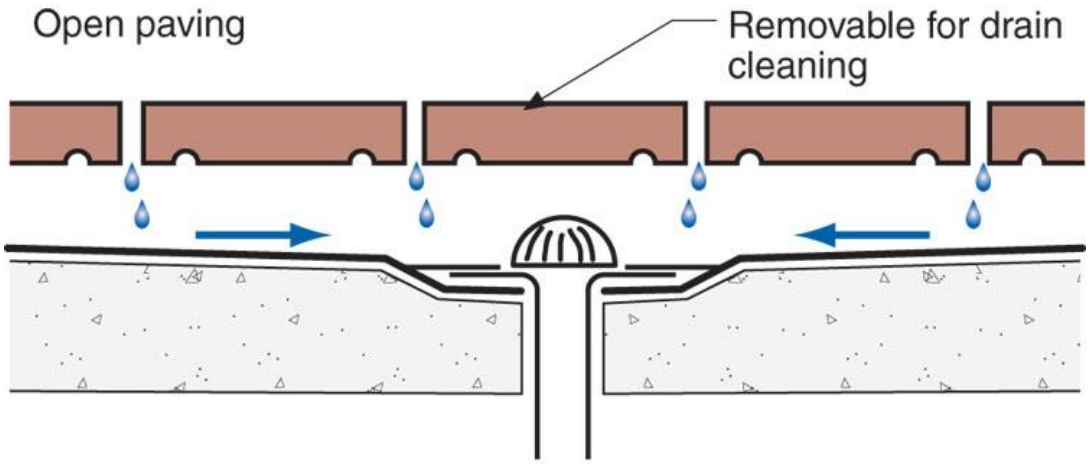

Pavers
Pedestals
Insulation
Drainage space/
drainage layer
Sloped concrete
roof deck
Roof membrane
(water control
layer/drainage
plane)
Concrete
structural deck


Planting medium
Drainage layer/ protection layer
Insulation
Drainage space/ drainage layer
Sloped concrete roof deck
Roof membrane (water control layer/drainage plane)
Concrete structural deck

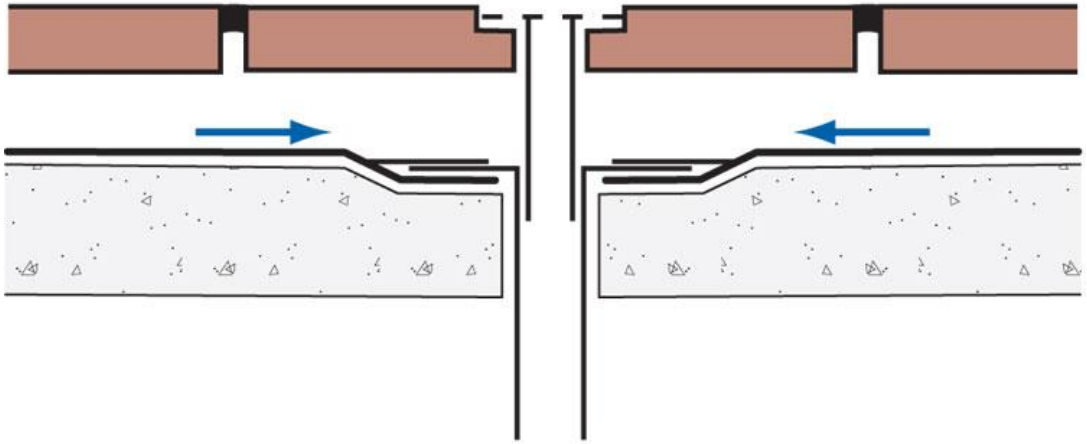

Concrete curb or paver
Planting medium
Sloped concrete topping
Concrete structural deck
Gravel
Drainage space
Filter fabric
Root barrier
Water retention layer/vent and drainage layer
Insulation
Drainage space
Roof membrane (water control layer/ drainage plane)



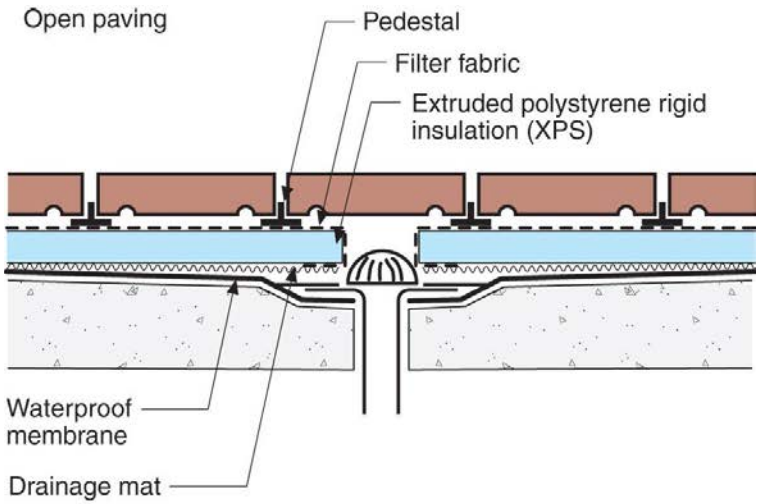
Plaza Decks

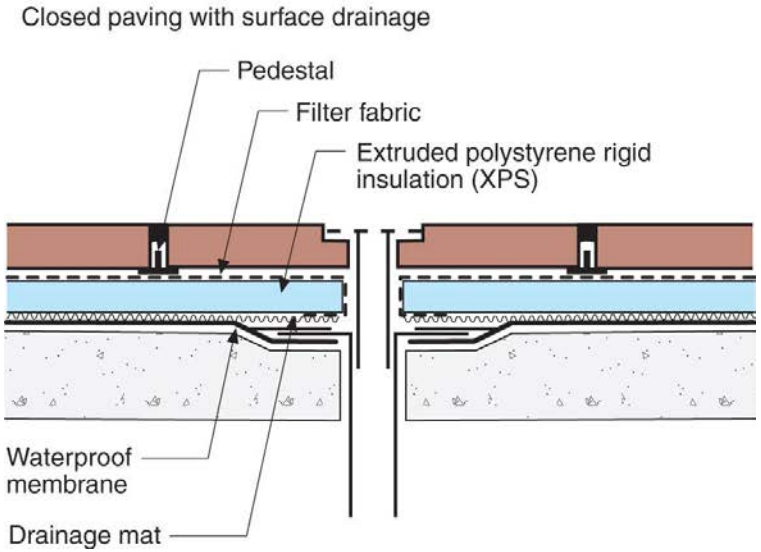


Closed paving with surface drainage

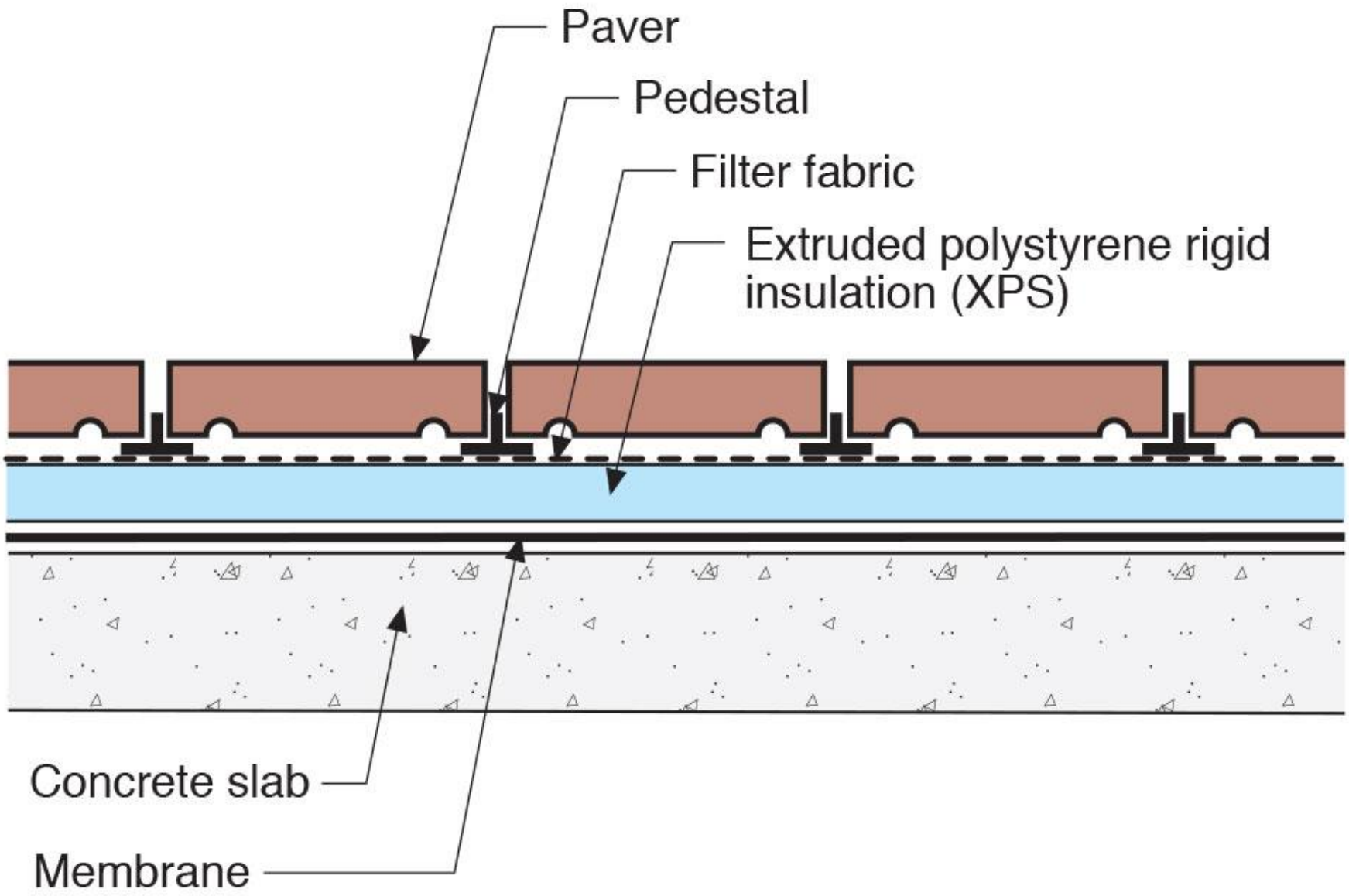


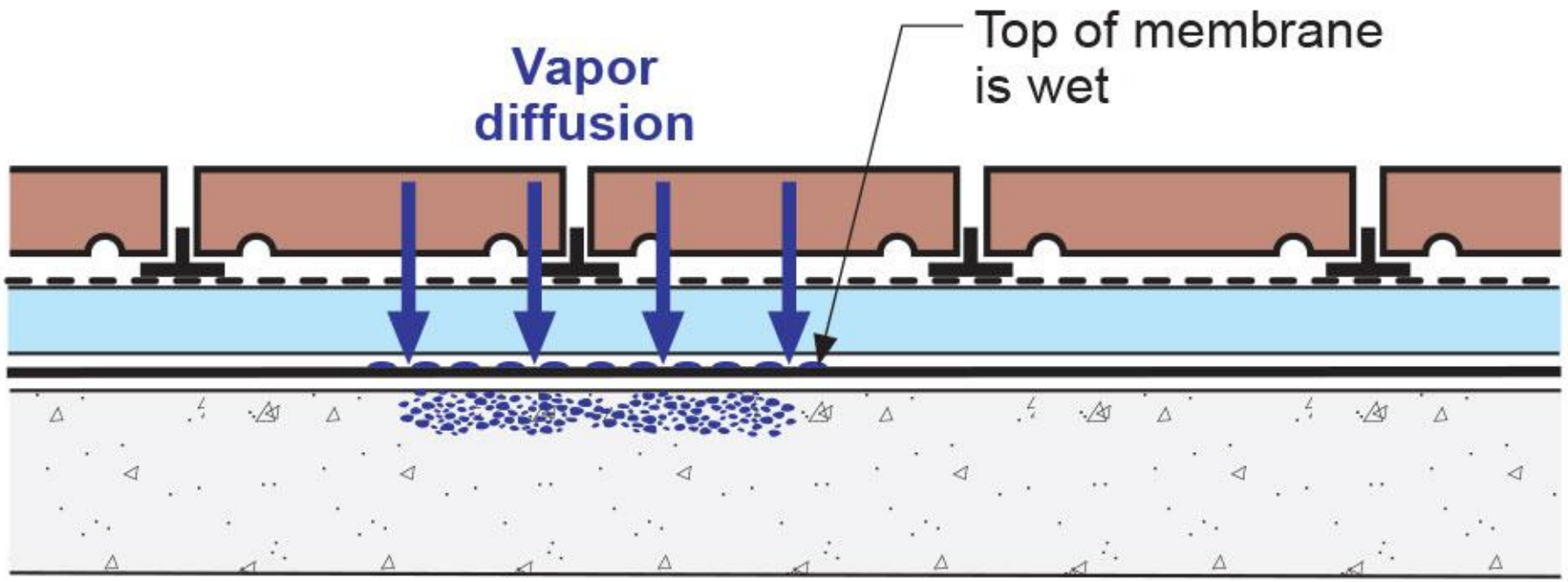
From Baker, M.; Roofs, 1980
Courtesy National Research Council of Canada

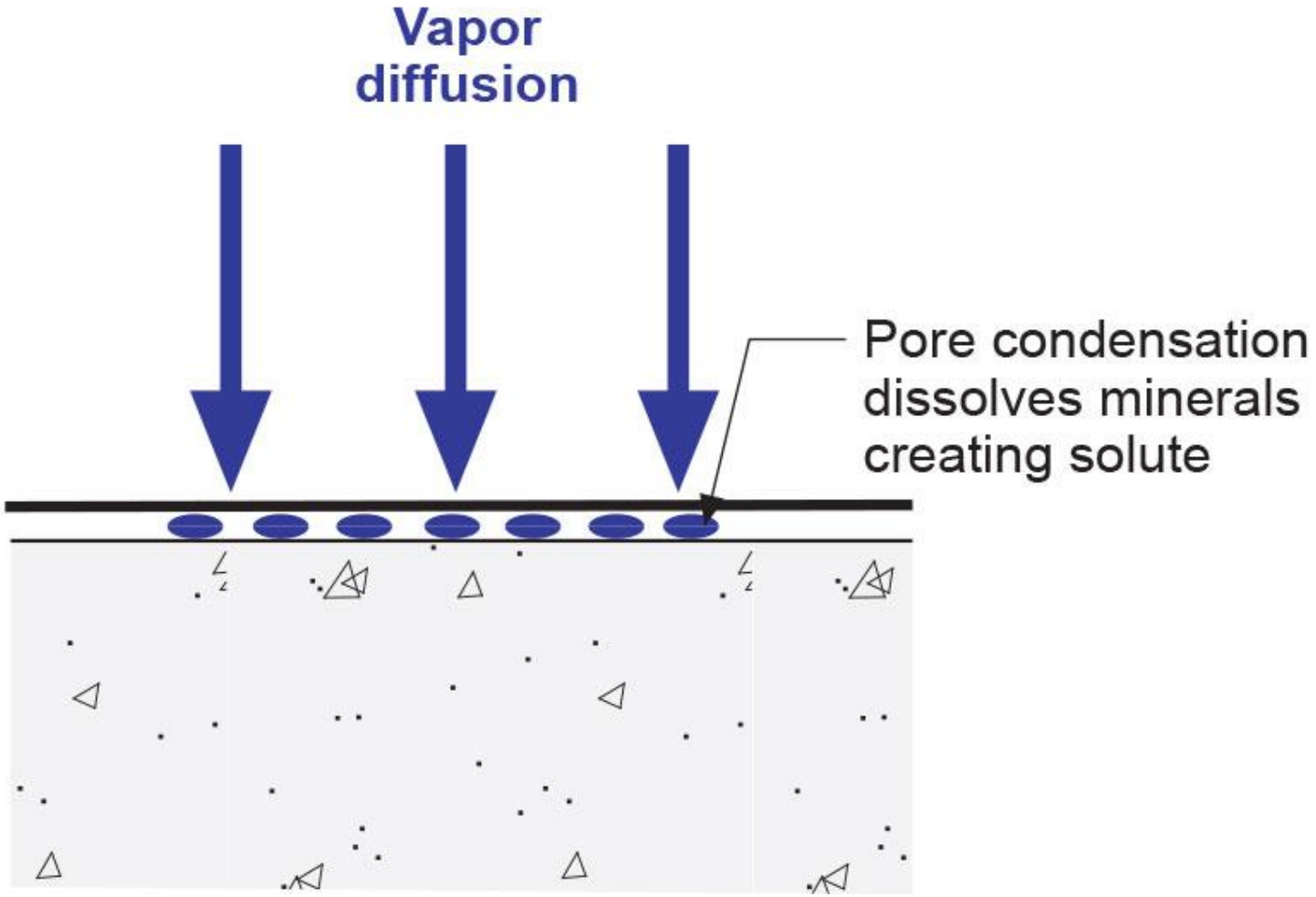

Open paving
Pedestal
Filter fabric
Extruded polystyrene rigid insulation (XPS)
Waterproof membrane
Drainage mat

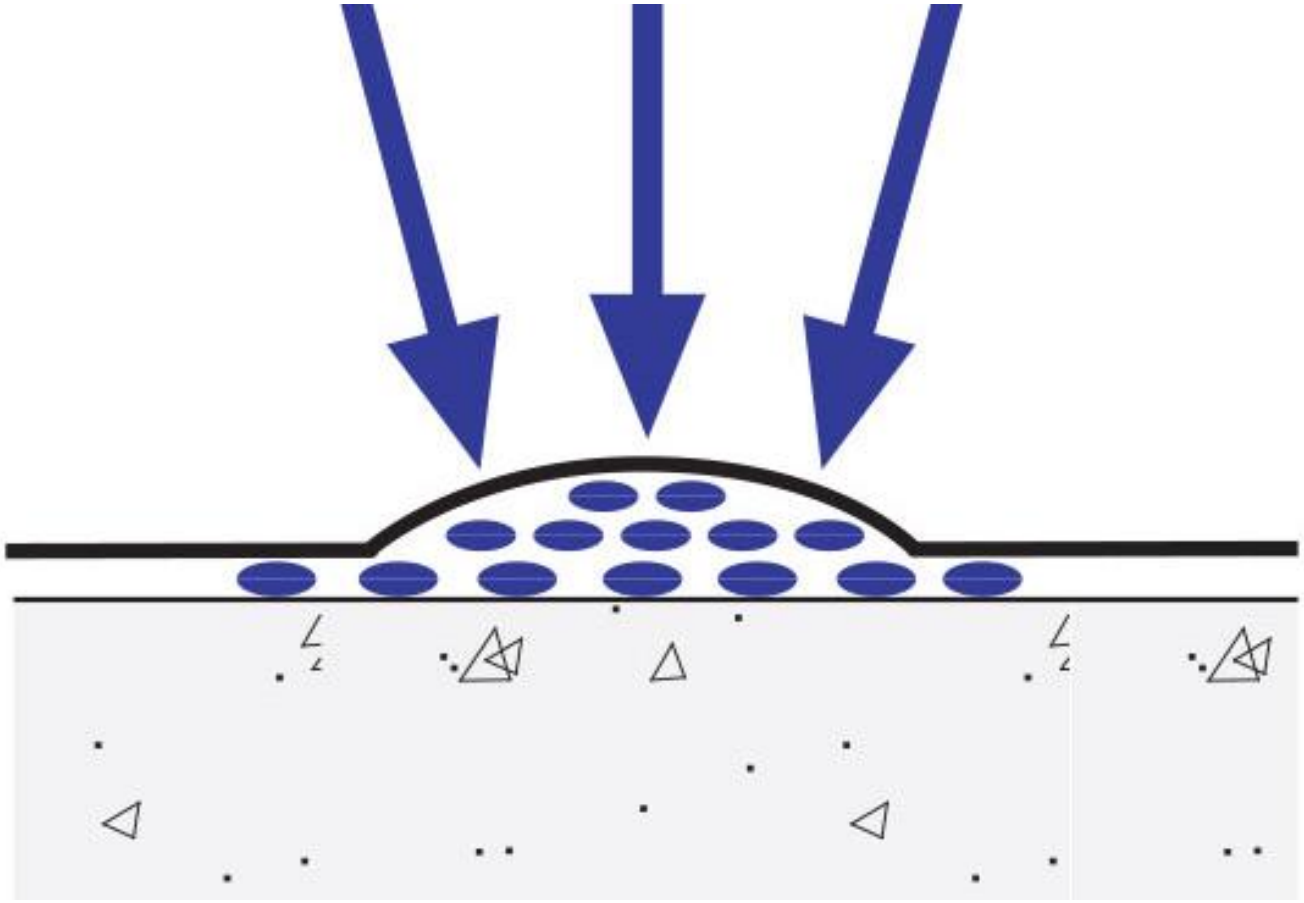

Closed paving with surface drainage
Pedestal
Filter fabric
Extruded polystyrene rigid insulation (XPS)
Waterproof membrane
Drainage mat

Osmosis

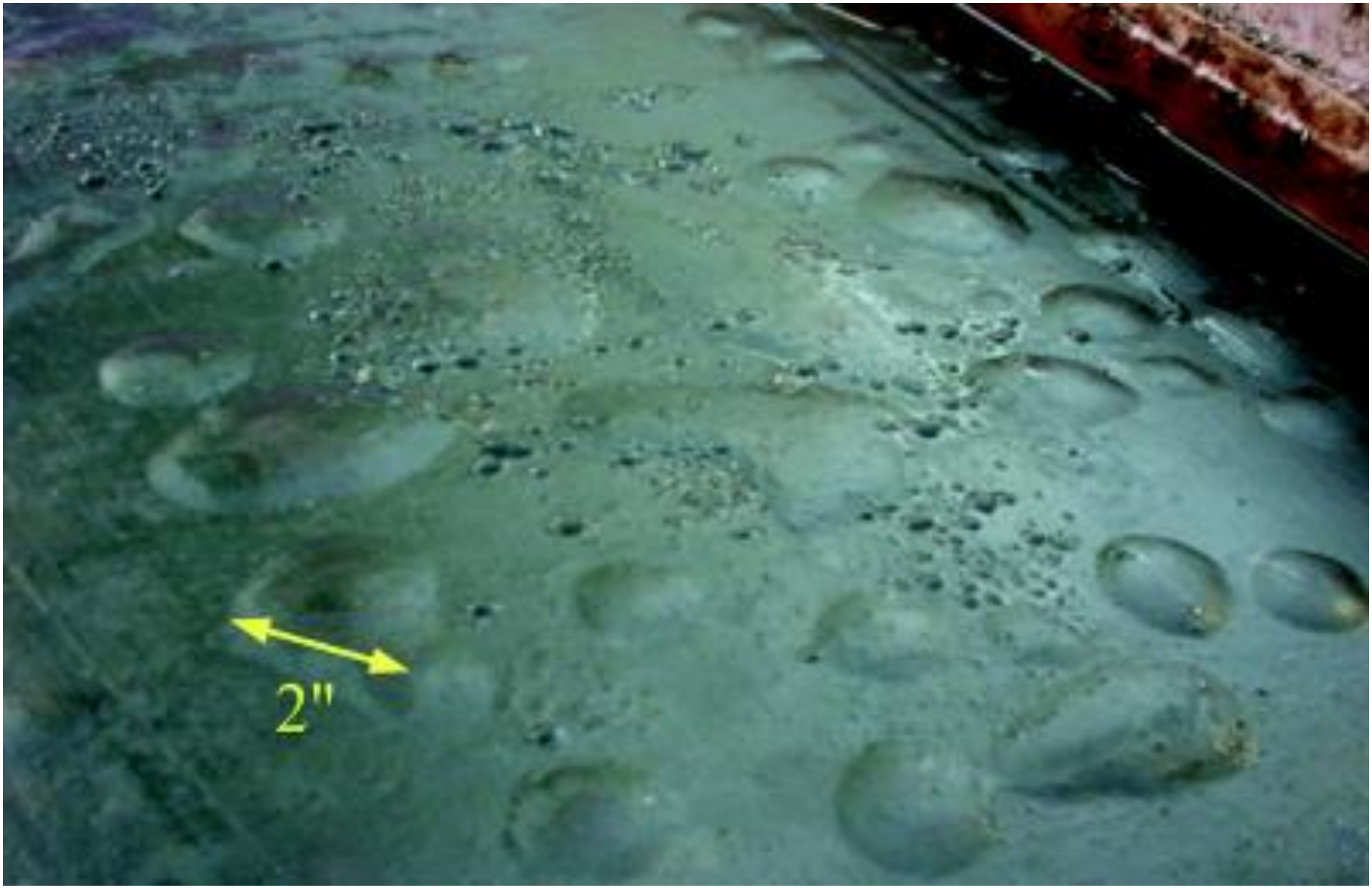

Paver
Pedestal
Filter fabric
Extruded polystyrene rigid insulation (XPS)
Concrete slab
Membrane

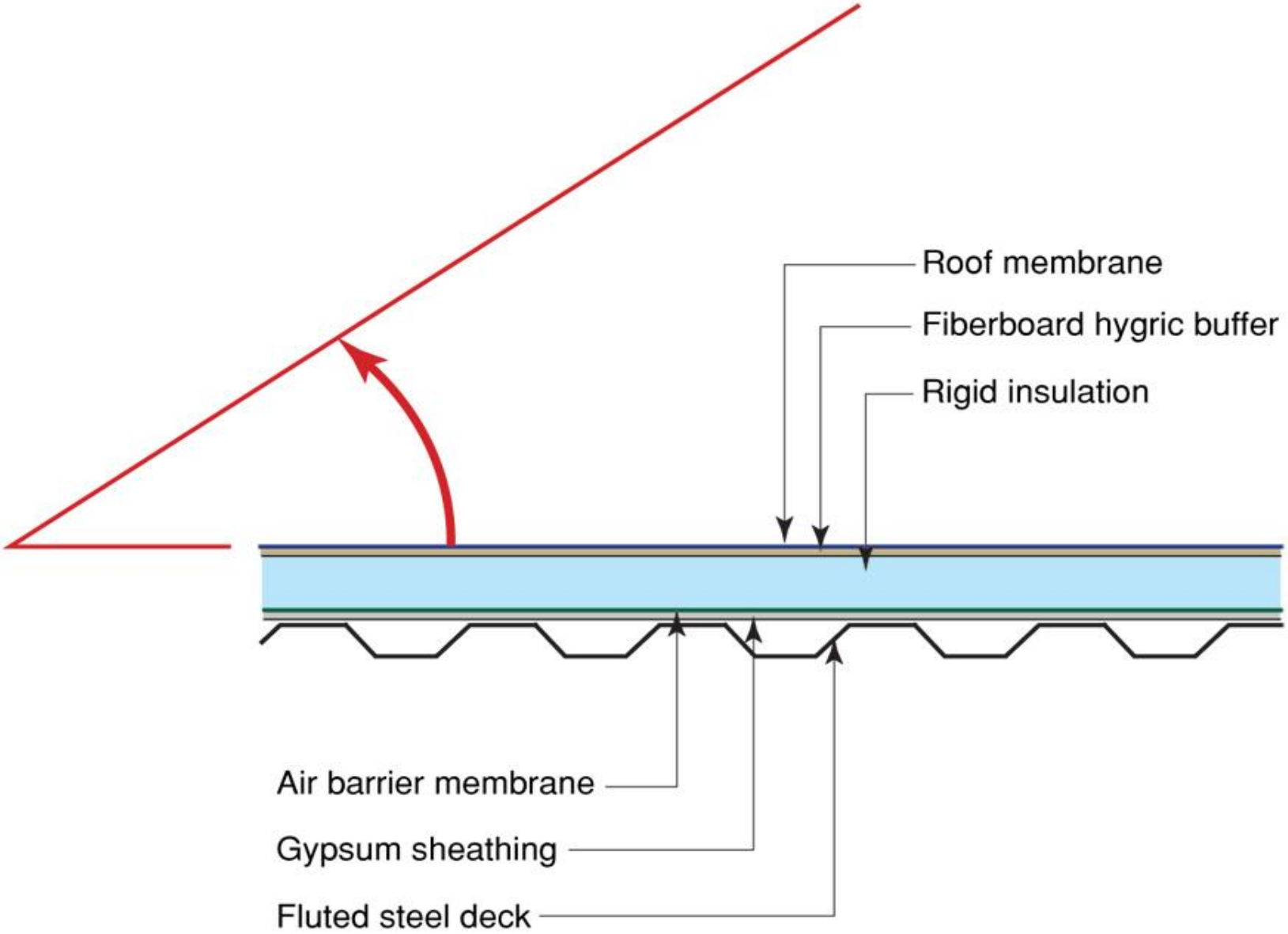

Vapor
diffusion
Top of membrane
is wet

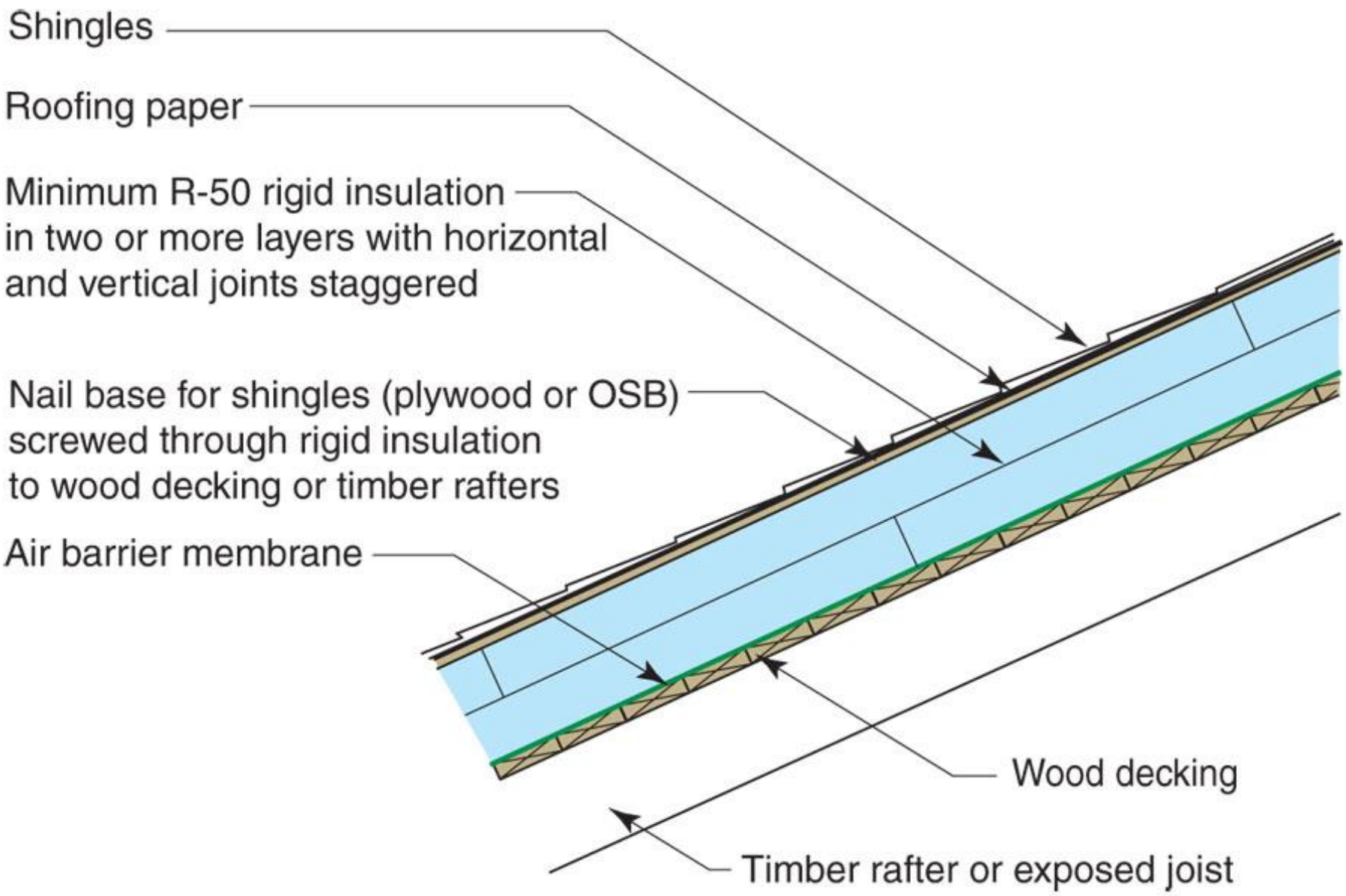

Vapor
diffusion
Pore condensation
dissolves minerals
creating solute

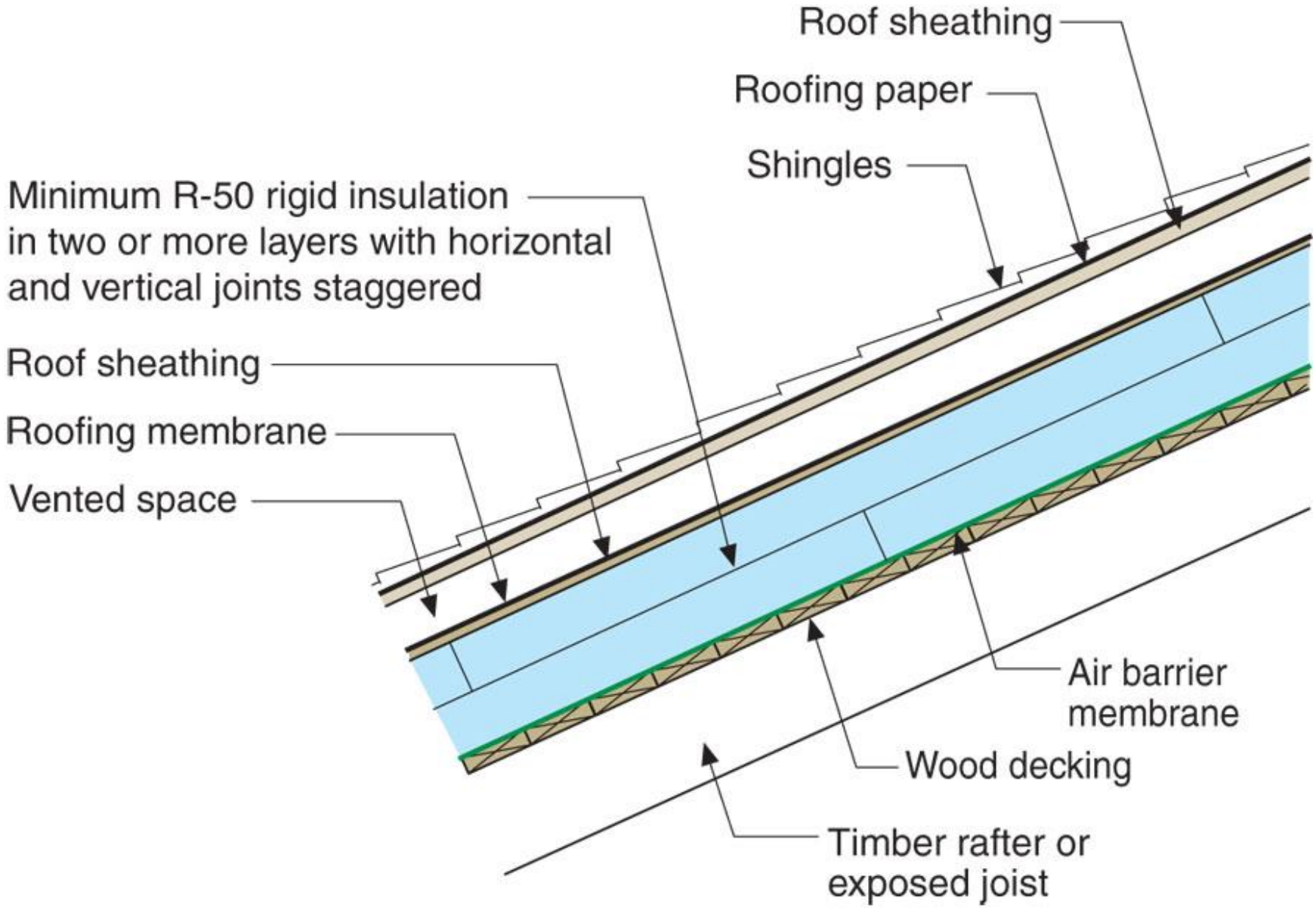



Really Heavy
Pink Stuff
Liquid Waterproofing
over Concrete Deck


2"

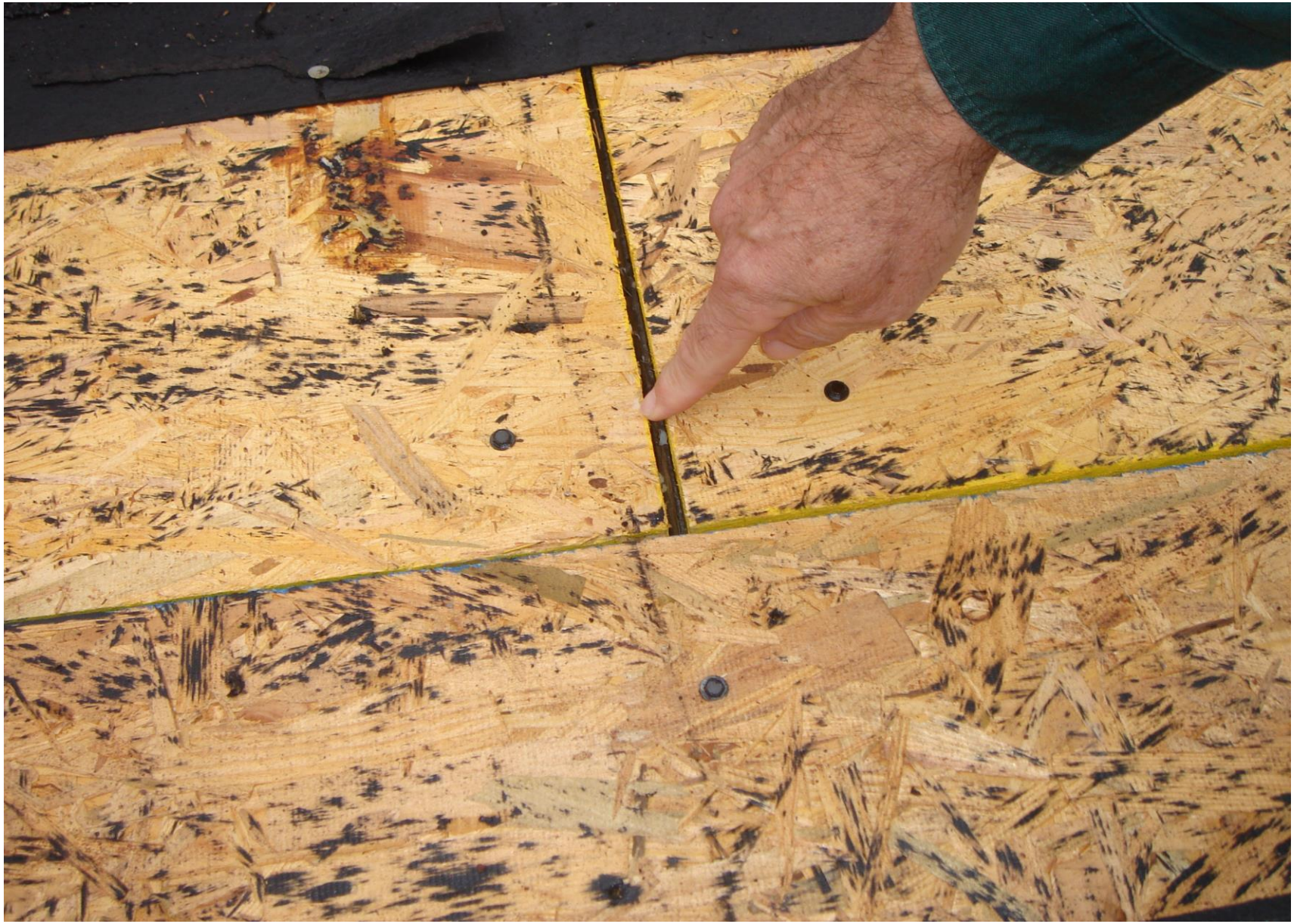

Roof membrane
Fiberboard hygric buffer
Rigid insulation
Air barrier membrane
Gypsum sheathing
Fluted steel deck

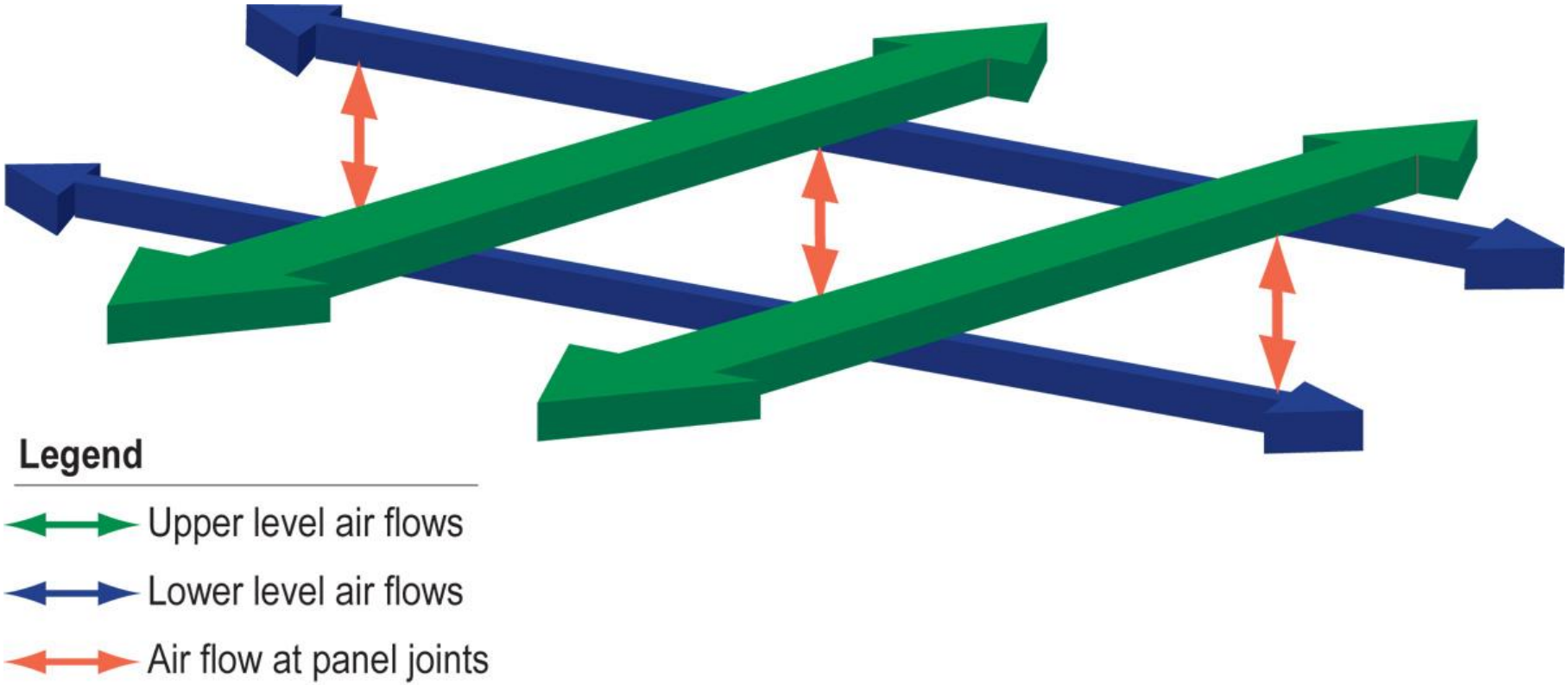

Shingles
Roofing paper
Minimum R-50 rigid insulation
in two or more layers with horizontal
and vertical joints staggered
Nail base for shingles (plywood or OSB)
screwed through rigid insulation
to wood decking or timber rafters
Air barrier membrane
Wood decking
Timber rafter or exposed joist

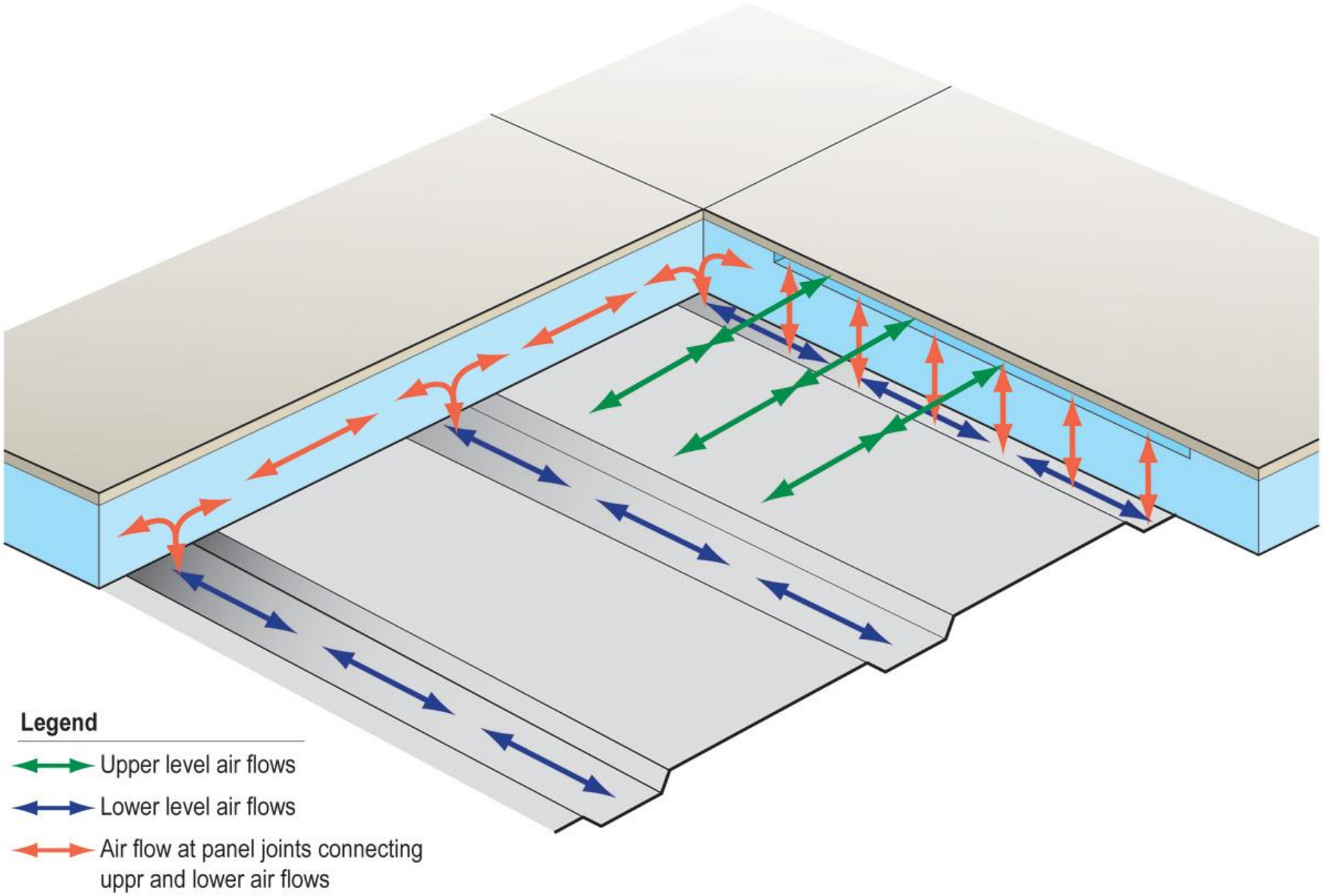

Roof sheathing
Roofing paper
Shingles
Minimum R-50 rigid insulation
in two or more layers with horizontal
and vertical joints staggered
Roof sheathing
Roofing membrane
Vented space
Air barrier
membrane
Wood decking
Timber rafter or
exposed joist

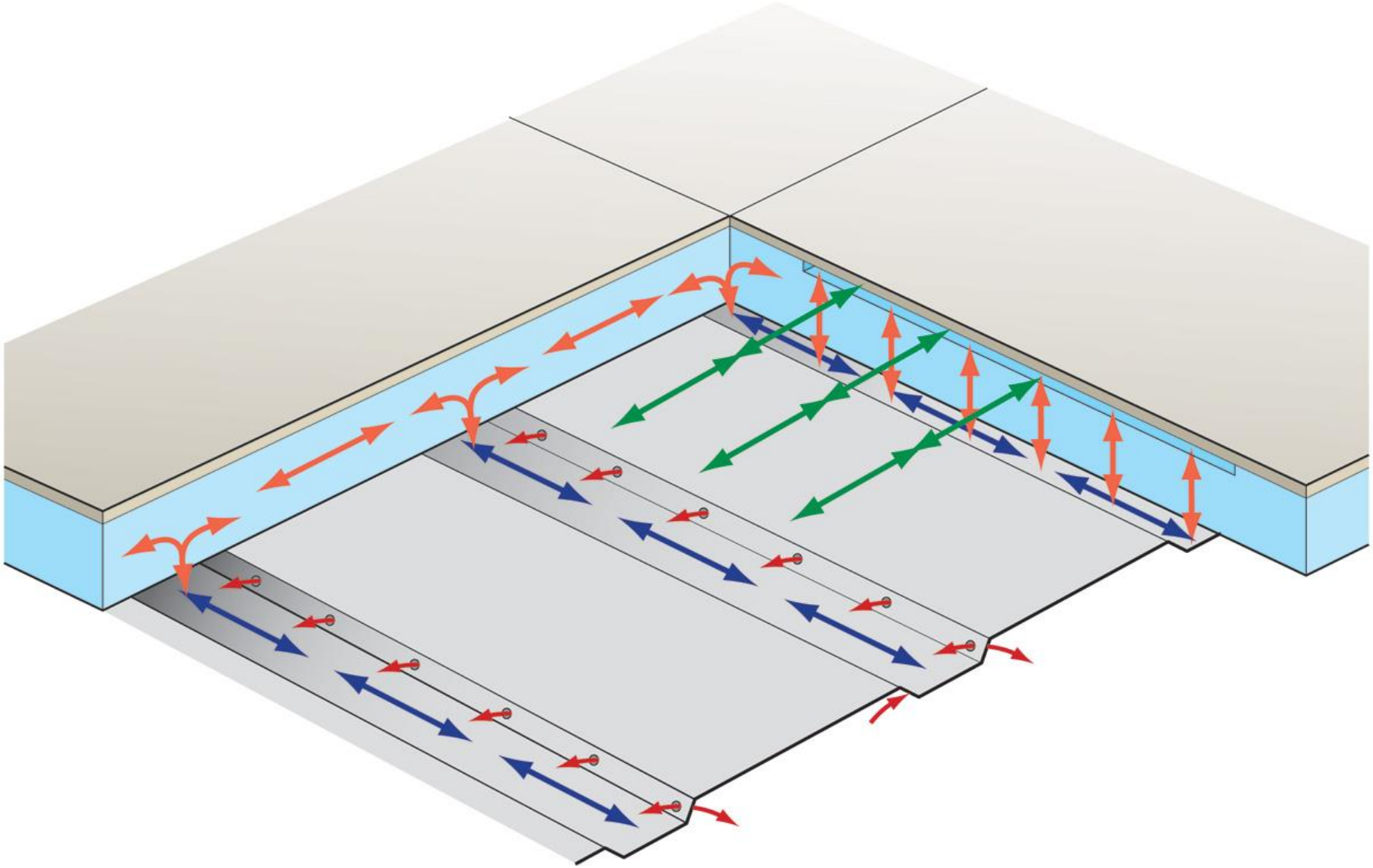

SATURN

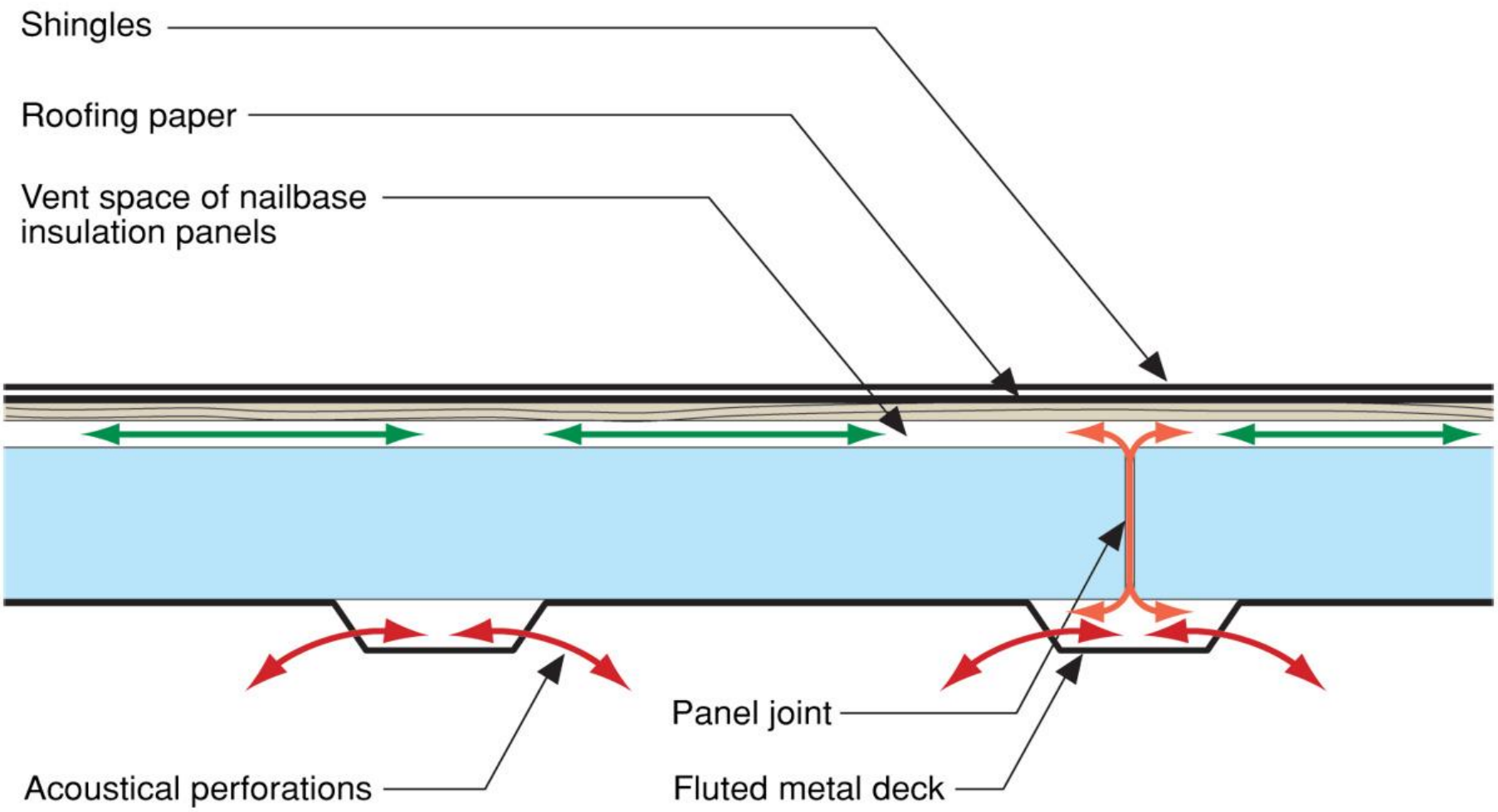

DIET
Exercises Promoting Physical Fitness
Frequency
Intensity
Time
Type
Stretching
Aerobic

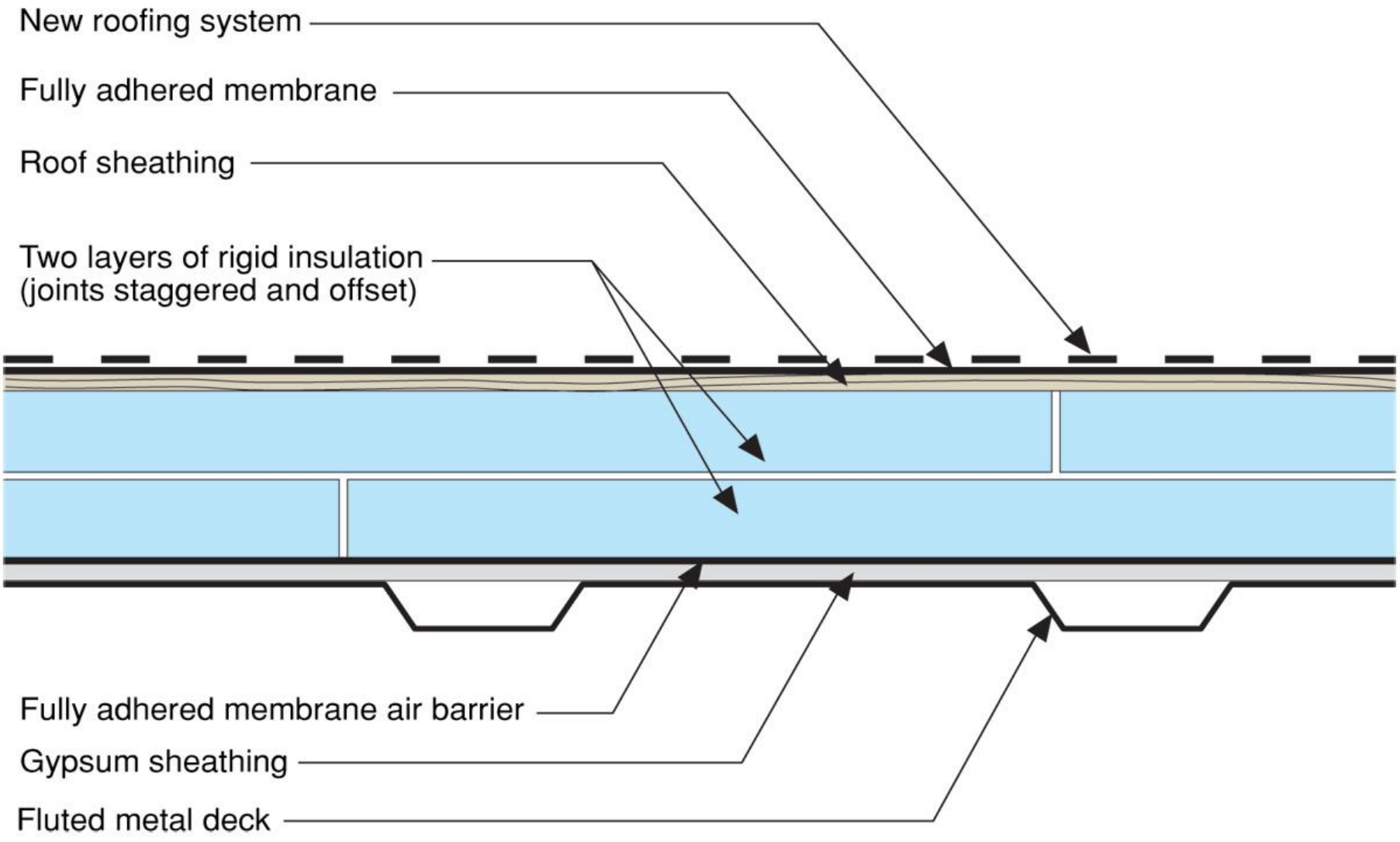


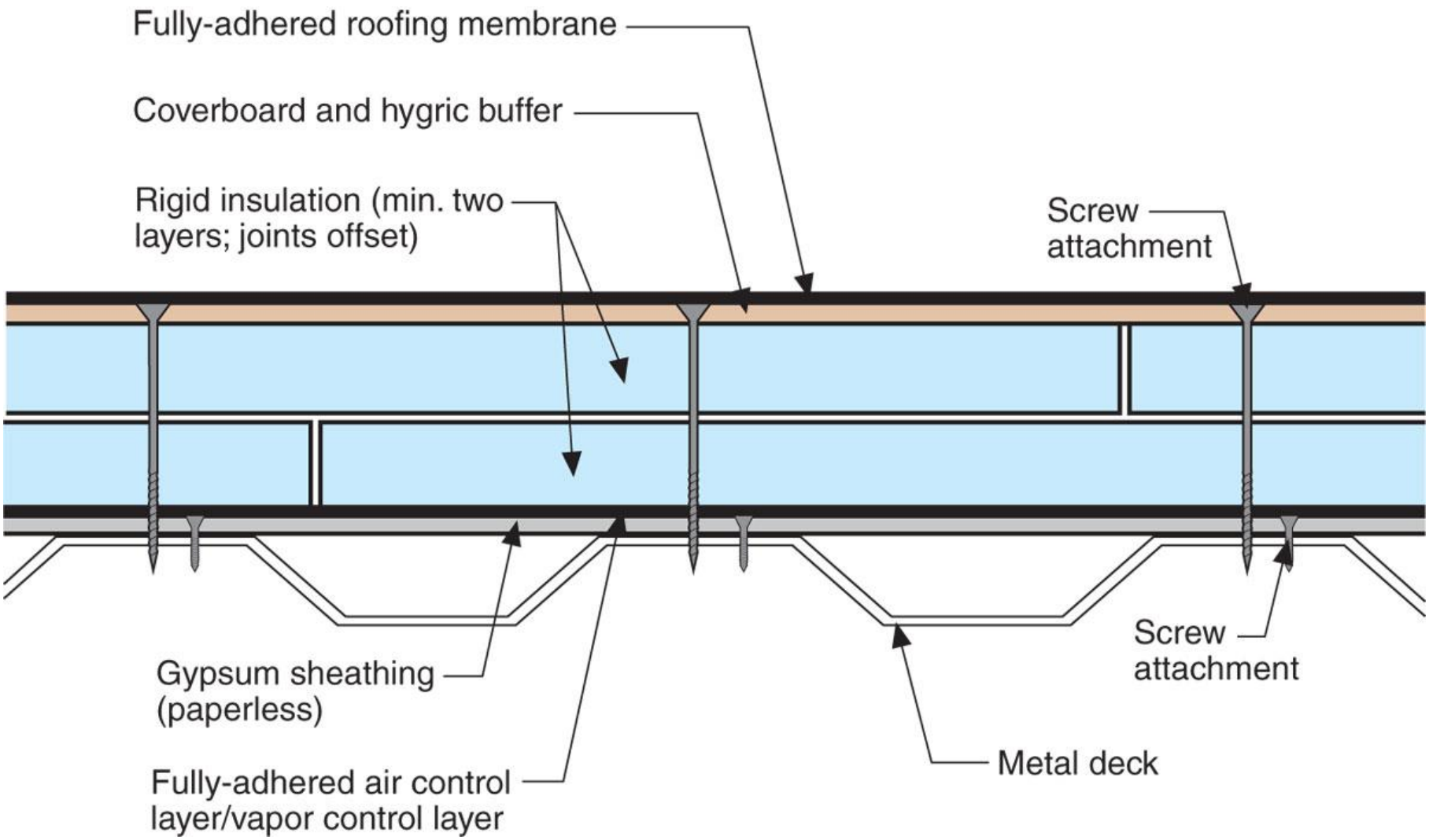

Legend
Upper level air flows
Lower level air flows
Air flow at panel joints

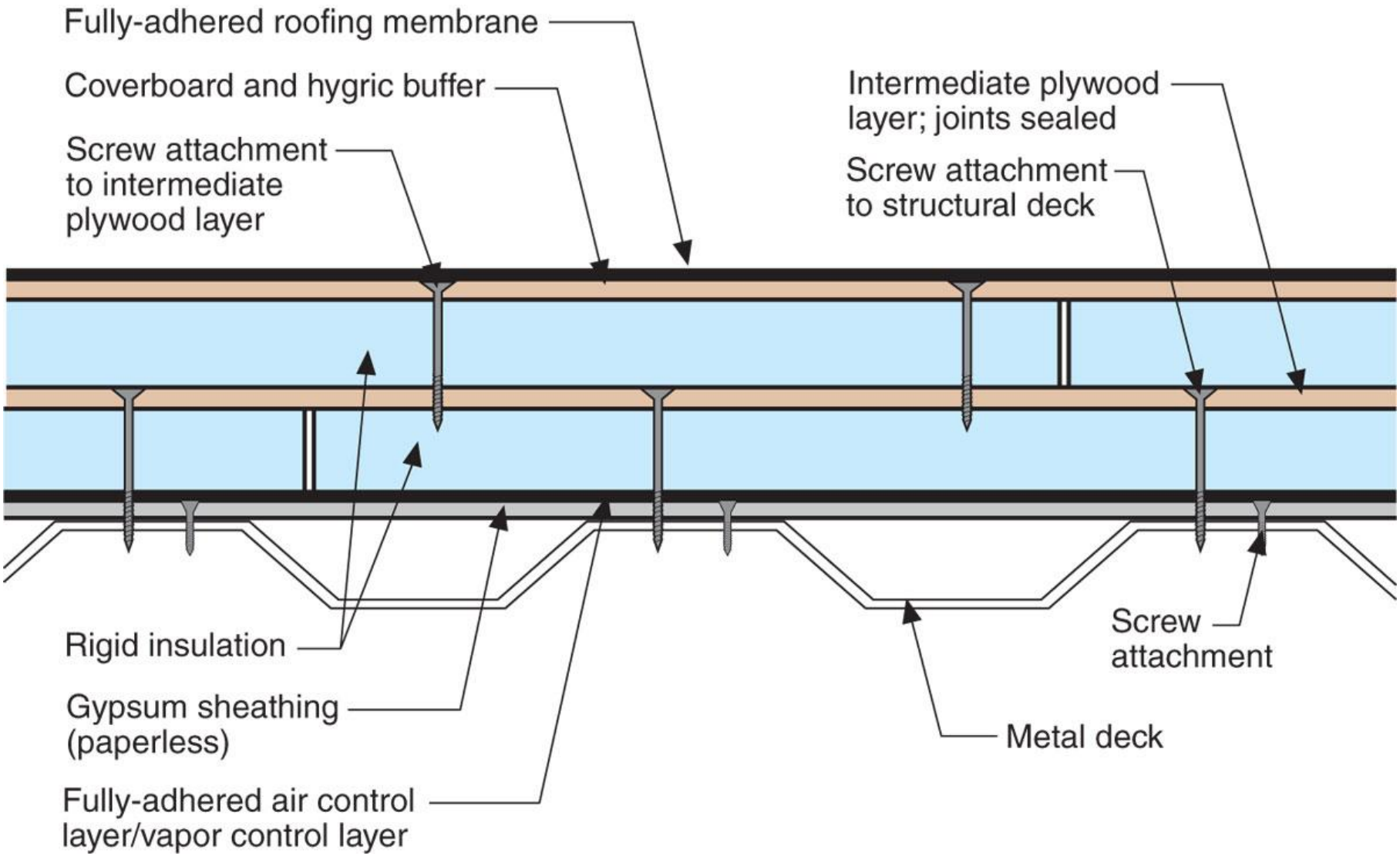

Legend
Upper level air flows
Lower level air flows
Air flow at panel joints connecting uppr and lower air flows

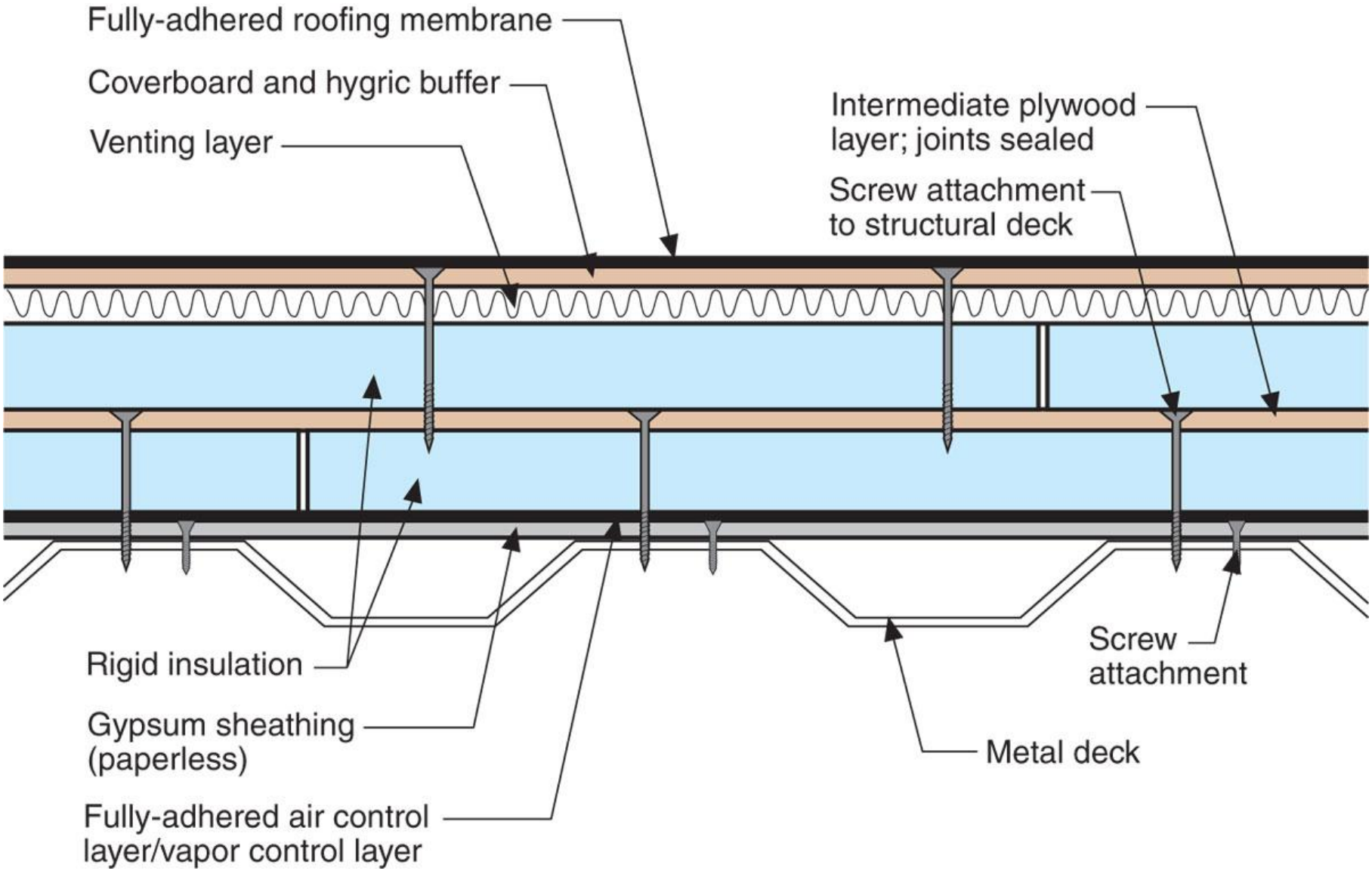


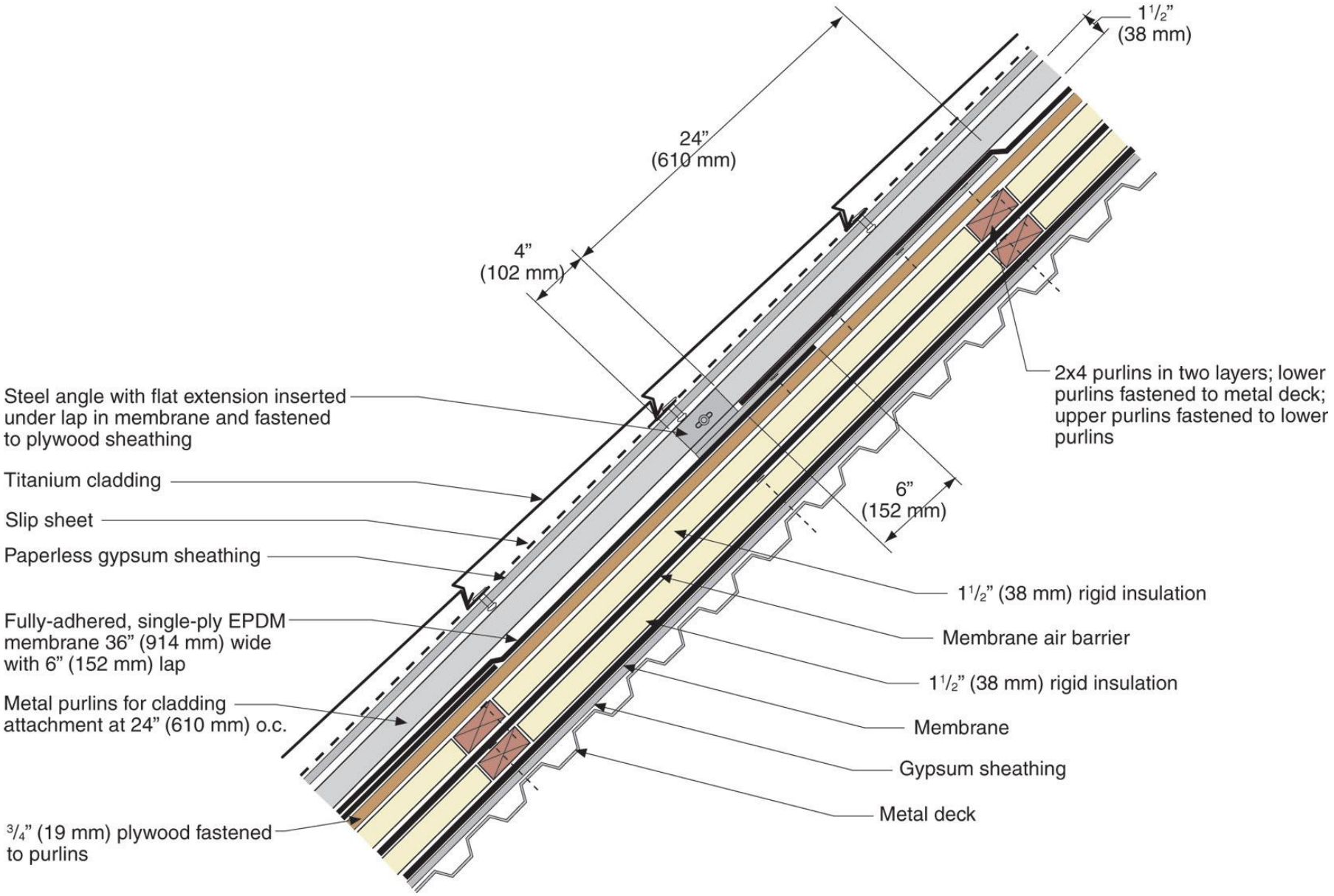

Shingles
Roofing paper
Vent space of nailbase insulation panels
Panel joint
Acoustical perforations
Fluted metal deck

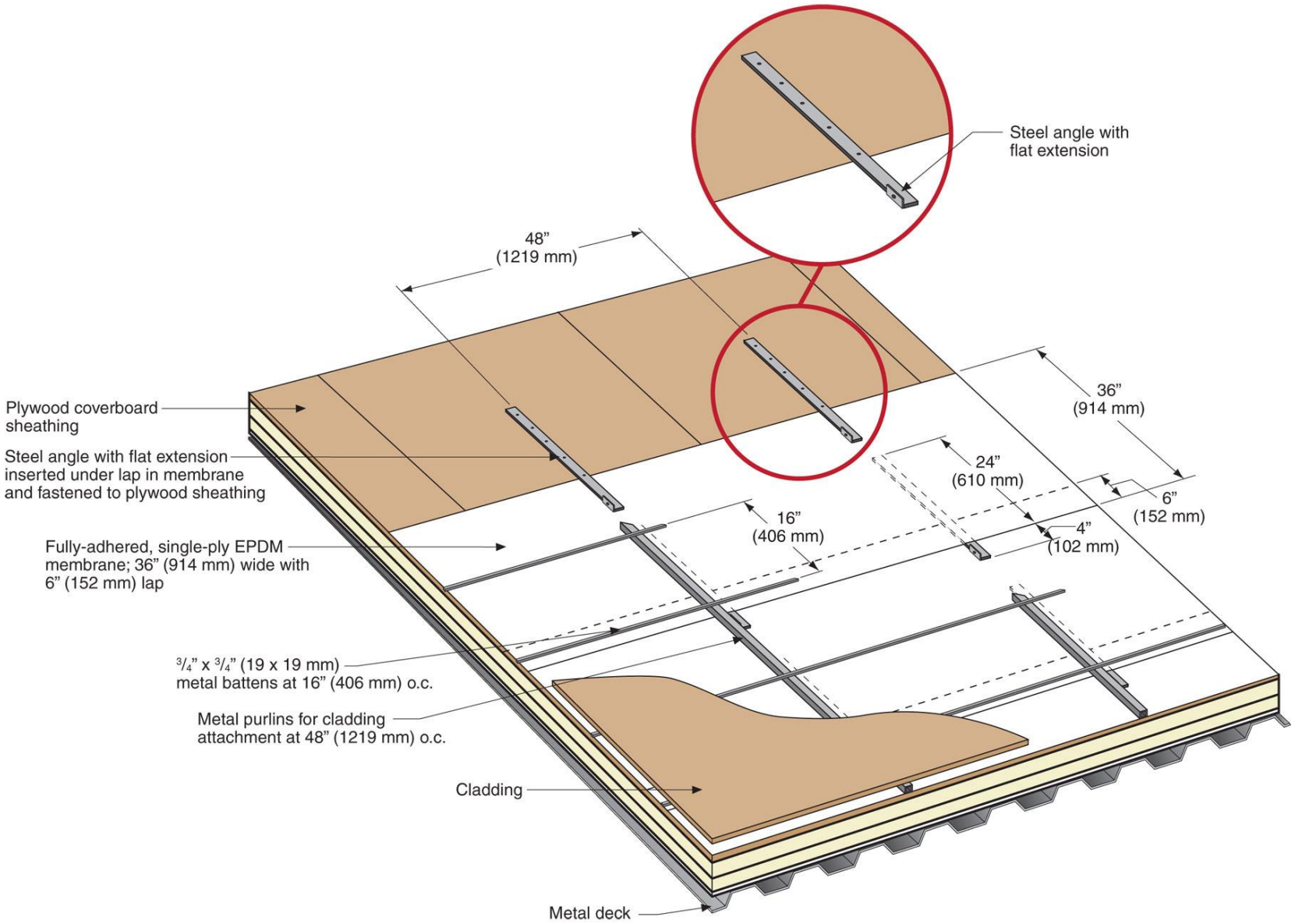

New roofing system
Fully adhered membrane
Roof sheathing
Two layers of rigid insulation
(joints staggered and offset)
Fully adhered membrane air barrier
Gypsum sheathing
Fluted metal deck


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
Metal deck
Screw attachment


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
3/4" x 3/4" (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
16" (406 mm)
24" (610 mm)
36" (914 mm)
6" (152 mm)
4" (102 mm)