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

Building Science

Adventures In Building Science

www.buildingscience.com

Environmental Separation

Definition of a Building

A Building is an Environmental Separator

- Control heat flow
- Control airflow
- Control water vapor flow
- Control rain
- Control ground water
- Control light and solar radiation
- Control noise and vibrations
- Control contaminants, environmental hazards and odors
- Control insects, rodents and vermin
- Control fire
- Provide strength and rigidity
- Be durable
- Be aesthetically pleasing
- Be economical

Some Physics….

Arrhenius Equation

For Every 10 Degree K Rise

Reaction Rate Doubles

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

Damage Functions

Water

Heat

Ultra-violet Radiation

2nd Law of Thermodynamics

Heat Flow Is From Warm To Cold

Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

Air Flow Is From A Higher Pressure to a Lower Pressure

Gravity Acts Down

Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

Thermal Gradient – Thermal Diffusion

Concentration Gradient – Molecular Diffusion

Moisture Flow Is From Warm To Cold

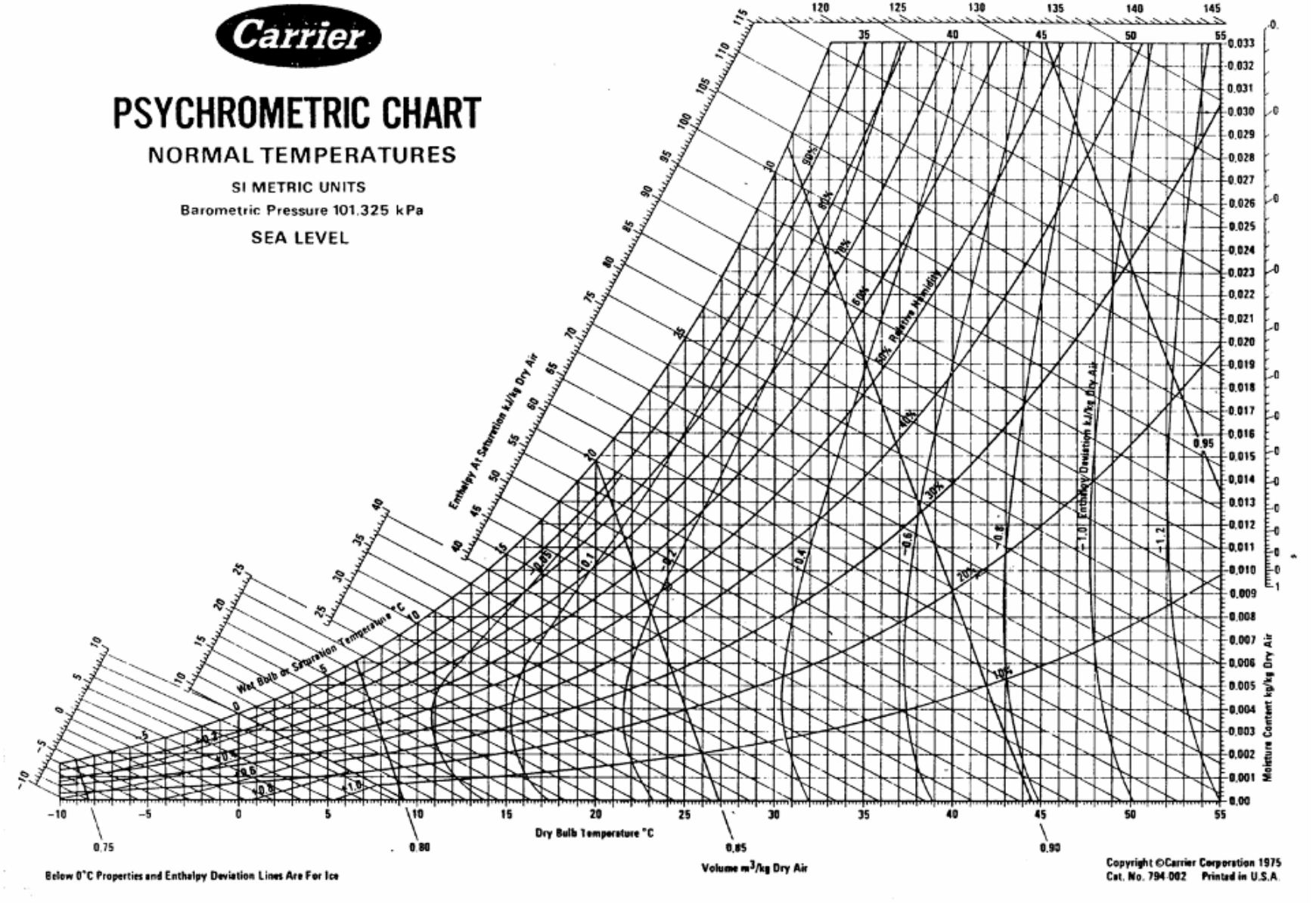
Moisture Flow Is From More To Less

Thermal Gradient – Thermal Diffusion

Concentration Gradient – Molecular Diffusion

Vapor Diffusion

Thermodynamic Potential


Carrier
PSYCHROMETRIC CHART
NORMAL TEMPERATURES
SI METRIC UNITS
Barometric Pressure 101.325 kPa
SEA LEVEL
Wet Bulb or Saturation Temperature °C
Enthalpy At Saturation kJ/kg Dry Air
Dry Bulb Temperature °C
Moisture Content kg/kg Dry Air
50% Relative Humidity
Below 0°C Properties and Enthalpy Deviation Lines Are For Ice
Volume m³/kg Dry Air
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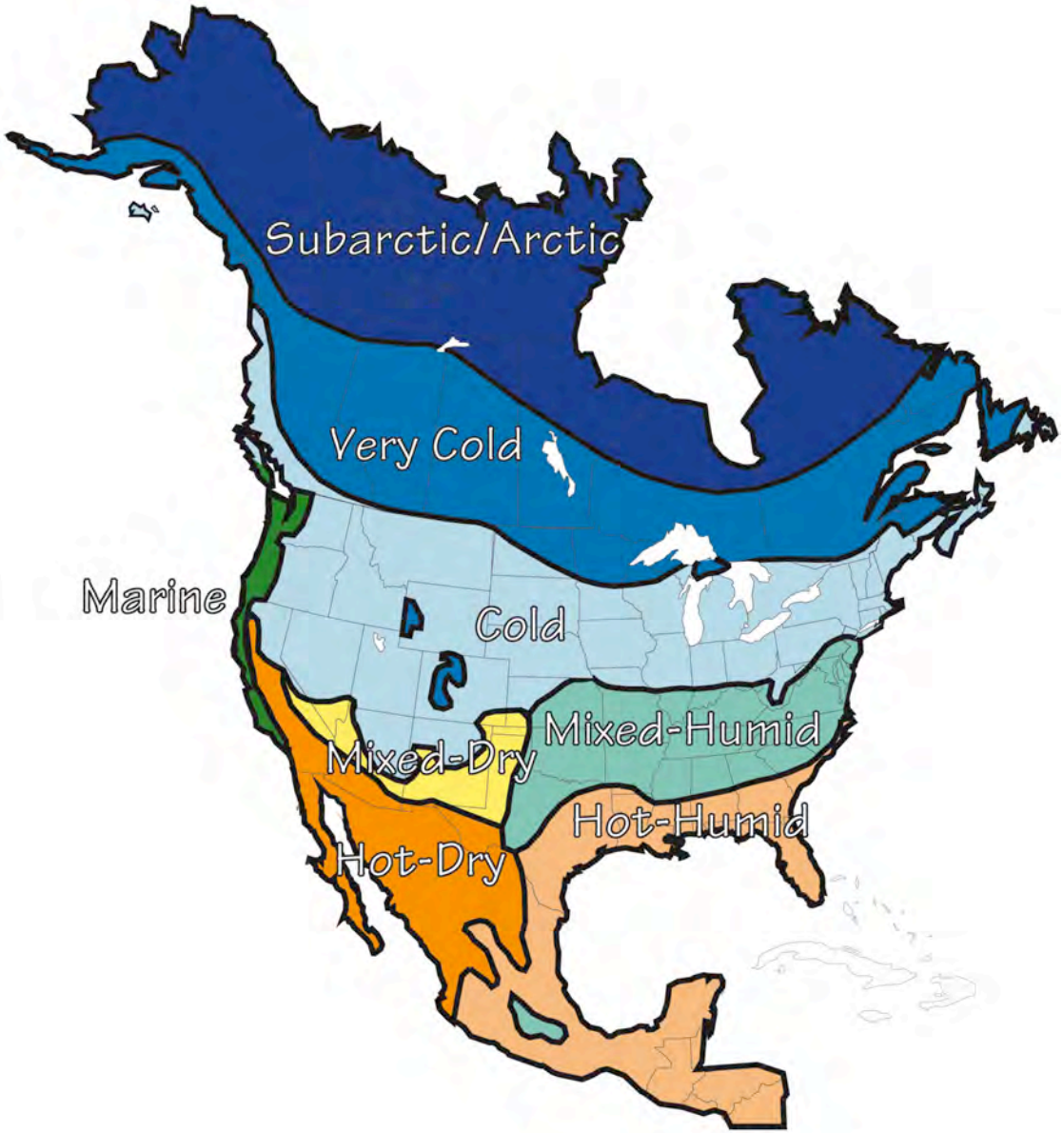
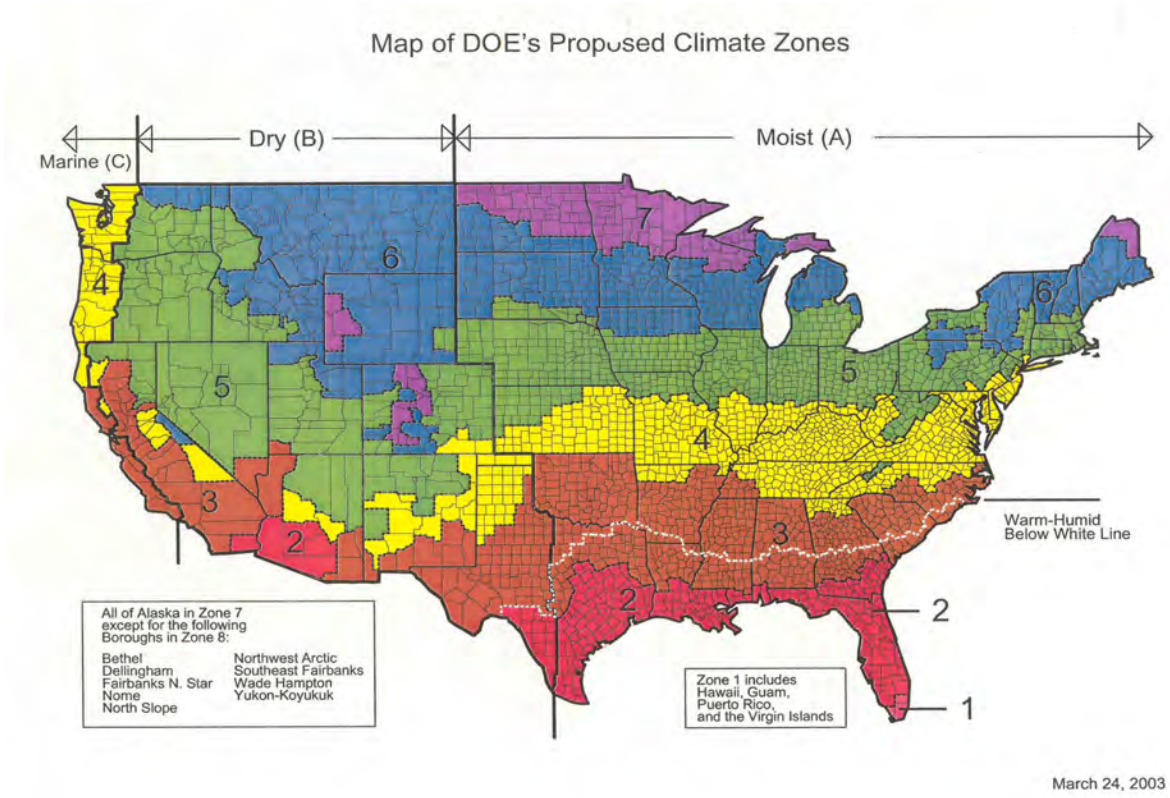
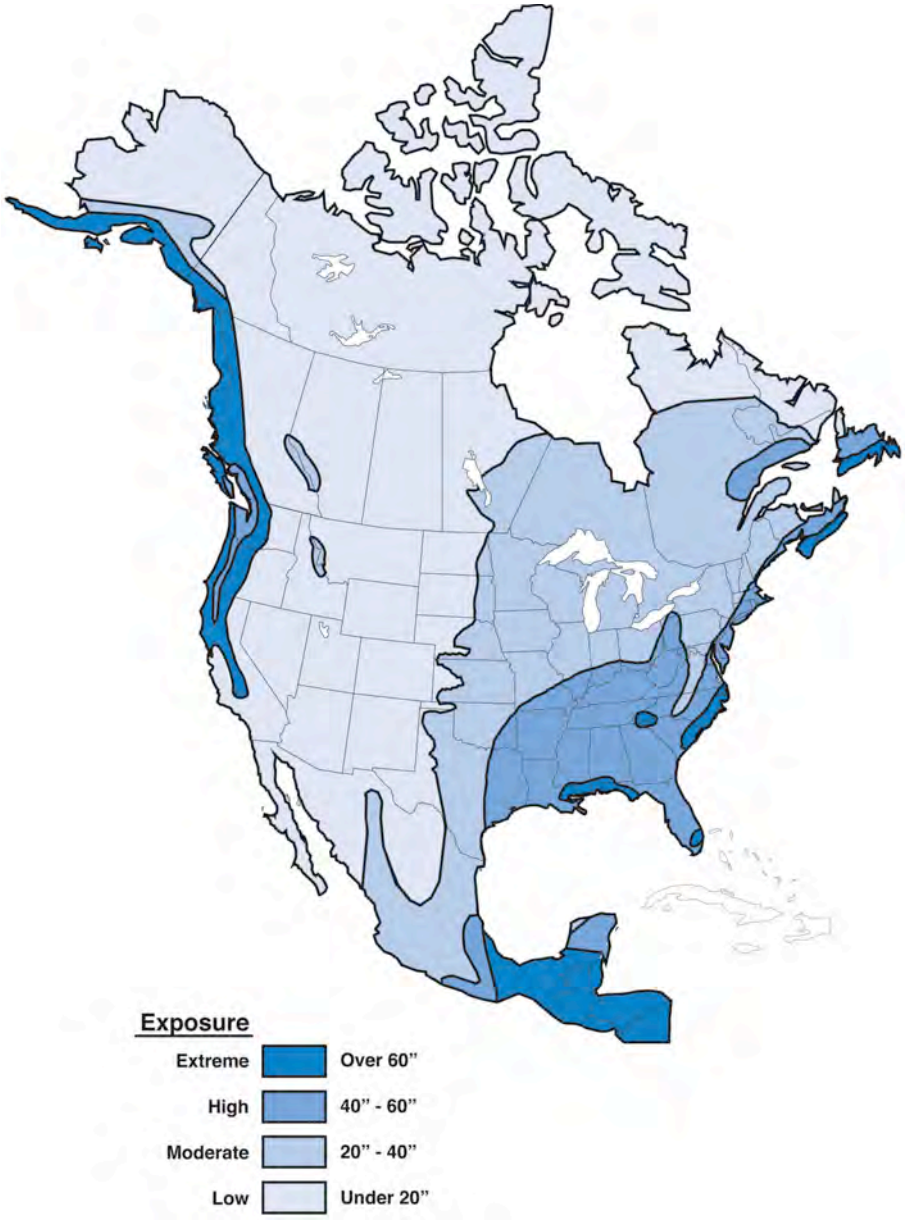
Cat. No. 794-002 Printed in U.S.A.

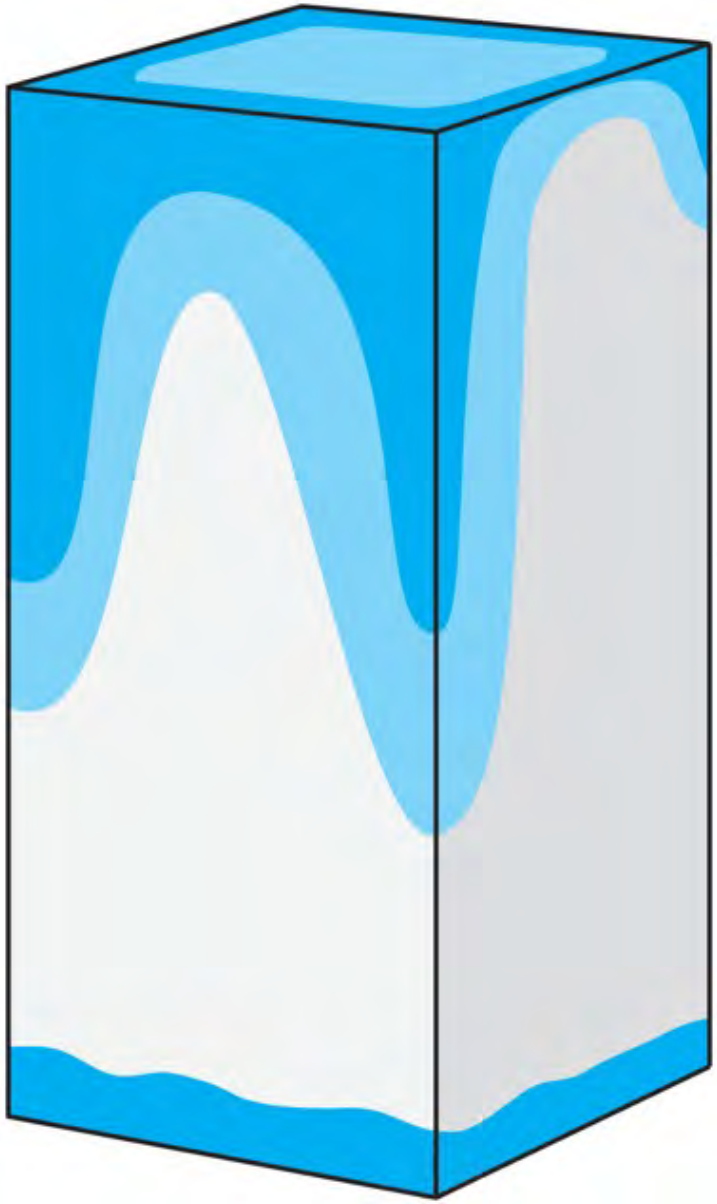
The Effect of Climate

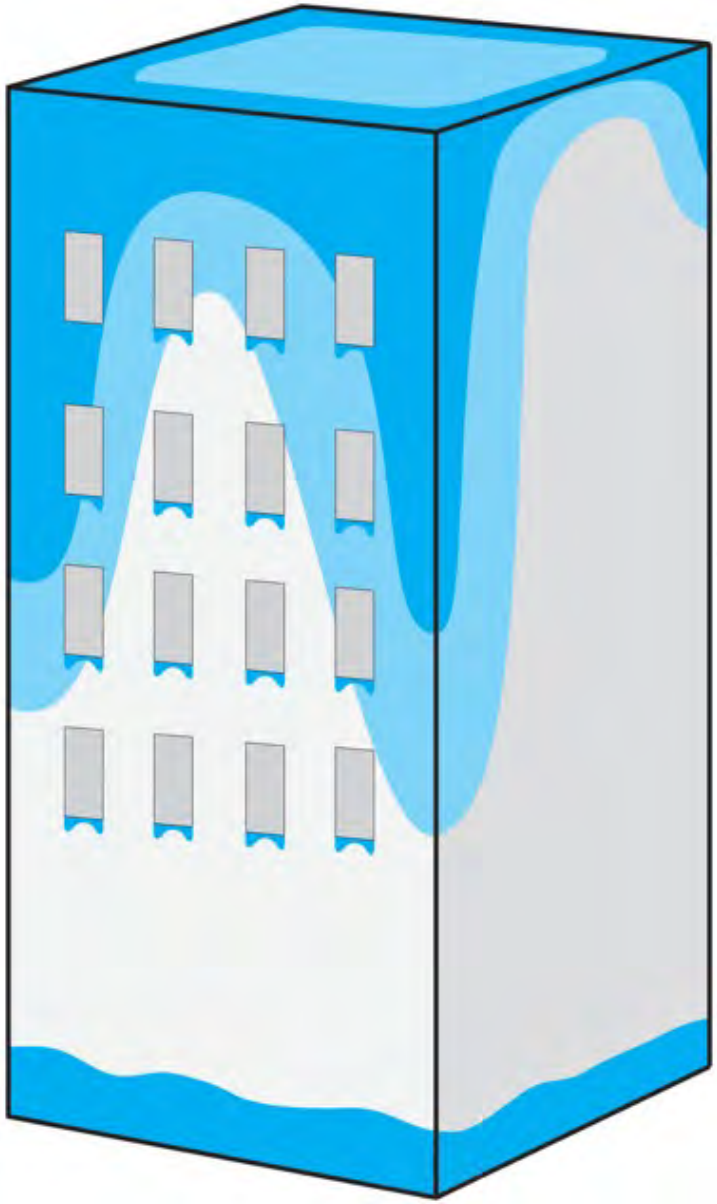

Subarctic/Arctic
Very Cold
Marine
Cold
Mixed-Humid
Mixed-Dry
Hot-Humid
Hot-Dry


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


Map of DOE's Proposed Climate Zones
Marine (C)
Dry (B)
Moist (A)
Warm-Humid
Below White Line
All of Alaska in Zone 7
except for the following
Boroughs in Zone 8:
Bethel
Dellingham
Fairbanks N. Star
Nome
North Slope
Northwest Arctic
Southeast Fairbanks
Wade Hampton
Yukon-Koyukuk
Zone 1 includes
Hawaii, Guam,
Puerto Rico,
and the Virgin Islands
March 24, 2003


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





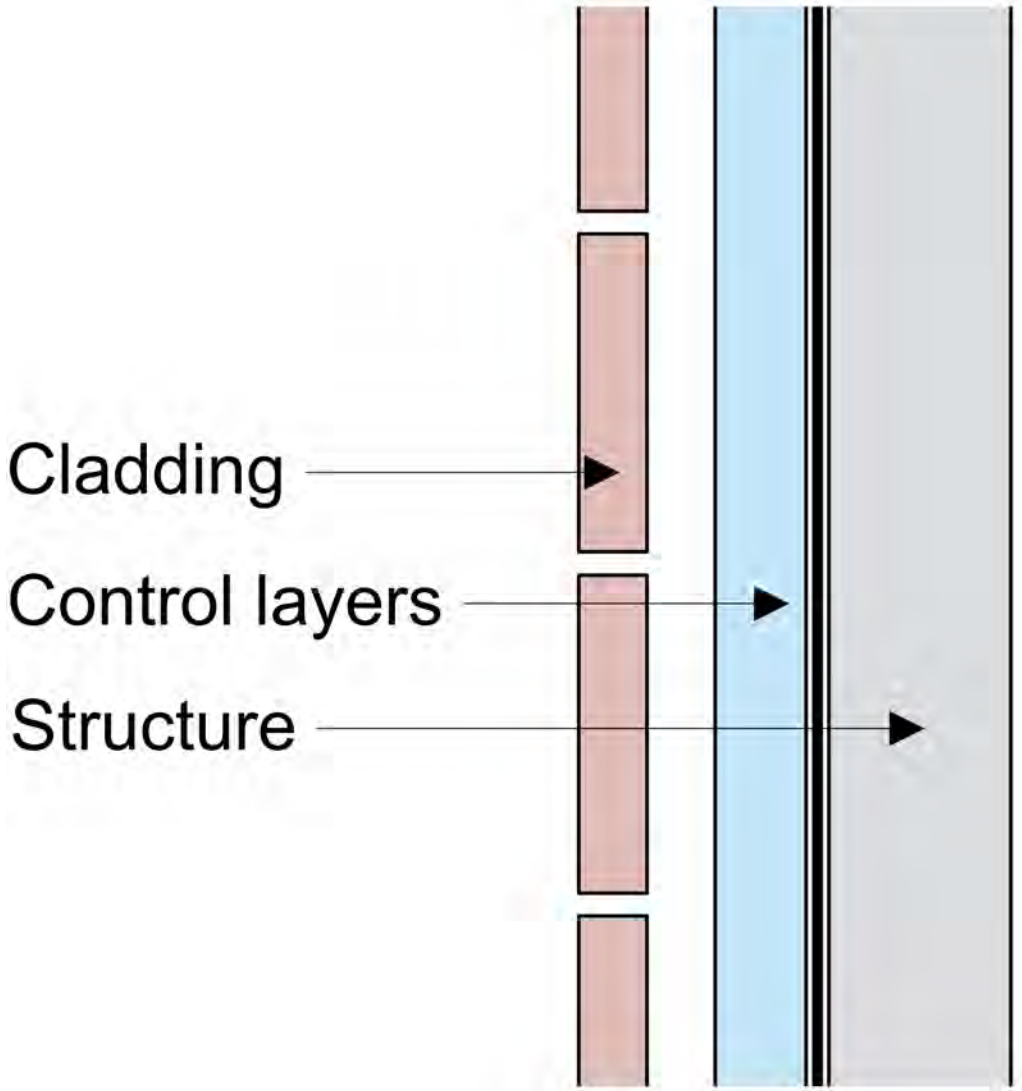
The Perfect Wall

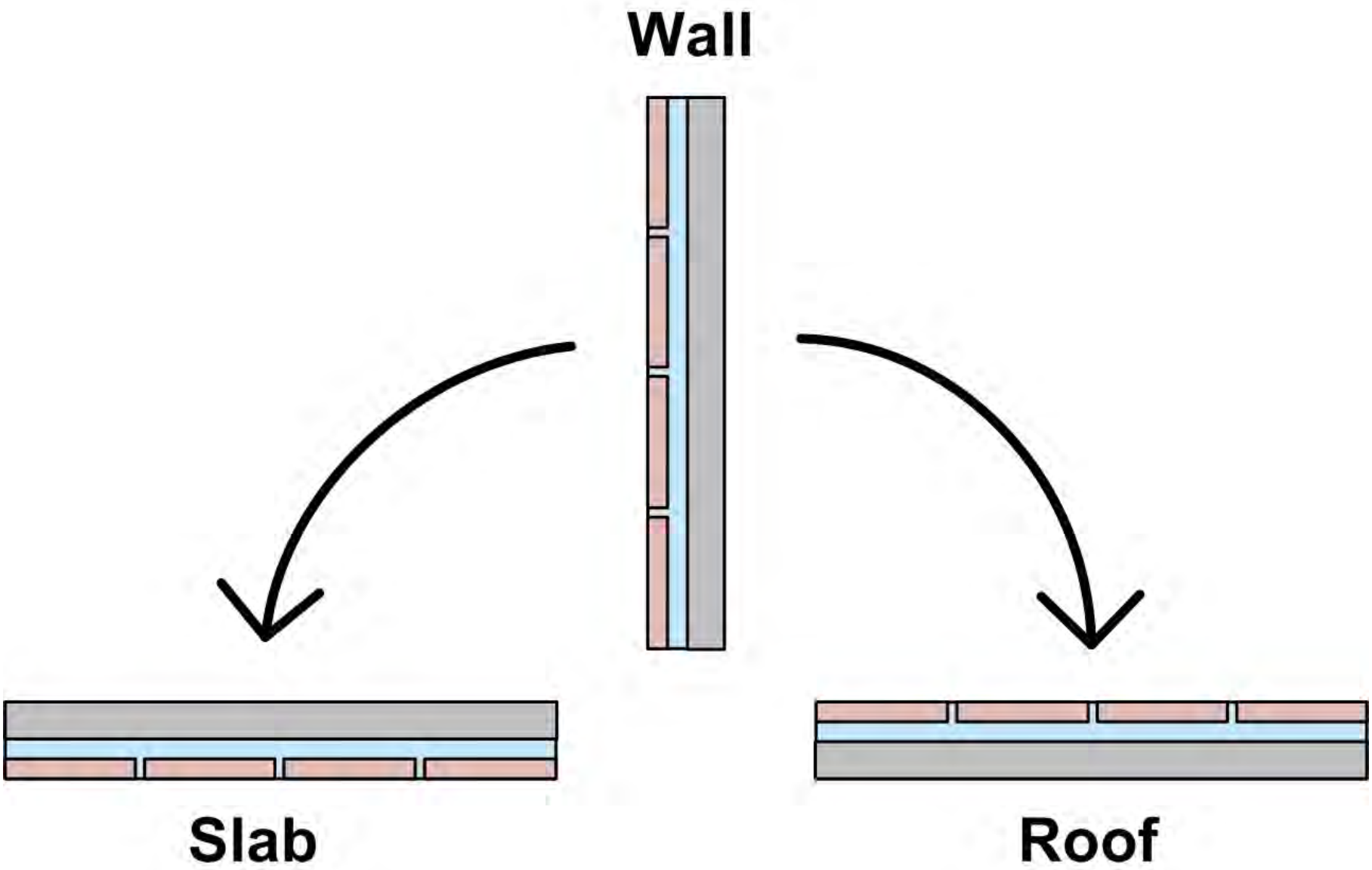
Water Control Layer

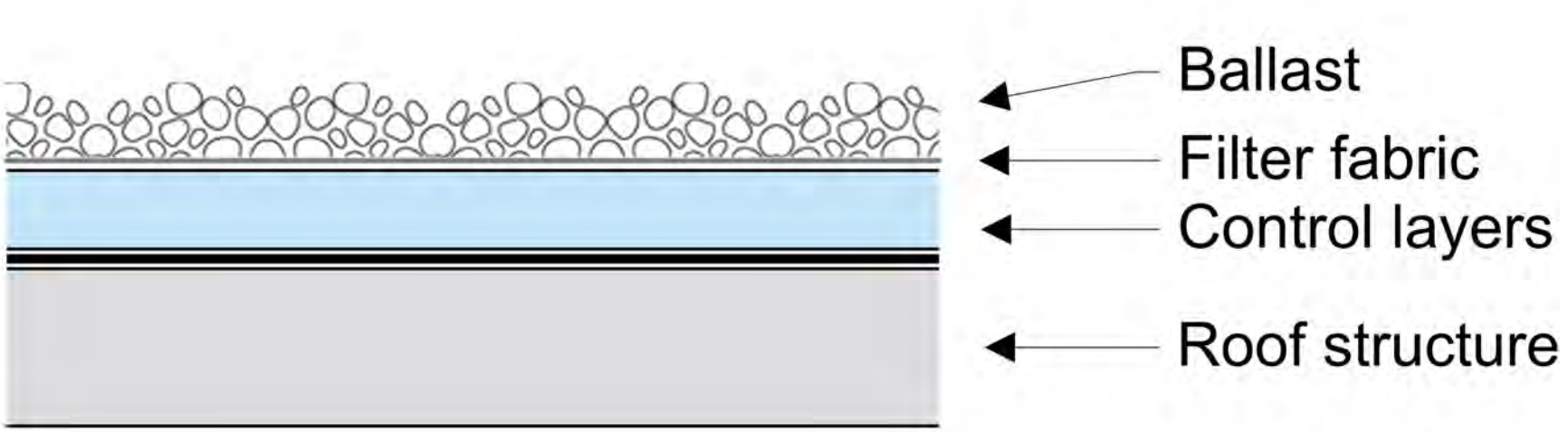
Air Control Layer

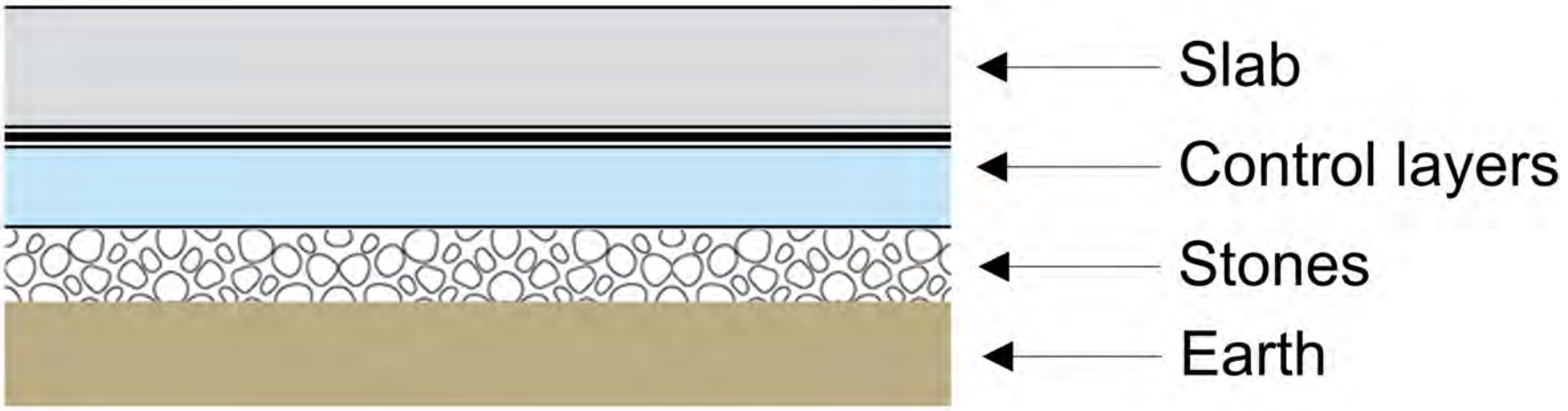
Vapor Control Layer

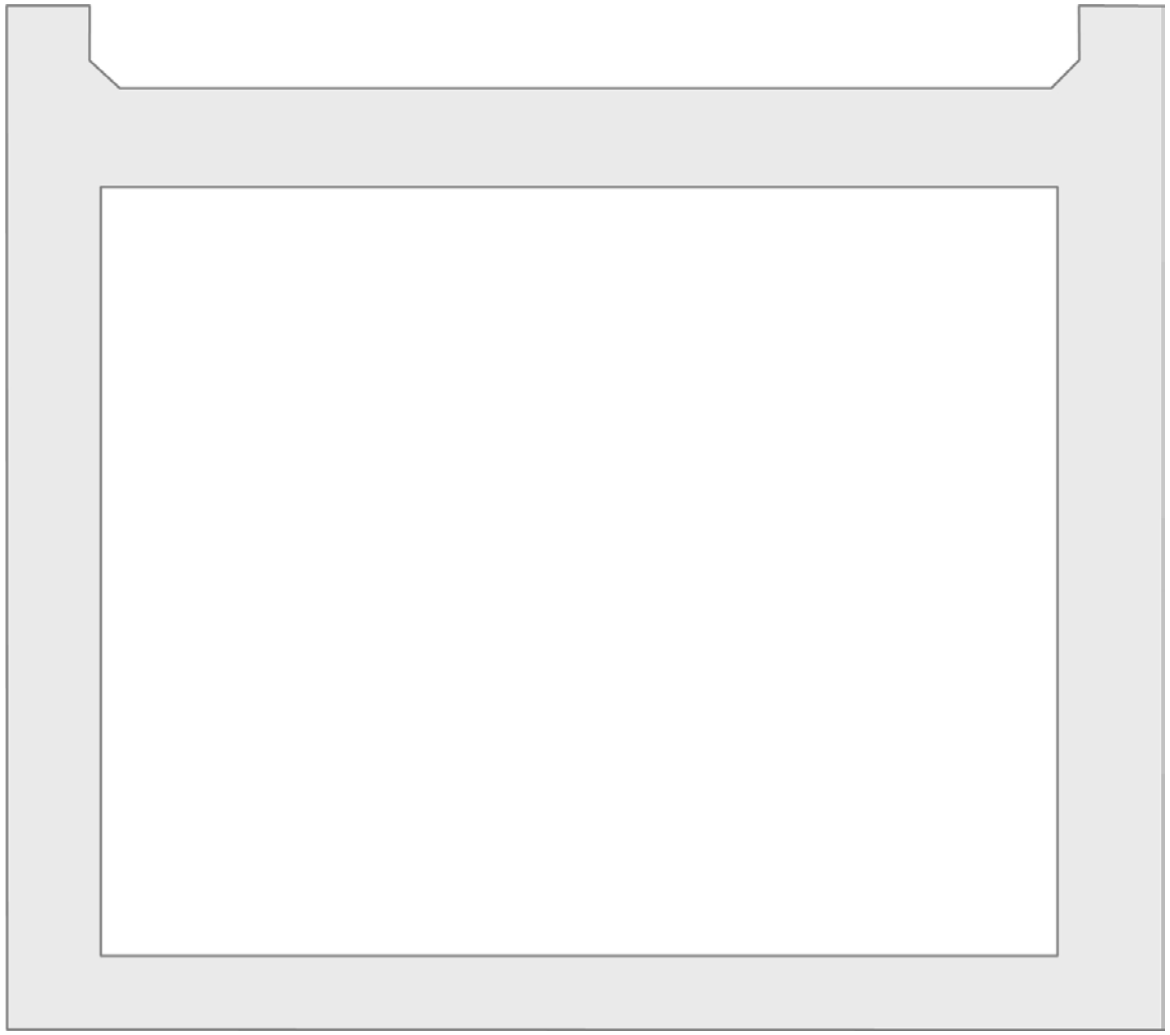
Thermal Control Layer

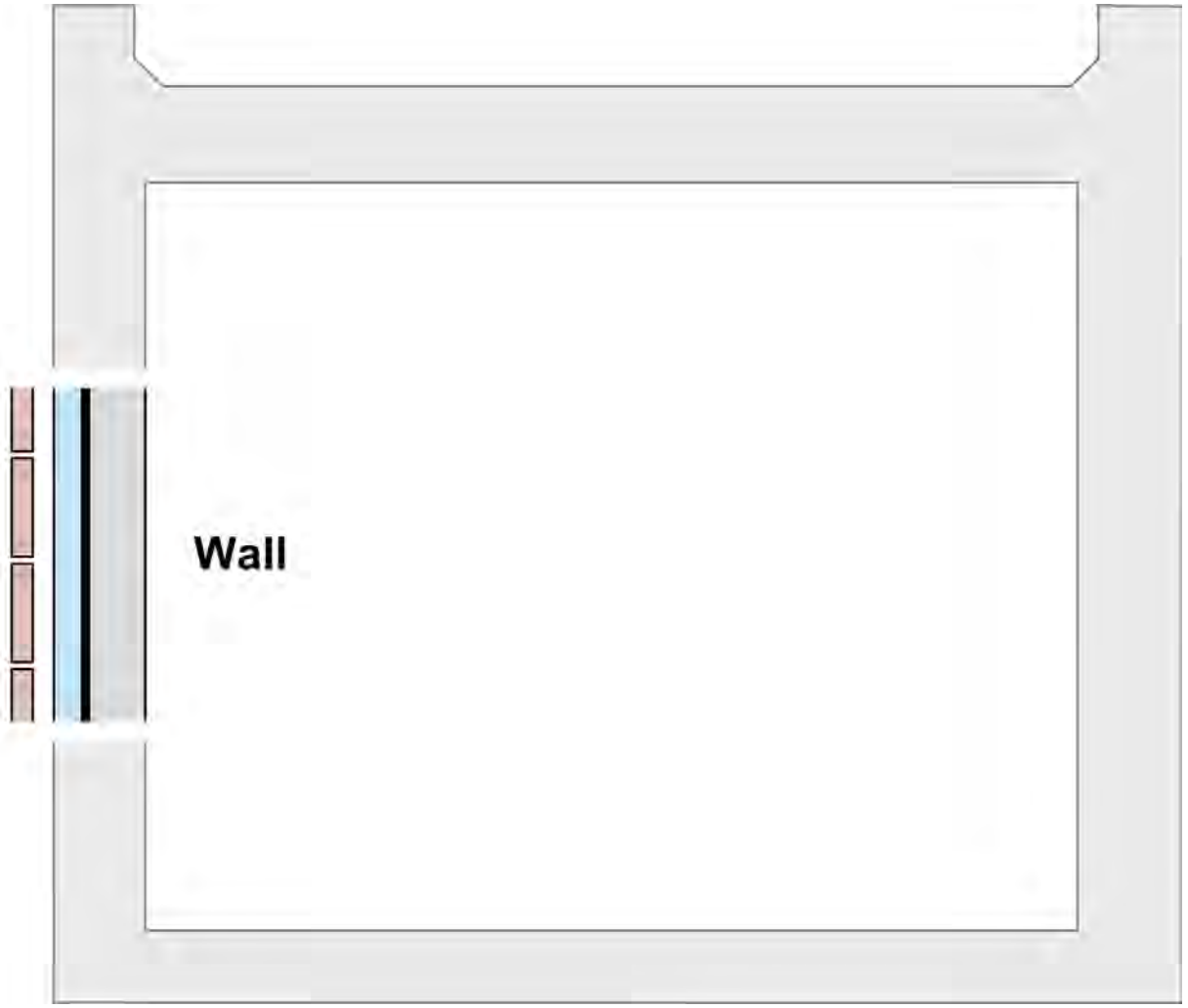

Cladding
Control layers
Structure

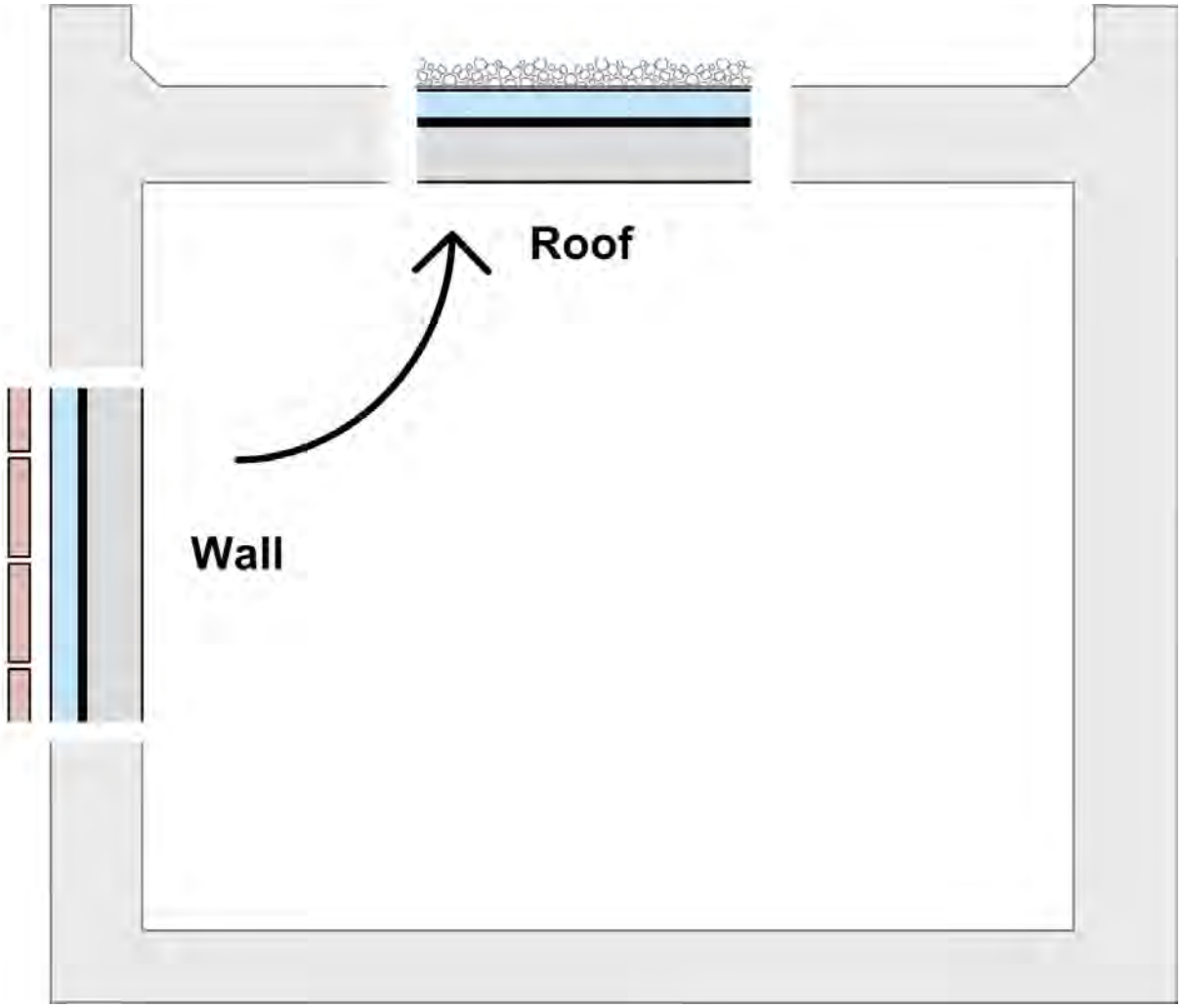

Wall
Slab
Roof

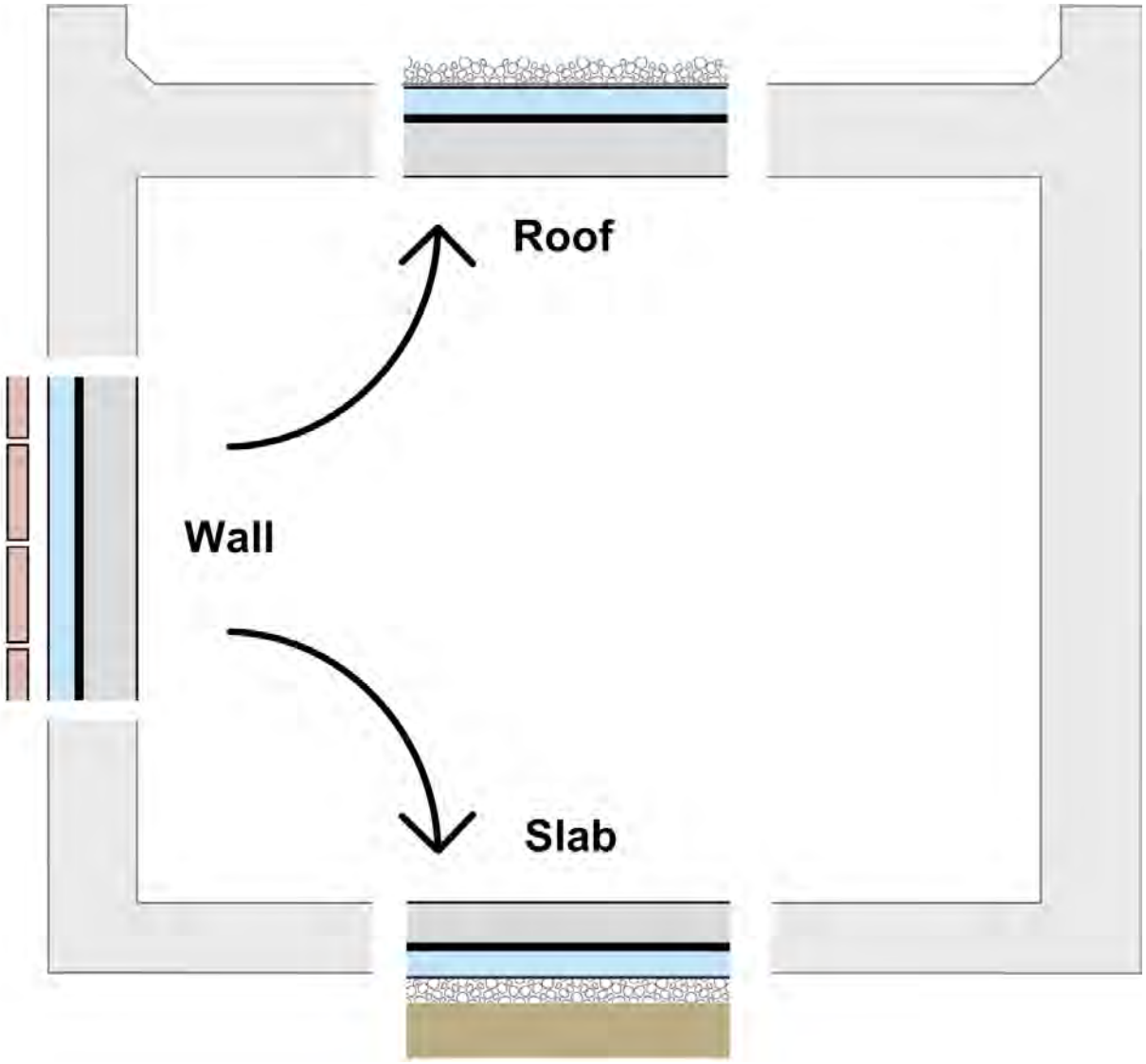

Ballast
Filter fabric
Control layers
Roof structure

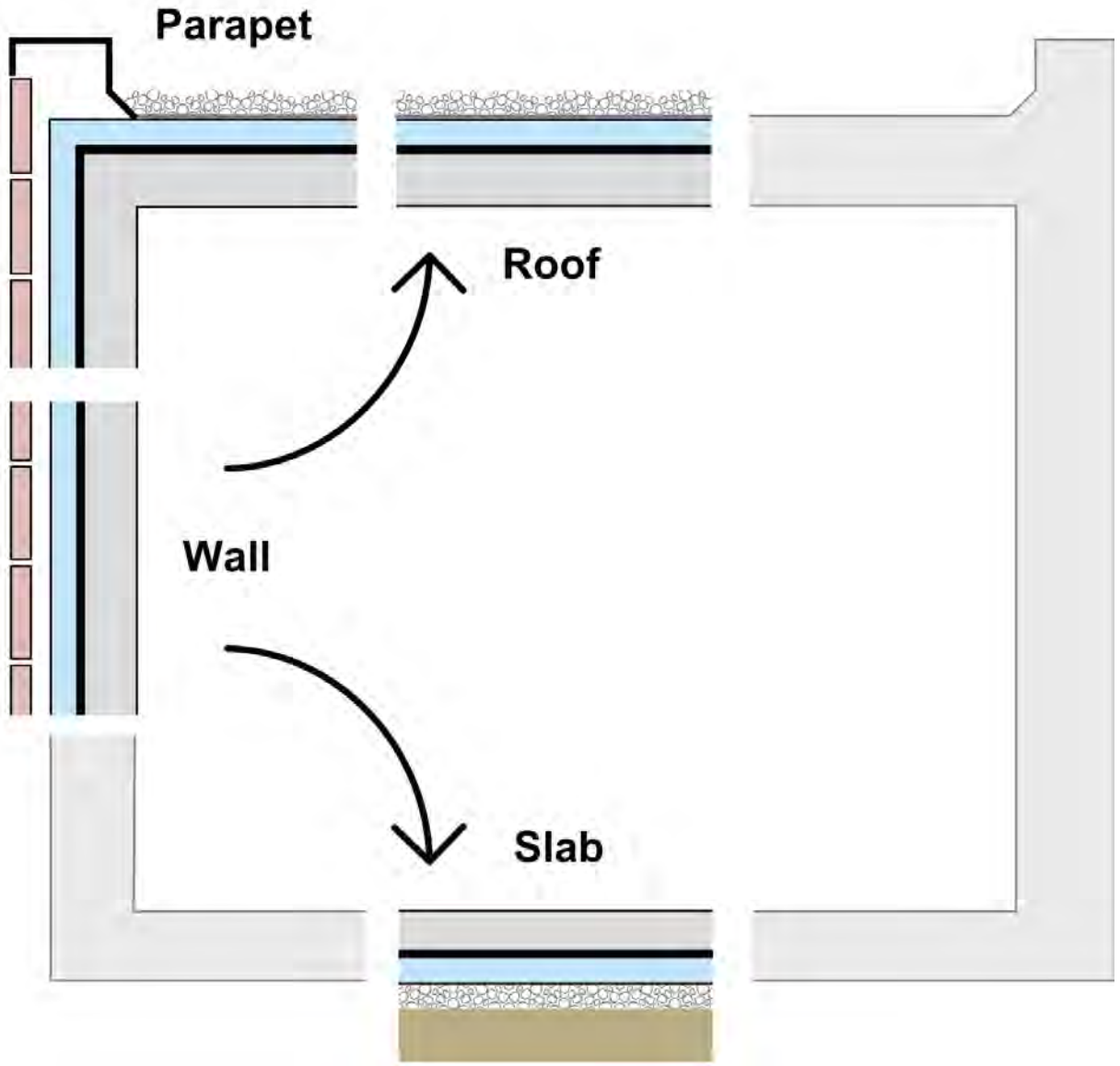

Slab
Control layers
Stones
Earth

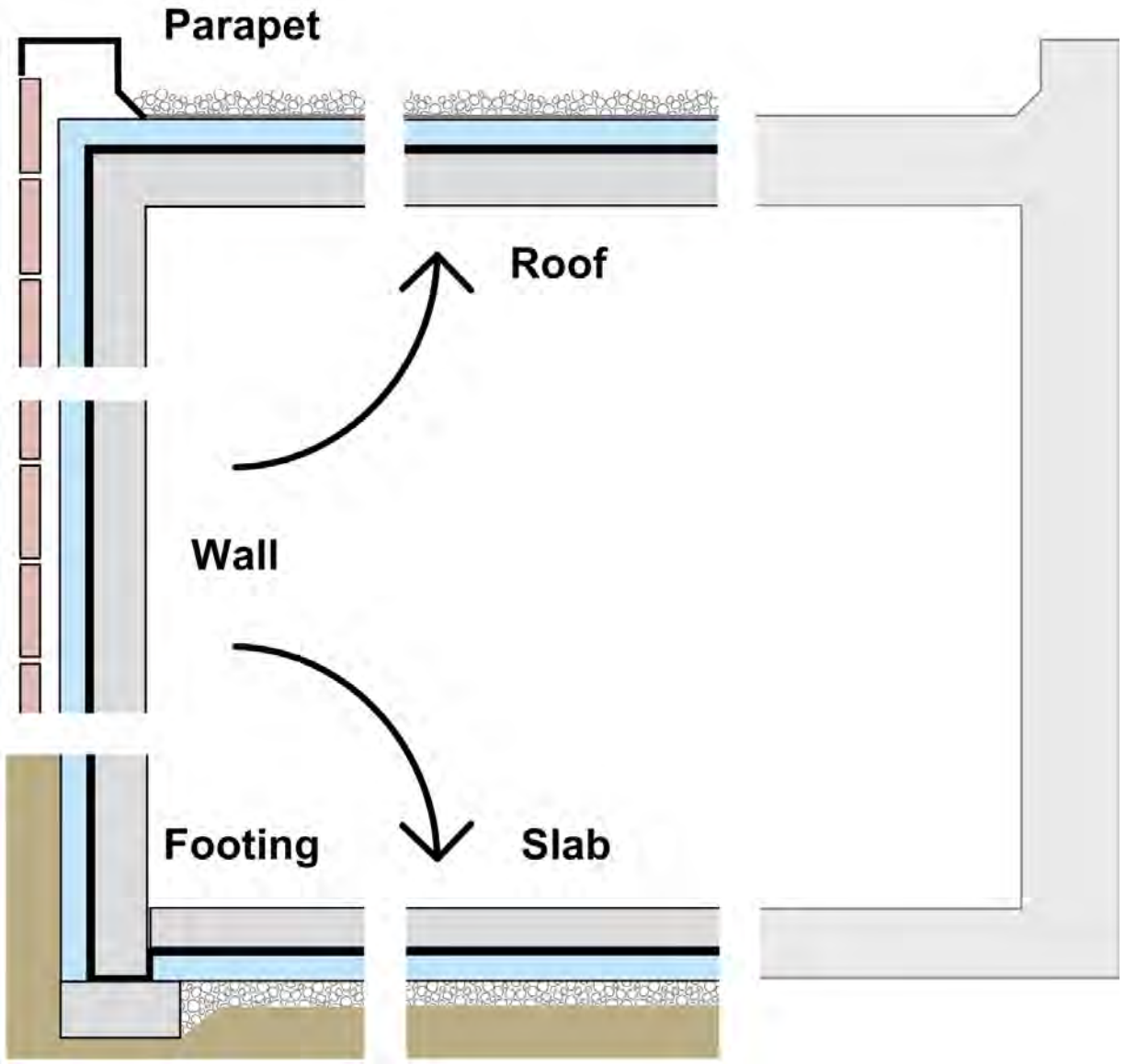


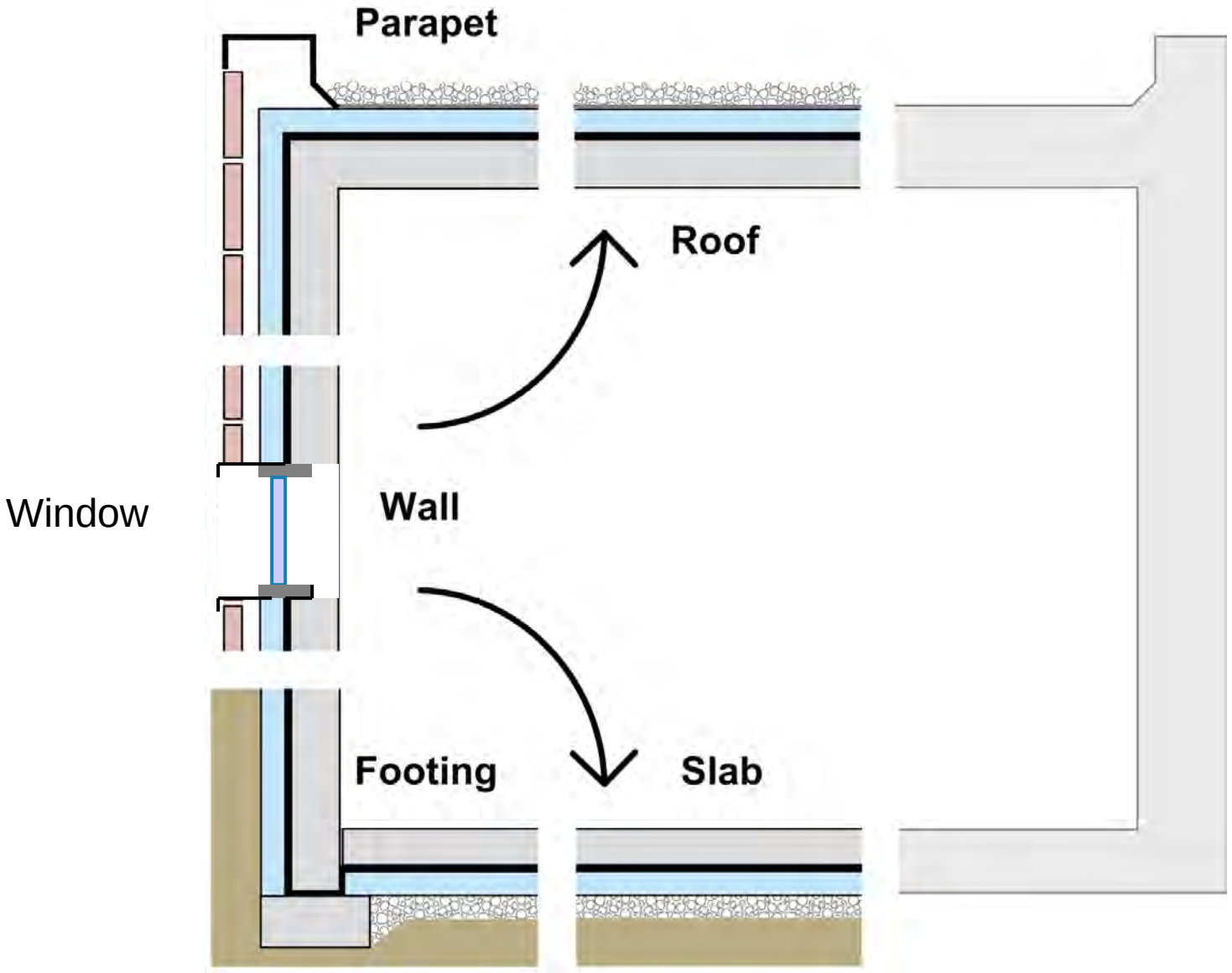

Wall

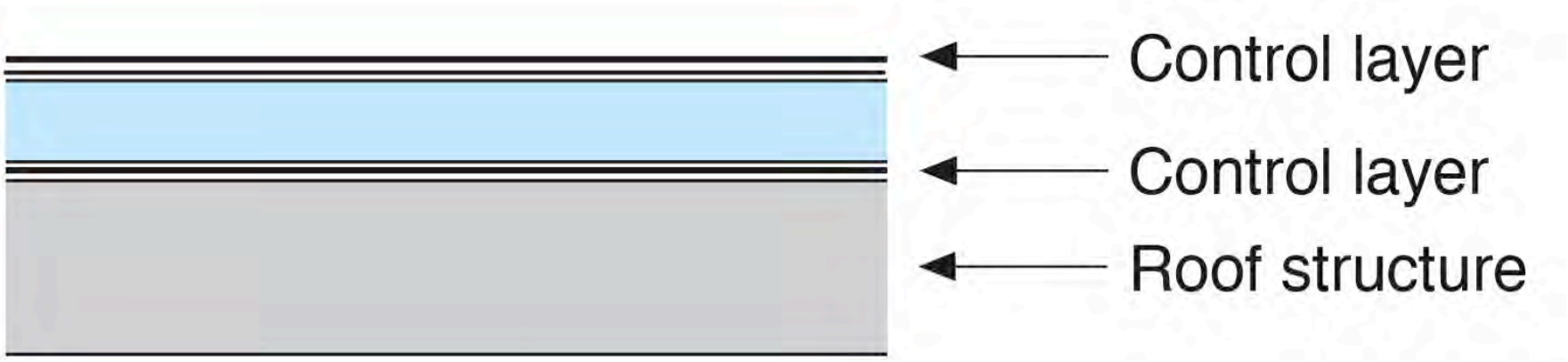

Roof
Wall

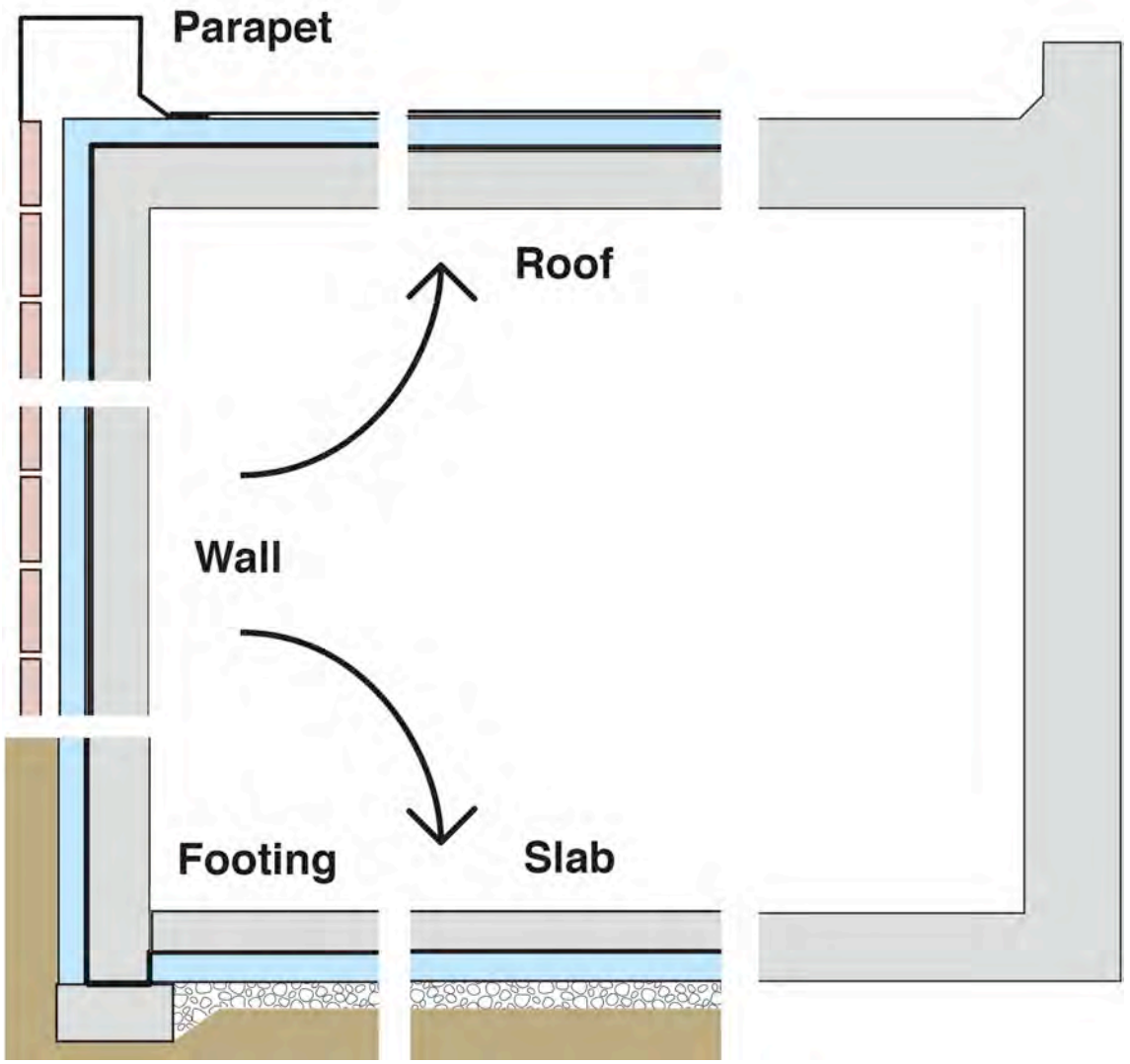

Roof
Wall
Slab

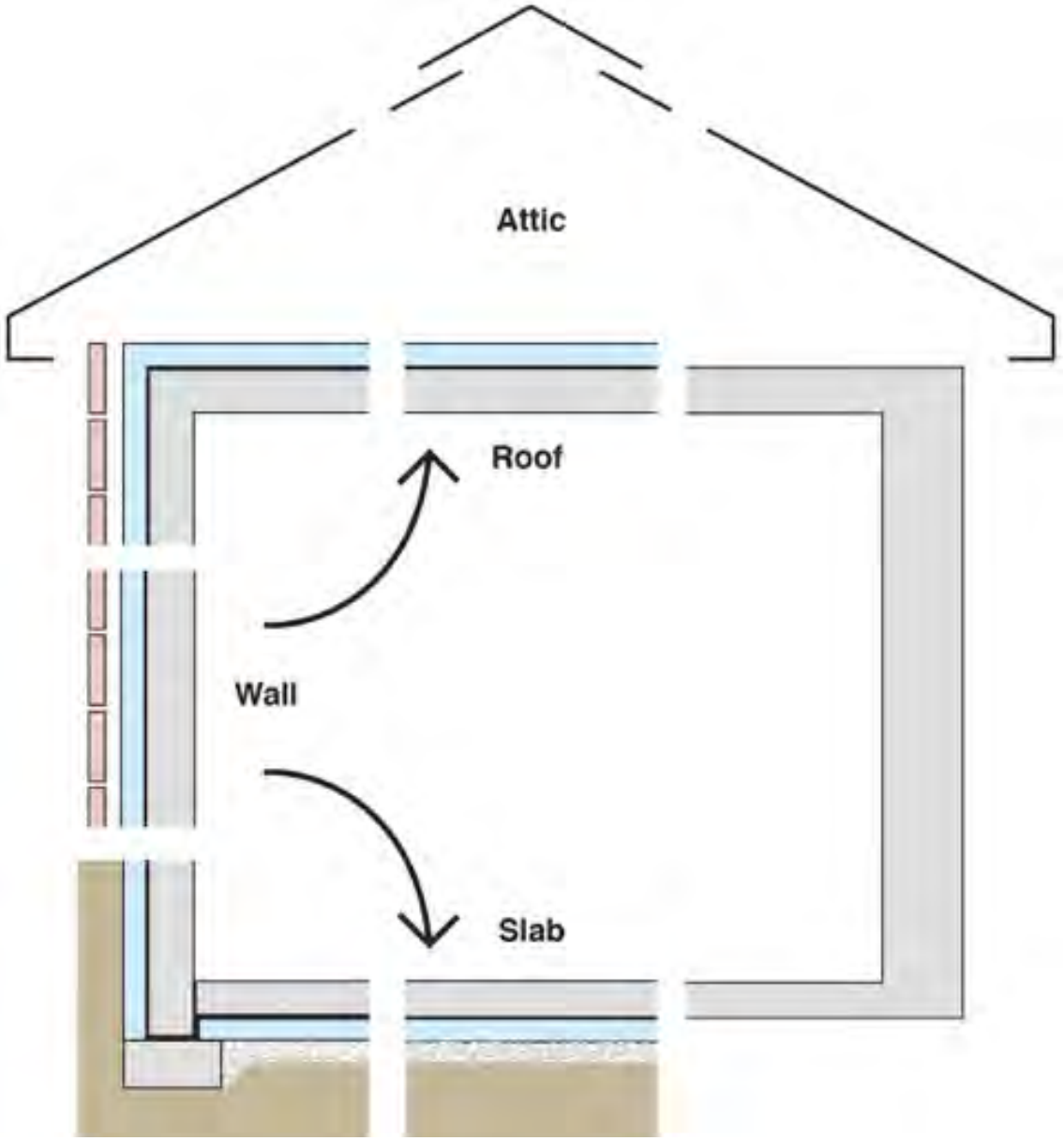

Parapet
Roof
Wall
Slab

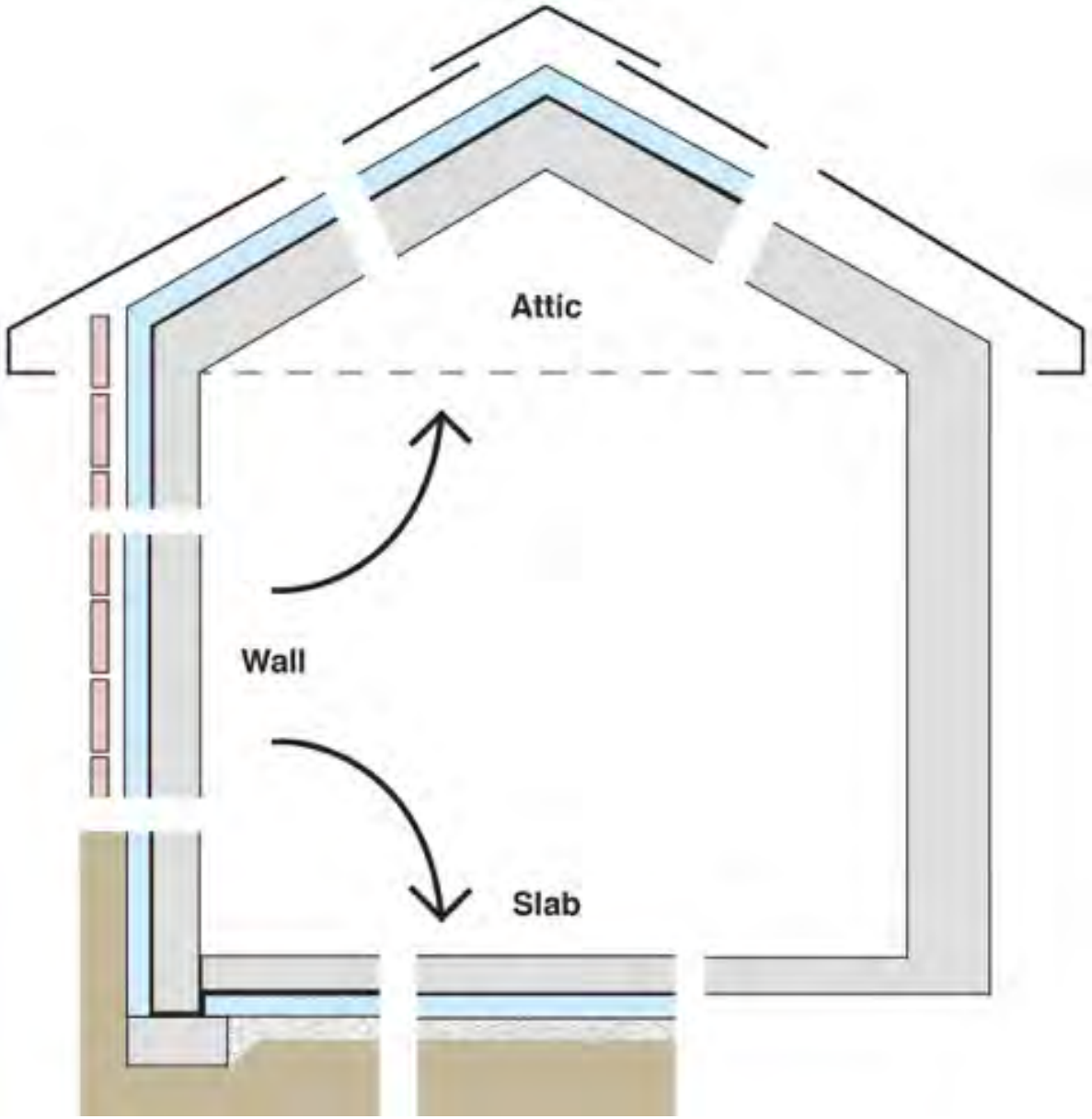

Parapet
Roof
Wall
Footing
Slab

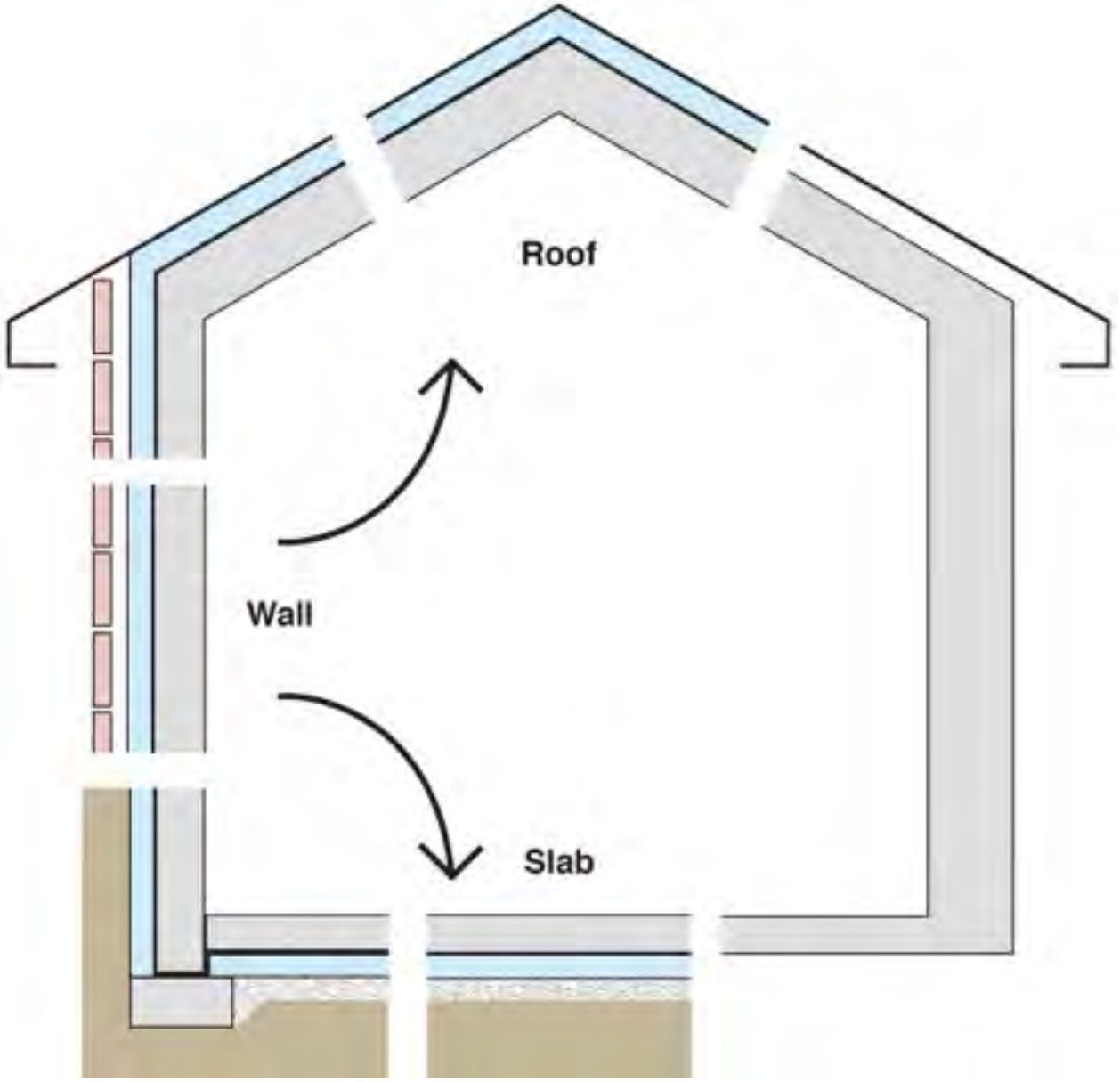

Parapet
Roof
Window
Wall
Footing
Slab

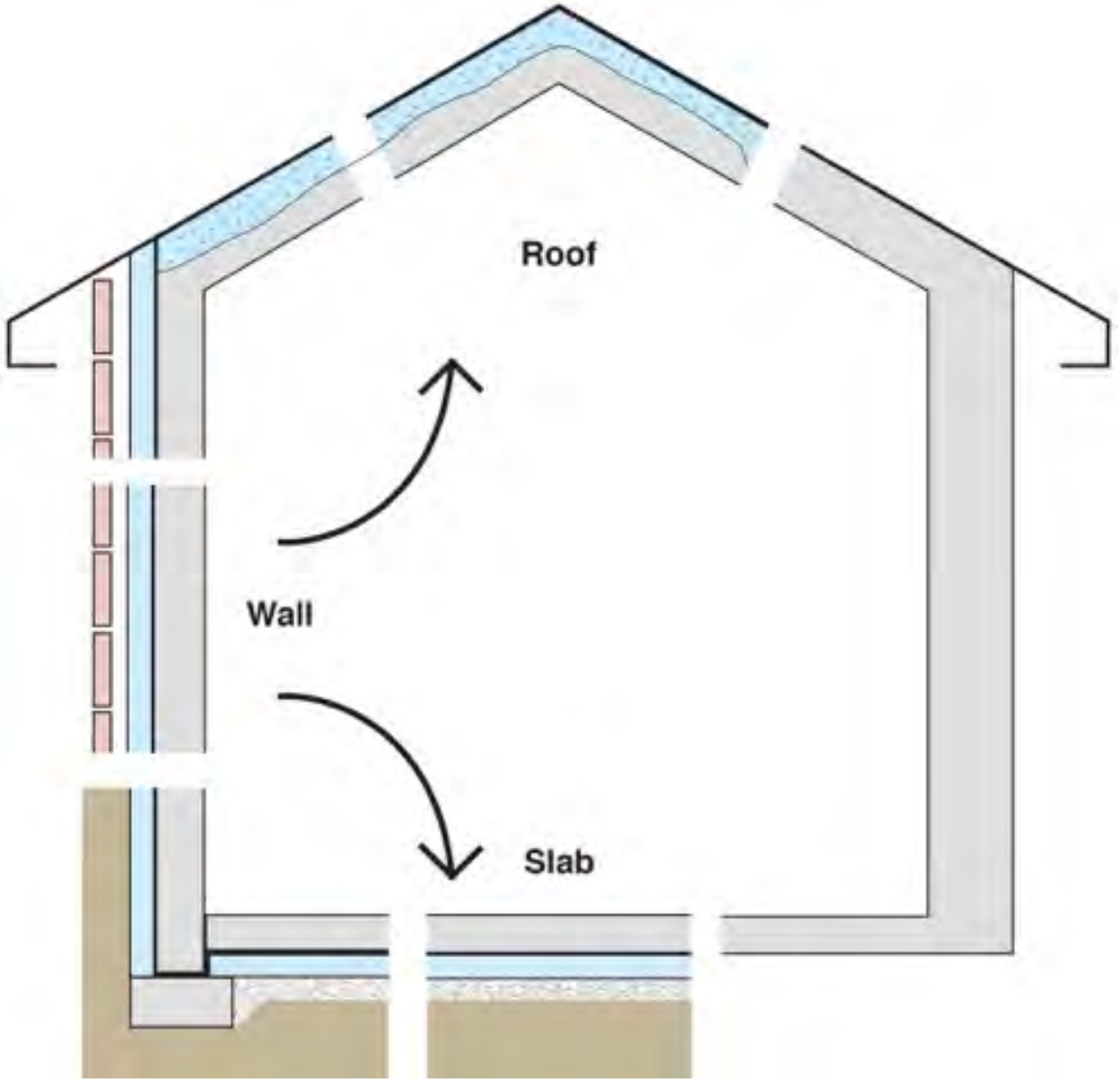

Control layer
Control layer
Roof structure


Parapet
Roof
Wall
Footing
Slab

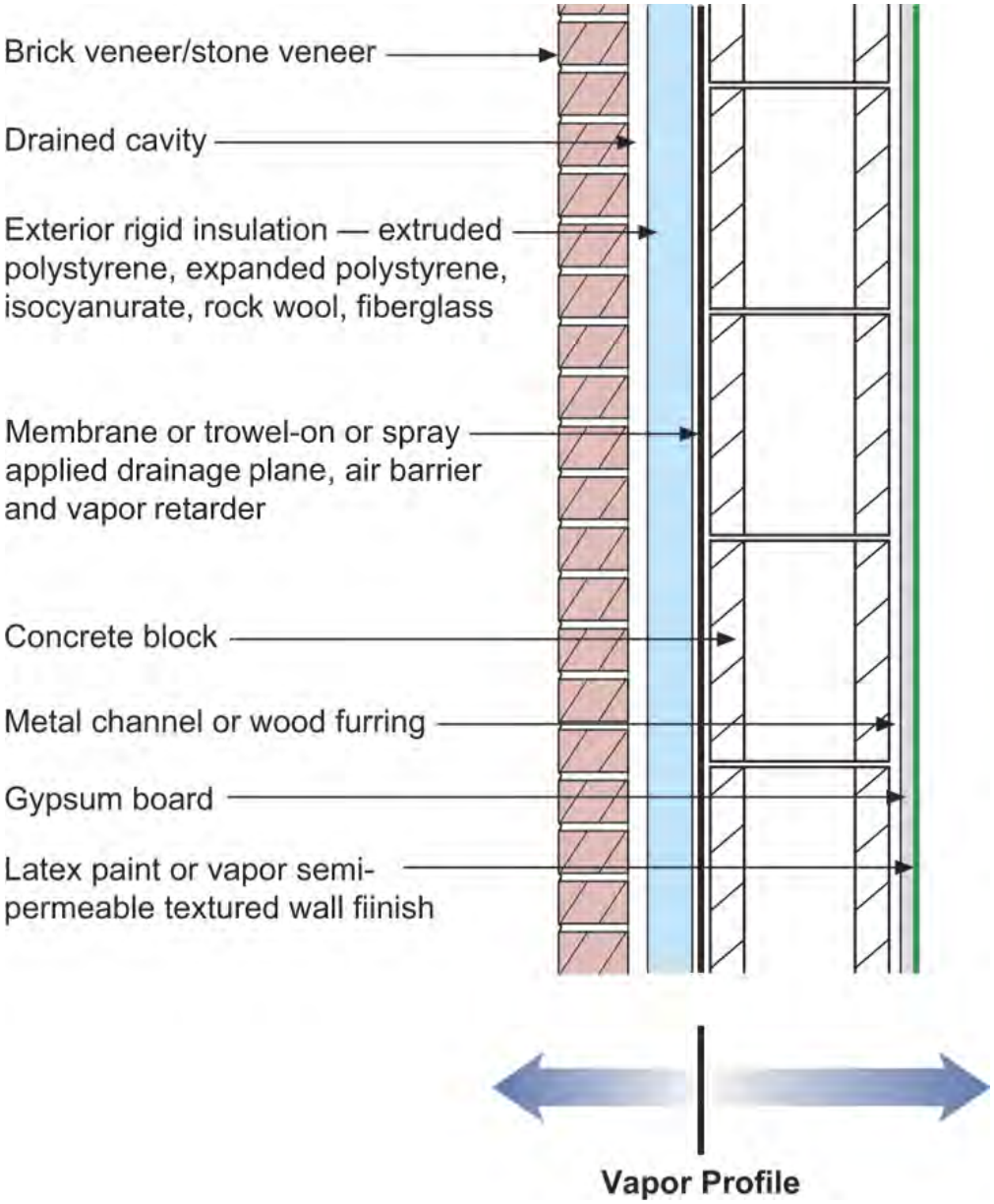

Attic
Roof
Wall
Slab

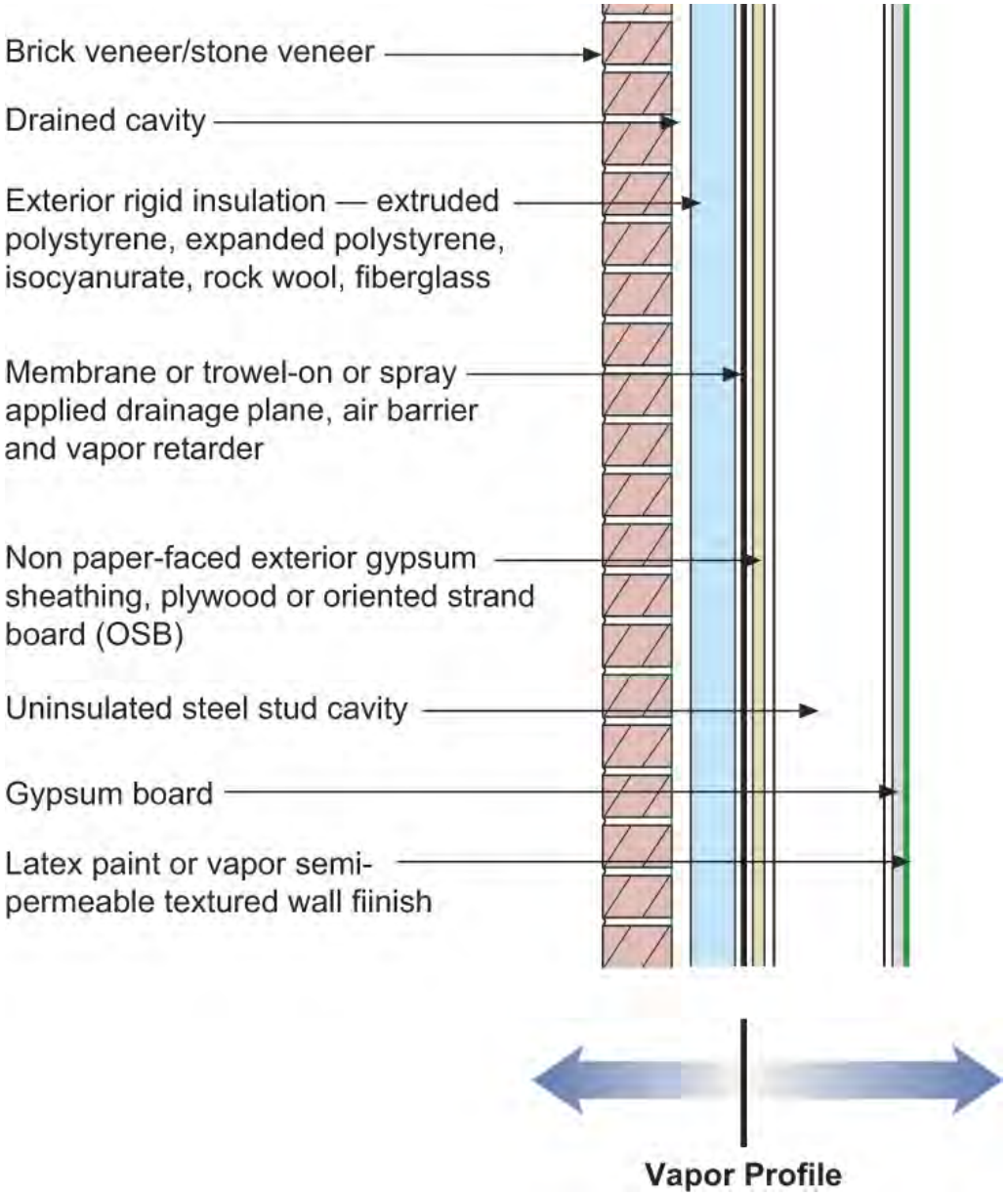

Attic
Wall
Slab

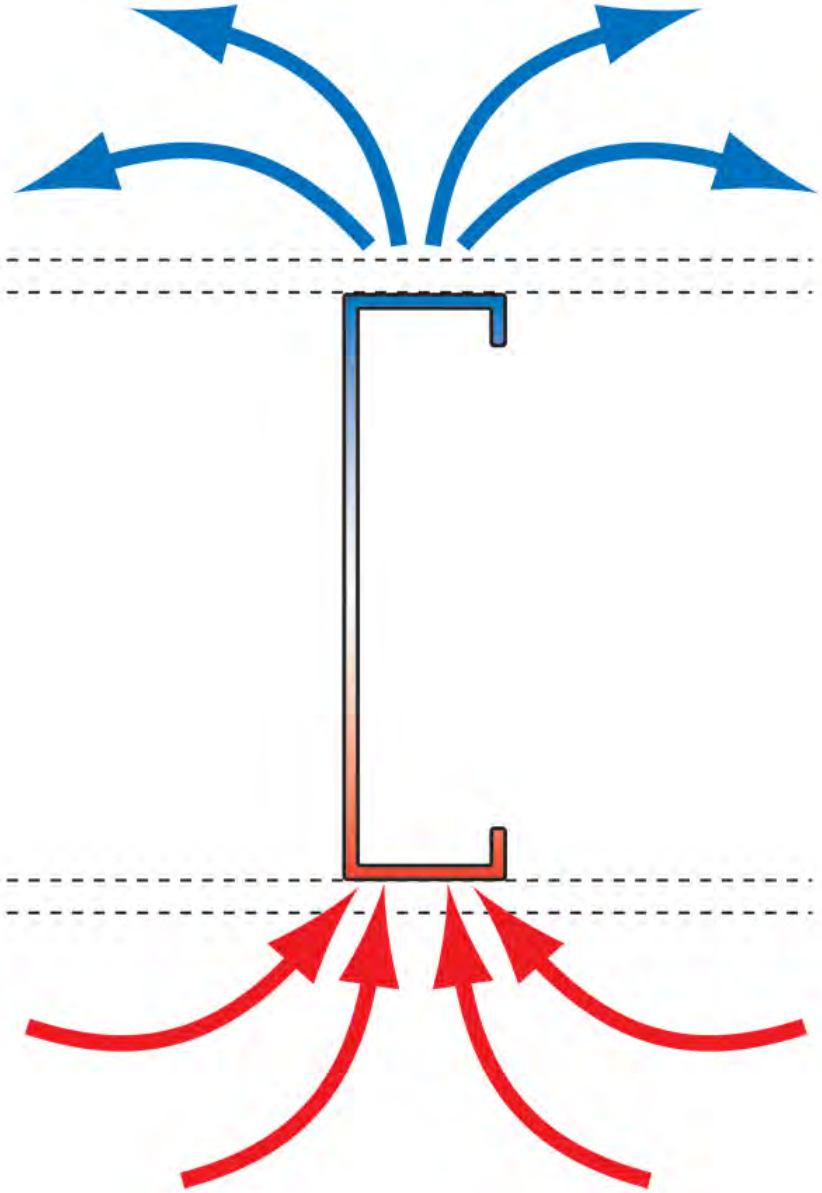

Roof
Wall
Slab

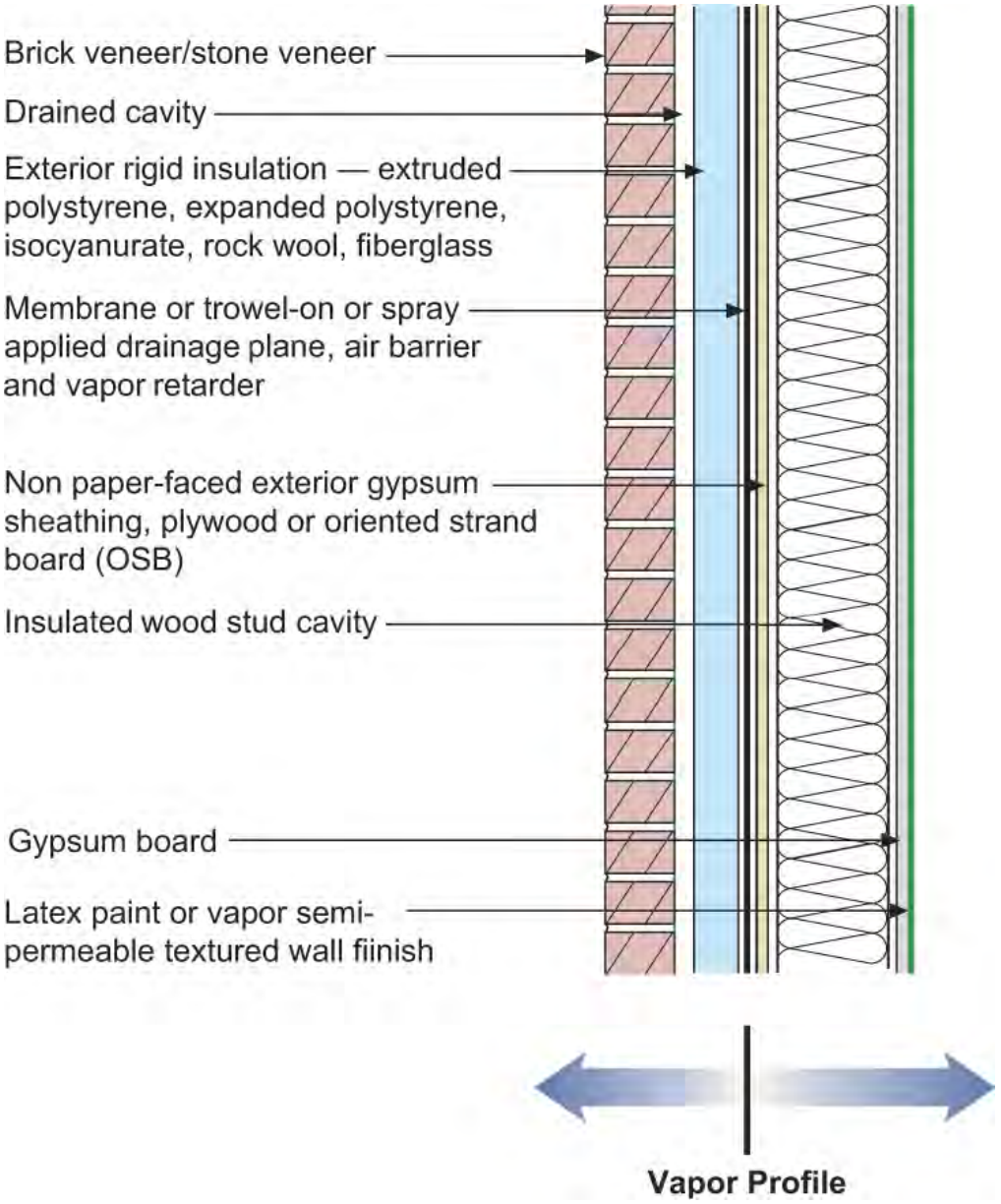

Roof
Wall
Slab

Configurations of the Perfect Wall

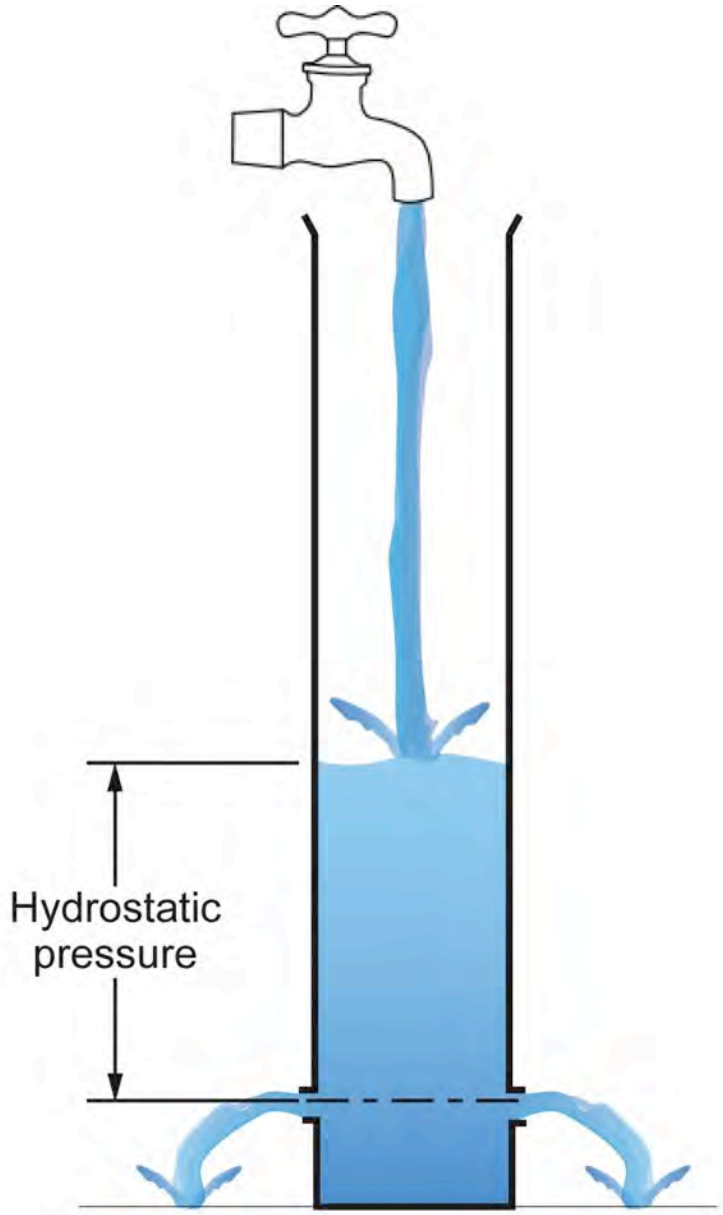

Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Concrete block
Metal channel or wood furring
Gypsum board
Latex paint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

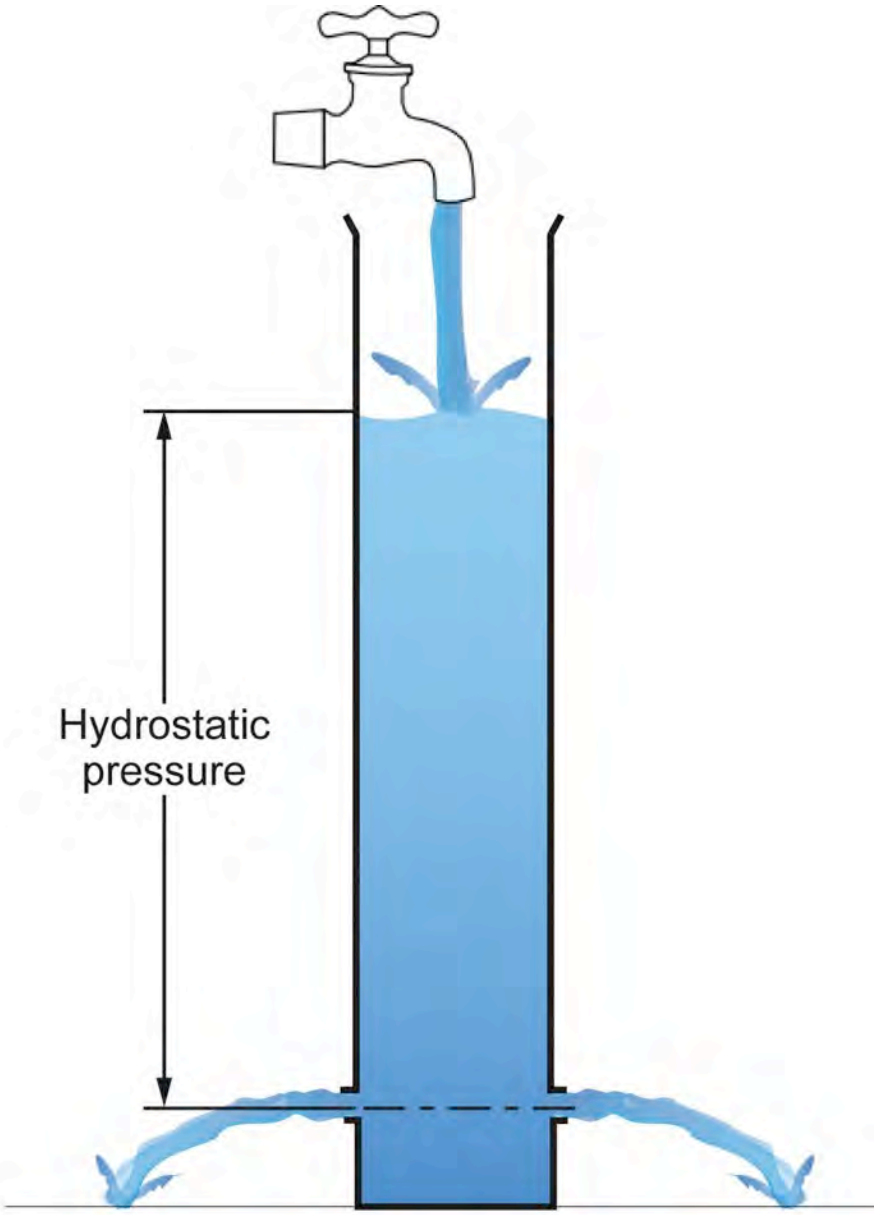

Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Non paper-faced exterior gypsum sheathing, plywood or oriented strand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

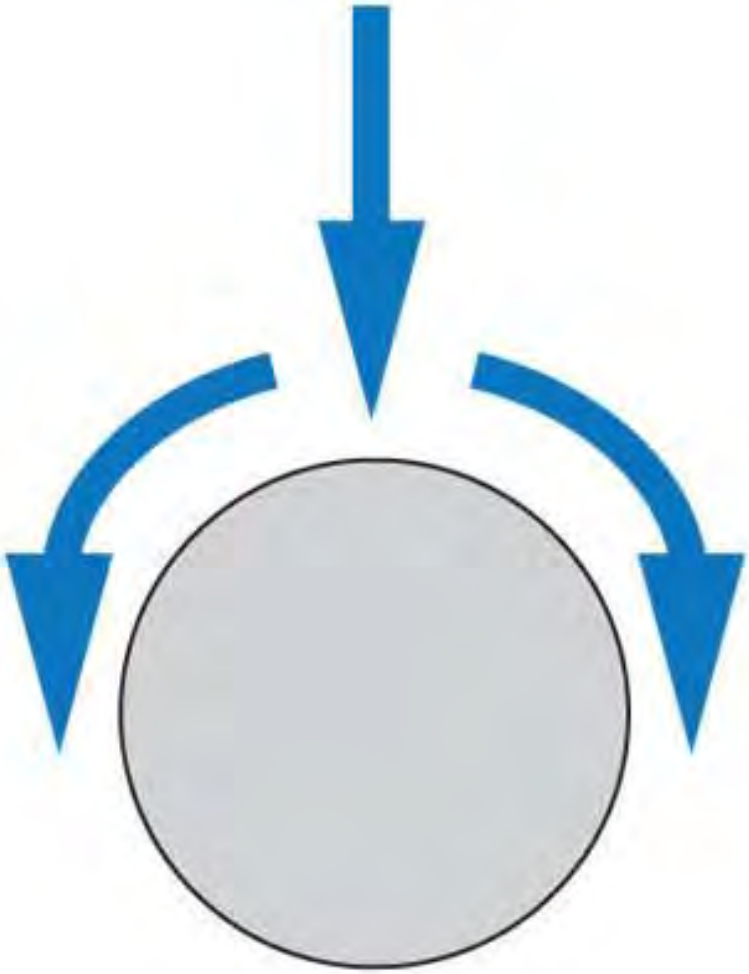


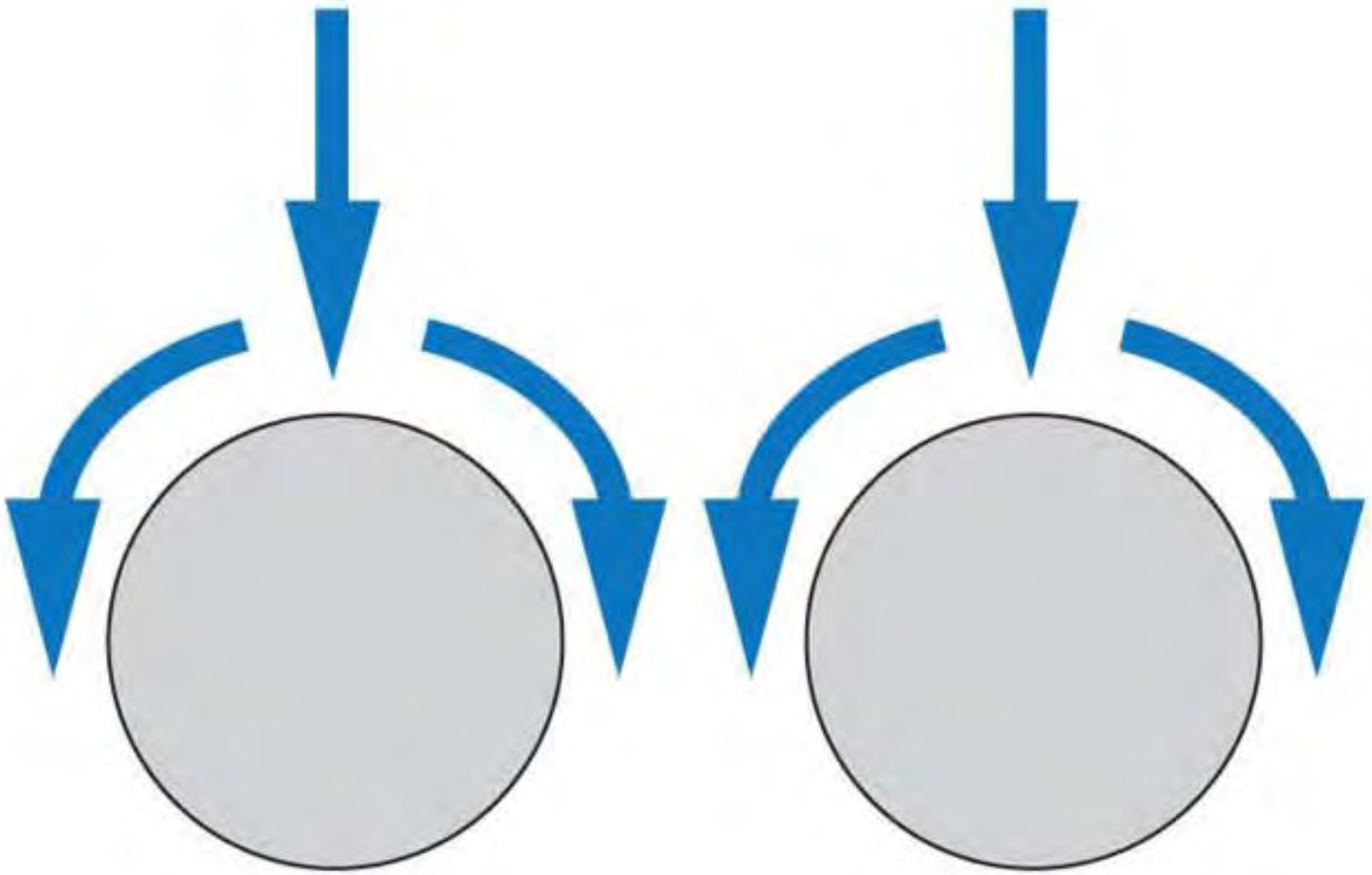

Brick veneer/stone veneer
Drained cavity
Exterior rigid insulation — extruded polystyrene, expanded polystyrene, isocyanurate, rock wool, fiberglass
Membrane or trowel-on or spray applied drainage plane, air barrier and vapor retarder
Non paper-faced exterior gypsum sheathing, plywood or oriented strand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

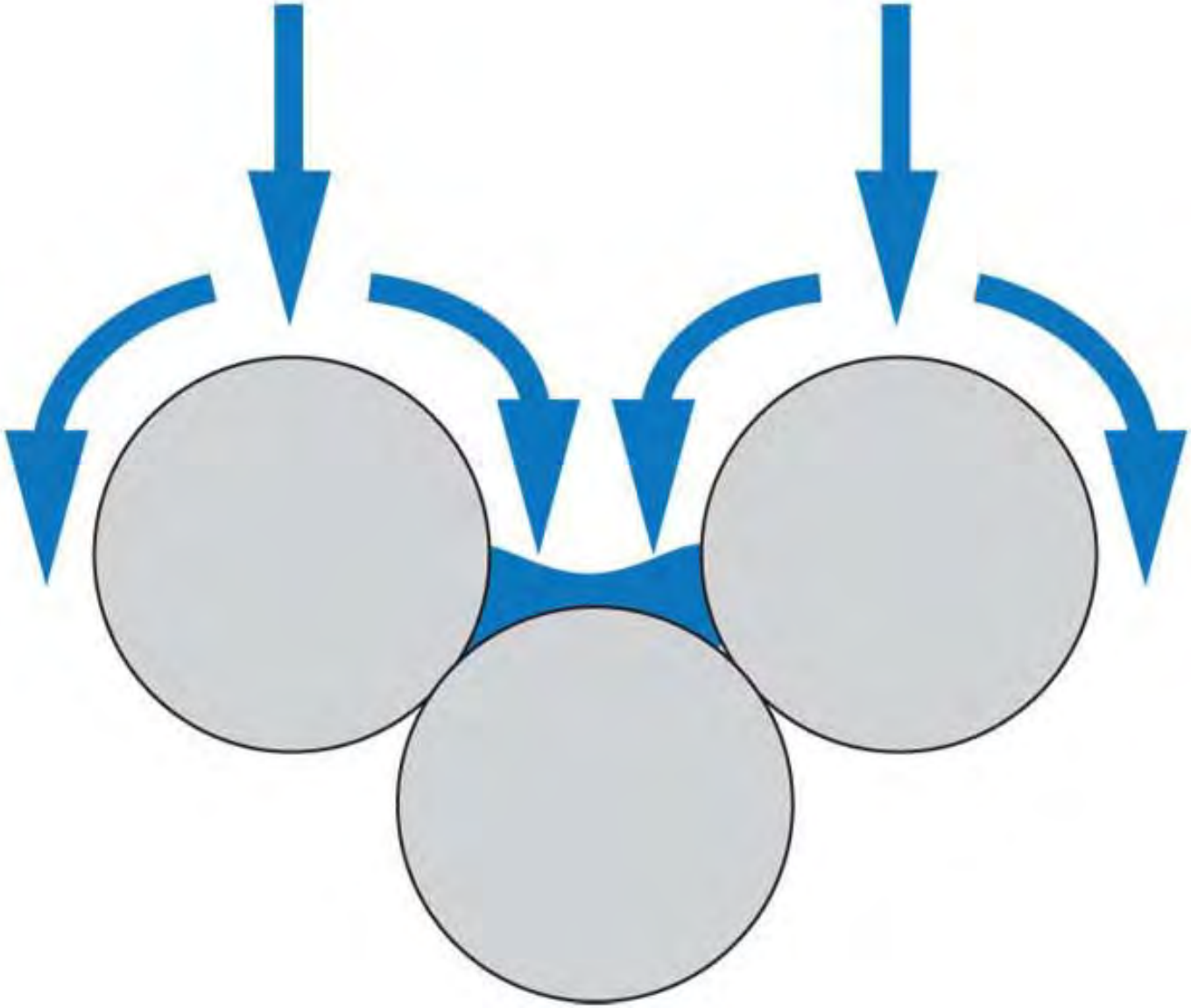
Rain

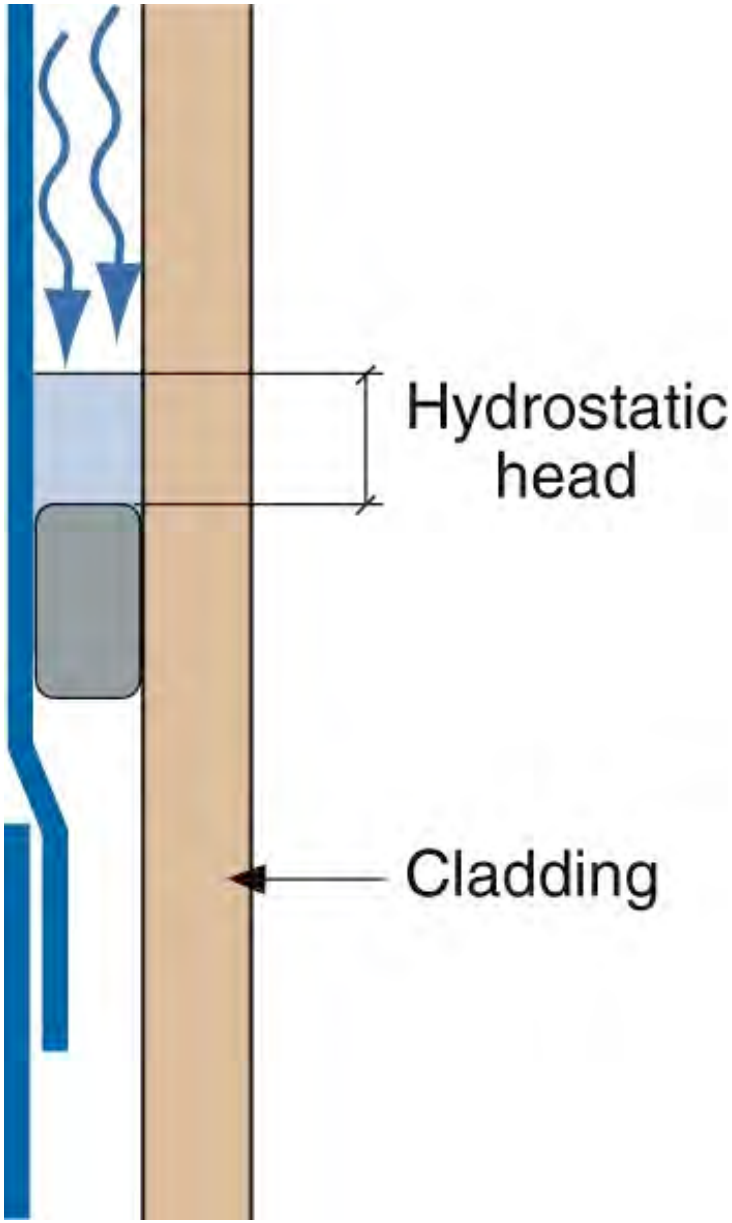

Hydrostatic
pressure

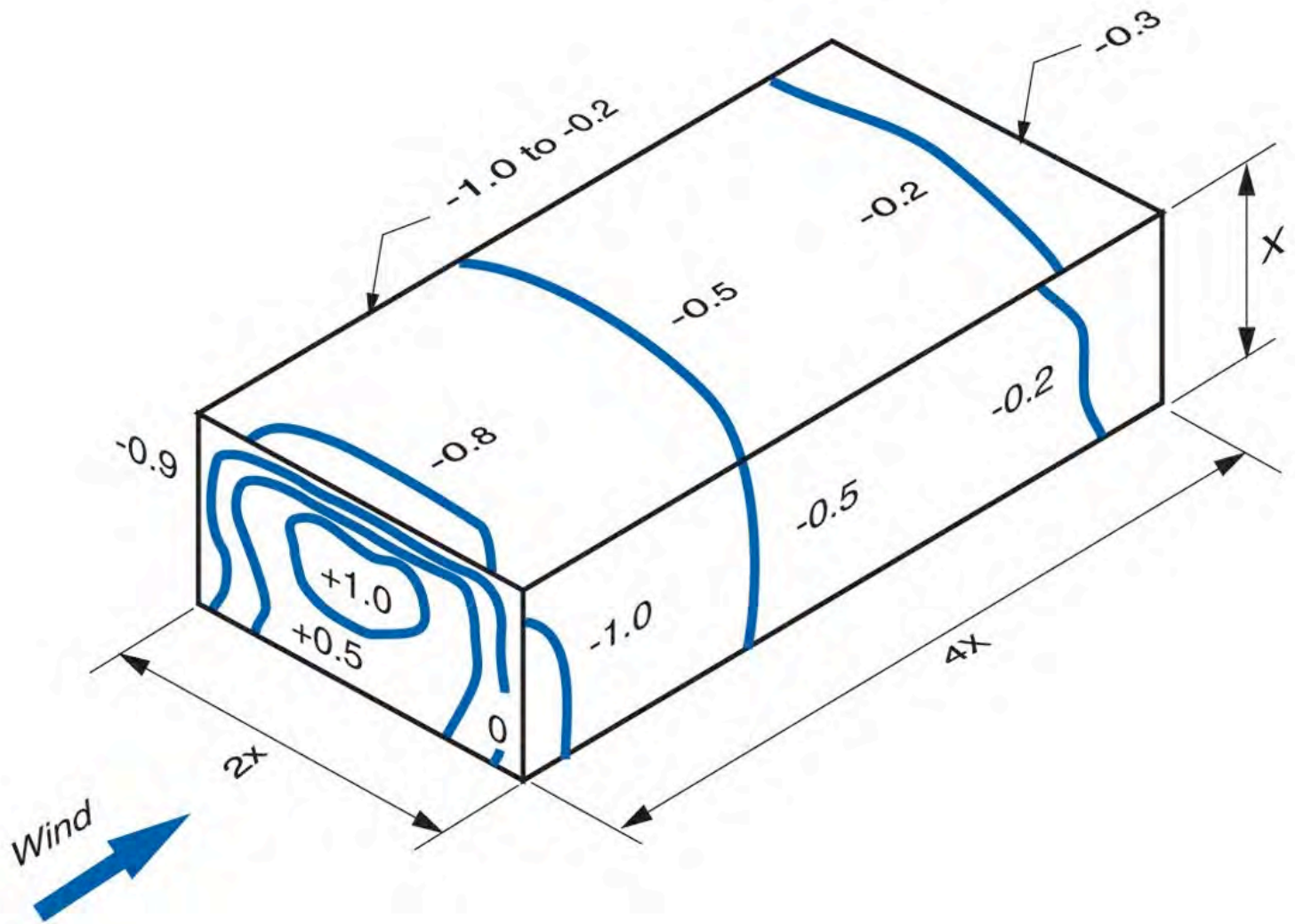

Hydrostatic
pressure



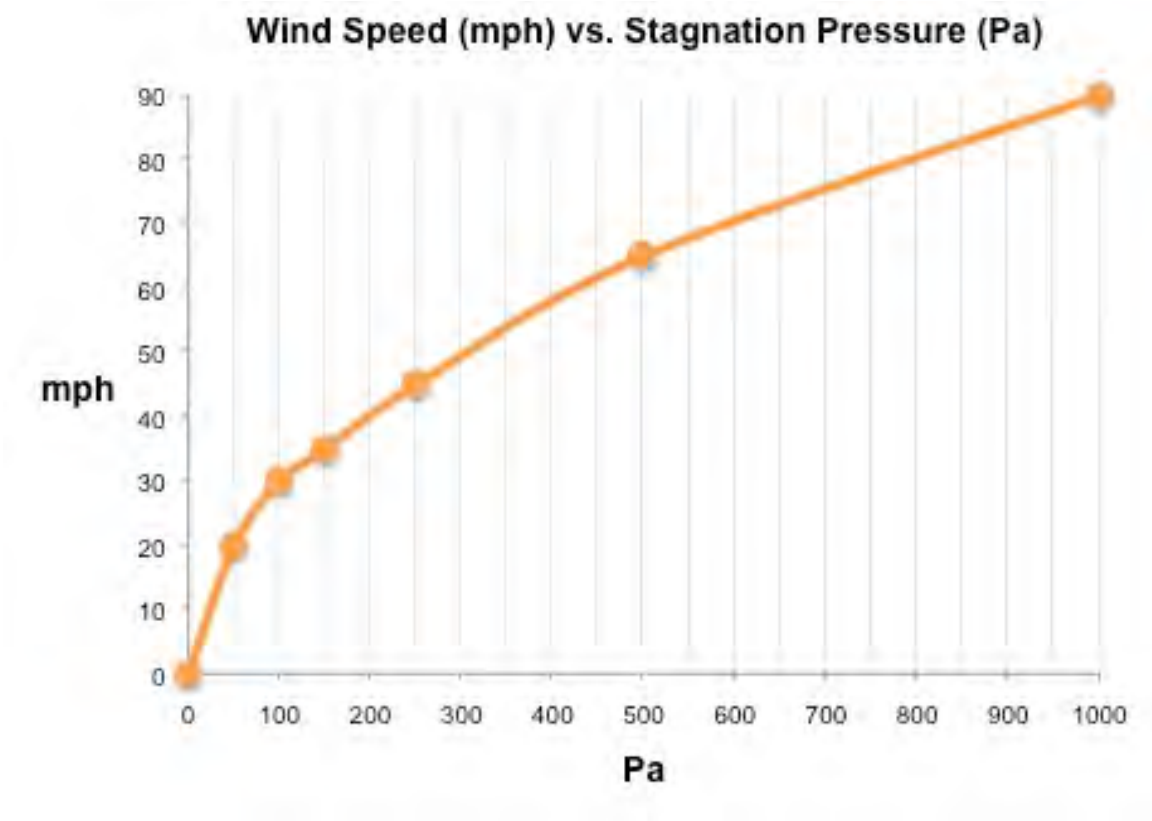





Hydrostatic
head
Cladding

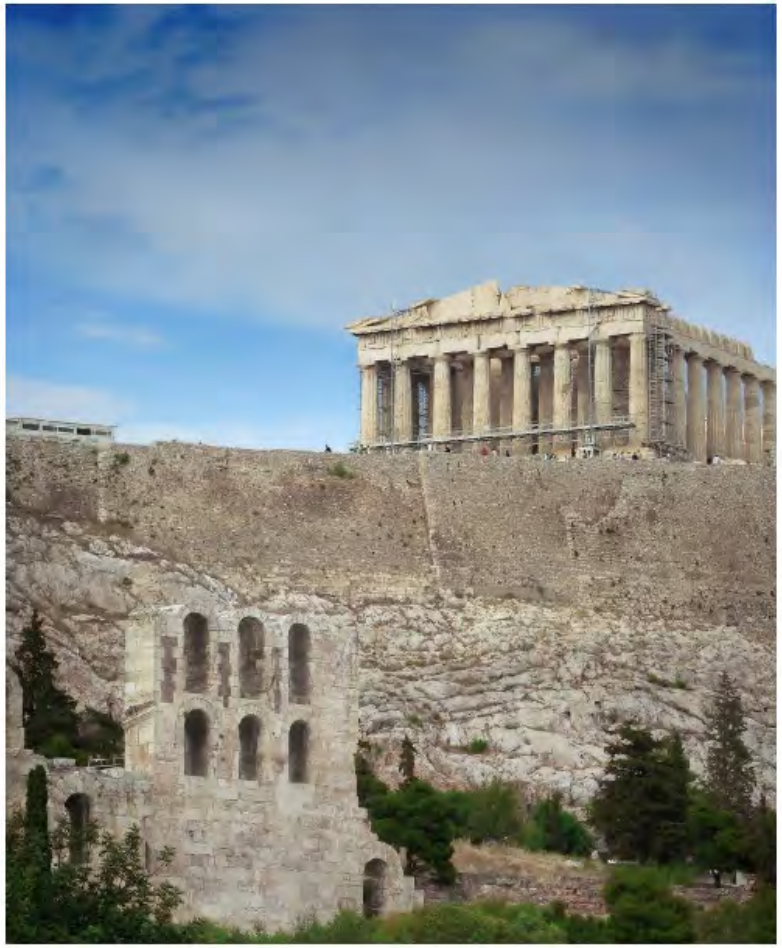

-0.3
-1.0 to -0.2
-0.2
-0.5
-0.2
-0.9
-0.8
-0.5
+1.0
+0.5
-1.0
0
X
2X
4X
Wind

Pascals		mph
50	Pa =	20 mph
100	Pa =	30 mph
150	Pa =	35 mph
250	Pa =	45 mph
500	Pa =	65 mph
1,000	Pa =	90 mph




panago
QUILTED TREASURES


panago
QUILTED TREASURES

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IV-7


W1
W3


LOWER
N-2


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omeWrap
Tyvek
HomeWrap


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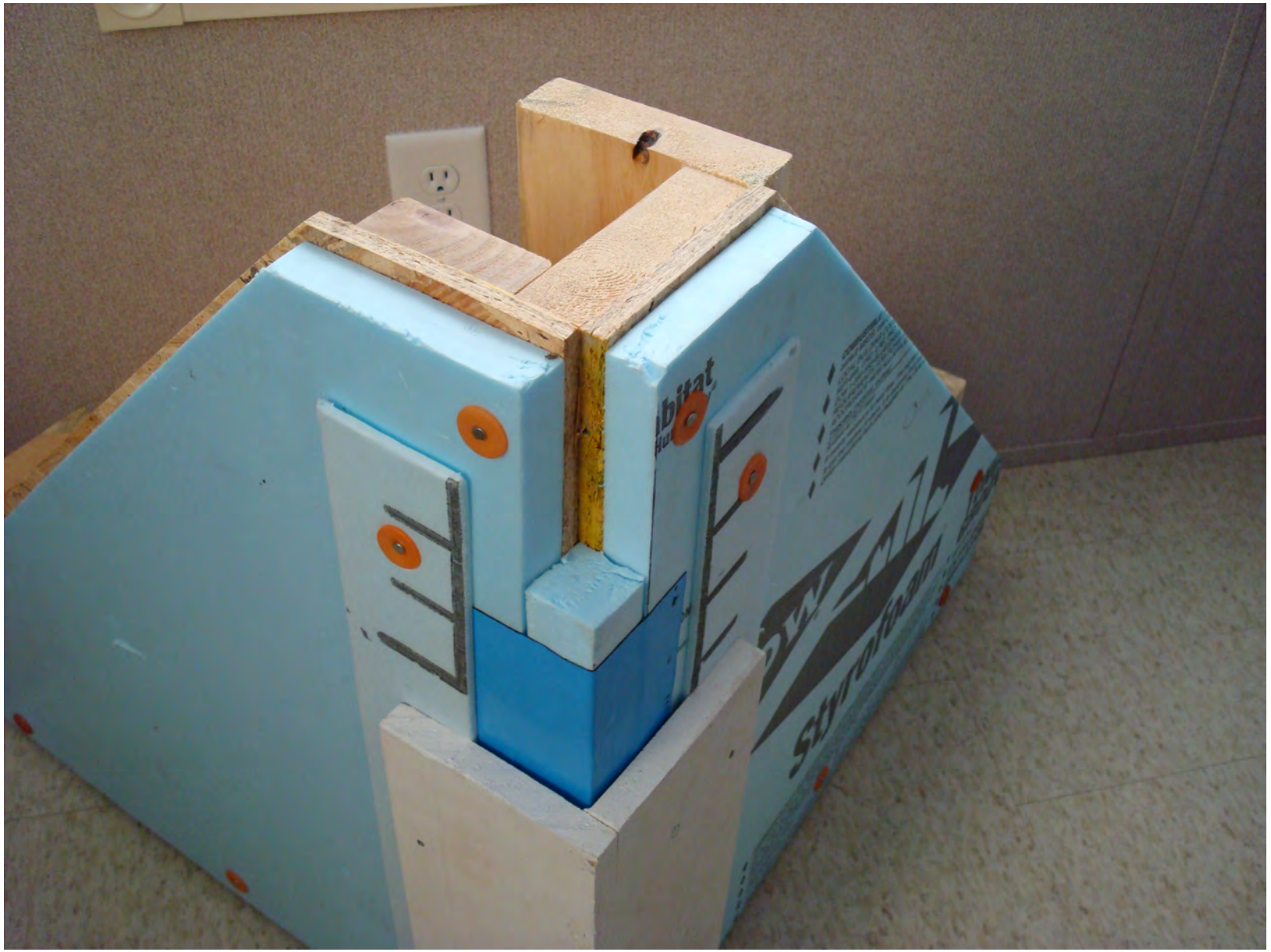
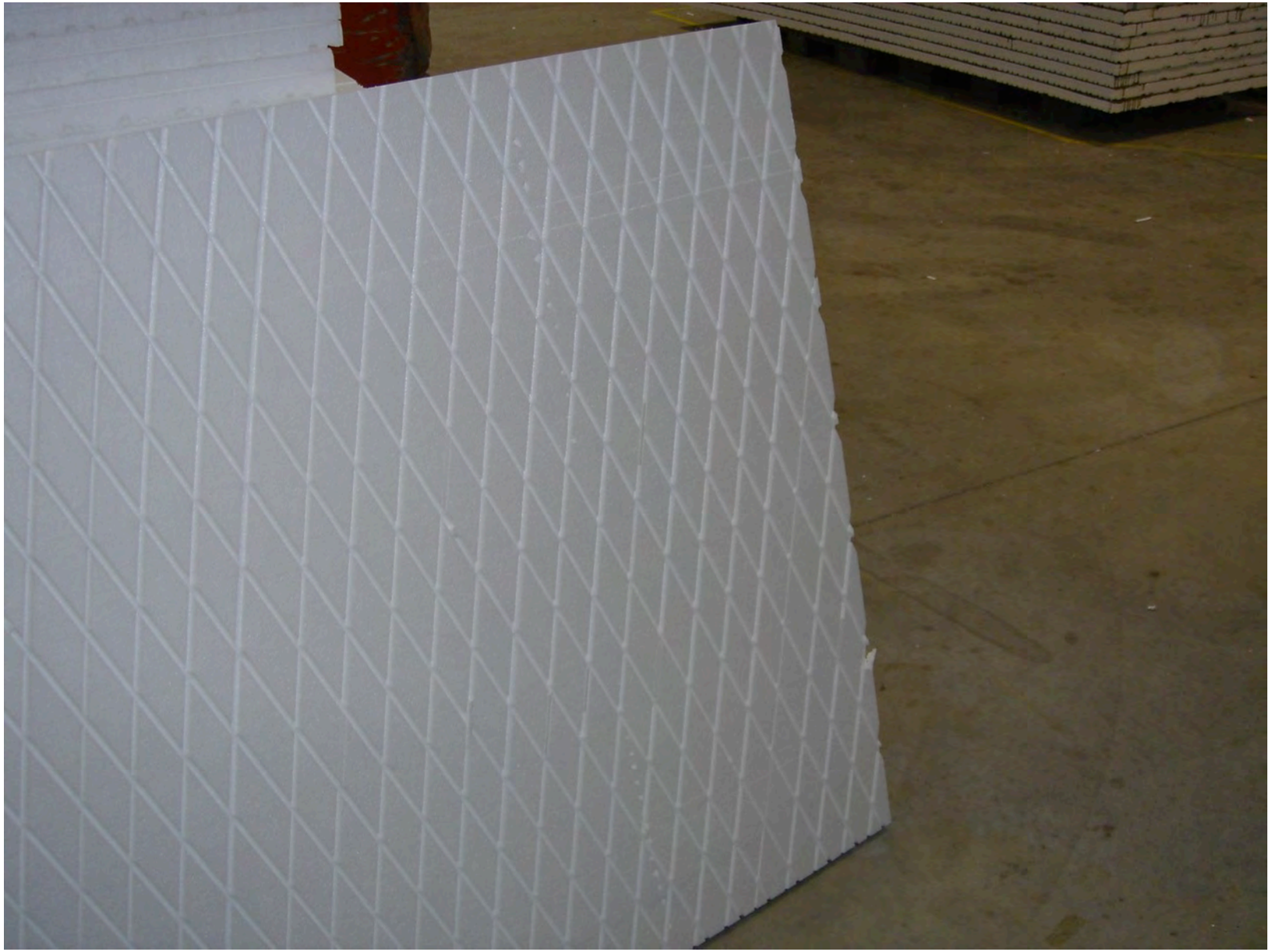
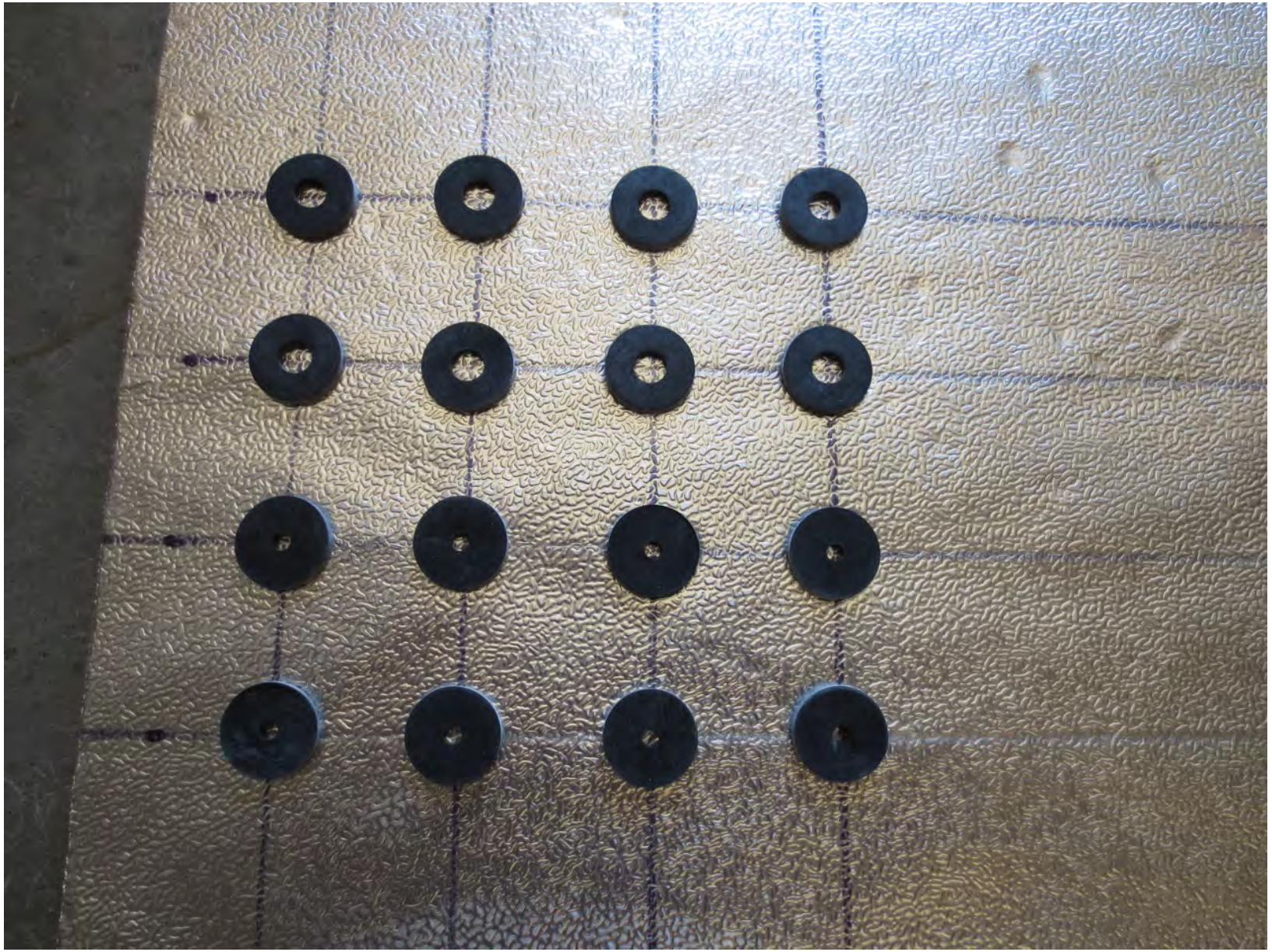

Styrofoam

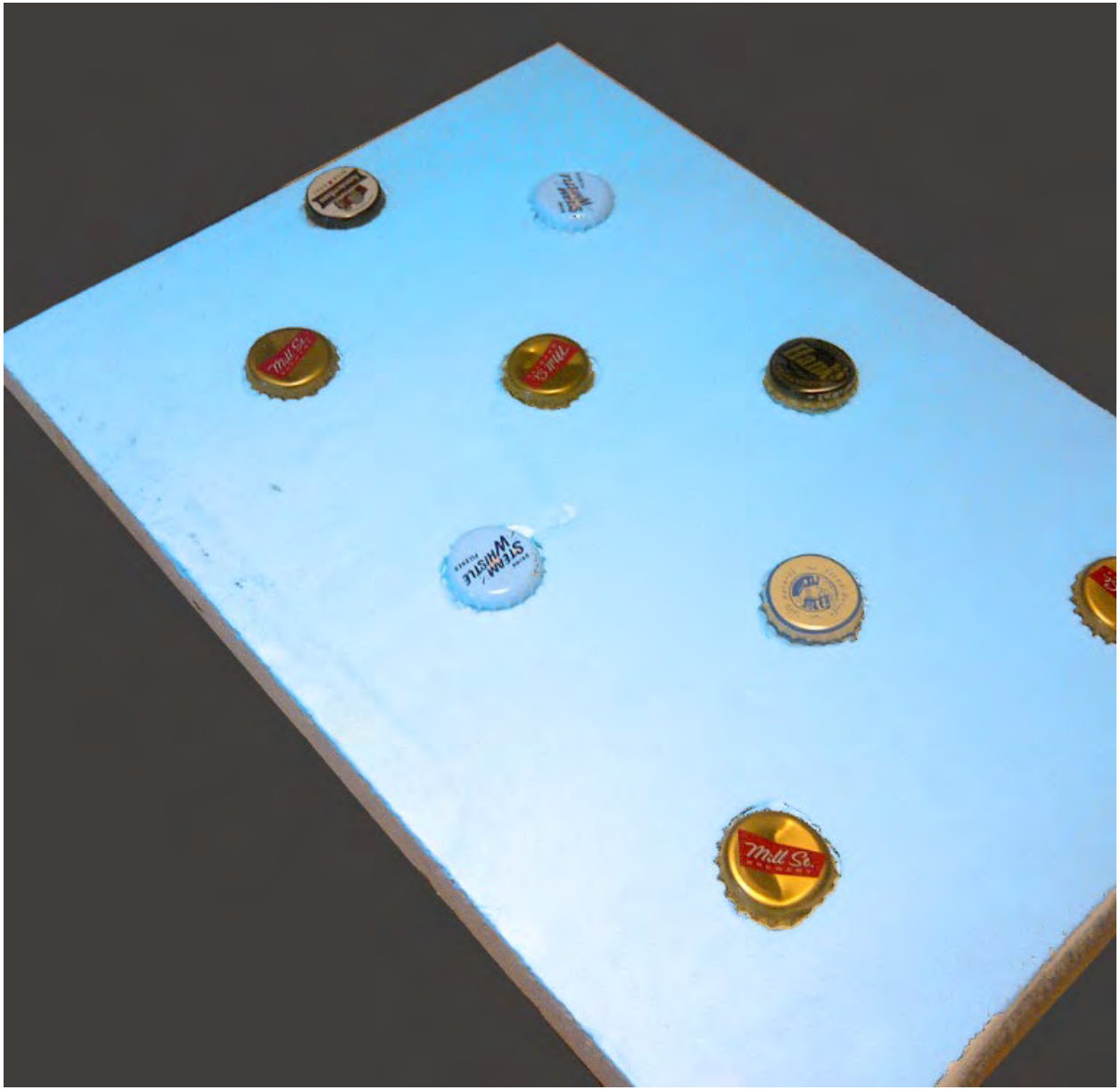

DuPont
Tyvek
Tape
DuPont
Tyvek
Tape



Rain Screen



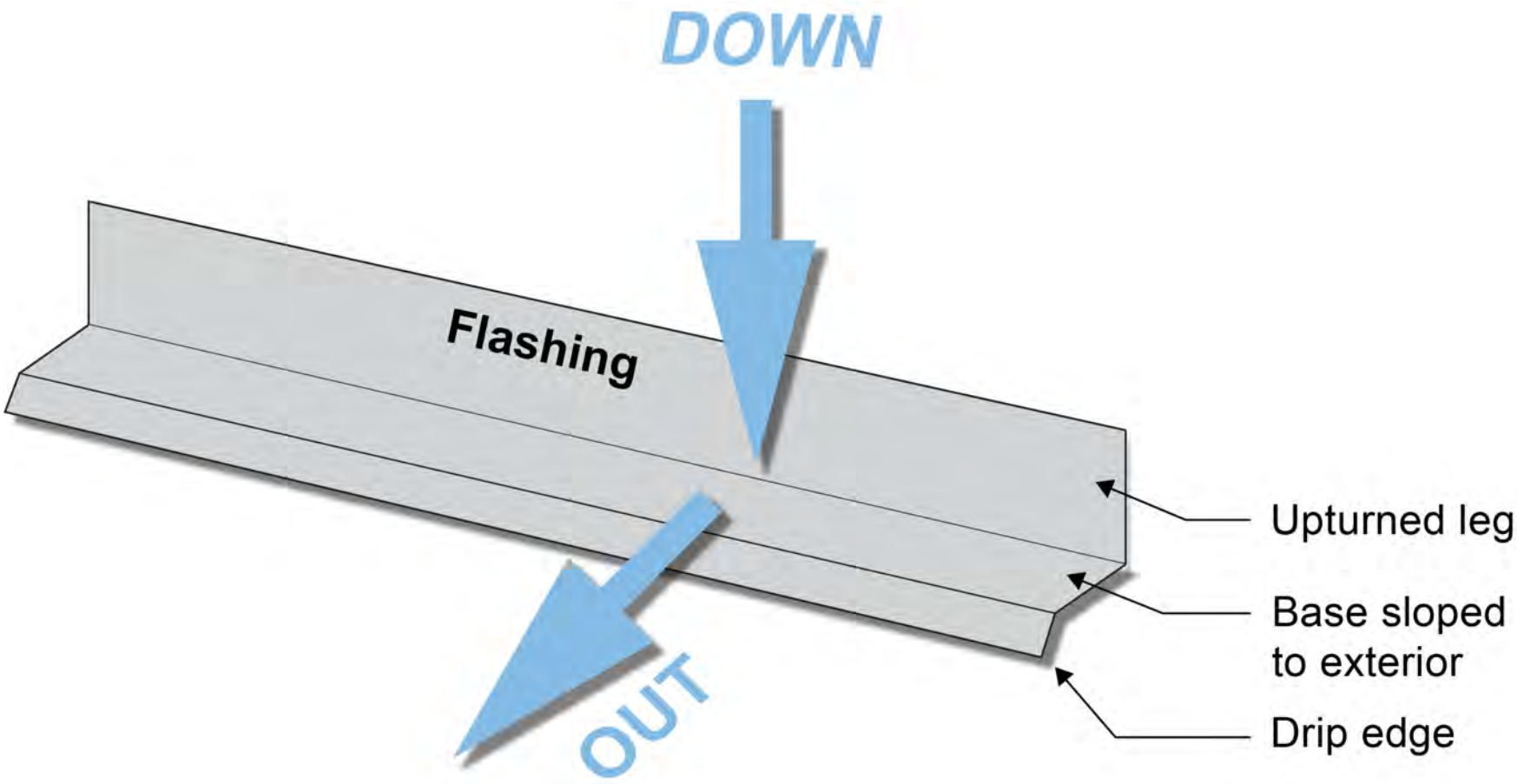
Beer Screen?

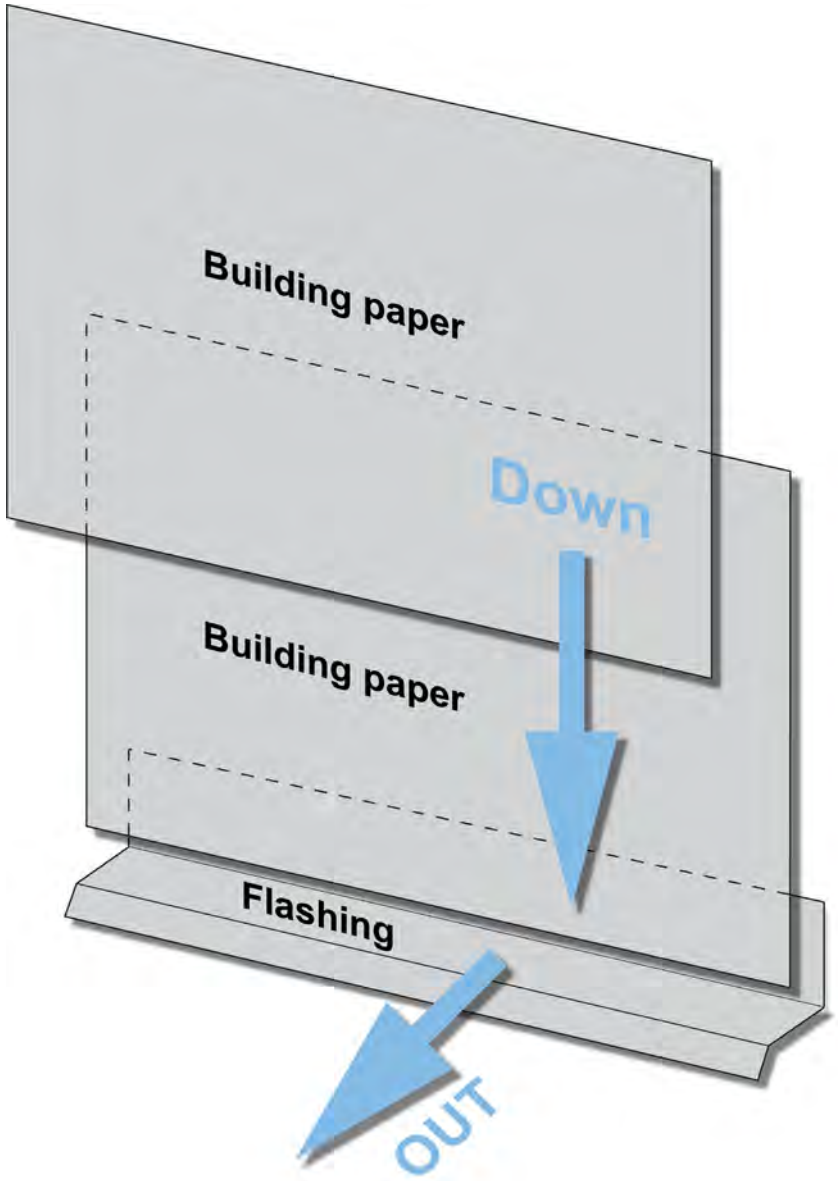

Mill St.
Steam Whistle
Mill St.

Drain the Rain on the Plane

If You Want to Save Cash…Flash

Don’t Be a Dope…Slope

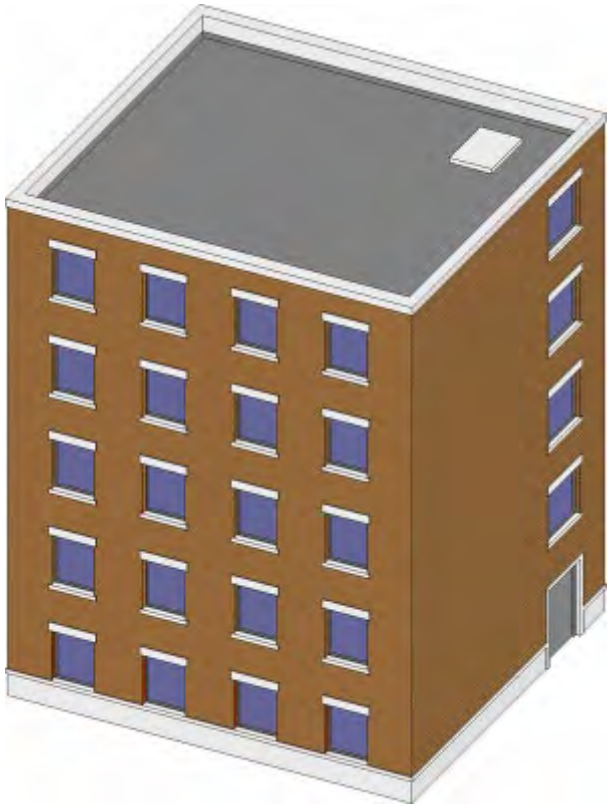

DOWN
Flashing
OUT
Upturned leg
Base sloped
to exterior
Drip edge


Building paper
Down
Building paper
Flashing
OUT

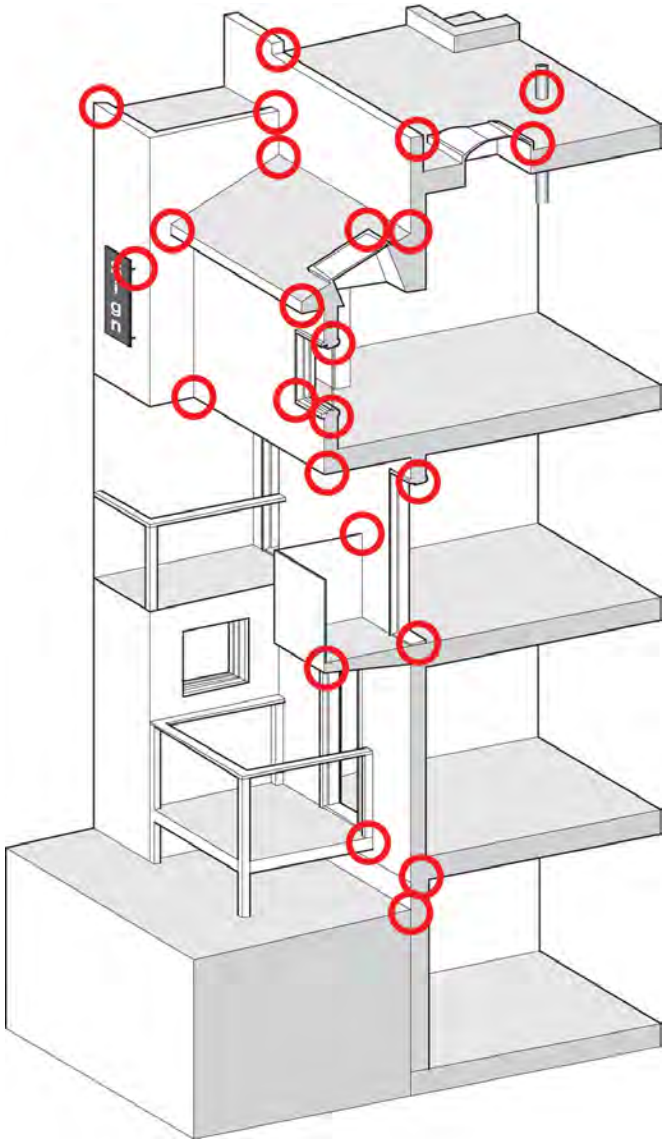

GP
sGlass™
eathing
GP
DensG
Sheathi
CAUTION!
THIS SIDE OUT
ROOFS.

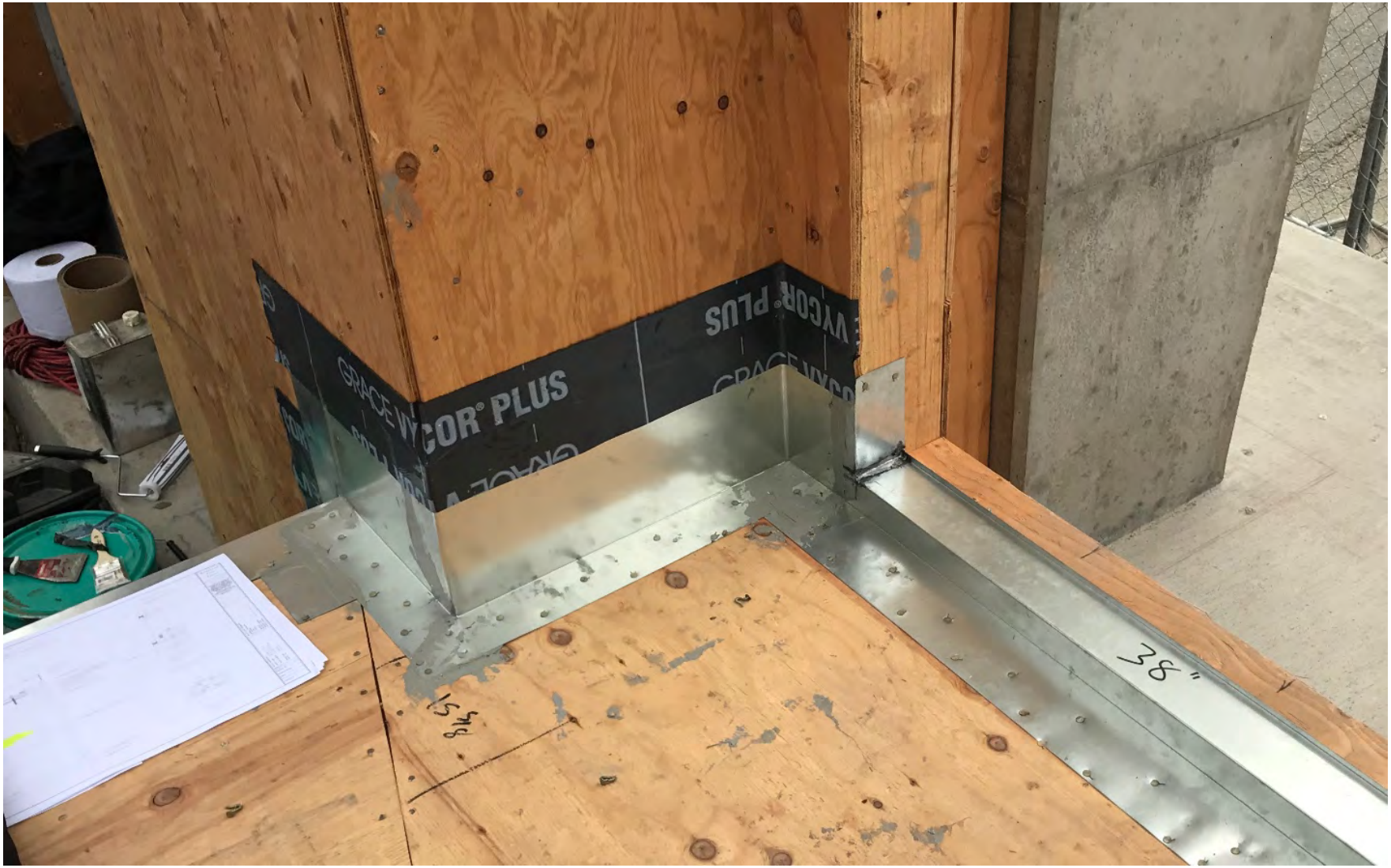

rmax ci ™
Isolant extérie
Thermax ci
Aislamiento Ext
THERM X ci

Commercial Enclosure: Simple Layers



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

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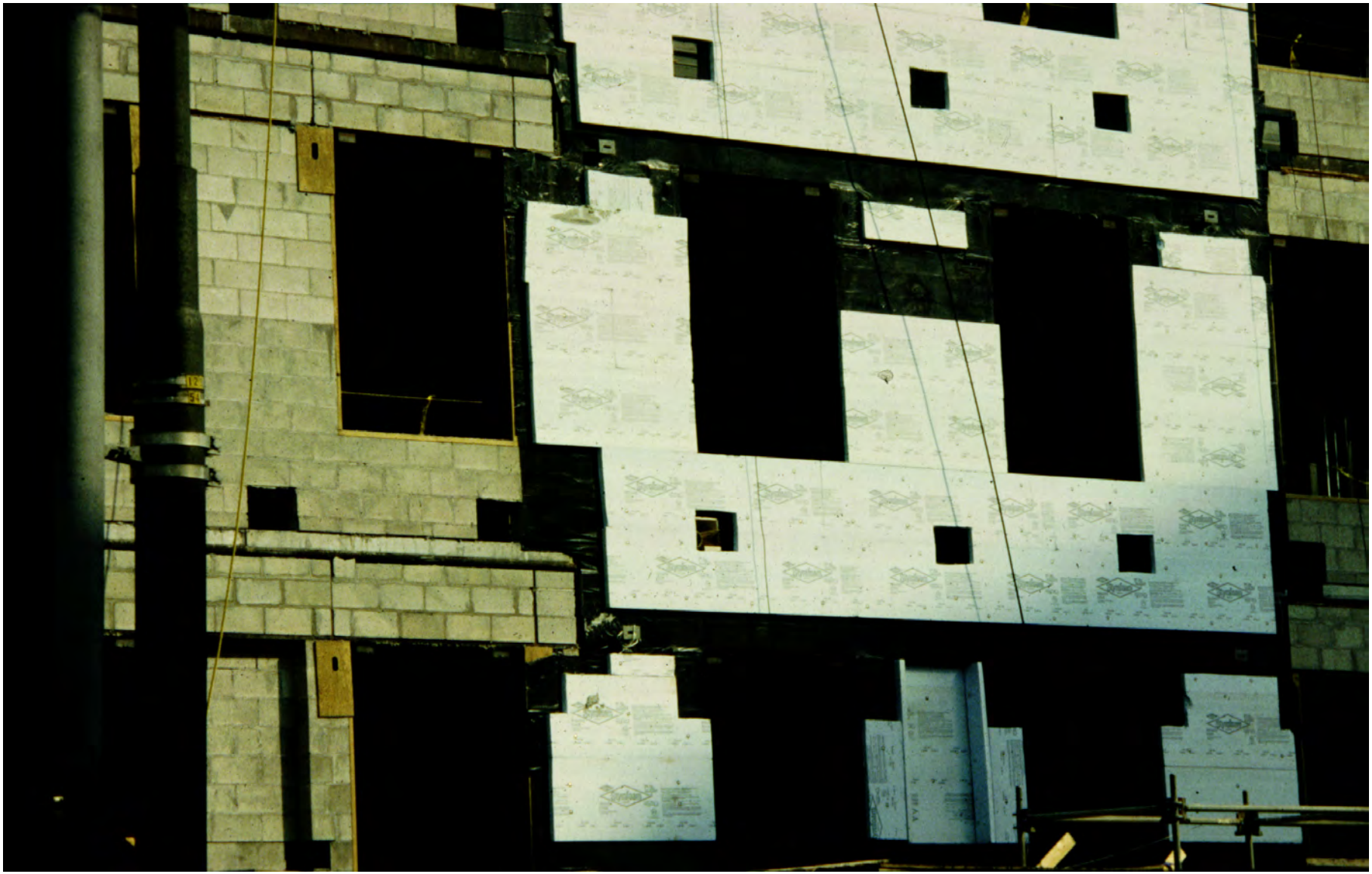
StraightFlash


StraightFlash
DUPONT


StraightFlash
StraightFlash


J·A·J Co., Inc.
MASONS
781-395-5510
JULIAN
PURCHASE
CONGRESS ST




HARVARD SCHOOL OF PUBLIC HEALTH


ALL VISITORS
MUST SIGN IN
AT
JOHN MORIARTY
AND ASSOCIATES
FIELD OFFICE
CAUTION
HARD HAT
AREA
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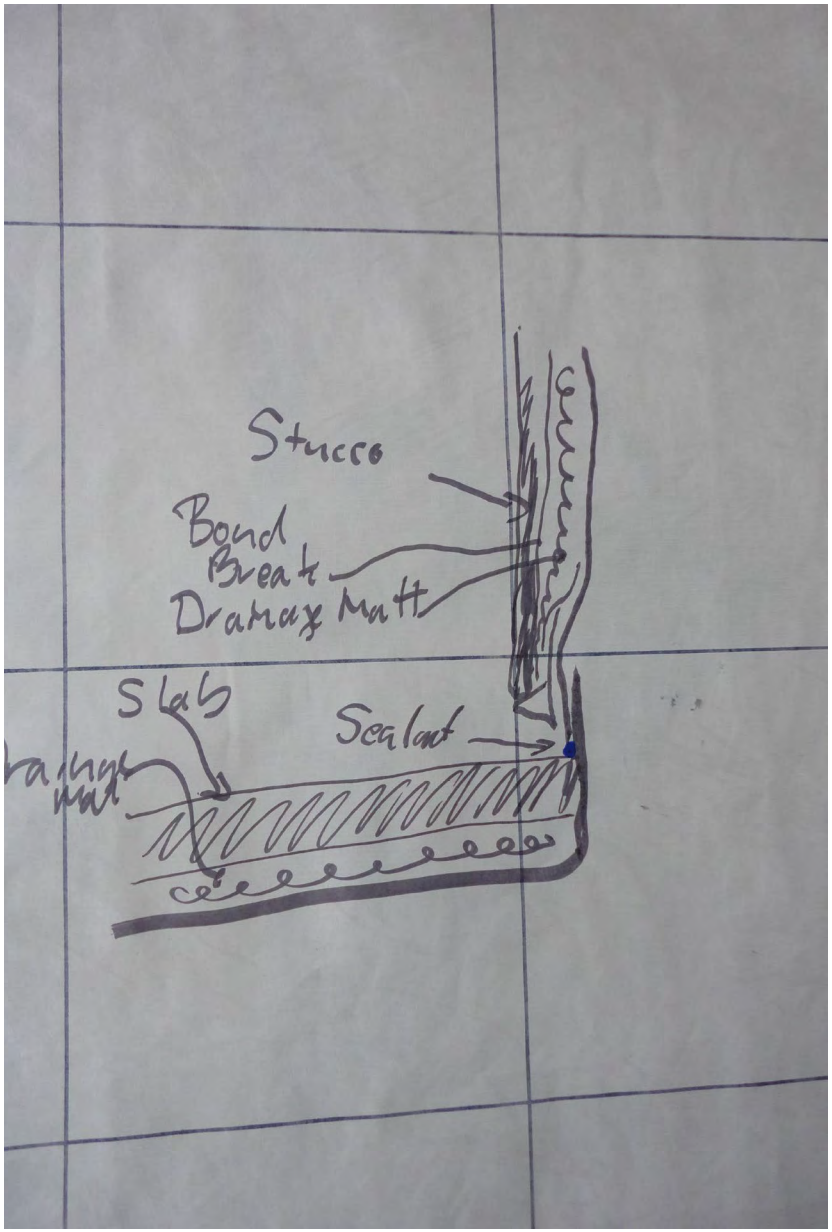
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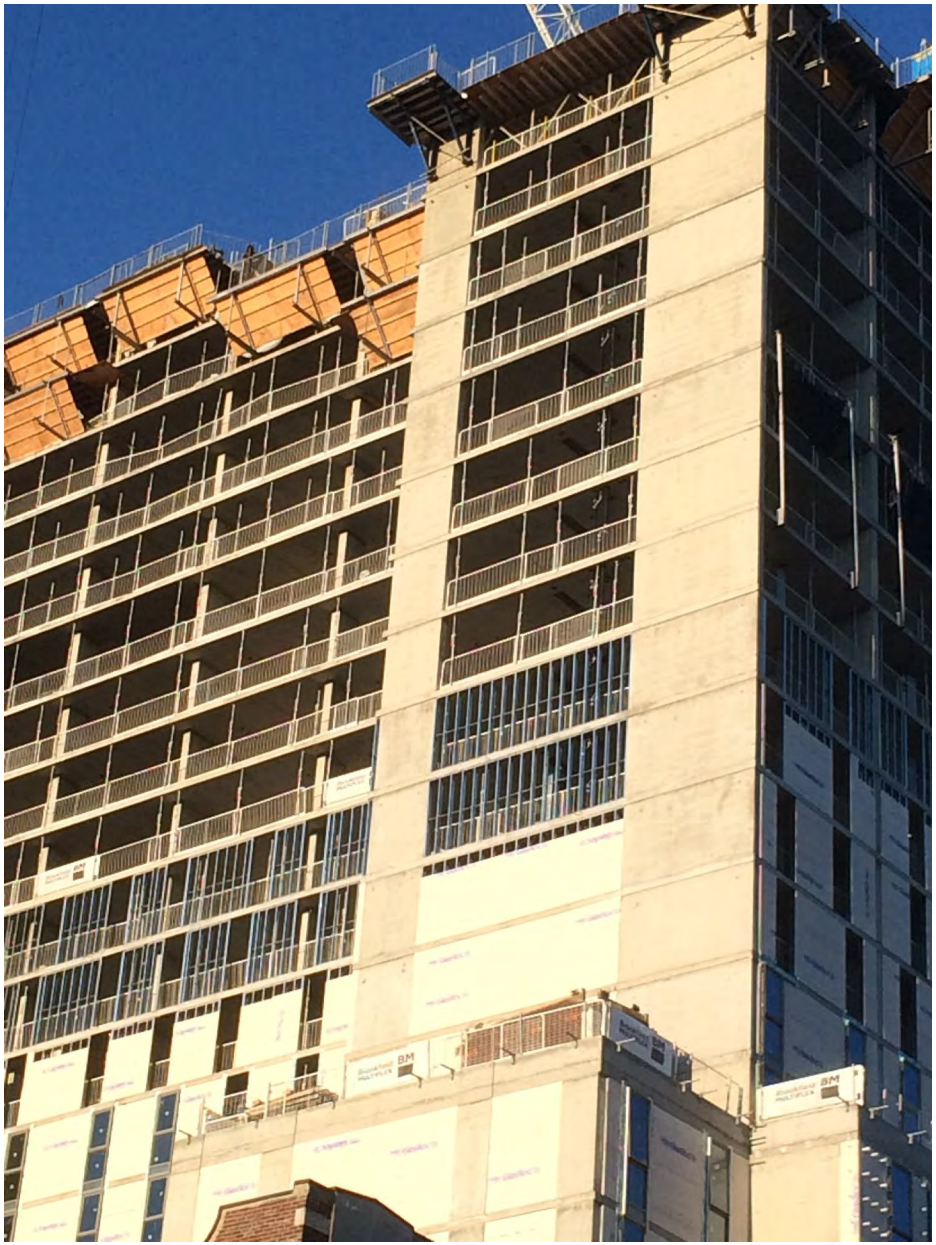


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FOR LEASE
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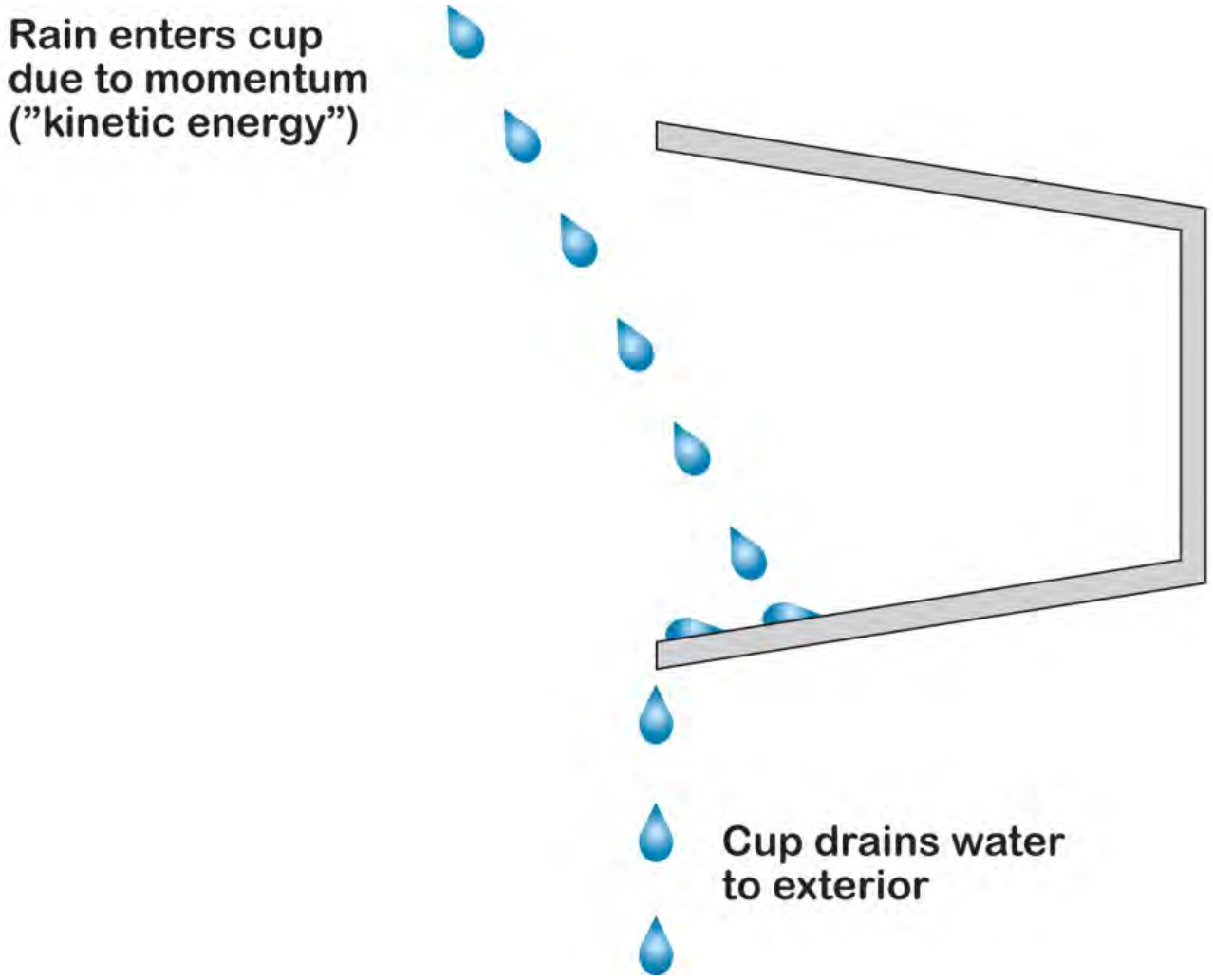
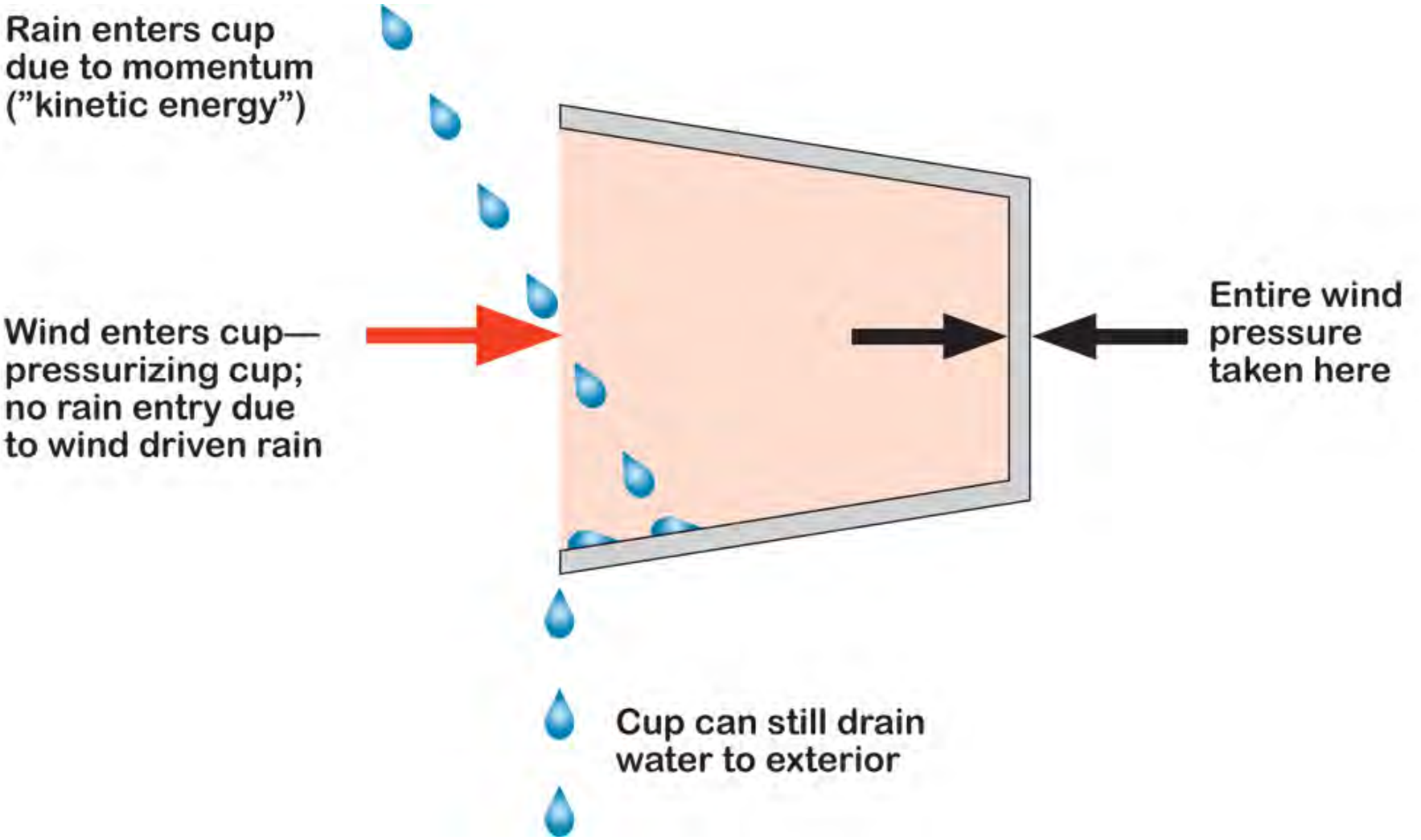
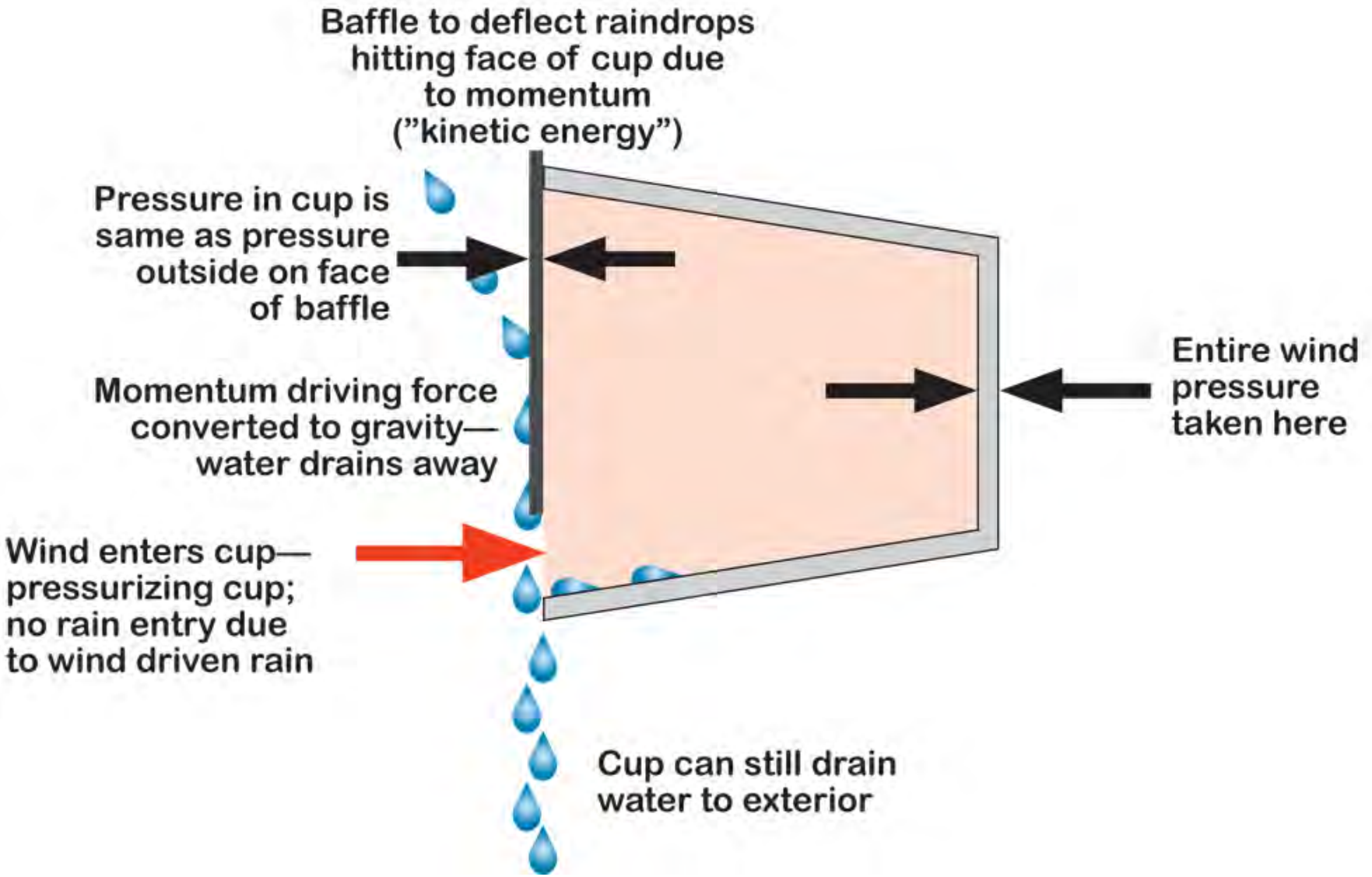
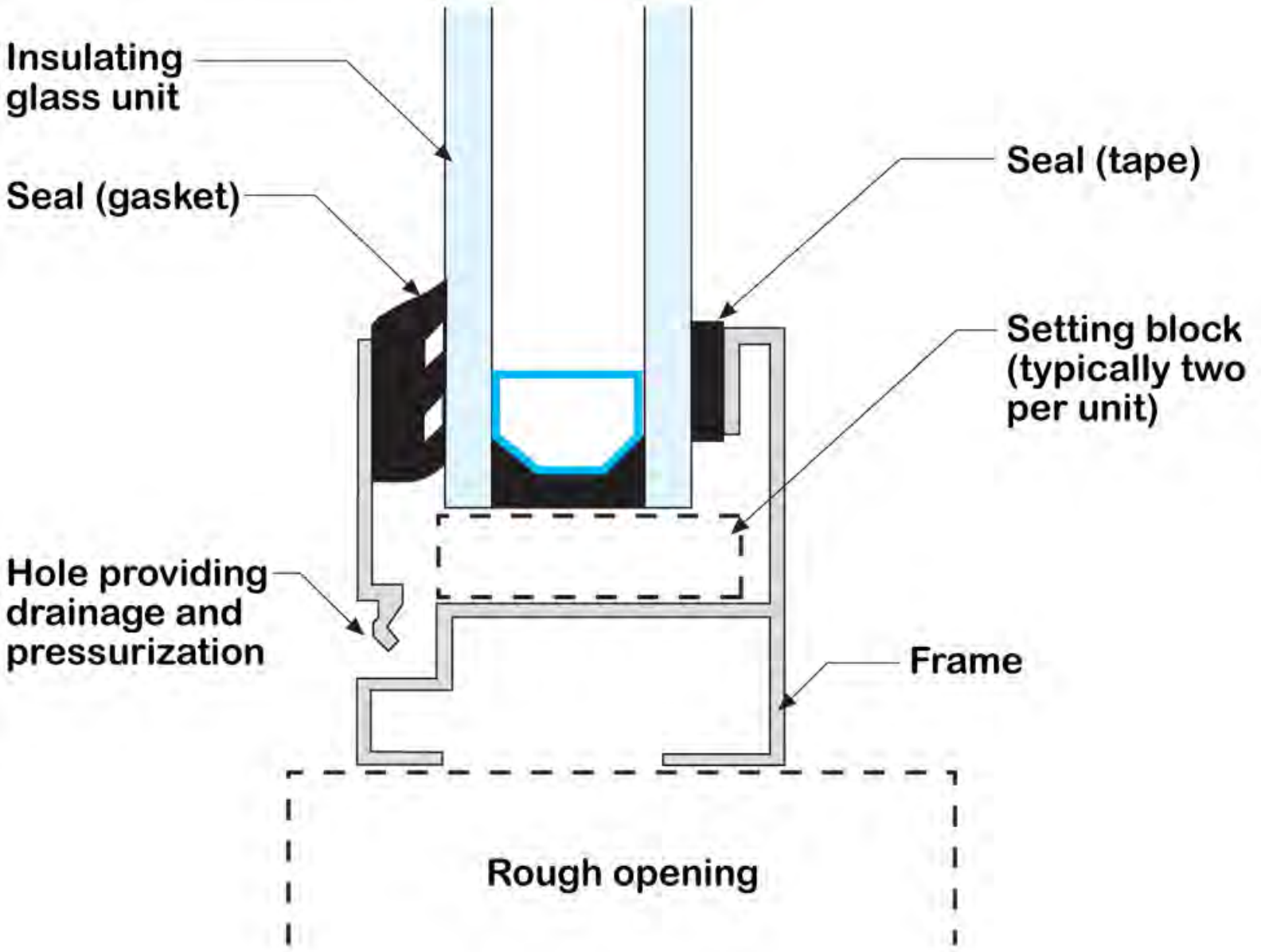
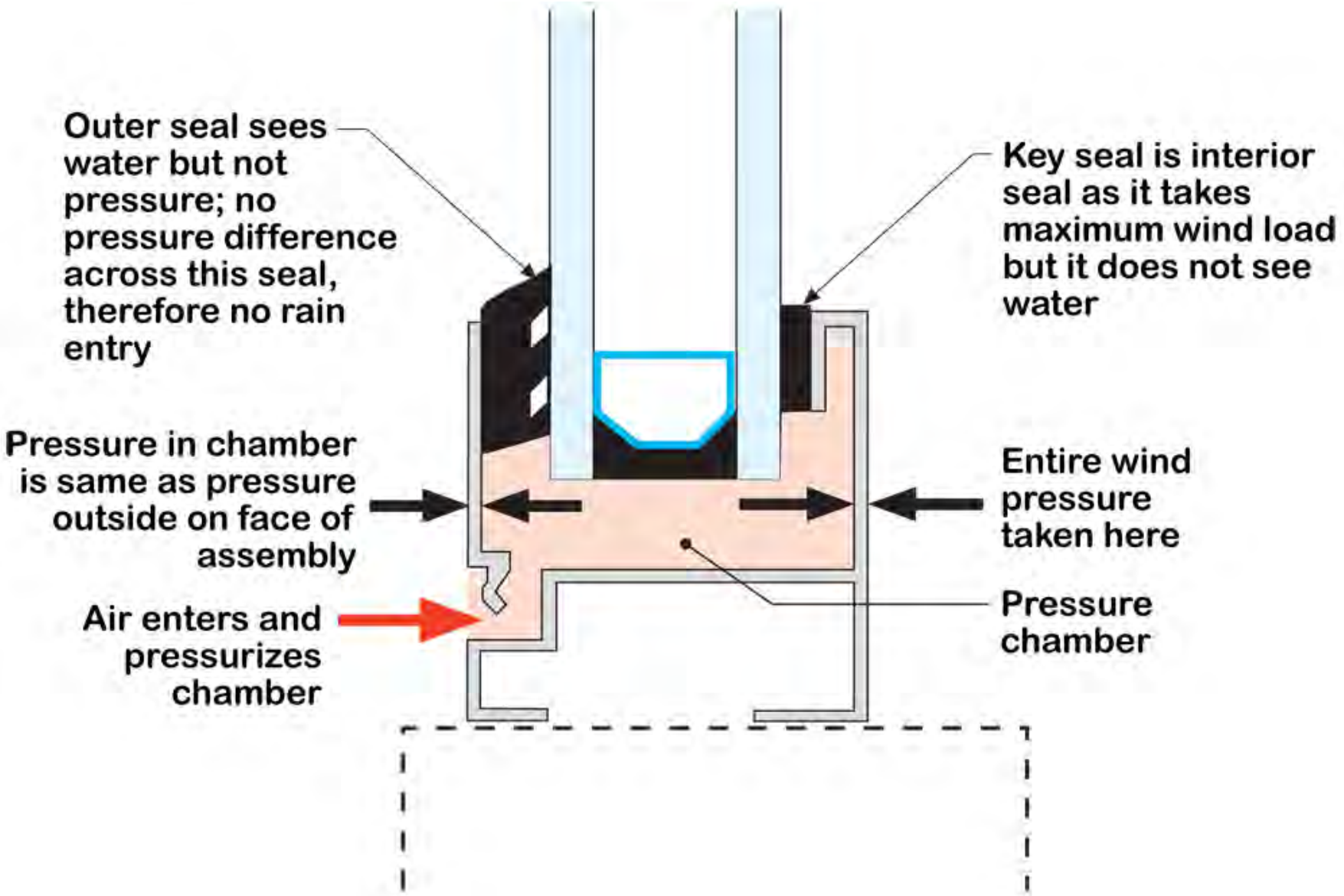
Tribute

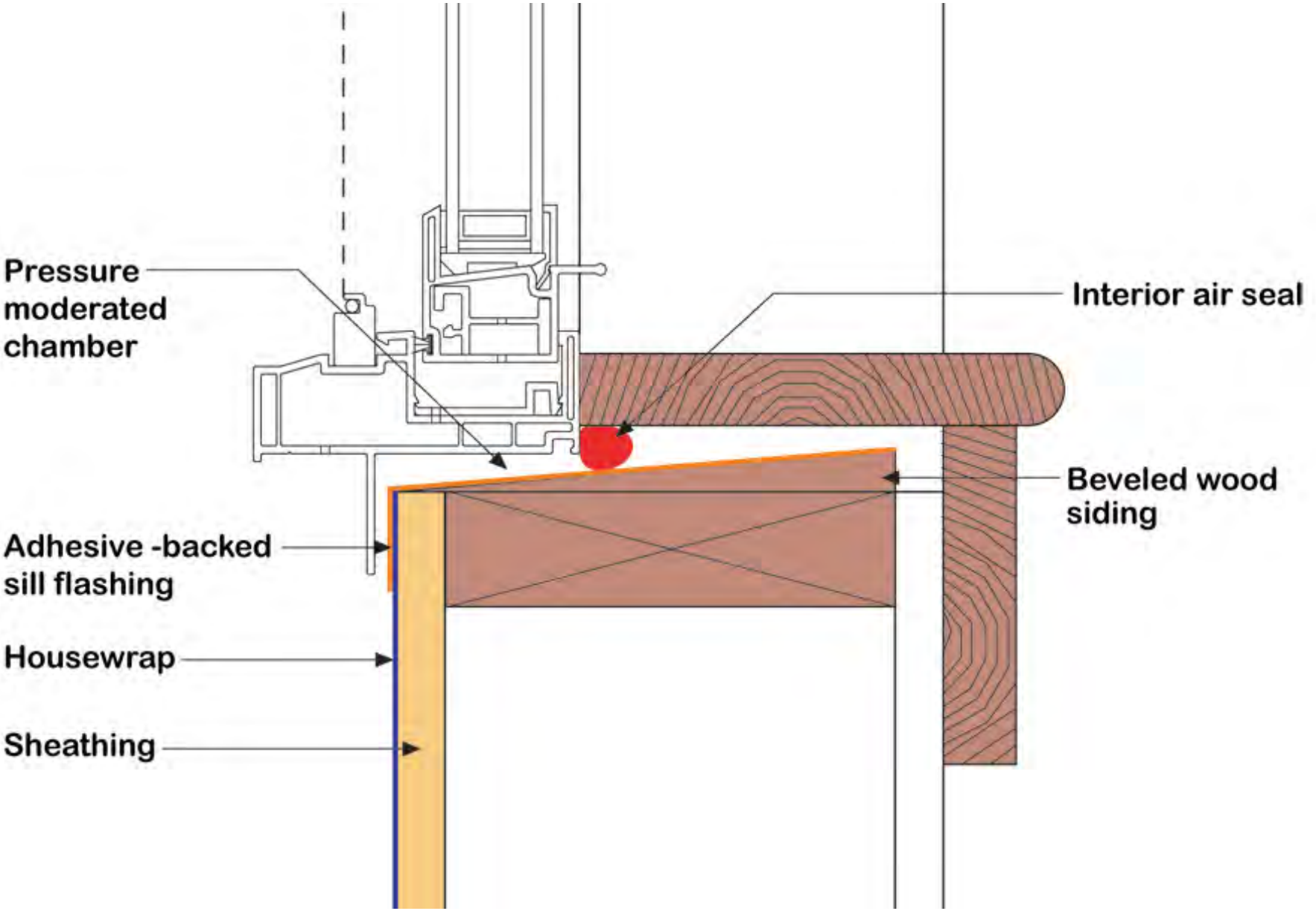

Rain enters cup
due to momentum
("kinetic energy")
Cup drains water
to exterior


Rain enters cup due to momentum ("kinetic energy")
Wind enters cup— pressurizing cup; no rain entry due to wind driven rain
Entire wind pressure taken here
Cup can still drain water to exterior

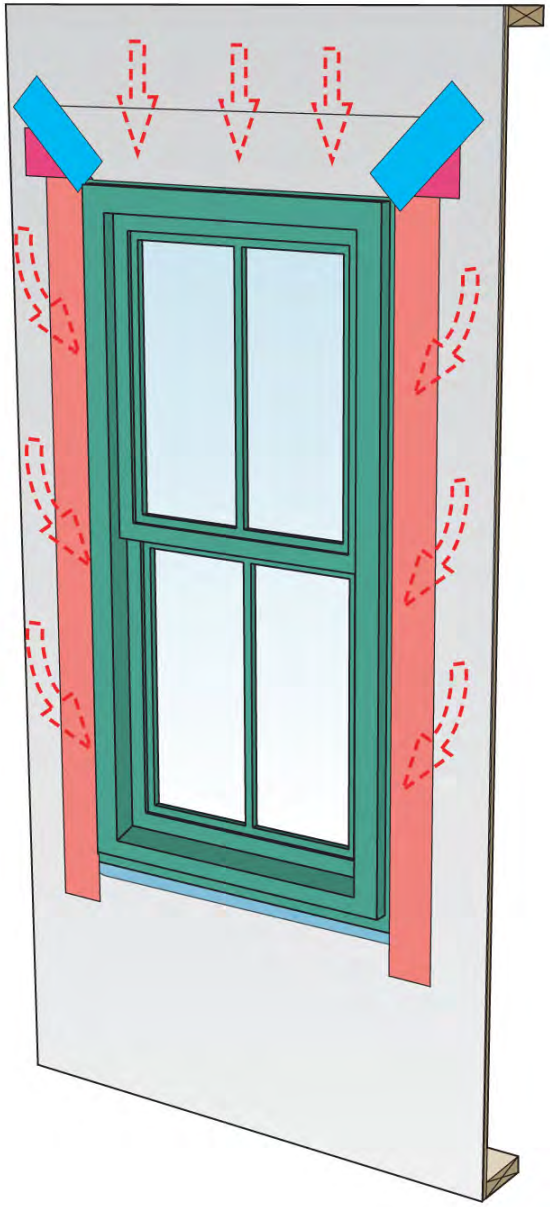

Baffle to deflect raindrops hitting face of cup due to momentum ("kinetic energy")
Pressure in cup is same as pressure outside on face of baffle
Momentum driving force converted to gravity— water drains away
Wind enters cup— pressurizing cup; no rain entry due to wind driven rain
Entire wind pressure taken here
Cup can still drain water to exterior

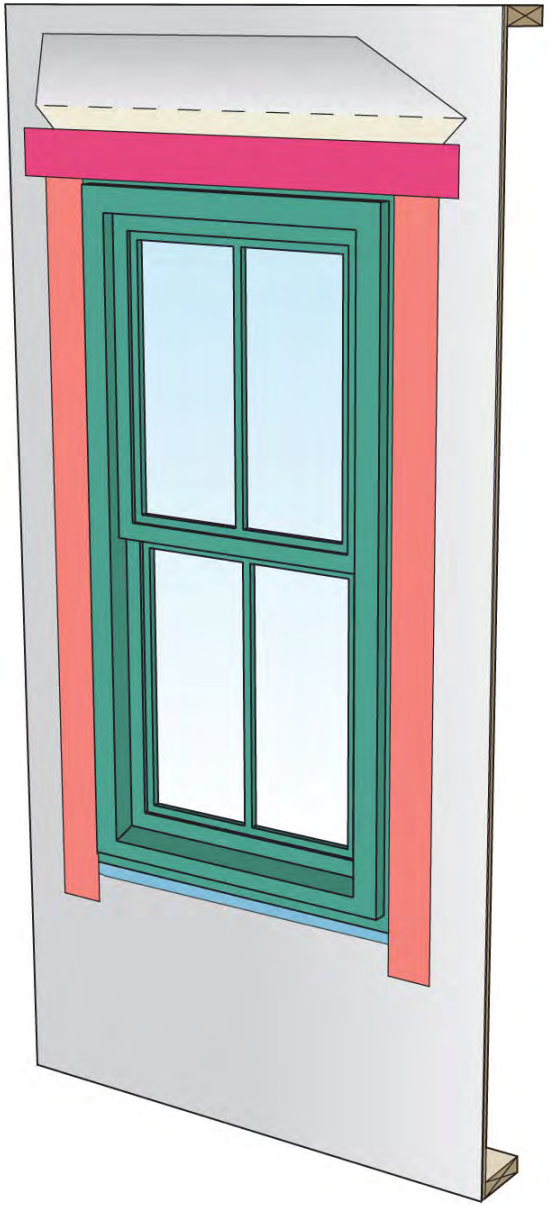

Insulating glass unit
Seal (gasket)
Seal (tape)
Setting block (typically two per unit)
Hole providing drainage and pressurization
Frame
Rough opening

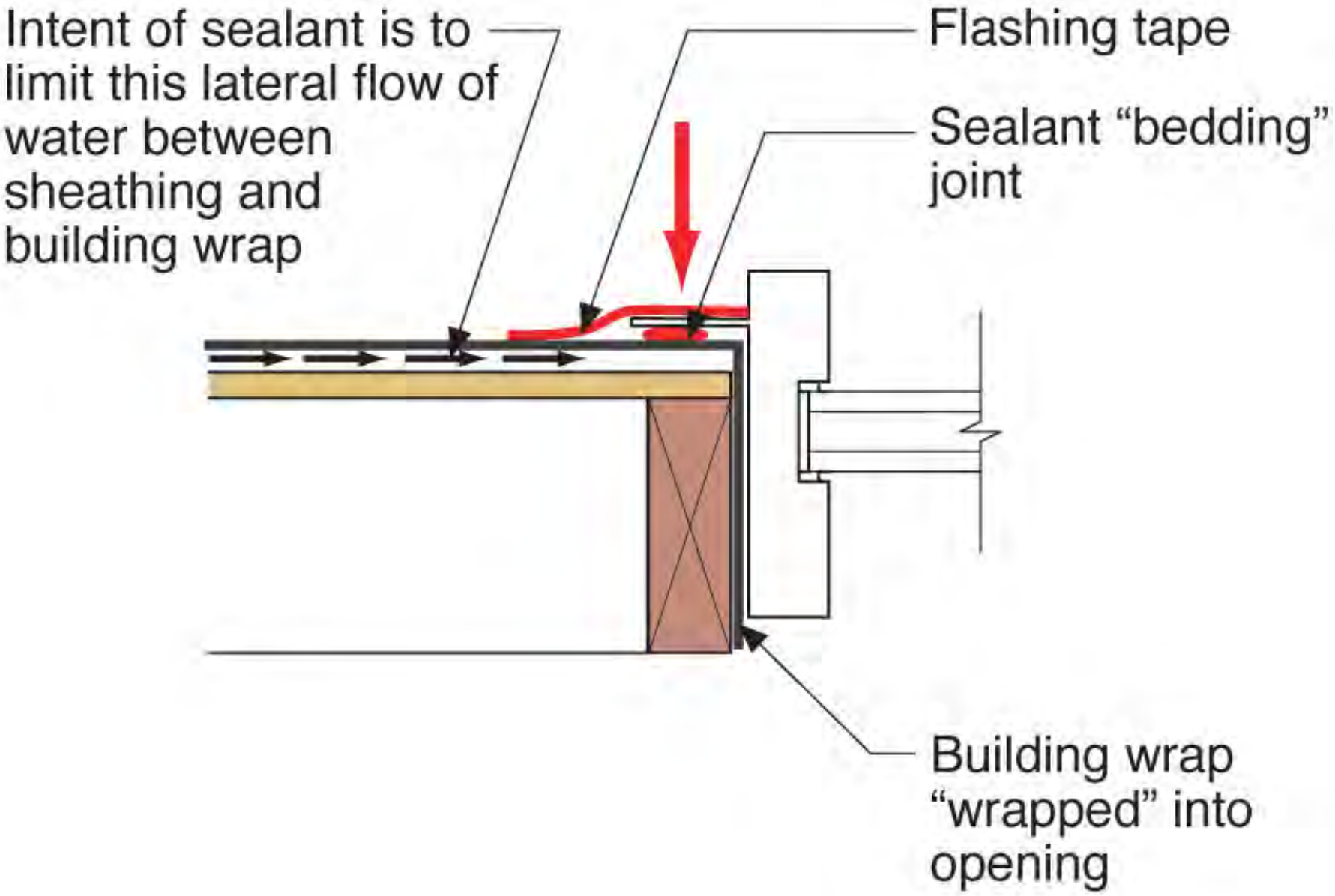

Outer seal sees water but not pressure; no pressure difference across this seal, therefore no rain entry
Key seal is interior seal as it takes maximum wind load but it does not see water
Pressure in chamber is same as pressure outside on face of assembly
Entire wind pressure taken here
Air enters and pressurizes chamber
Pressure chamber

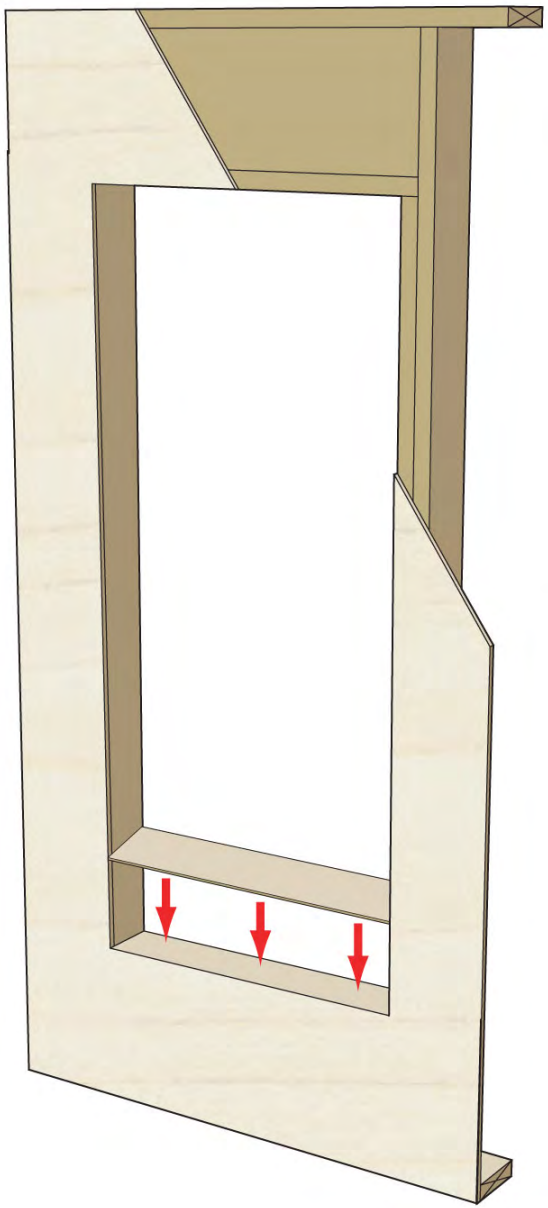

Pressure moderated chamber
Interior air seal
Beveled wood siding
Adhesive -backed sill flashing
Housewrap
Sheathing

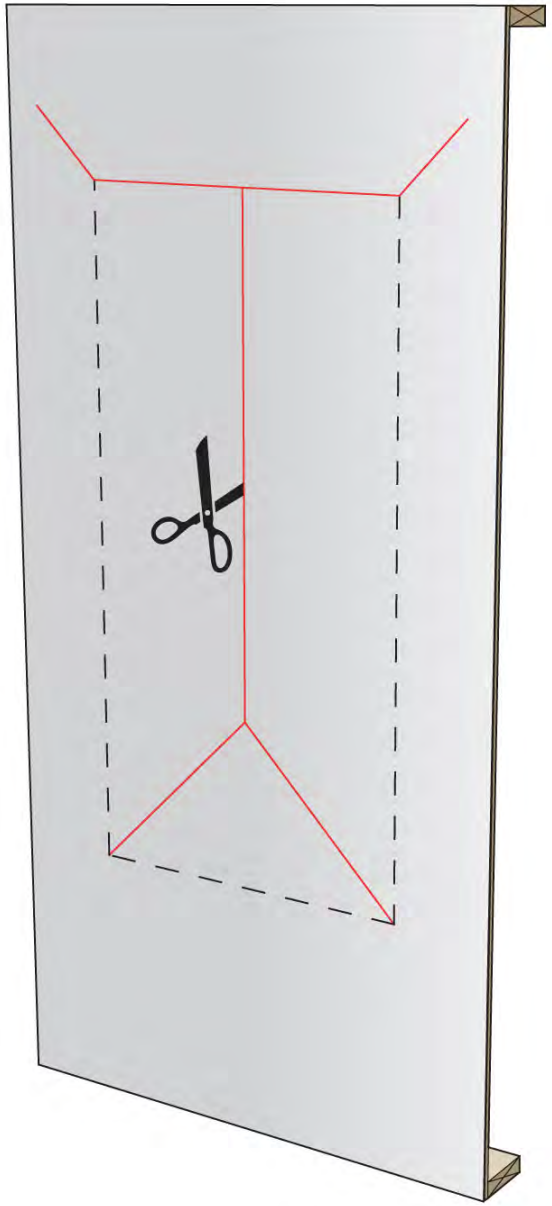

DOW
Styrofoam

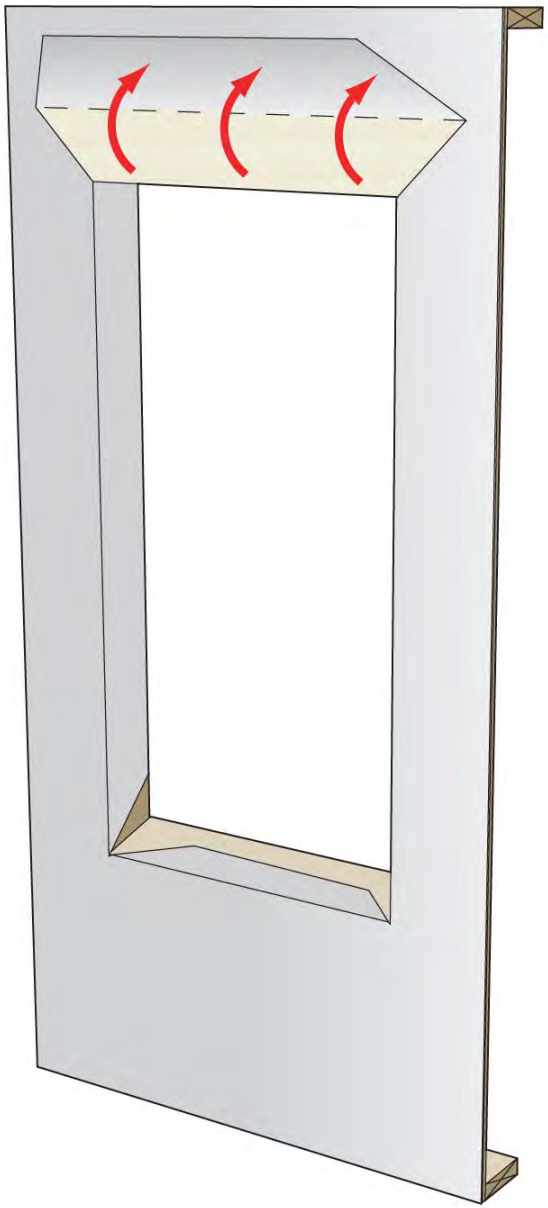


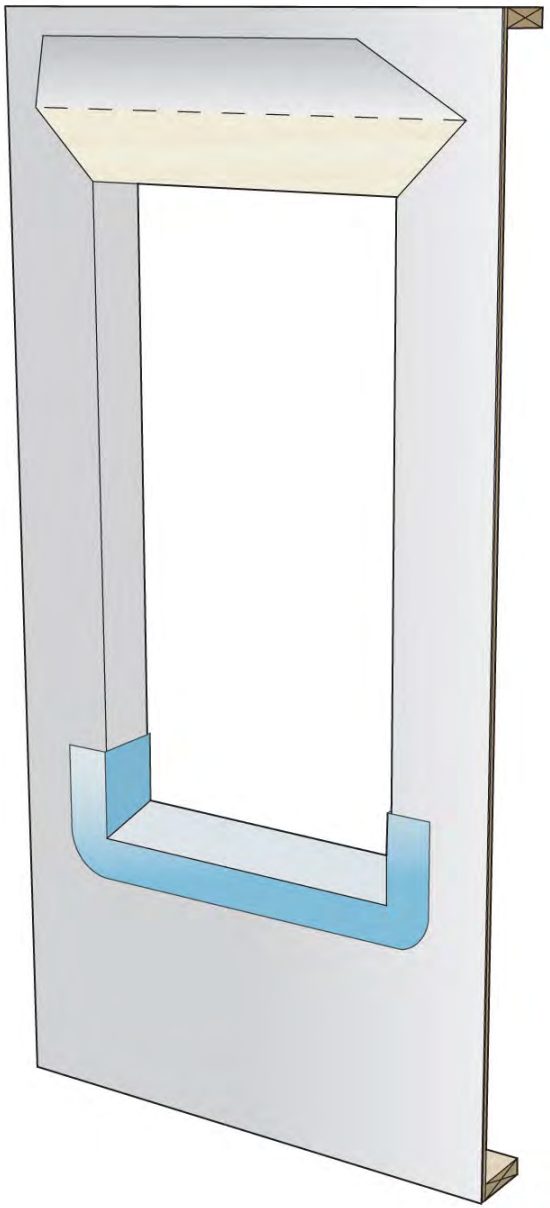


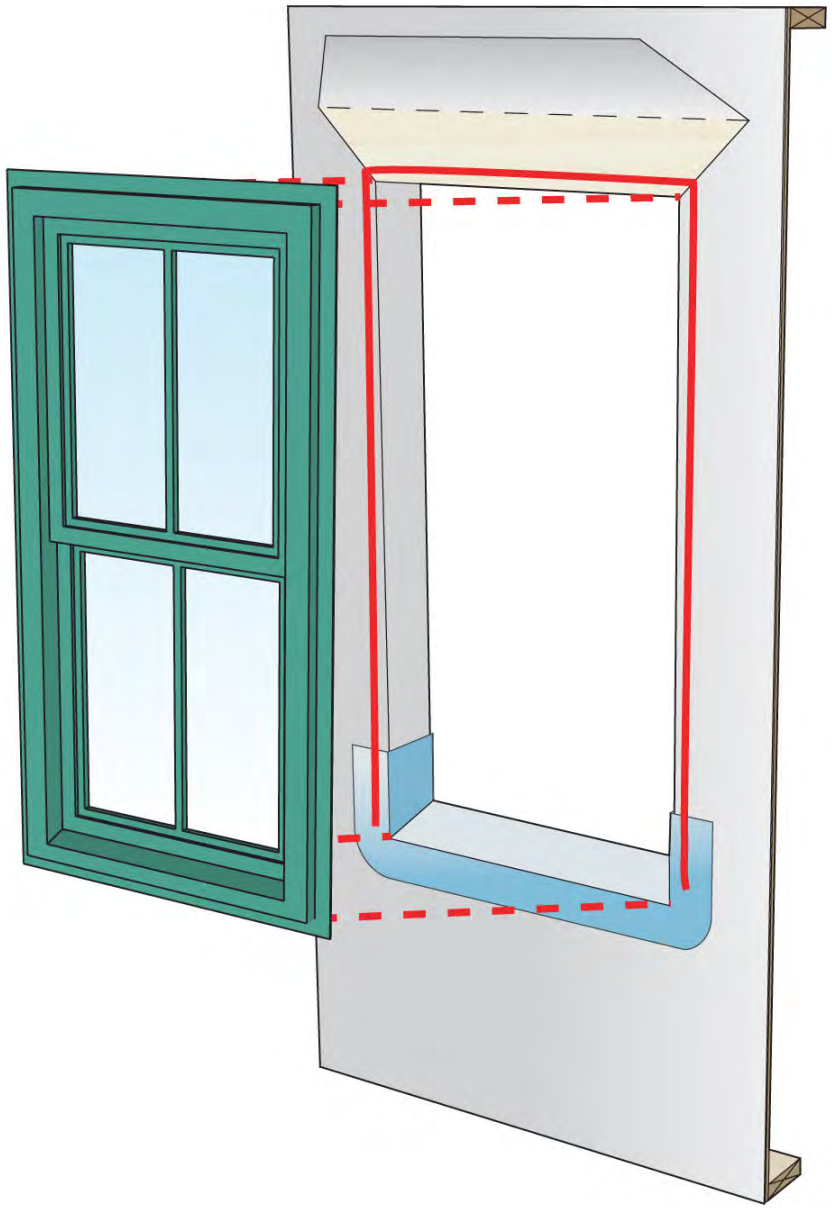

Intent of sealant is to limit this lateral flow of water between sheathing and building wrap
Flashing tape
Sealant “bedding” joint
Building wrap “wrapped” into opening

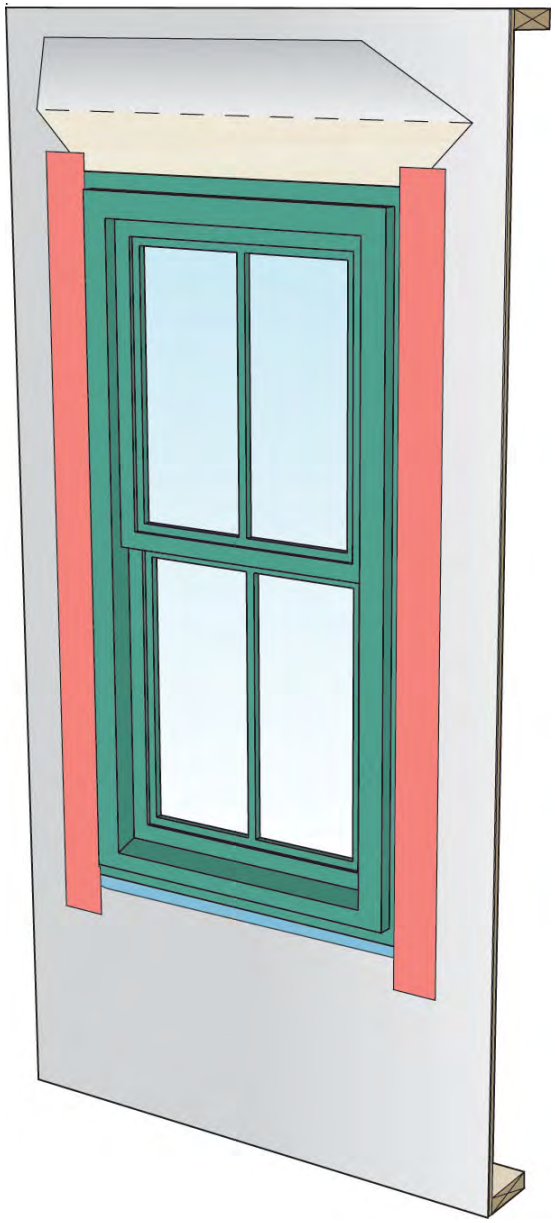


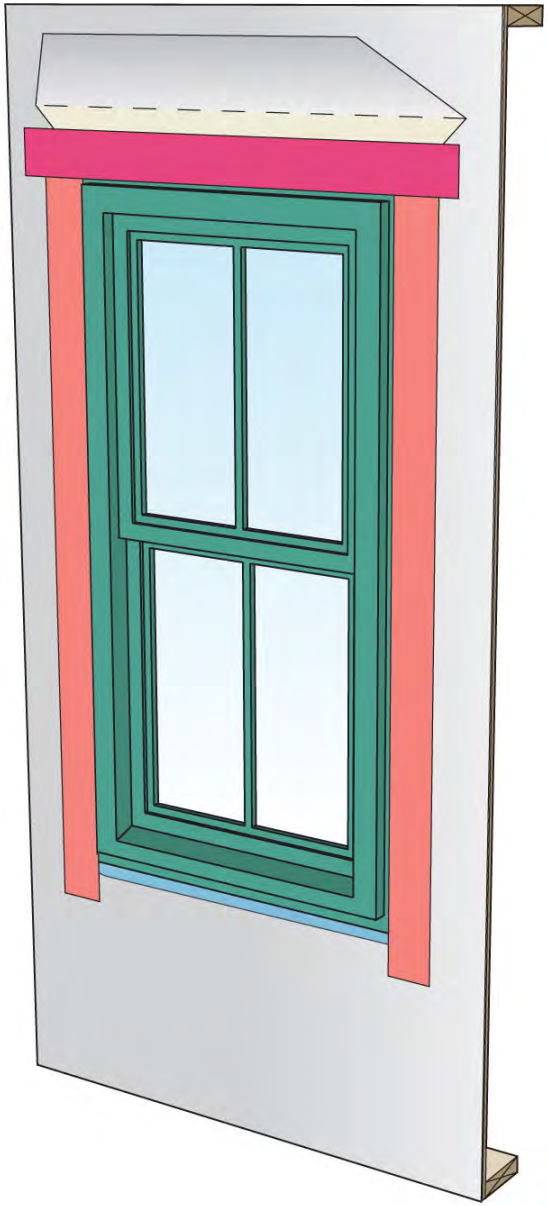


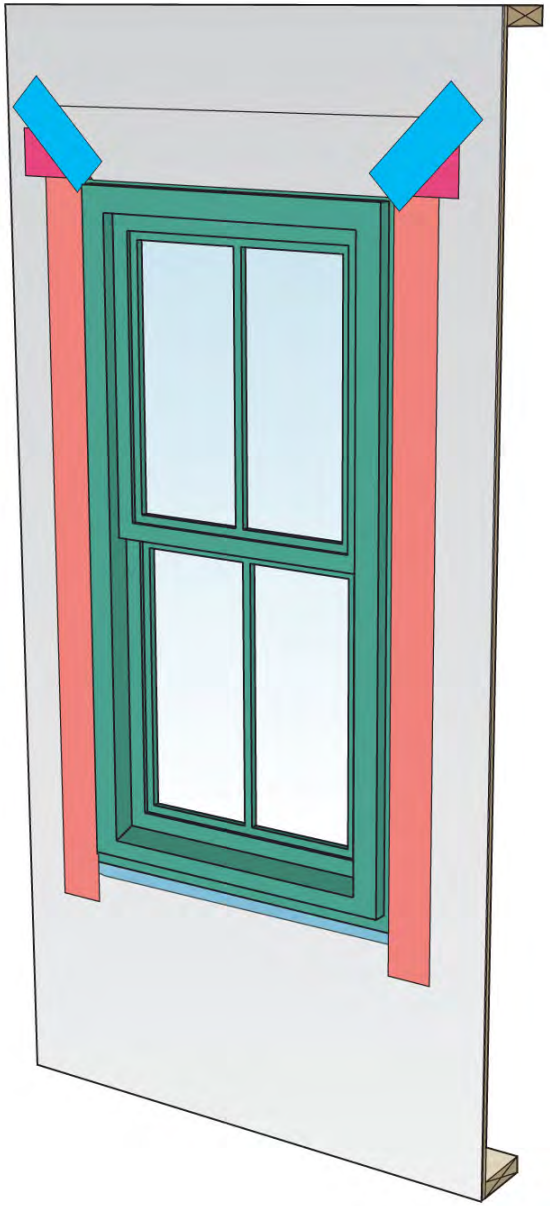


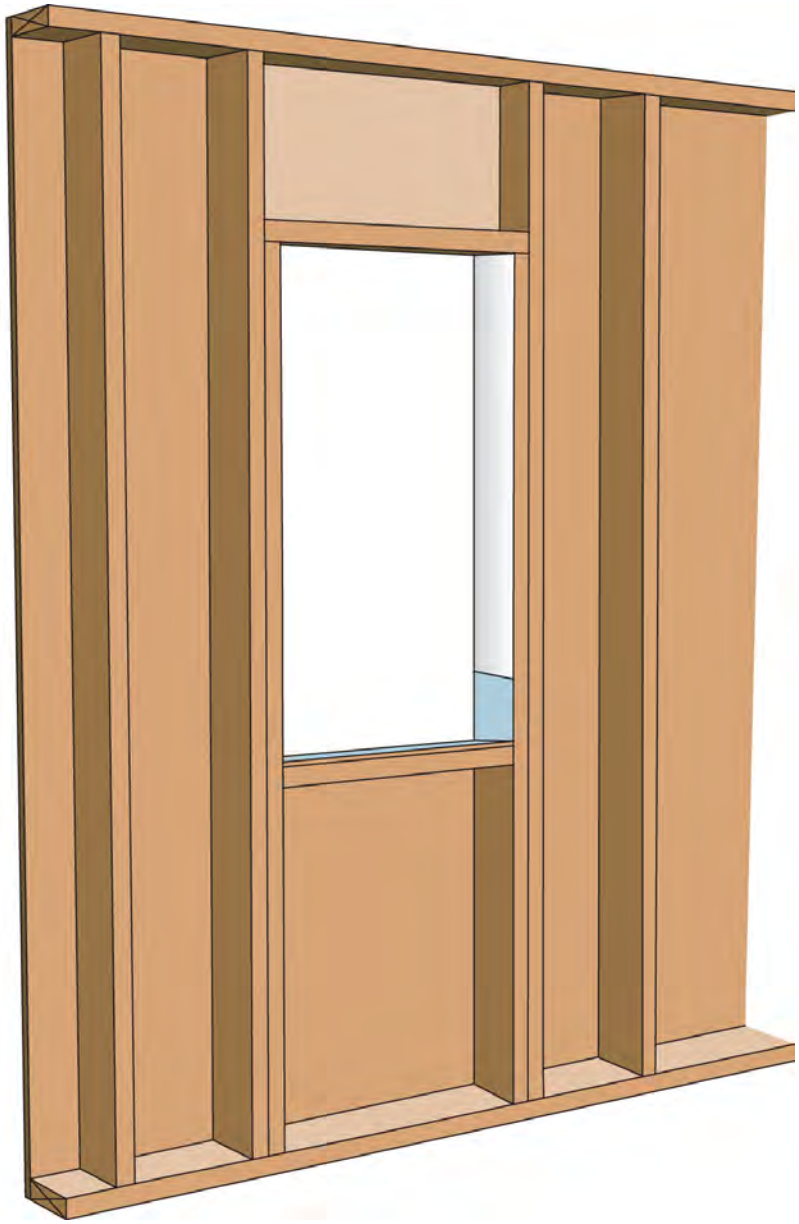


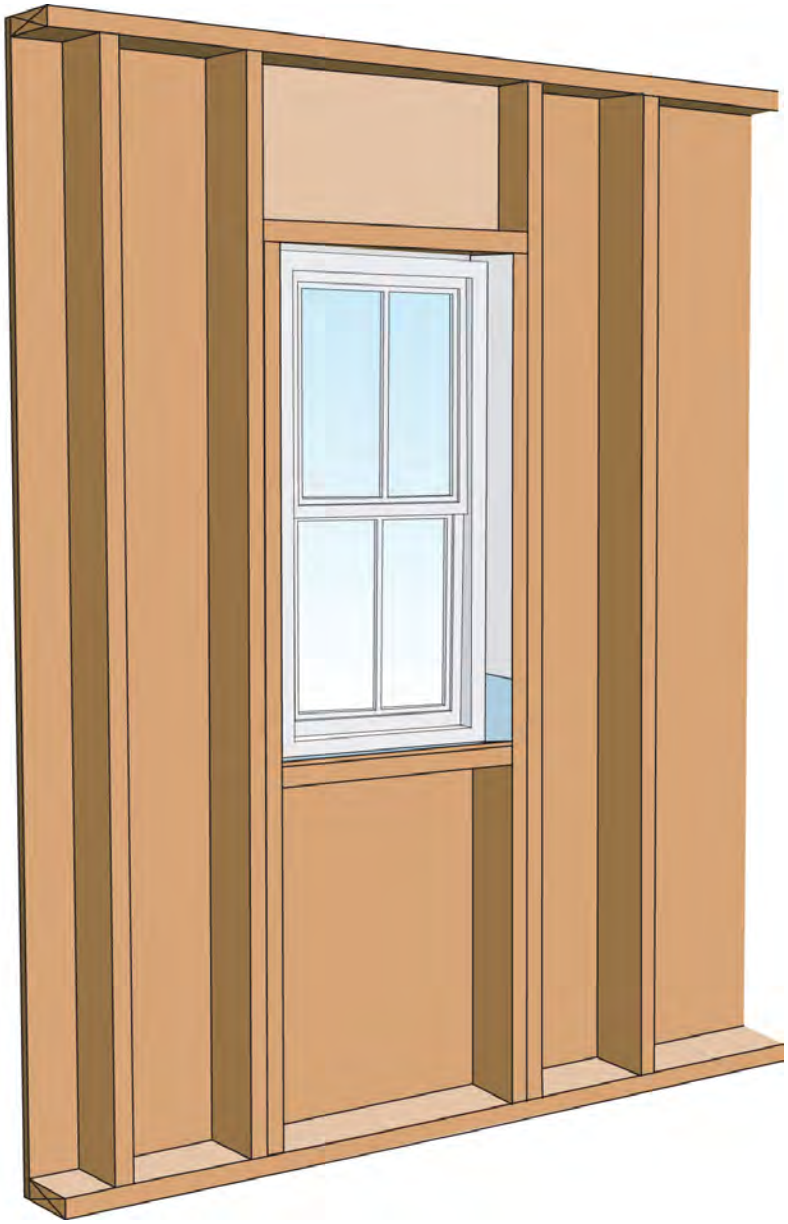










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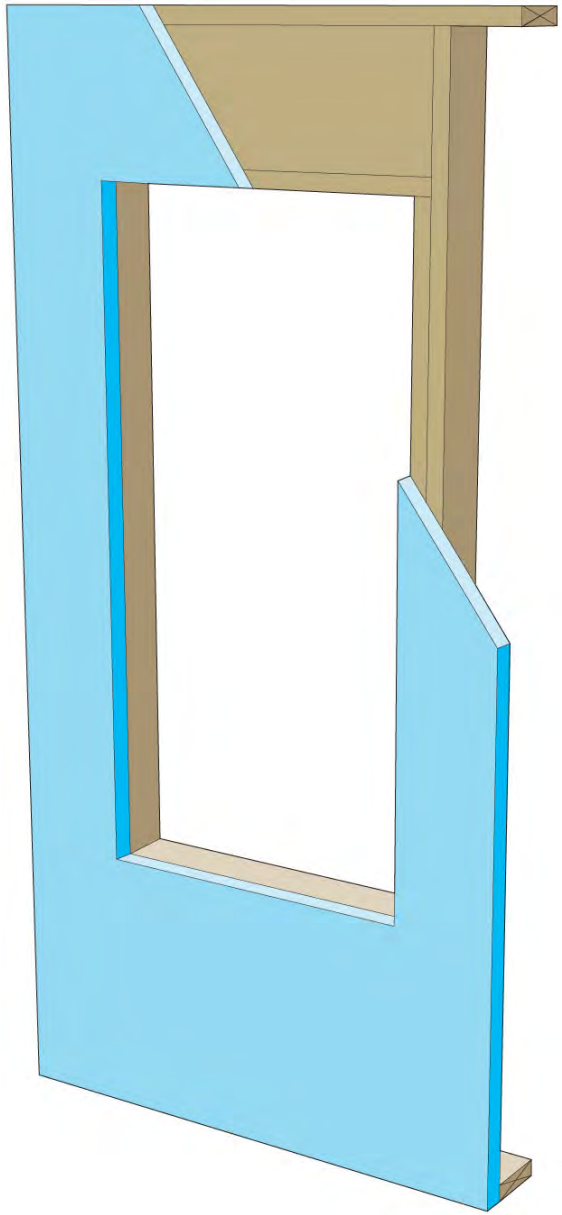

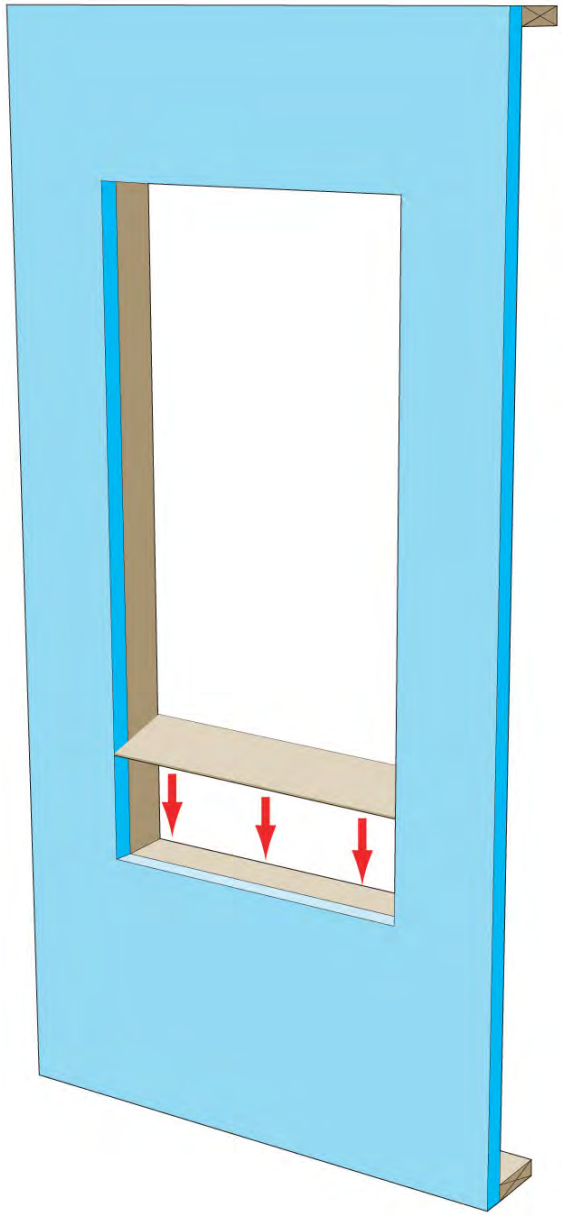

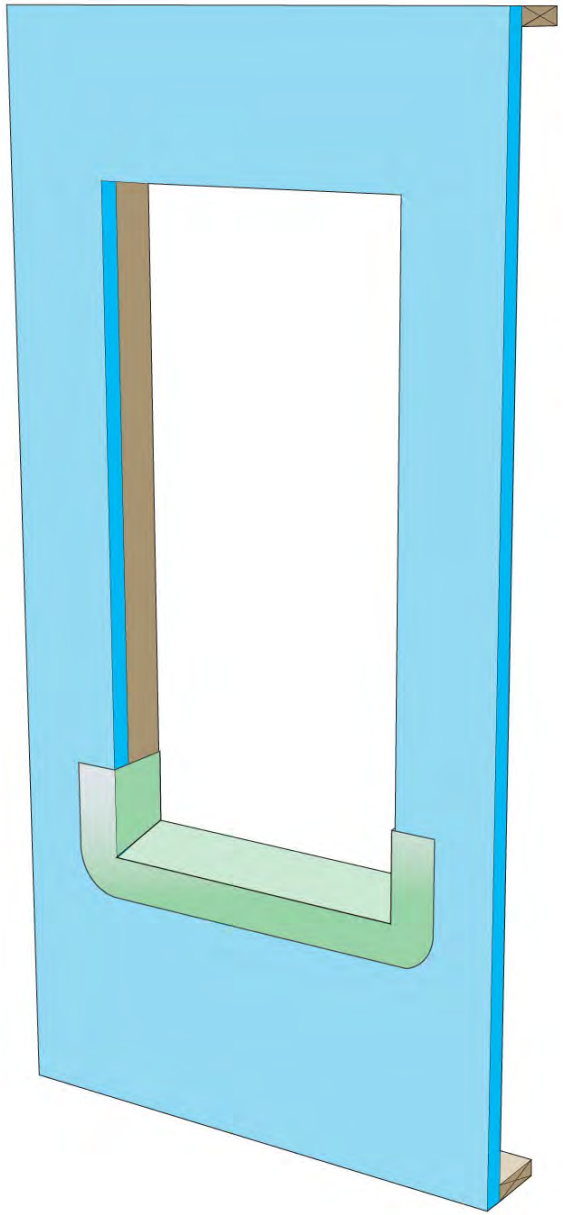

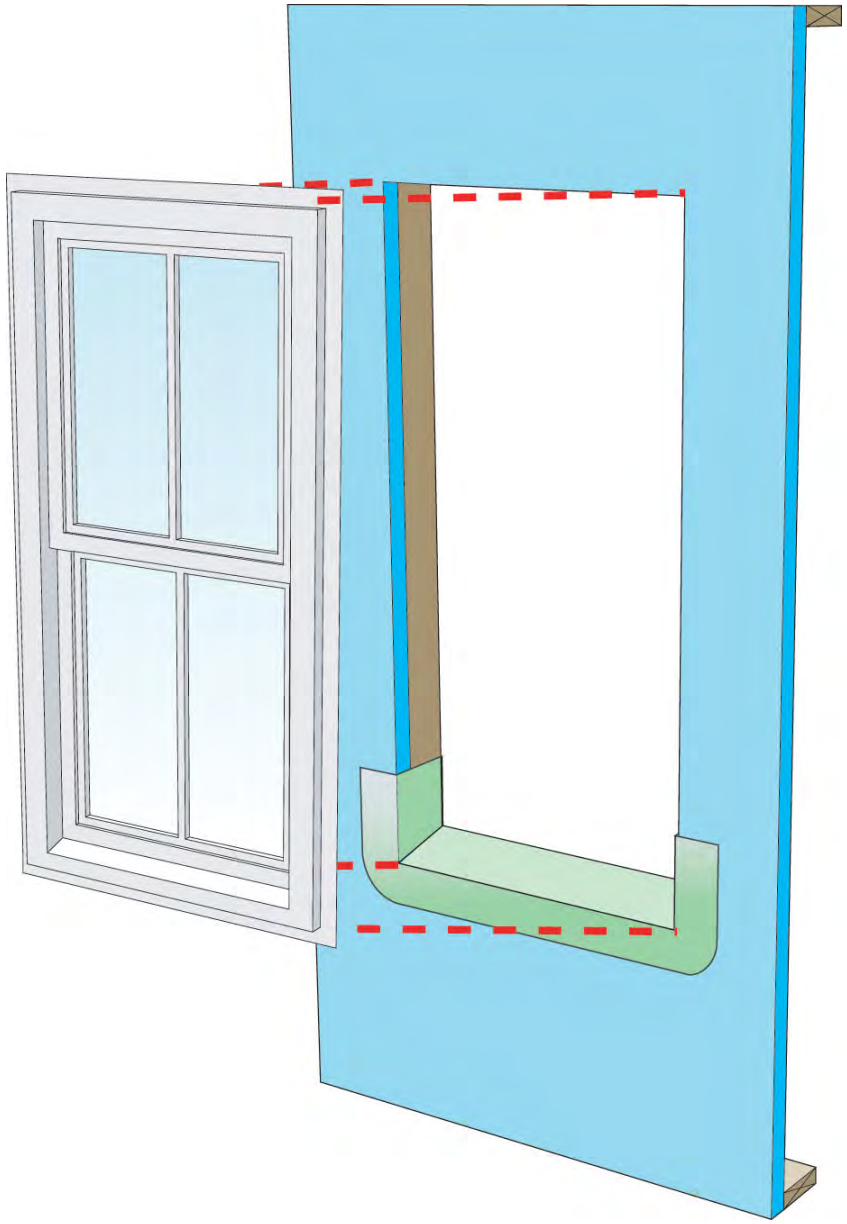

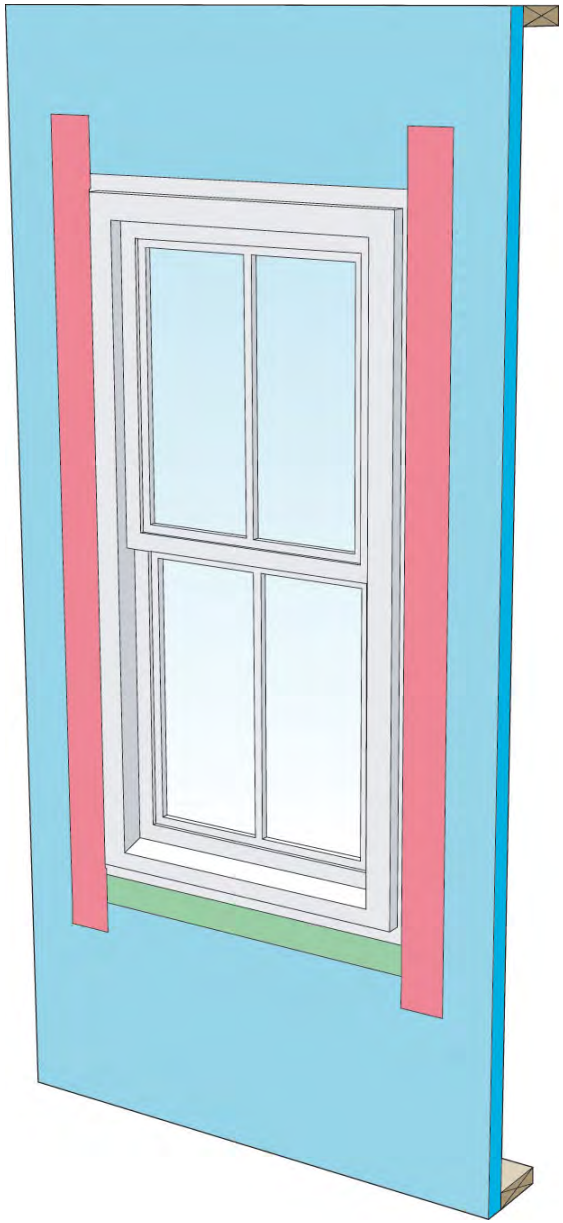

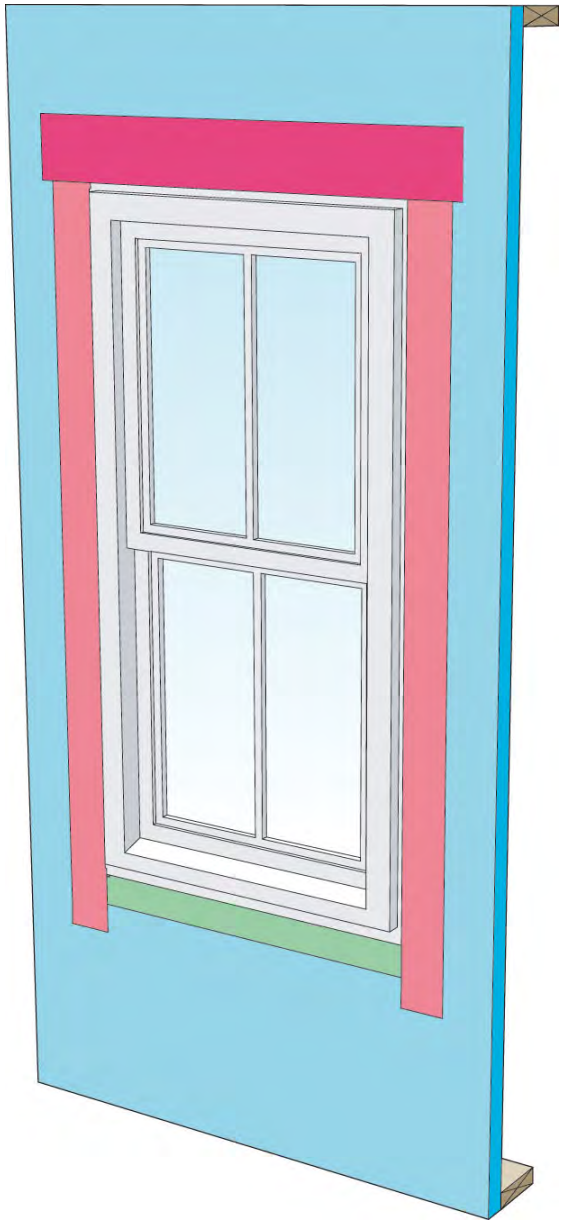

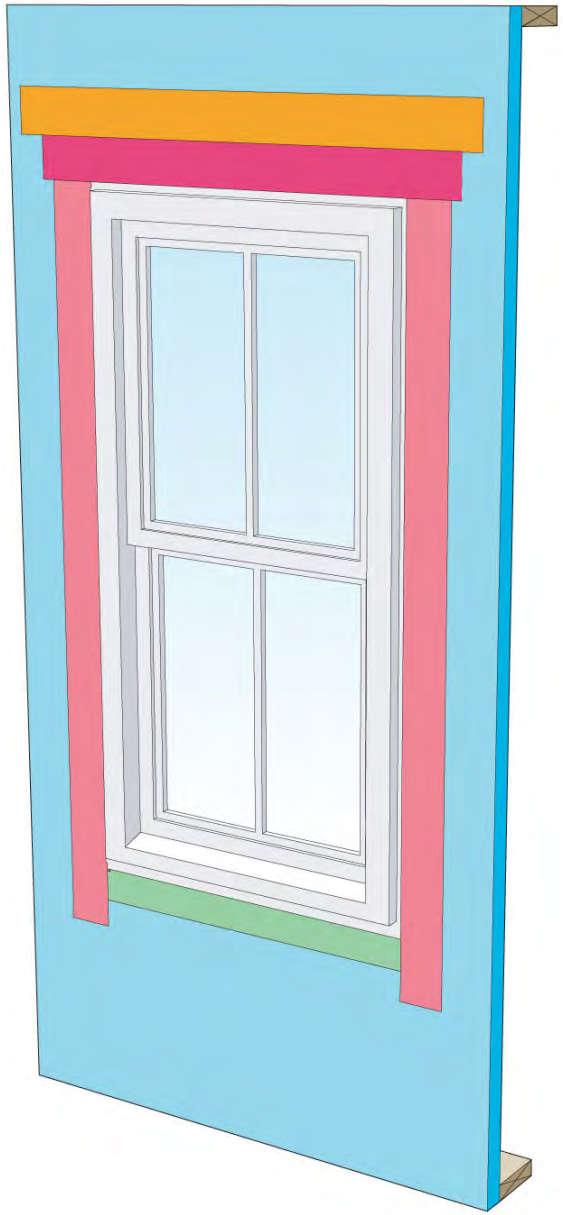

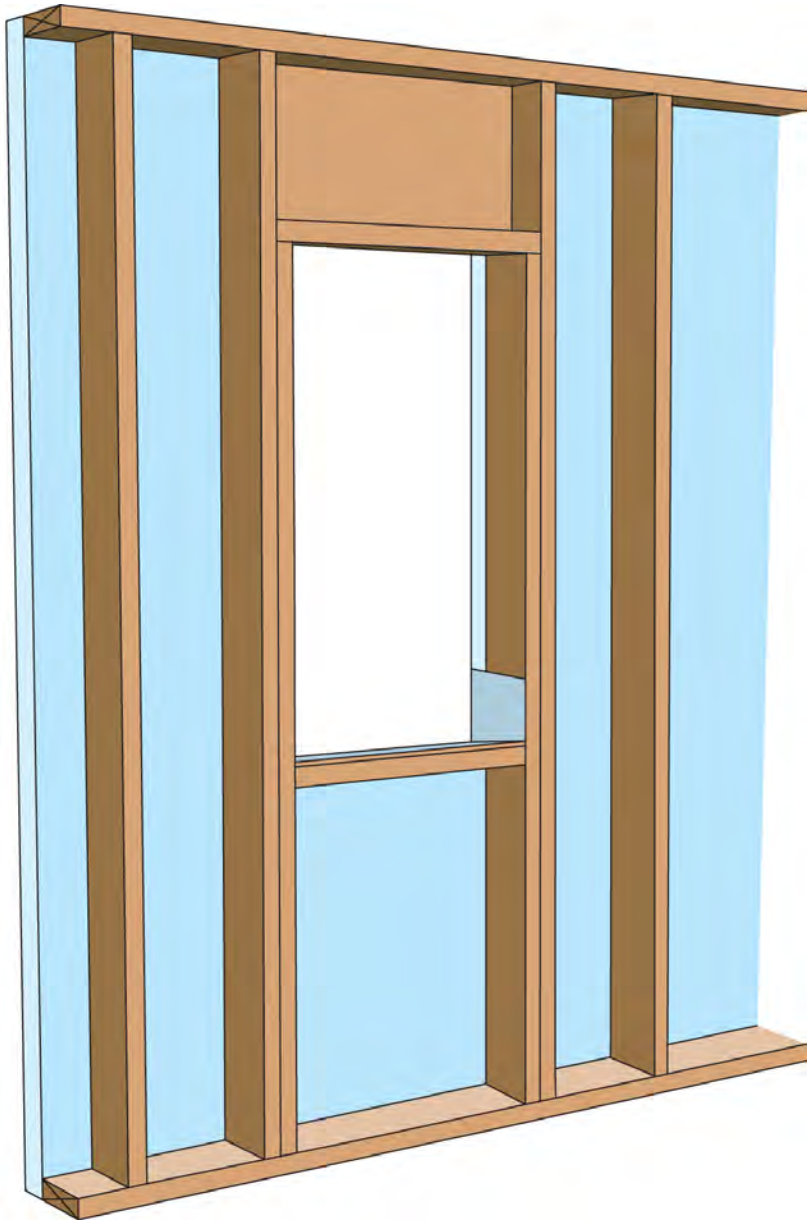

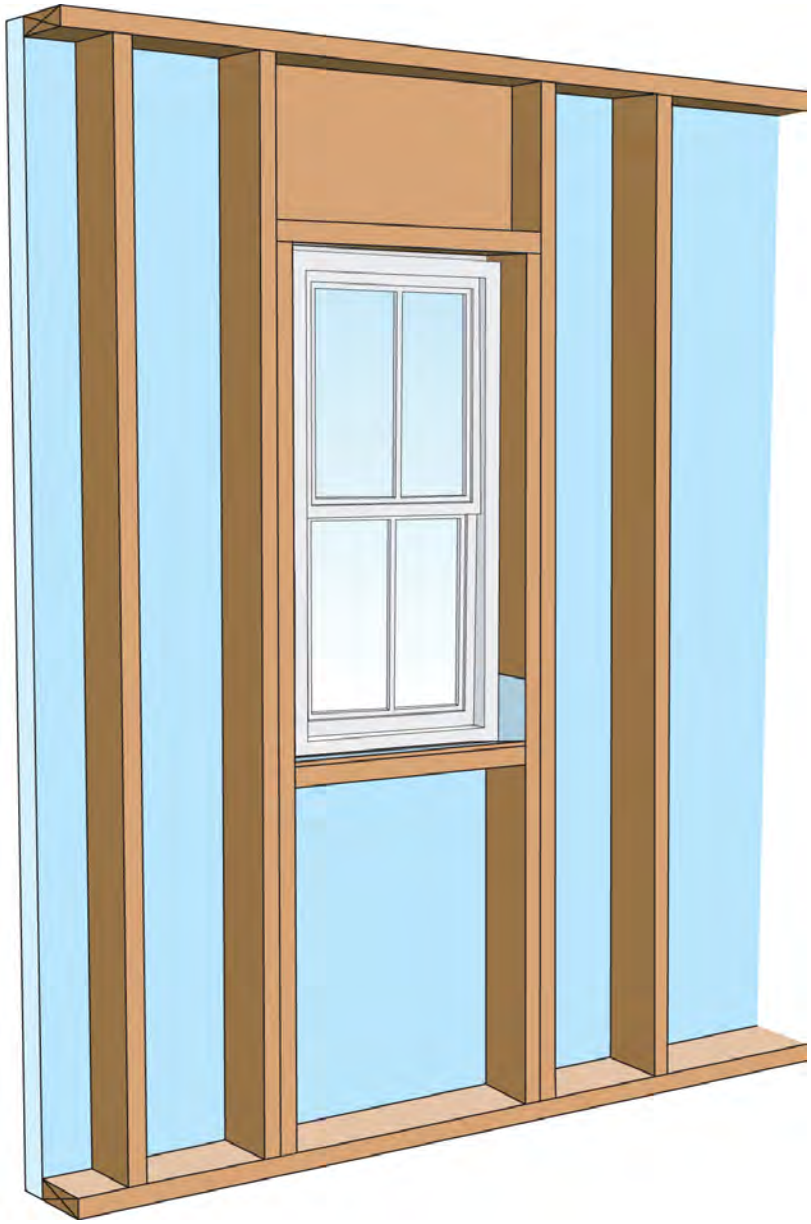

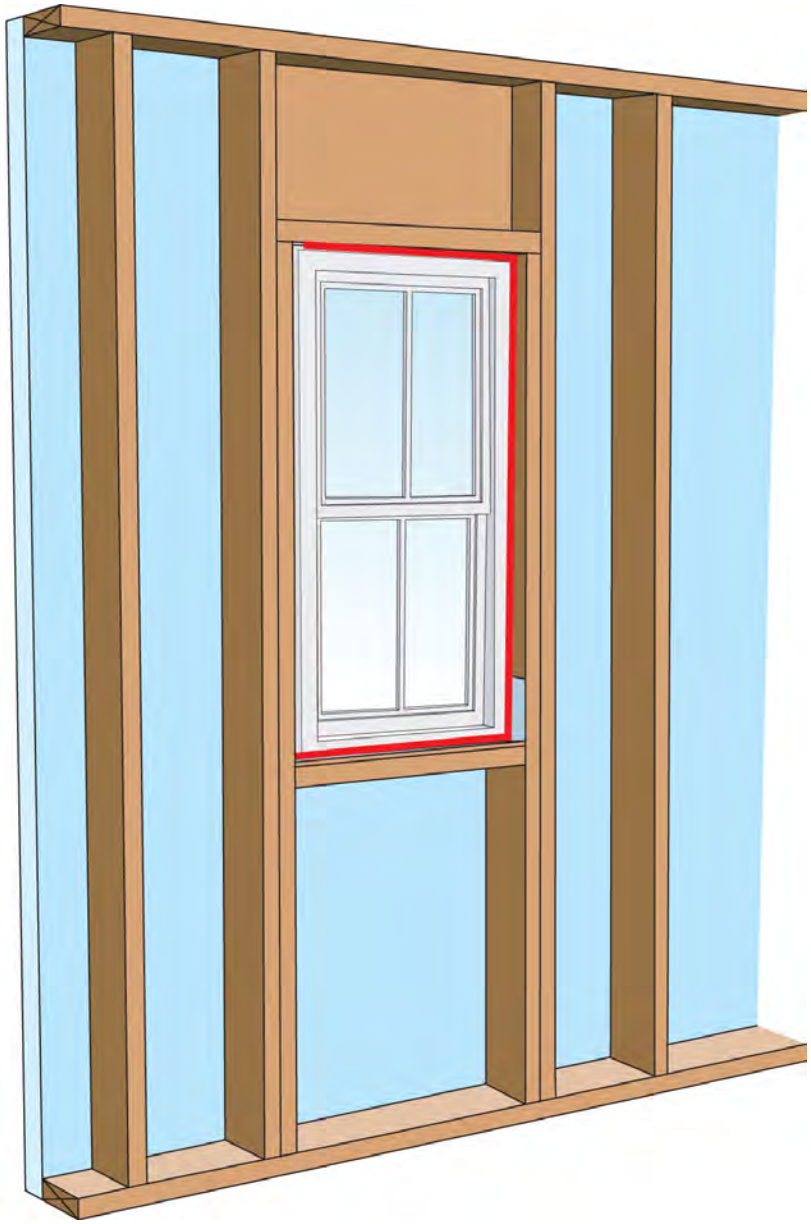


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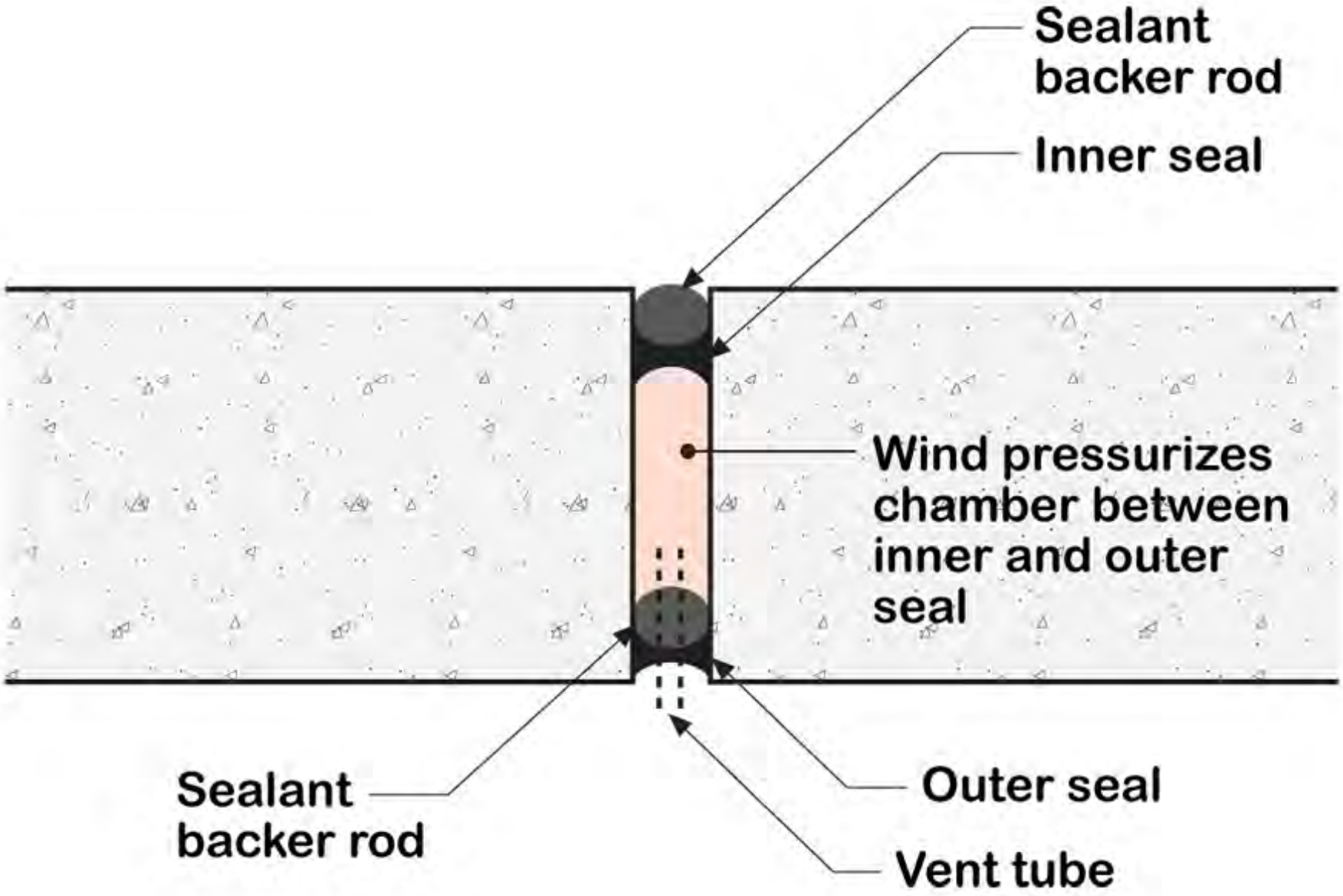
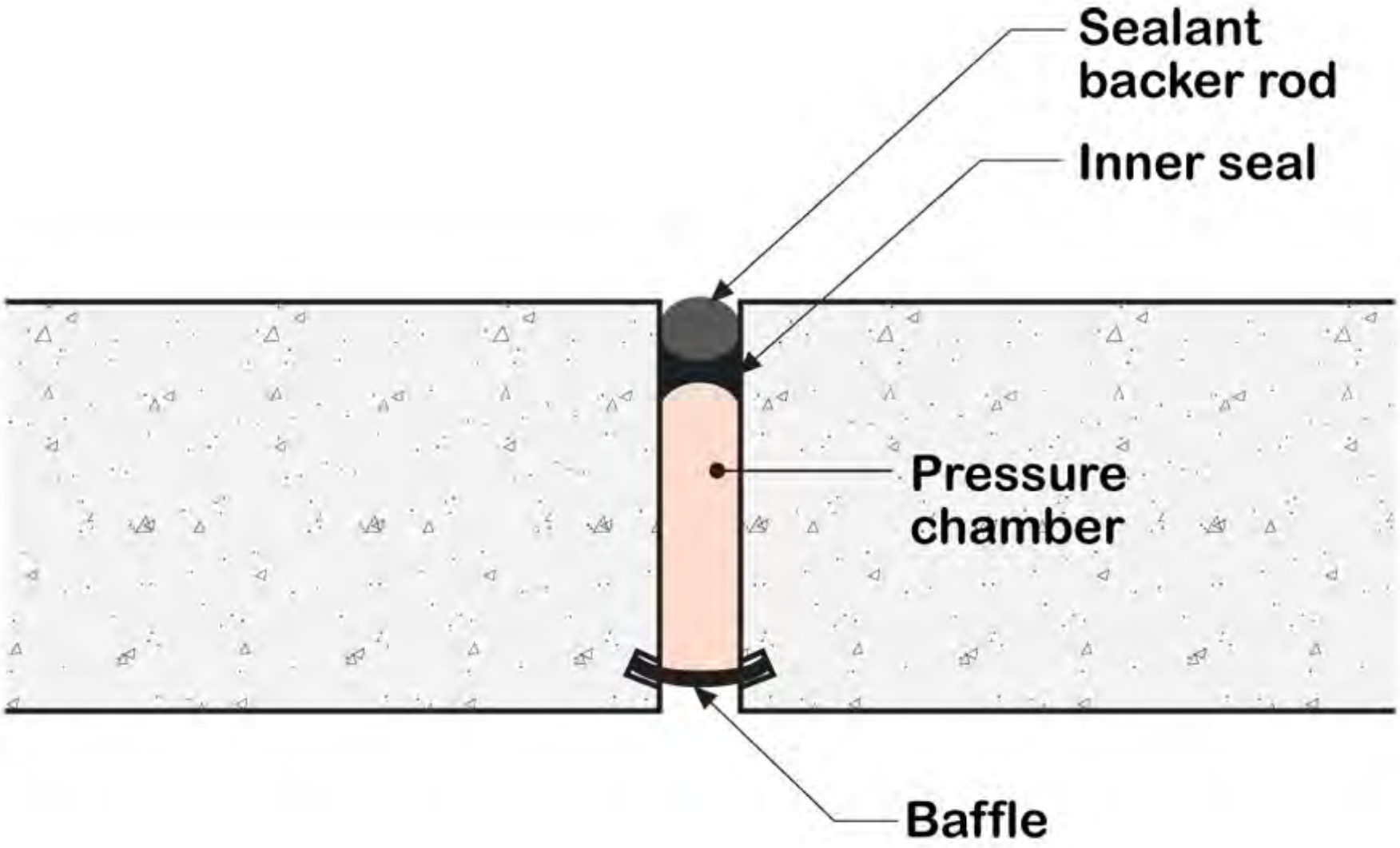
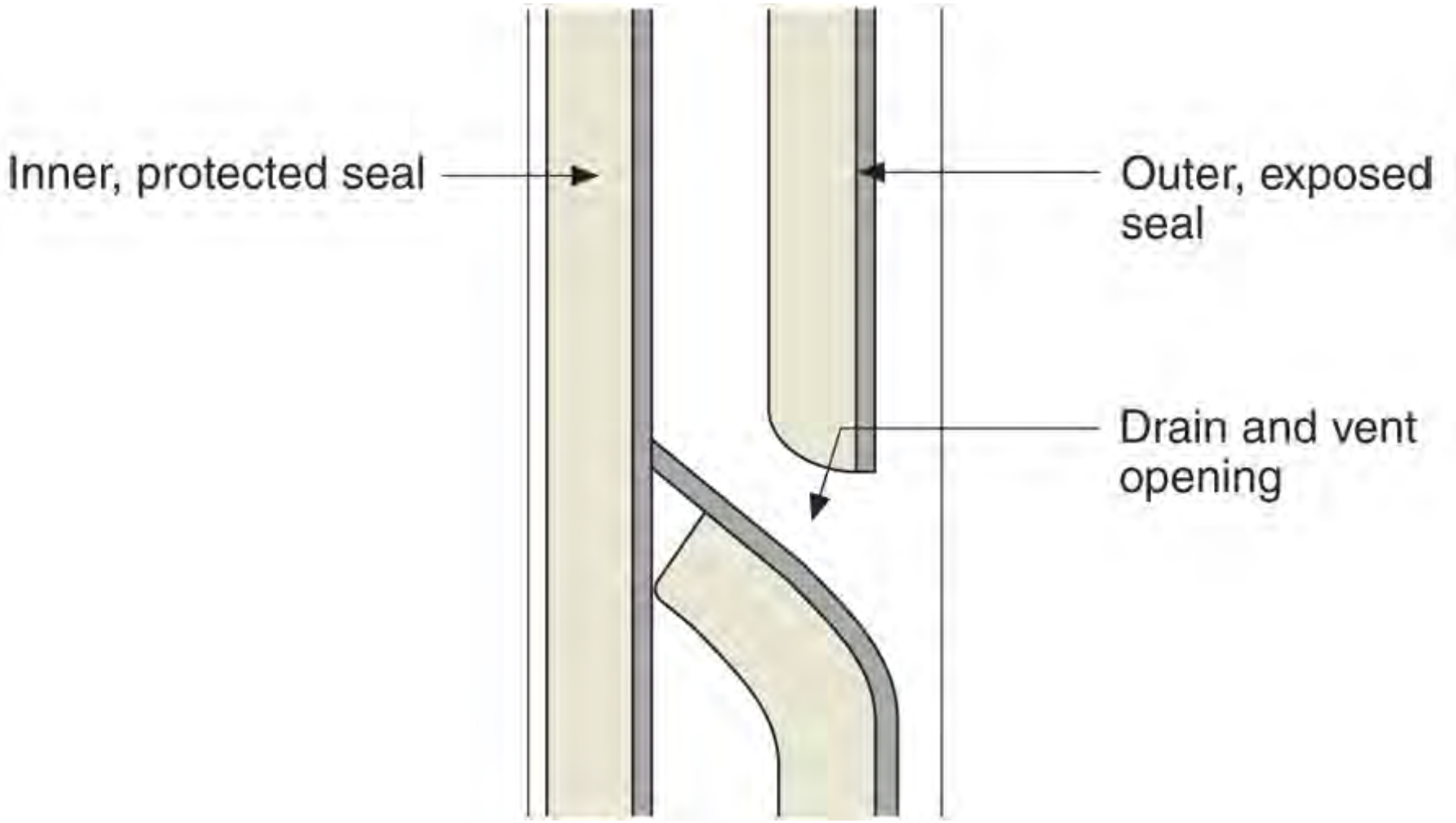
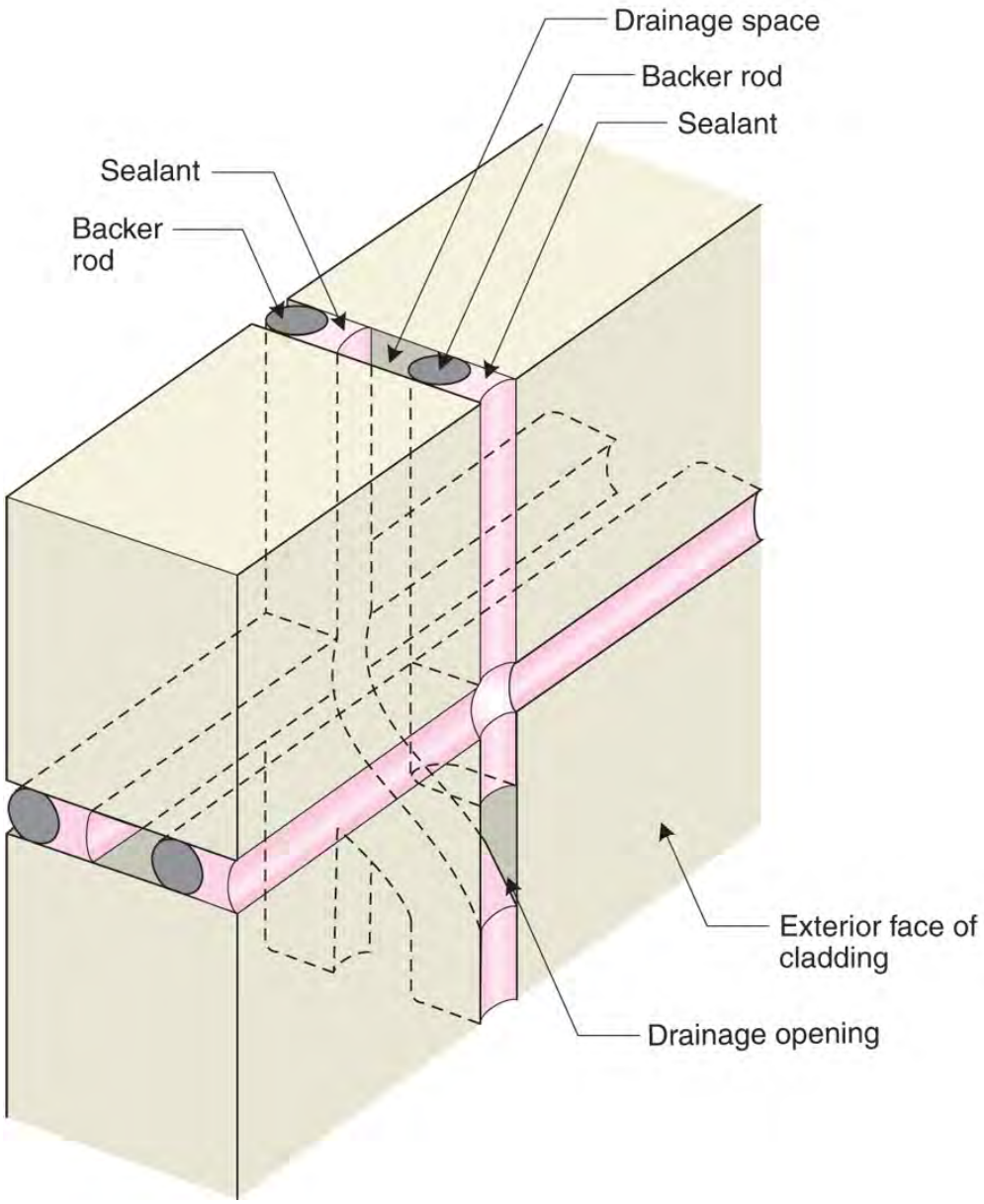

Sealant backer rod
Inner seal
Wind pressurizes chamber between inner and outer seal
Sealant backer rod
Outer seal
Vent tube

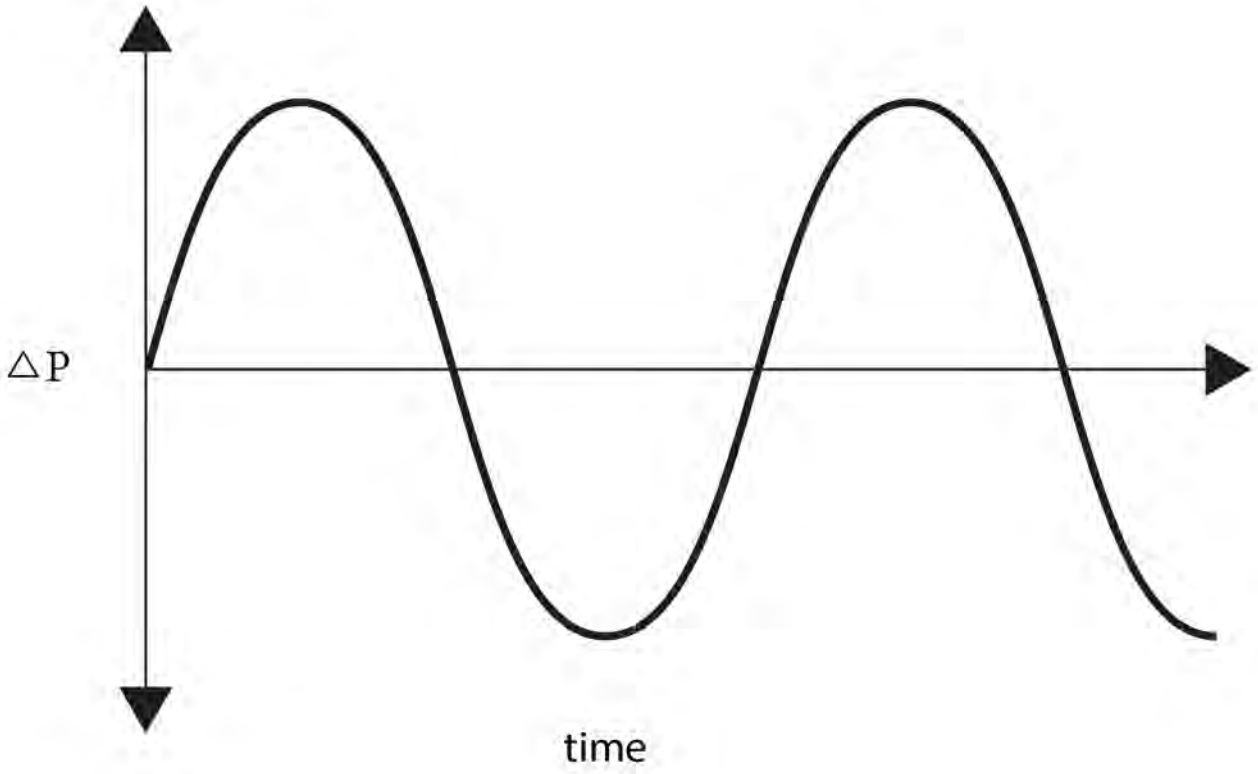

Sealant
backer rod
Inner seal
Pressure
chamber
Baffle

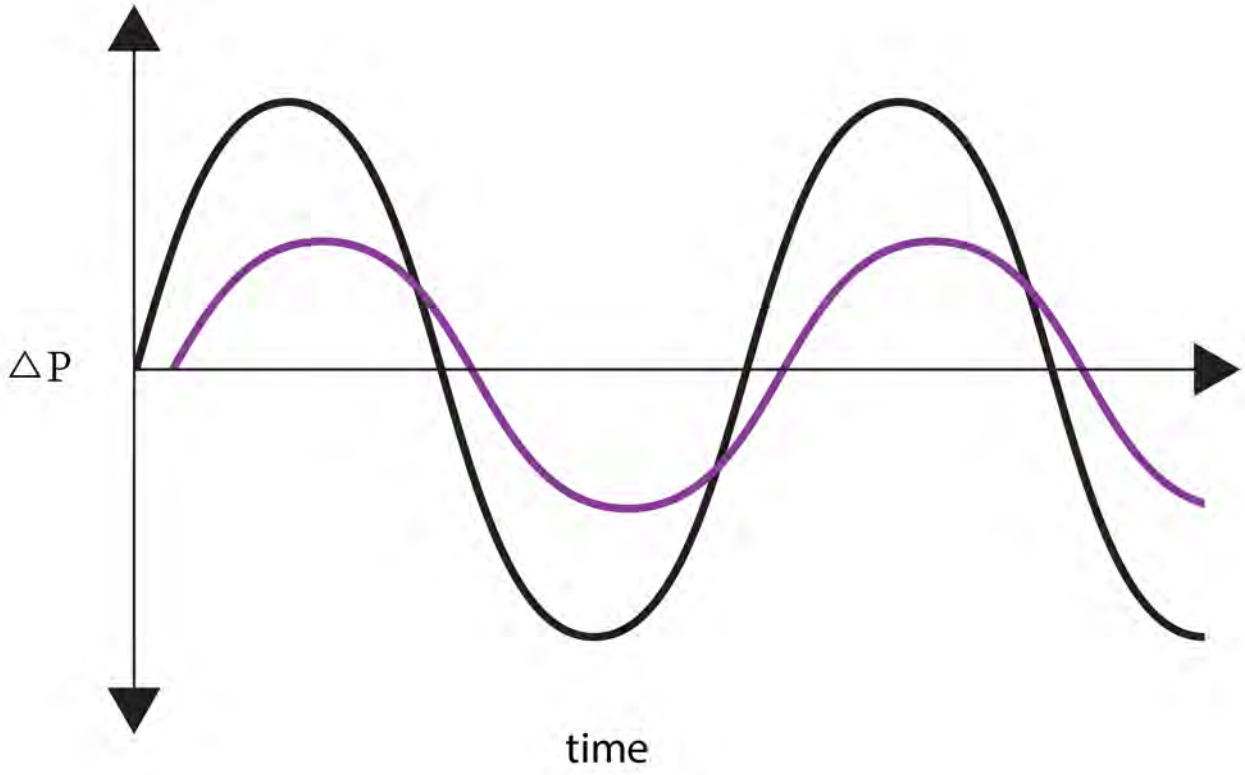

Inner, protected seal
Outer, exposed seal
Drain and vent opening

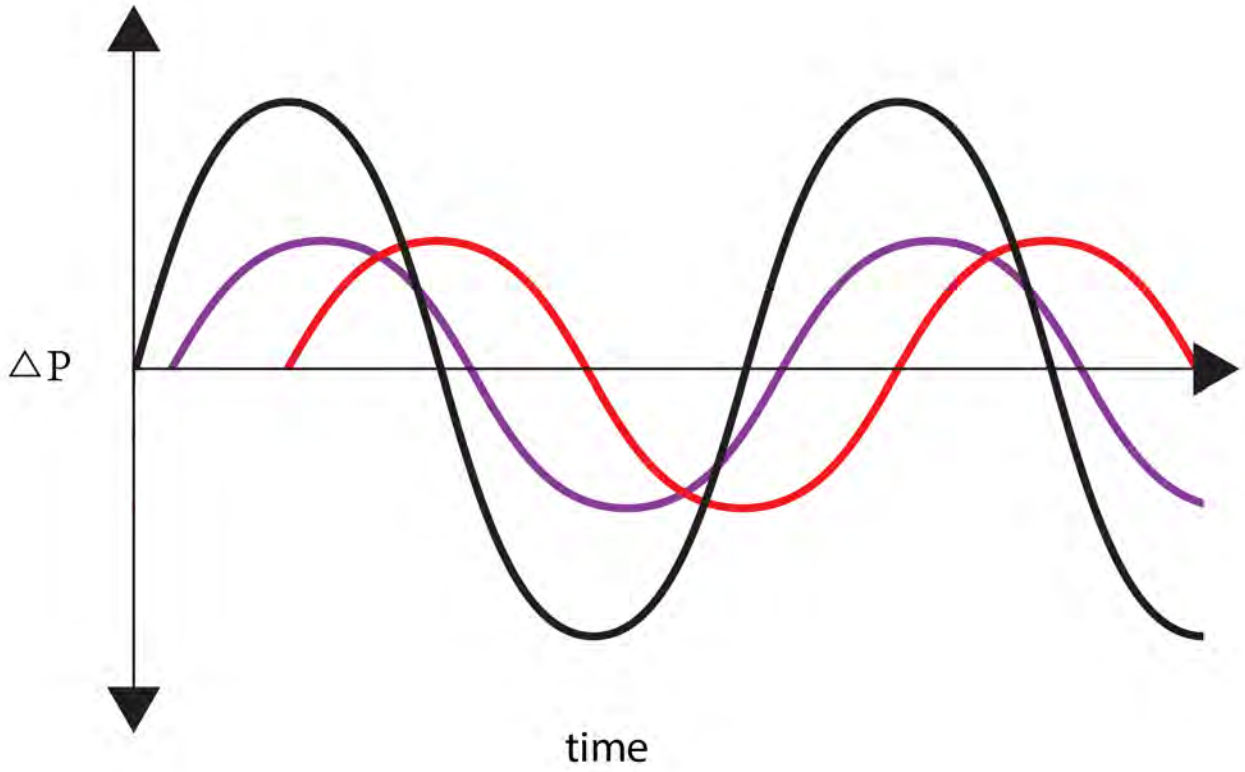

Drainage space
Backer rod
Sealant
Sealant
Backer rod
Exterior face of cladding
Drainage opening

Open Joints vs Closed Joints

Open Joints vs Closed Joints
Limits of Pressure Equalization


△P
time


△P
time


△P
time

- Pressure Equalization Needs to be Perfect
- Pressure Equalization Reduces Drying
- Prevention of Wetting Is Not As Important As Drying
- Assume Things Get Wet…Design Them to Dry
- Ventilated Claddings Promote Drying

Capillarity

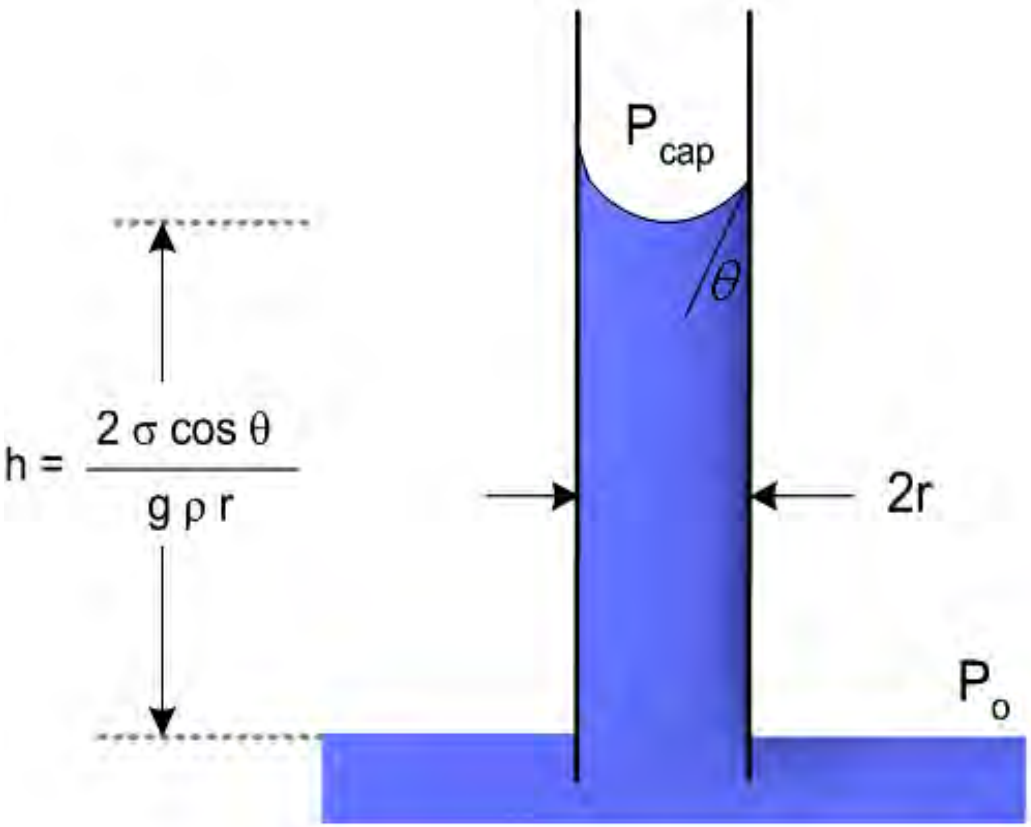
William Thomson

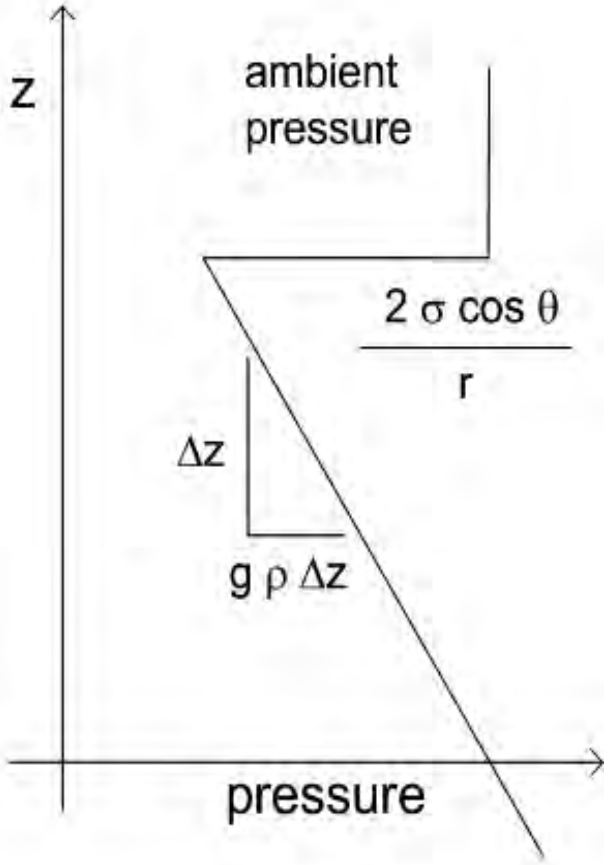
William Thomson – Lord Kelvin

Kelvin Equation

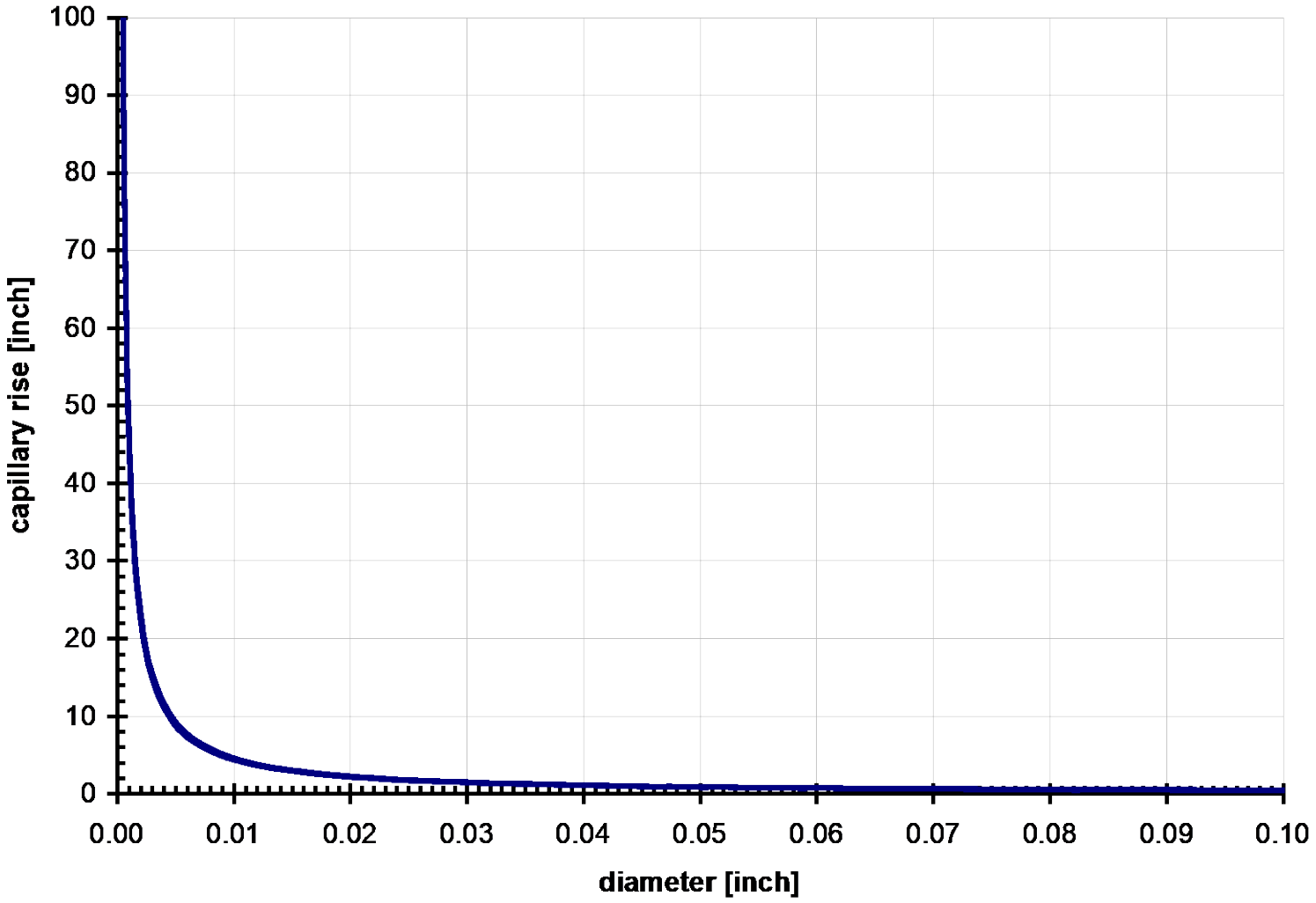
$$\ln \frac{p}{p_0} = \frac{2\gamma V_{\mathrm{m}}}{rRT}$$

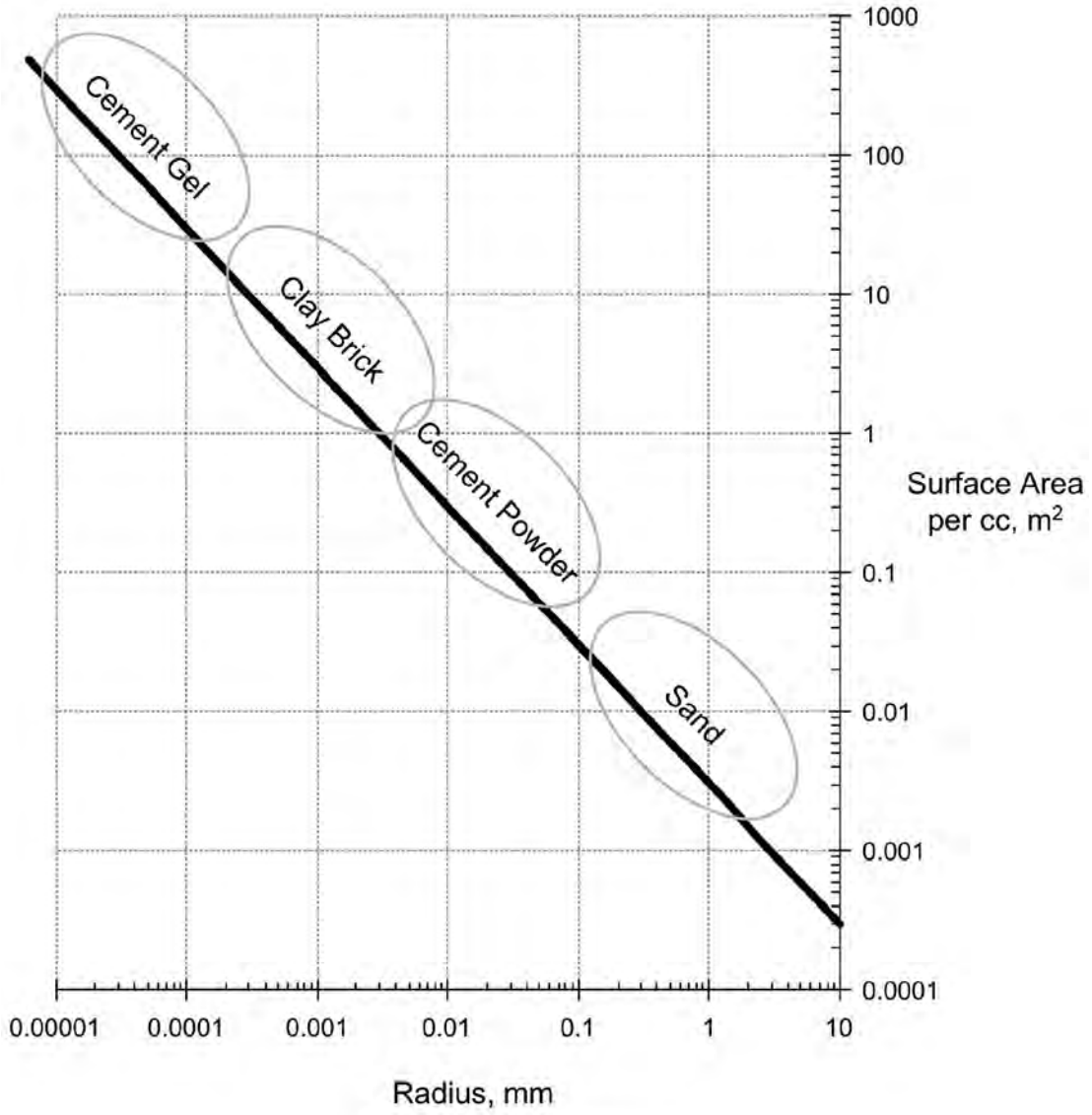
Calculating capillary rise





Capillary rise versus diameter





Surface area vs. particle size
From Straube & Burnett, 2005

Figure 1c. Gypsum, hydrated from plaster of paris and water, porosity 30 per cent.

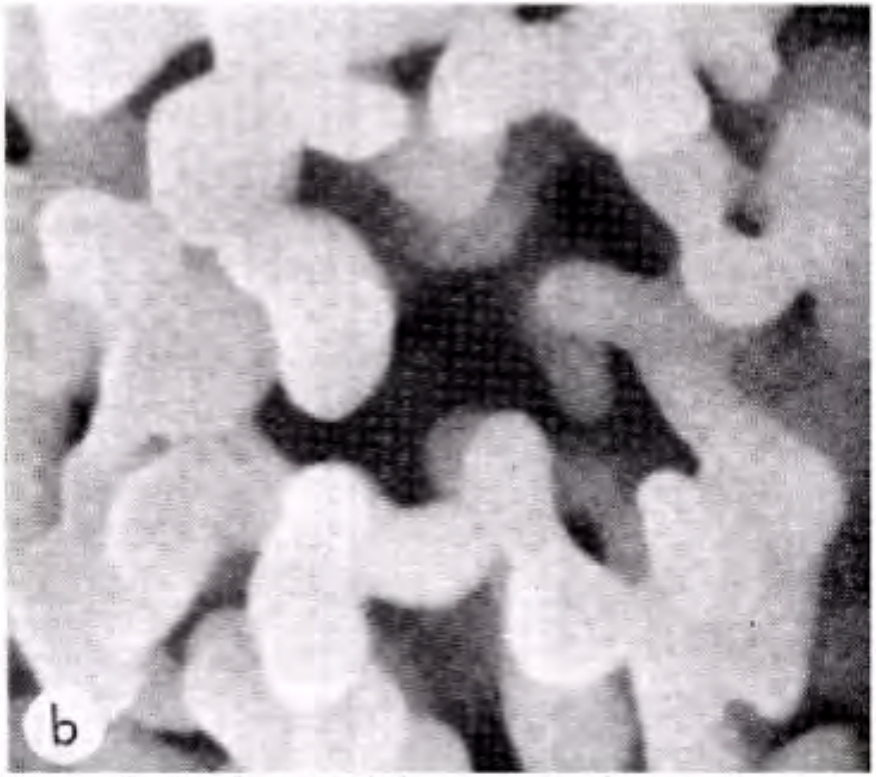
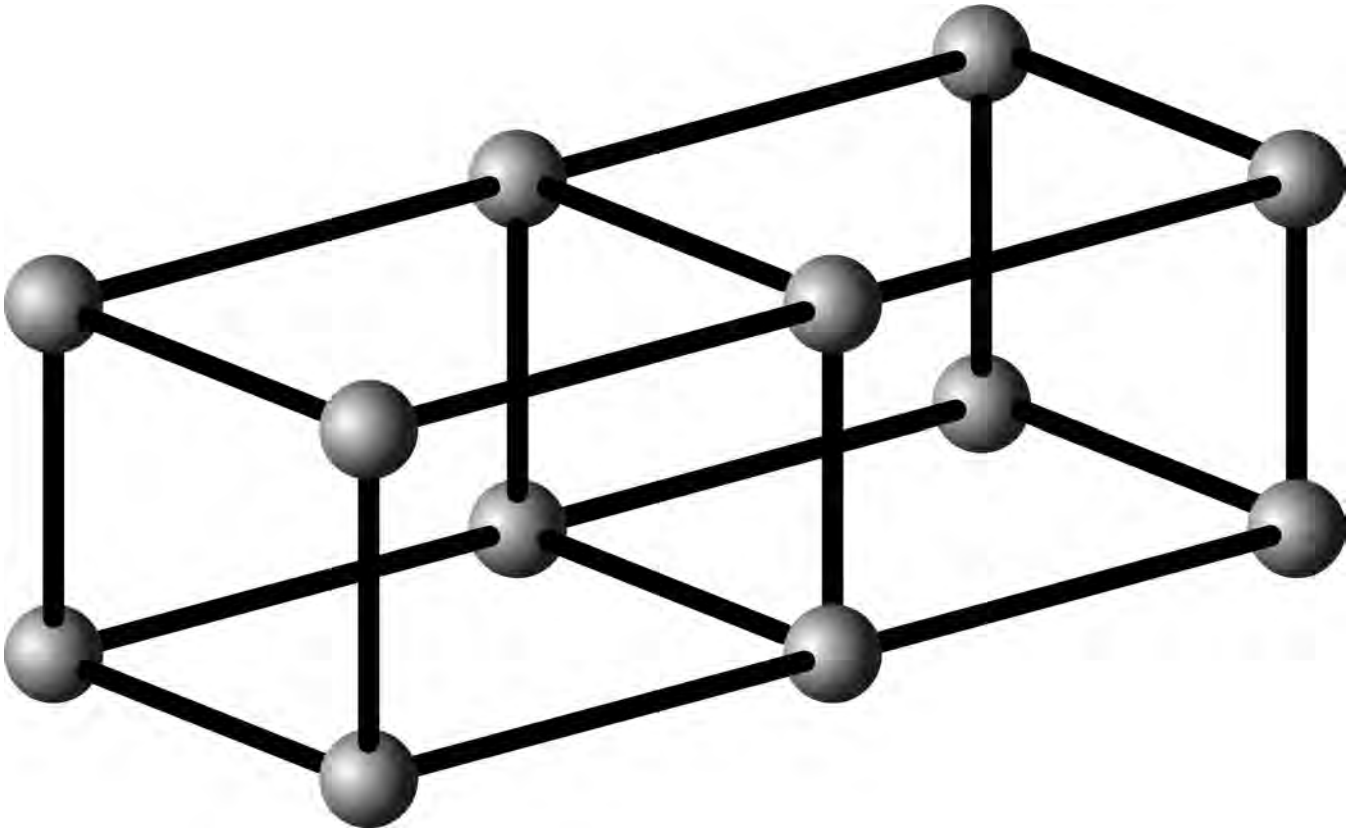
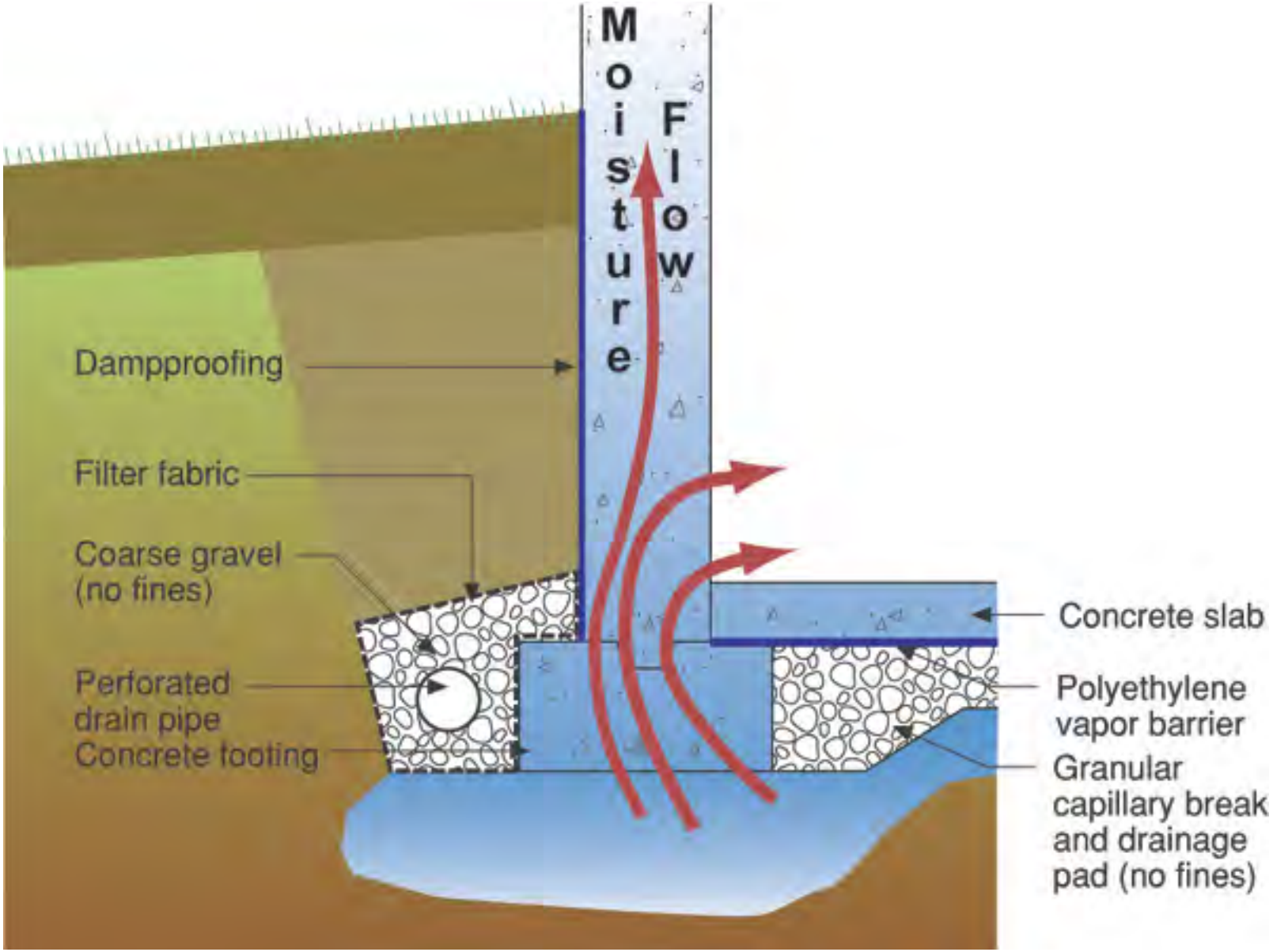
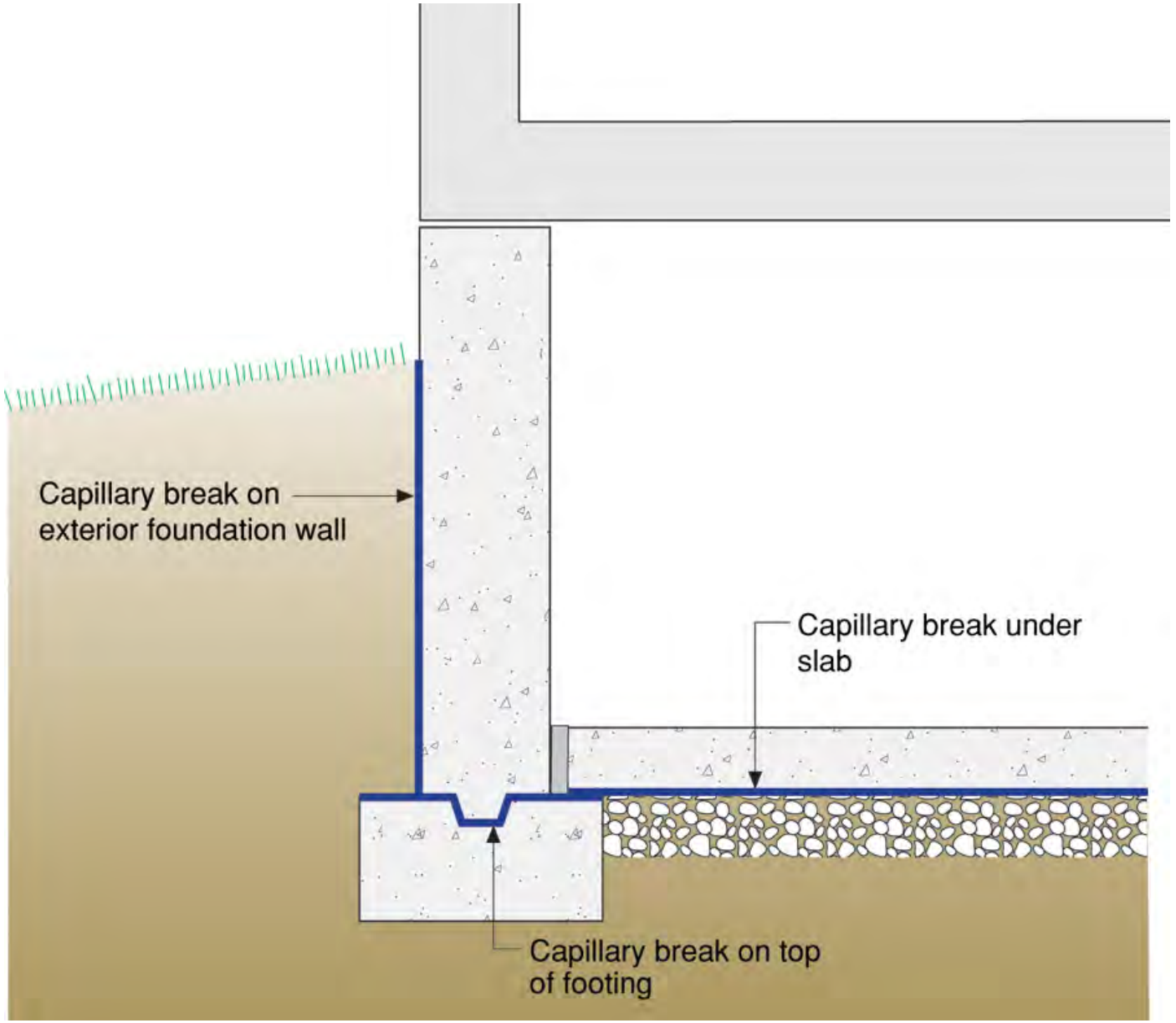


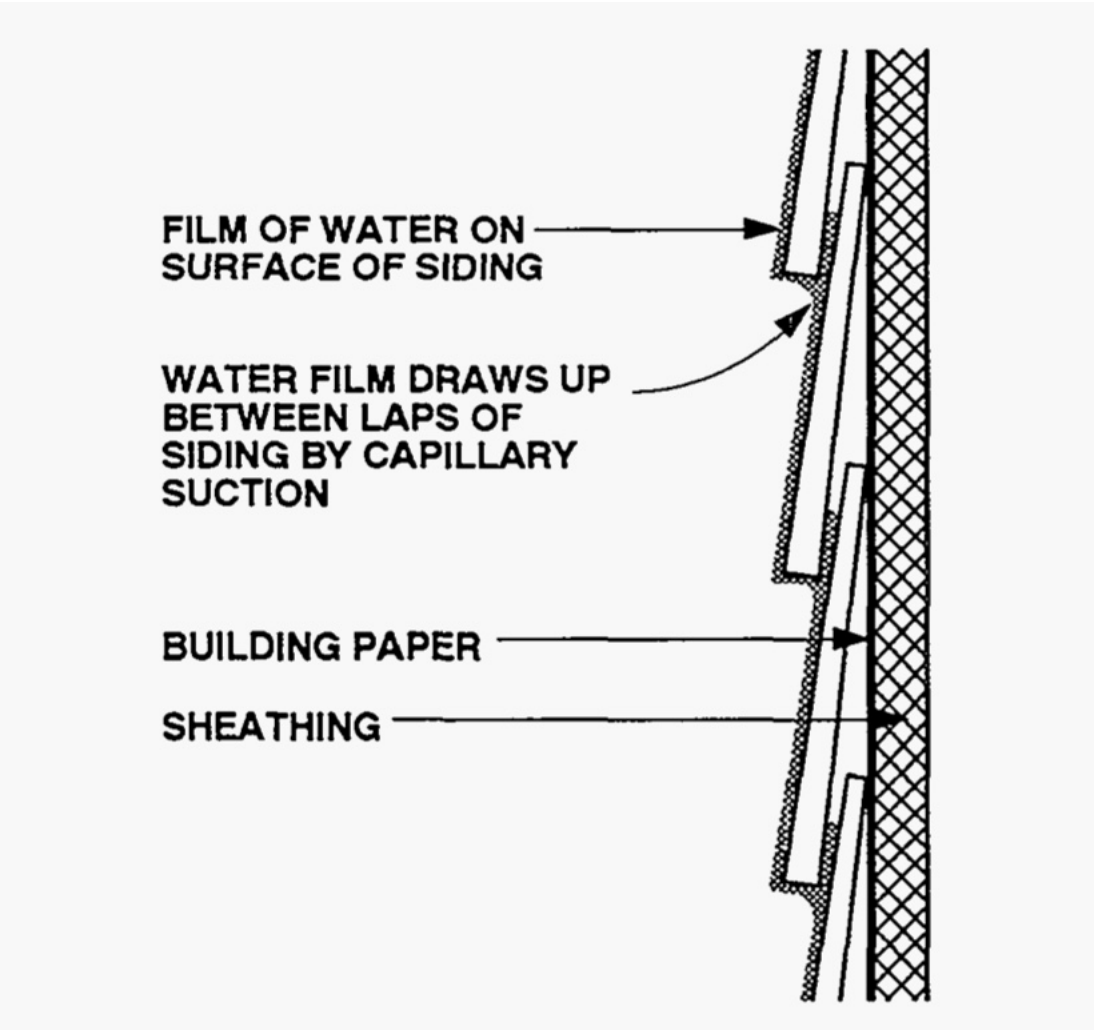
Figure 1b. Brick, sintered clay, porosity 40 per cent.

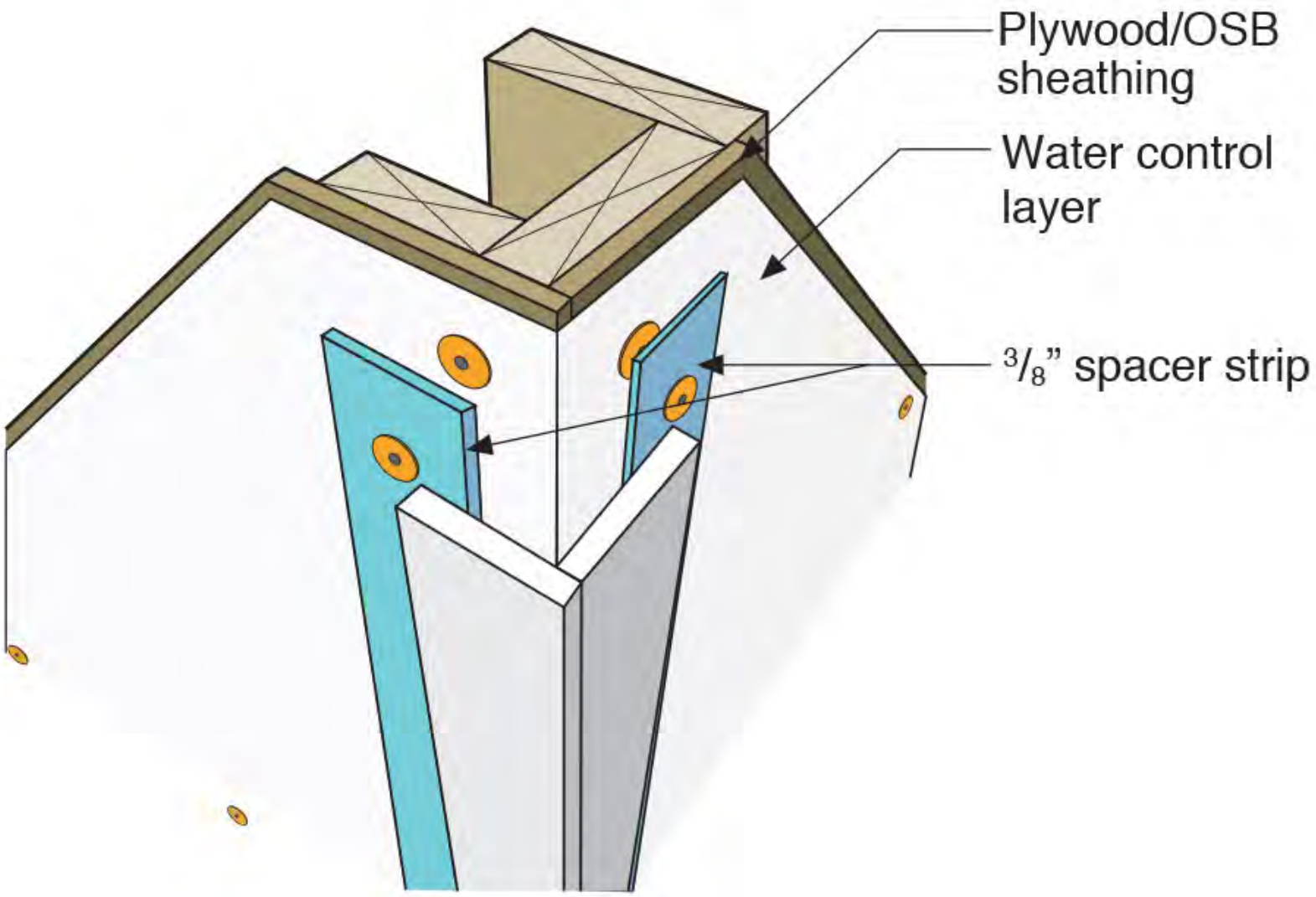


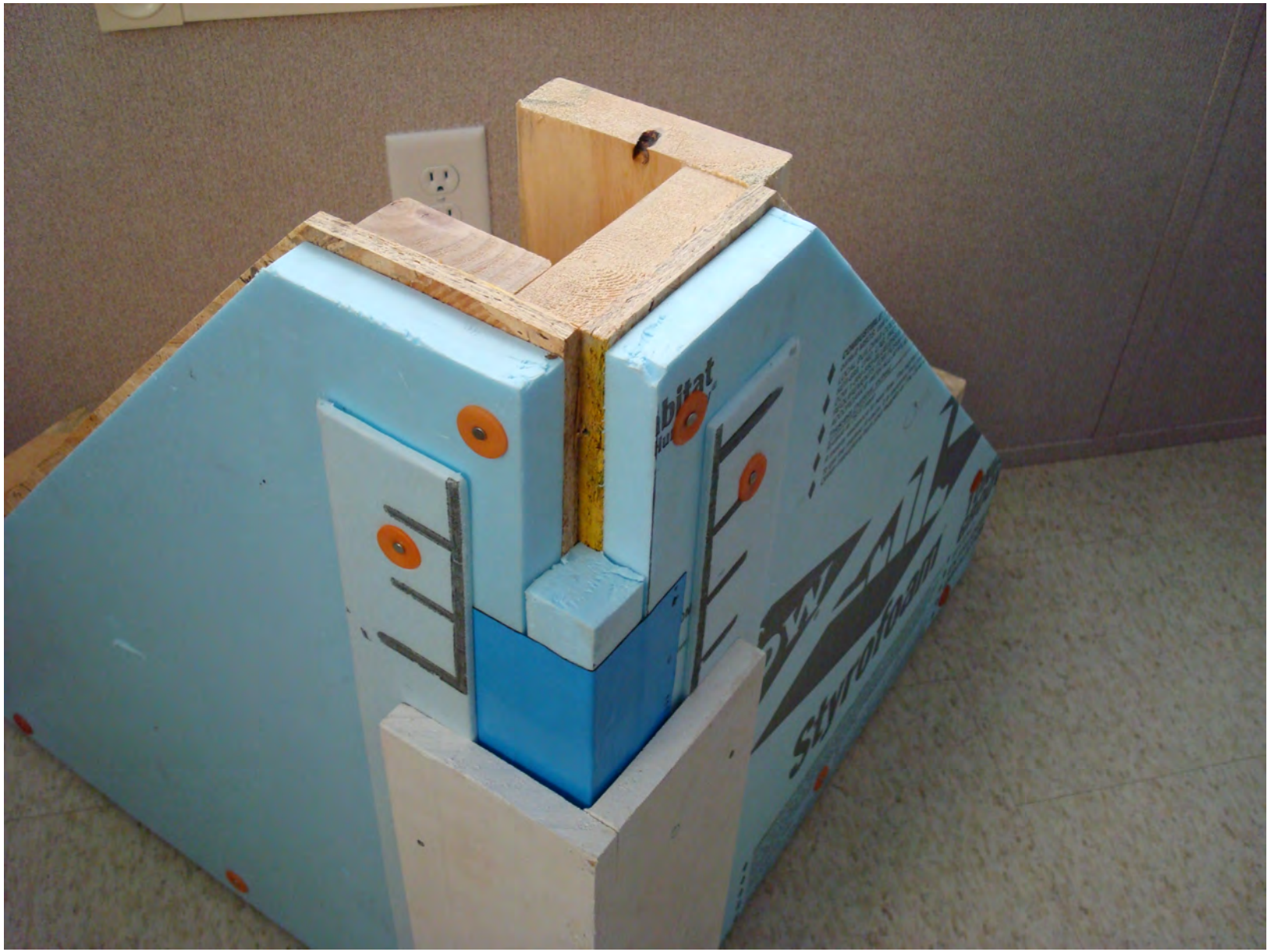

Moisture Flow
Dampproofing
Filter fabric
Coarse gravel
(no fines)
Perforated
drain pipe
Concrete footing
Concrete slab
Polyethylene
vapor barrier
Granular
capillary break
and drainage
pad (no fines)


Capillary break on
exterior foundation wall
Capillary break under
slab
Capillary break on top
of footing

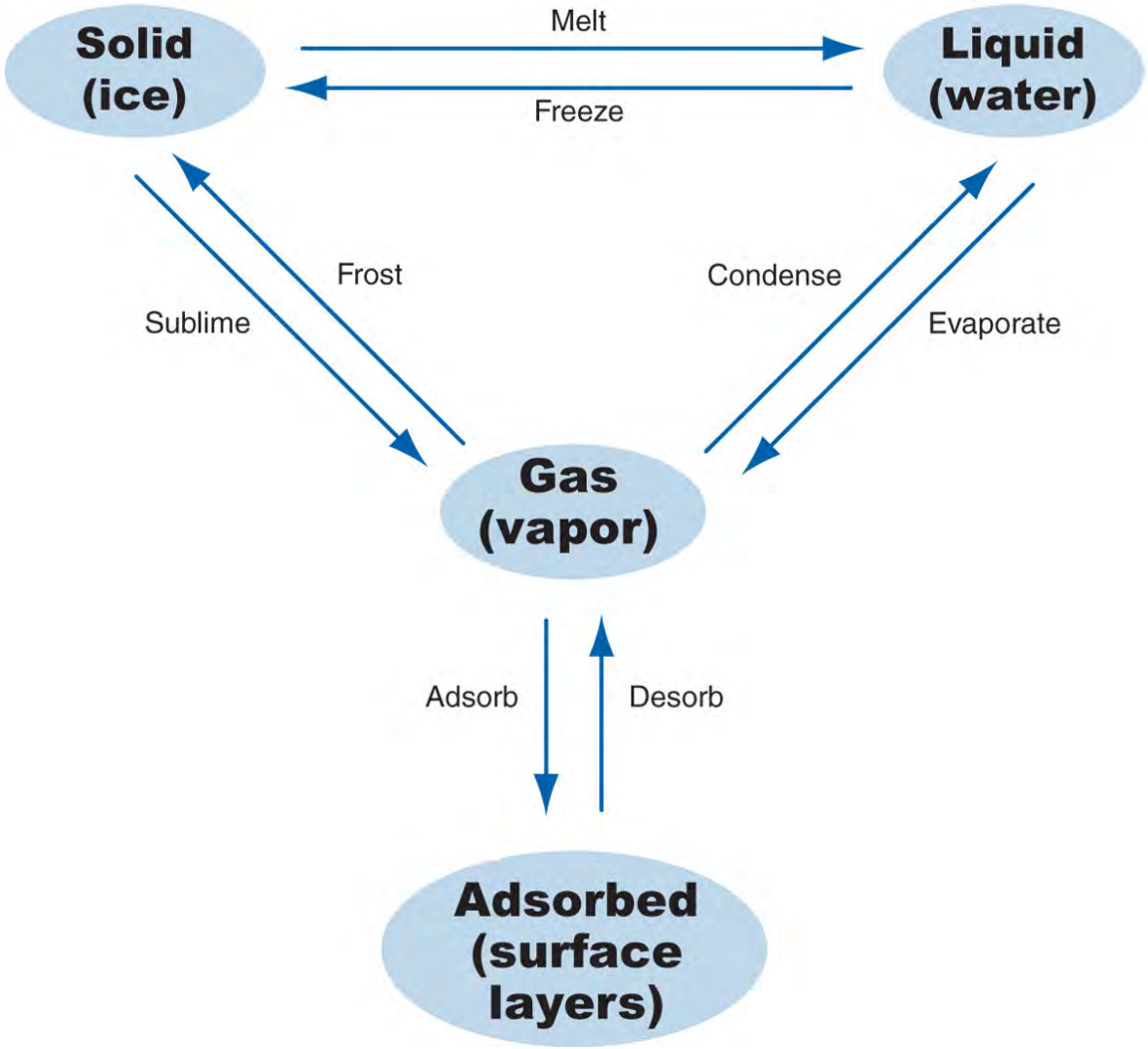
Siding Laps

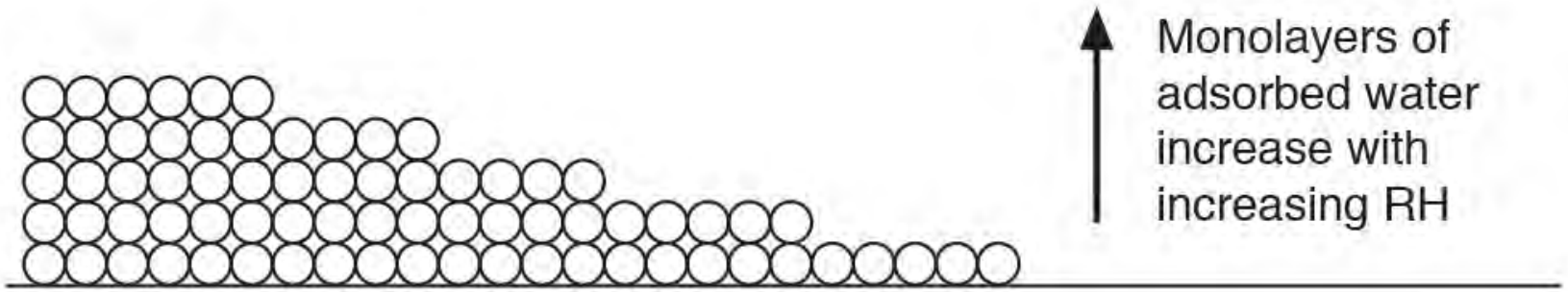

FILM OF WATER ON SURFACE OF SIDING
WATER FILM DRAWS UP BETWEEN LAPS OF SIDING BY CAPILLARY SUCTION
BUILDING PAPER
SHEATHING

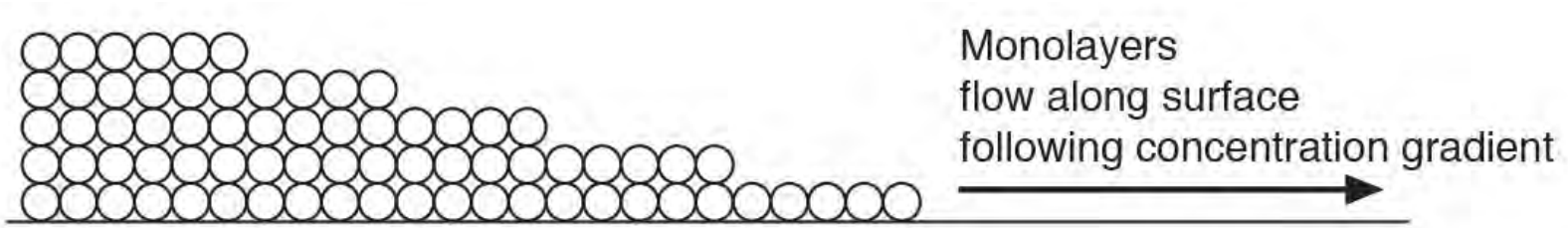

Plywood/OSB sheathing
Water control layer
3/8" spacer strip


Styrofoam

Phases of Water

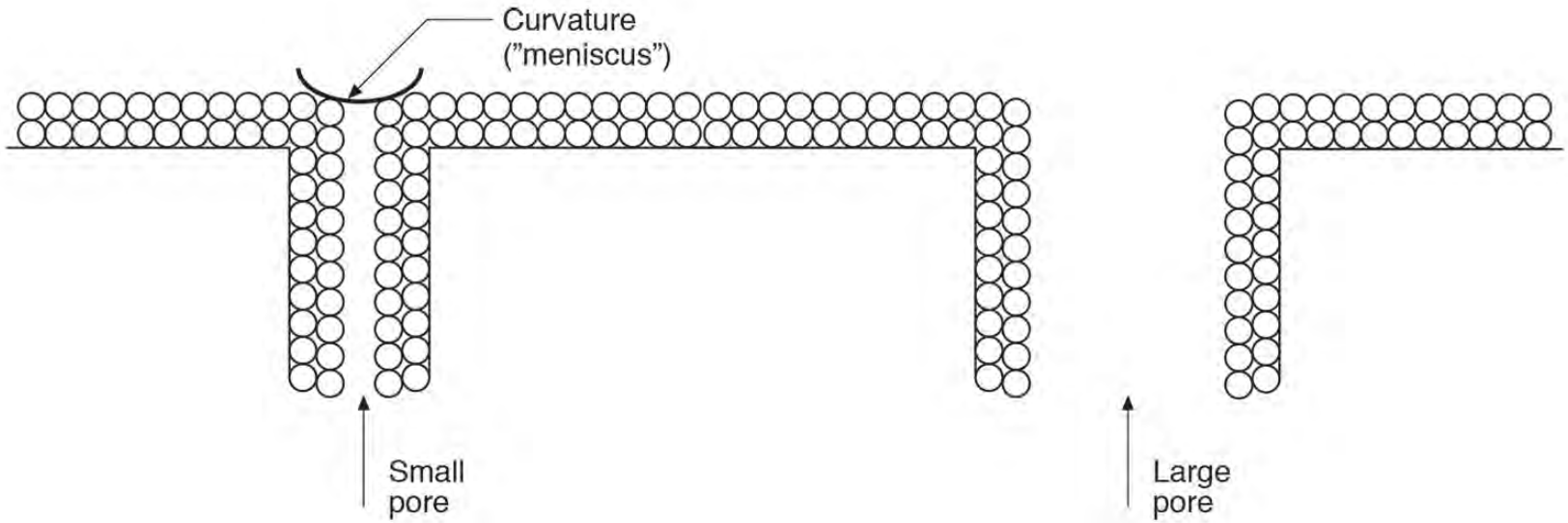

Solid (ice)
Melt
Freeze
Liquid (water)
Frost
Sublime
Condense
Evaporate
Gas (vapor)
Adsorb
Desorb
Adsorbed (surface layers)


Monolayers of
adsorbed water
increase with
increasing RH


Monolayers
flow along surface
following concentration gradient

Kelvin Equation Again….

$$\ln \frac{p}{p_0} = \frac{2\gamma V_{\mathrm{m}}}{rRT}$$


Curvature
("meniscus")
Small
pore
Large
pore

Pressures and IAQ

Definition of a Problem

People

Pollutant (hot, wet, UV, ozone)

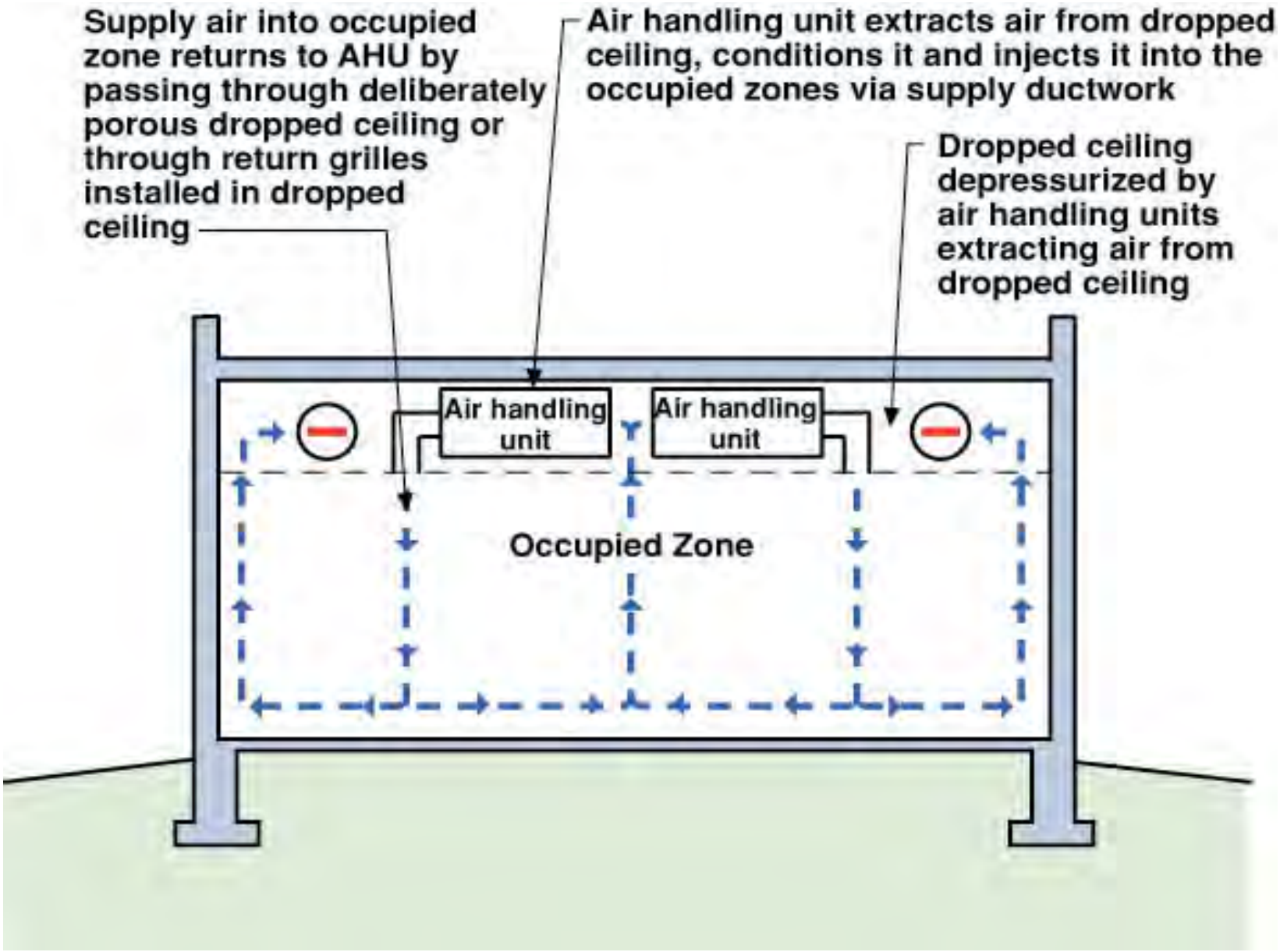
Path

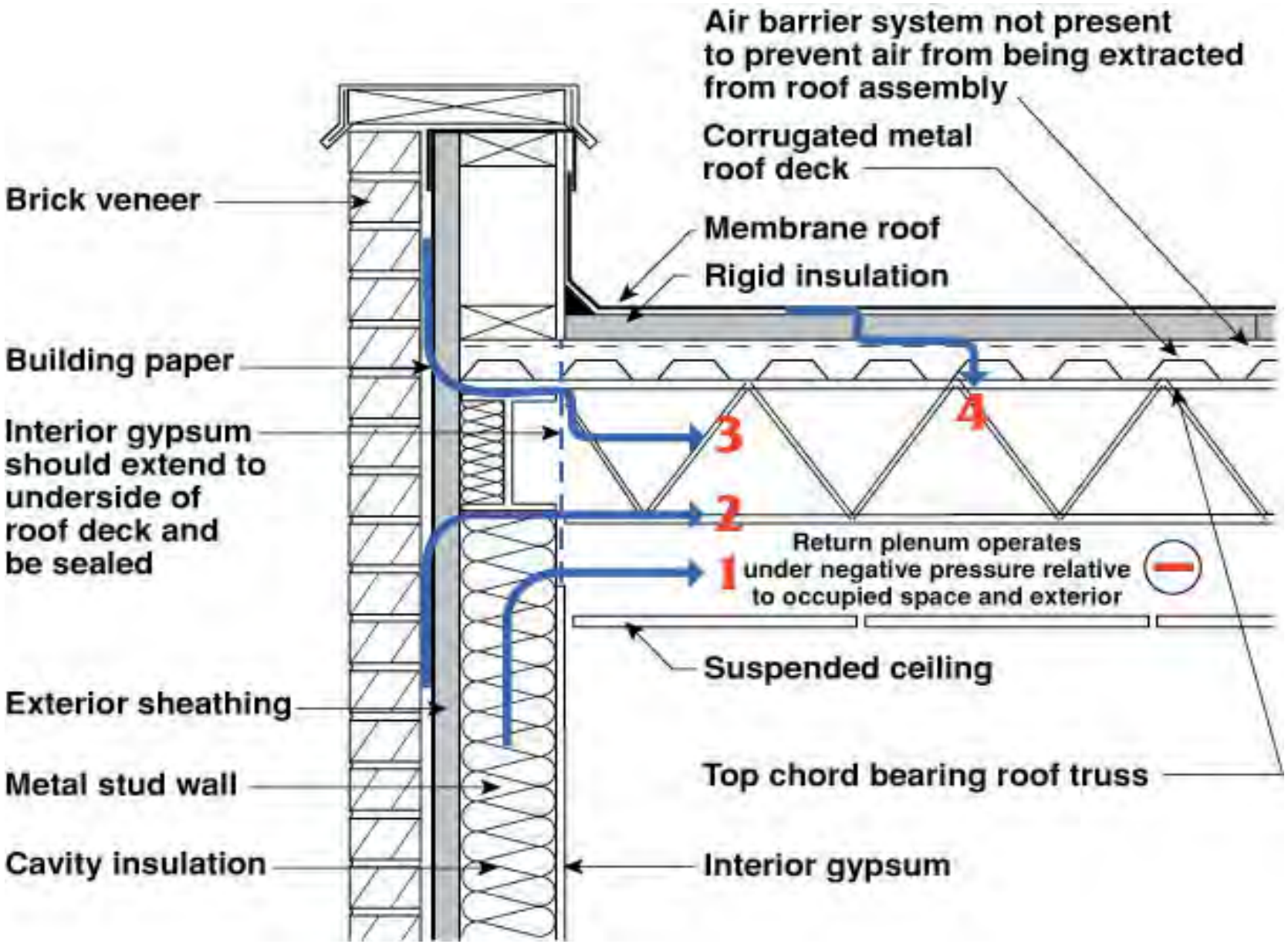
Pressure

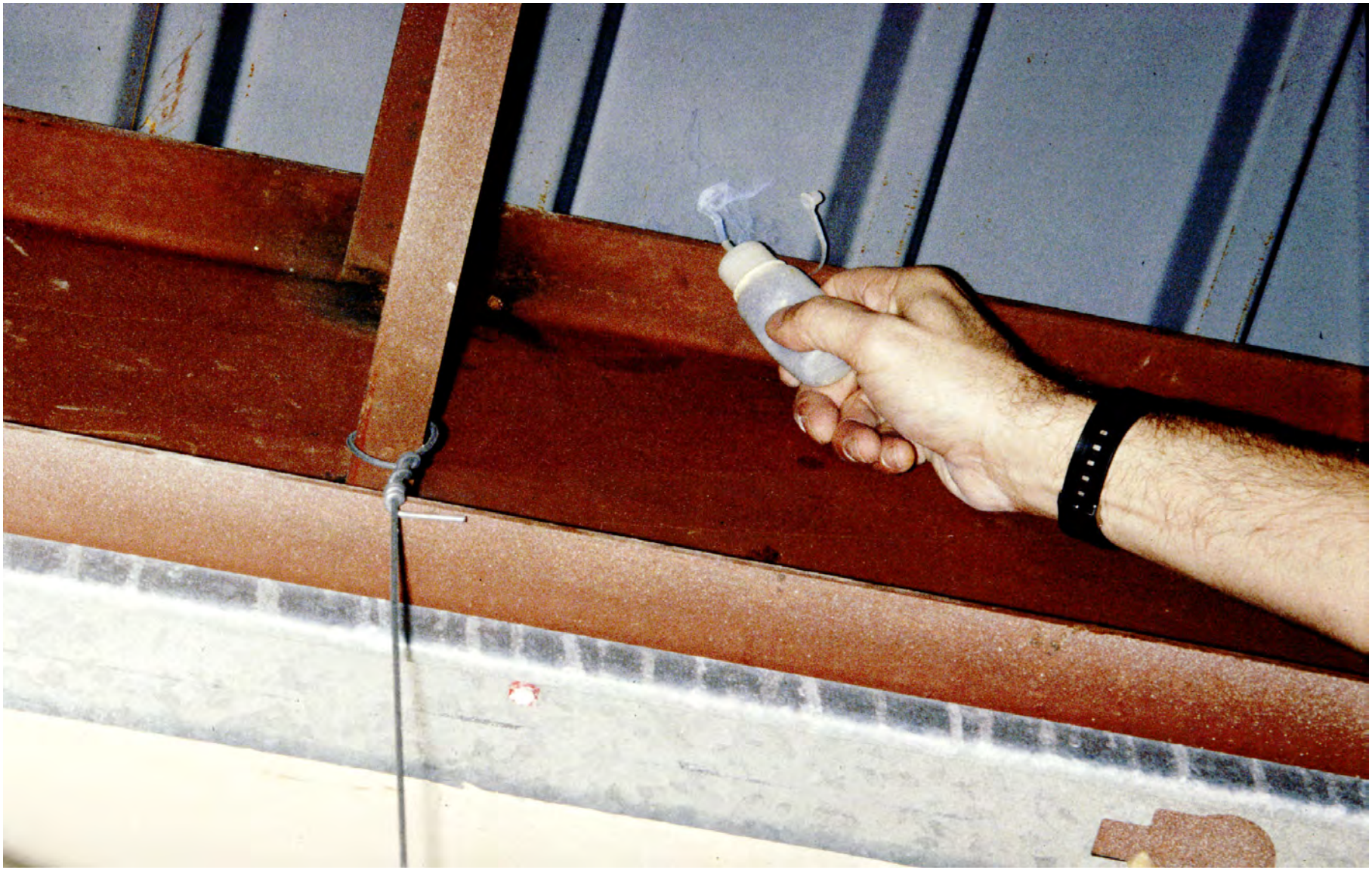

PUBLIC SERVICES


STOP


EXIT

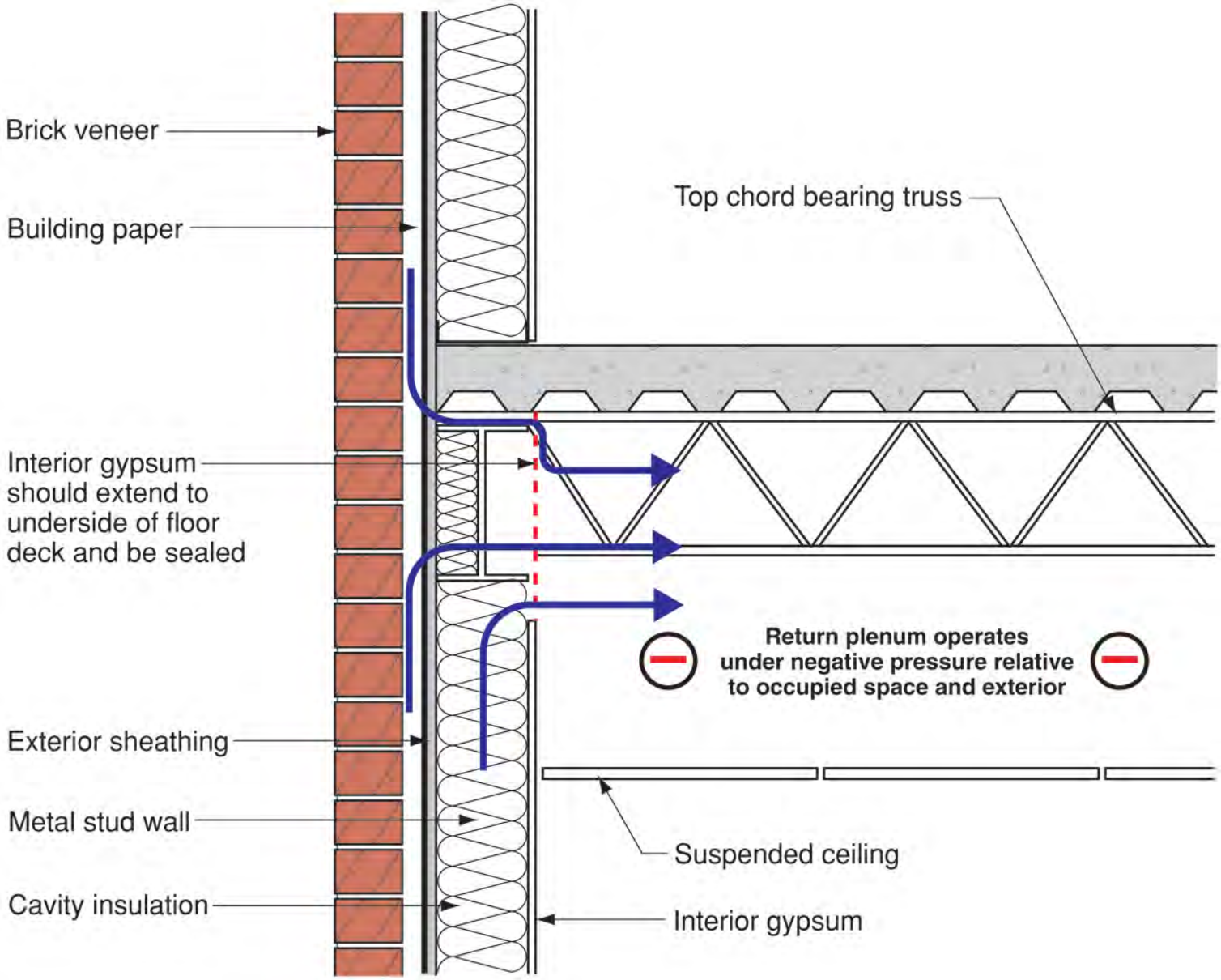

Supply air into occupied zone returns to AHU by passing through deliberately porous dropped ceiling or through return grilles installed in dropped ceiling
Air handling unit extracts air from dropped ceiling, conditions it and injects it into the occupied zones via supply ductwork
Dropped ceiling depressurized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

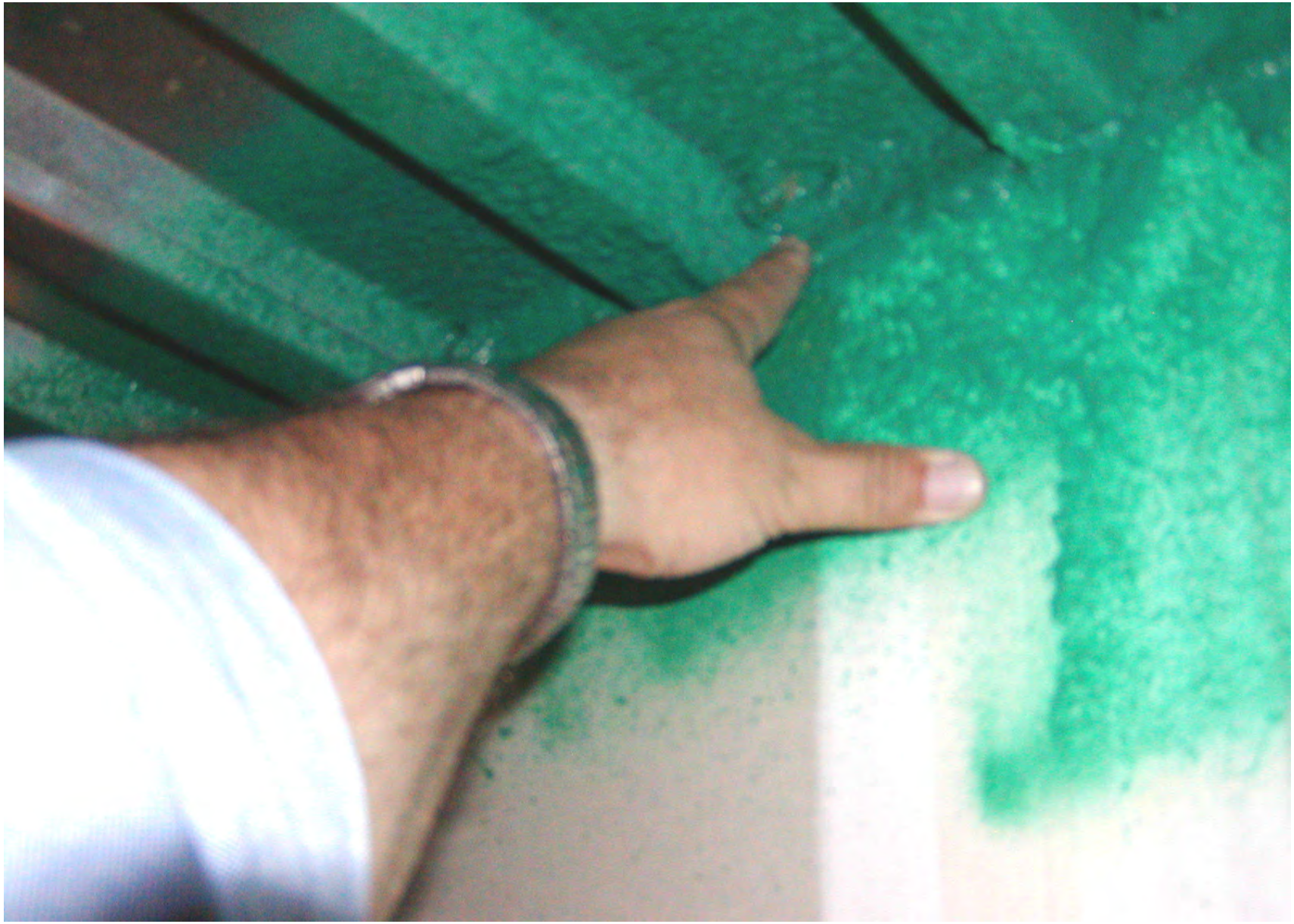

Air barrier system not present to prevent air from being extracted from roof assembly
Corrugated metal roof deck
Membrane roof
Rigid insulation
Brick veneer
Building paper
Interior gypsum should extend to underside of roof deck and be sealed
3
4
2
1
Return plenum operates under negative pressure relative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

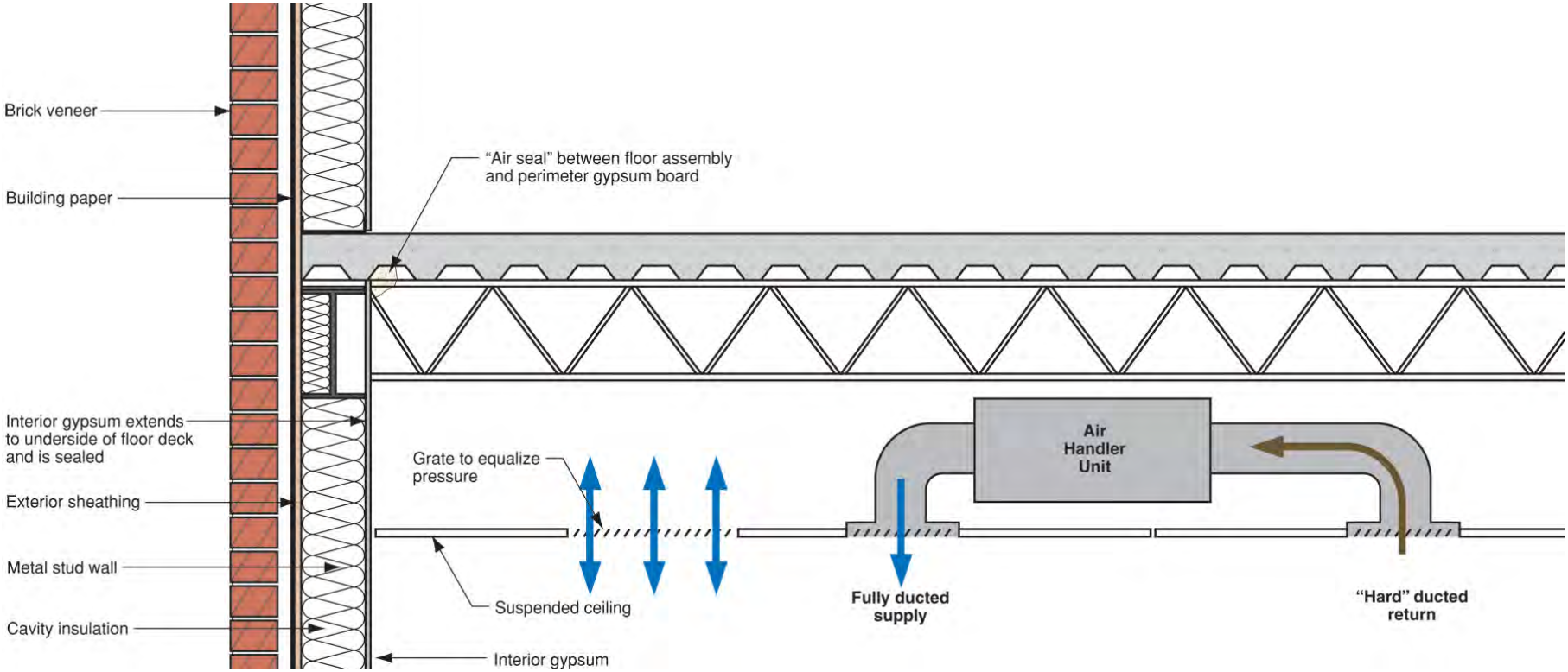


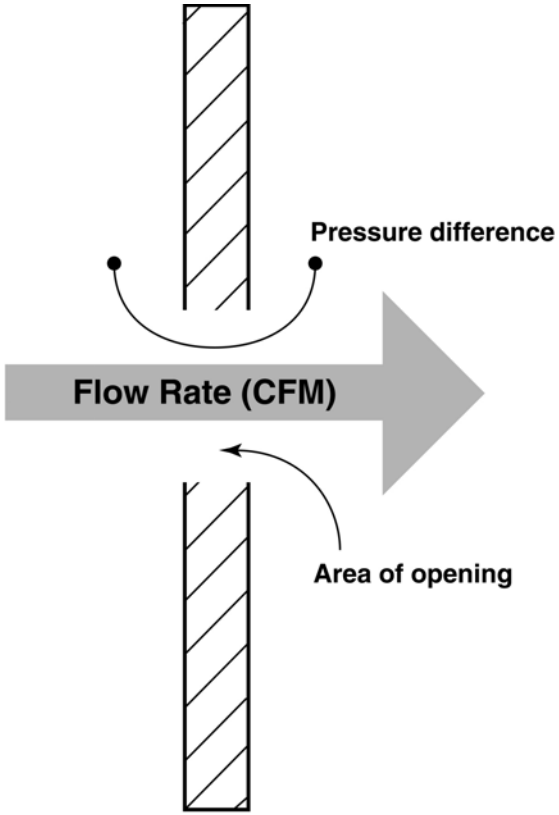

Tyvek


RE COMPANY


Brick veneer
Building paper
Top chord bearing truss
Interior gypsum should extend to underside of floor deck and be sealed
Return plenum operates under negative pressure relative to occupied space and exterior
Exterior sheathing
Metal stud wall
Cavity insulation
Suspended ceiling
Interior gypsum




Brick veneer
Building paper
"Air seal" between floor assembly and perimeter gypsum board
Interior gypsum extends to underside of floor deck and is sealed
Exterior sheathing
Metal stud wall
Cavity insulation
Grate to equalize pressure
Suspended ceiling
Interior gypsum
Air Handler Unit
Fully ducted supply
"Hard" ducted return



Air Flow

- Air flow depends on size of hole
- Air flow depends on pressure difference

  Flow ≅ Area x $\sqrt{\Delta P}$ x Coefficient
- Air flows from higher pressure to lower pressure

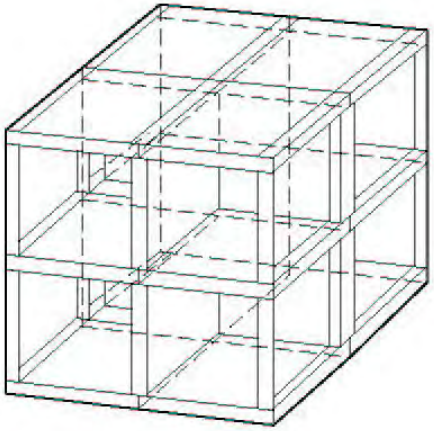


Figure 2.11
Three Dimensional Multi-Layer Multi-Cell Analogue

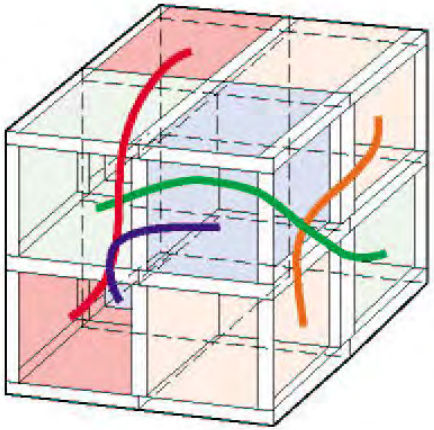
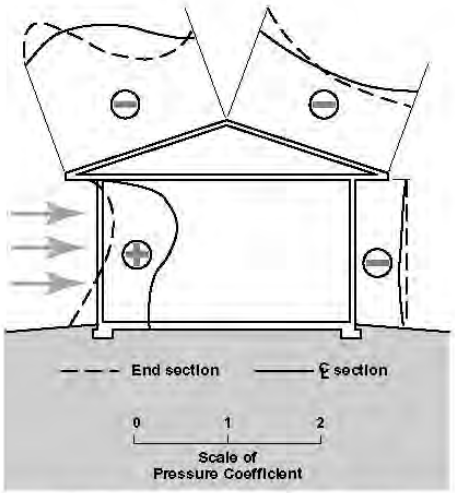


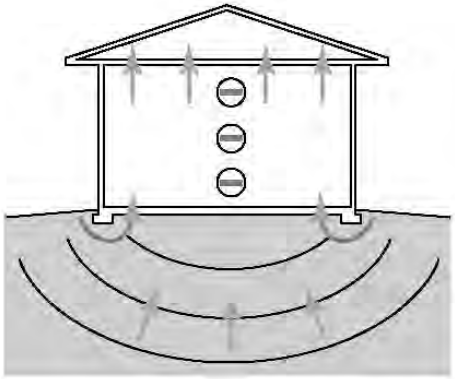
Figure 2.12
Three Dimensional Multi-Layer Multi-Cell Non-Contiguous Analogue

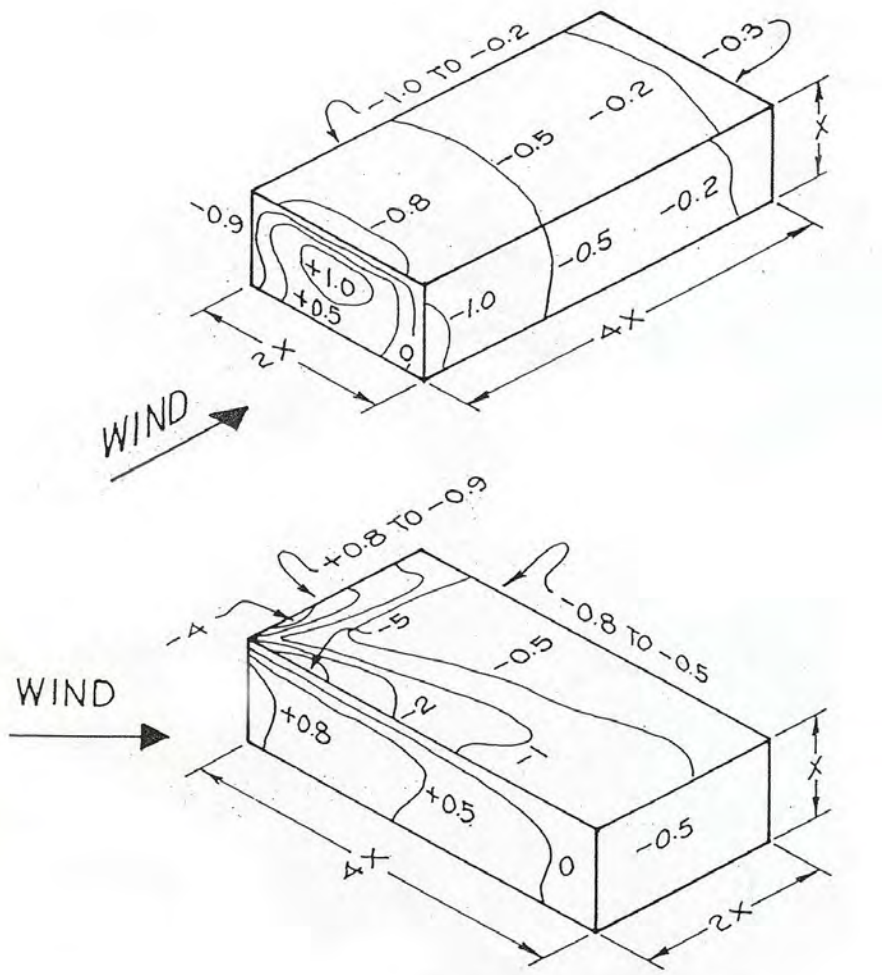
Figure 3.1
Exterior Air Pressure Field
(from Hutcheon & Handegord, 1983)



Distribution of pressures (+) and suctions (-) on a house with a low-sloped roof with wind perpendicular to eave

Figure 3.2
Exterior Air Pressure Field Extending Below Grade





Pressure coefficients on walls and roof of rectangular buildings without parapets.

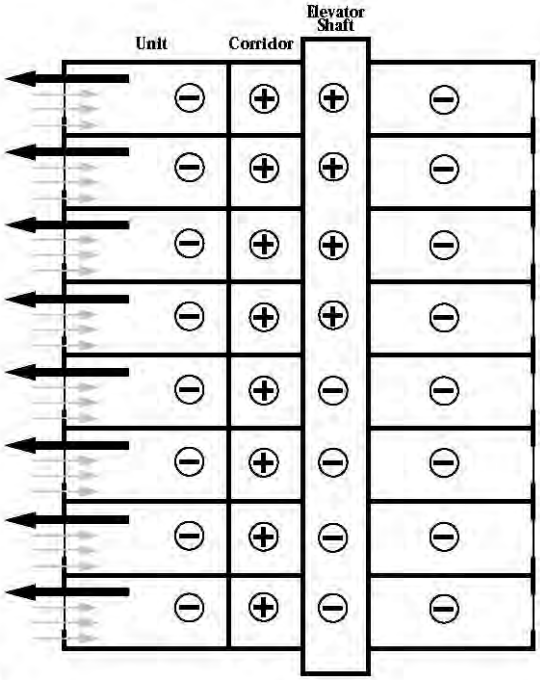


Figure 3.3
Interior Air Pressure Field

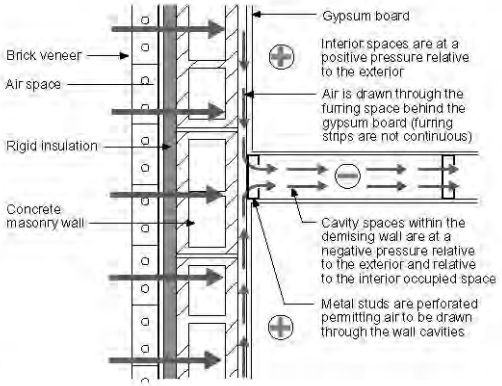


Figure 3.4
Interstitial Air Pressure Field

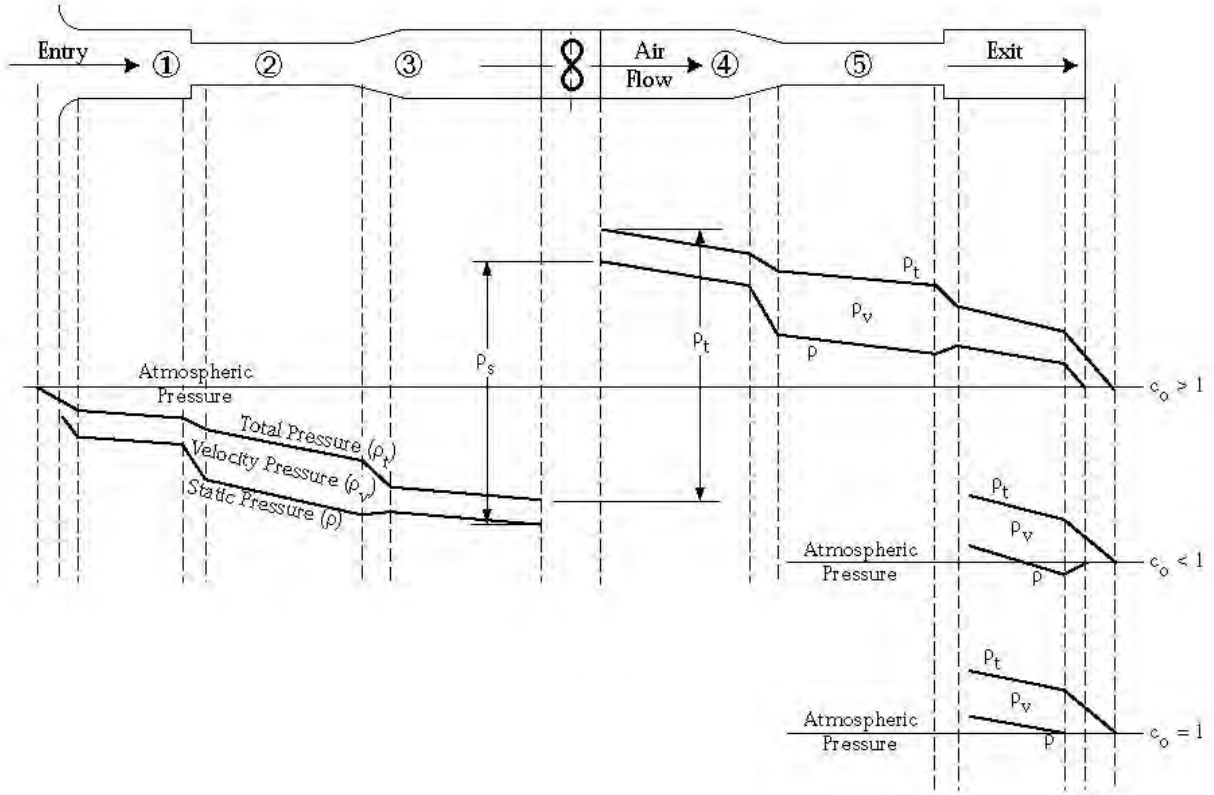


Figure 3.5
Air Conveyance System Air Pressure Field
(from Sauer & Howell, 1990)

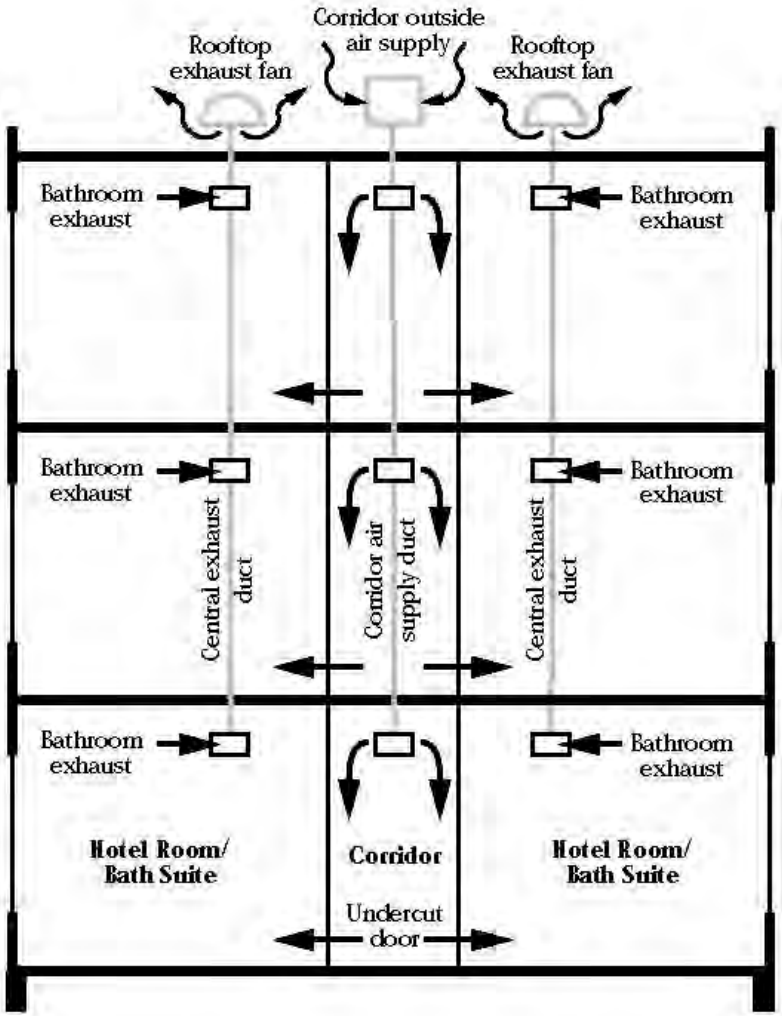
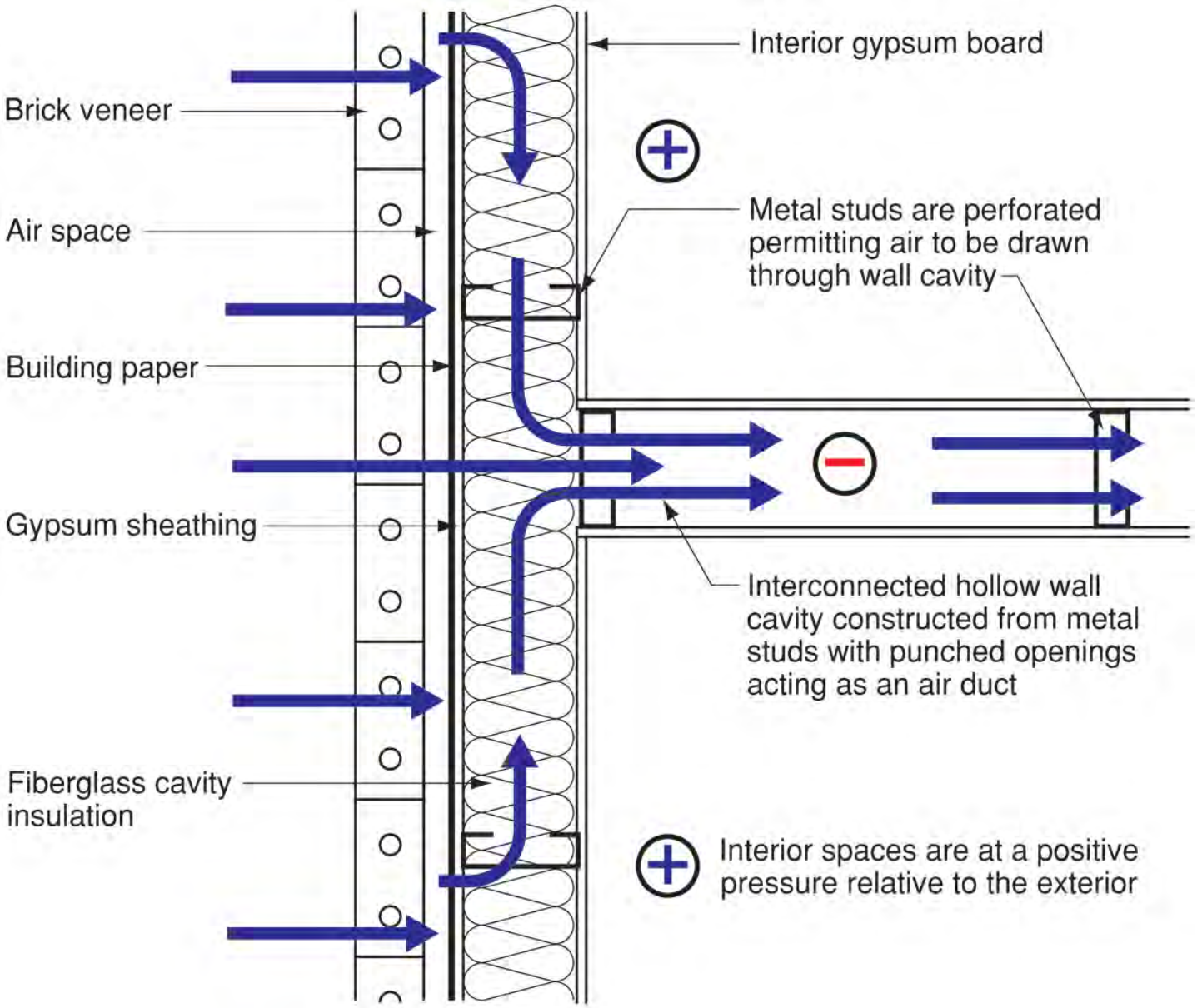


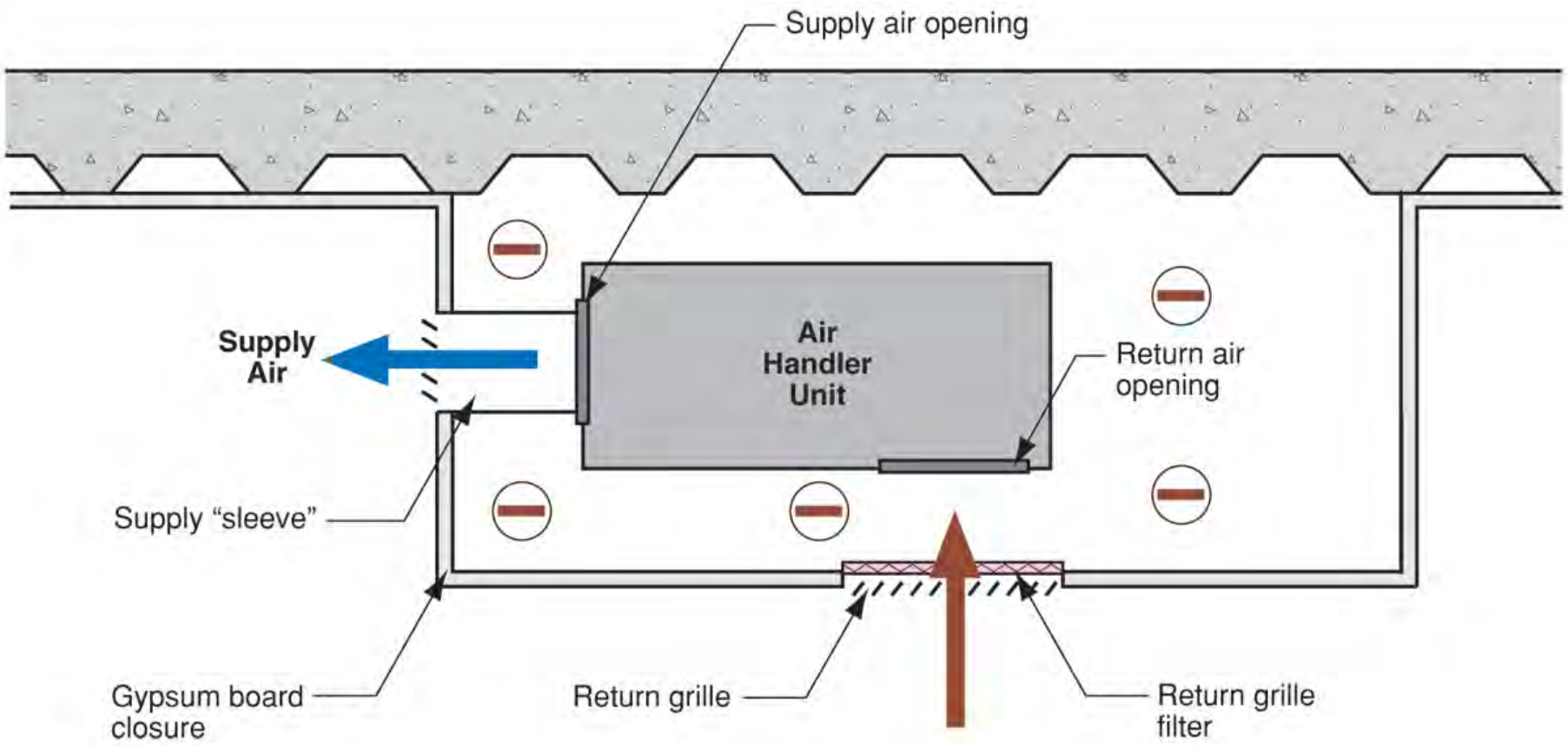
Figure 3.8

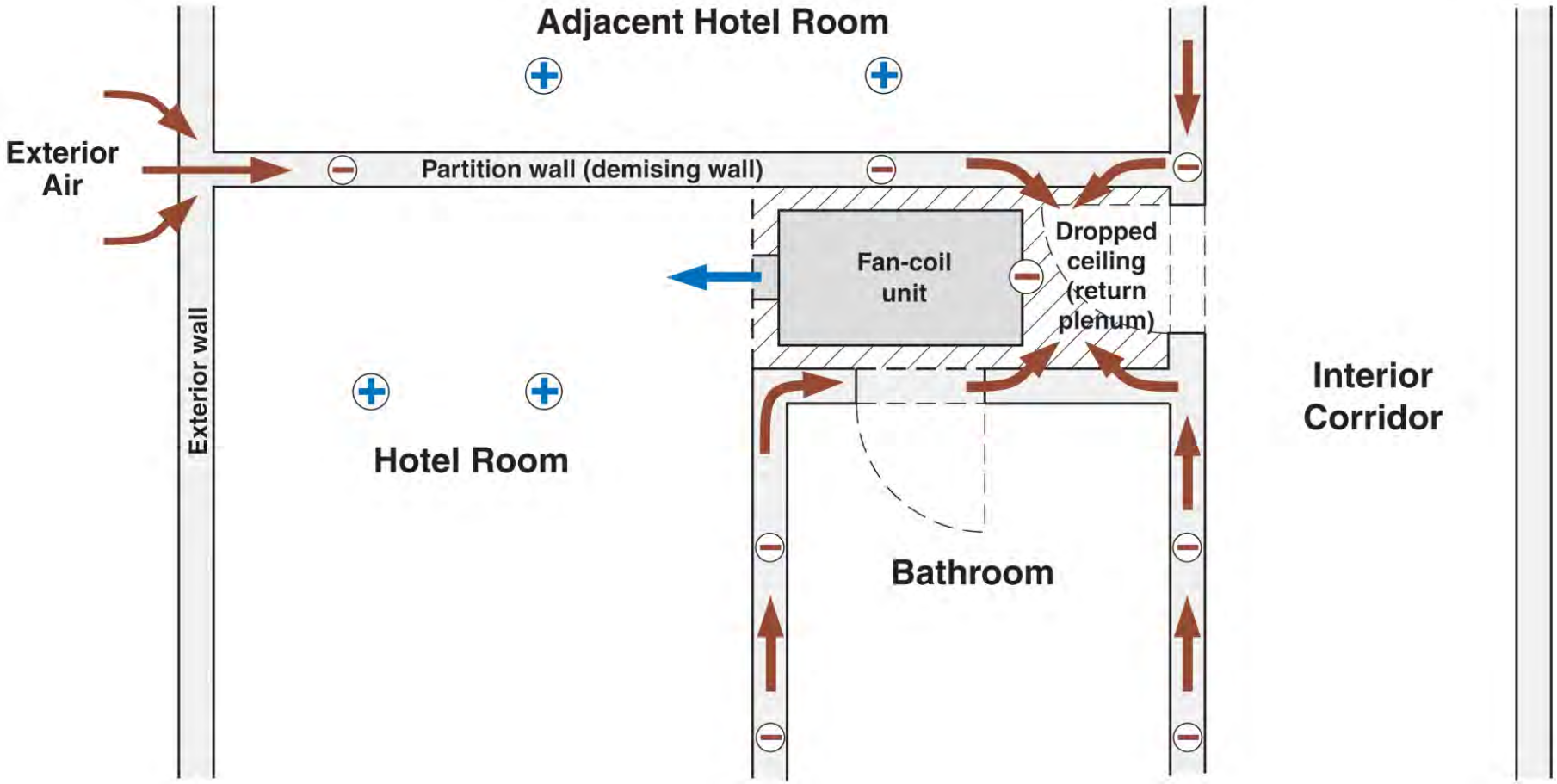
Hotel HVAC System

- Air exhausted from bathrooms via central rooftop exhaust fans
- Air supplied from corridors via undercut doors


zenith


Brick veneer
Air space
Building paper
Gypsum sheathing
Fiberglass cavity insulation
Interior gypsum board
Metal studs are perforated permitting air to be drawn through wall cavity
Interconnected hollow wall cavity constructed from metal studs with punched openings acting as an air duct
Interior spaces are at a positive pressure relative to the exterior


Supply air opening
Supply
Air
Air
Handler
Unit
Return air
opening
Supply "sleeve"
Gypsum board
closure
Return grille
Return grille
filter


Adjacent Hotel Room
Exterior Air
Partition wall (demising wall)
Exterior wall
Fan-coil unit
Dropped ceiling (return plenum)
Interior Corridor
Hotel Room
Bathroom

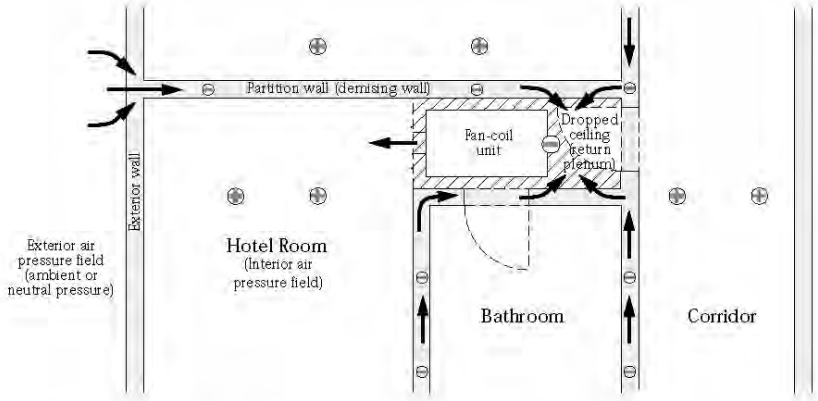


Figure 3.10
Pressure Field Due to Fan-Coil Unit
Plan View

- Room is at positive air pressure relative to exterior-driven air from corridor and air supplied to room from fan-coil unit pulling air from exterior through the demising wall
- Fan-coil unit depressurizes dropped ceiling assembly due to return plenum design
- Demising wall cavity pulled negative due to connection to dropped ceiling return plenum

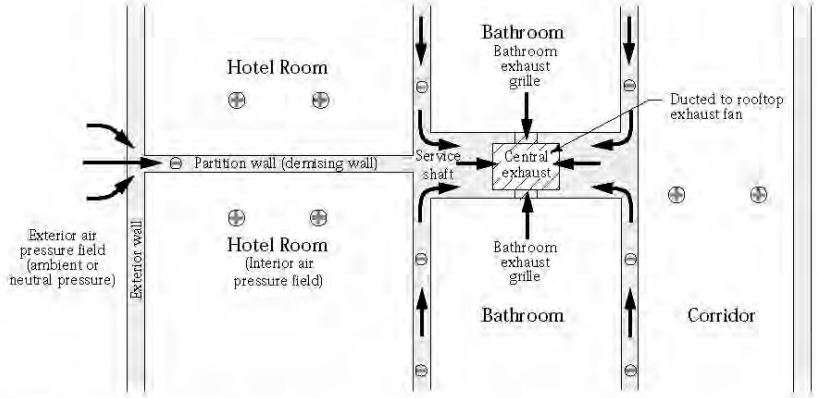
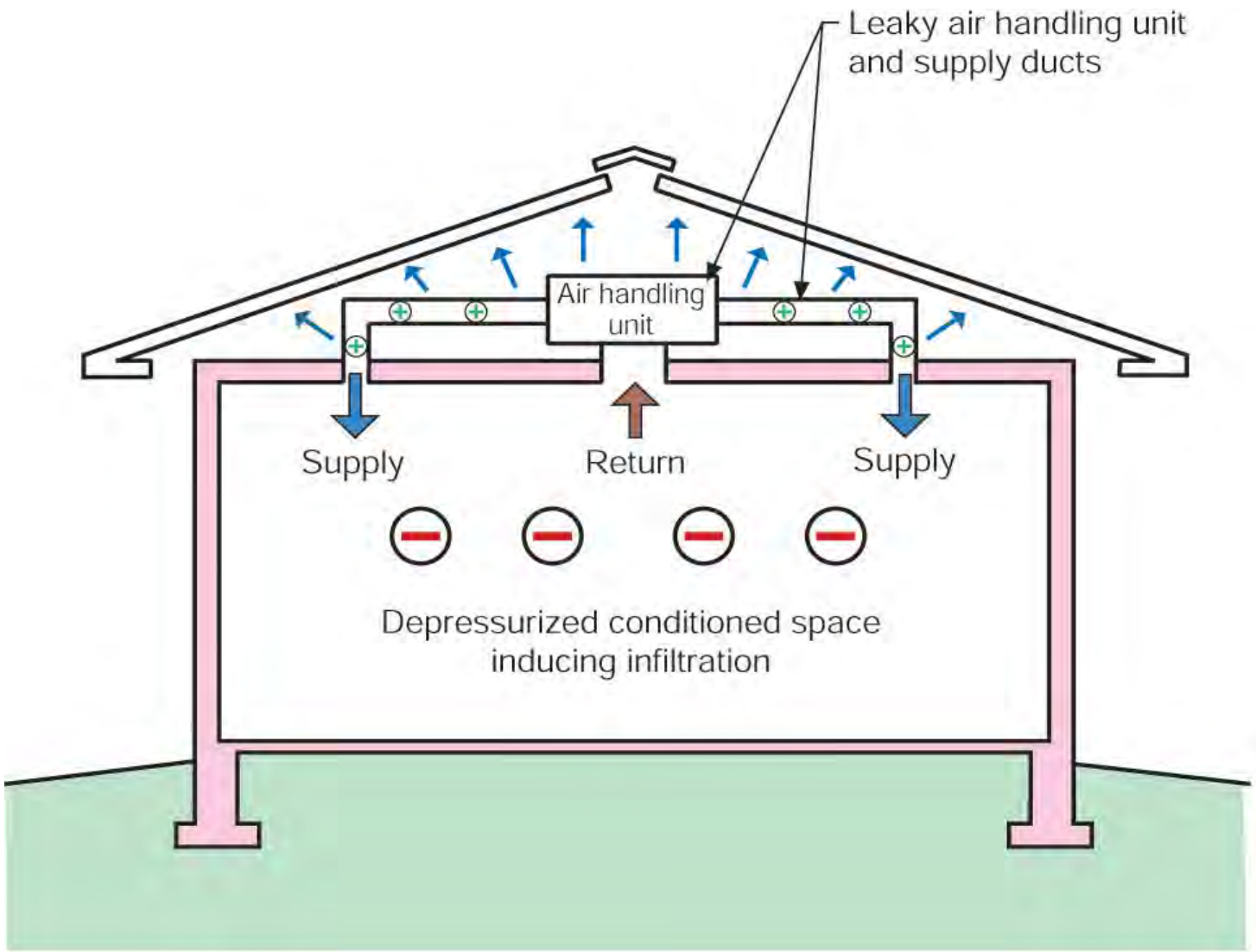


Figure 3.11
Pressure Field Due to Central Exhaust
Plan View

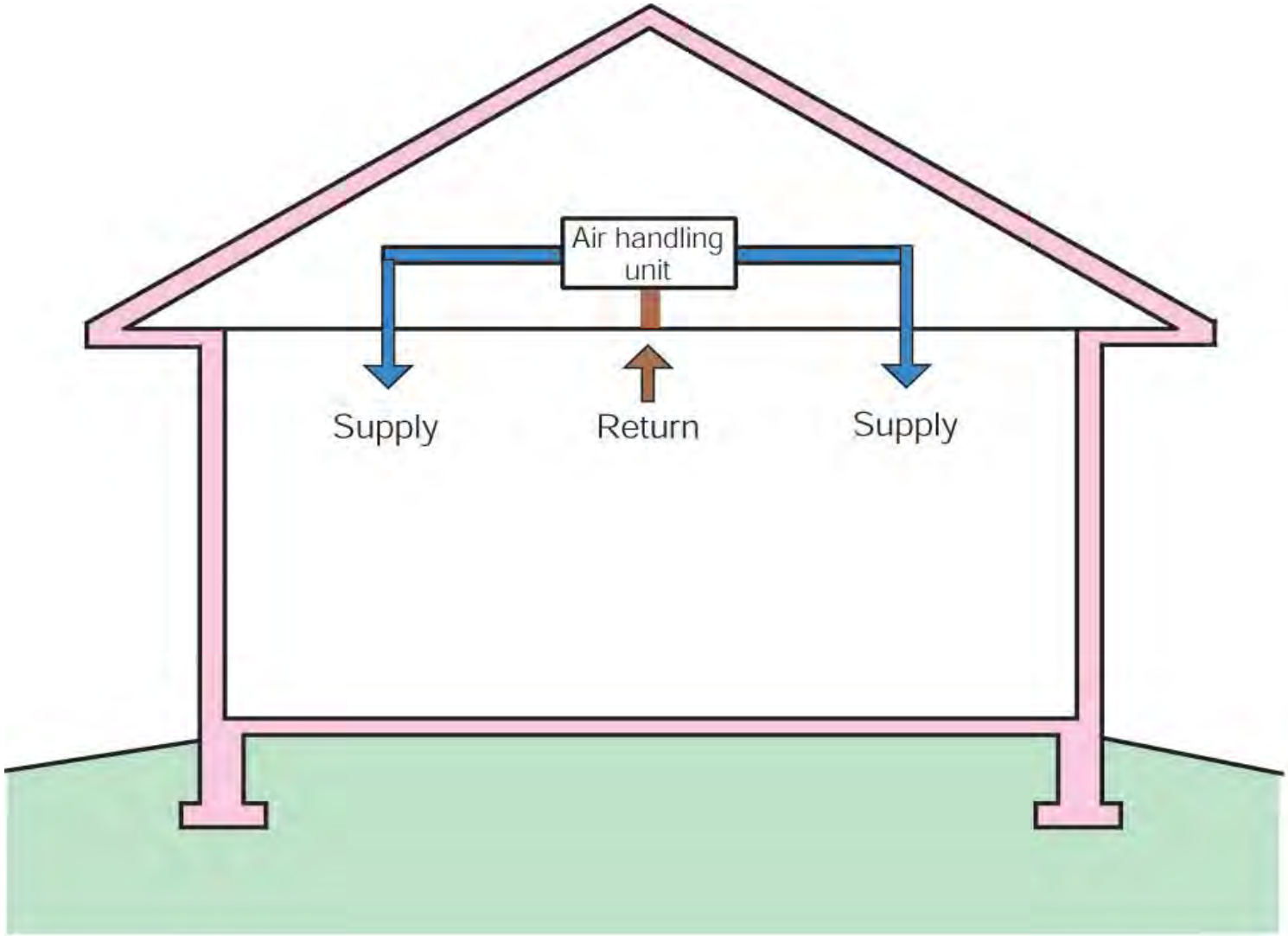
- Leakage of central exhaust duct pulls air out of service shaft depressurizing shaft and demising walls


DAYS INN


-.002

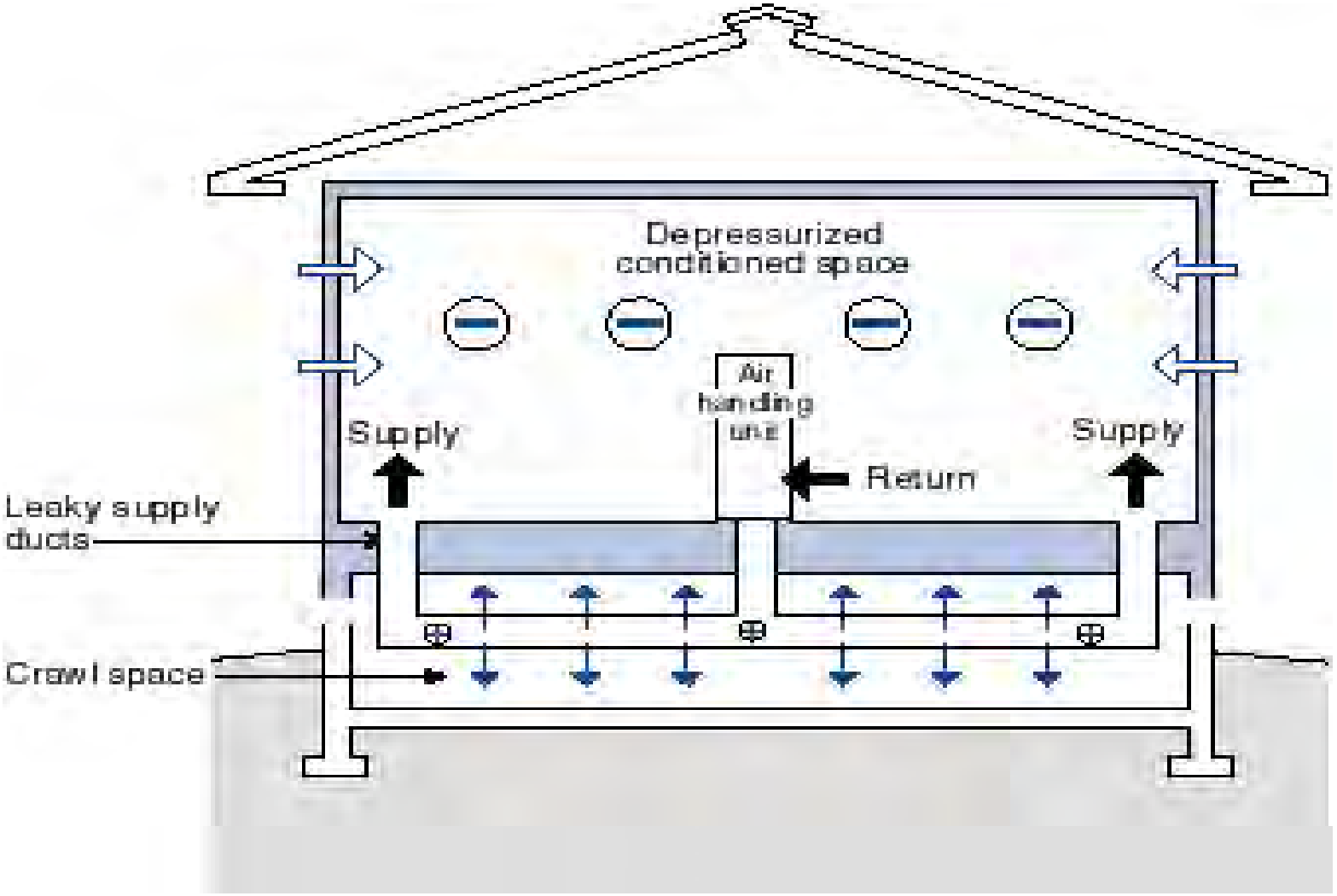


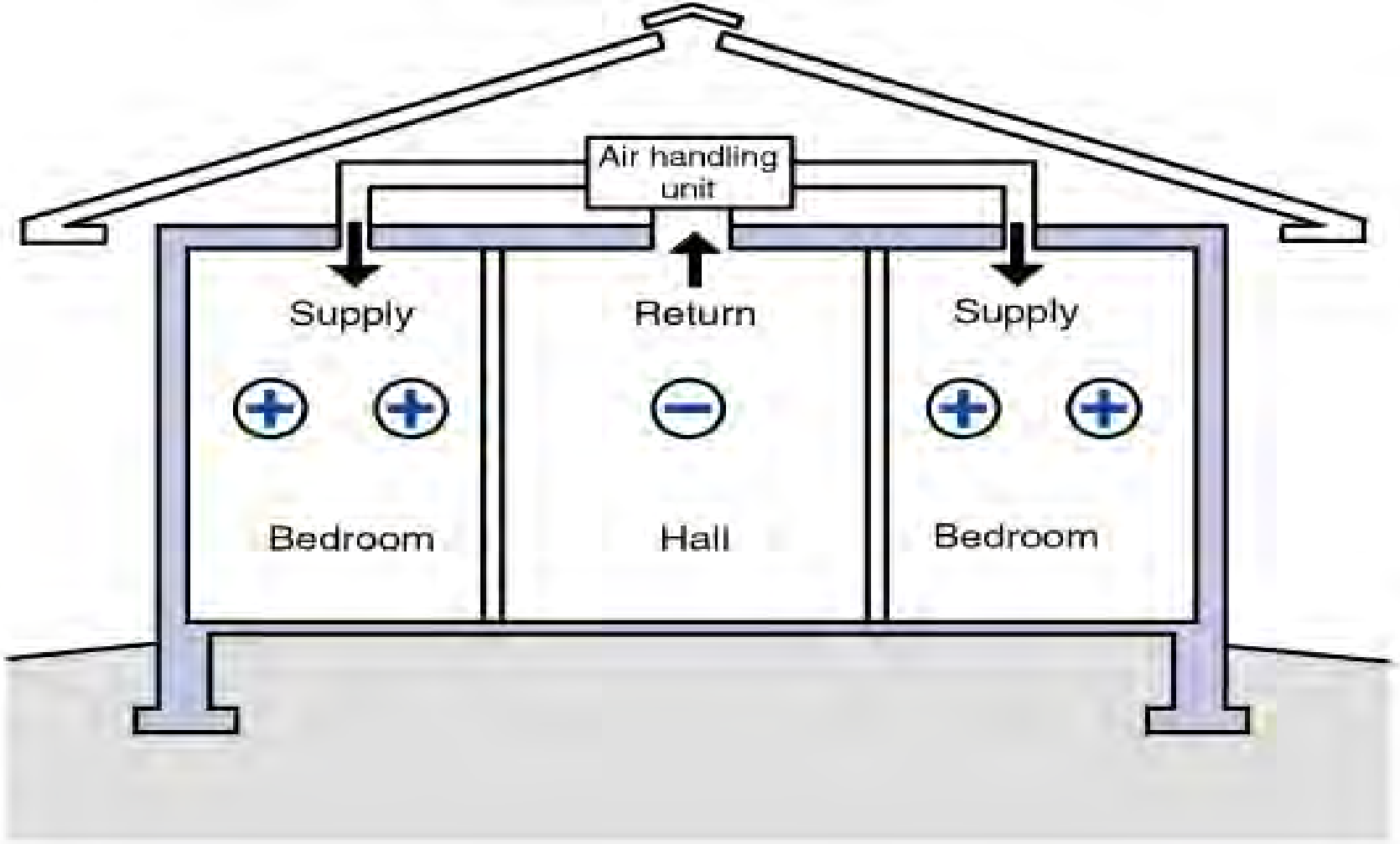
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.



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

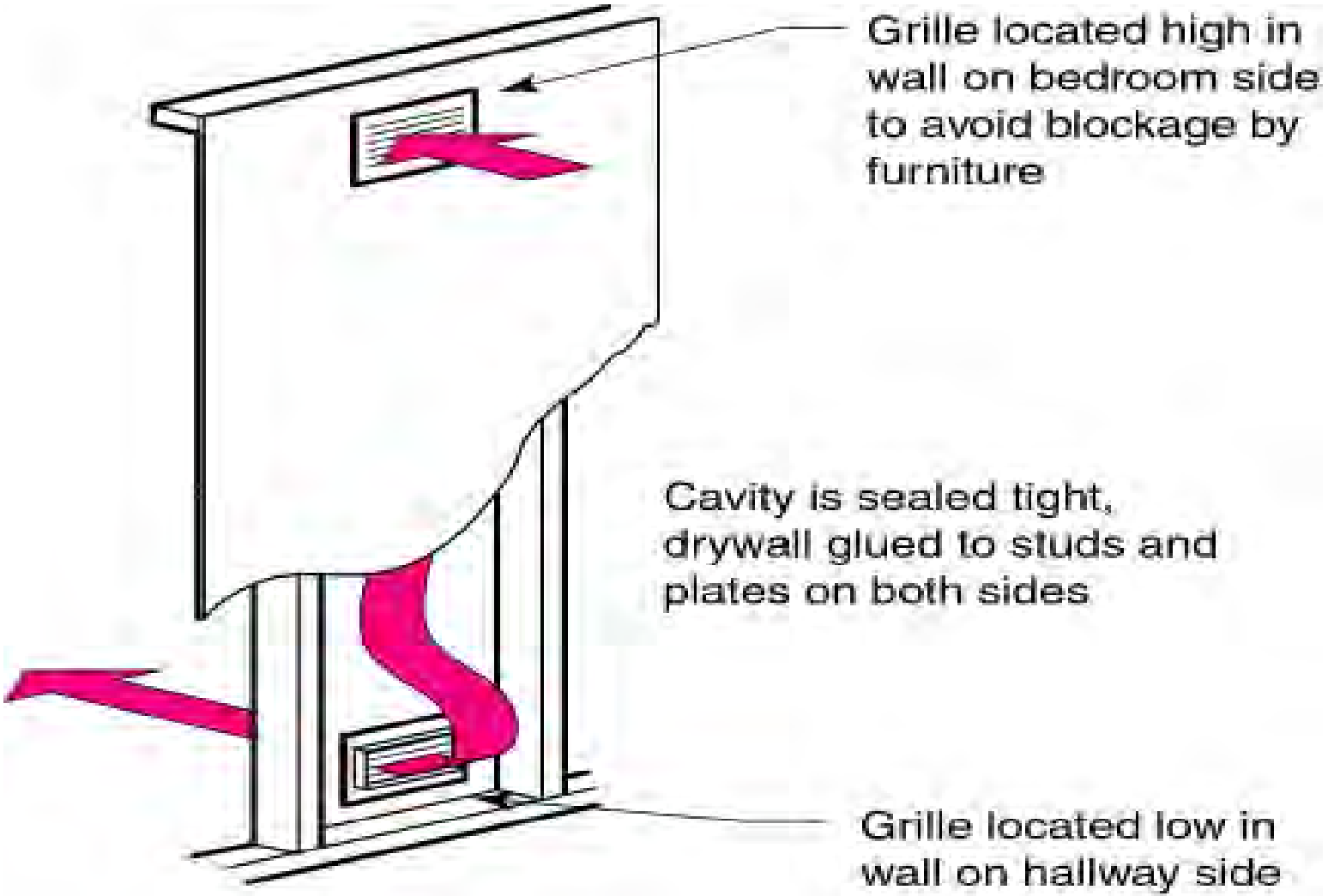
Depressurized conditioned space
inducing infiltration
Supply
Return
Supply
Air handling
unit
Leaky air handling unit
and supply ducts

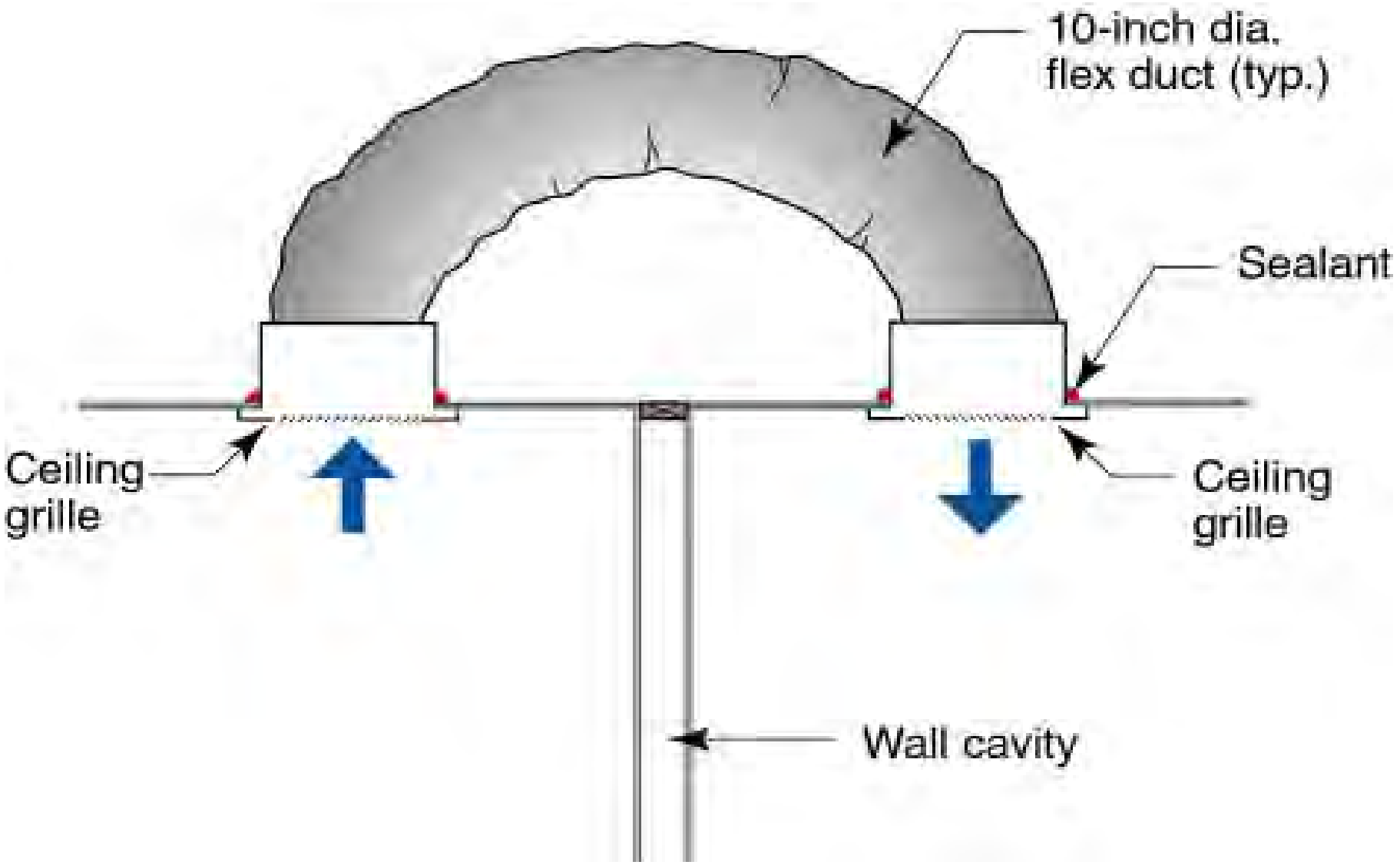

Depressurized conditioned space
Air handling unit
Supply
Supply
Return
Leaky supply ducts
Crawl space

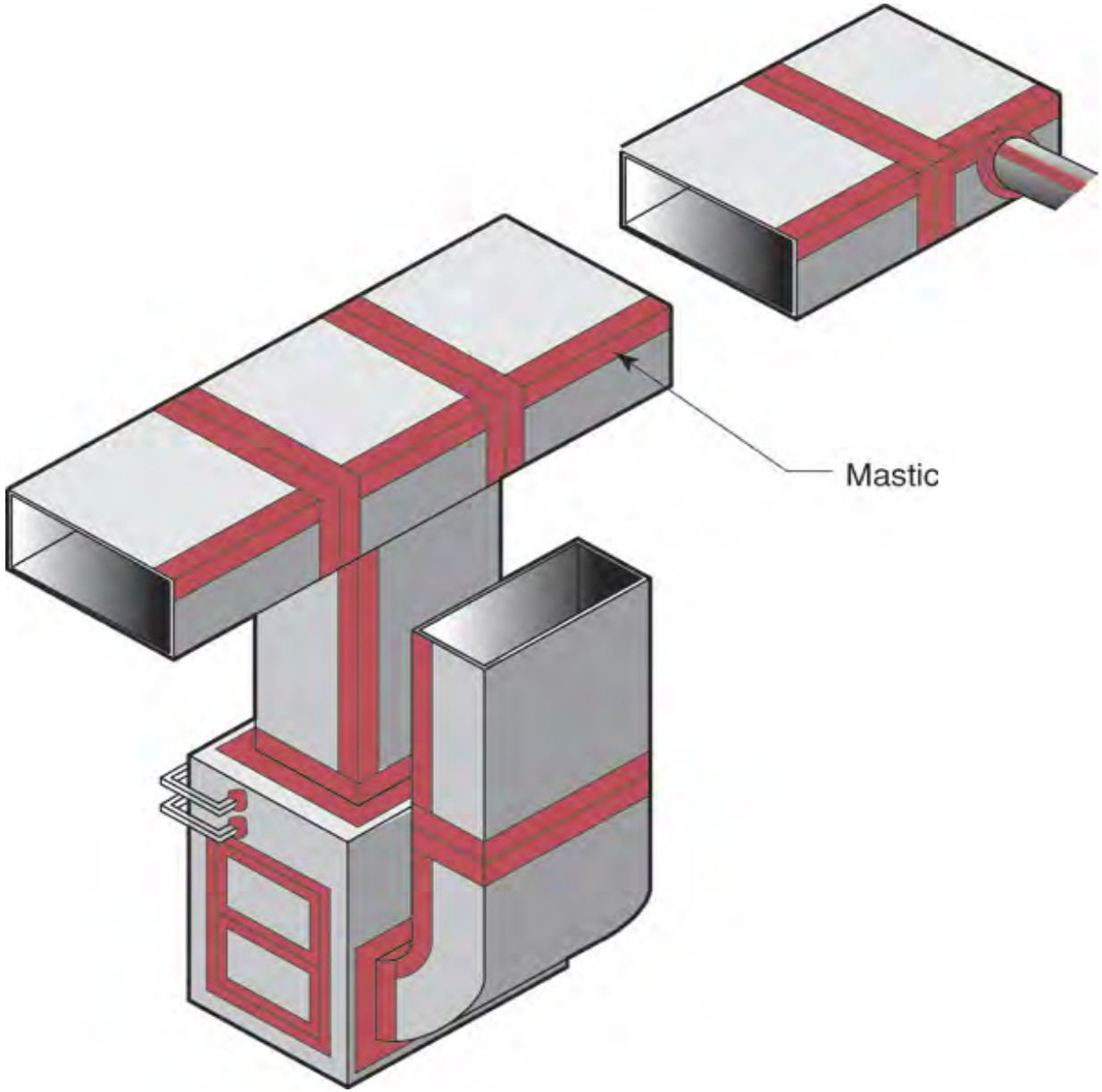

Air handling unit
Supply
Return
Supply
Bedroom
Hall
Bedroom


PULTE
Richly
Scented Candle
Trim the wick to 1/4" before burning. Keep
the wick centered and trimmed at all times
to avoid blackening the container. Never
leave a burning candle unattended or
within the reach of child
EMPIRE
Kansas City, MO
$1099
Net Wt. 23 oz. (651g)


YANKEE


Grille located high in wall on bedroom side to avoid blockage by furniture
Cavity is sealed tight, drywall glued to studs and plates on both sides
Grille located low in wall on hallway side


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


Mastic