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

Building Science

Airflow In Buildings I

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Stuff That Is Not Particularly Useful But Studied and Researched to Death

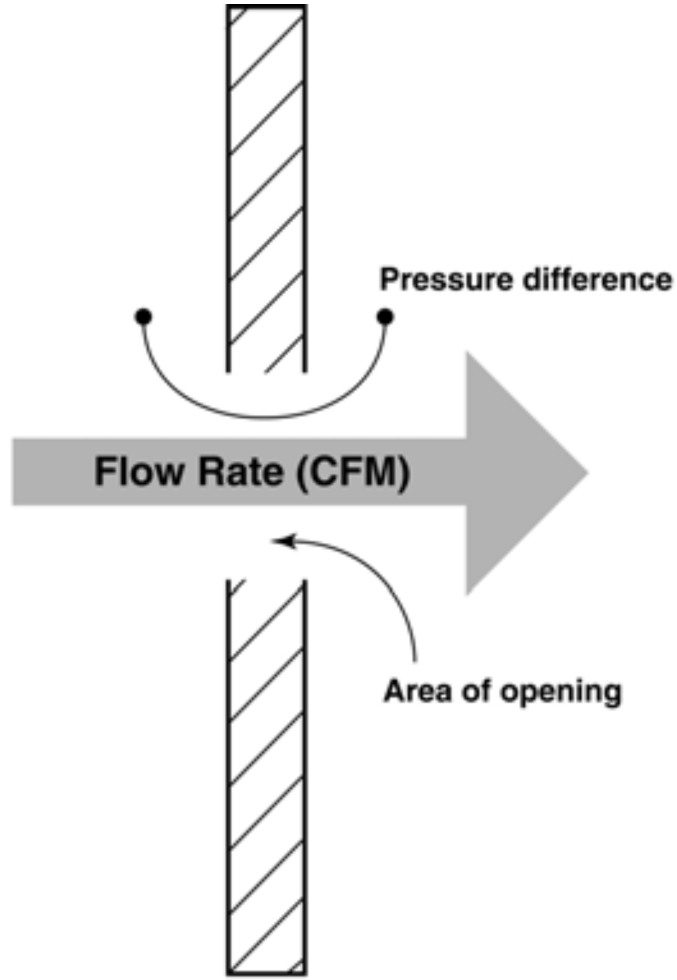
Stuff That Is Very Useful but Ignored by the Research Community

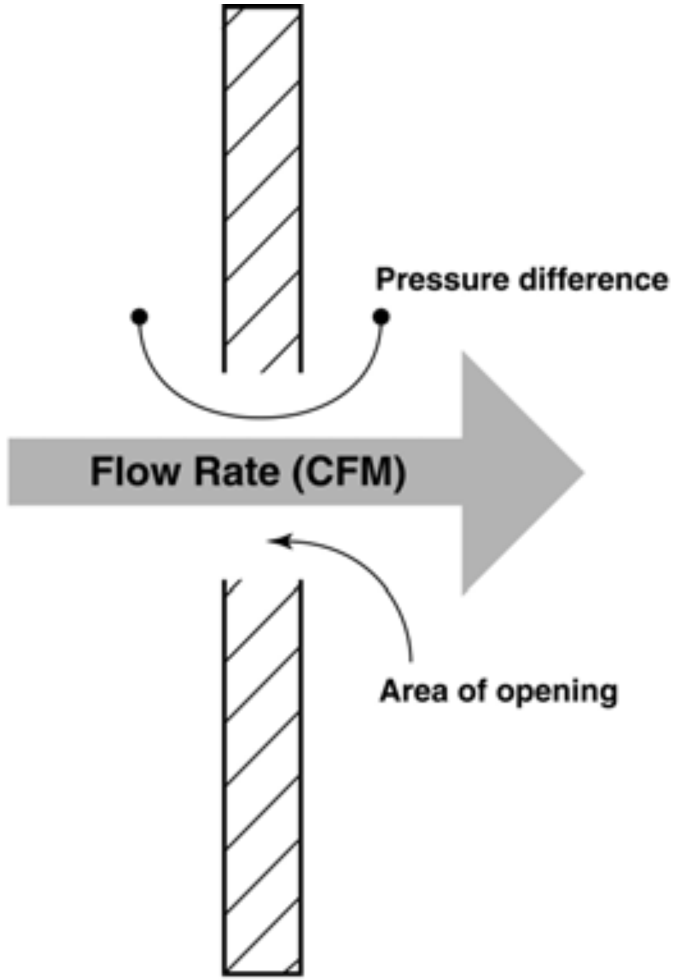
Stuff That Is Not Particularly Useful But Studied and Researched to Death

"this is called Physics"

Stuff That Is Very Useful but Ignored by the Research Community

"this is called Engineering"


Pressure difference
Flow Rate (CFM)
Area of opening



"this is a lie"

Flow Through Orifices

Turbulent Flow - “inertial effects”

Flow Through Porous Media

Laminar Flow - “viscosity effects”

Flow Through Orifices

Turbulent Flow - “inertial effects”

Flow Through Porous Media

Laminar Flow - “viscosity effects”

“true but not useful”

$$Q = A \cdot C_D \left[\frac{2}{\rho} (\Delta P) \right]^{\frac{1}{2}}$$

Bernoulli

$$Q = C_K \frac{\rho}{\mu} (\Delta P)$$

Darcy

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Bernoulli

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Darcy

$$Q = A \cdot C (\Delta P)^{\frac{1}{2}}$$

$$Q = C (\Delta P)$$

$$Q = A \cdot C (\Delta P)^{n}$$

Kronval "an engineer"

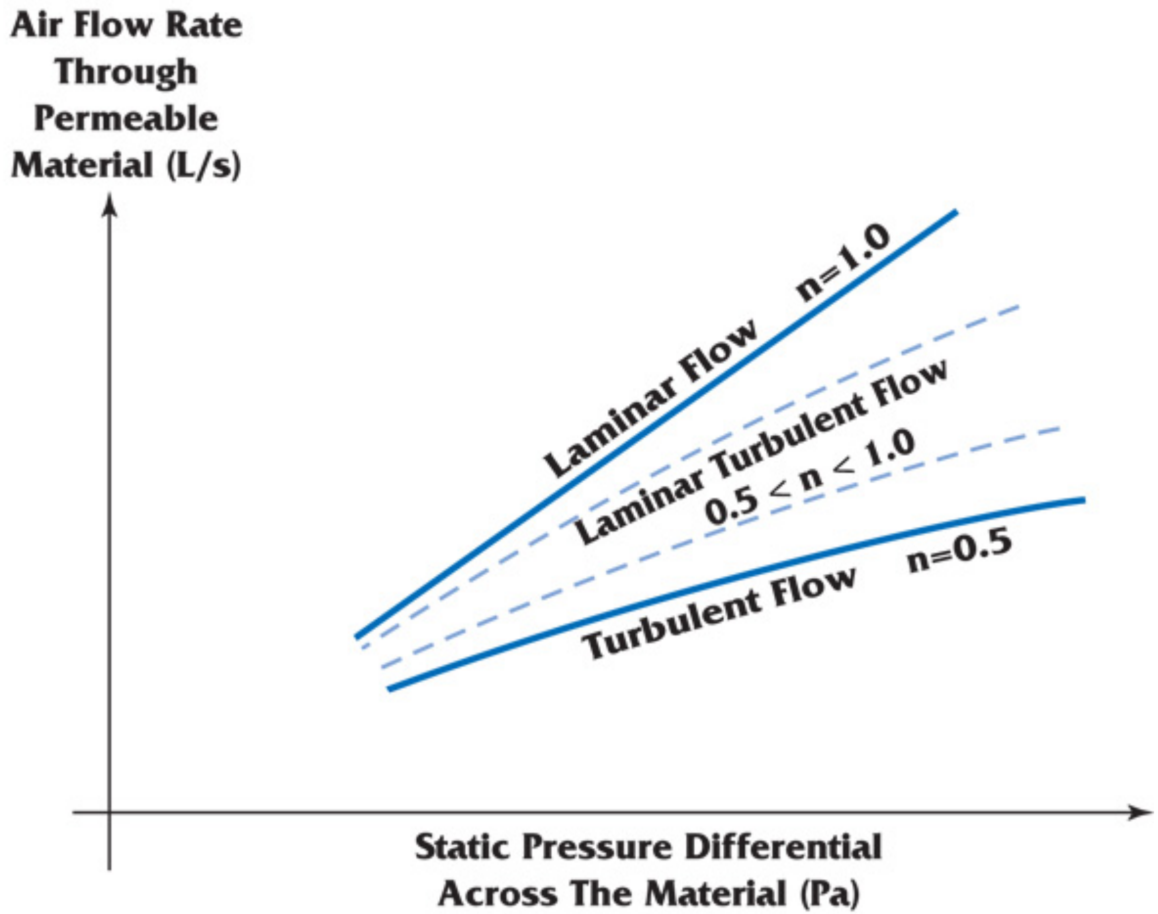
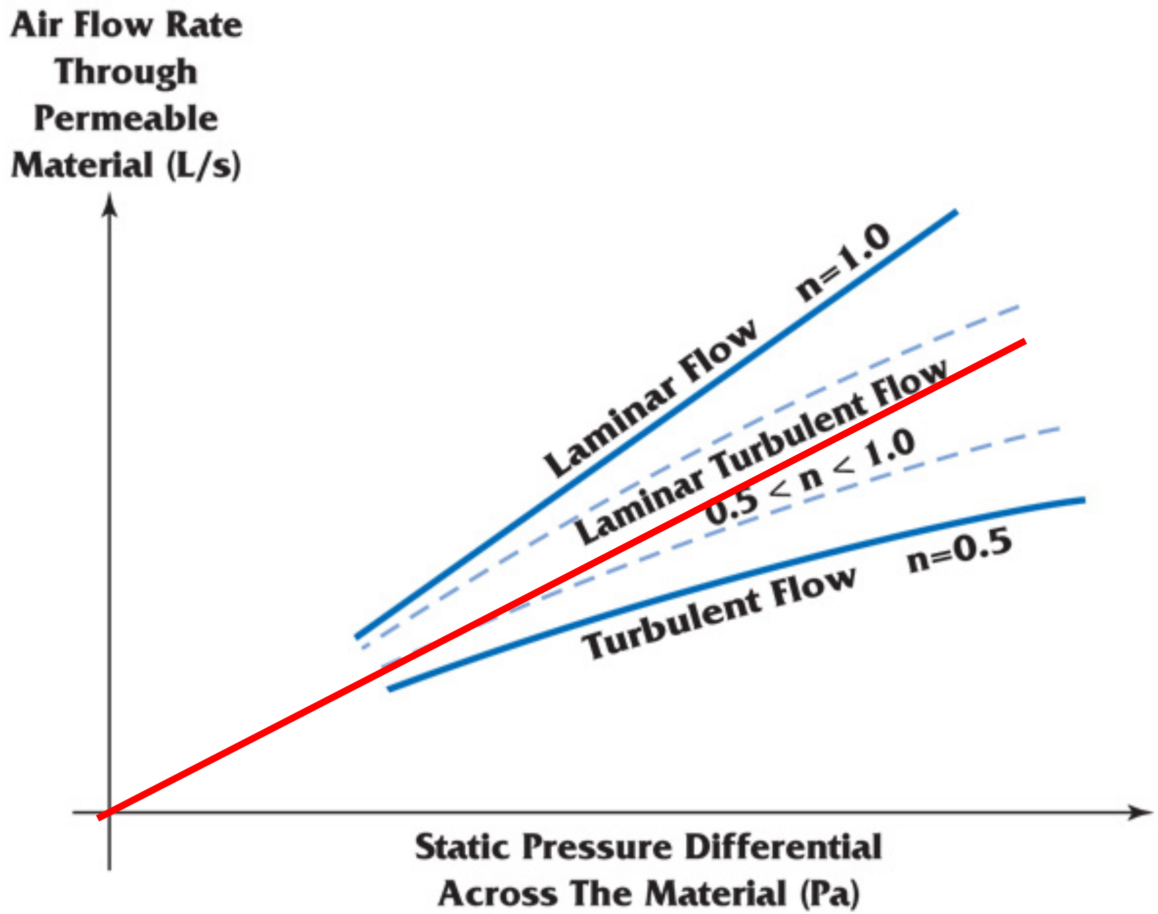


Figure 2.5

Modes of Air Flow

(from Bumbaru, Jutras and Patenaude, 1988)



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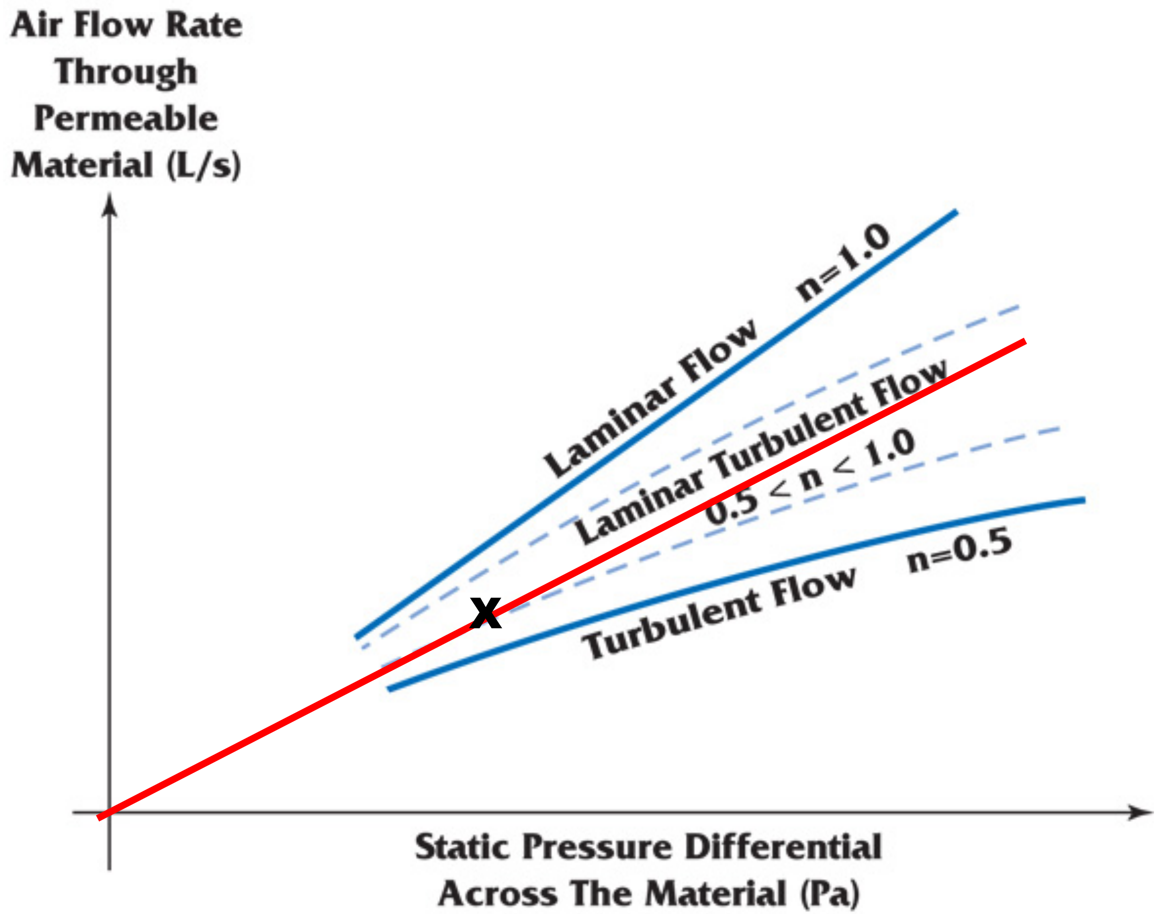

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Modes of Air Flow

(from Bumbaru, Jutras and Patenaude, 1988)

$$\mathbf{Q = f\ (Dp)}\ » \ \mathbf{k\ (Dp)}^{b}$$

Q	=	air flow, volume/unit of time
D**p**	=	pressure difference
k	=	coefficient
b	=	exponent in approximate leakage function

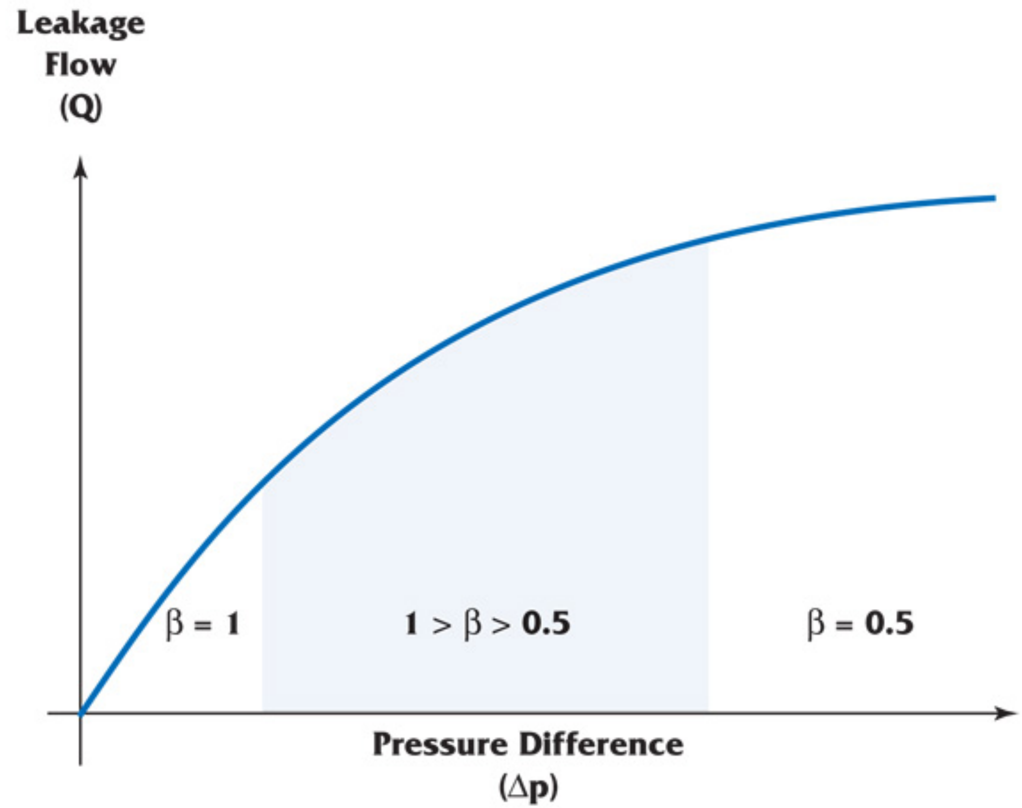
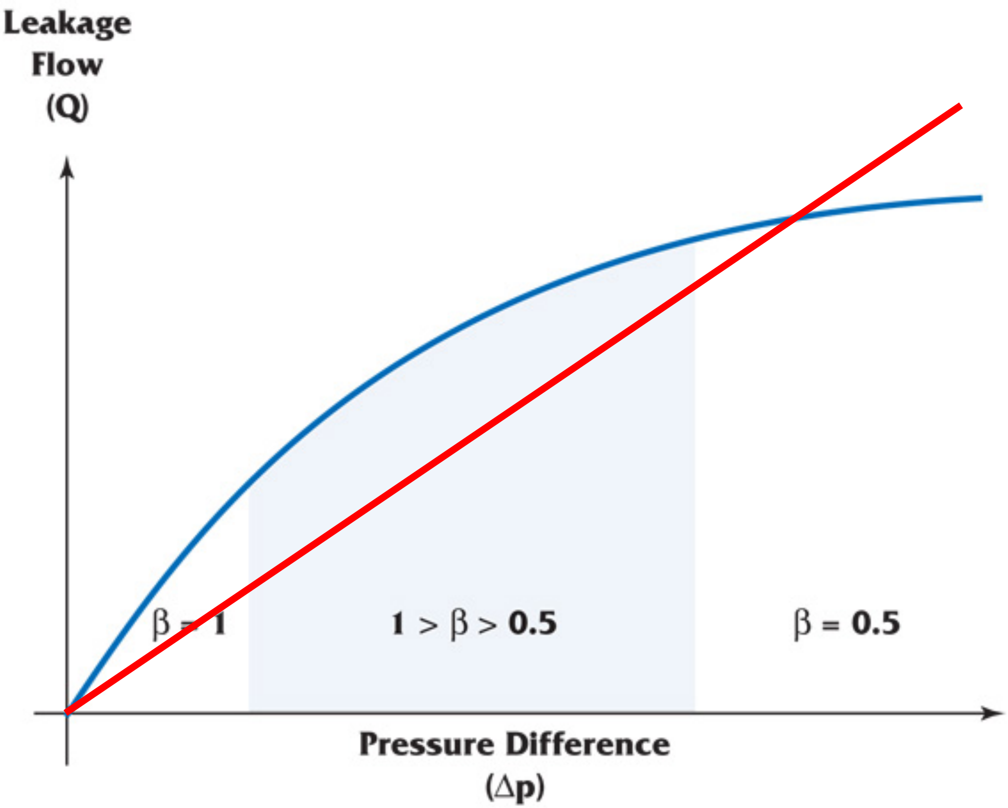


Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)



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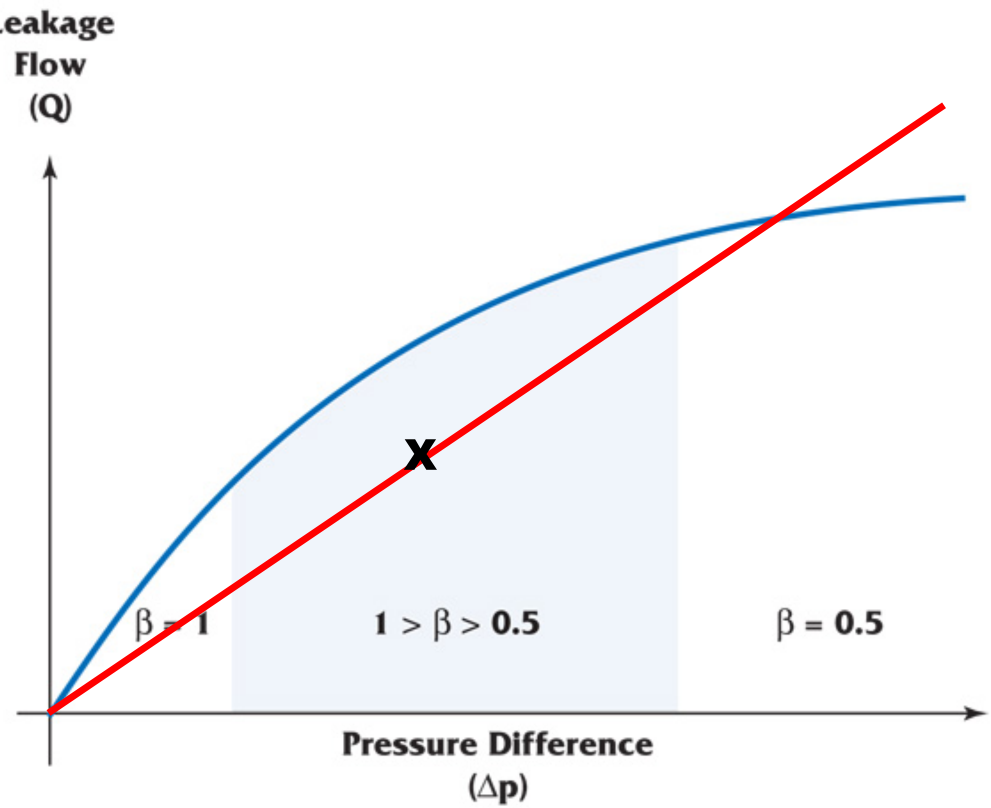

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Characteristic Curve of Leakage Flow as a Function of Pressure Difference

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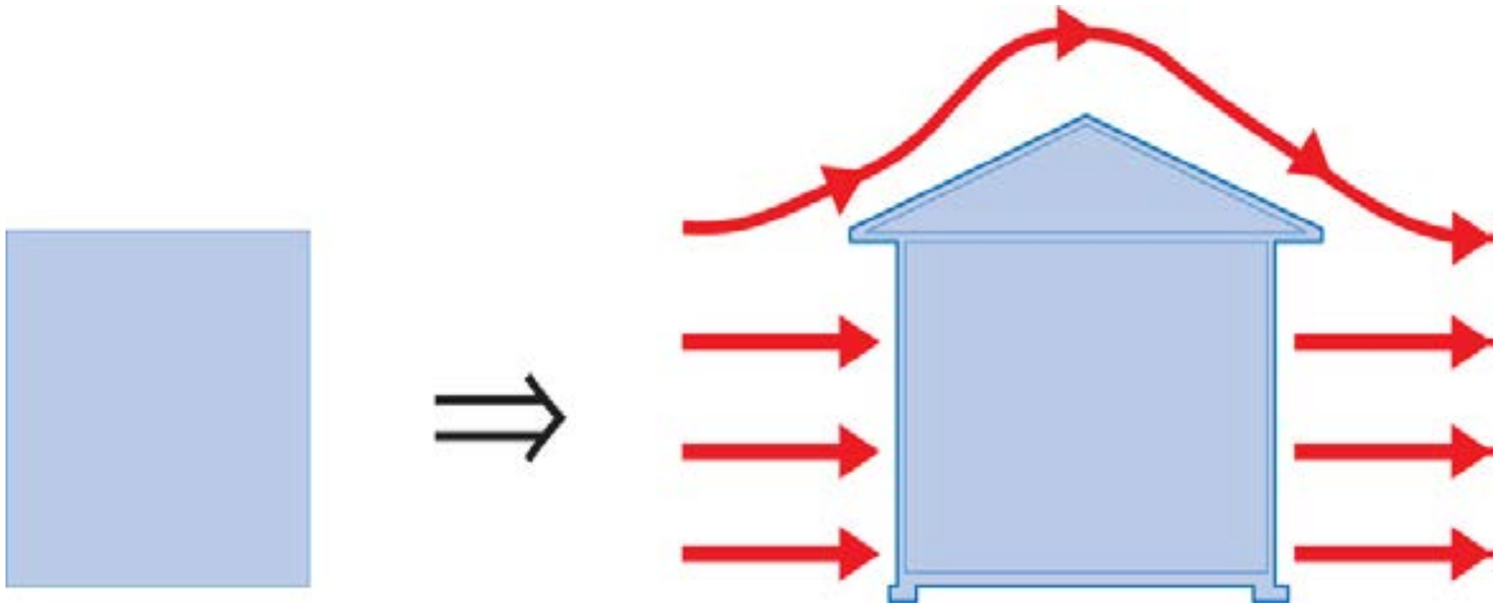
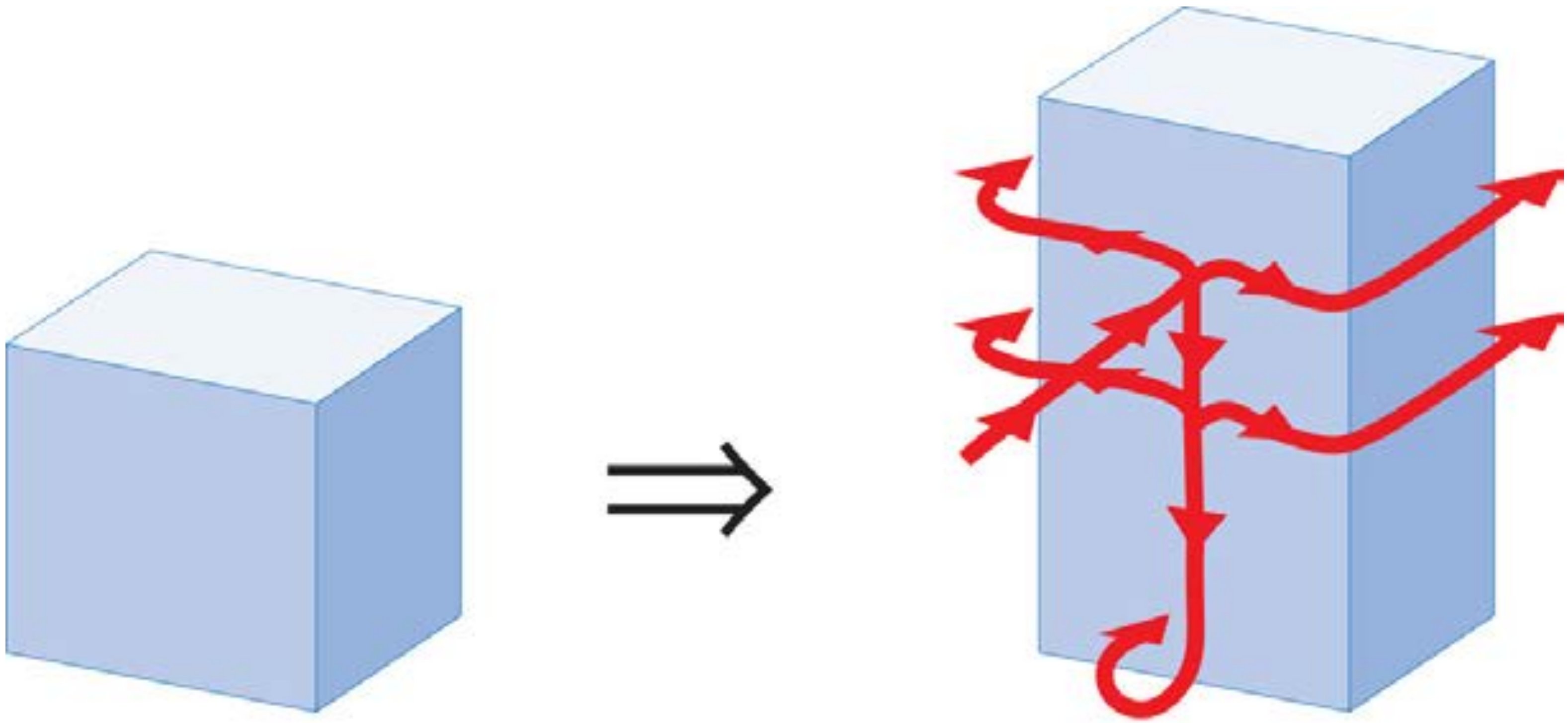
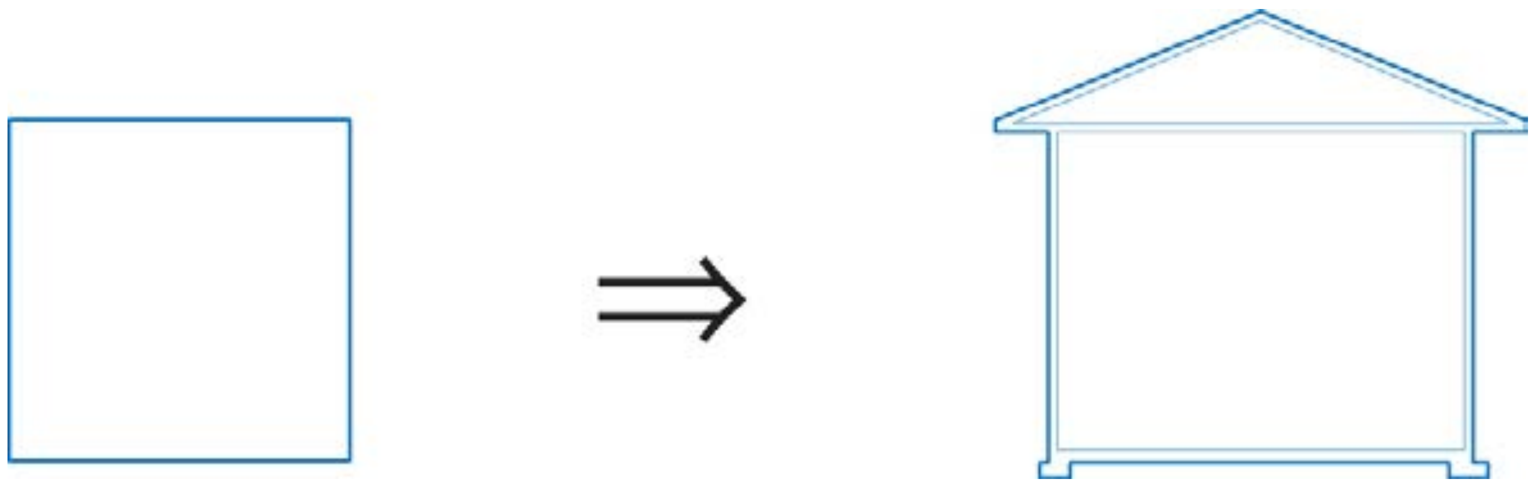
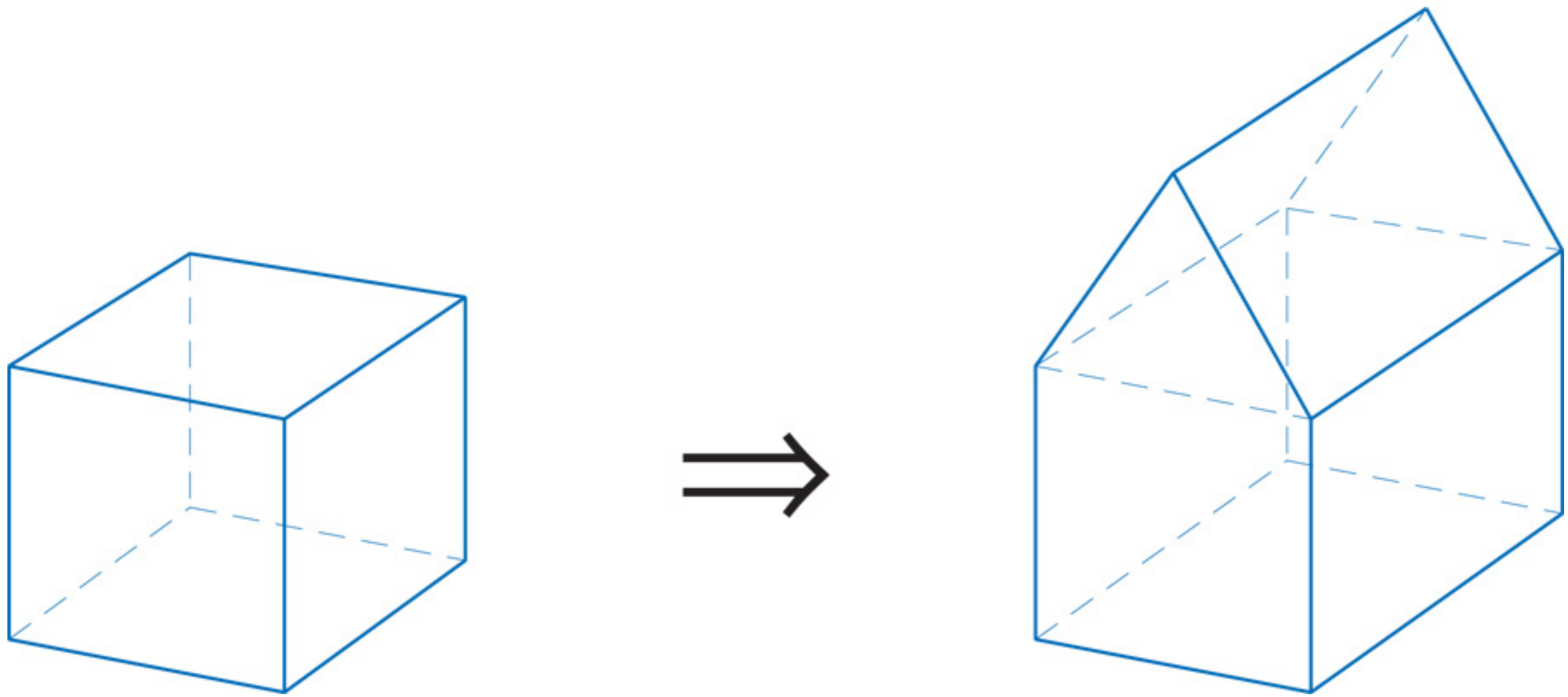








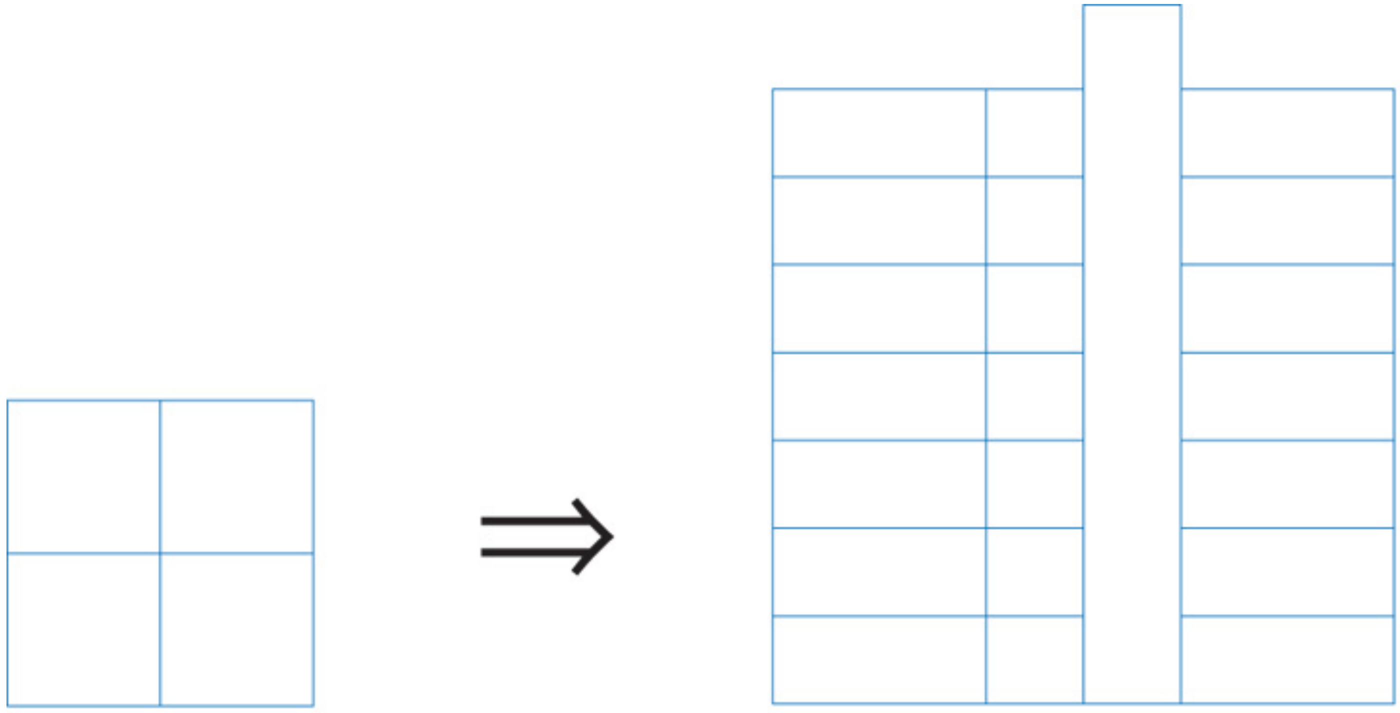


Figure 2.7

Two Dimensional Multi-Cell Analogue

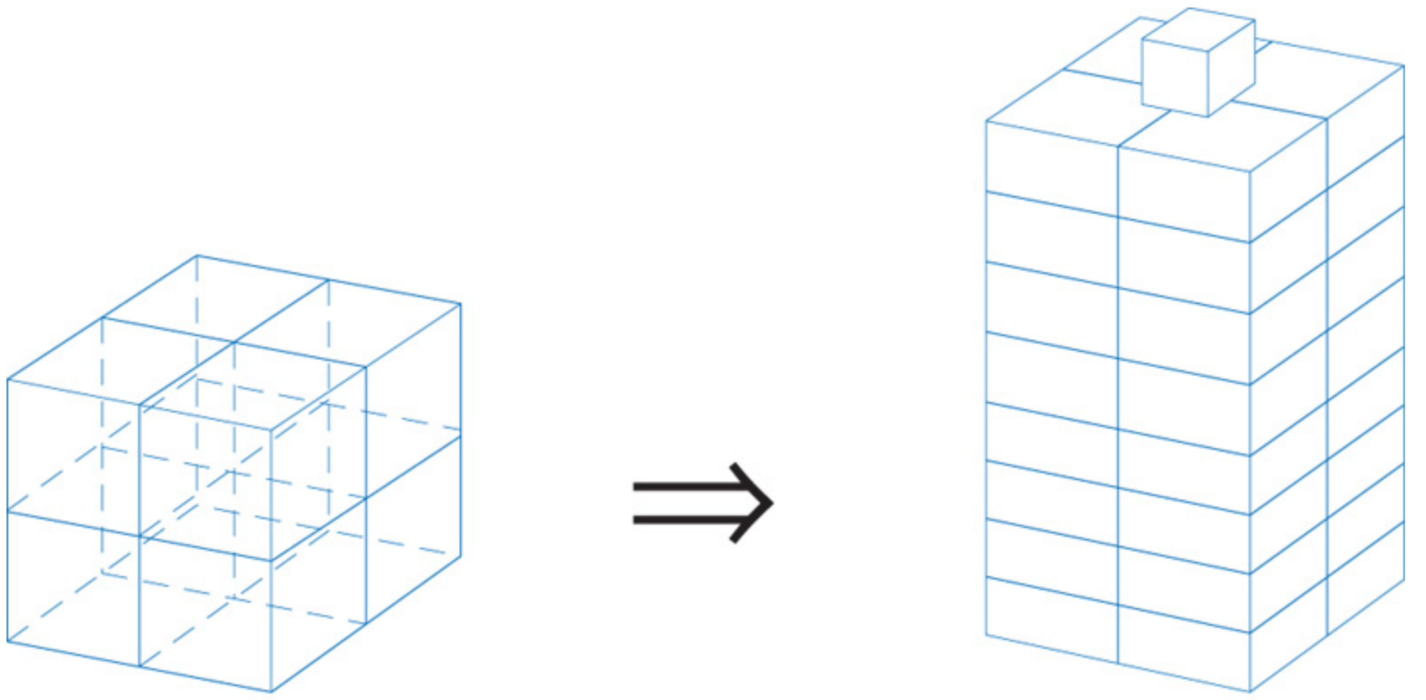


Figure 2.8

Three Dimensional Multi-Cell Analogue

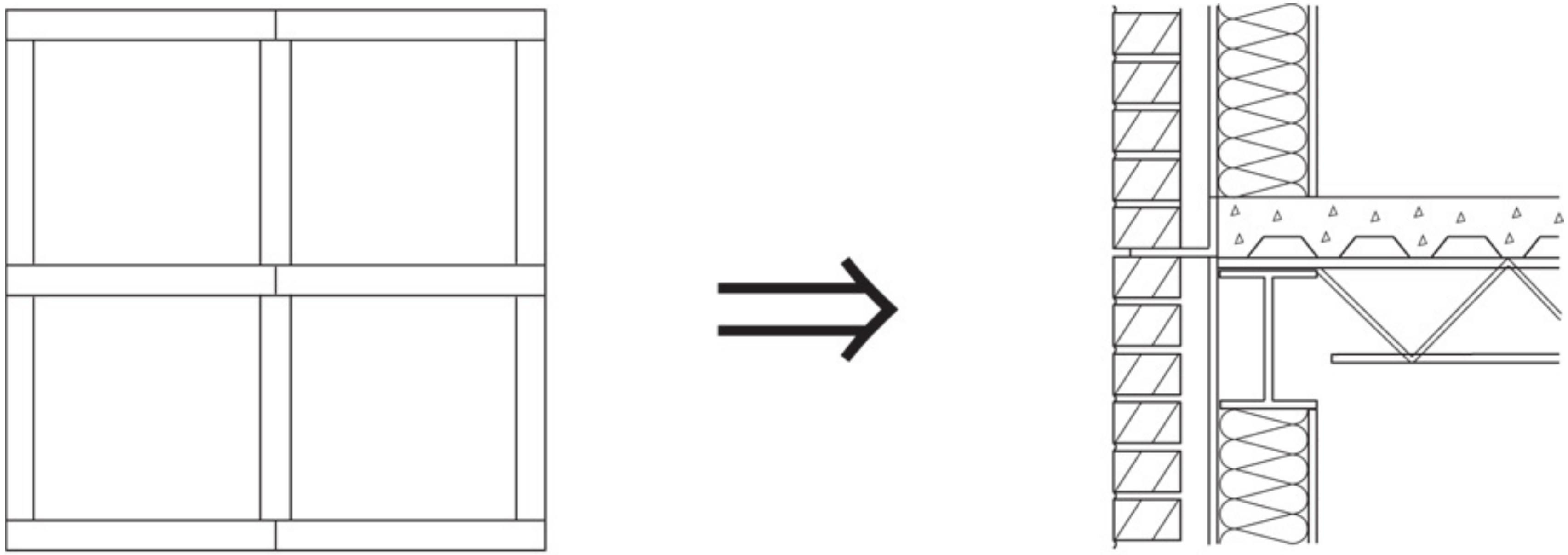
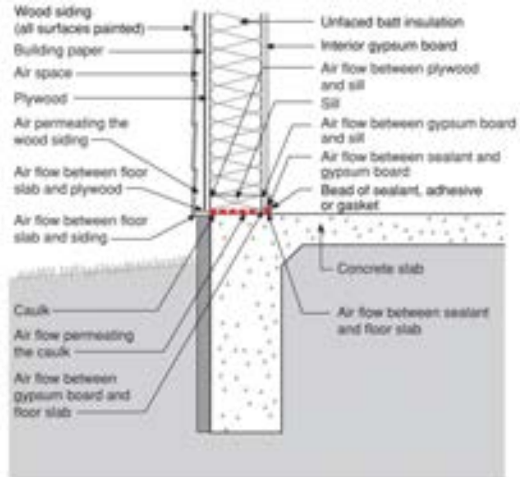
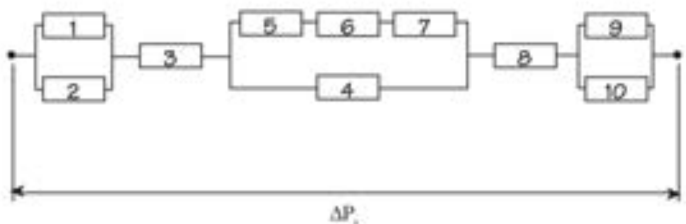


Figure 2.9
Two Dimensional Multi-Layer Multi-Cell Analogue



Possible air flows around sill of a wood-framed house modelled as a resistance network



1. Air permeating the wood-panel cladding
2. Air flow between floor slab and panel
3. Air flow between floor slab and wind protection
4. Air permeating the caulking
5. Air flow between wind protection and sill
6. Air flow bewteen insulation material and sill
7. Air flow between inner lining and sill
8. Air flow between inner lining and floor slab
9. Air flow between fillet and inner lining
10. Air flow between fillet and floor slab

Figure 2.10
Resistance Network
(from Kronvall, 1980)

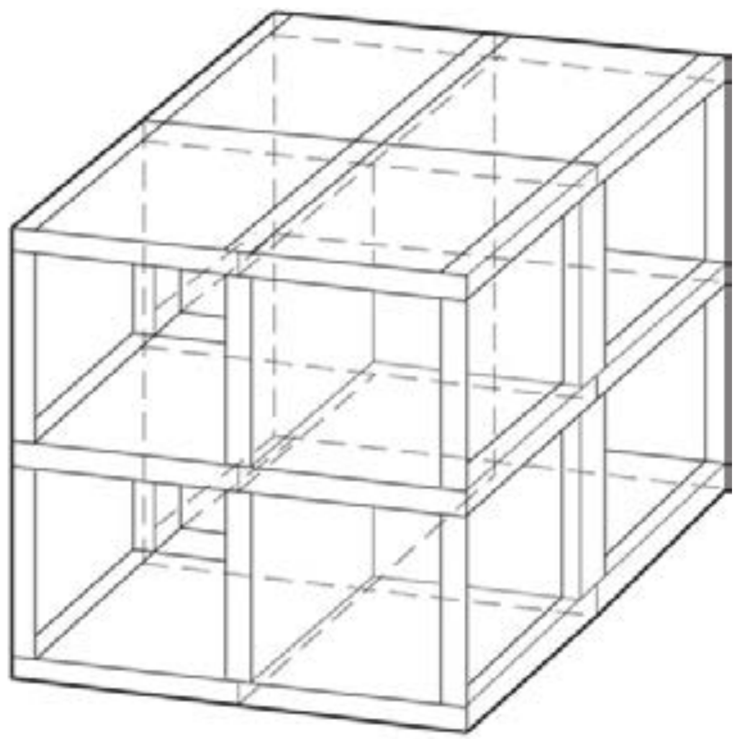


Figure 2.11
Three Dimensional Multi-Layer Multi-Cell Analogue

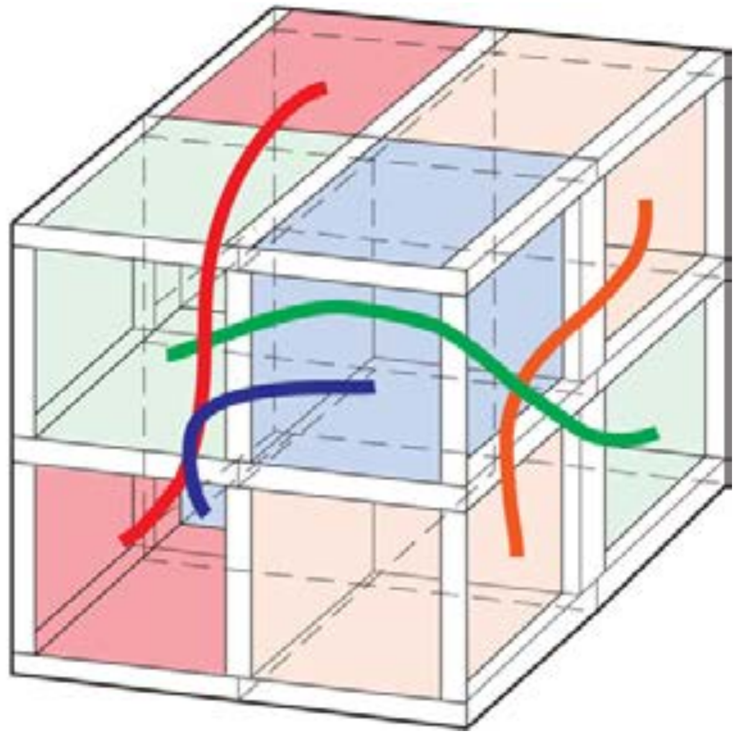
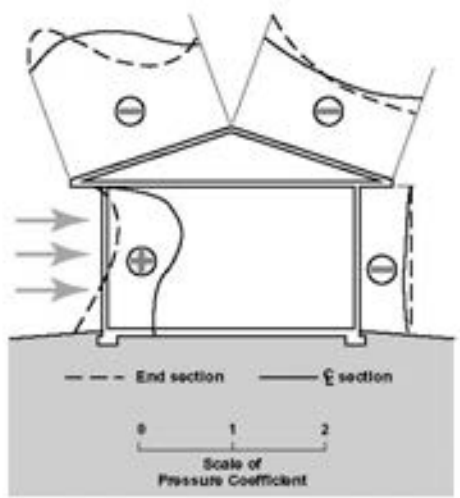


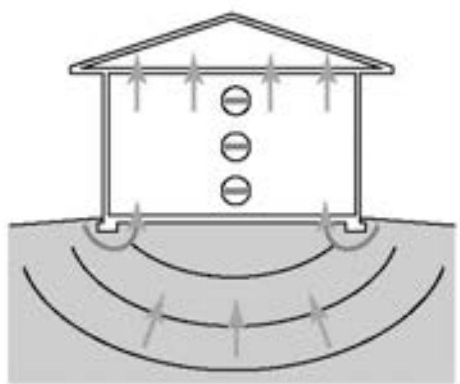
Figure 2.12
Three Dimensional Multi-Layer Multi-Cell Non-Contiguous Analogue

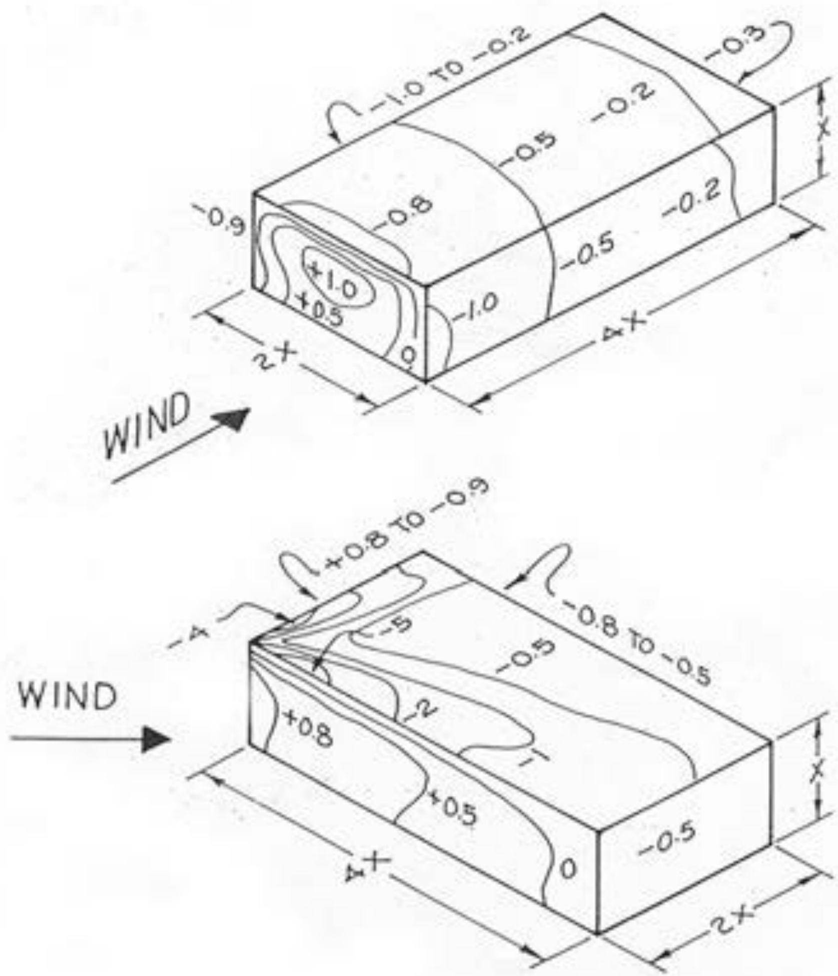
Figure 3.1
Exterior Air Pressure Field
(from Hutcheon & Handegord, 1983)



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.

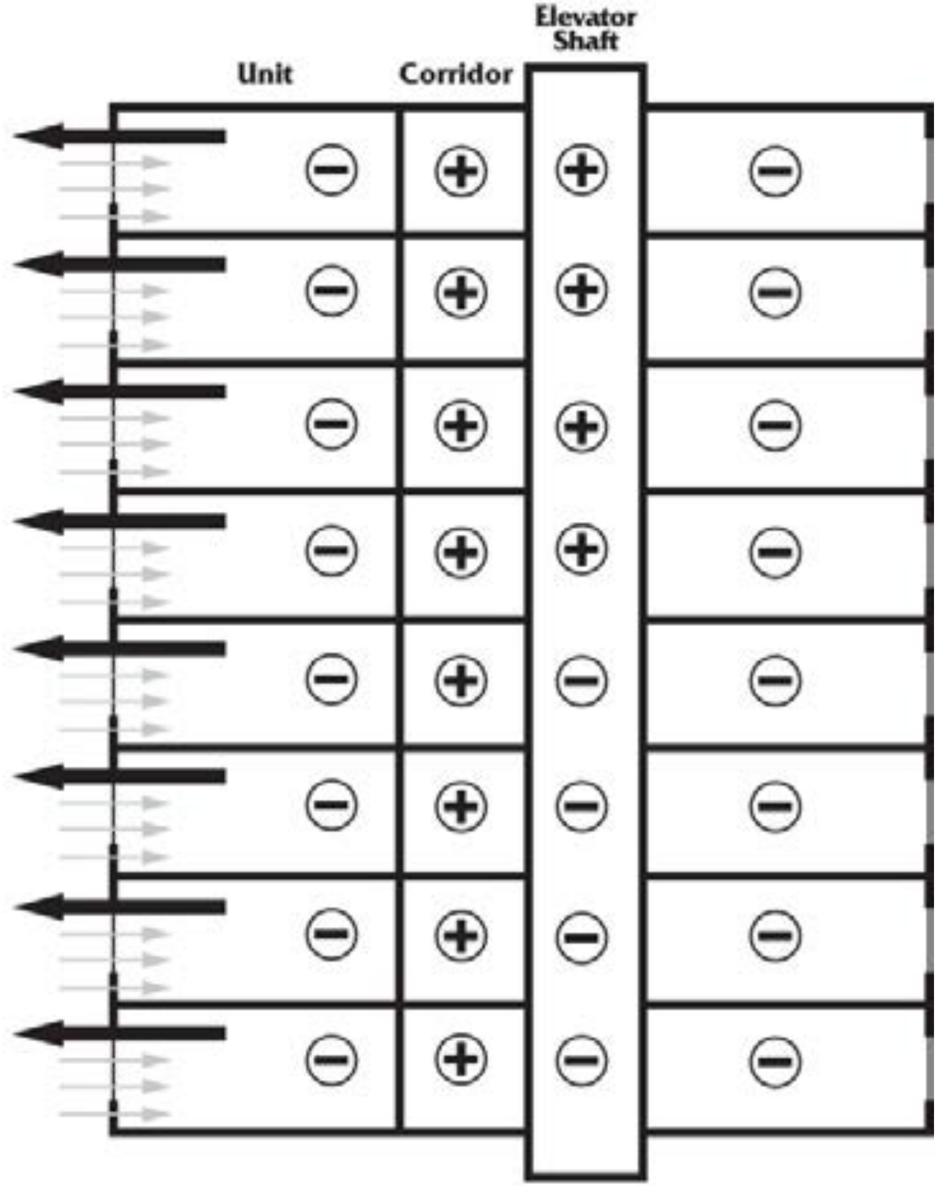


Figure 3.3
Interior Air Pressure Field

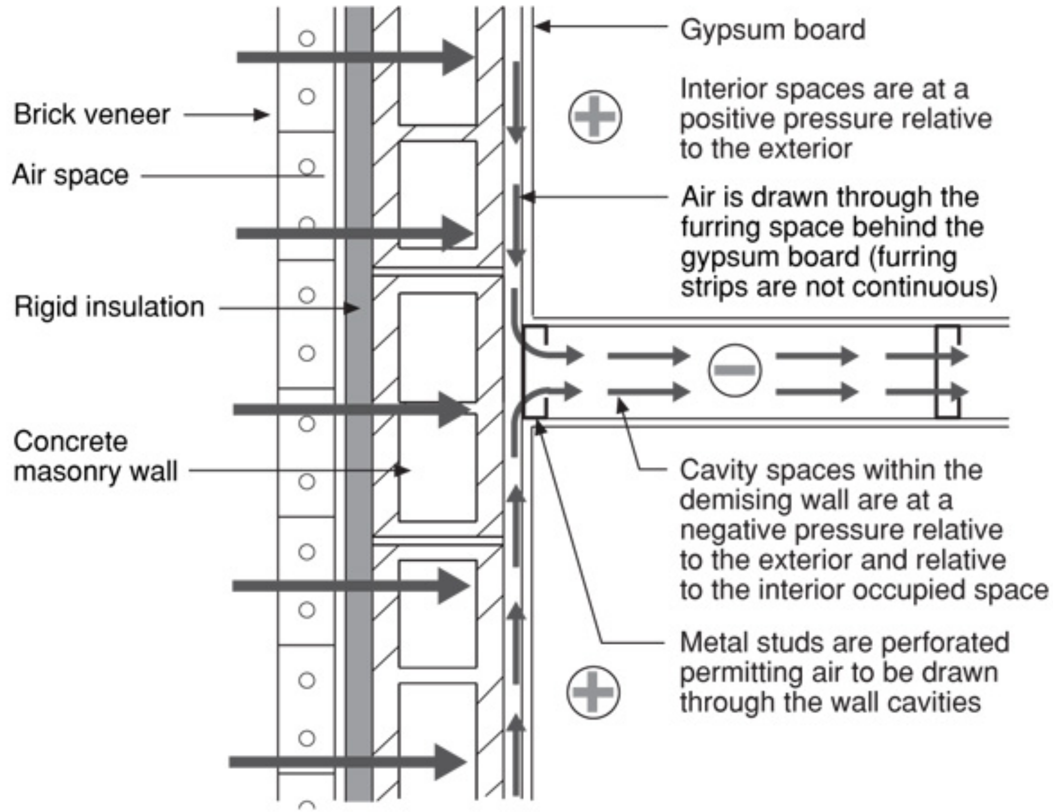


Figure 3.4
Interstitial Air Pressure Field

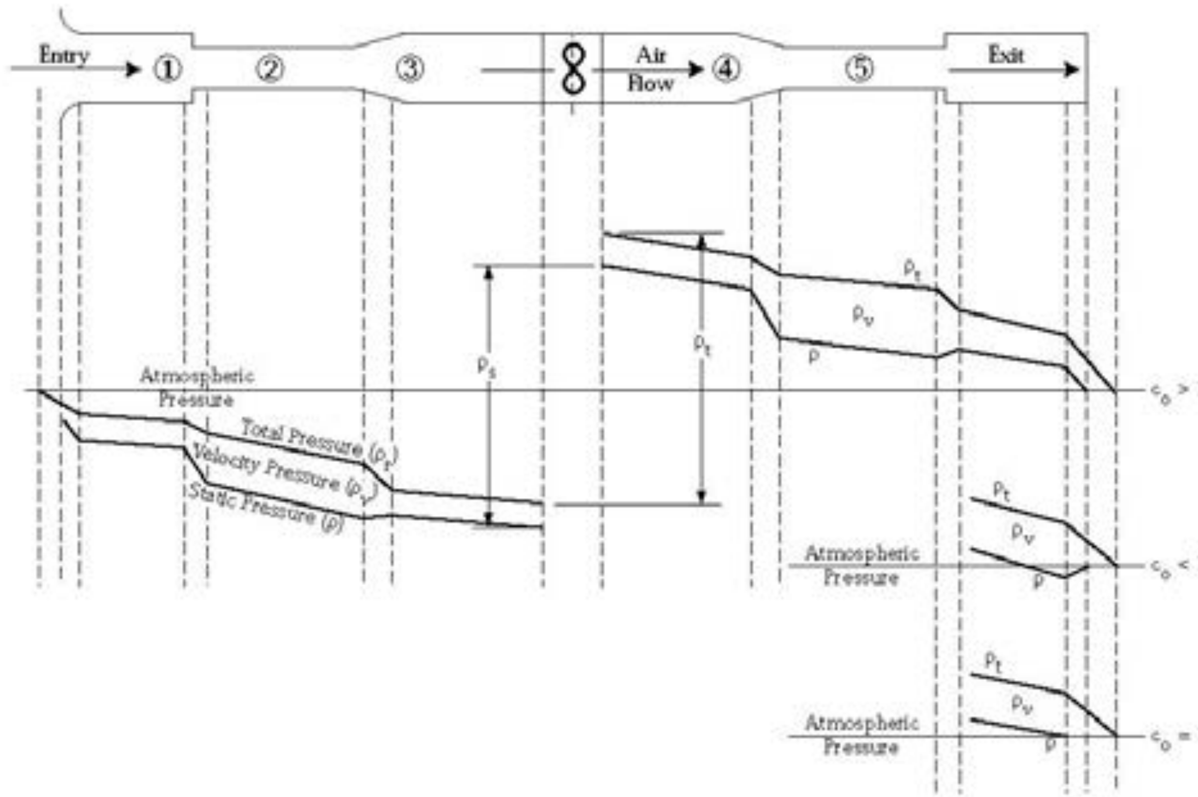
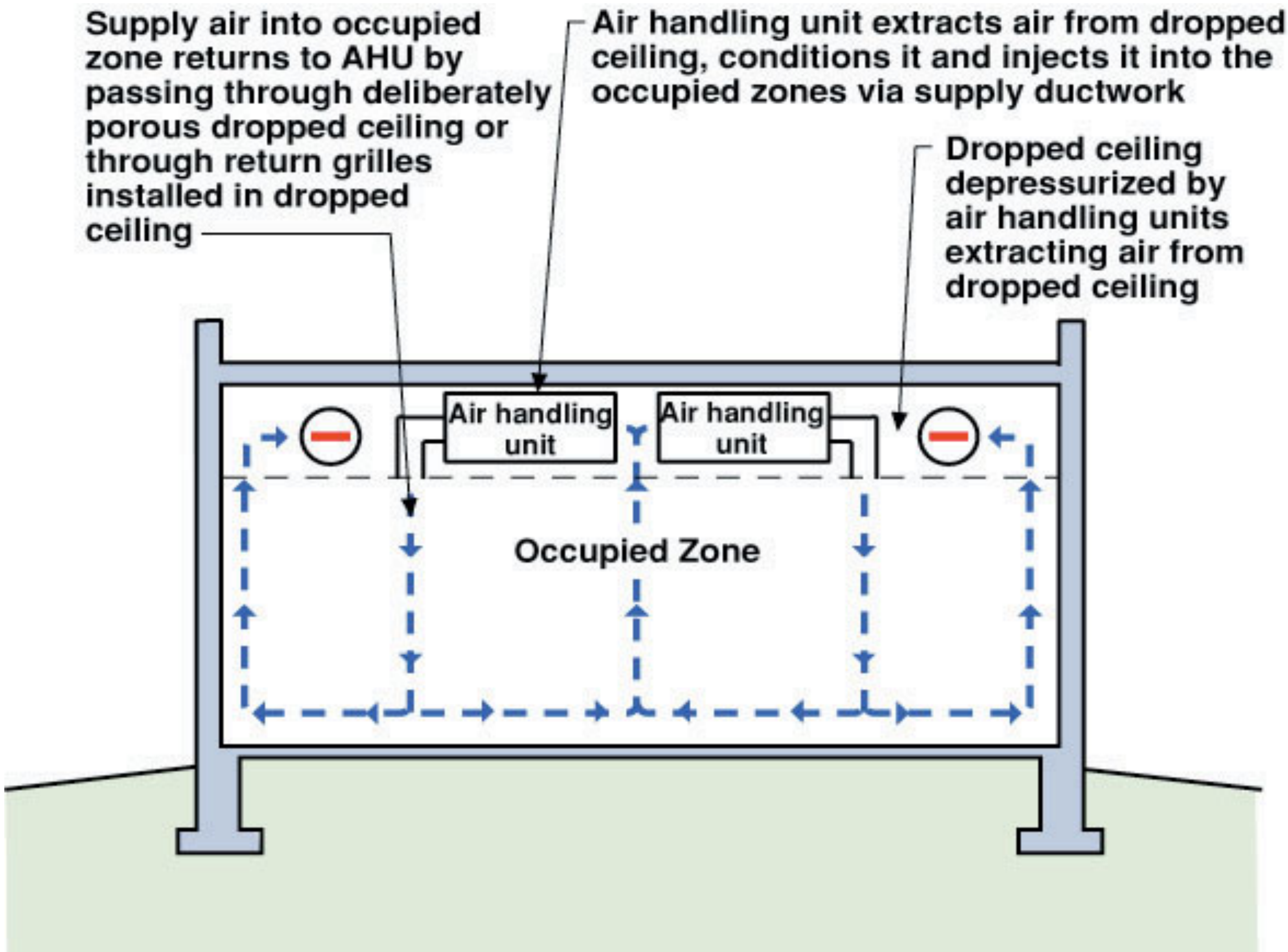
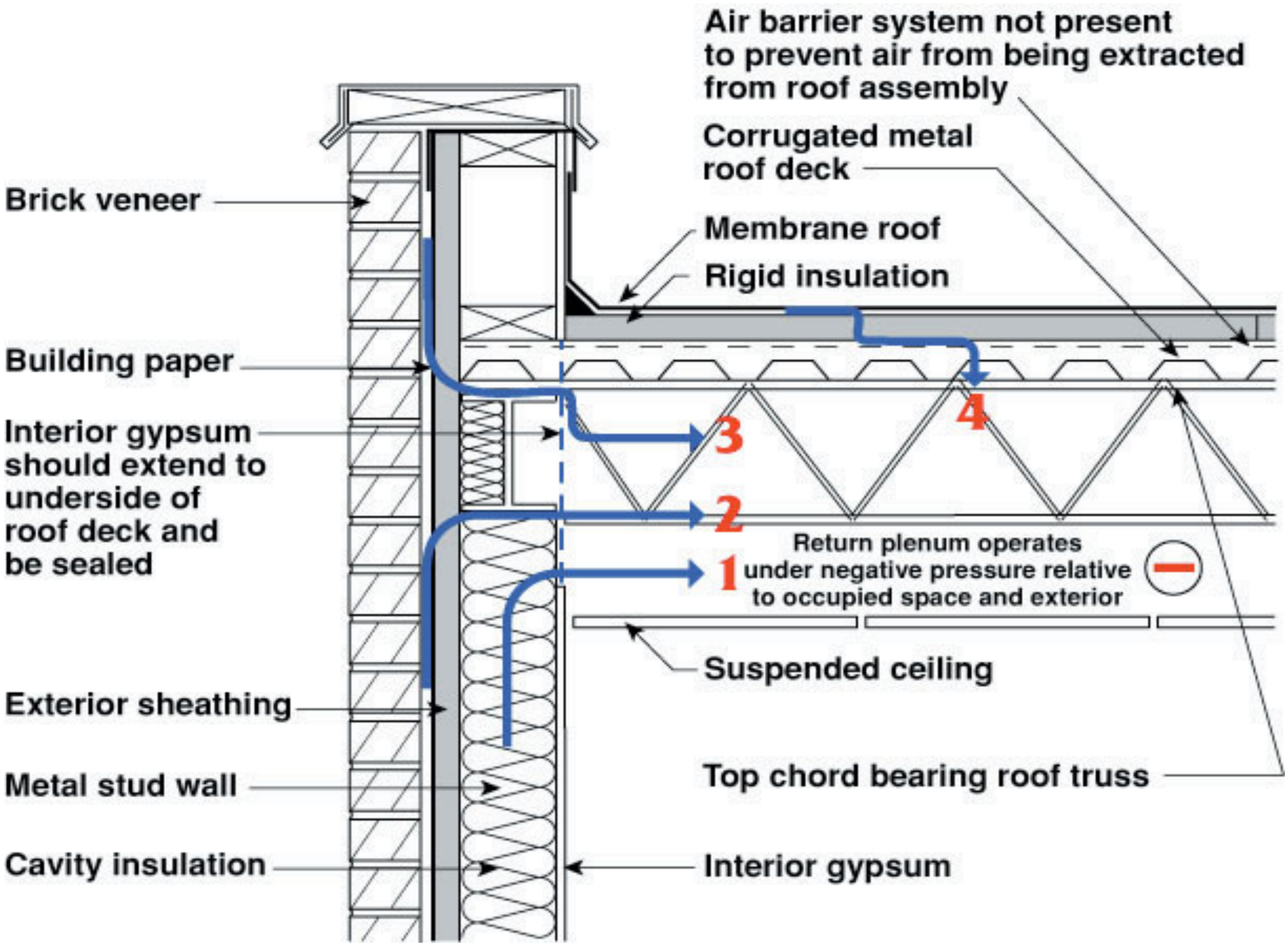


Figure 3.5

Air Conveyance System Air Pressure Field

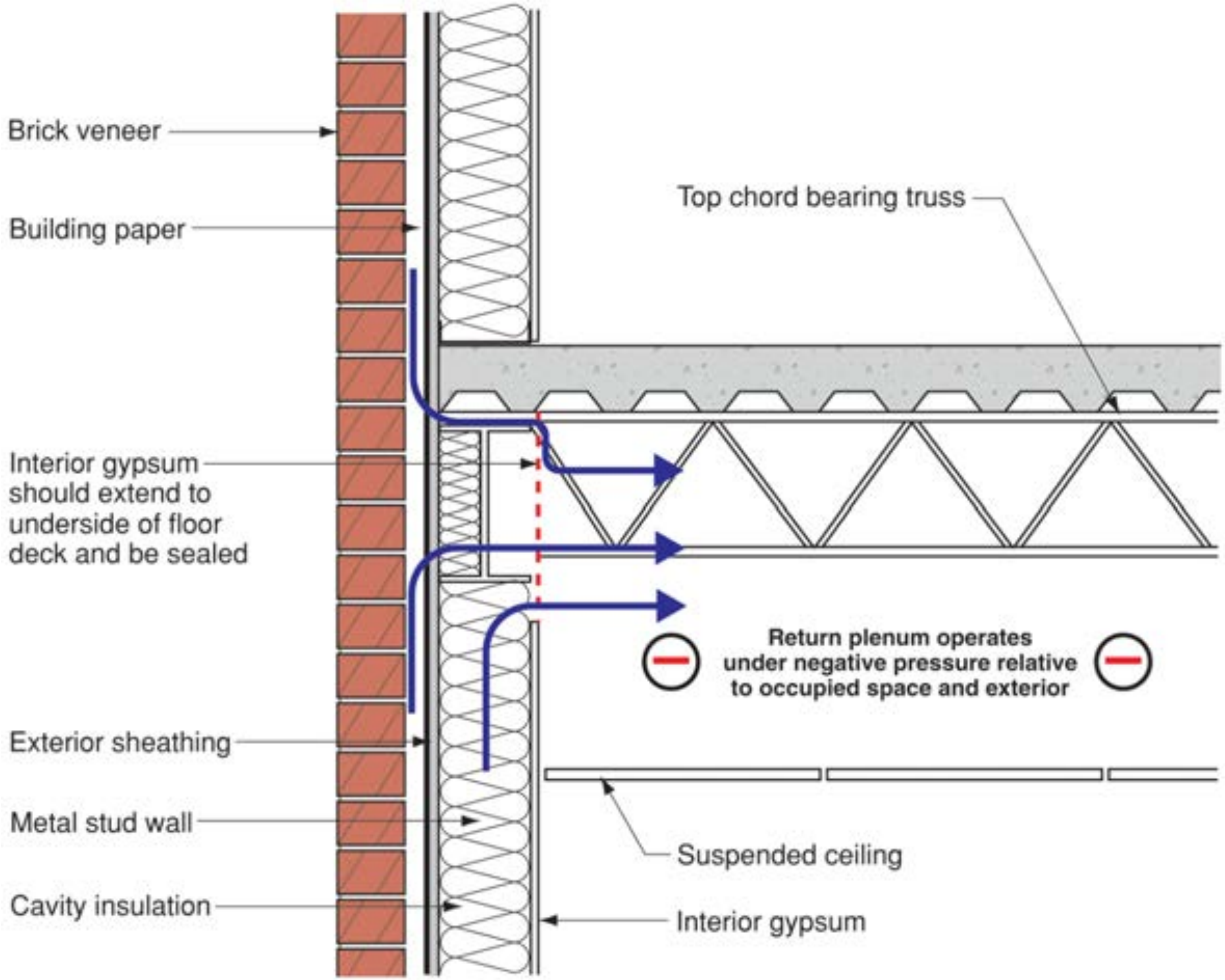
(from Sauer & Howell, 1990)

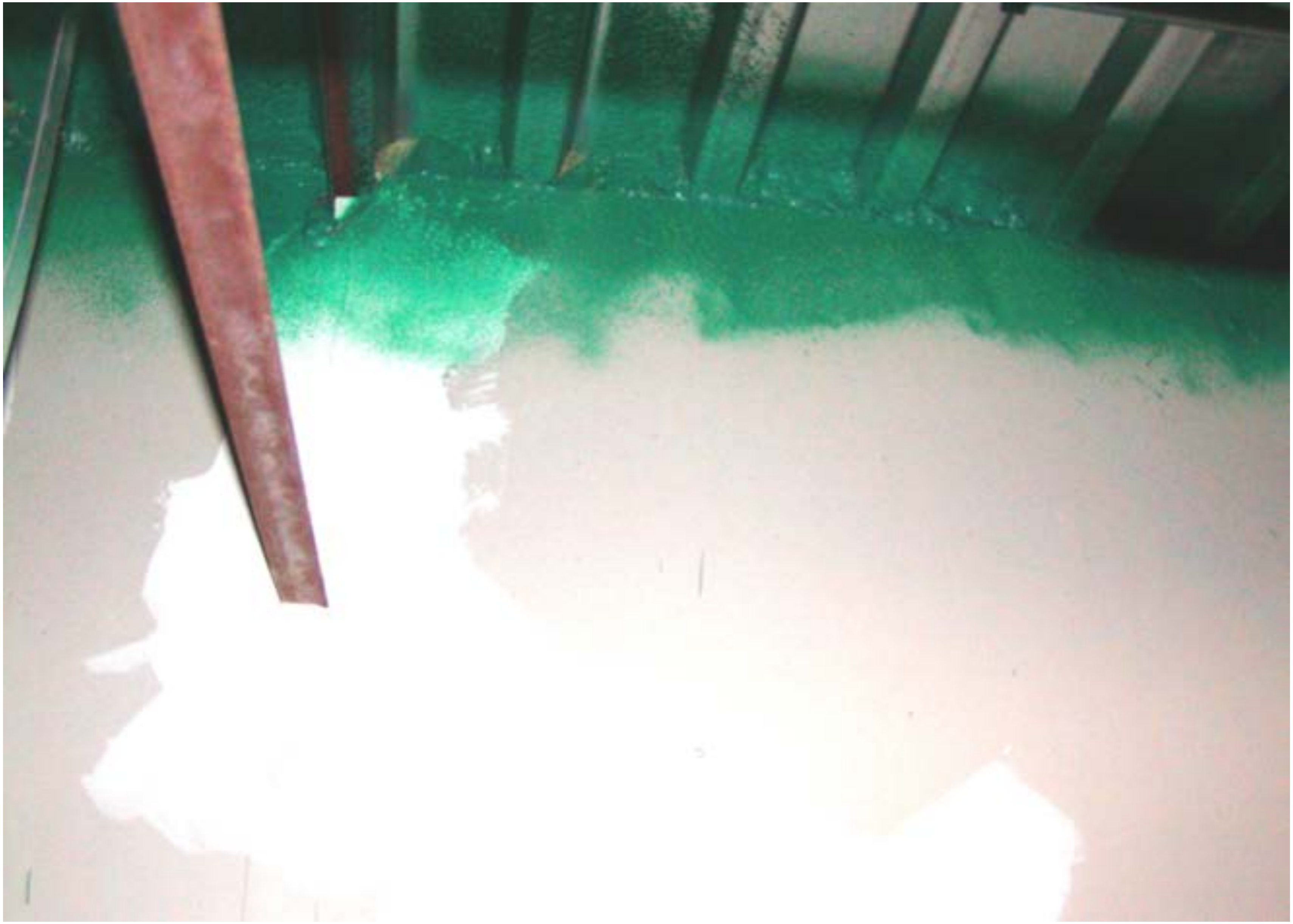

Supply air into occupied zone returns to AHU by passing through deliberately porous dropped ceiling or through return grilles installed in dropped ceiling
Air handling unit extracts air from dropped ceiling, conditions it and injects it into the occupied zones via supply ductwork
Dropped ceiling depressurized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

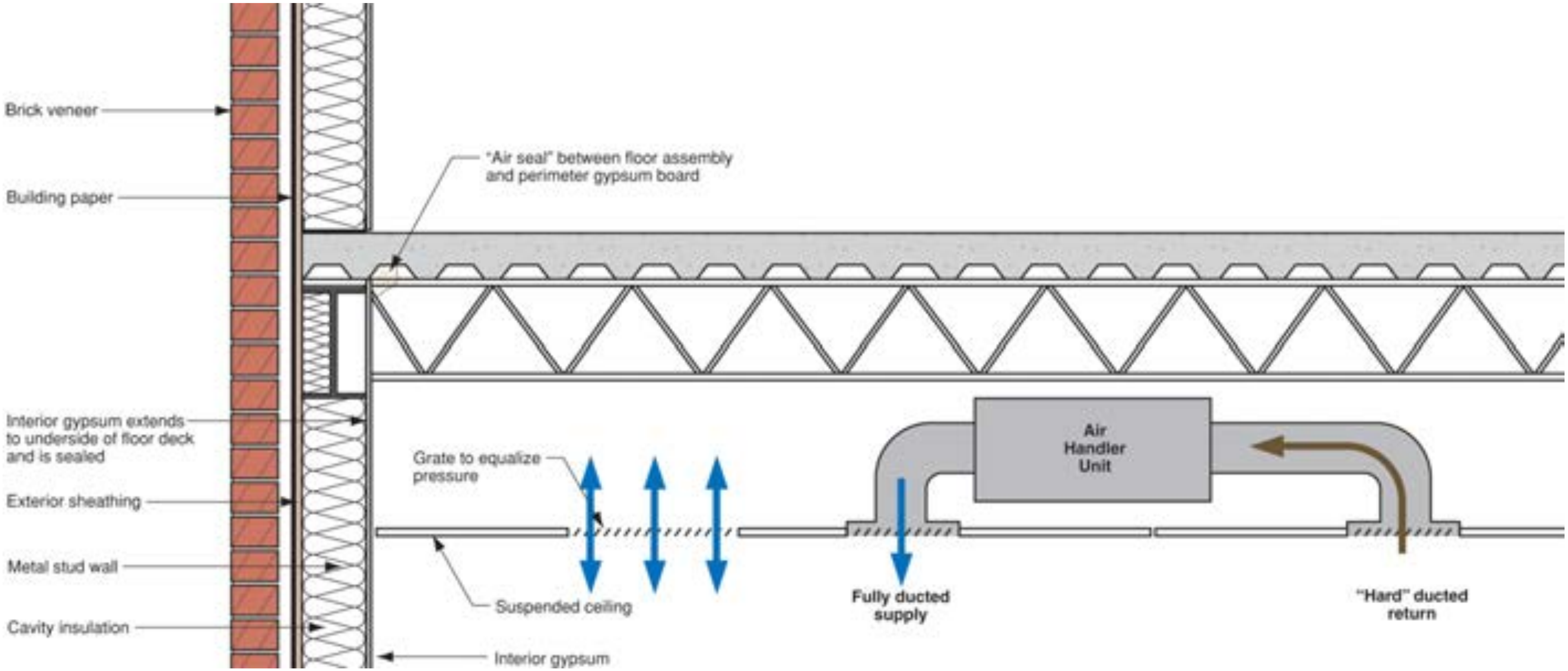


Air barrier system not present to prevent air from being extracted from roof assembly
Corrugated metal roof deck
Membrane roof
Rigid insulation
Brick veneer
Building paper
Interior gypsum should extend to underside of roof deck and be sealed
Exterior sheathing
Metal stud wall
Cavity insulation
3
4
2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


COMPANY


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




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

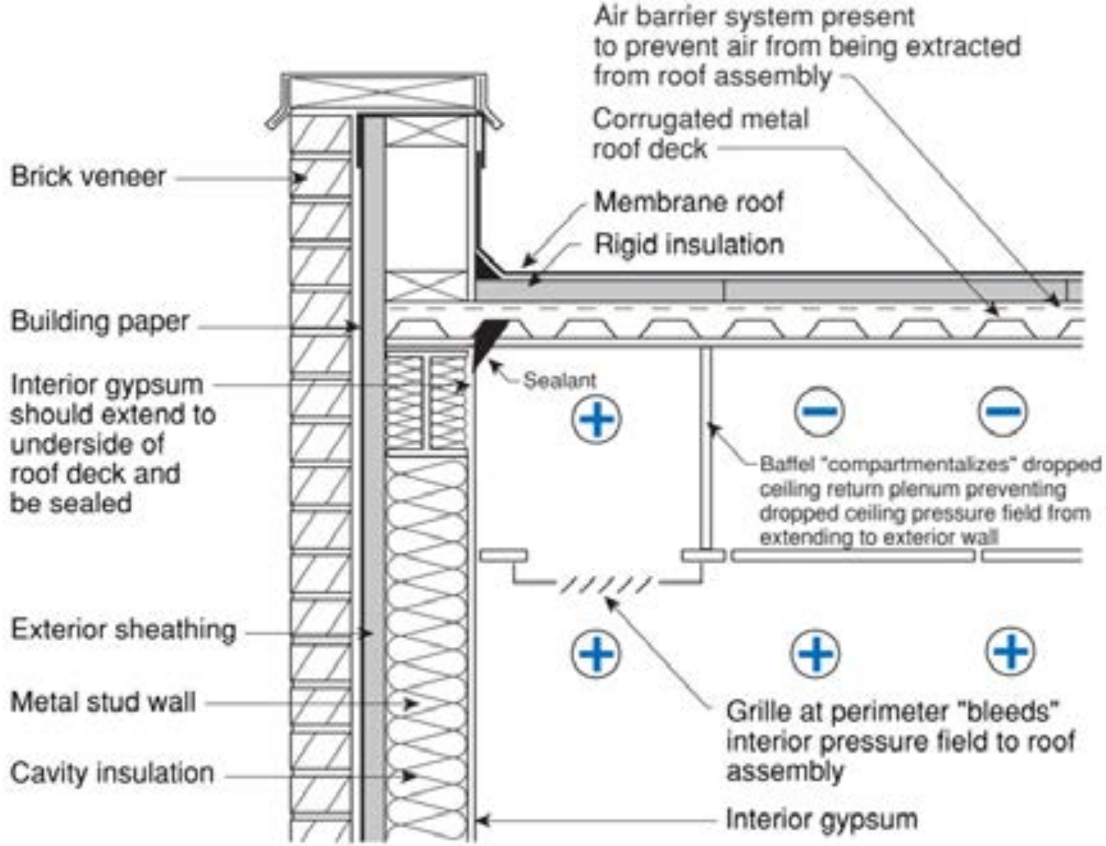
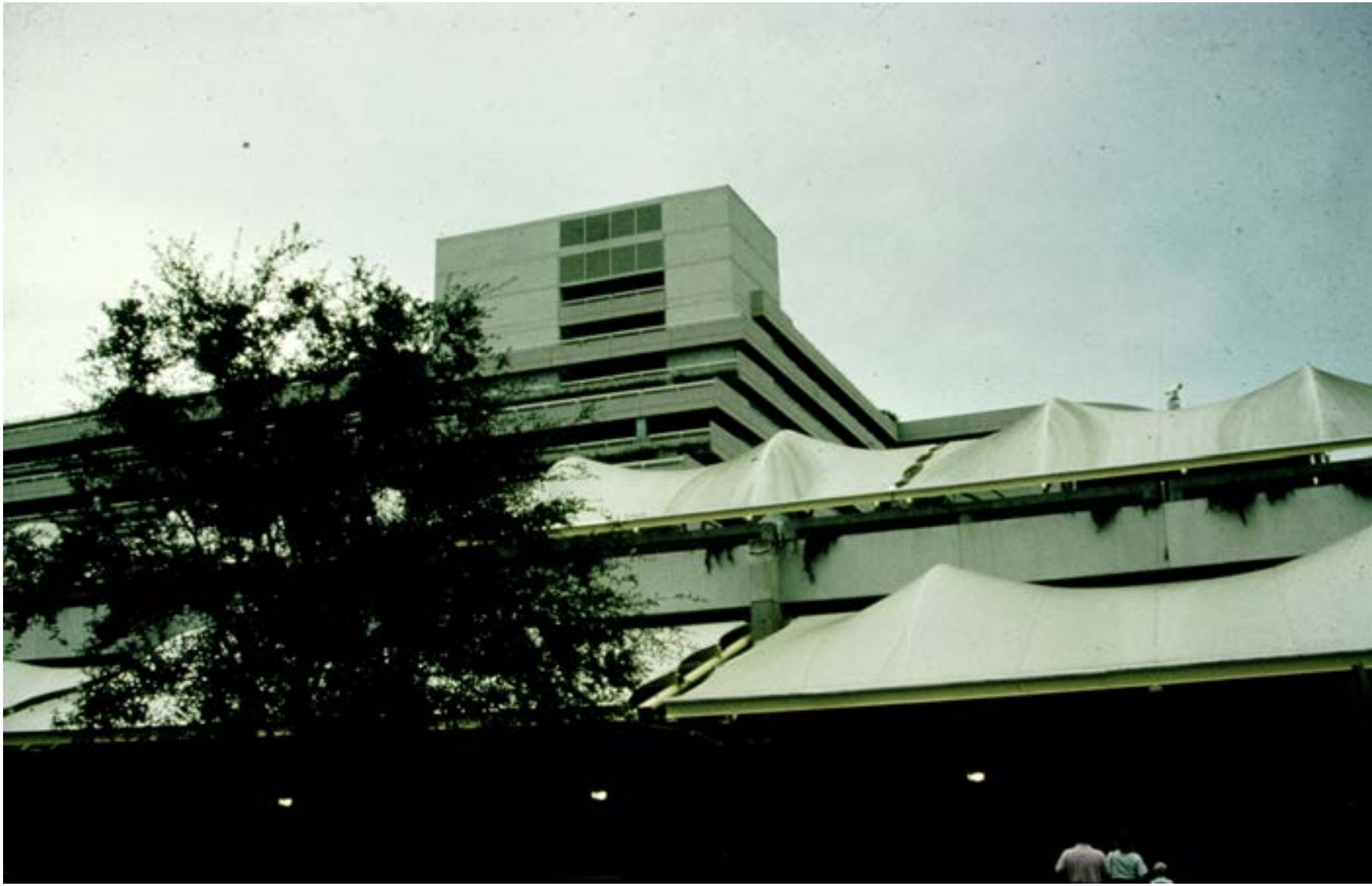


Figure 6.1

Compartmentalizing Dropped Ceiling


McCarthy Companies



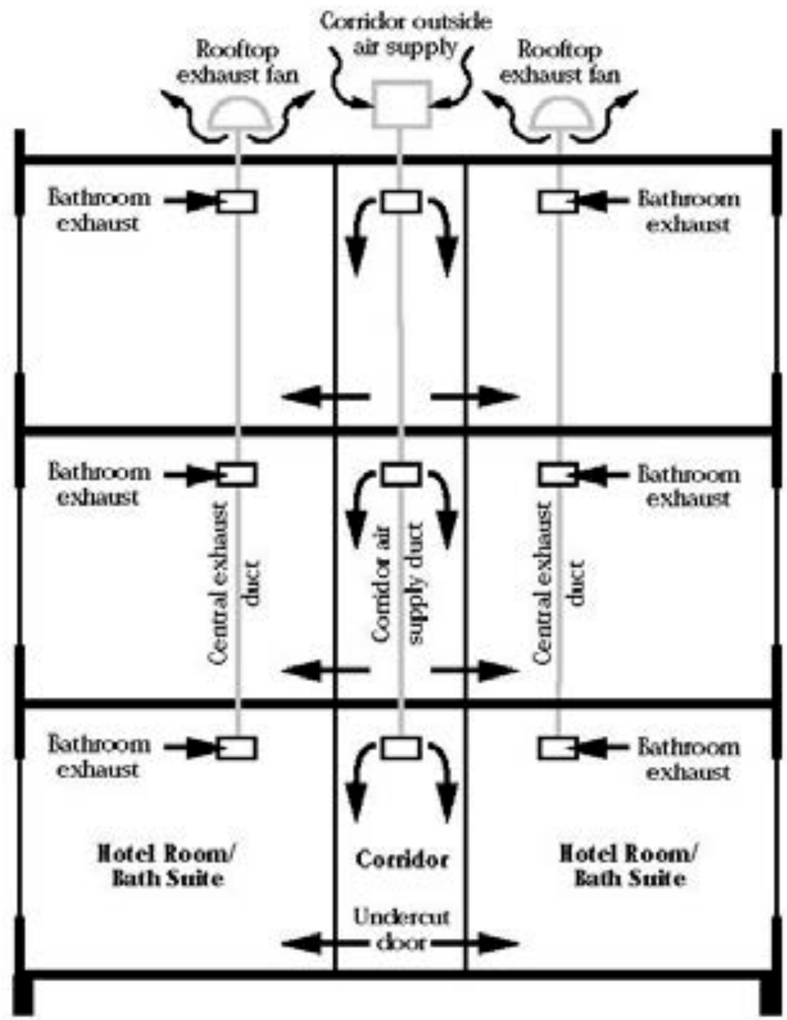
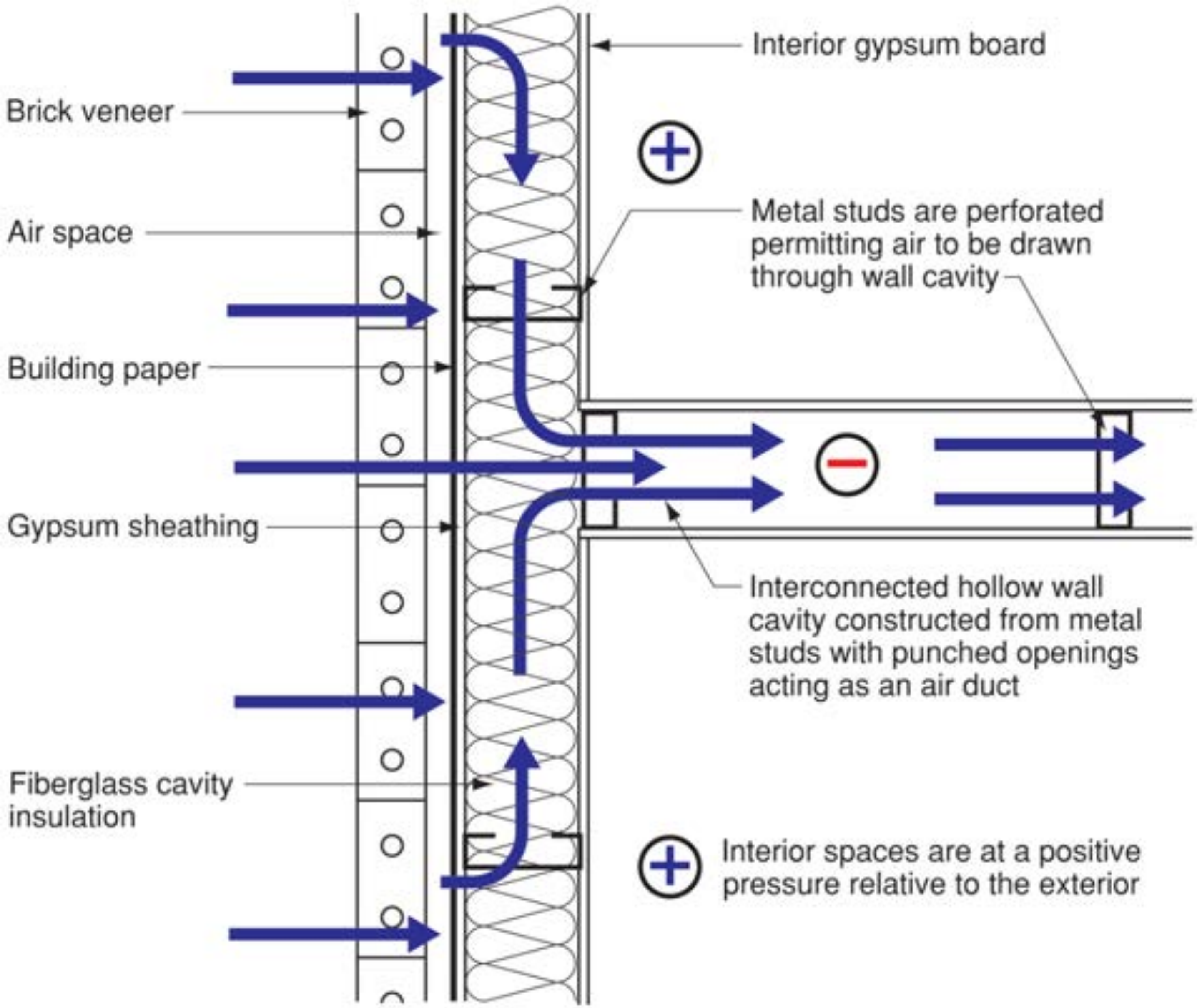


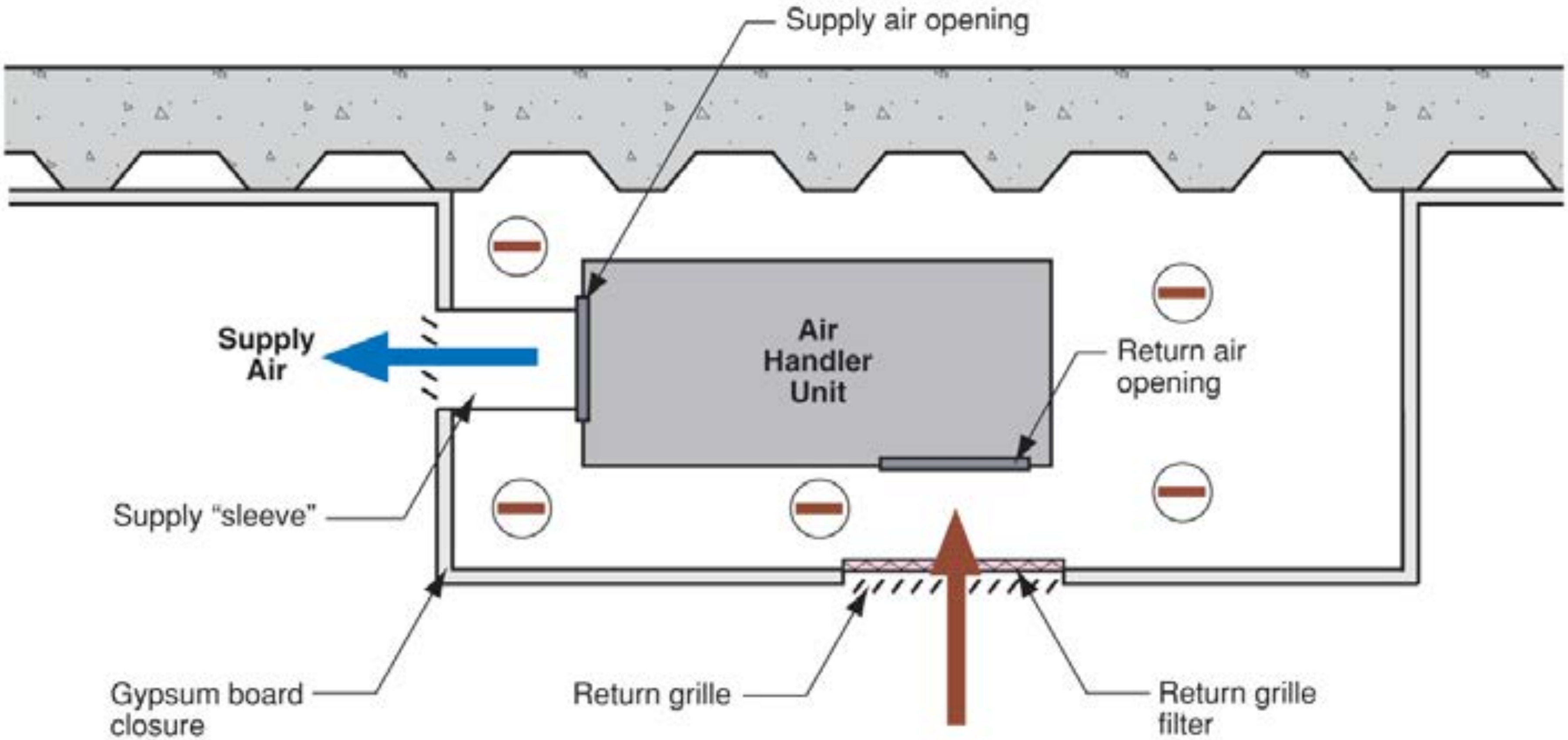
Figure 3.8

Hotel HVAC System

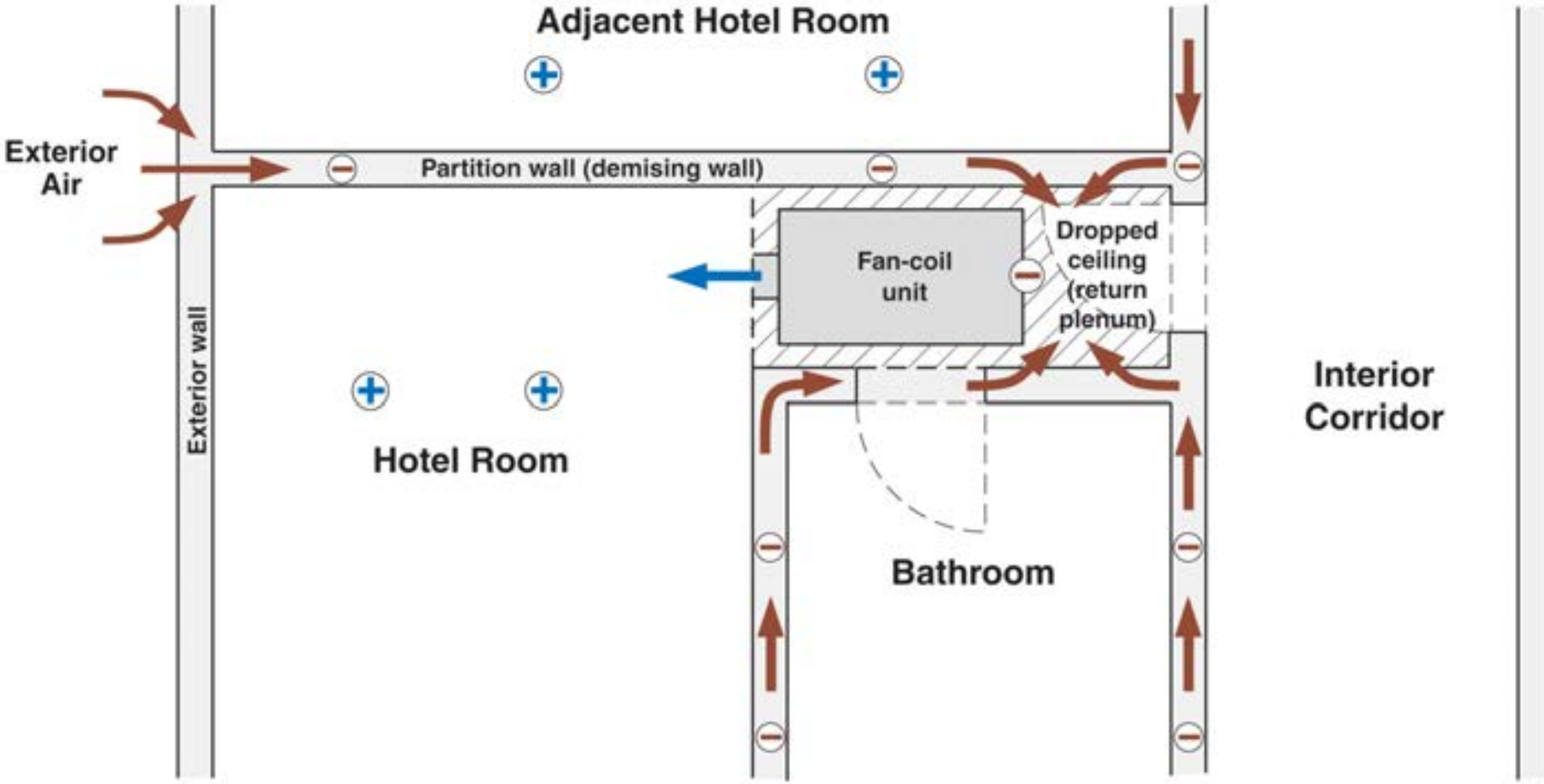
- Air exhausted from bathrooms via central rooftop exhaust fans
- Air supplied from corridors via undercut doors



Interior gypsum board
Brick veneer
Air space
Metal studs are perforated permitting air to be drawn through wall cavity
Building paper
Gypsum sheathing
Interconnected hollow wall cavity constructed from metal studs with punched openings acting as an air duct
Fiberglass cavity insulation
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)
Dropped ceiling (return plenum)
Fan-coil unit
Exterior wall
Hotel Room
Interior Corridor
Bathroom

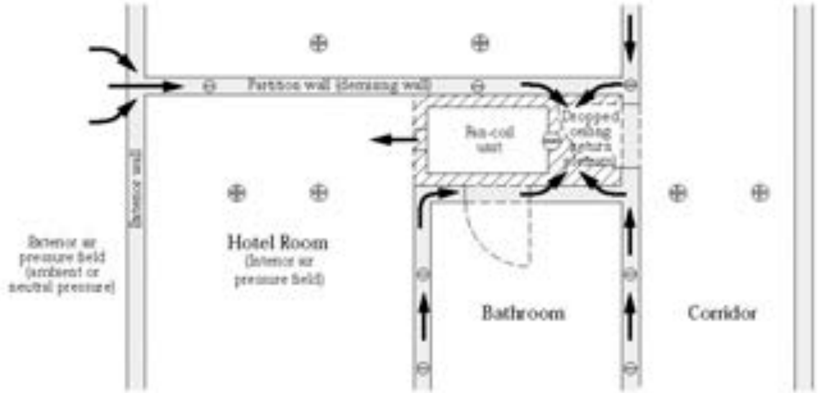


Figure 3.10
Pressure Field Due to Fan-Coil Unit
Plan View

- 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

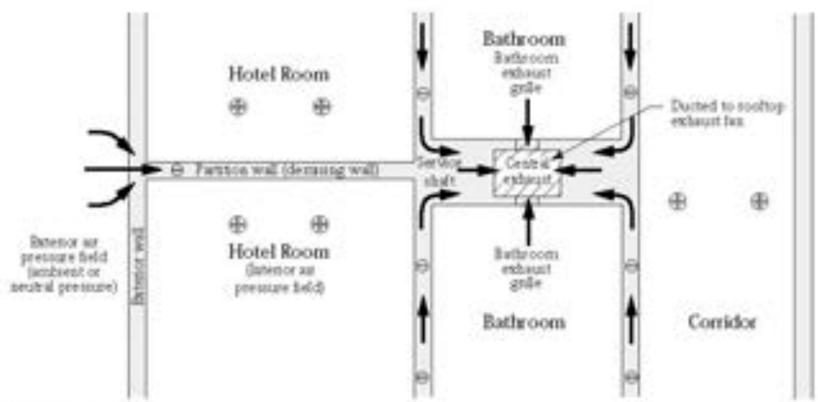


Figure 3.11
Pressure Field Due to Central Exhaust
Plan View

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


DAYS INN

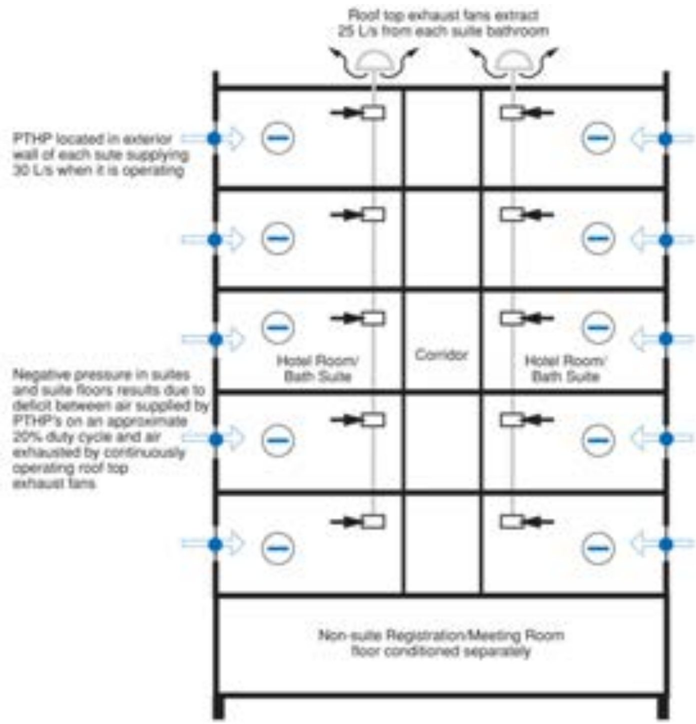
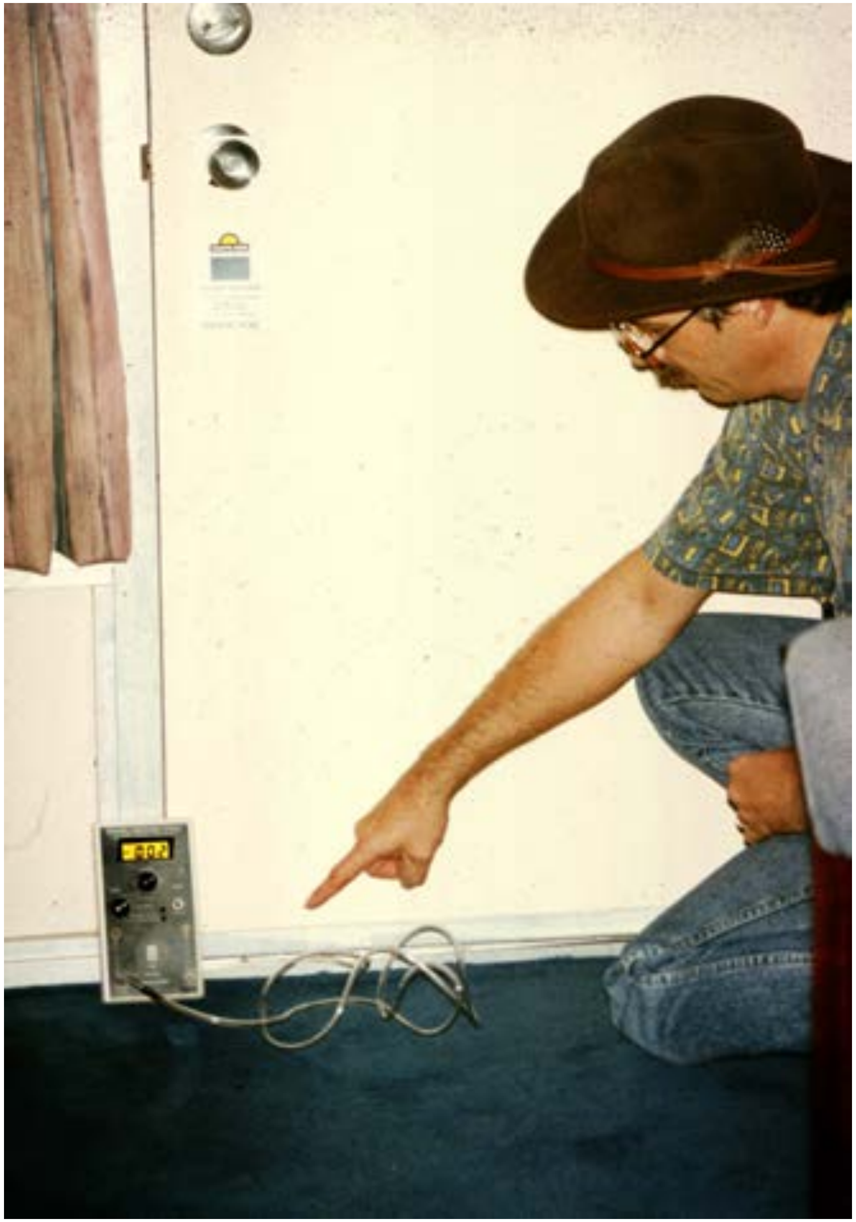
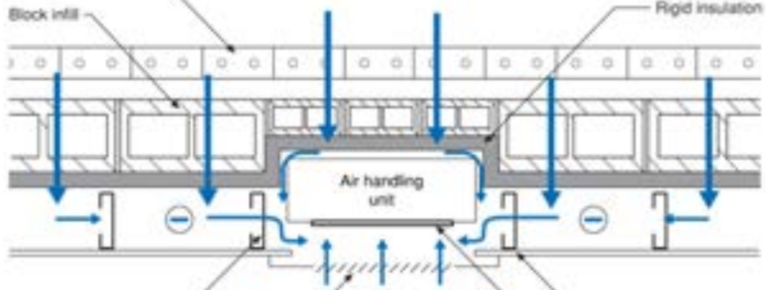


Figure 5.5

HVAC System for Hotel

- 25 L/s is extracted from each suite
- 15 suites per floor plus 100 L/s extracted from each corridor
- 475 L/s extracted per floor
- 2,850 L/s extracted from 6 floors with suites
- Each suite's PTHP supplies 30 L/s when it is operating. One additional PTHP serves each corridor supplying 100 L/s of outside air. A total of 550 L/s is supplied per floor when all the PTHP's on a floor are operating.
- However, the typical duty cycle of a PTHP is approximately 20%, i.e. 80% of the units are off at any one time.
- When 3 suite PTHP's and the corridor PTHP are operating only 190 L/s supplied to a floor. If 475 L/s is extracted per floor, a deficit of 285 L/s exists per floor or 1,710 L/s for all the suite floors combined.





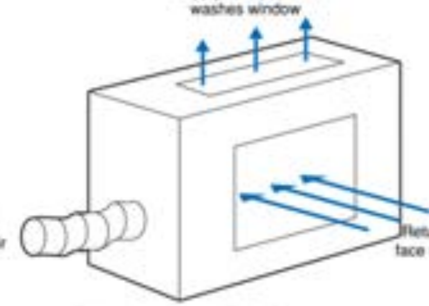
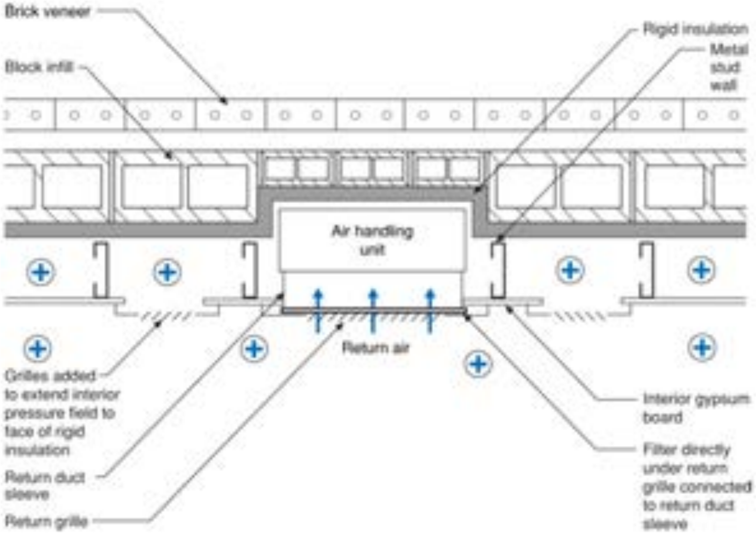


Figure 3.23
AHU Depressurizing Exterior Wall Assembly Plan View



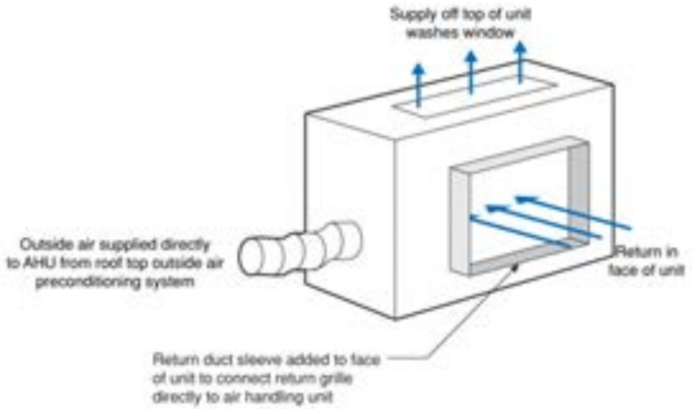


Figure 6.3
"Bleeding" Pressure Fields

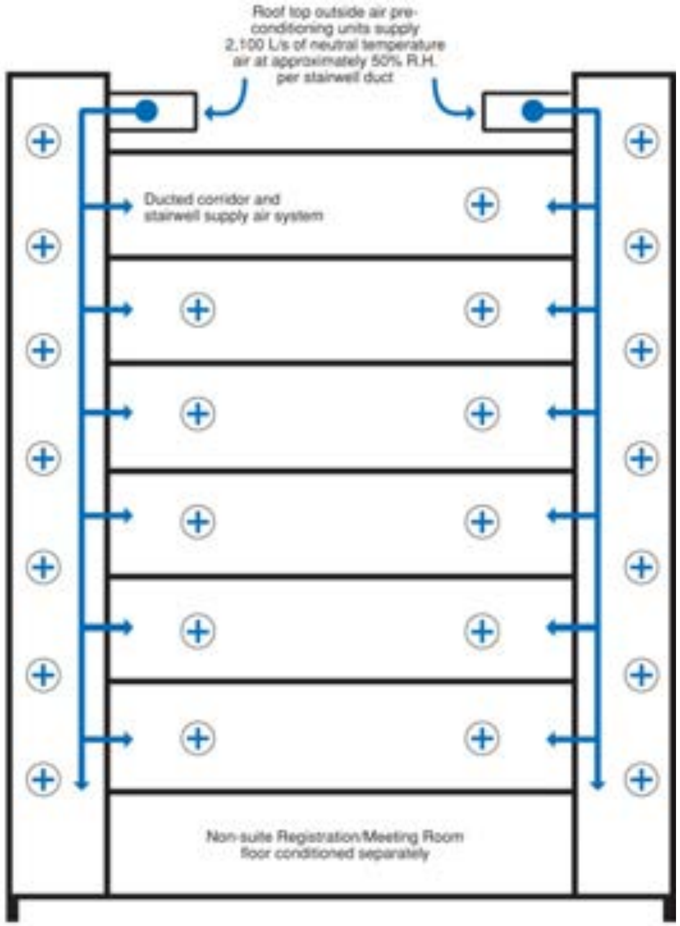


Figure 5.7
New Air Pressure Relationships

- Hotel suite floors supplied with 4,200 L/s of preconditioned air
- Hotel suite floors are exhausted to a total of 2,850 L/s
- Surplus of 1350 L/s pressurizes suite floors
- Stairwell held open with magnetic latches

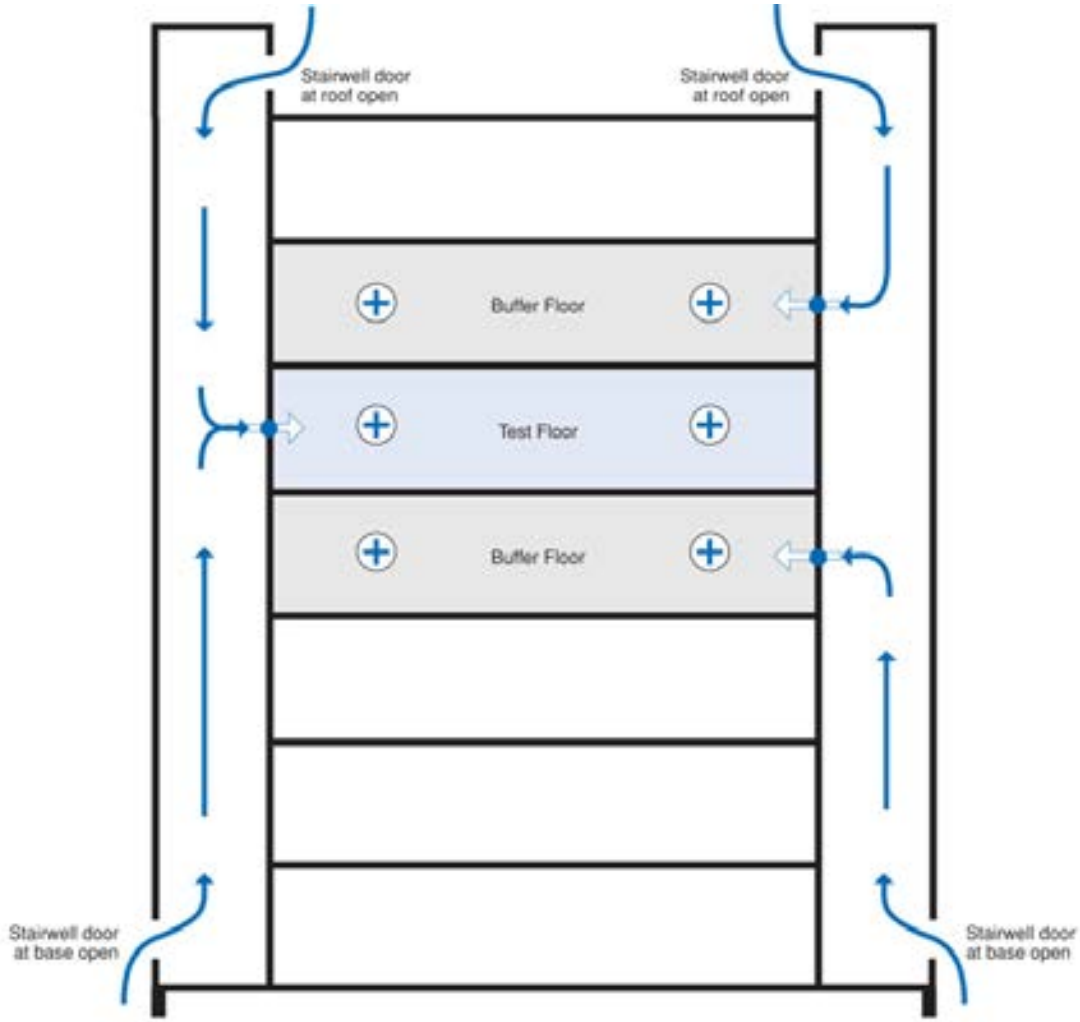


Figure 5.6
Air Leakage Test Zones

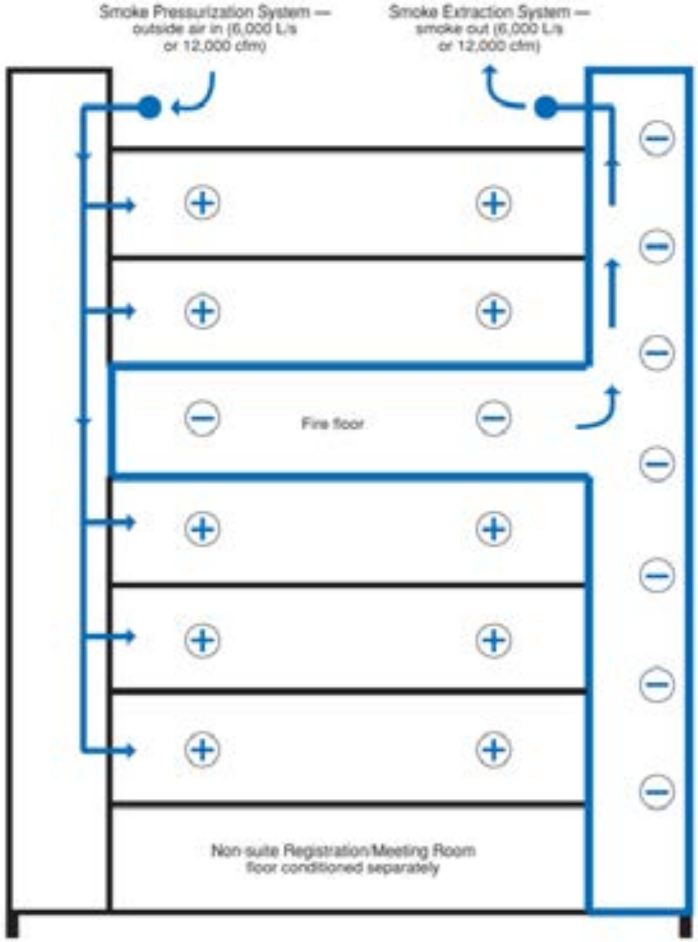


Figure 5.9

Smoke Extraction System

- If hotel is pressurized 25 Pa and smoke floor/floors are depressurized 25 Pa, net minimum smoke control pressure difference is greater than the design specified 25 Pa
- Approximately 1,000 L/s per floor is required to pressurized each floor 25 Pa relative to the exterior or approximately 6,000 L/s to pressurize the 6 hotel floors with suites when the roof top exhaust systems are not operating


EXIT

Figure 3.12

Ductwork and Air Handlers in Basements

- No air pressure differences result in a house with an air handler and ductwork located in a basement if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed

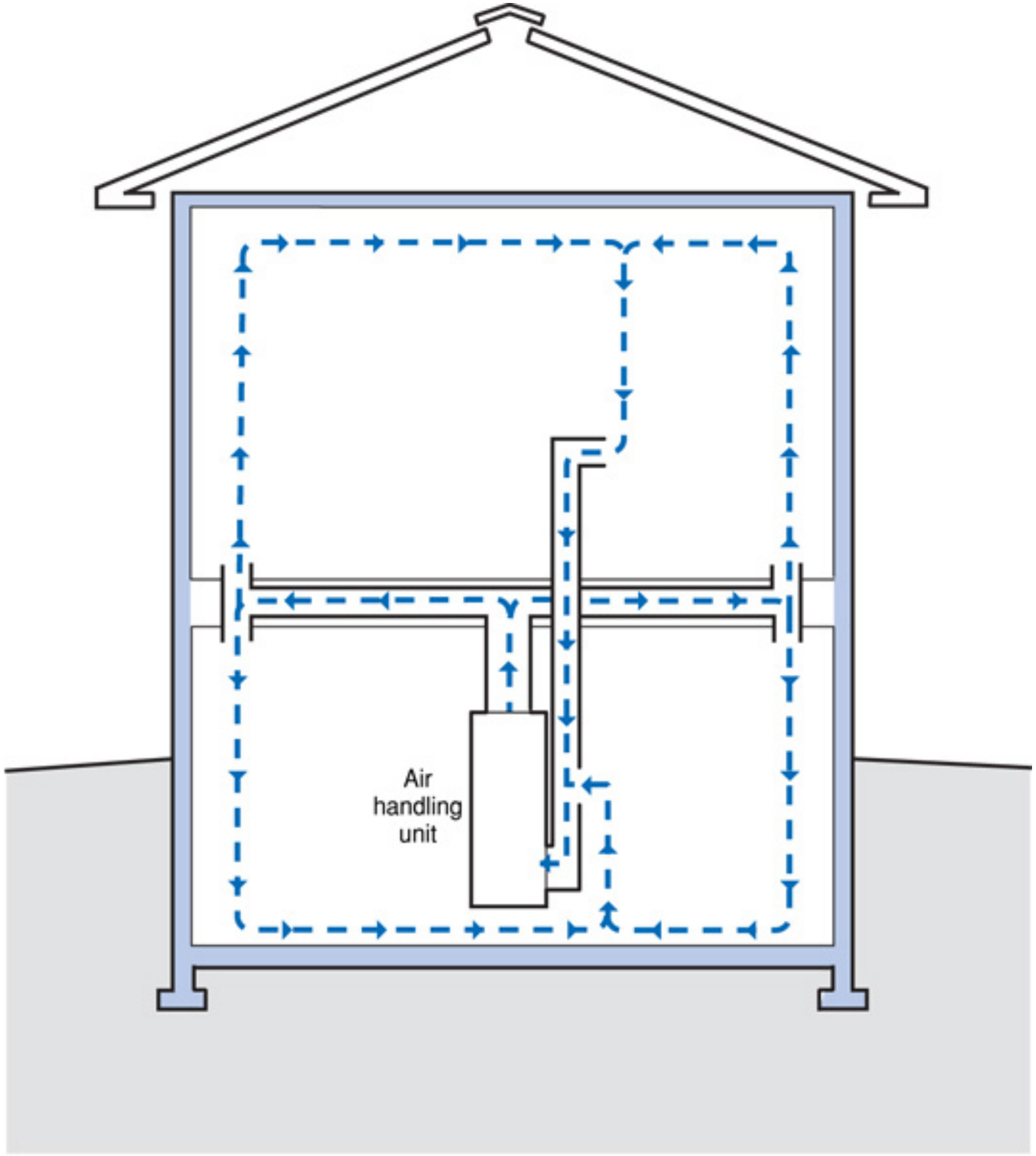
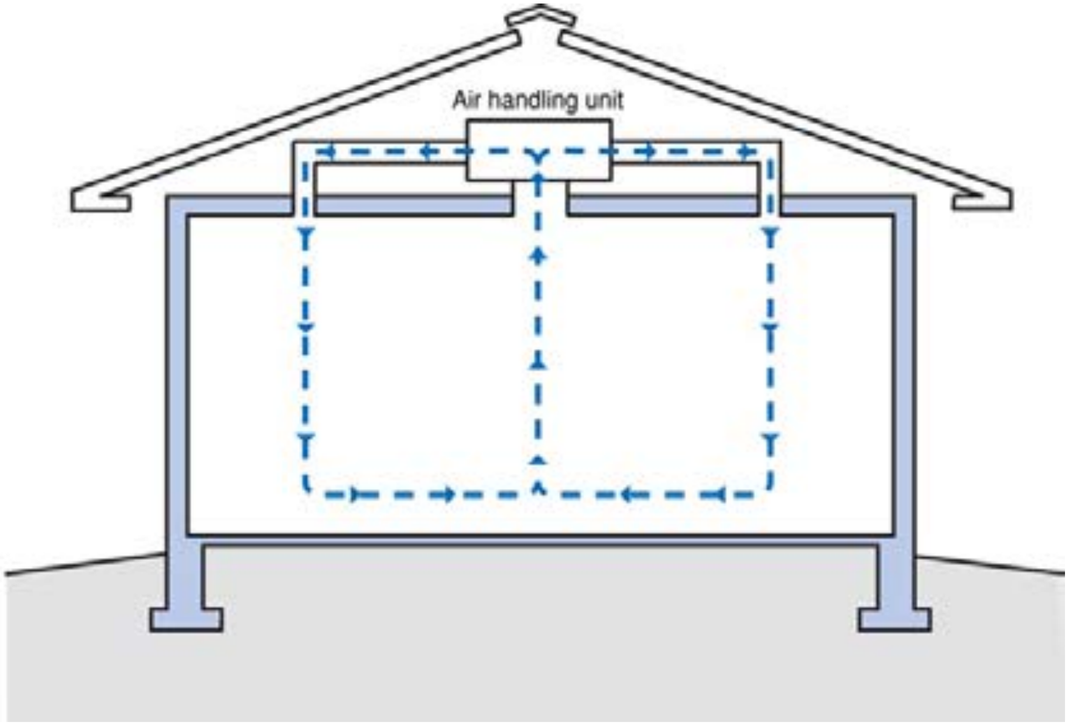


Figure 3.13

Ductwork and Air Handlers in Vented Attics

- No air pressure differences result in a house with an air handler and ductwork located in a vented attic if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed



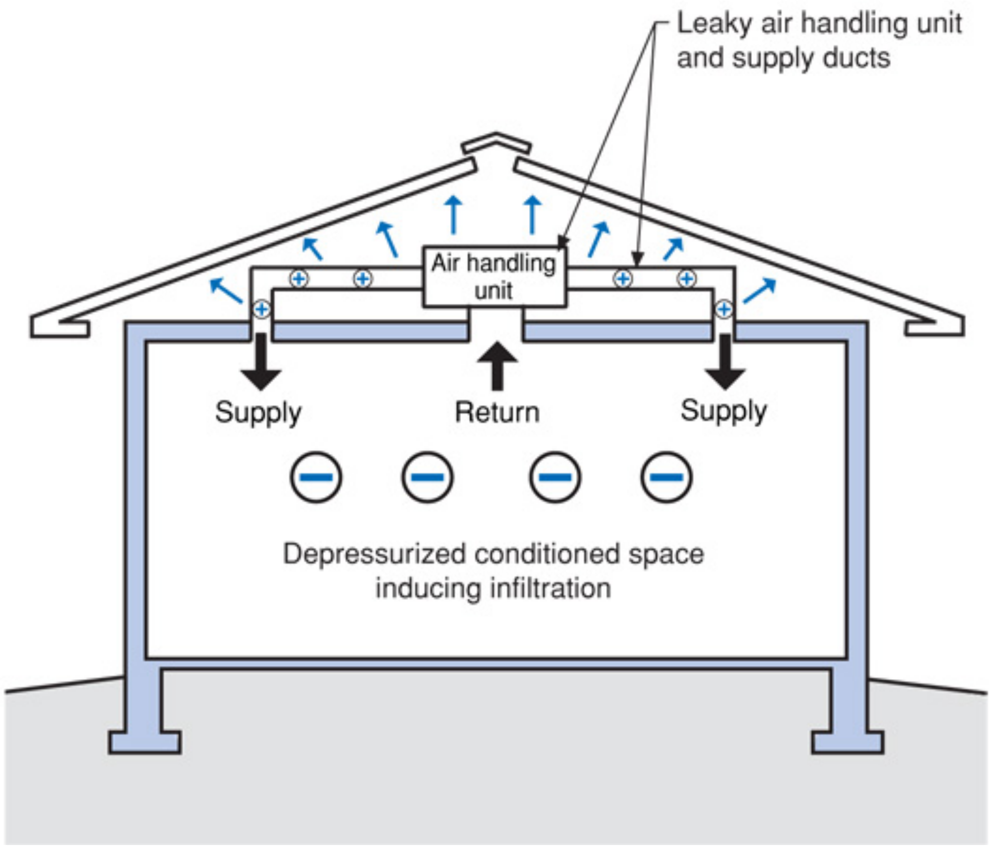


Figure 3.15

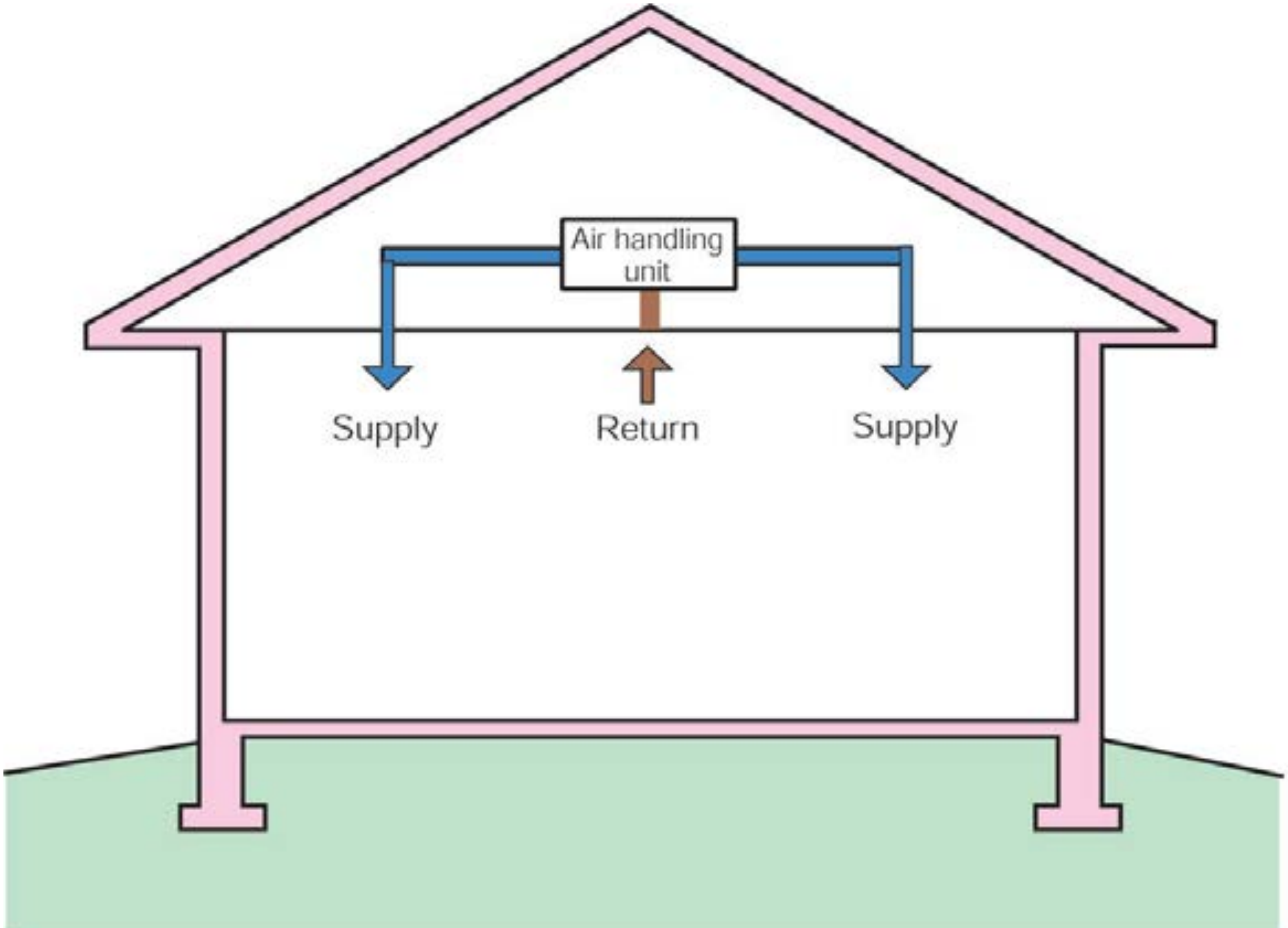
Leaky Ductwork and Air Handlers in Vented Attics

- Supply ductwork and air handler leakage is typically 20% or more of the flow through the system

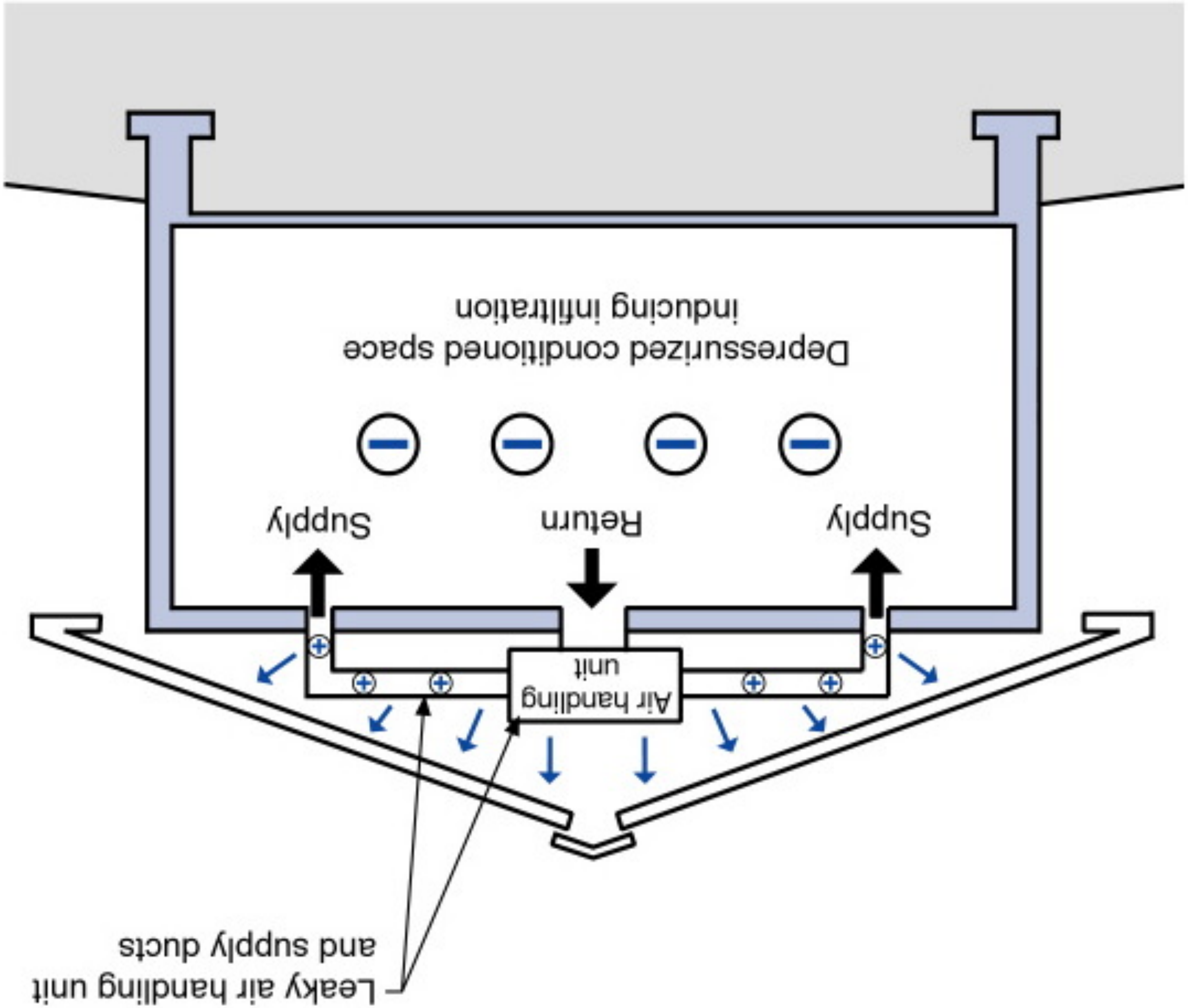

15


021

Duct Leakage Should Be Less Than 5% of Rated Flow As Tested By Pressurization To 25 Pascals



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

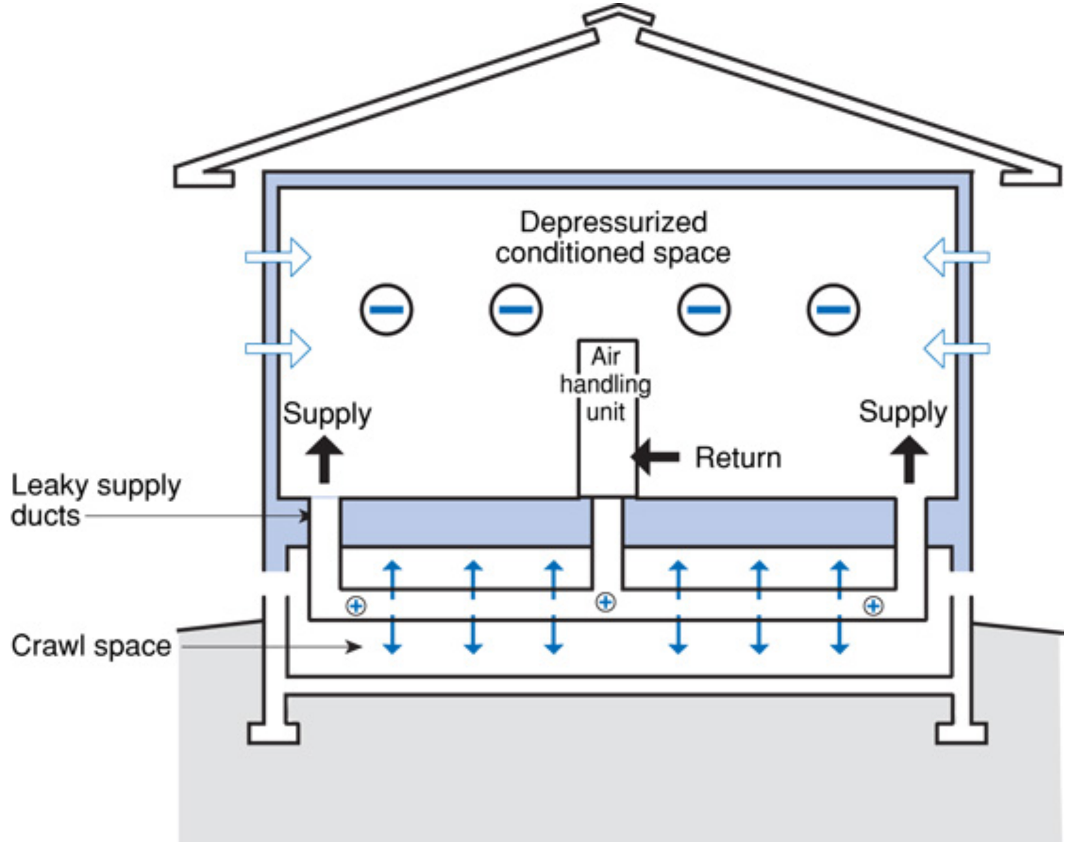


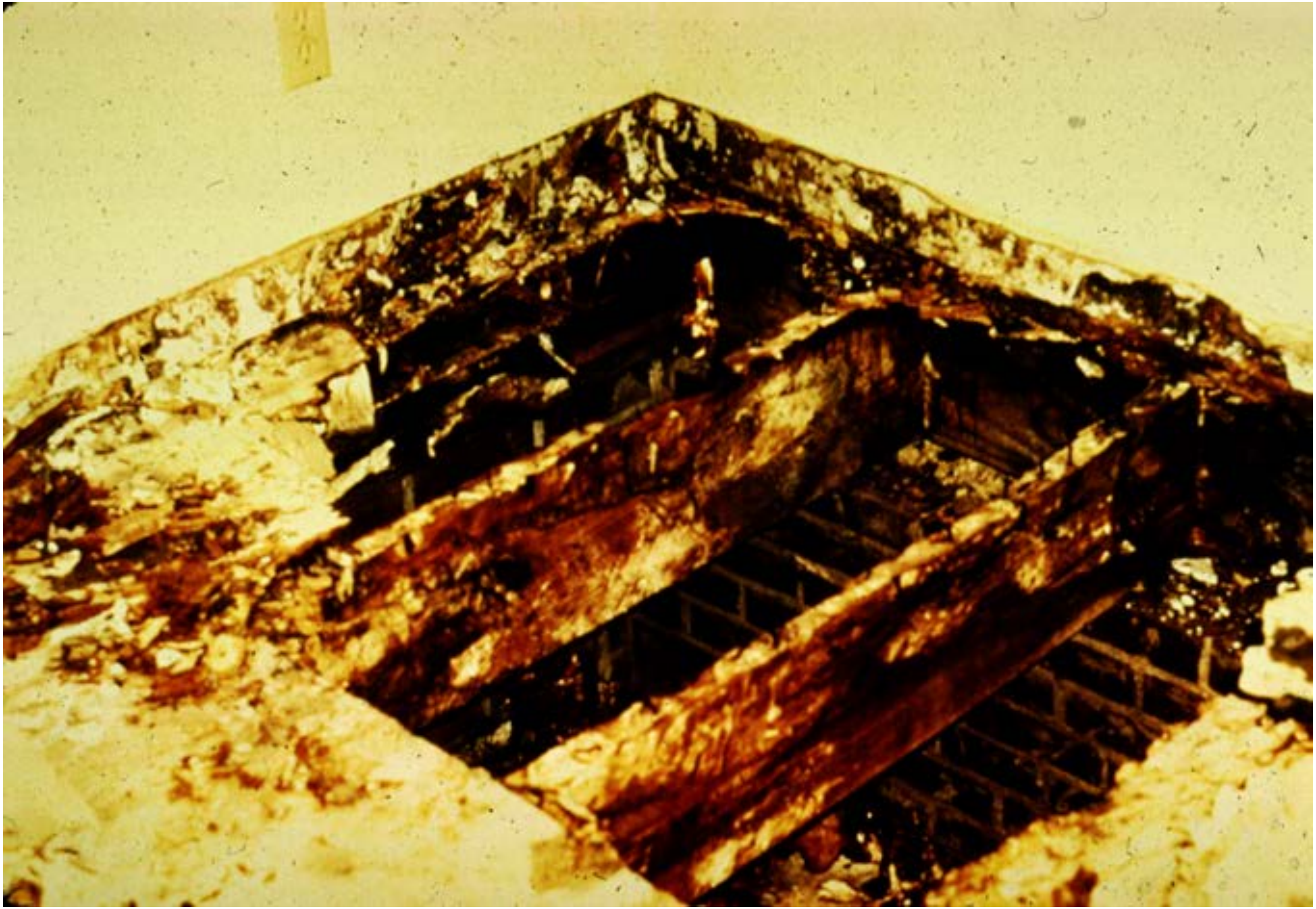
Depressurized conditioned space
inducing infiltration
Supply
Return
Supply
Air handling
unit
Leaky air handling unit
and supply ducts

Figure 3.16

Leaky Supply Ductwork in Vented Crawl Space

- Air pressurization pattern with mechanical system ducts in the crawl space





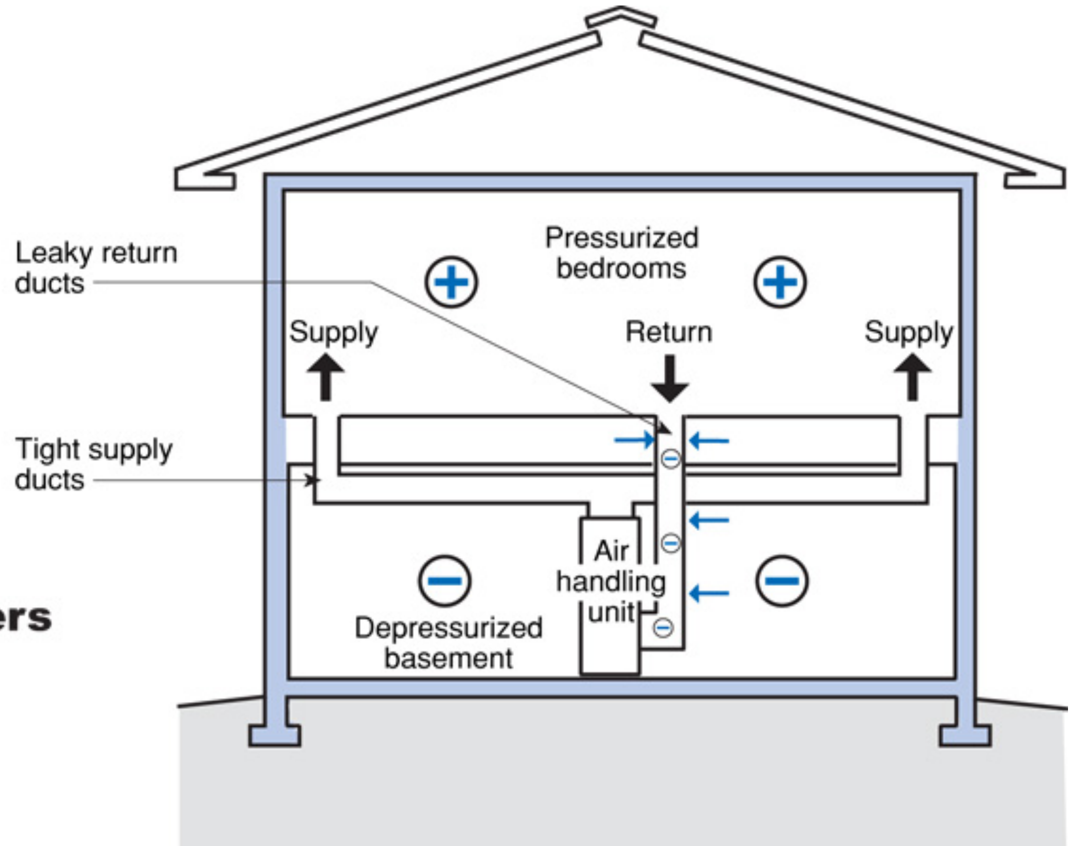


Figure 3.14

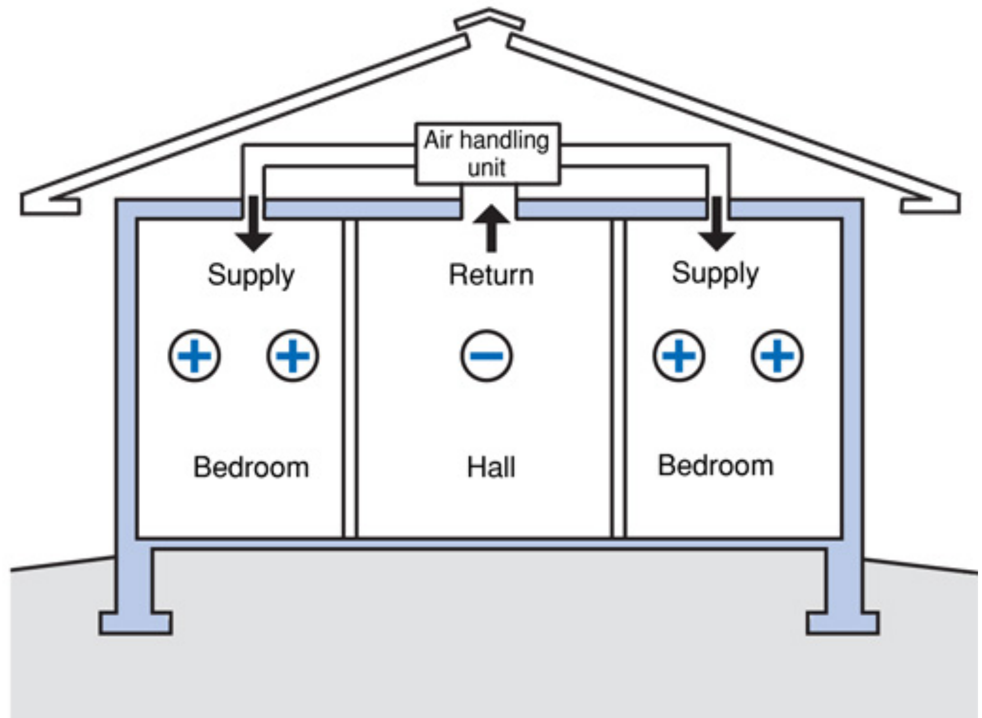
Leaky Ductwork and Air Handlers in Basements

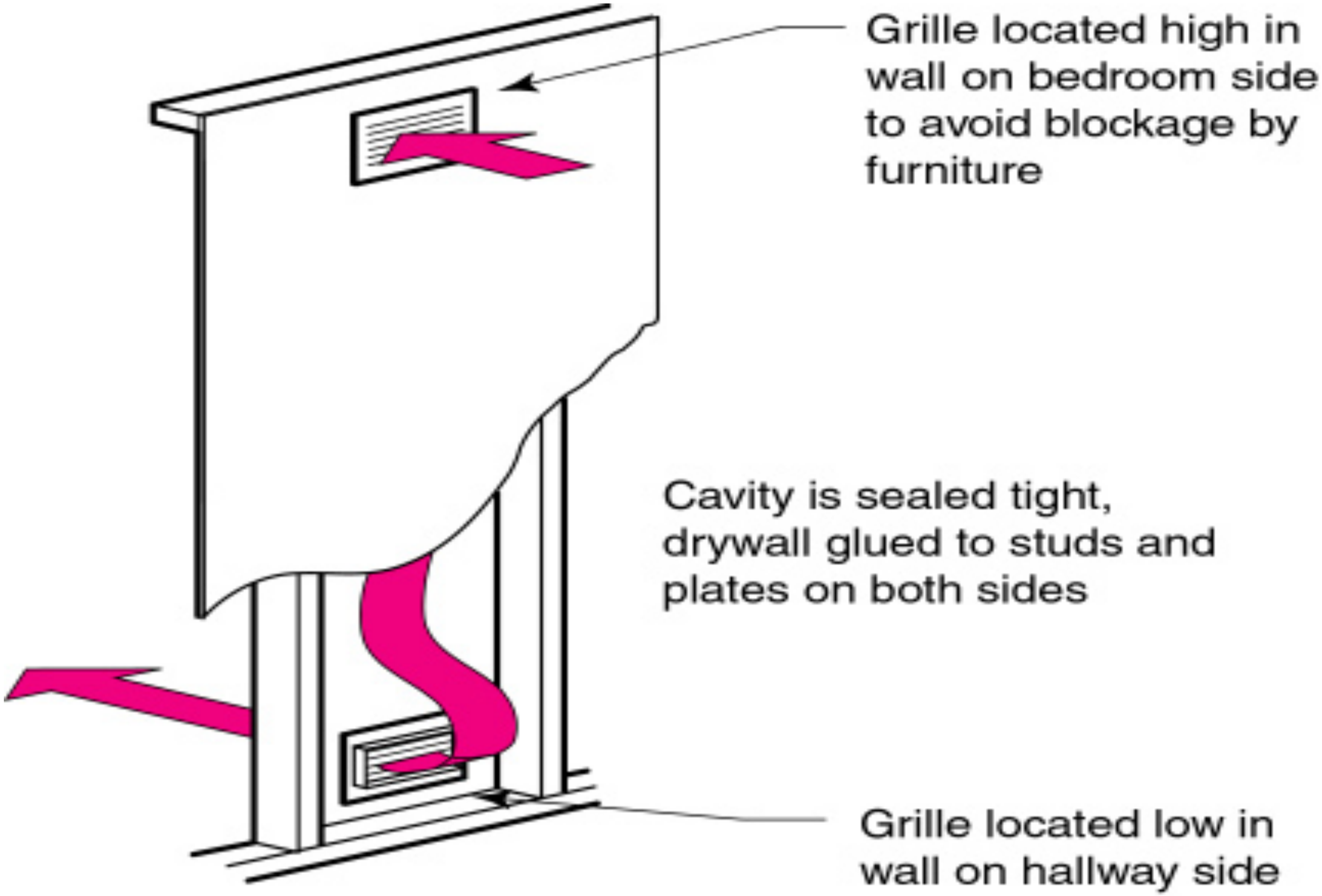
- Air pressurization patterns in a house with leaky ductwork in the basement

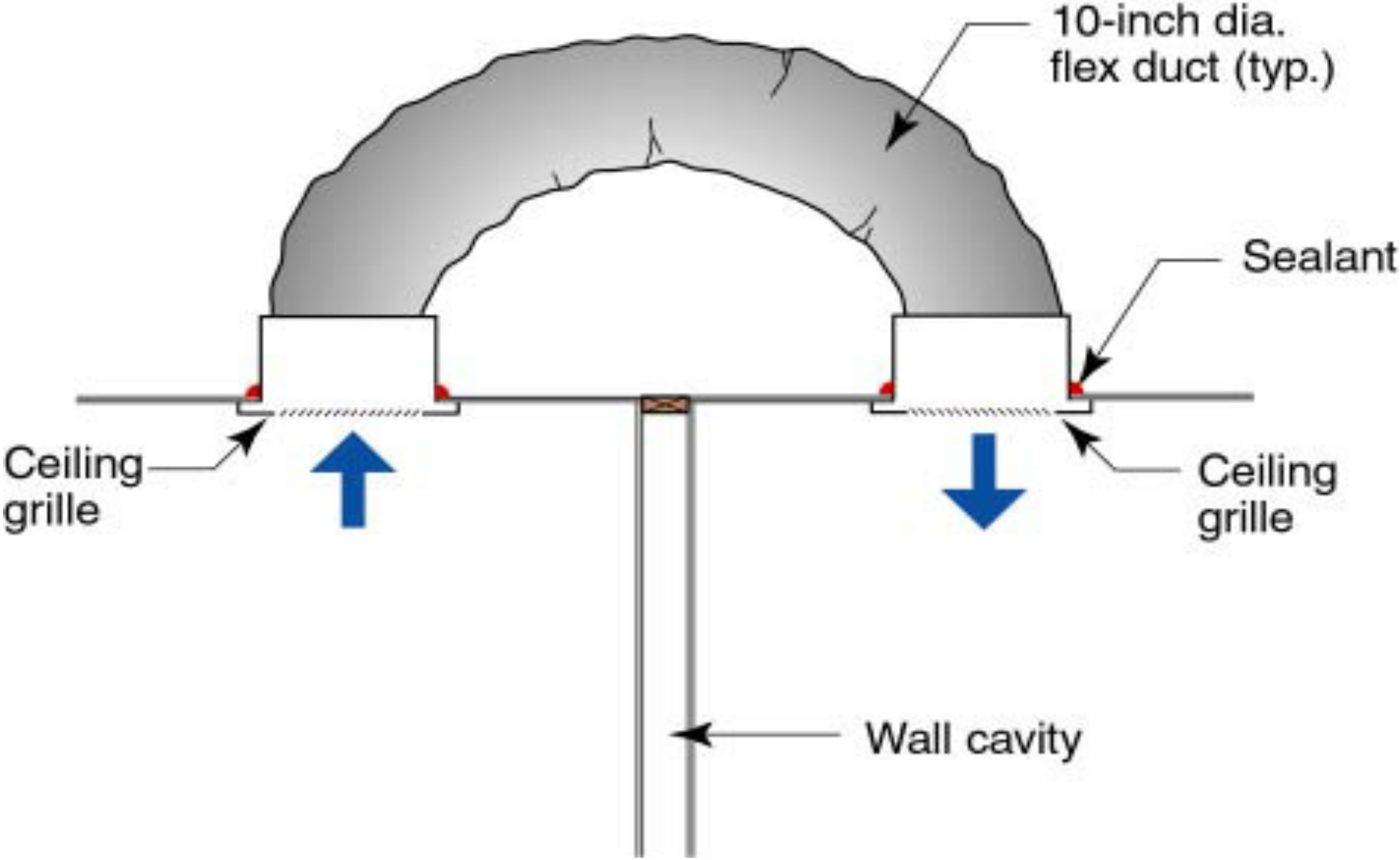
Figure 3.18

Insufficient Return Air Paths

- Pressurization of bedrooms often occurs if insufficient return pathways are provided; undercutting bedroom doors is usually insufficient; transfer grilles, jump ducts or fully ducted returns may be necessary to prevent pressurization of bedrooms
- Master bedroom suites are often the most pressurized as they typically receive the most supply air
- When bedrooms pressurized, common areas depressurize; this can have serious consequences when fireplaces are located in common areas and subsequently backdraft




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


2002 02 01

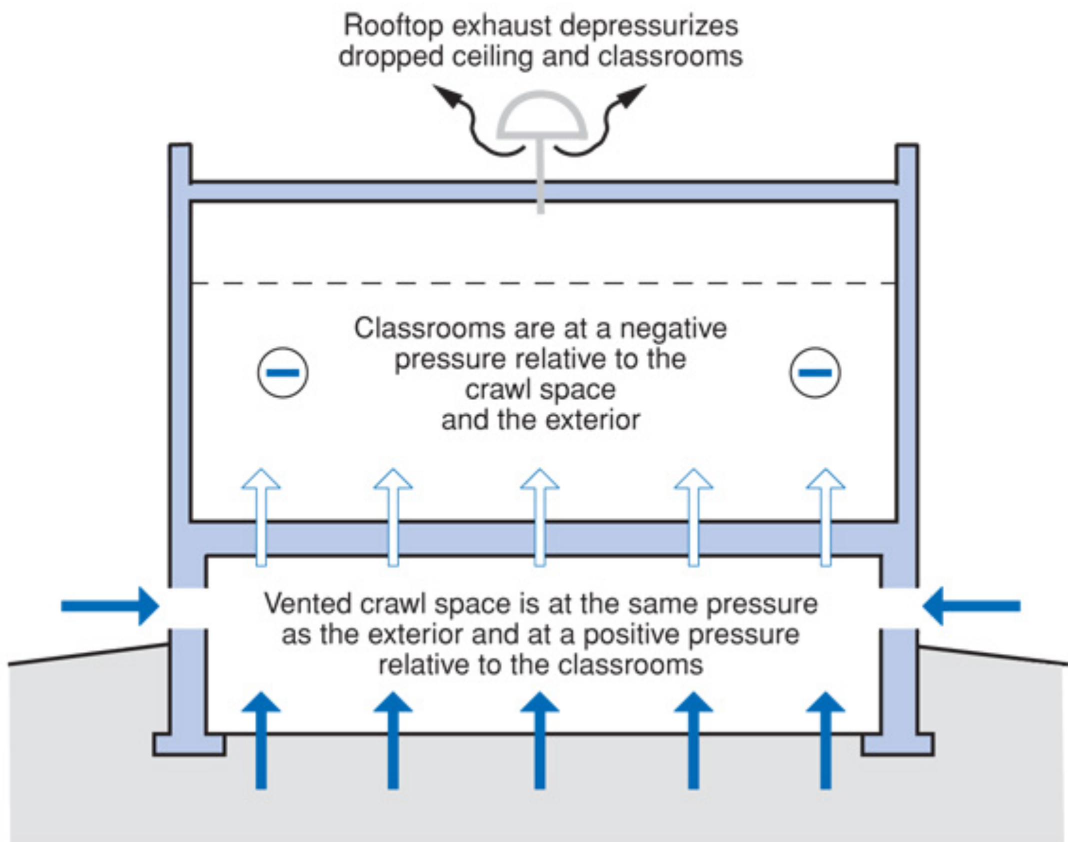


Figure 5.1

Problem Pressure Relationship

- The classrooms in this school operate at a negative pressure with respect to the crawl space

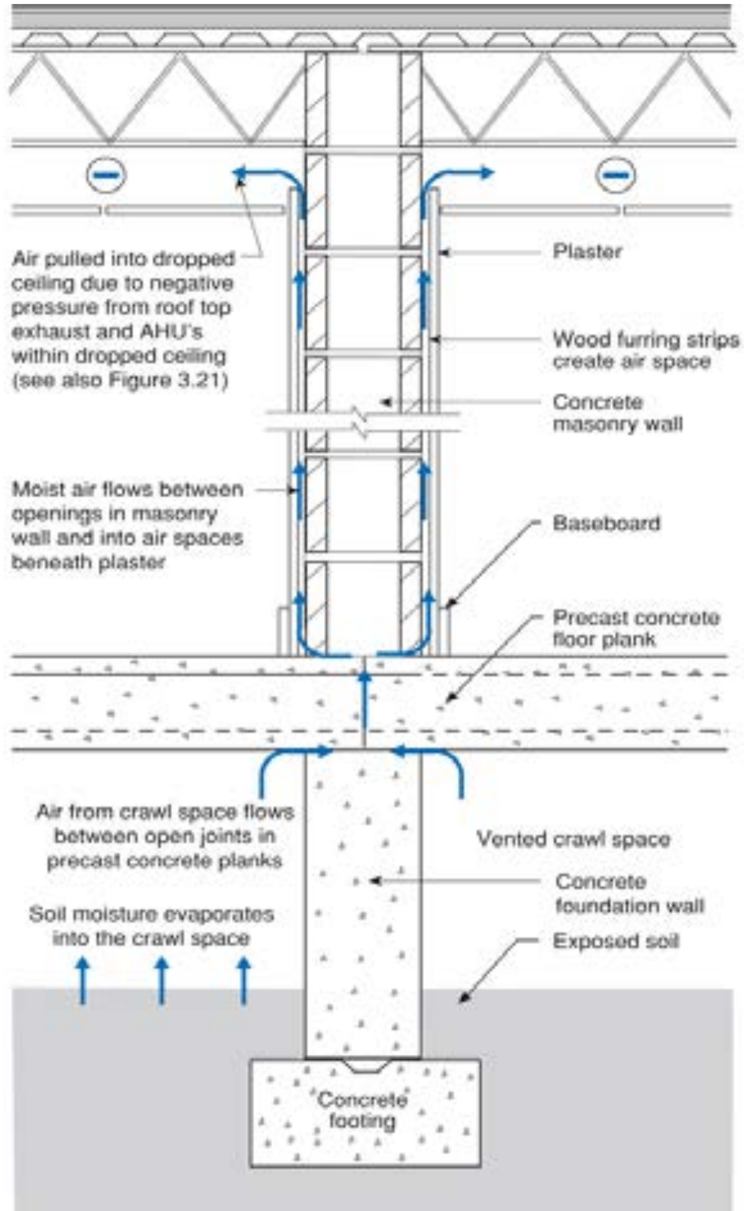


Figure 5.2

Moisture Movement

- This wall section illustrates moisture movement from the crawl space into the wall cavities and dropped ceiling

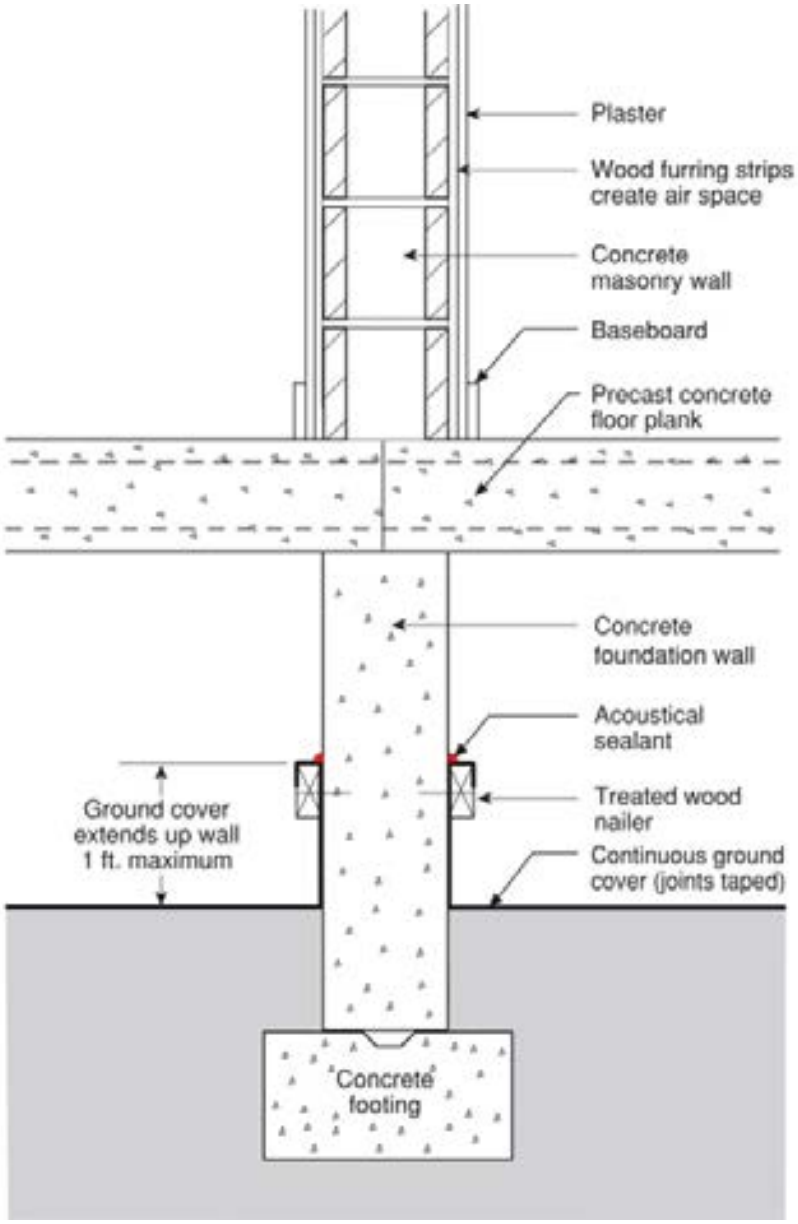
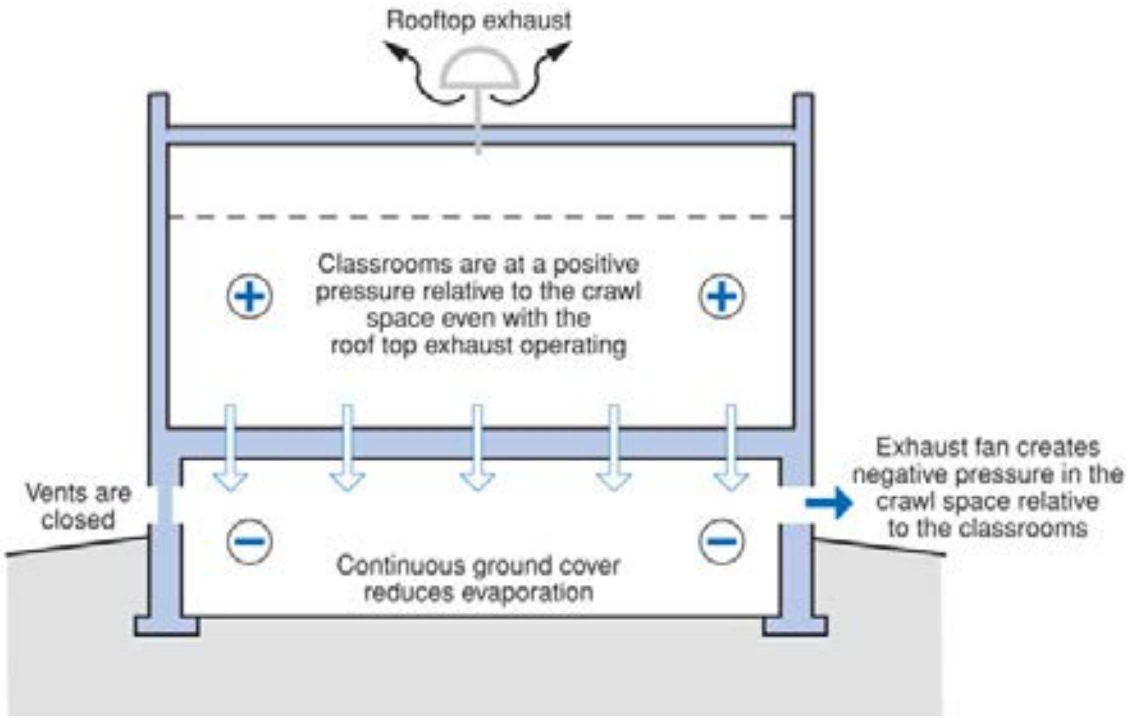


Figure 5.3

Ground Cover Installation

- This wall section illustrates proper installation of the polyethylene ground cover

Figure 5.4
New Air Pressure Relationship
- Closing the crawl space vents and using an exhaust fan in the crawl space depressurizes the crawl space relative to the classrooms



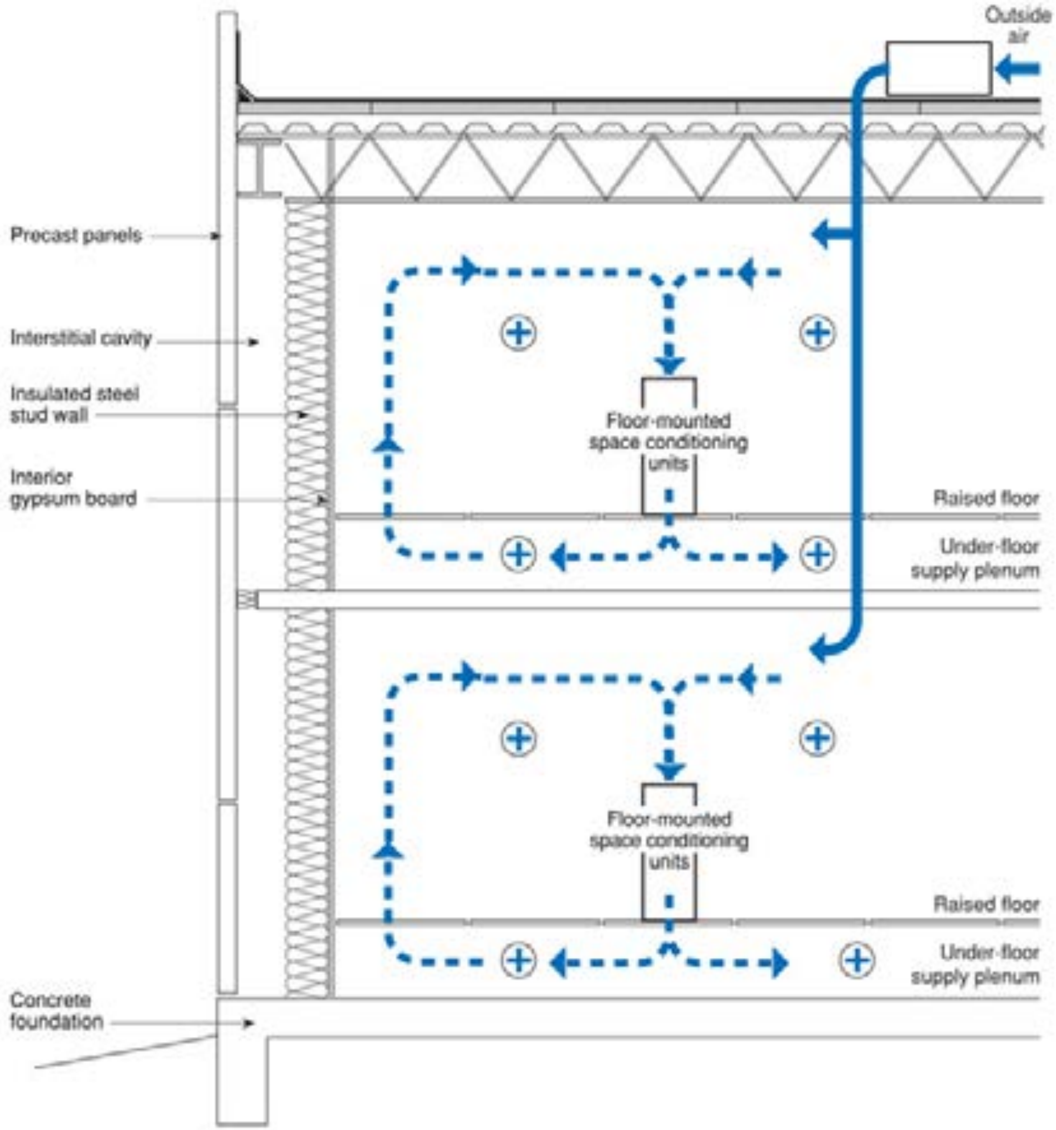


Figure 5.10
HVAC System as Designed

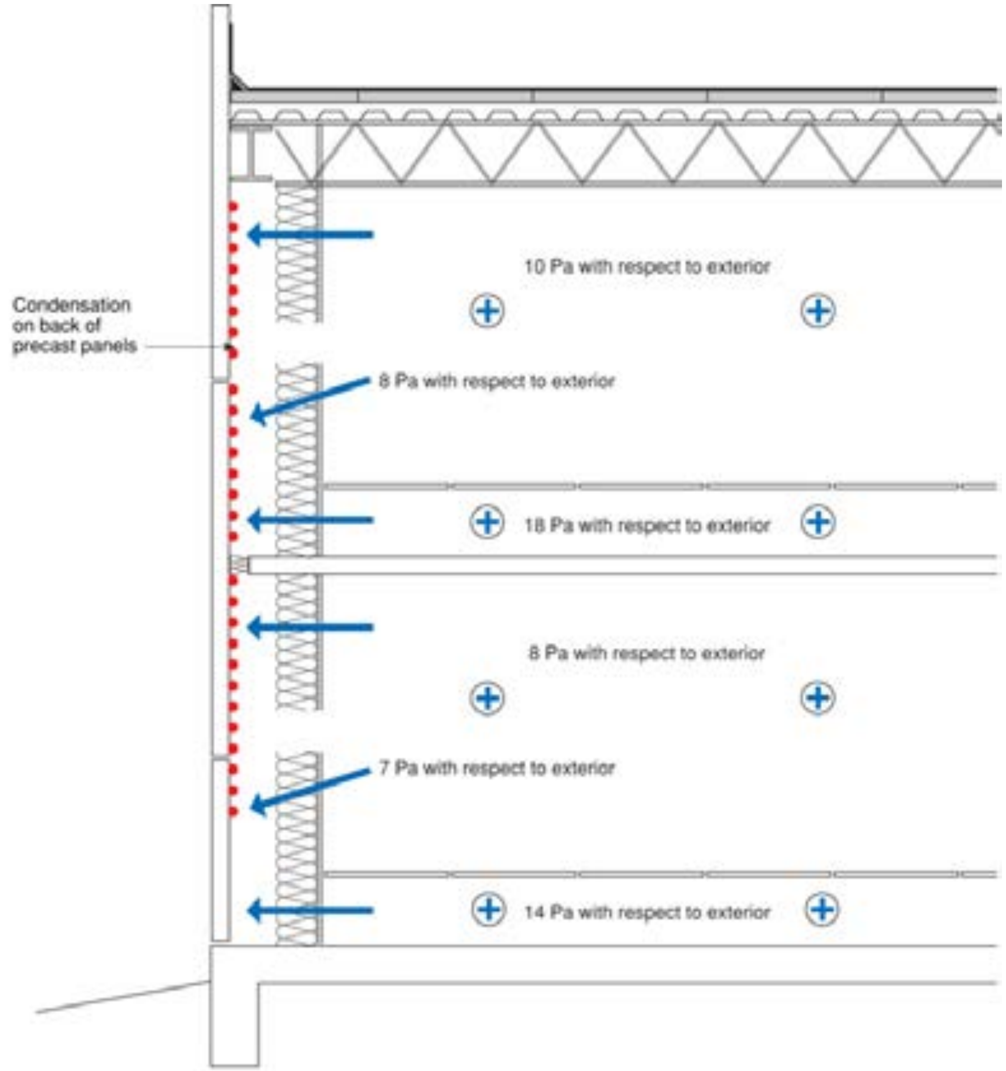


Figure 5.11
Unintended Pressurization of Interstitial Cavity

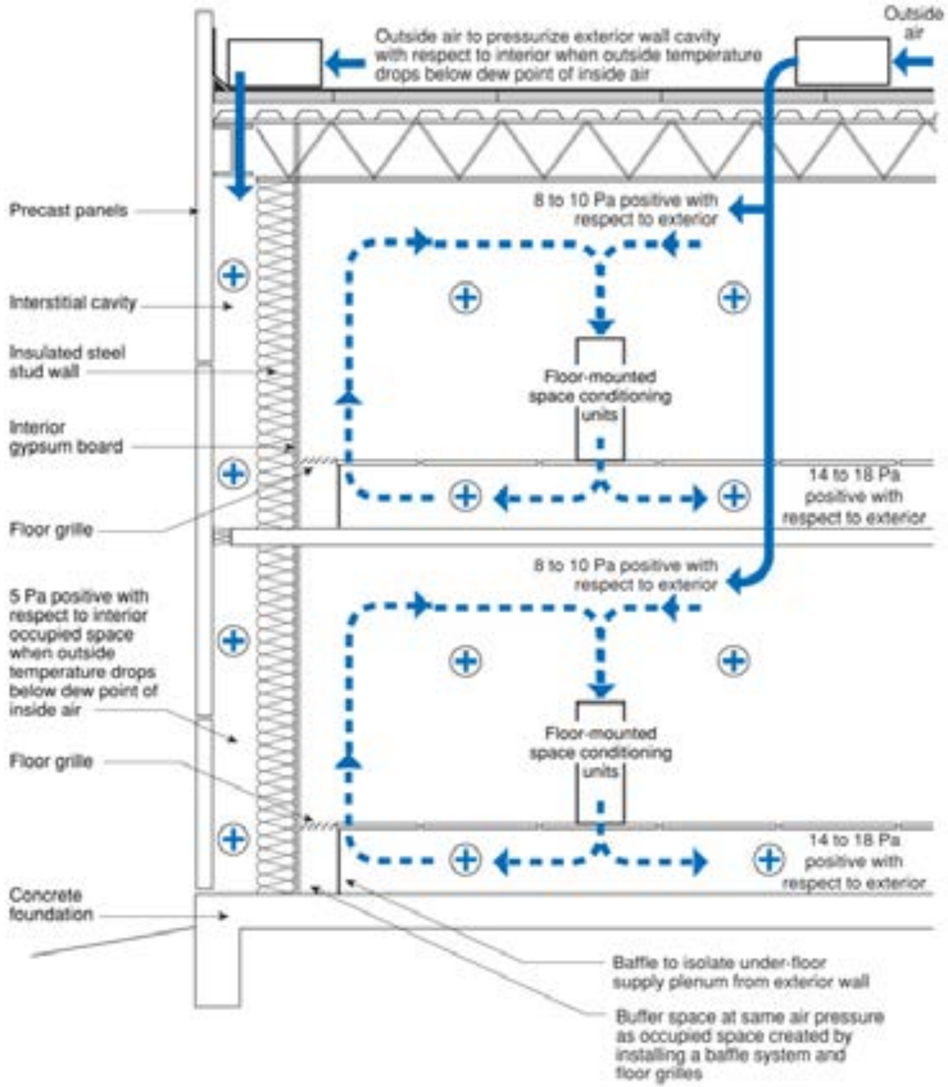
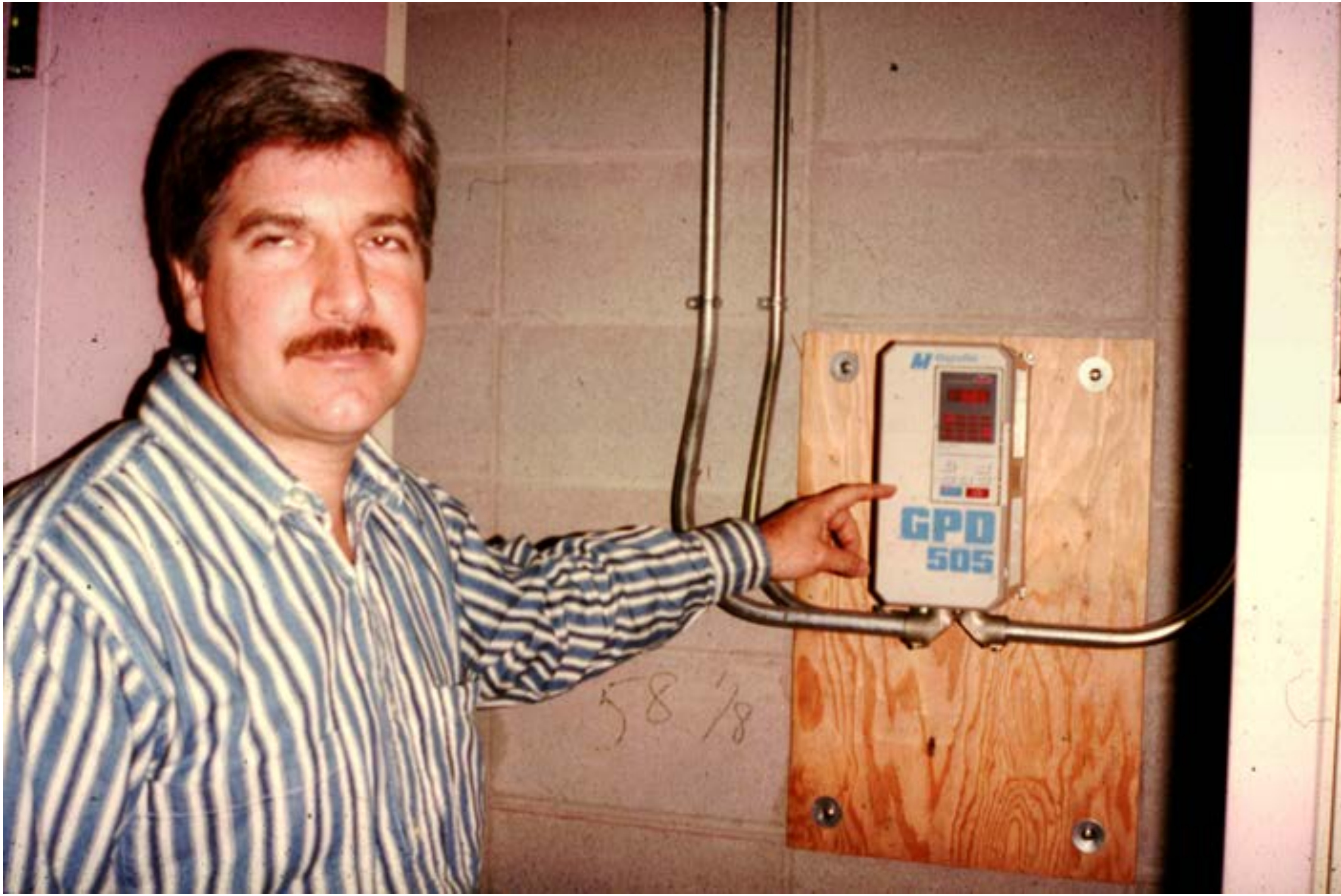
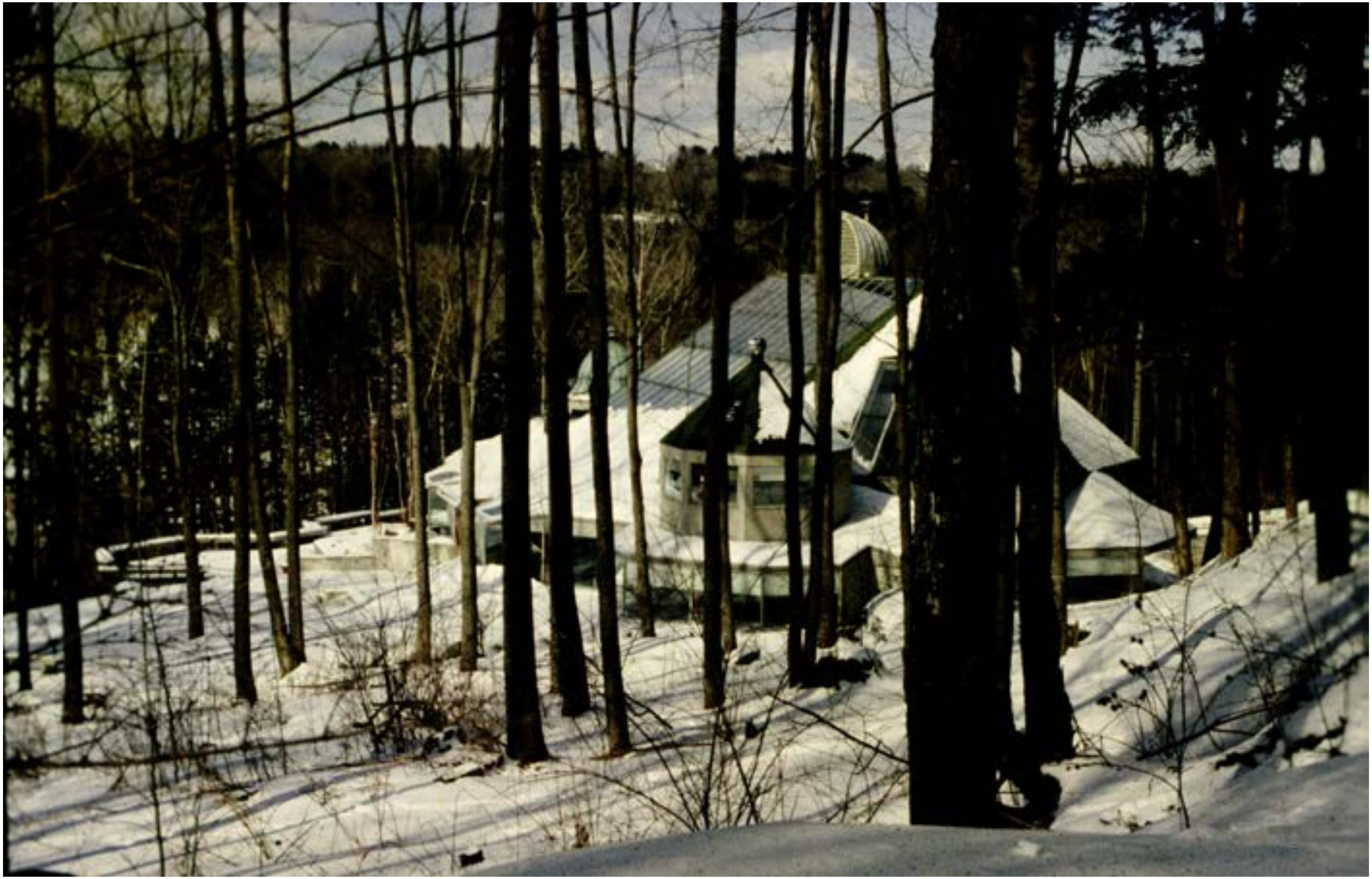
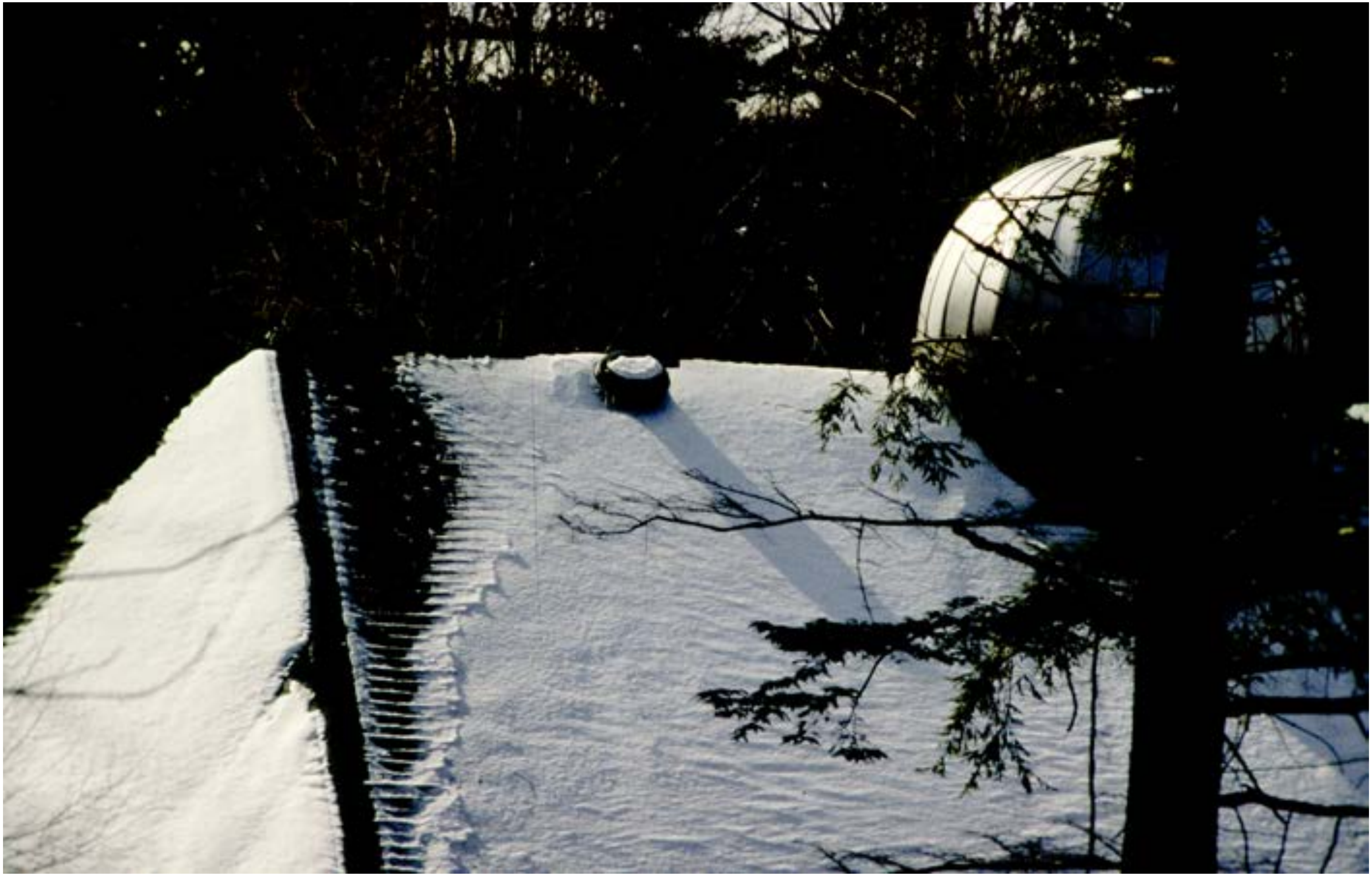


Figure 5.12
Modified Pressure Relationship


GPD
505
58 1/8


CABINET 32
CDP PRESSURIZATION FANS

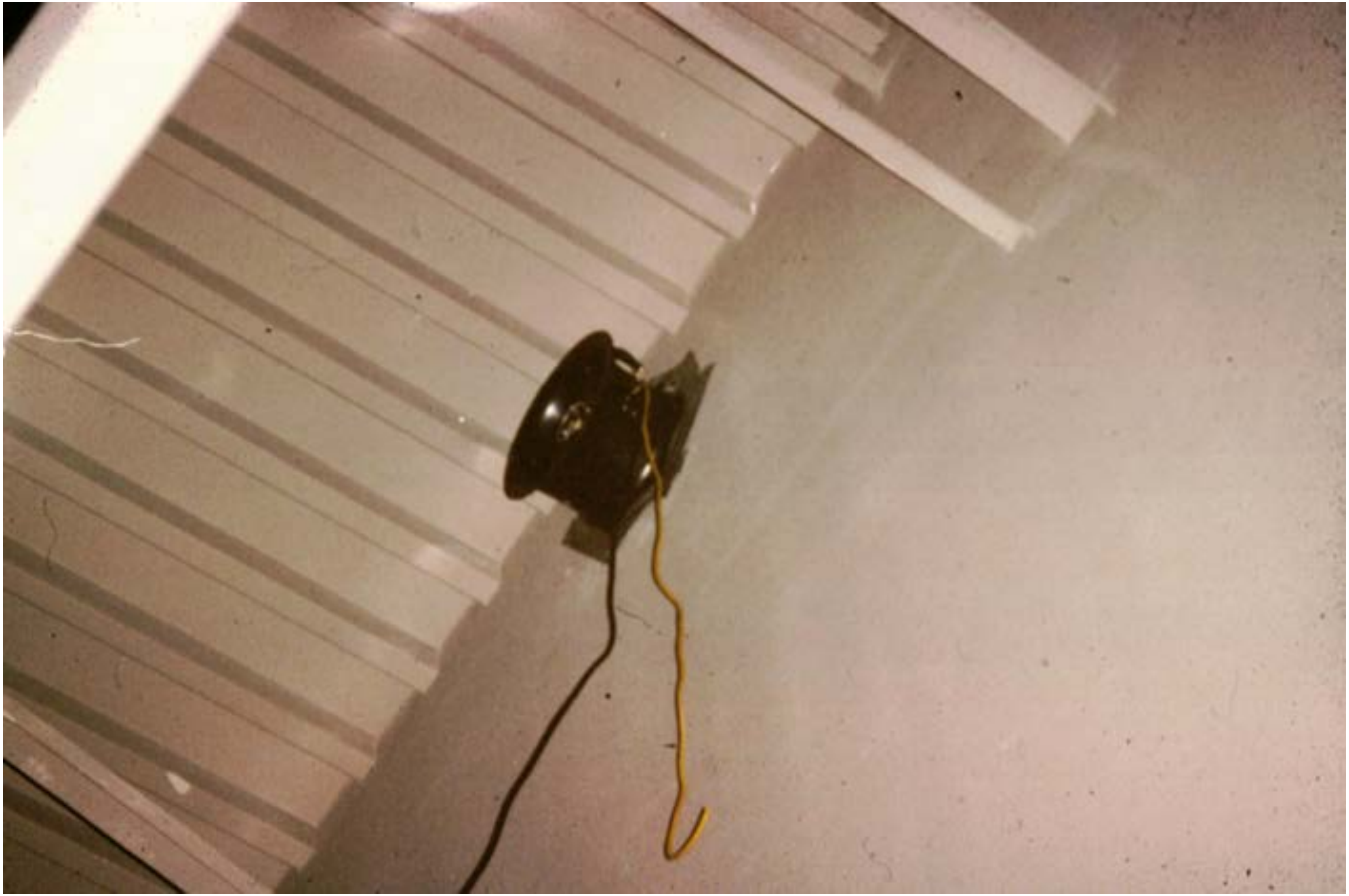





GEORGIA MUSEUM of A


GEORGIA MUS


LABELWAGON 2000 XL



P_o = outside air pressure

P_I = inside air pressure

P_c = cavity air pressure

A_E = leakage area across exterior of wall assembly

A_I = leakage area across interior of wall assembly

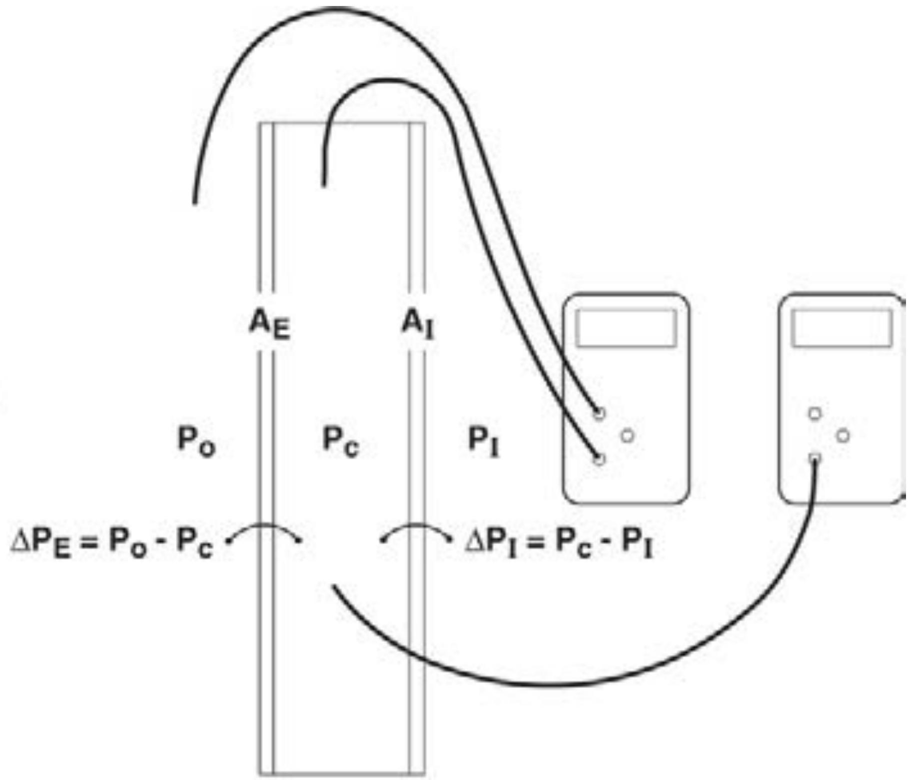


Figure 4.5

Measurement of Series Differential Pressure

$$Q = C_E A_E \Delta P_E{}^n = C_I A_I \Delta P_I{}^n$$

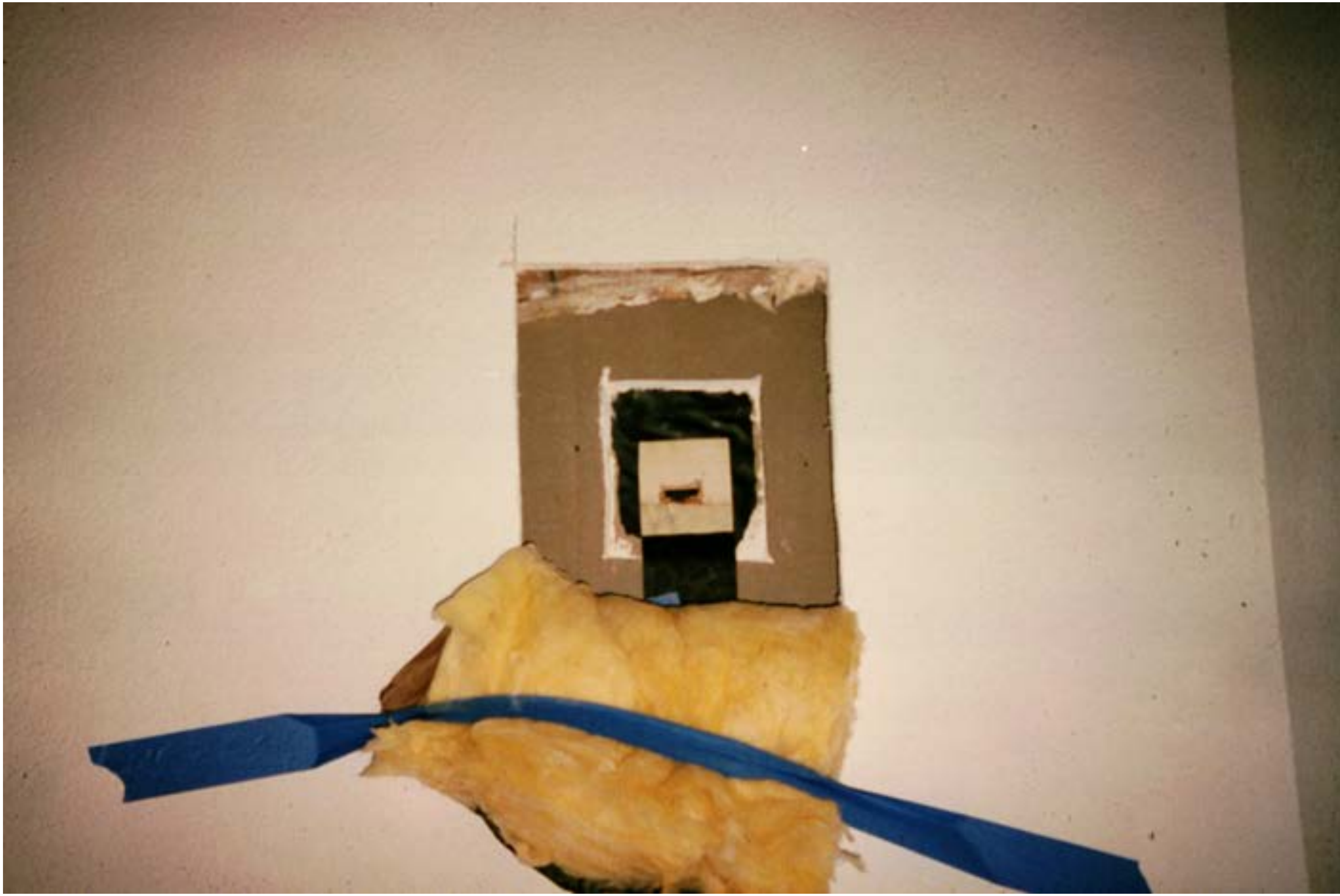
$$\frac{C_E A_E}{C_I A_I} = \frac{\Delta P_I{}^n}{\Delta P_E{}^n}$$

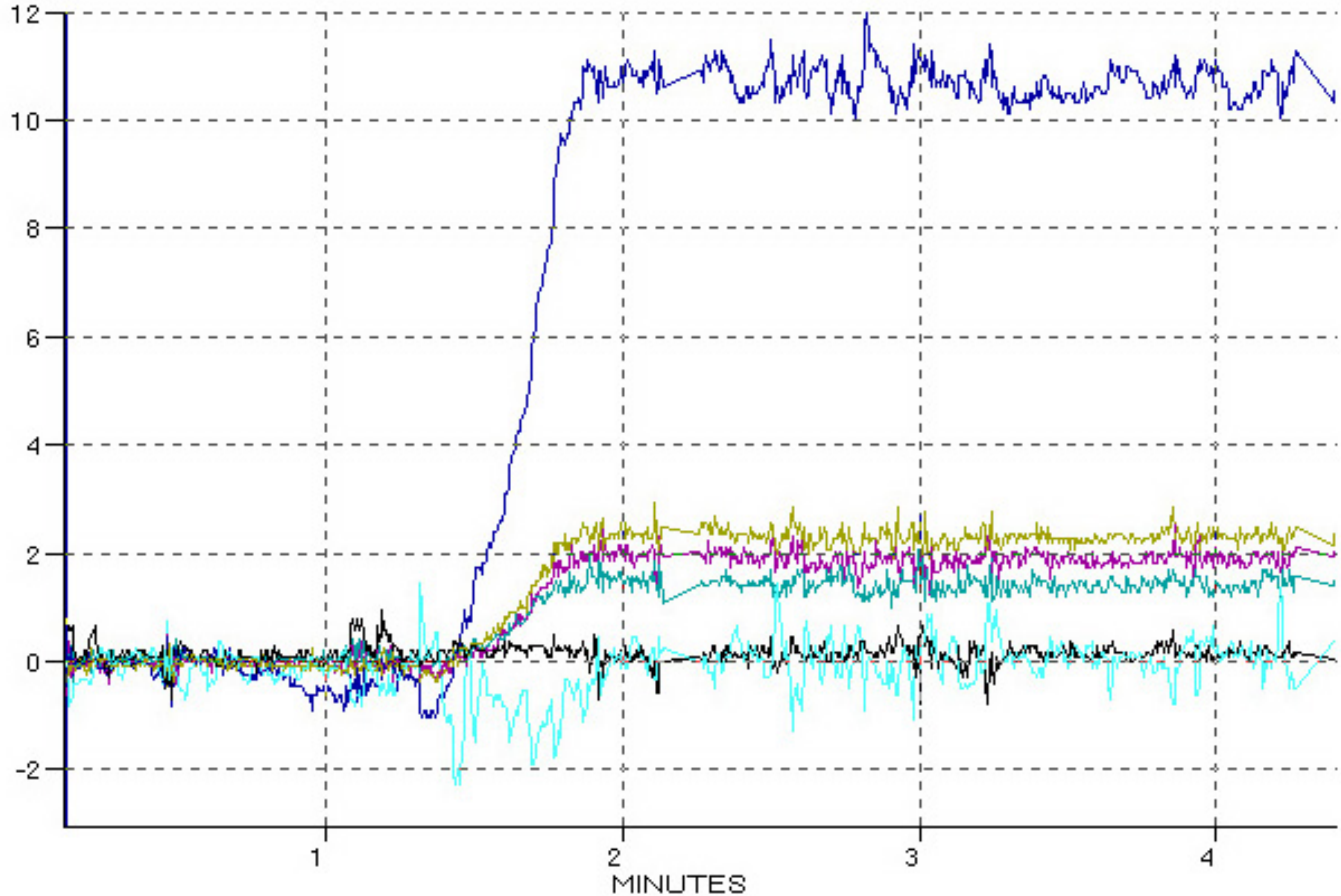
$$\cong \frac{A_E}{A_I} = \left(\frac{\Delta P_I}{\Delta P_E}\right)^n$$

$$\cong \left(\frac{A_E}{A_I}\right)^{\frac{1}{n}} = \frac{\Delta P_I}{\Delta P_E}$$

from Hutcheon & Handegord, 1983


D
C




12
10
8
6
4
2
0
-2
1
2
3
4
MINUTES

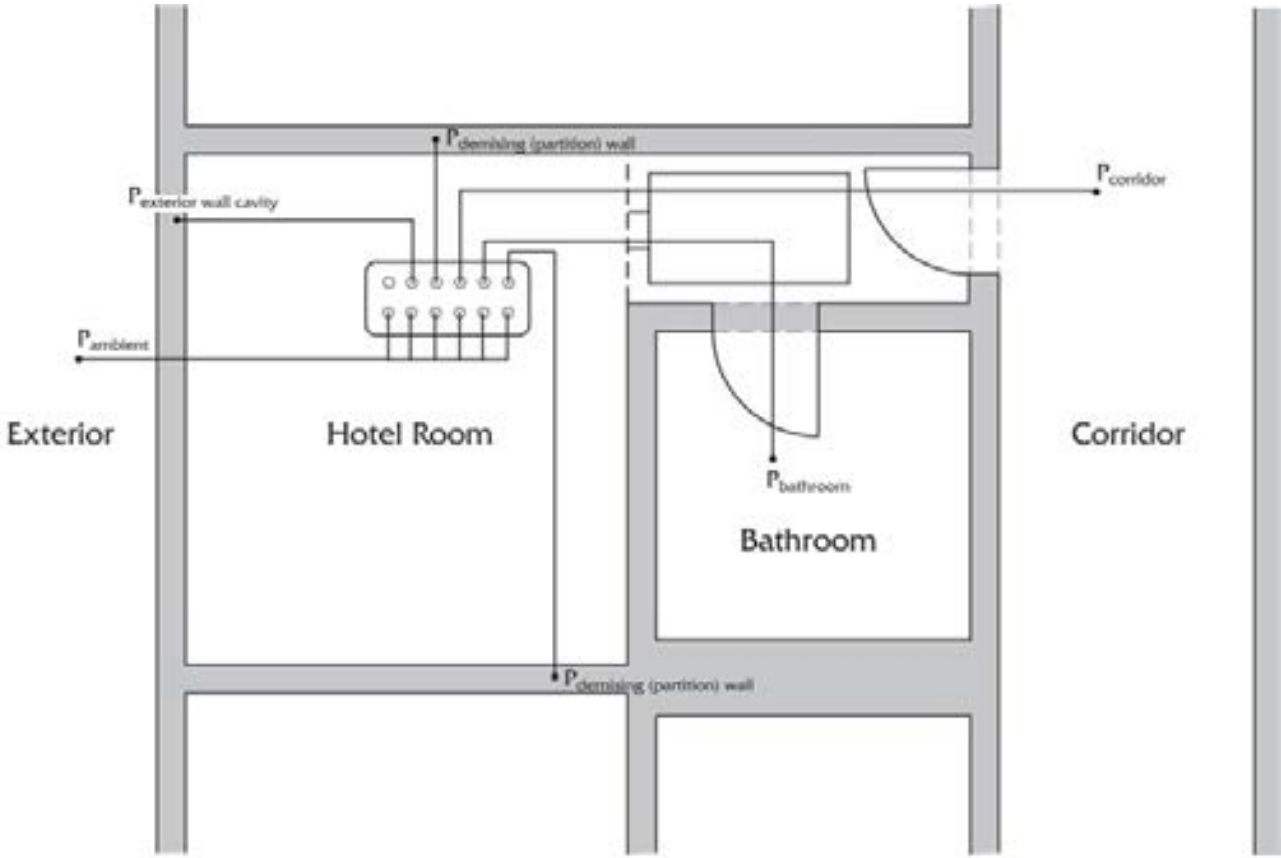
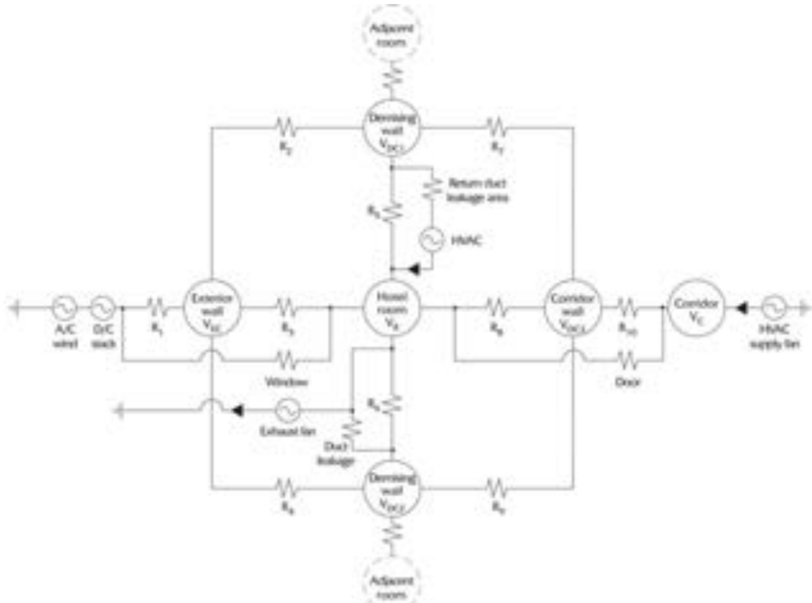


Figure 4.3

Multi-Channel Pressure Measurements

- Six channel micromanometer connected to laptop computer used to map pressure in the hotel room described in Figure 3.6
- All pressures measured relative to exterior air pressure
- Pressure response determined by opening and closing doors, cycling fan-coil, rooftop exhaust and corridor make-up air systems



R_1 = Leakage area between ambient and exterior wall cavity
R_2 = Leakage area between exterior wall cavity and demising (partition) wall cavity
R_3 = Leakage area between exterior wall cavity and hotel room
R_4 = Leakage area between exterior wall cavity and demising (partition) wall cavity
R_5 = Leakage area between demising (partition) wall cavity and hotel room
R_6 = Leakage area between demising (partition) wall cavity and hotel room
R_7 = Leakage area between demising (partition) wall cavity and corridor demising wall cavity
R_8 = Leakage area between hotel room and corridor demising wall cavity
R_9 = Leakage area between demising (partition) wall cavity and corridor demising wall cavity
R_{10} = Leakage area between corridor demising wall cavity and corridor
V_{EC} = Pressure in exterior wall
V_R = Pressure in hotel room
V_C = Pressure in corridor
V_{DC1} = Pressure in demising (partition) wall cavity
V_{DC2} = Pressure in demising (partition) wall cavity
V_{DC3} = Pressure in corridor demising wall cavity

Figure 3.25
Electrical Analogue of Hotel Room

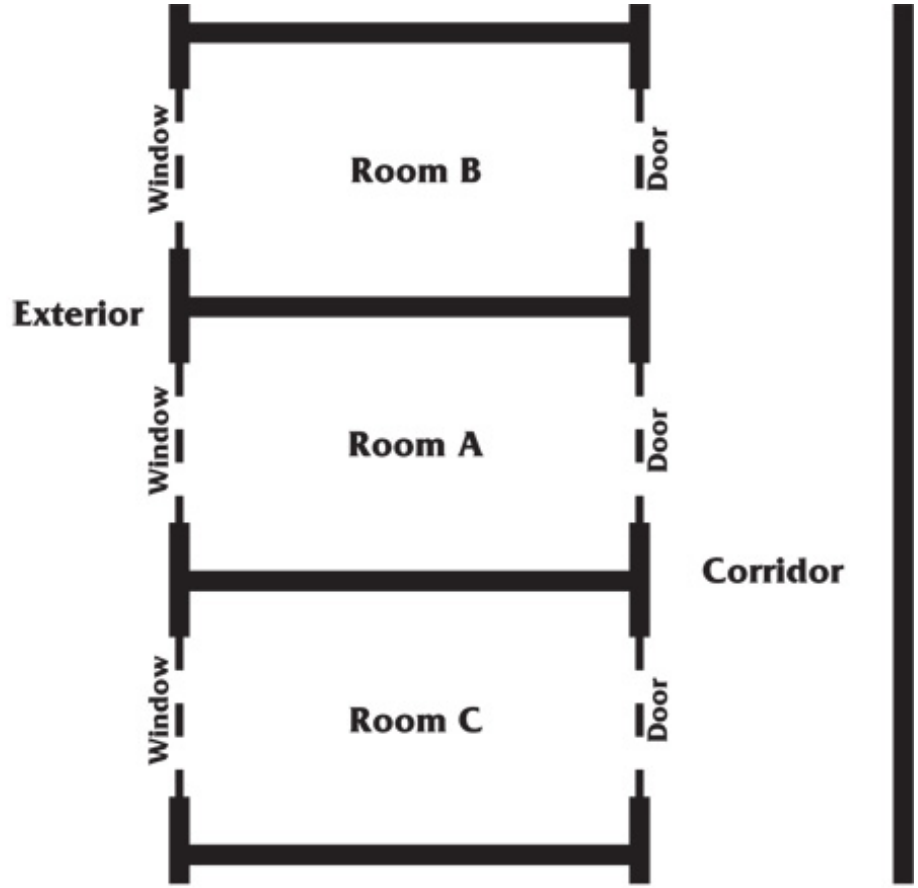
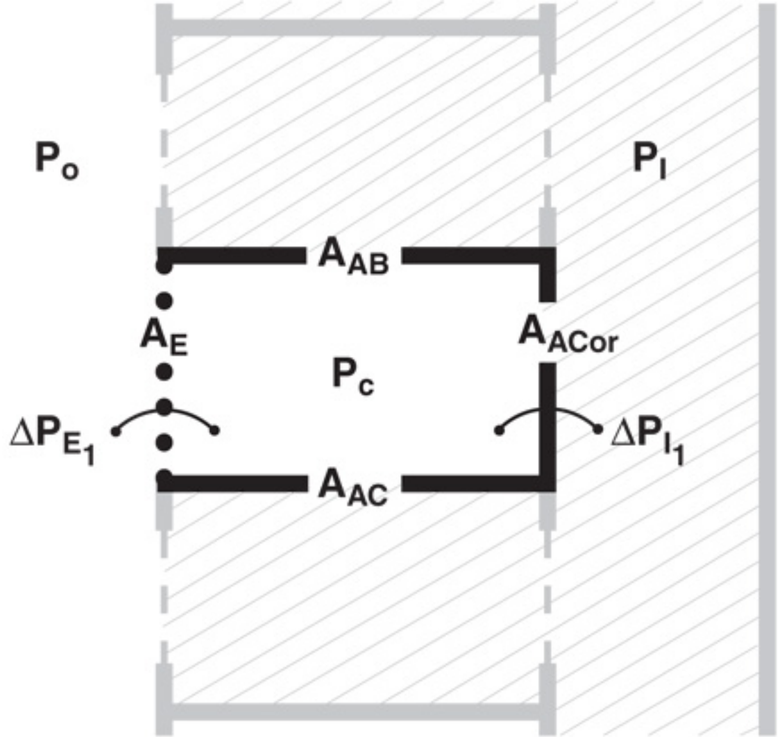


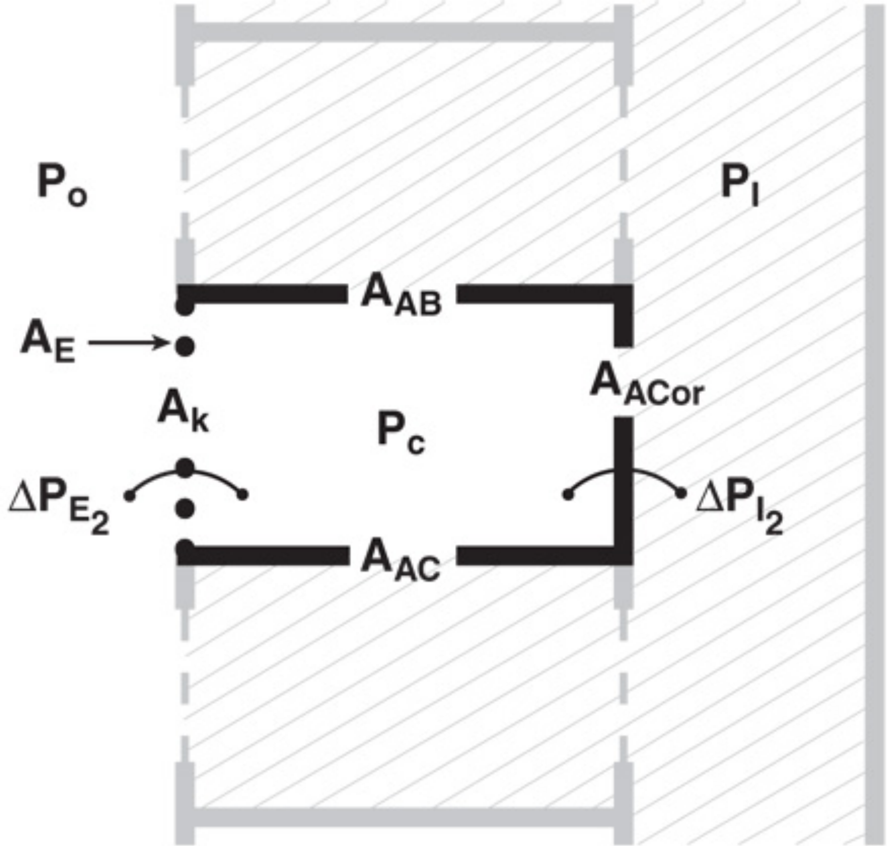
Figure 4.6
Series of Rooms Connected to Corridor



$$A_I = A_{AB} + A_{AC} + A_{ACor}$$

Figure 4.7
Initial Pressure Measurements

- Door to corridor in Room A closed
- Doors to corridor for Rooms B and C are open
- Windows in all rooms closed



$$A_I = A_{AB} + A_{AC} + A_{ACor}$$

Figure 4.8

Subsequent Pressure Measurements

- An opening of known size, $A_{k,}$ is added to A_E (i.e. window in Room A is opened)

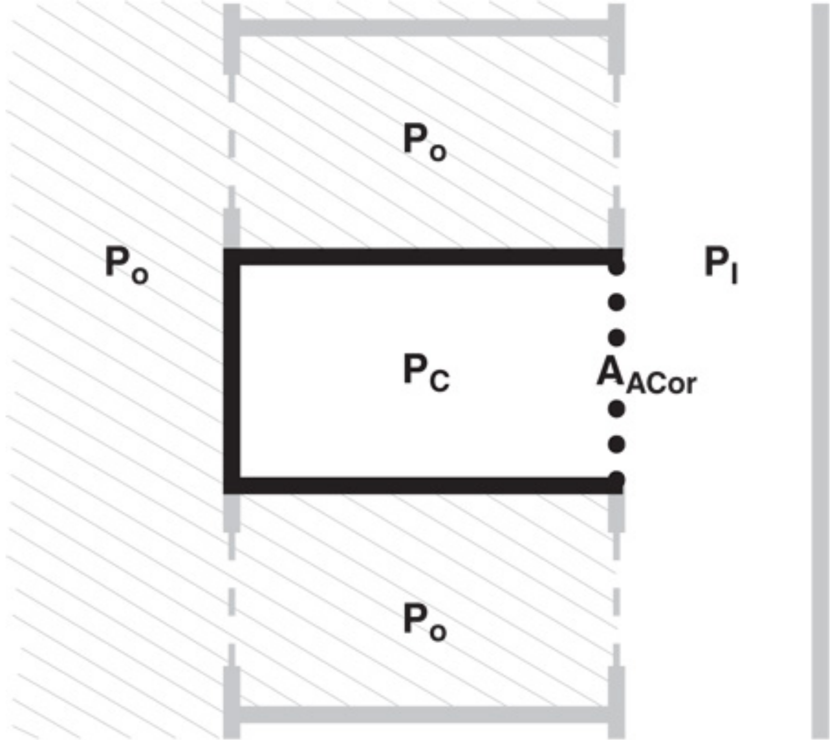
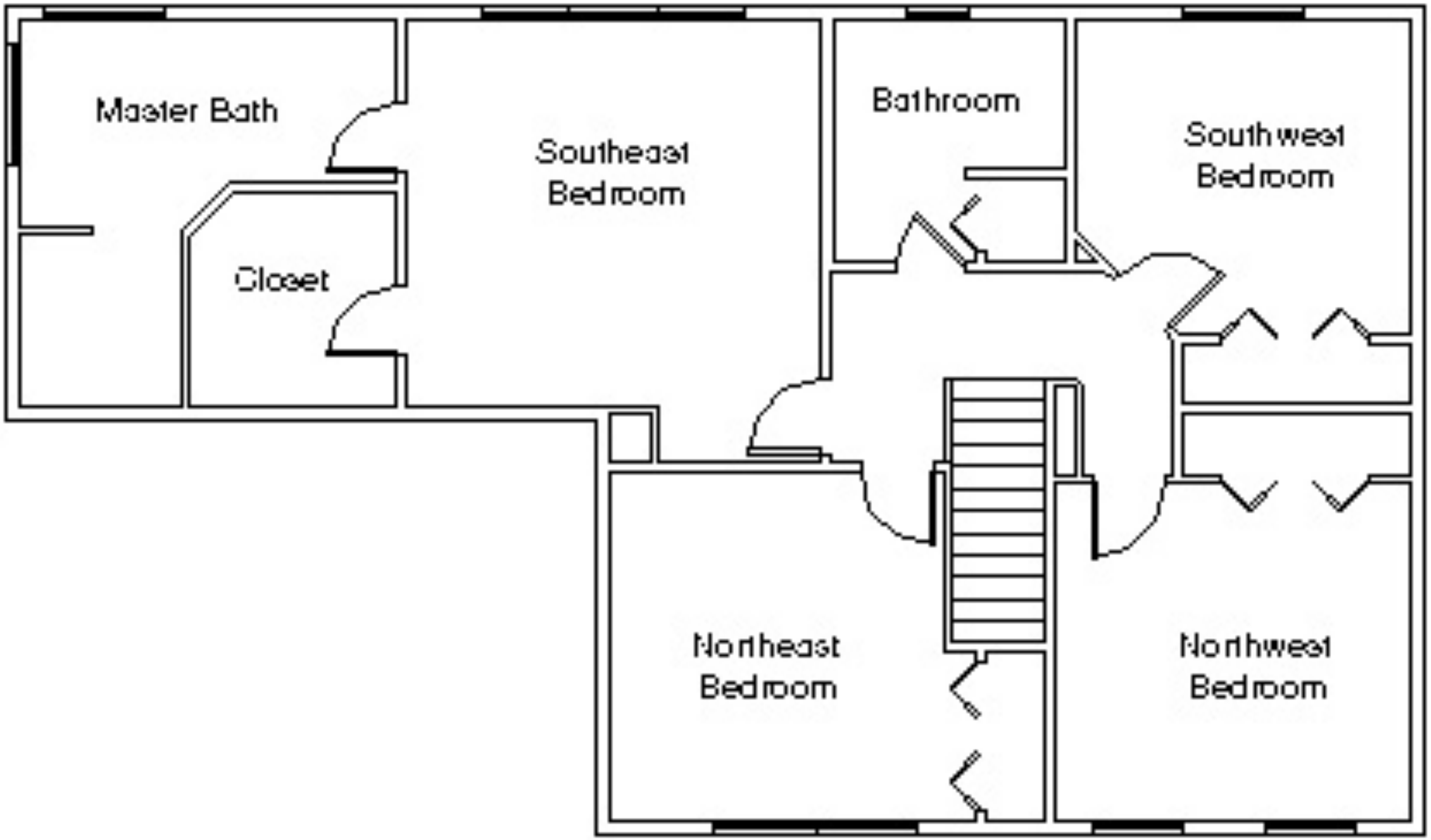
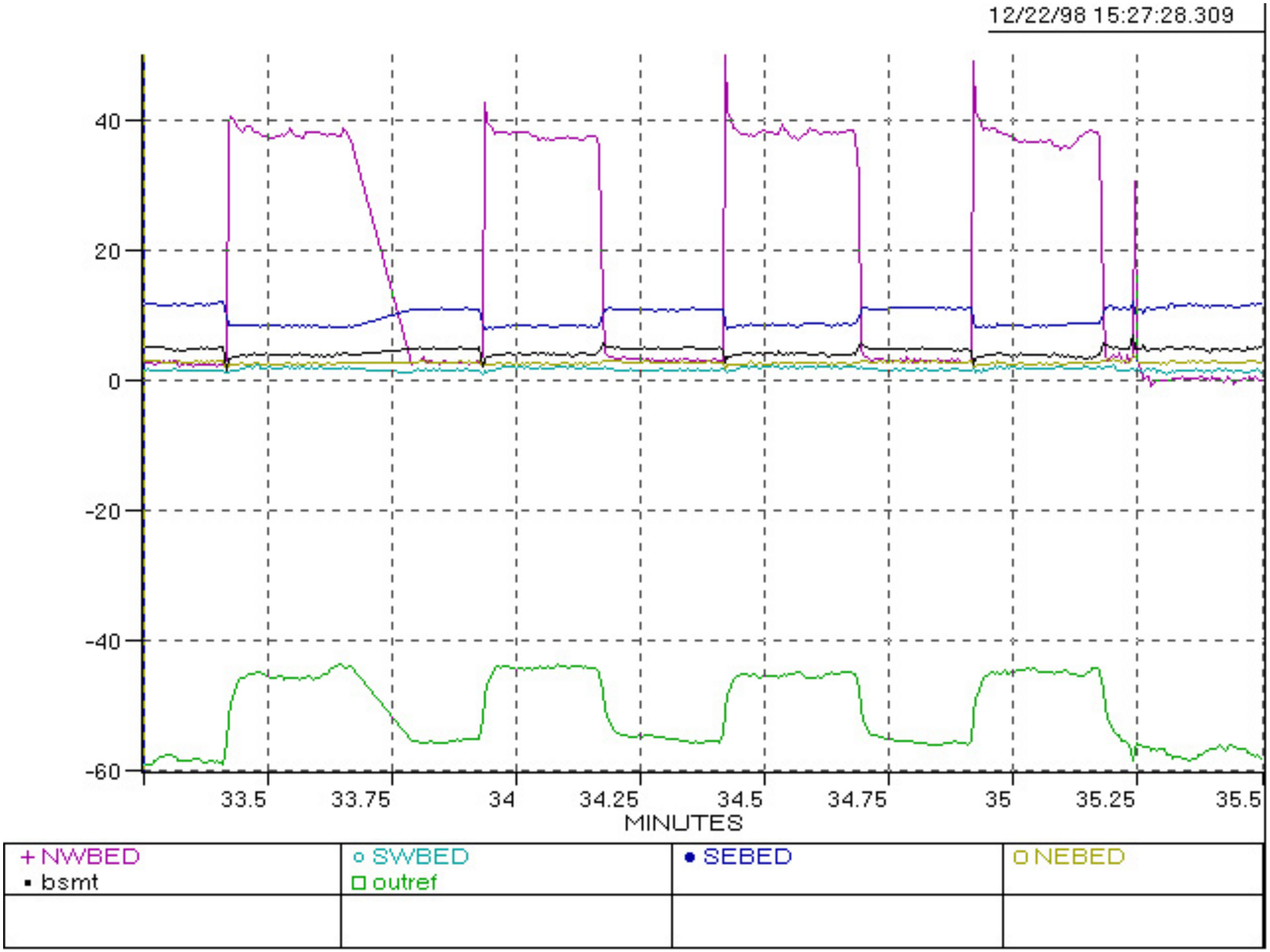


Figure 4.9

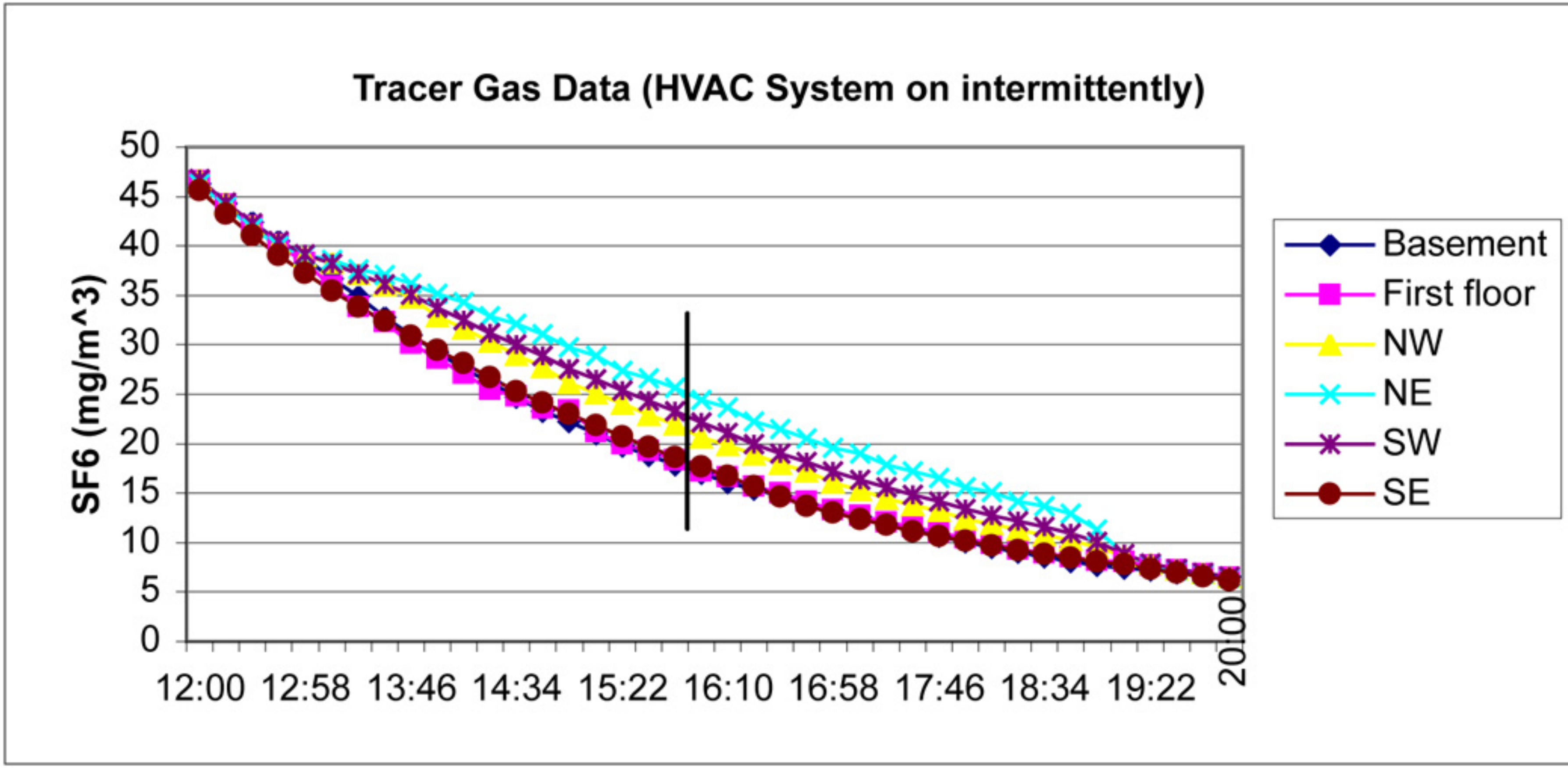
Determining Leakage Area A_{ACor}

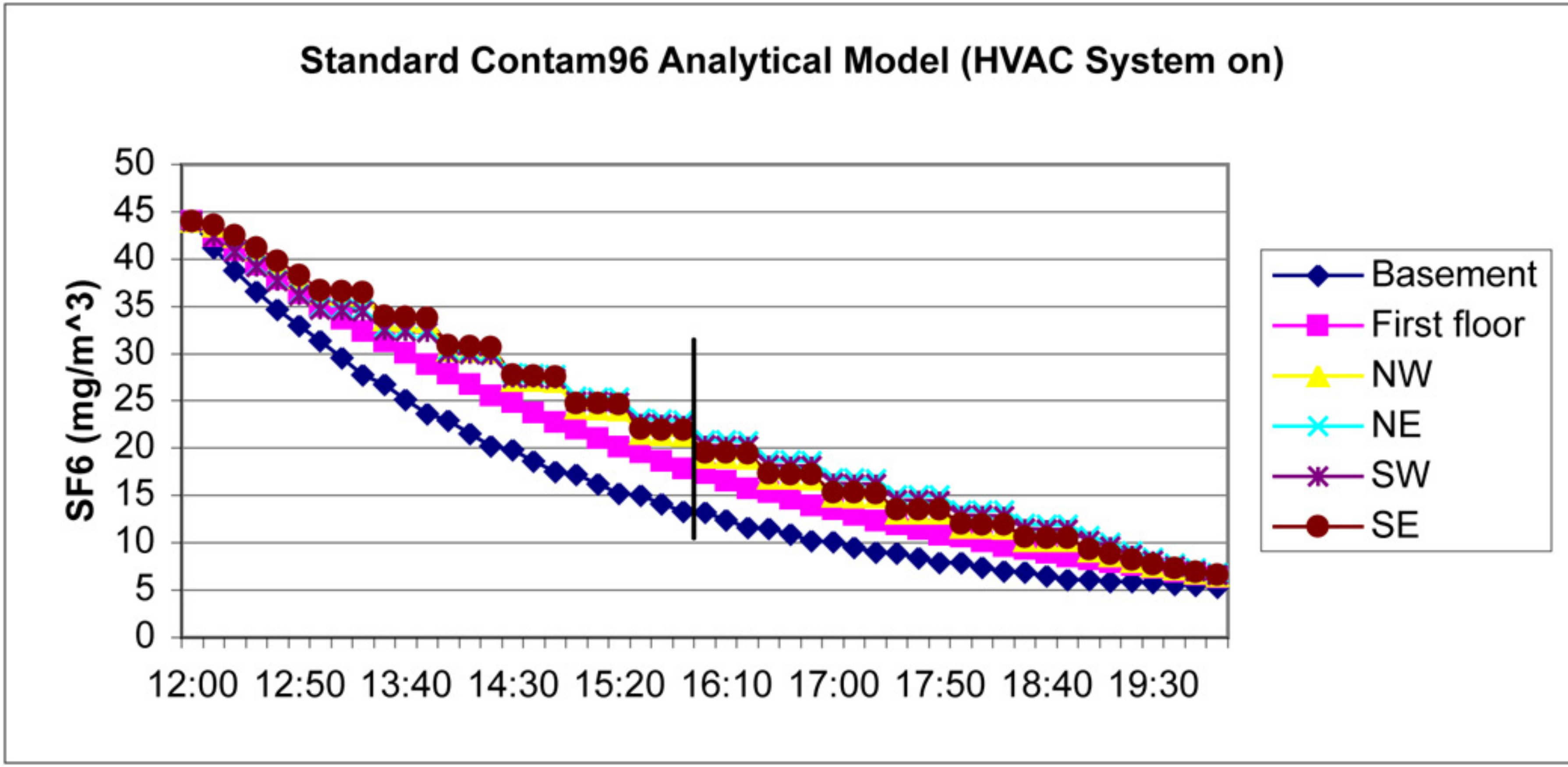
- Windows in Rooms B and C are opened
- Windows in Room A are closed
- Doors to corridor for all rooms are initially closed; door in Room A subsequently opened


Master Bath
Southeast
Bedroom
Bathroom
Southwest
Bedroom
Closet
Northeast
Bedroom
Northwest
Bedroom



12/22/98 15:27:28.309
40
20
0
-20
-40
-60
33.5
33.75
34
34.25
34.5
34.75
35
35.25
35.5
MINUTES
+ NWBED
▪ bsmt
○ SWBED
□ outref
● SEBED
○ NEBED

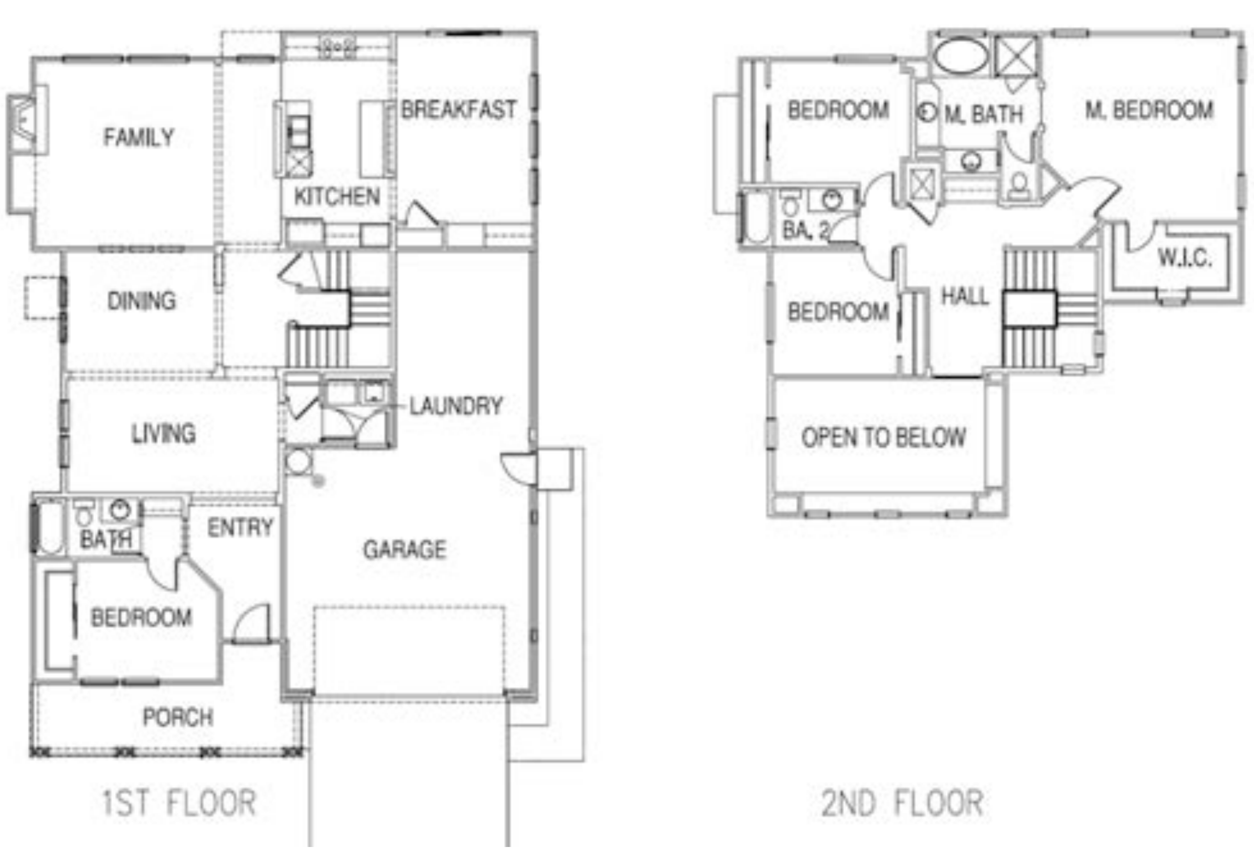

Tracer Gas Data (HVAC System on intermittently)
SF6 (mg/m^3)
50
45
40
35
30
25
20
15
10
5
0
12:00
12:58
13:46
14:34
15:22
16:10
16:58
17:46
18:34
19:22
20:00
Basement
First floor
NW
NE
SW
SE



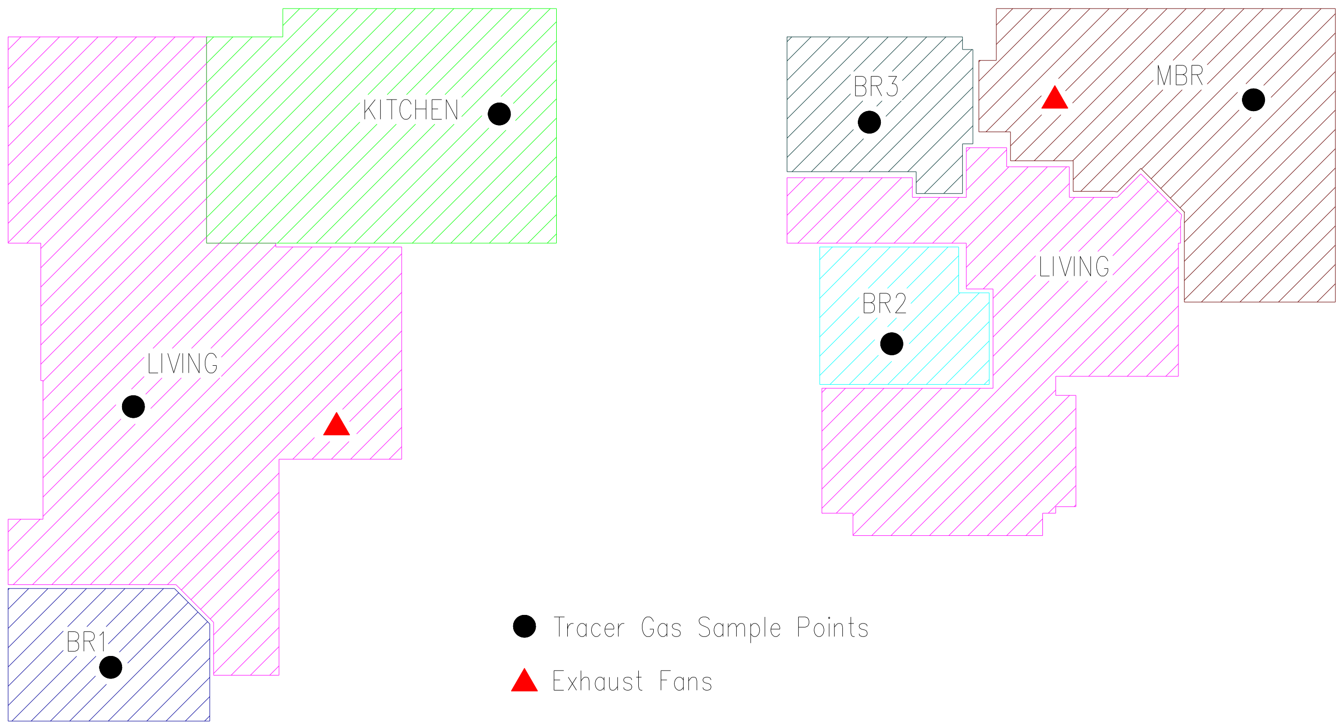
Standard Contam96 Analytical Model (HVAC System on)
SF6 (mg/m^3)
50
45
40
35
30
25
20
15
10
5
0
12:00
12:50
13:40
14:30
15:20
16:10
17:00
17:50
18:40
19:30
Basement
First floor
NW
NE
SW
SE

- Tracer gas test of a production Building America house in Sacramento
- 2-story, 4 bedrooms, ~2500 square feet
- Ventilation systems tested: supply and exhaust ventilation, with and without mixing via central air handler

Floor Plan - 2 Story House

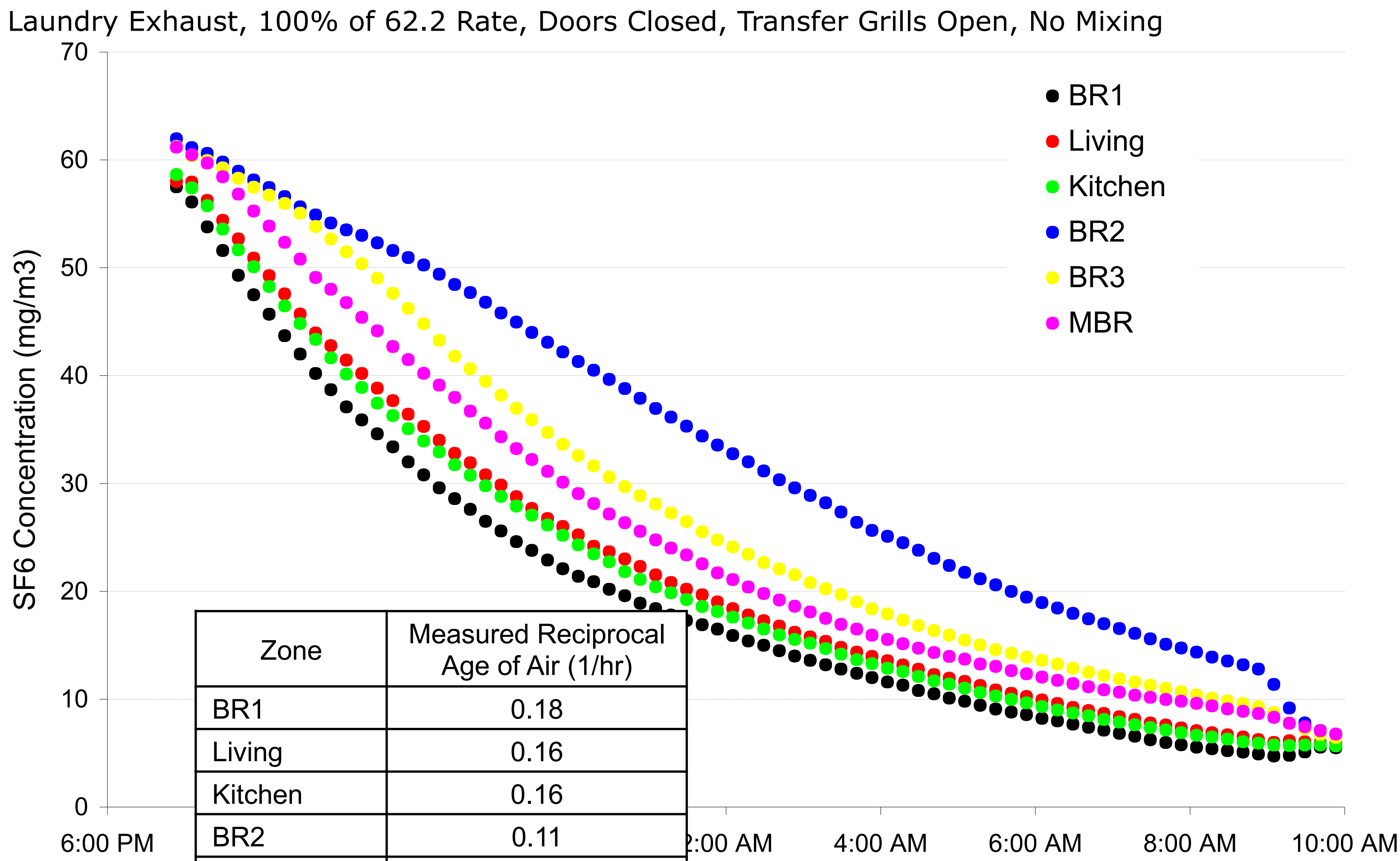


Zones – 2 Story House



- Tracer gas decay tests—establish uniform concentration of tracer gas and then activate ventilation system to remove it
- Reciprocal age-of-air can be calculated from decay curves (if weather conditions are sufficiently constant)

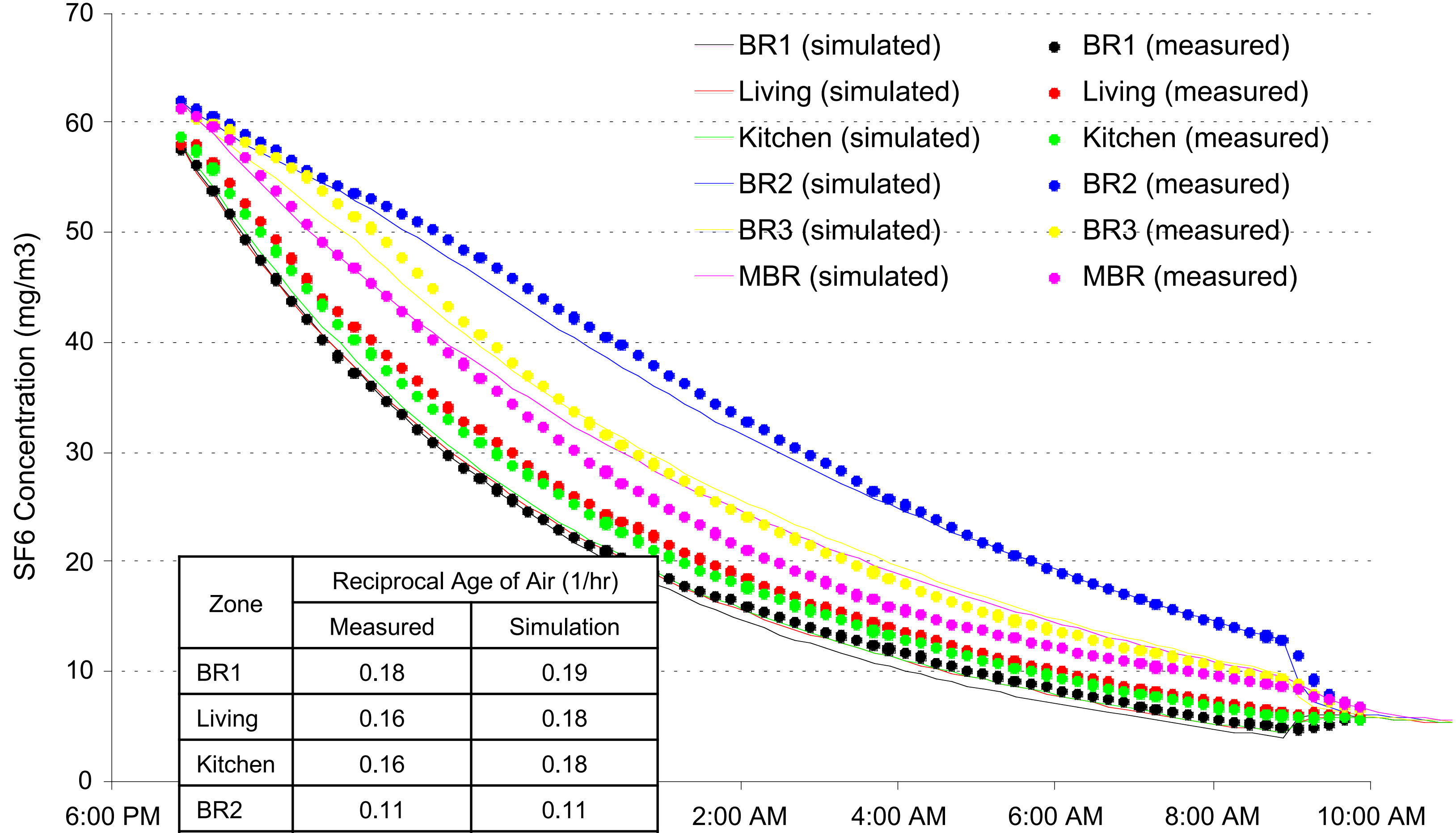
Example Results of Tracer Gas Testing



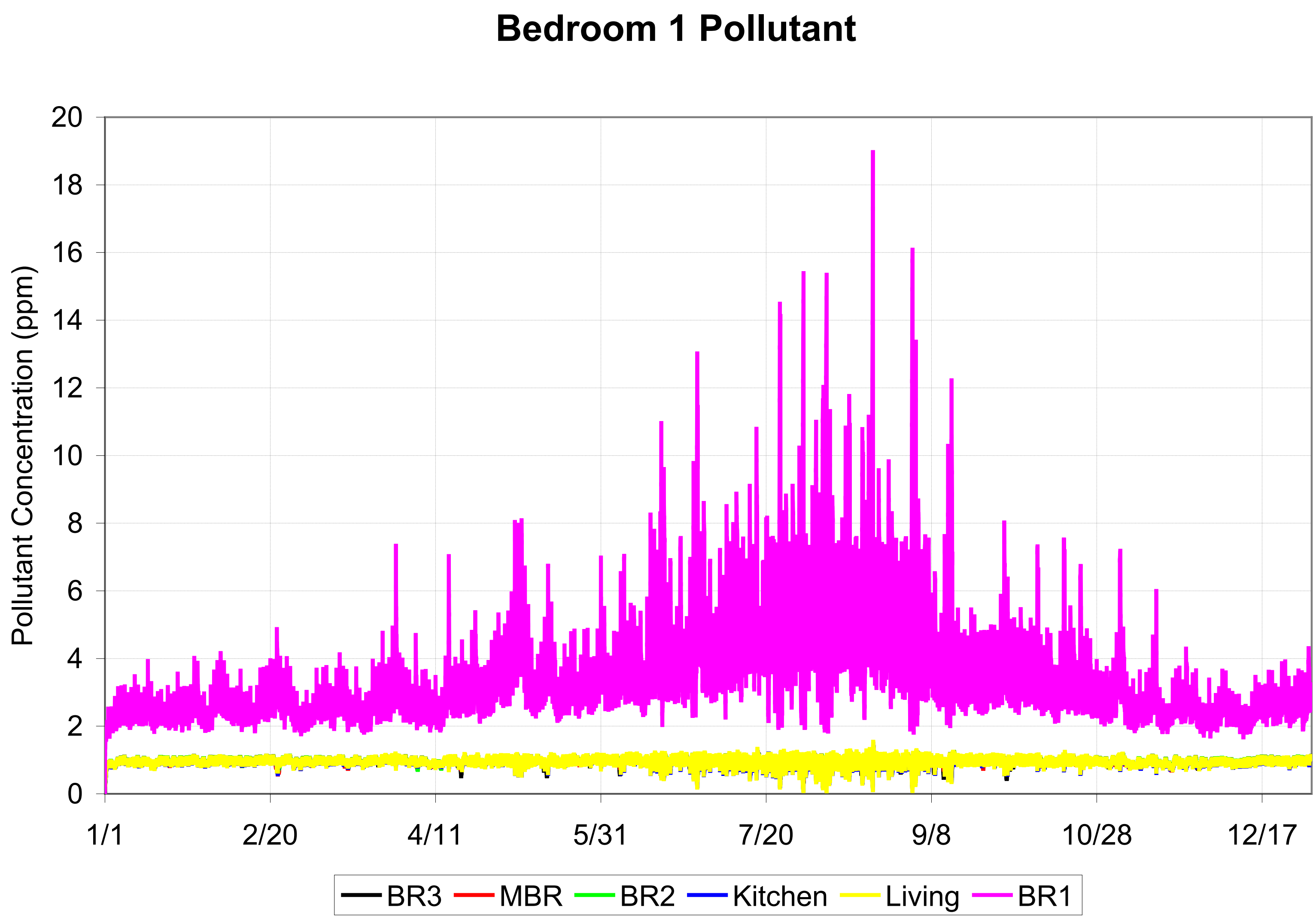
Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.18
Living	0.16
Kitchen	0.16
BR2	0.11
BR3	0.13
MBR	0.14

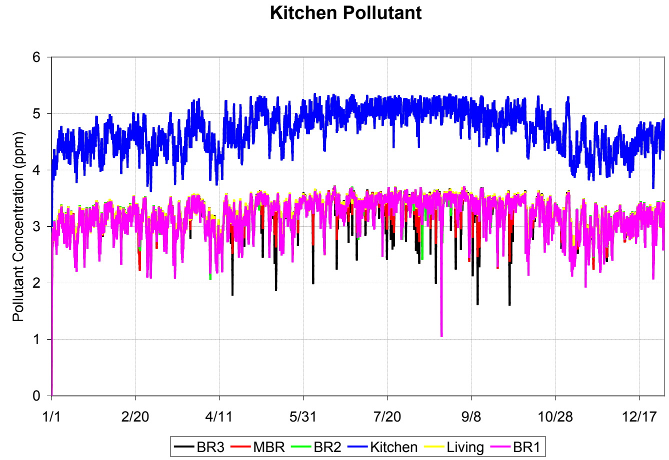
Example Results of Tuned CONTAM Model

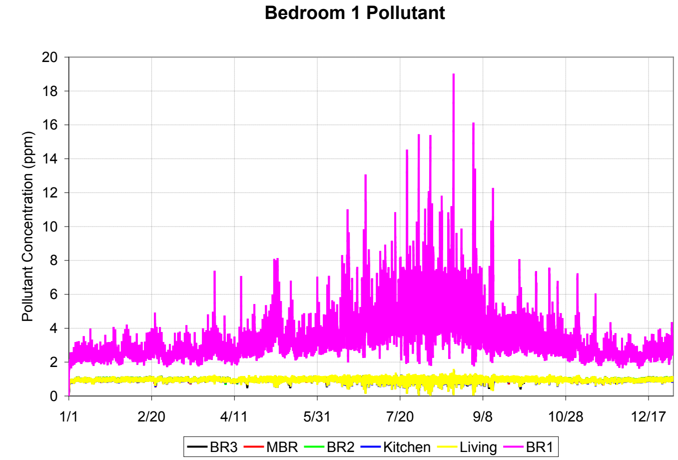
Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, Transfer Grills Open, No Mixing

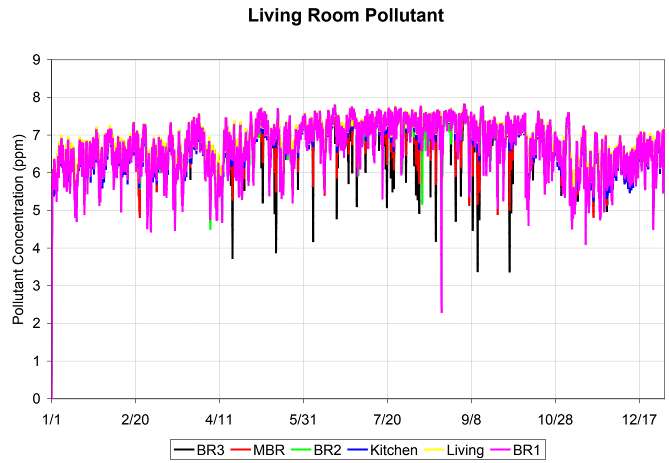


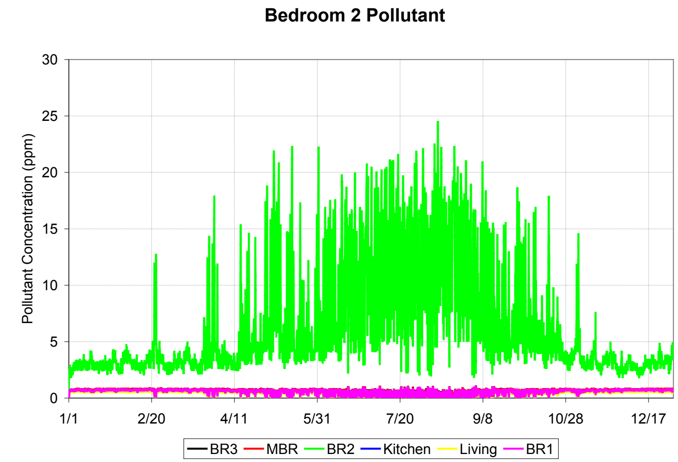
Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.18	0.19
Living	0.16	0.18
Kitchen	0.16	0.18
BR2	0.11	0.11
BR3	0.13	0.13
MBR	0.14	0.13

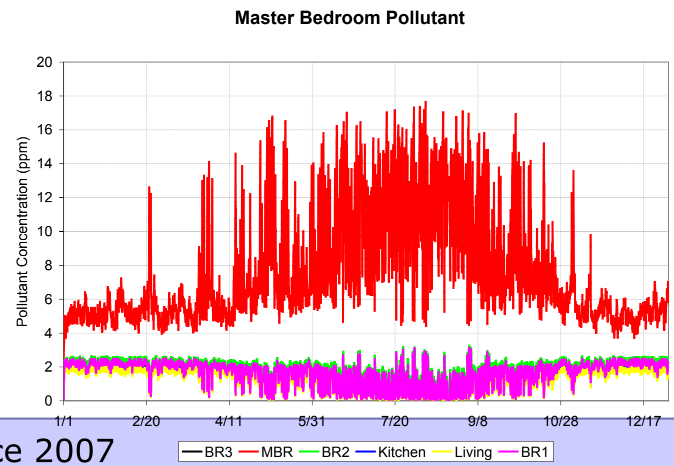

Bedroom 1 Pollutant
Pollutant Concentration (ppm)
20
18
16
14
12
10
8
6
4
2
0
1/1
2/20
4/11
5/31
7/20
9/8
10/28
12/17
BR3
MBR
BR2
Kitchen
Living
BR1

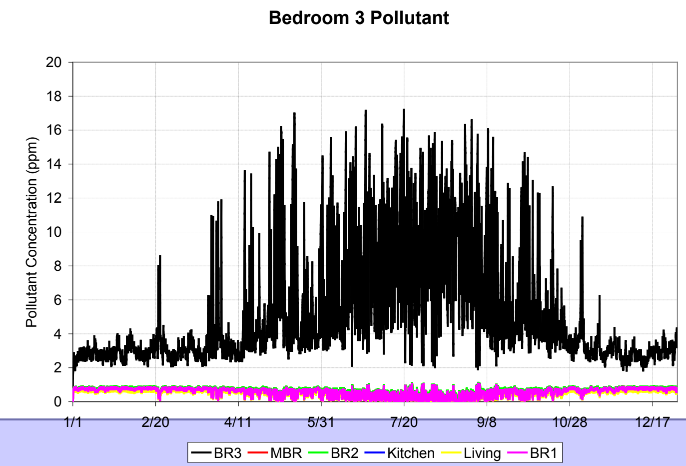

Kitchen Pollutant
Pollutant Concentration (ppm)
0 1 2 3 4 5 6
1/1 2/20 4/11 5/31 7/20 9/8 10/28 12/17
BR3 MBR BR2 Kitchen Living BR1


Bedroom 1 Pollutant
Pollutant Concentration (ppm)
0 2 4 6 8 10 12 14 16 18 20
1/1 2/20 4/11 5/31 7/20 9/8 10/28 12/17
BR3 MBR BR2 Kitchen Living BR1

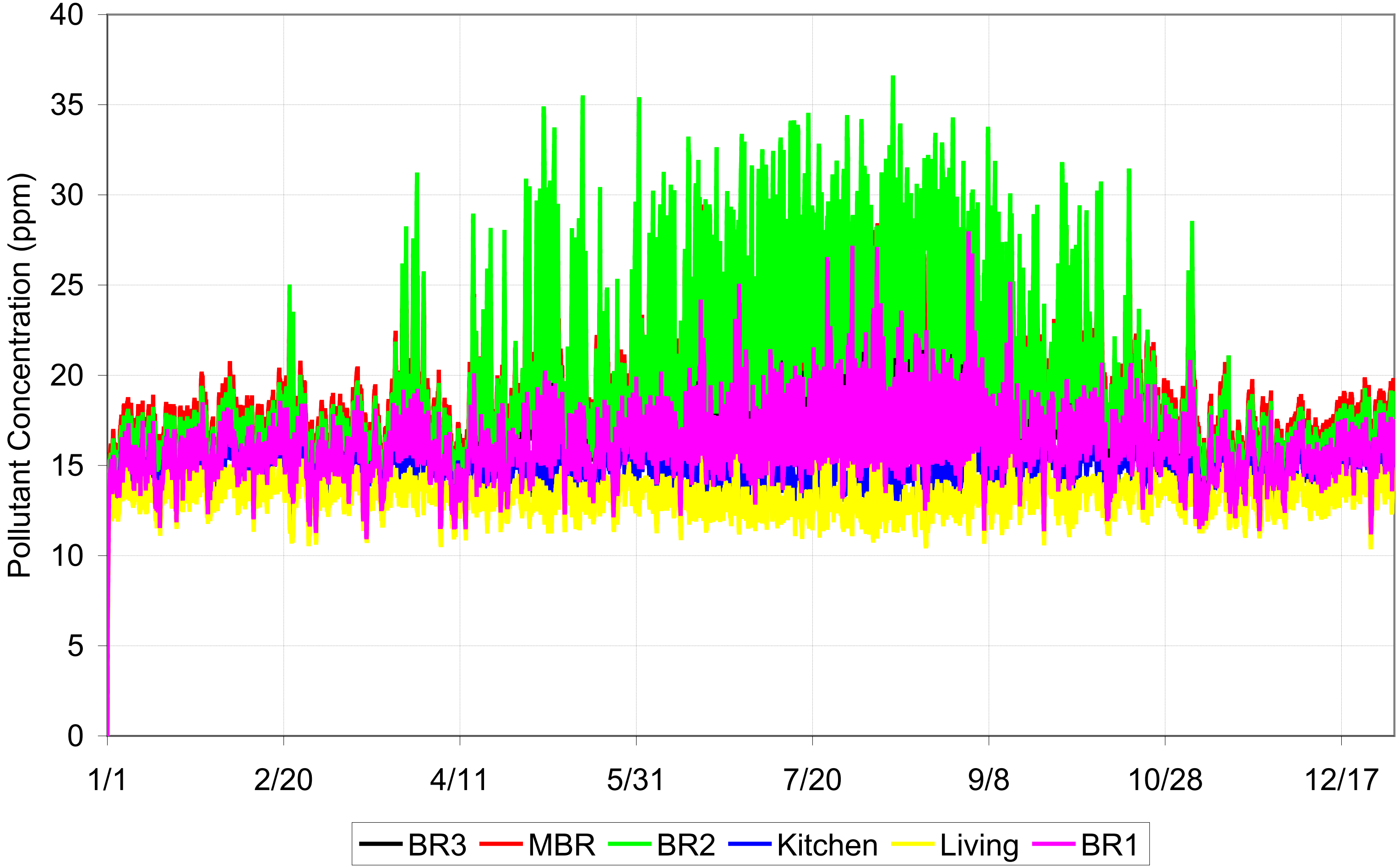

Living Room Pollutant
Pollutant Concentration (ppm)
0 1 2 3 4 5 6 7 8 9
1/1 2/20 4/11 5/31 7/20 9/8 10/28 12/17
BR3 MBR BR2 Kitchen Living BR1


Bedroom 2 Pollutant
Pollutant Concentration (ppm)
0 5 10 15 20 25 30
1/1 2/20 4/11 5/31 7/20 9/8 10/28 12/17
BR3 MBR BR2 Kitchen Living BR1


Master Bedroom Pollutant
Pollutant Concentration (ppm)
0 2 4 6 8 10 12 14 16 18 20
1/1 2/20 4/11 5/31 7/20 9/8 10/28 12/17
BR3 MBR BR2 Kitchen Living BR1


Bedroom 3 Pollutant
Pollutant Concentration (ppm)
0 2 4 6 8 10 12 14 16 18 20
1/1 2/20 4/11 5/31 7/20 9/8 10/28 12/17
BR3 MBR BR2 Kitchen Living BR1

Total Pollutant Concentration by Room



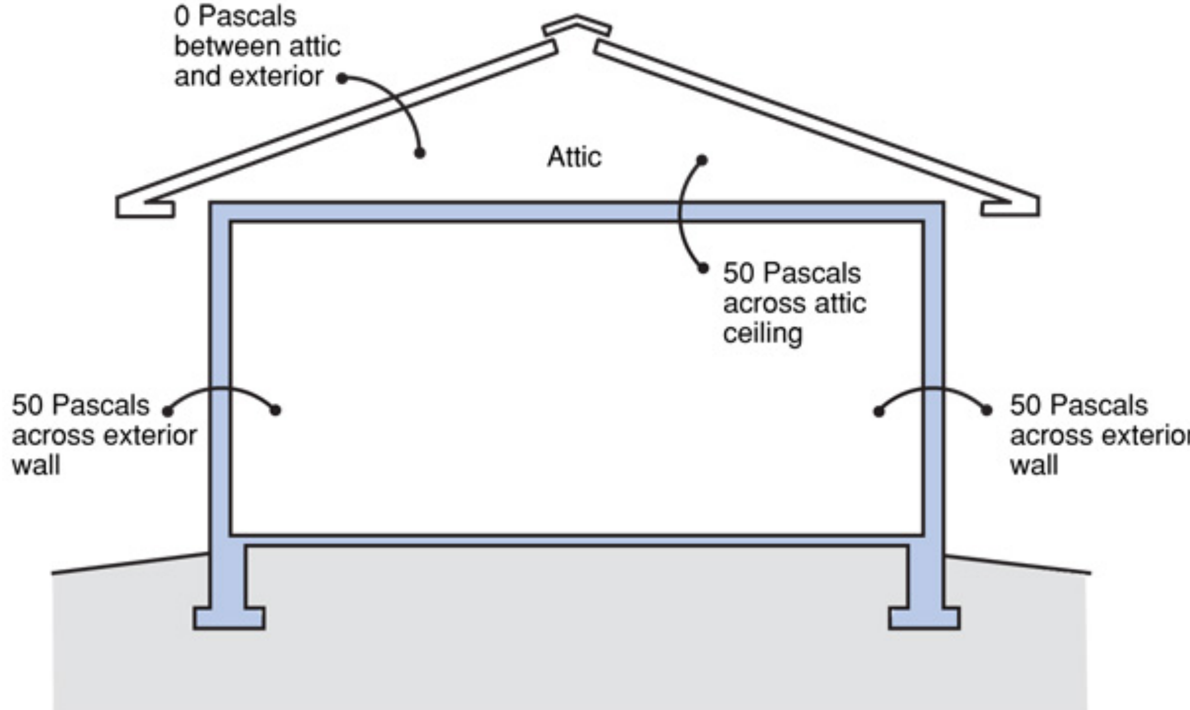


Figure 5.13

Well-Defined Pressure Boundary

- Pressure boundary defines effective building envelope environmental separator

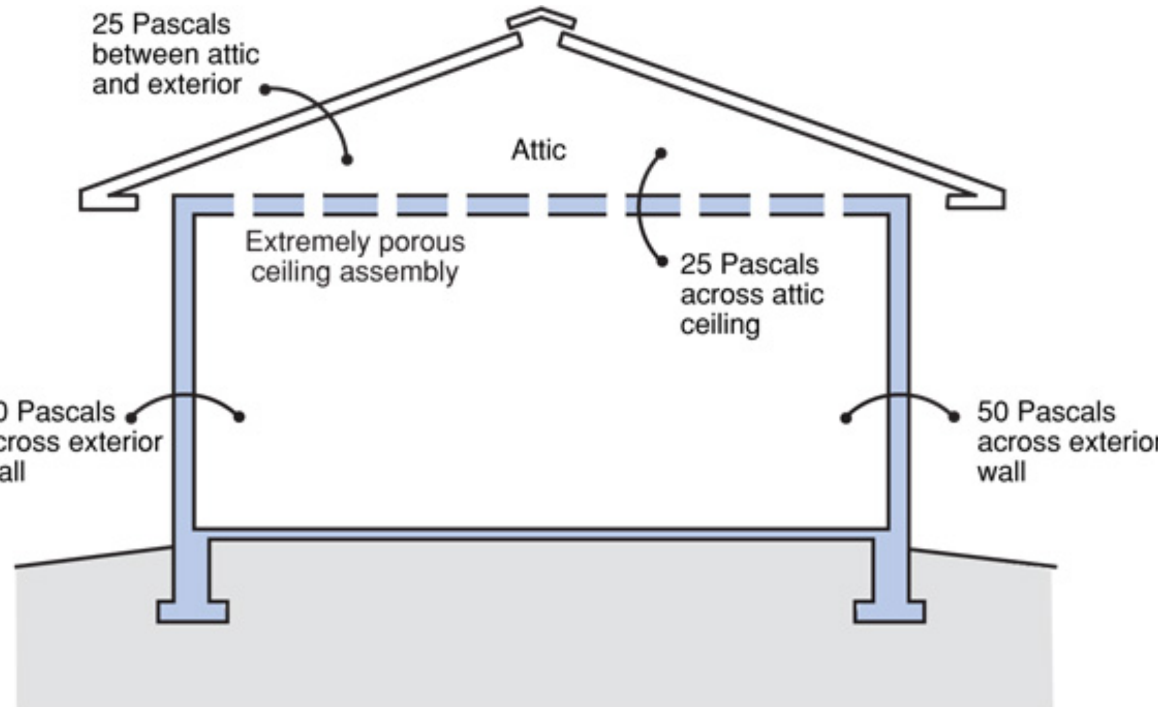


Figure 5.14

Poorly-Defined Pressure Boundary

- Pressure boundary poorly defined — ineffective at ceiling
- Pressure boundary not continuous at ceiling

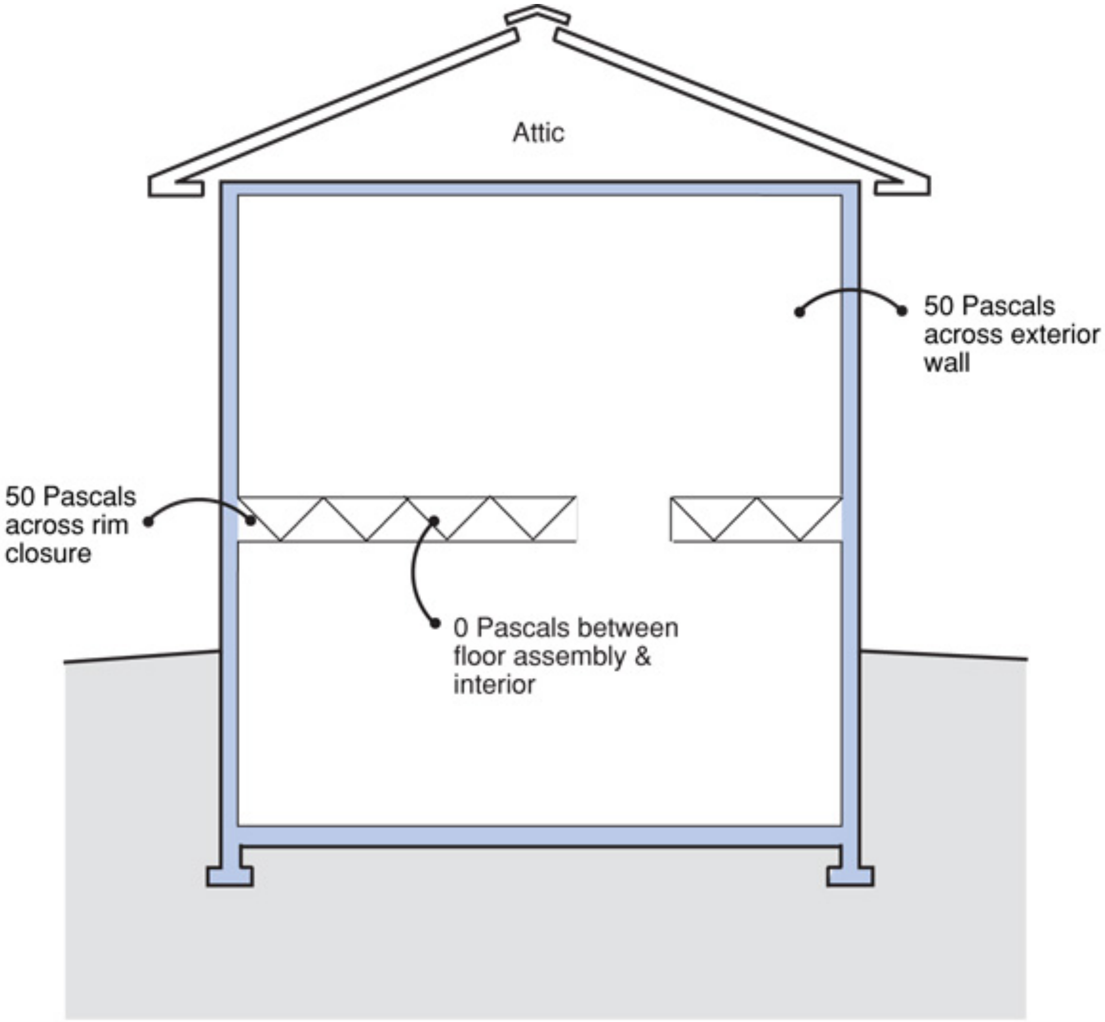


Figure 5.15
Tight Rim Closure

- Floor assembly "inside" well-defined pressure boundary
- Pressure boundary continuous at rim closure

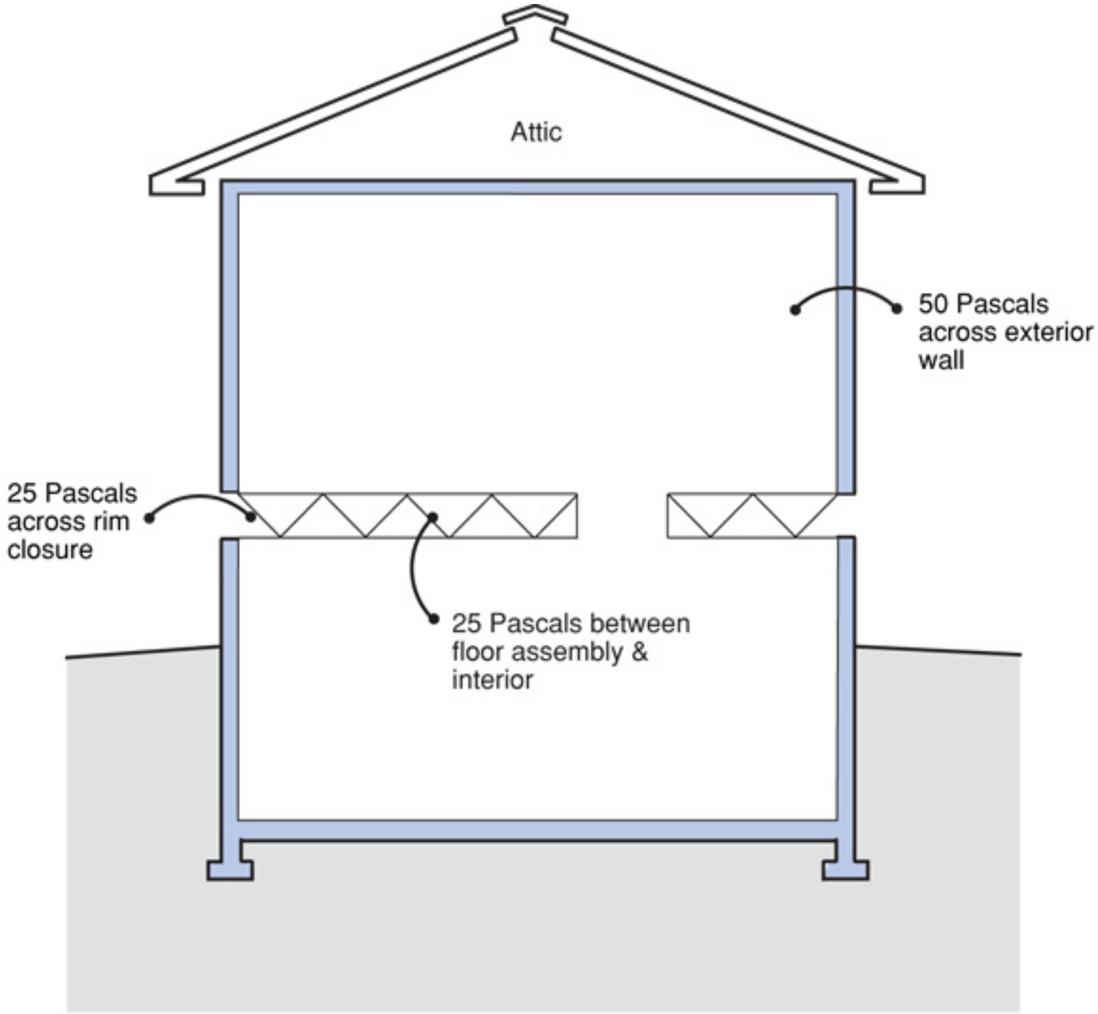


Figure 5.16

Leaky Rim Closure

- Floor assembly “outside” pressure boundary
- Pressure boundary not continuous at rim closure

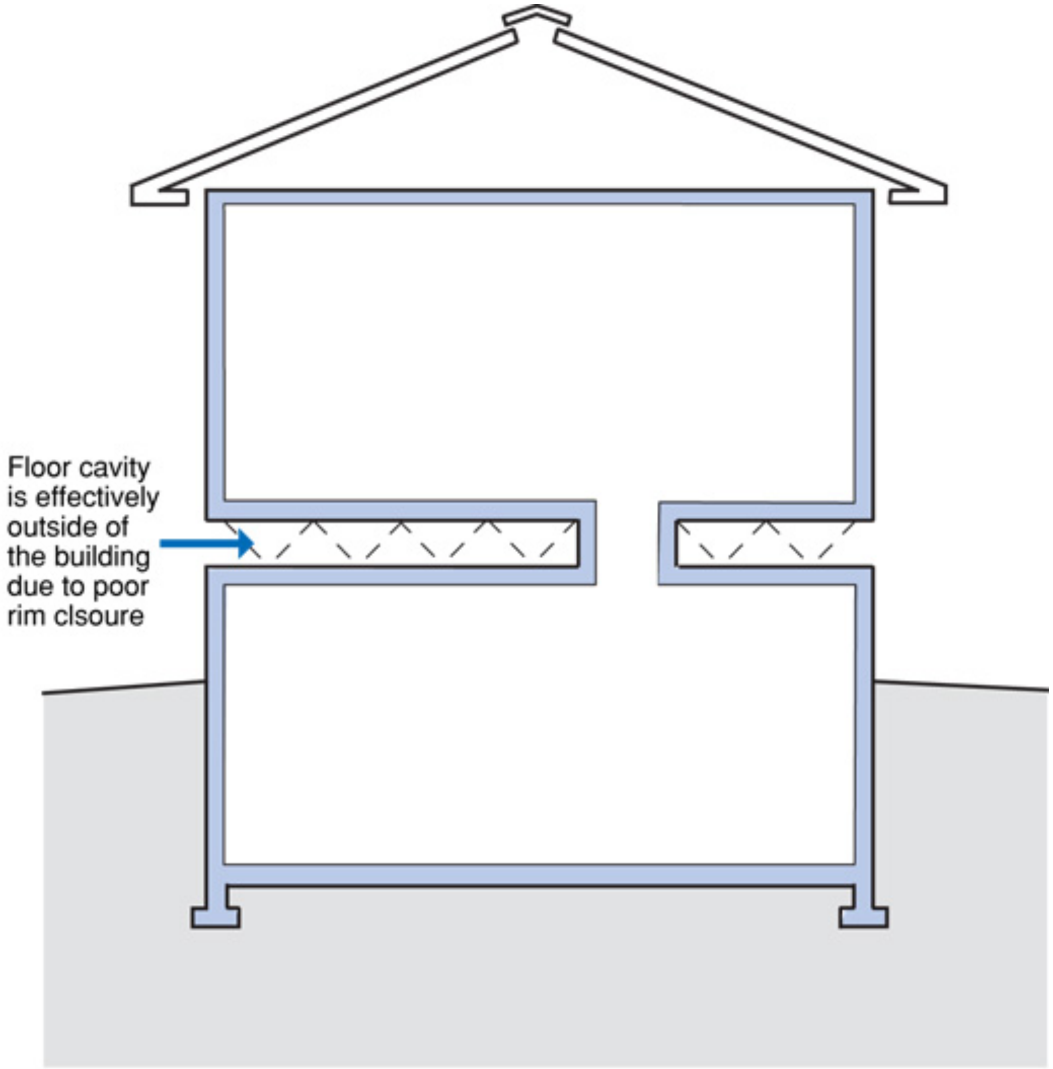


Figure 5.17

Pressure Boundary at Interior Floor

- Pressure boundary not contiguous with building envelope thermal boundary

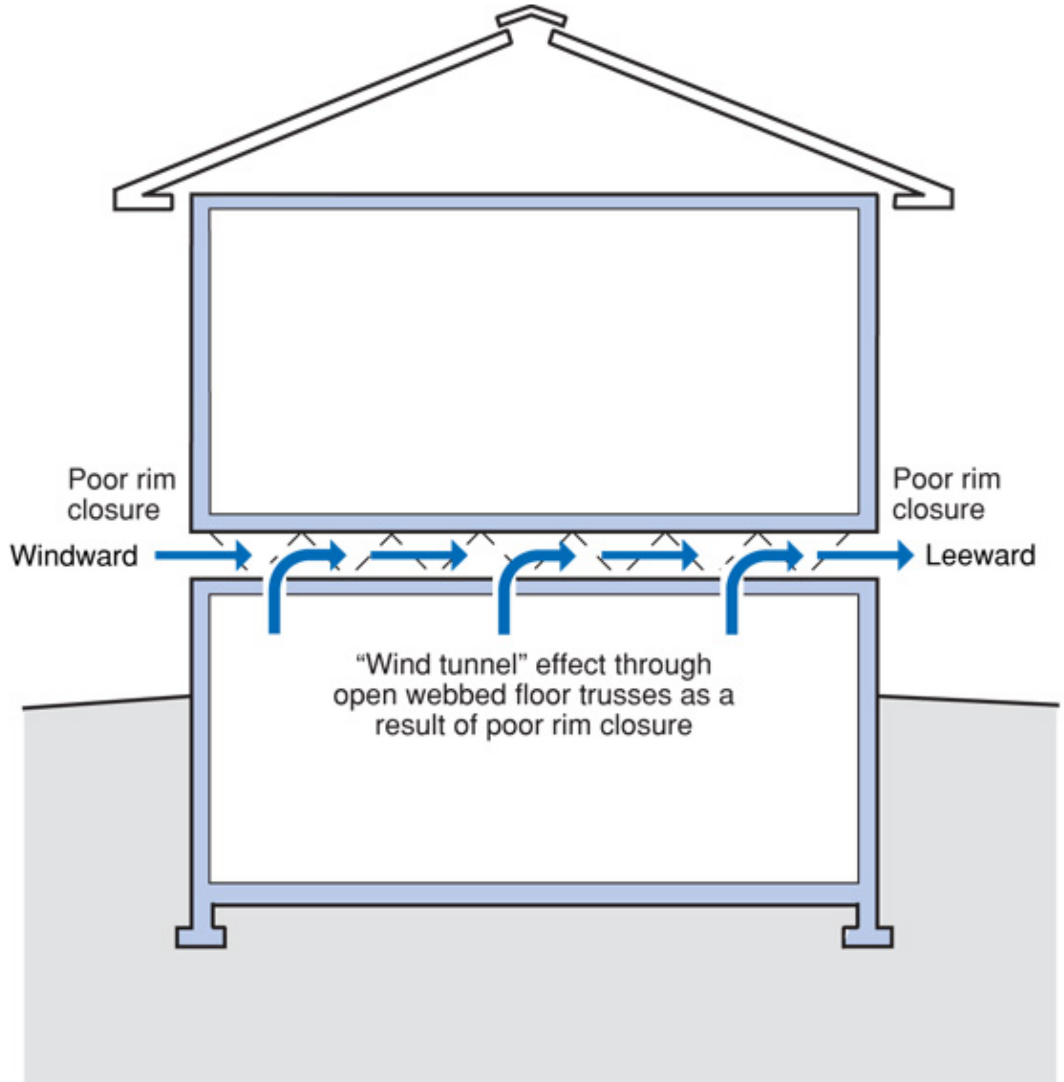


Figure 5.18
Wind Tunnel Effect

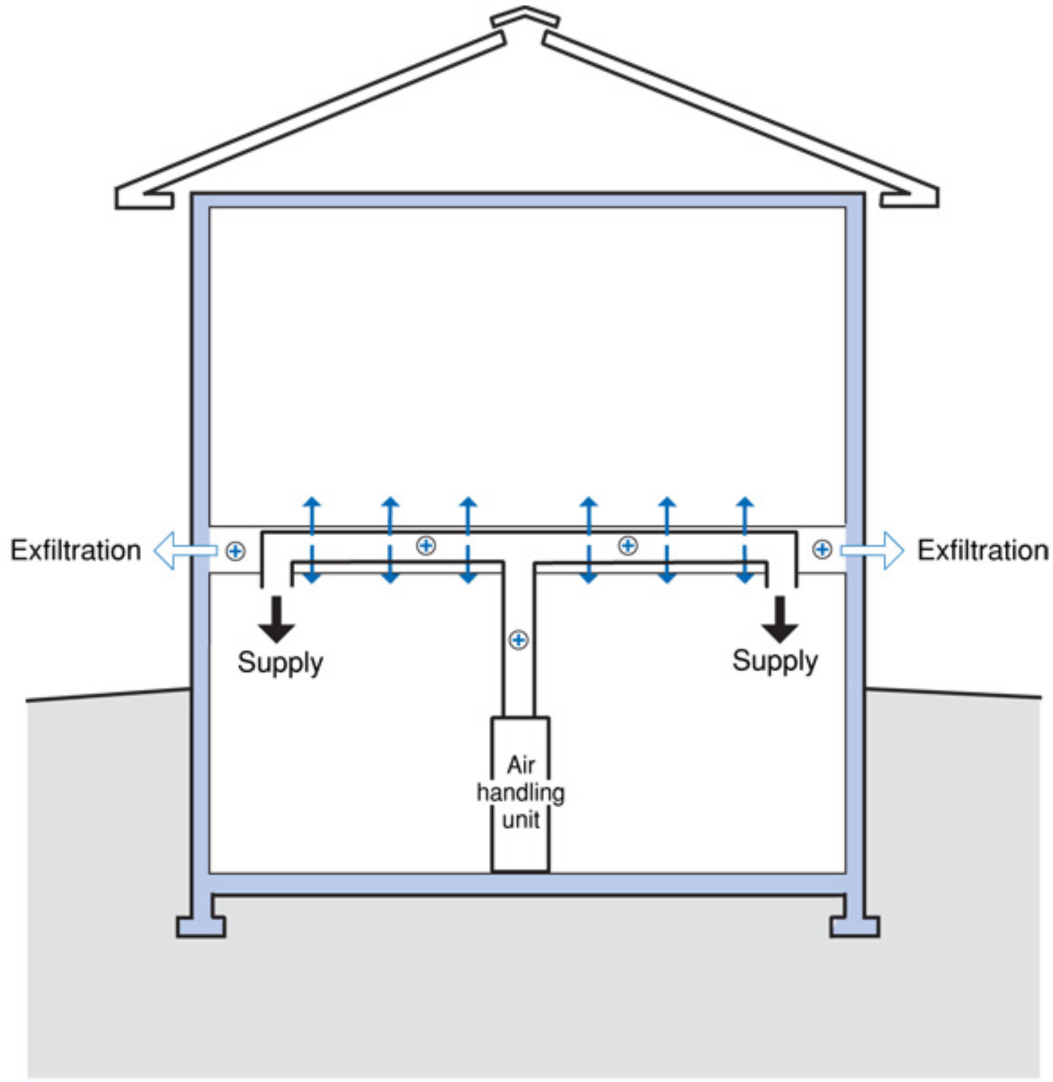


Figure 5.19

Supply Duct Leakage

- Leakage of supply ducts into floor space pressurizes floor space leading to exfiltration at rim closure

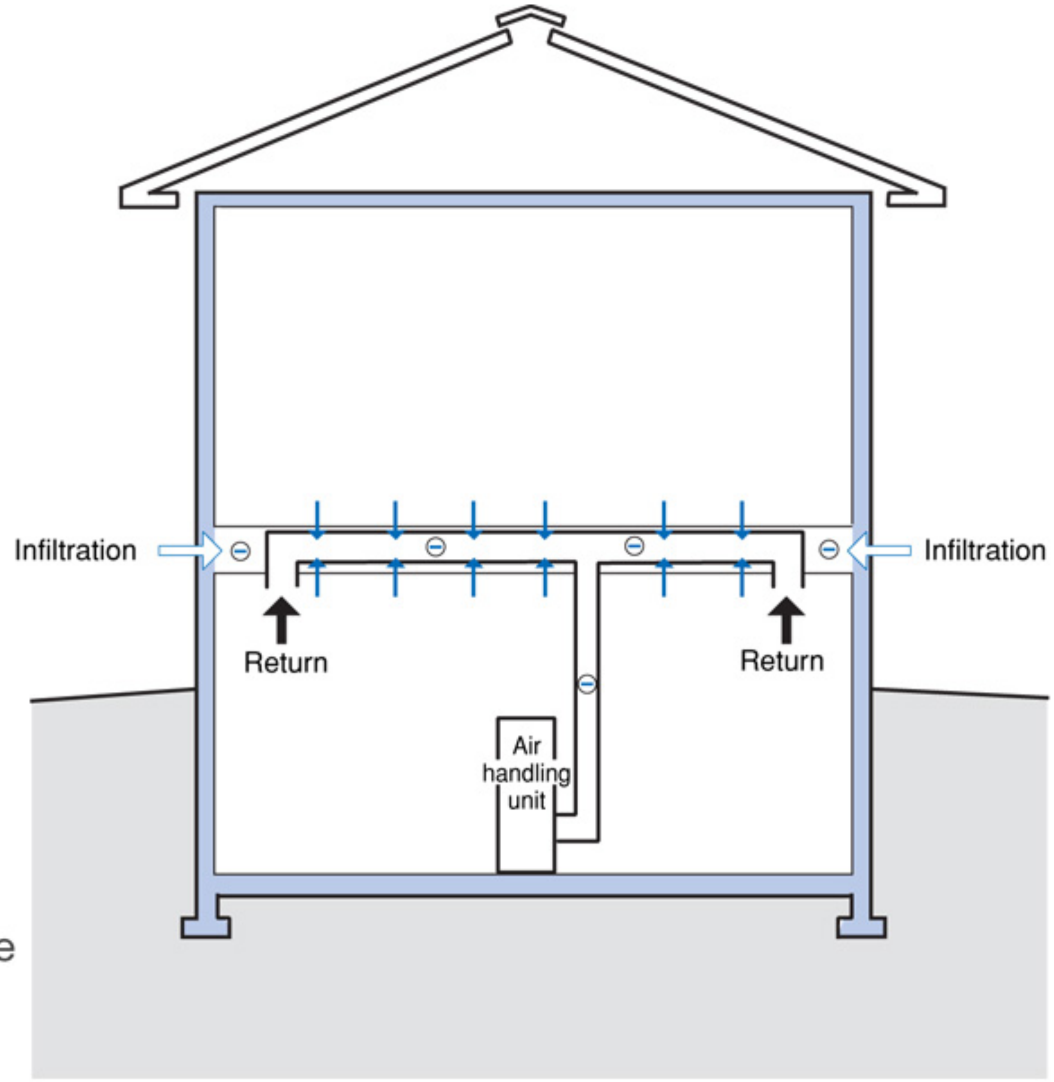


Figure 5.20

Return Duct Leakage

- Leakage of return ducts into floor space depressurizes floor space leading to infiltration at rim closure

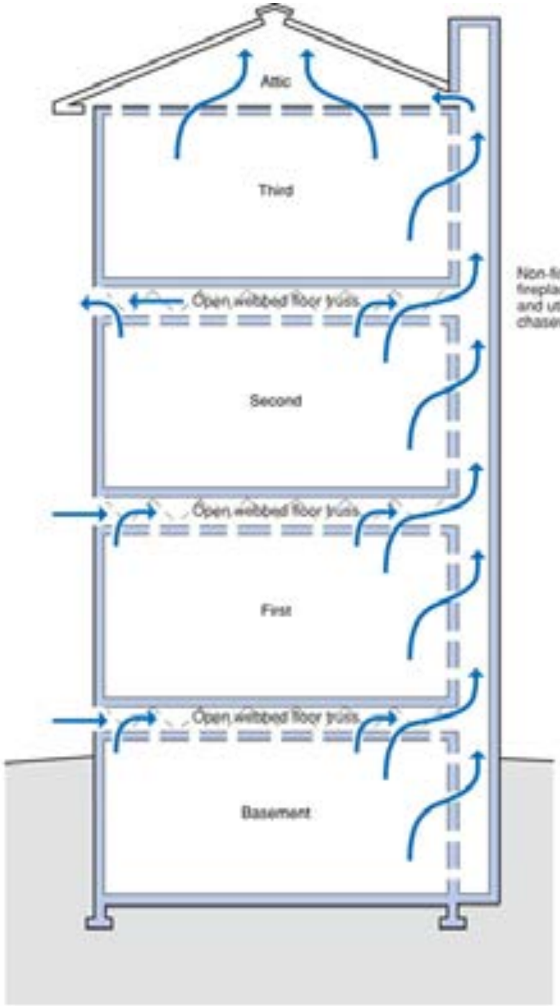


Figure 5.21

Combined Floor Paths and Pressure Drivers

- Vertical and horizontal communicationof open webbed floor trusses through fireplace and utility chaseways
- Pressure drivers are wind, the stack effect and the operation of the HVAC system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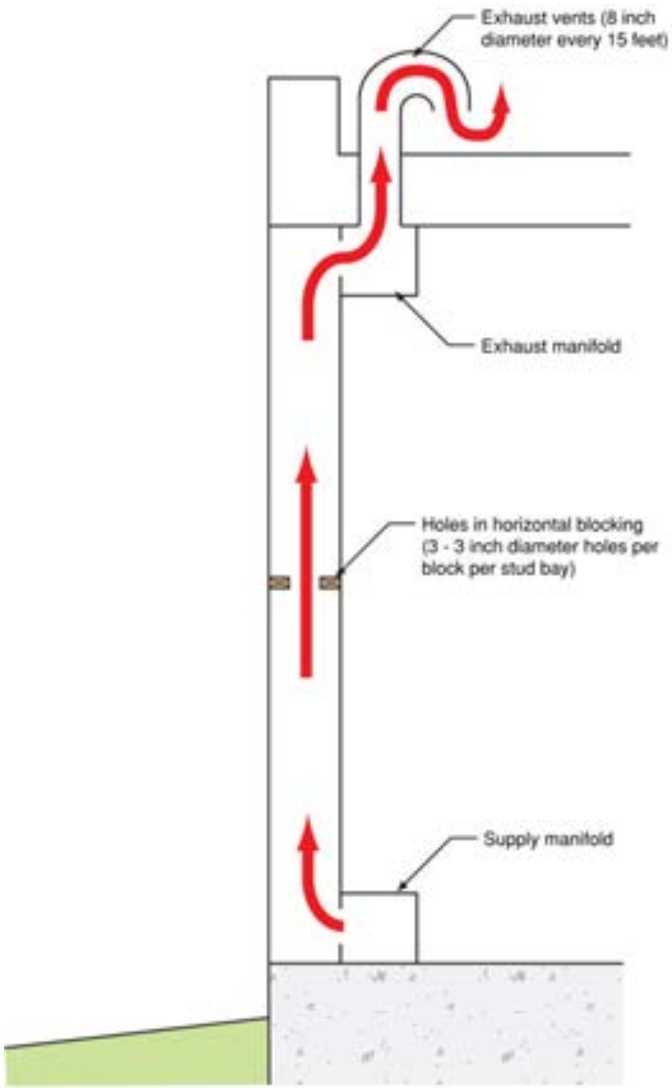


Figure 1: Ventilation of Exterior Walls

- Outside air supplied into suppy manifold
- Exhaust manifold vented through roof

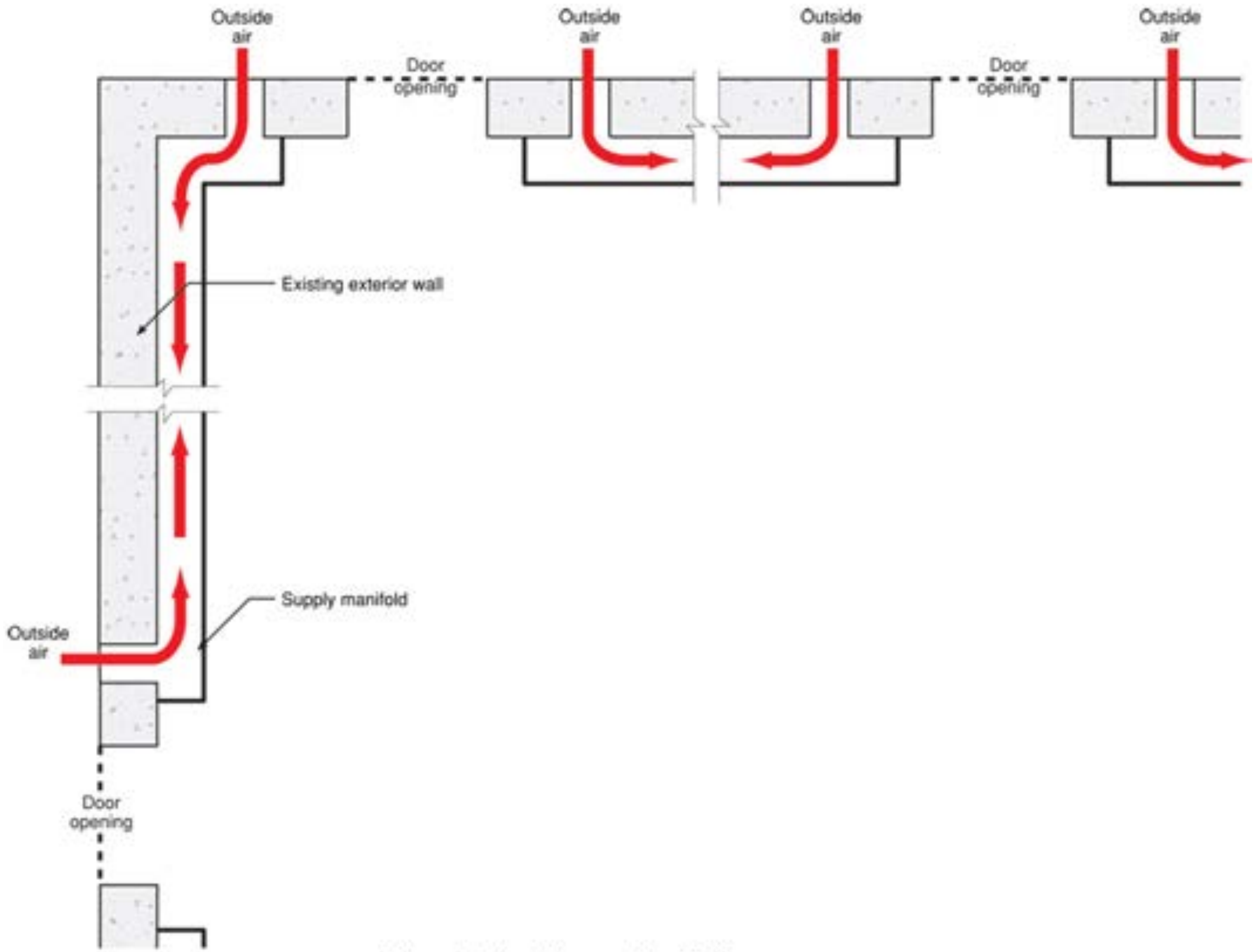


Figure 2: Plan View — Ventilation

- Outside air introduced into supply manifold at bottom of walls through vents penetrating exterior wall and stone
- Vents minimum 14 inches x 14 inches

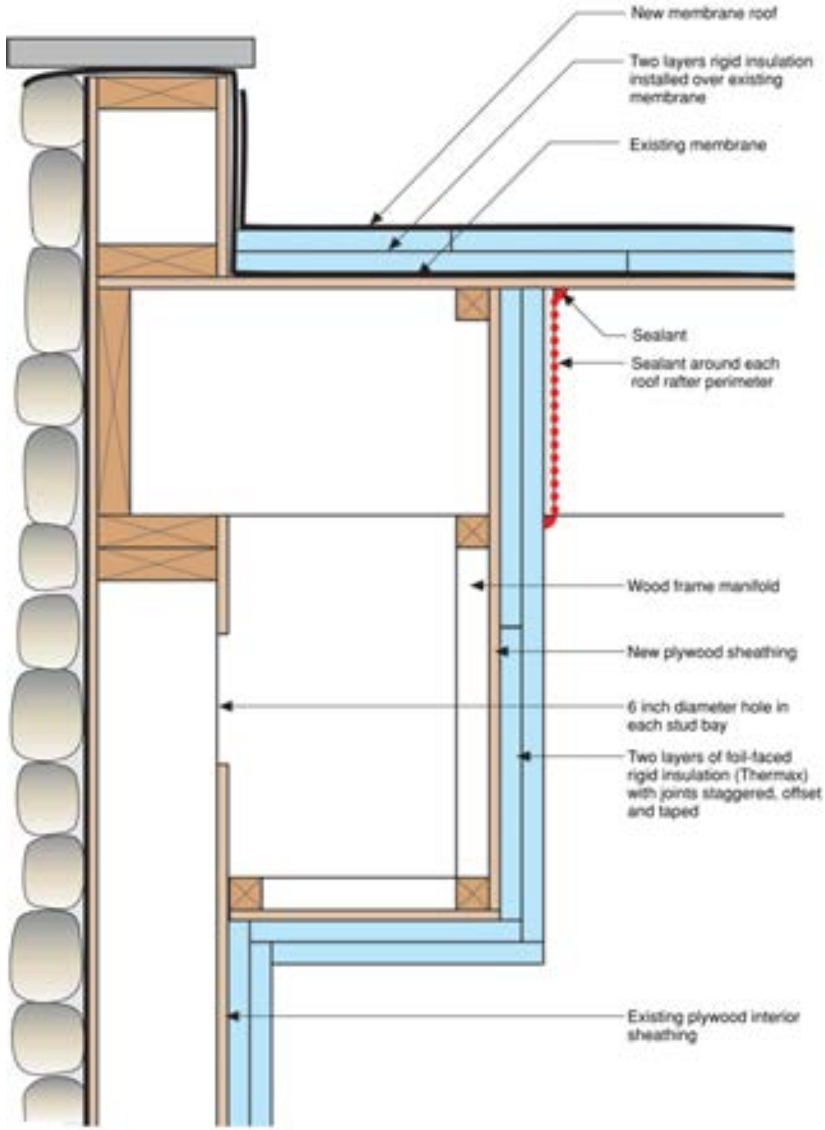


Figure 4: Exhaust Manifold

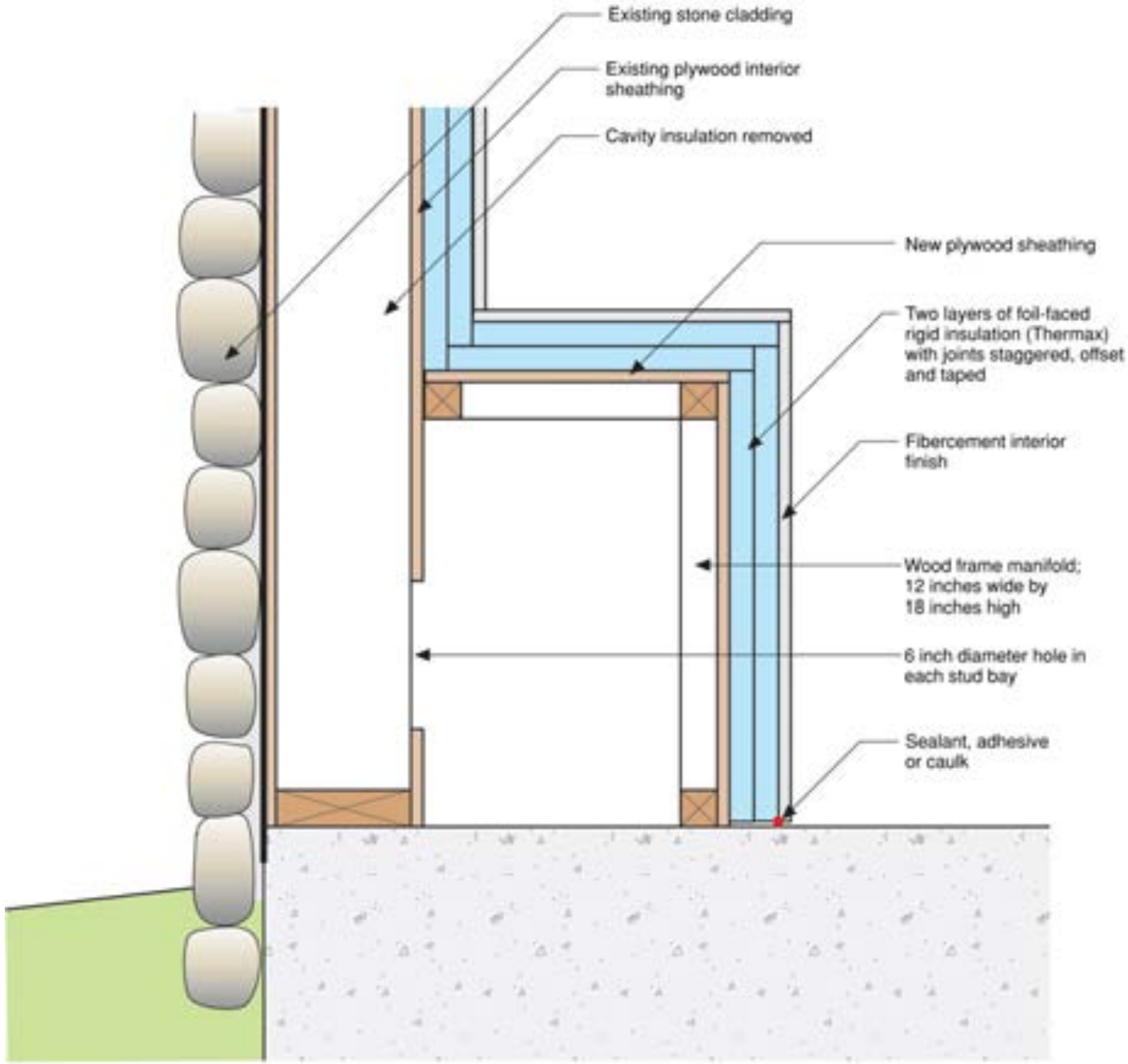
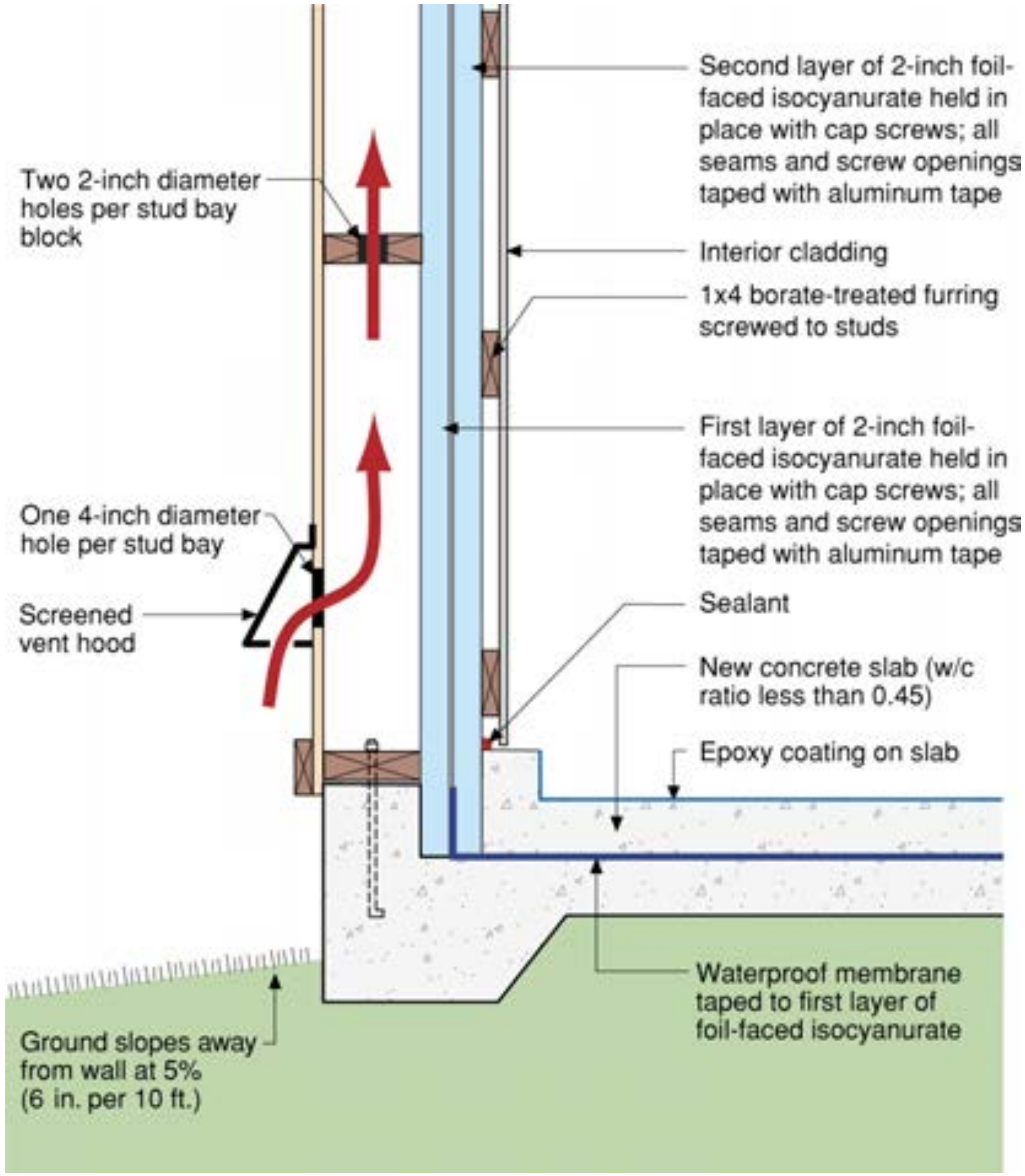
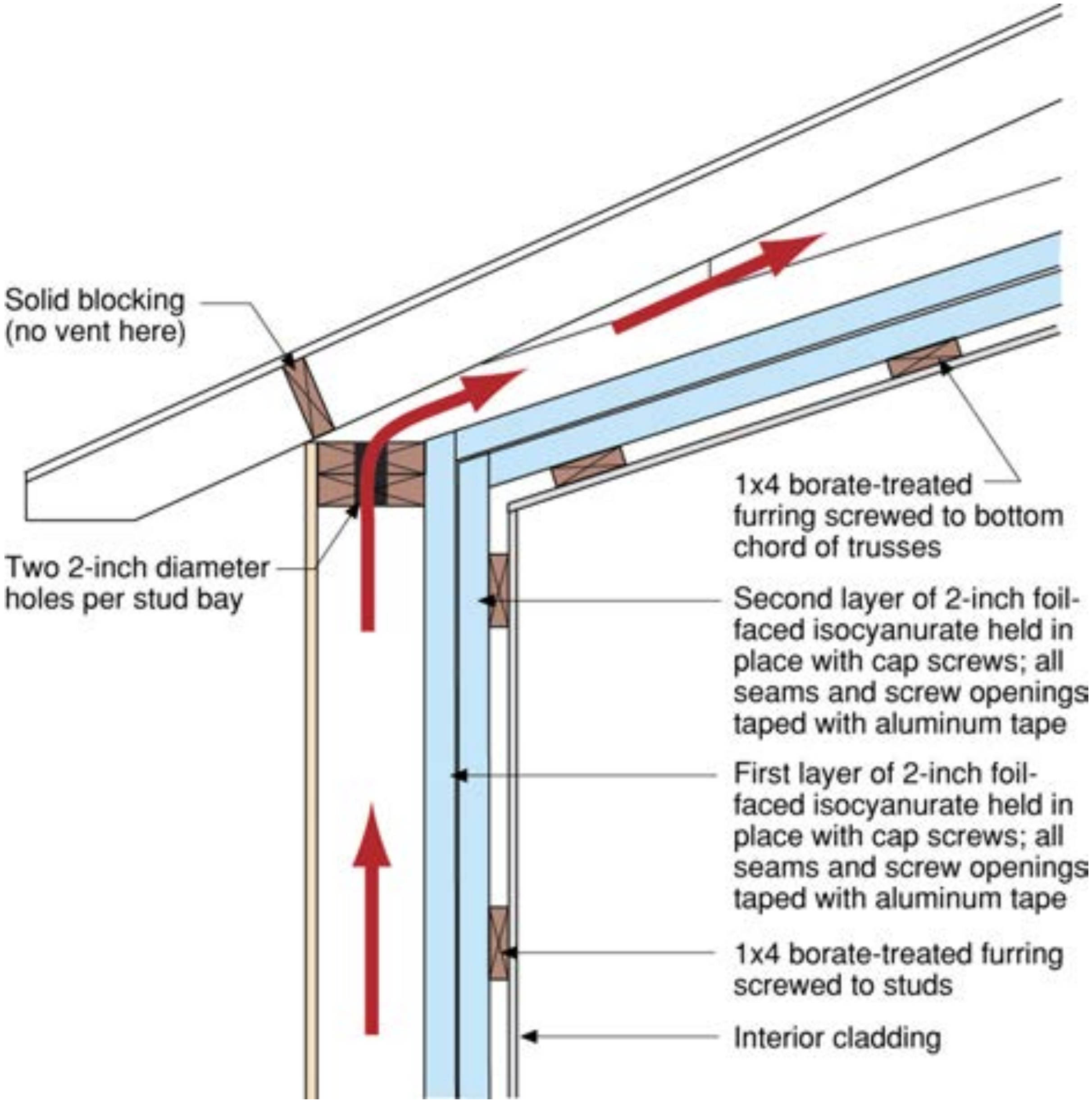


Figure 3: Supply Manifold



Second layer of 2-inch foil-faced isocyanurate held in place with cap screws; all seams and screw openings taped with aluminum tape
Two 2-inch diameter holes per stud bay block
Interior cladding
1x4 borate-treated furring screwed to studs
First layer of 2-inch foil-faced isocyanurate held in place with cap screws; all seams and screw openings taped with aluminum tape
One 4-inch diameter hole per stud bay
Sealant
Screened vent hood
New concrete slab (w/c ratio less than 0.45)
Epoxy coating on slab
Waterproof membrane taped to first layer of foil-faced isocyanurate
Ground slopes away from wall at 5% (6 in. per 10 ft.)


Solid blocking
(no vent here)
Two 2-inch diameter holes per stud bay
1x4 borate-treated furring screwed to bottom chord of trusses
Second layer of 2-inch foil-faced isocyanurate held in place with cap screws; all seams and screw openings taped with aluminum tape
First layer of 2-inch foil-faced isocyanurate held in place with cap screws; all seams and screw openings taped with aluminum tape
1x4 borate-treated furring screwed to studs
Interior cladding