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

Building Science

Adventures In Building Science

Mechanical Systems

Mechanical Systems

Cooling System To Make It Cold

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

Heating System To Make It Warm

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

Heating System To Make It Warm

Energy Recovery System To Keep It Cold and Dry and Warm and Comfortable

Mechanical Systems

Cooling System To Make It Cold

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Energy Recovery System To Keep It Cold and Dry and Warm and Comfortable

Distribution System To Make It Uniform

Mechanical Systems

Cooling System To Make It Cold

Dehumidification System To Make It Dry

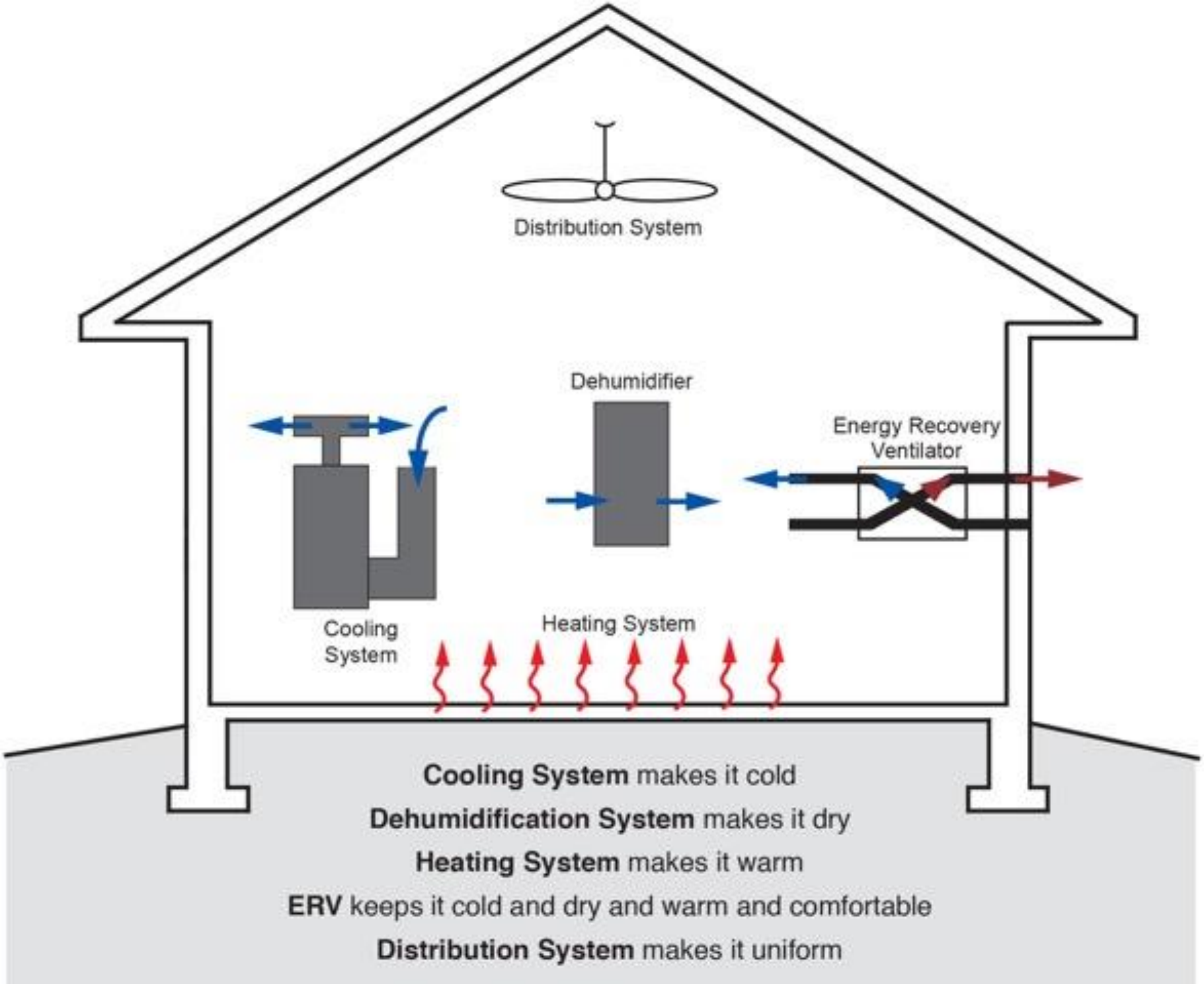
Heating System To Make It Warm

Energy Recovery System To Keep It Cold and Dry and Warm and Comfortable

Distribution System To Make It Uniform

Range Hoods Are A Special Kind of Hell

Don’t Try to Combine Them…...


Distribution System
Dehumidifier
Energy Recovery Ventilator
Cooling System
Heating System
Cooling System makes it cold
Dehumidification System makes it dry
Heating System makes it warm
ERV keeps it cold and dry and warm and comfortable
Distribution System makes it uniform

Build Tight - Ventilate Right

Build Tight - Ventilate Right

How Tight?

What’s Right?

Air Barrier Metrics

Material	0.02 l/(s-m2) @ 75 Pa
Assembly	0.20 l/(s-m2) @ 75 Pa
Enclosure	2.00 l/(s-m2) @ 75 Pa
	0.25 cfm/ft2 @ 50 Pa

Getting rid of big holes	3 ach@50
Getting rid of smaller holes	1.5 ach@50
Getting German	0.6 ach@50

Best

As Tight as Possible - with -

Balanced Ventilation

Energy Recovery

Distribution and Mixing

Source Control - Spot exhaust ventilation

Filtration

Material selection

Worst

Leaky - with – Nothing

Spot Ventilation in Bathroom/Kitchen

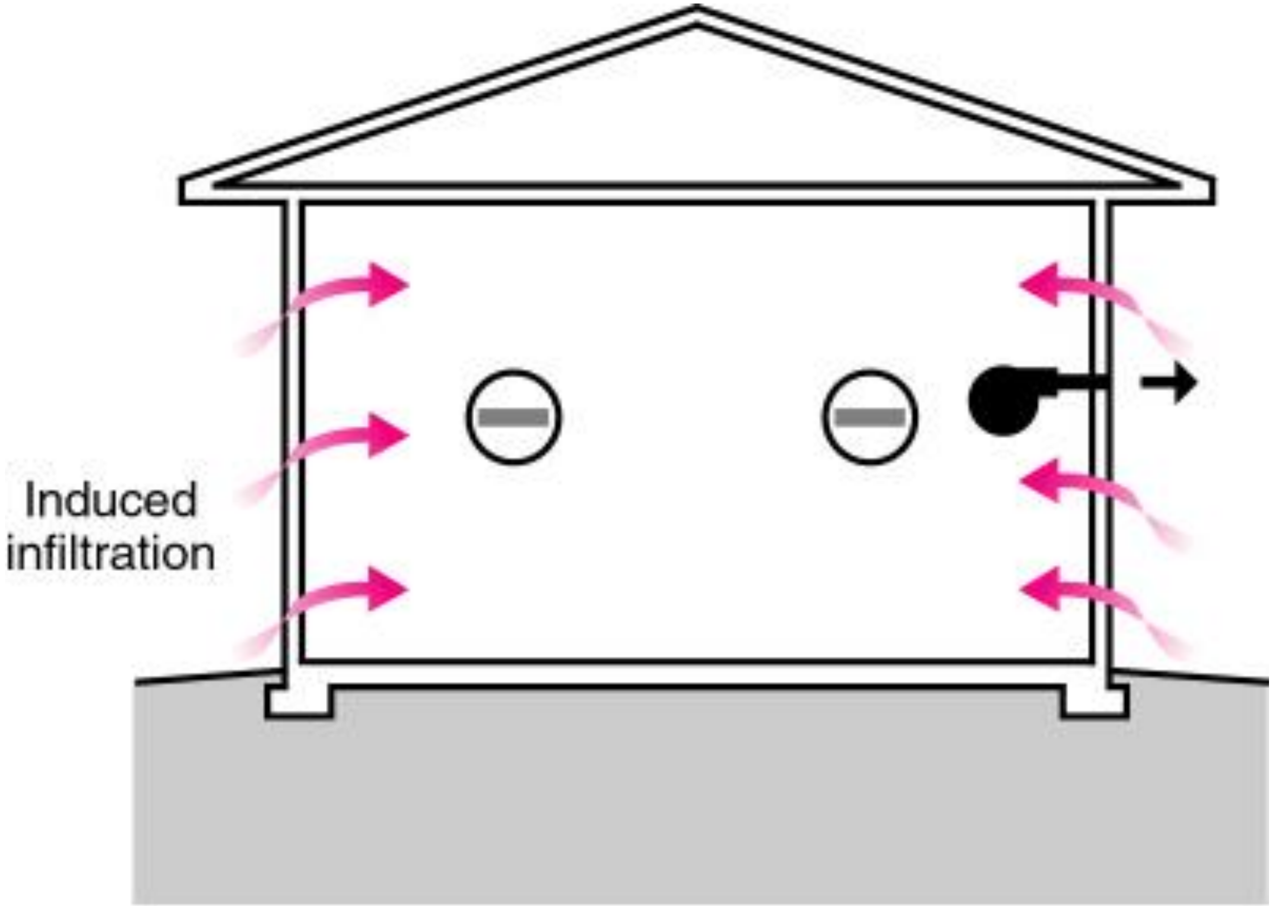
Exhaust Ventilation – with – No Distribution and No Mixing

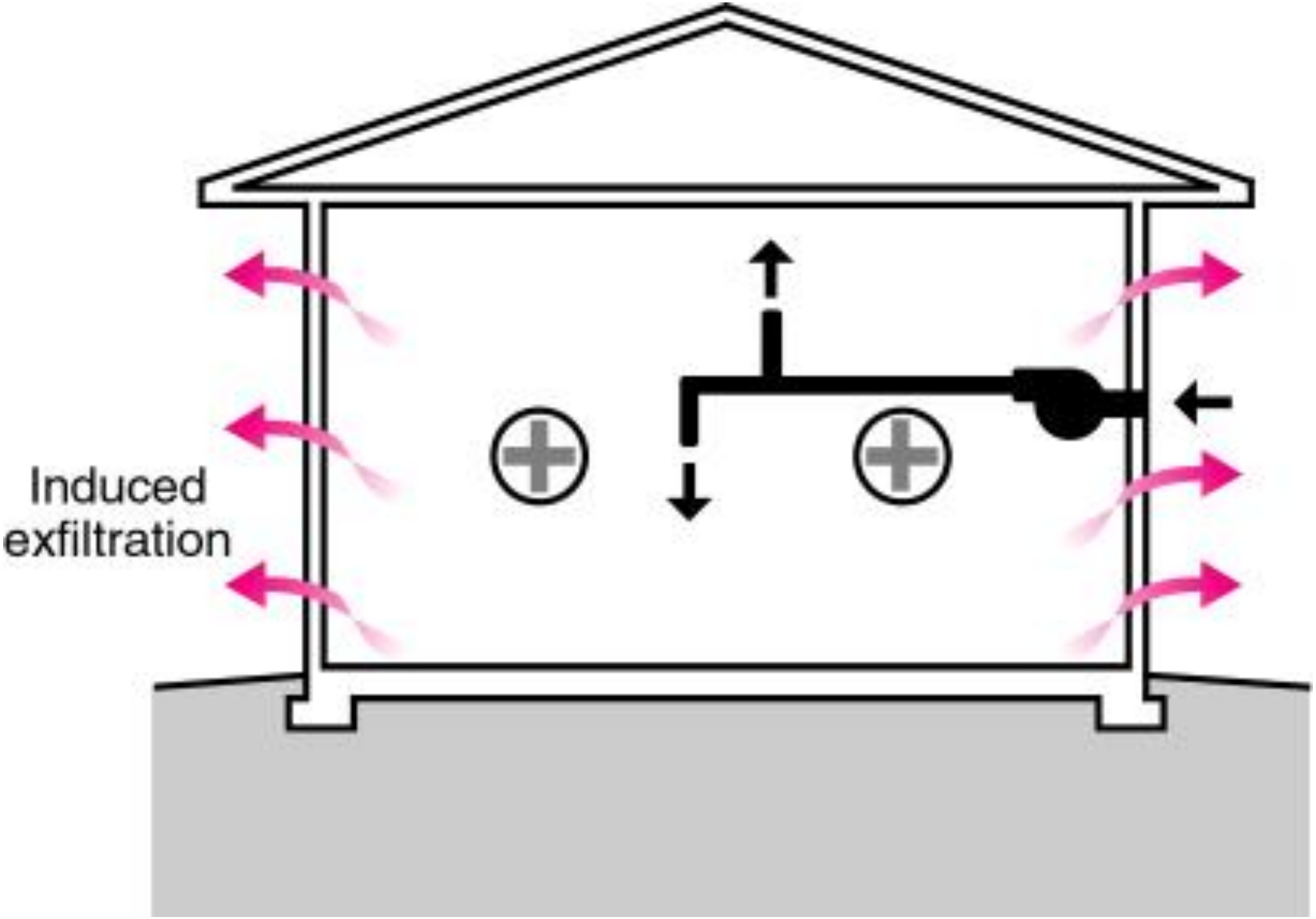
Three Types of Controlled Ventilation Systems

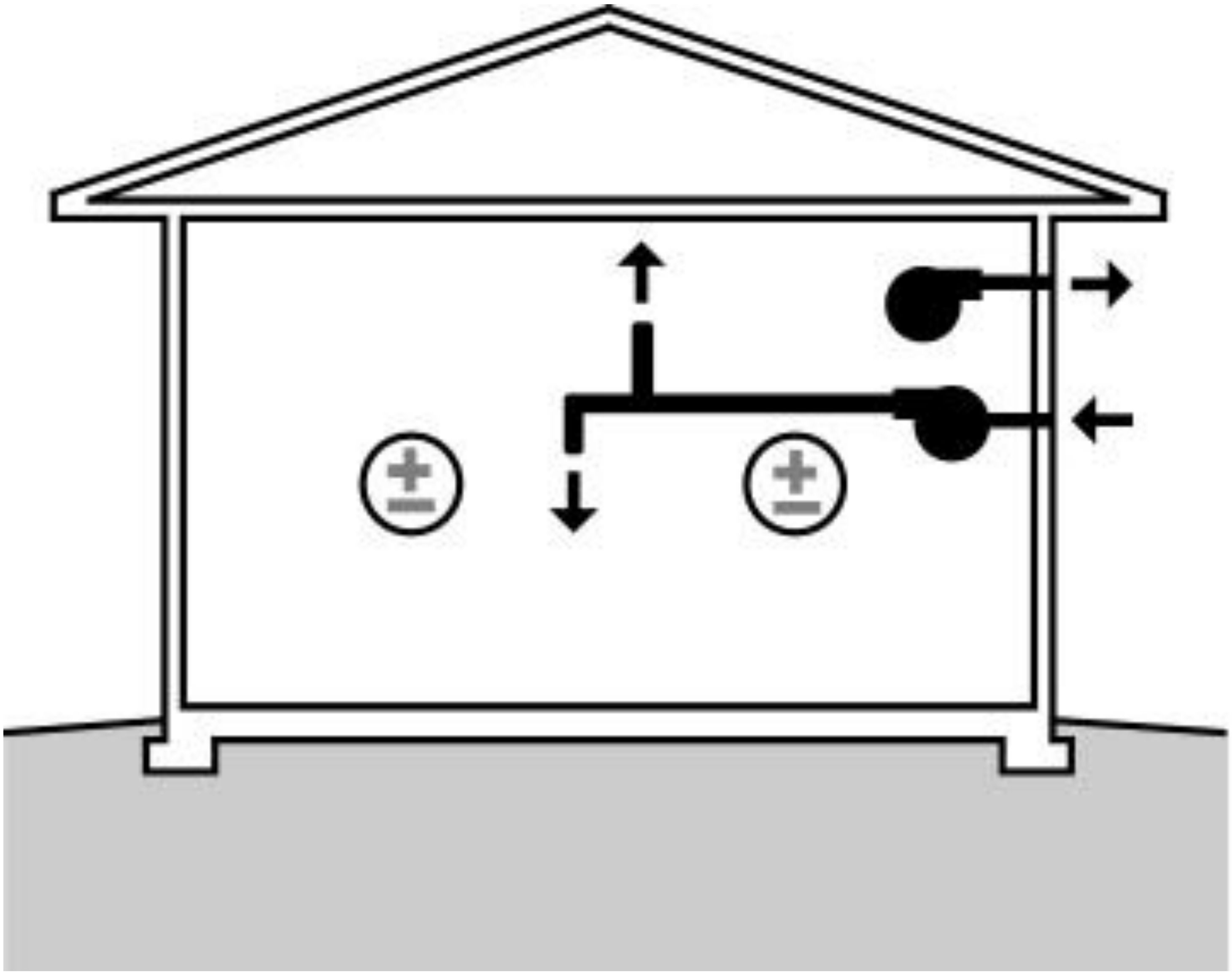
Exhaust Ventilation

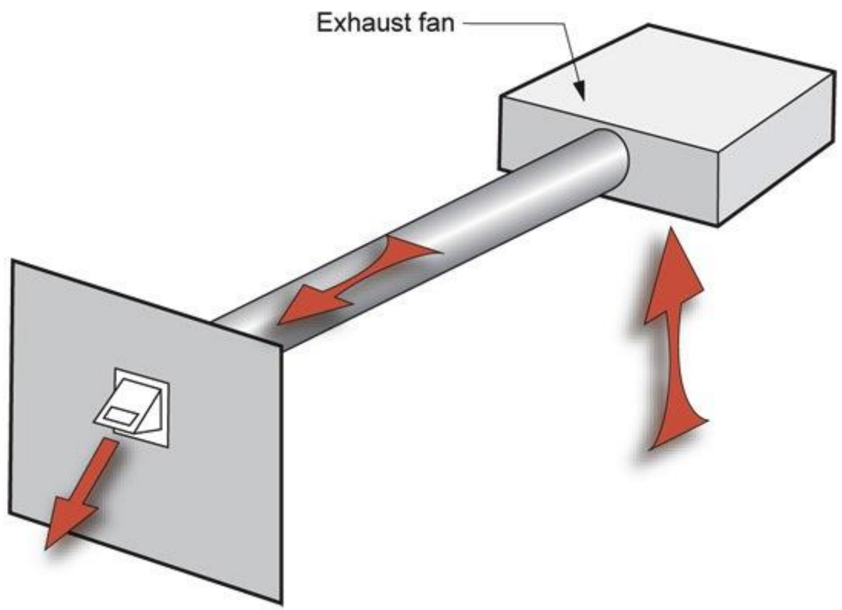
Supply Ventilation

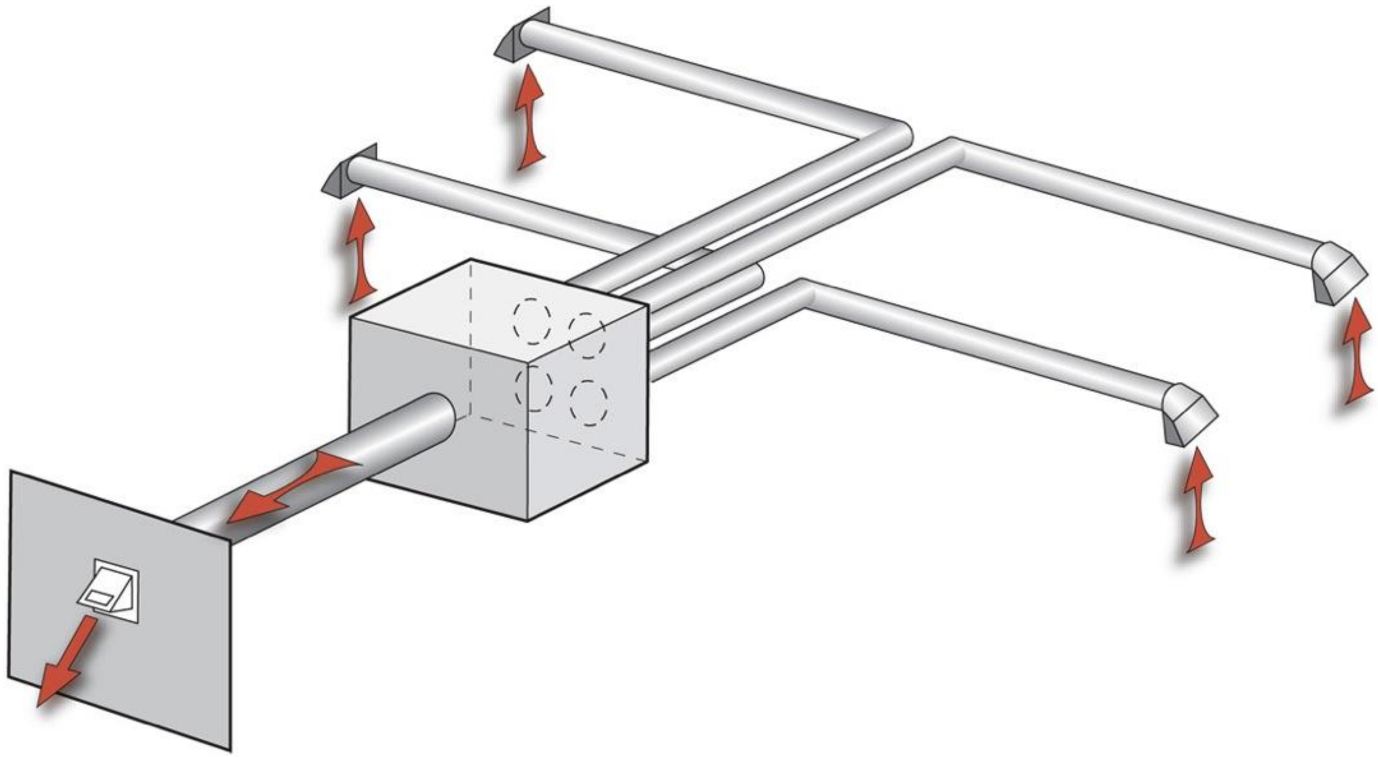
Balanced Ventilation

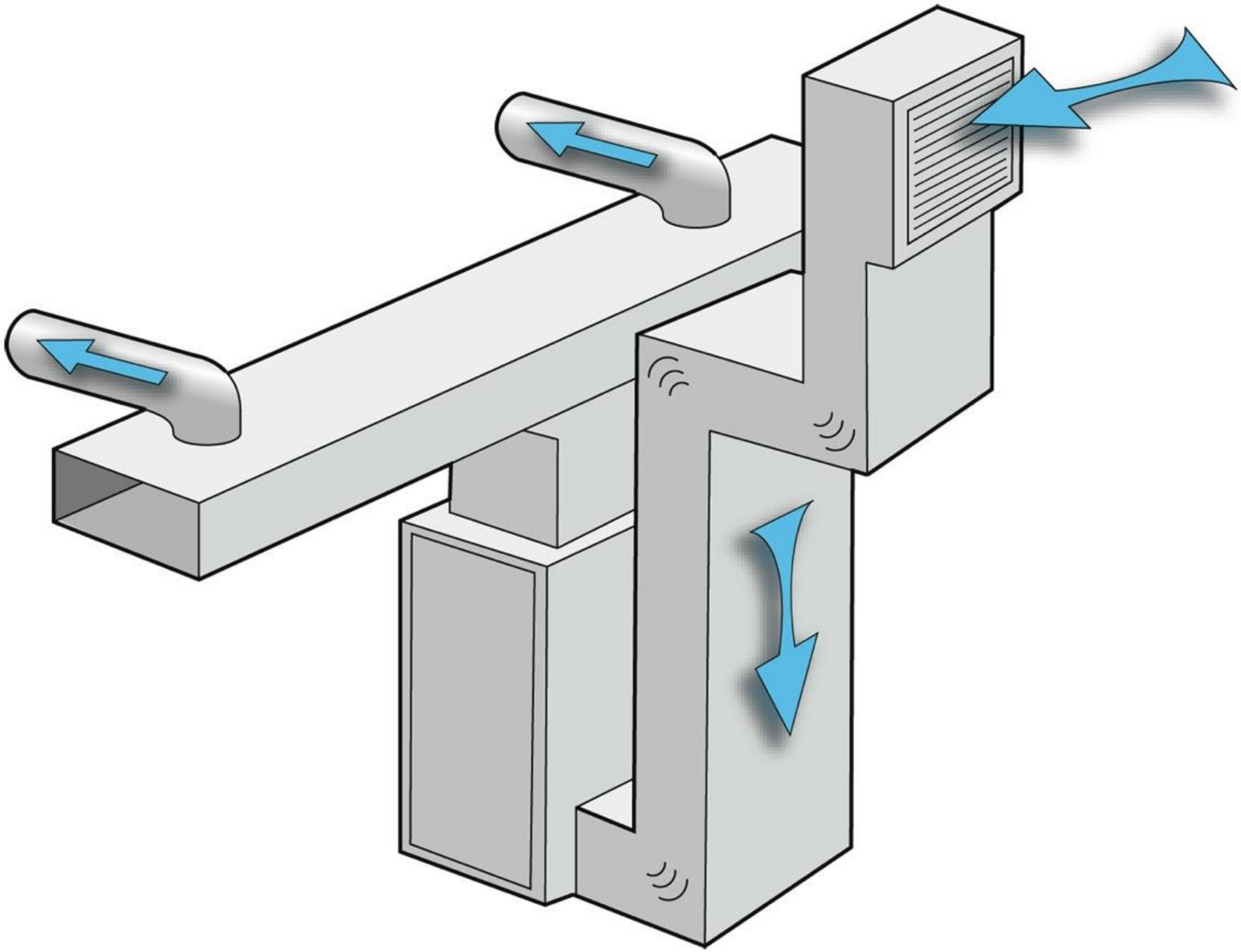

Induced
infiltration

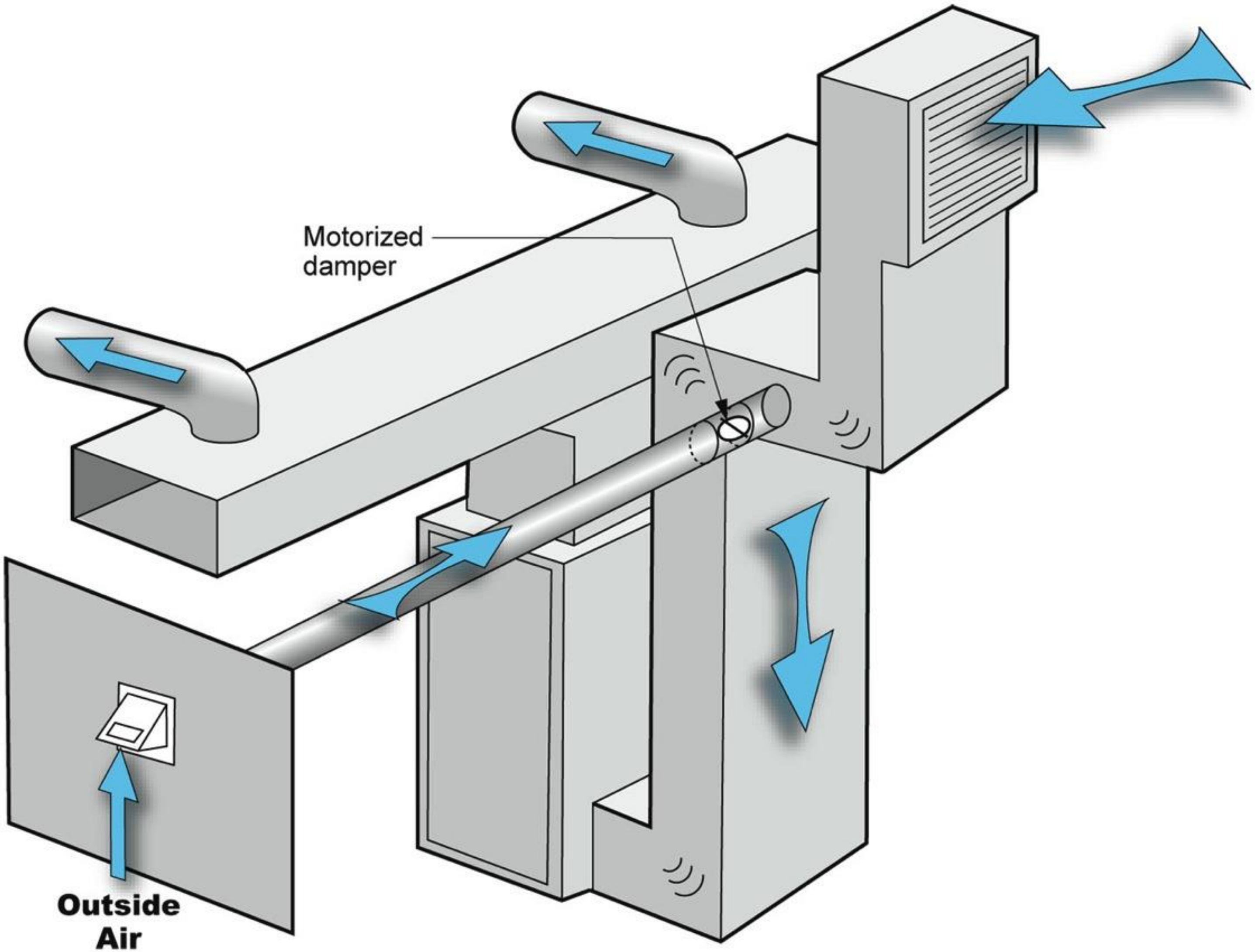

Induced
exfiltration

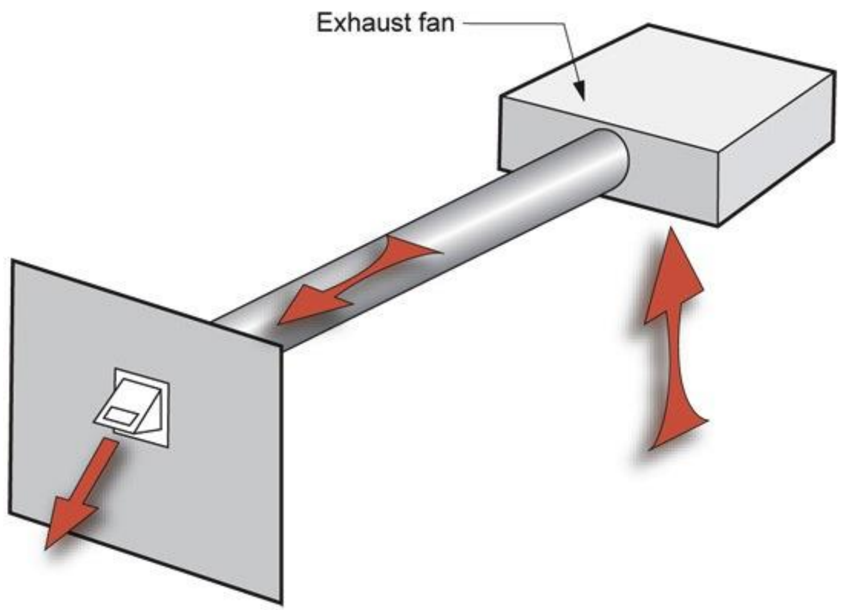


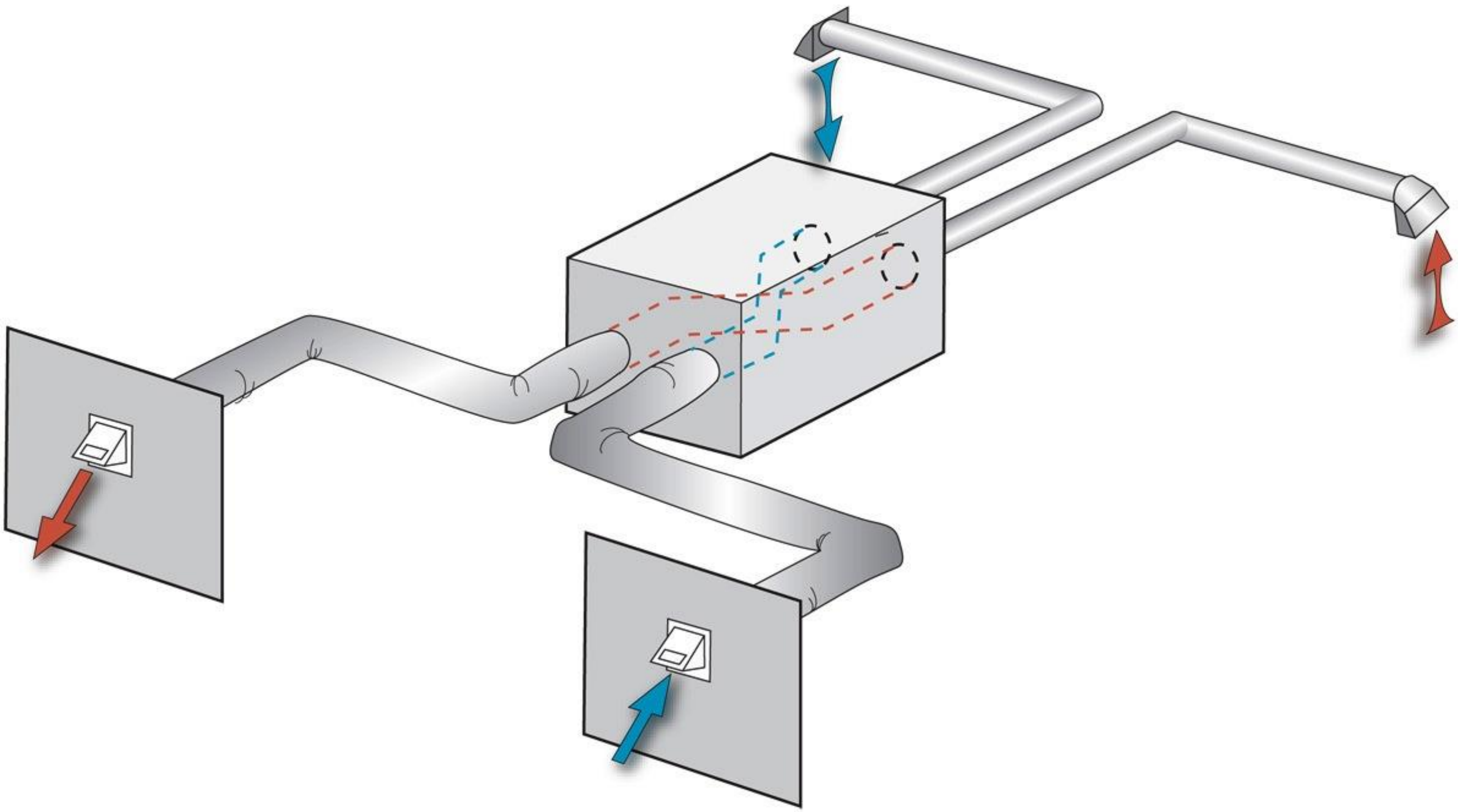

Exhaust fan






Motorized
damper
Outside
Air


Exhaust fan



Ventilation Rates Are Based on Odor Control

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Health Science Basis for Ventilation Rates is Extremely Limited

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Almost Nothing Cited Applies to Housing

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Health Science Basis for Ventilation Rates is Extremely Limited

Almost Nothing Cited Applies to Housing

The Applicable Studies Focus on Dampness

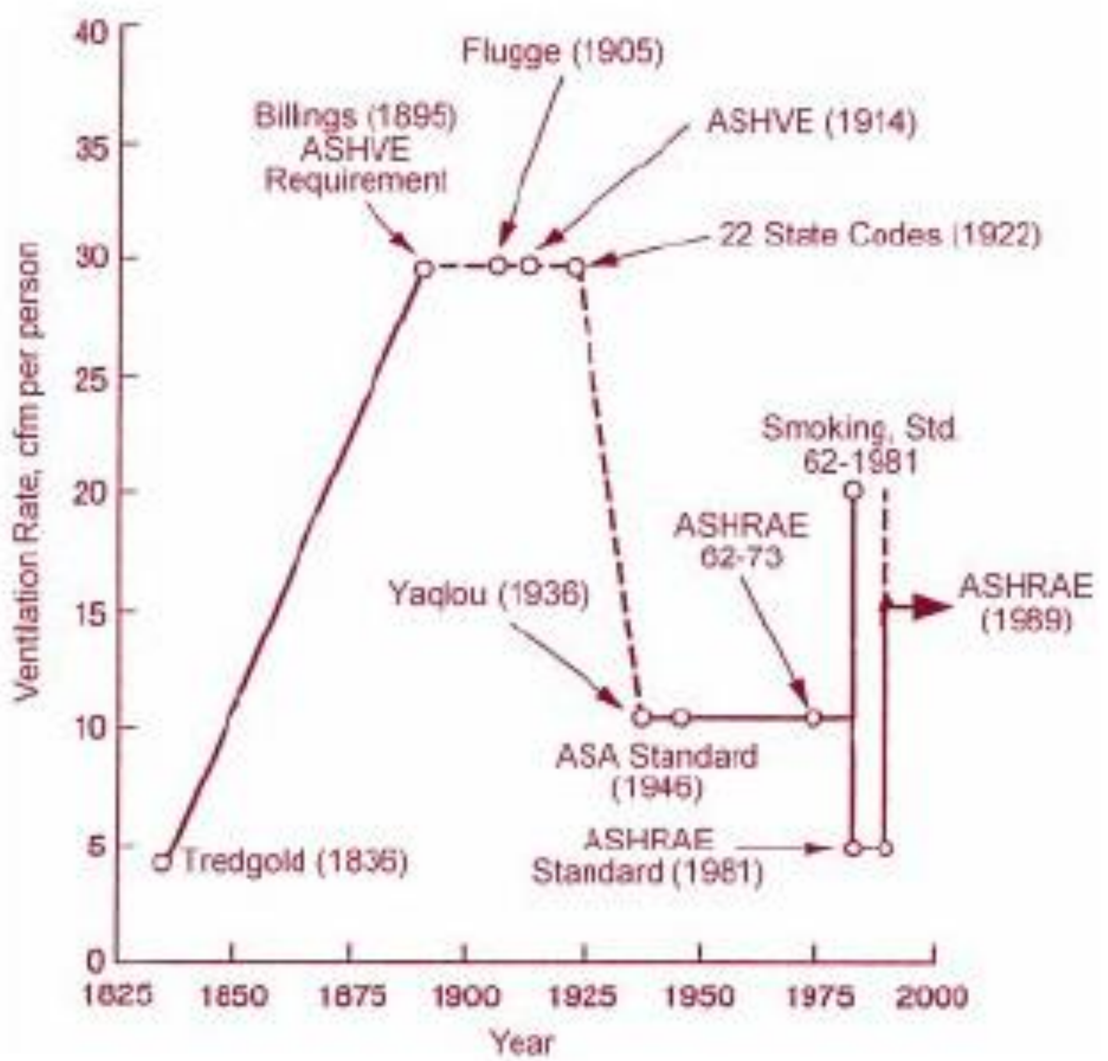

Figure 1: Minimum ventilating rate history.

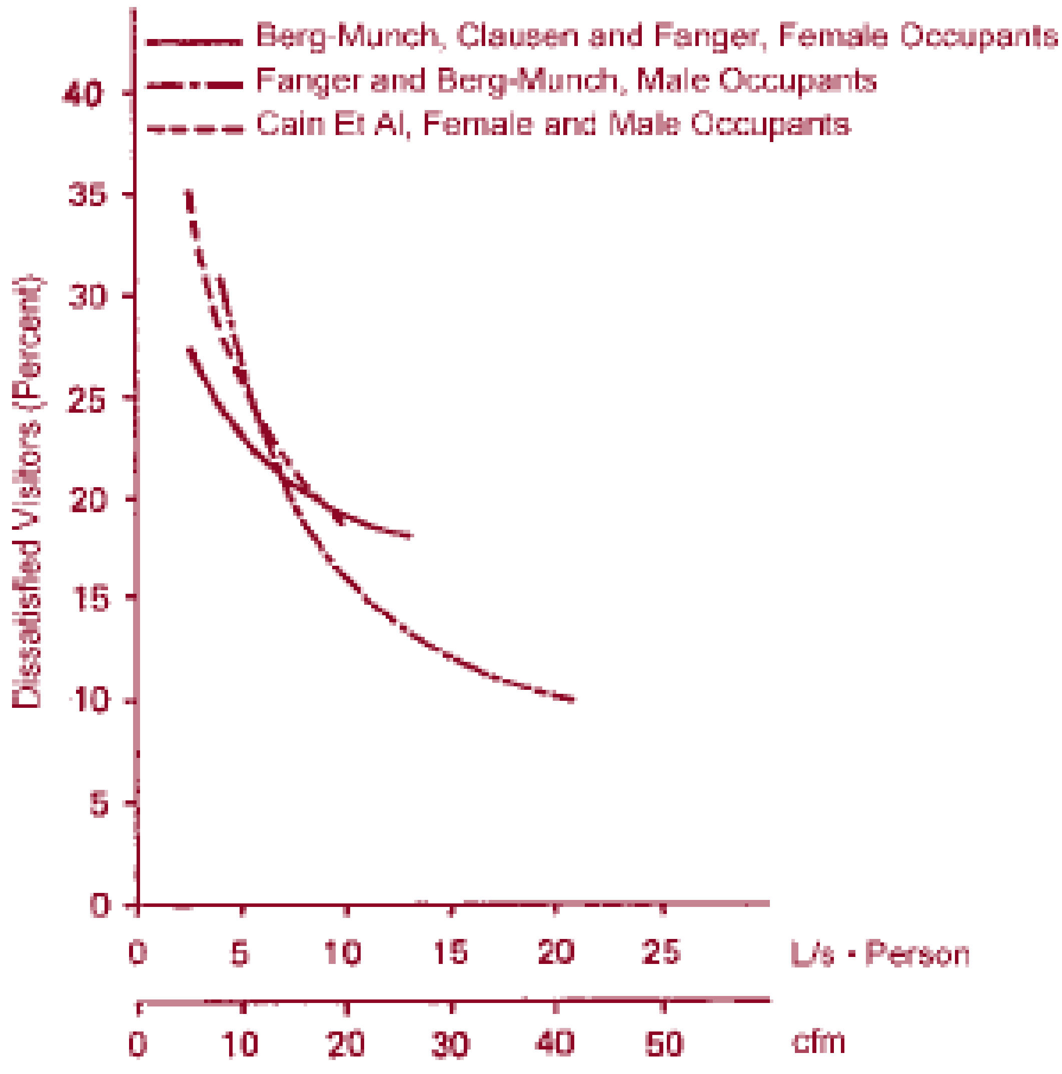

Figure 2: Odor acceptance.

House

2,000 ft^2
3 bedrooms
8 ft. ceiling
Volume: 16,000 ft^3

.35 ach	93 cfm
.30 ach	80 cfm
.25 ach	67 cfm
.20 ach	53 cfm
.15 ach	40 cfm

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Ventilation Rates

62 - 73	5 cfm/person	20 cfm
	10 cfm/person	40 cfm
62 - 89	15 cfm/person	60 cfm
	.35 ach	90 cfm
62.2 - 2010	7.5 cfm/person + 0.01	50 cfm
62.2 - 2013	7.5 cfm/person + 0.03	90 cfm

Office

Occupant Density

15/1000 ft^2 (67 ft^2/person) 15 cfm/person	62 - 89
5/1000 ft^2 (200 ft^2/person) 17 cfm/person	62.1 - 2007

Correctional Facility Cell

Occupant Density

20/1000 ft^2 (48 ft^2/person) 10 cfm/person	62.1 – 2007

C.P. Yaglou

Harvard School of Public Health
1936
1955

$150\ ft^3$ → 20 cfm/person

$300\ ft^3$ → 12 cfm/person

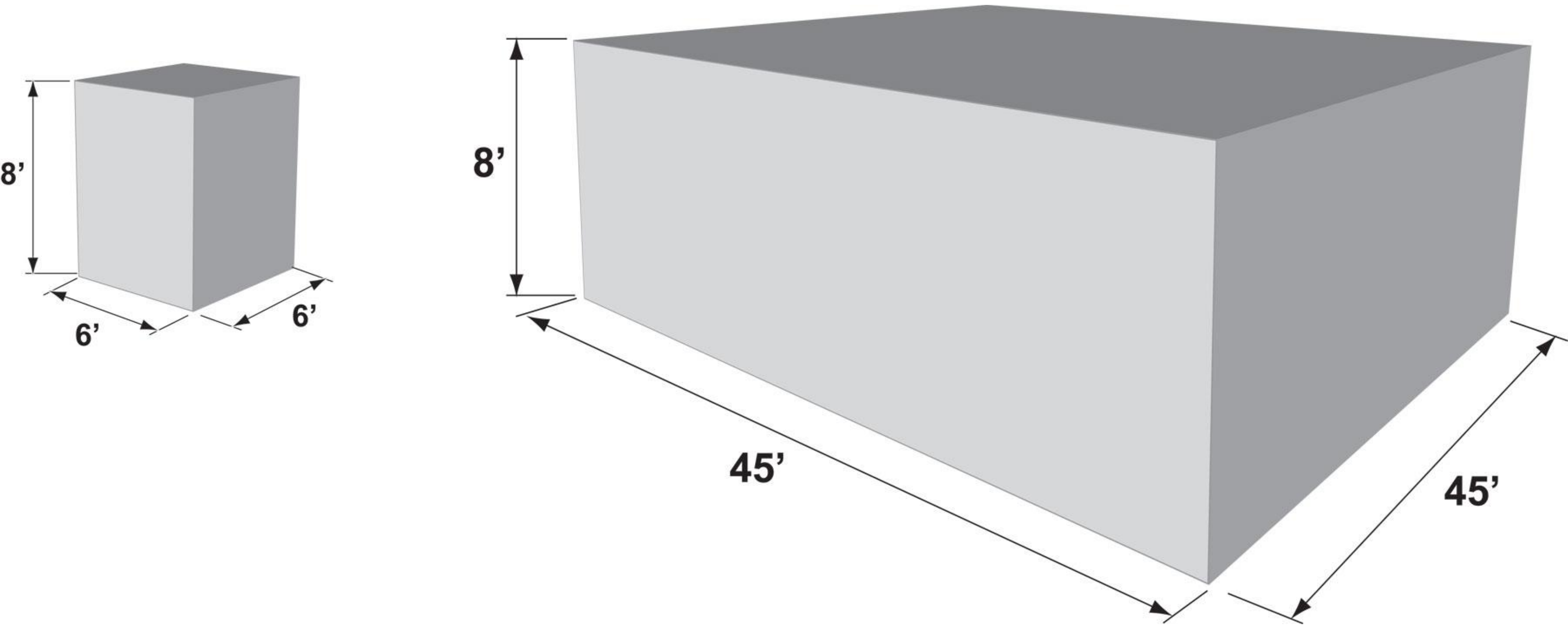
C.P. Yaglou

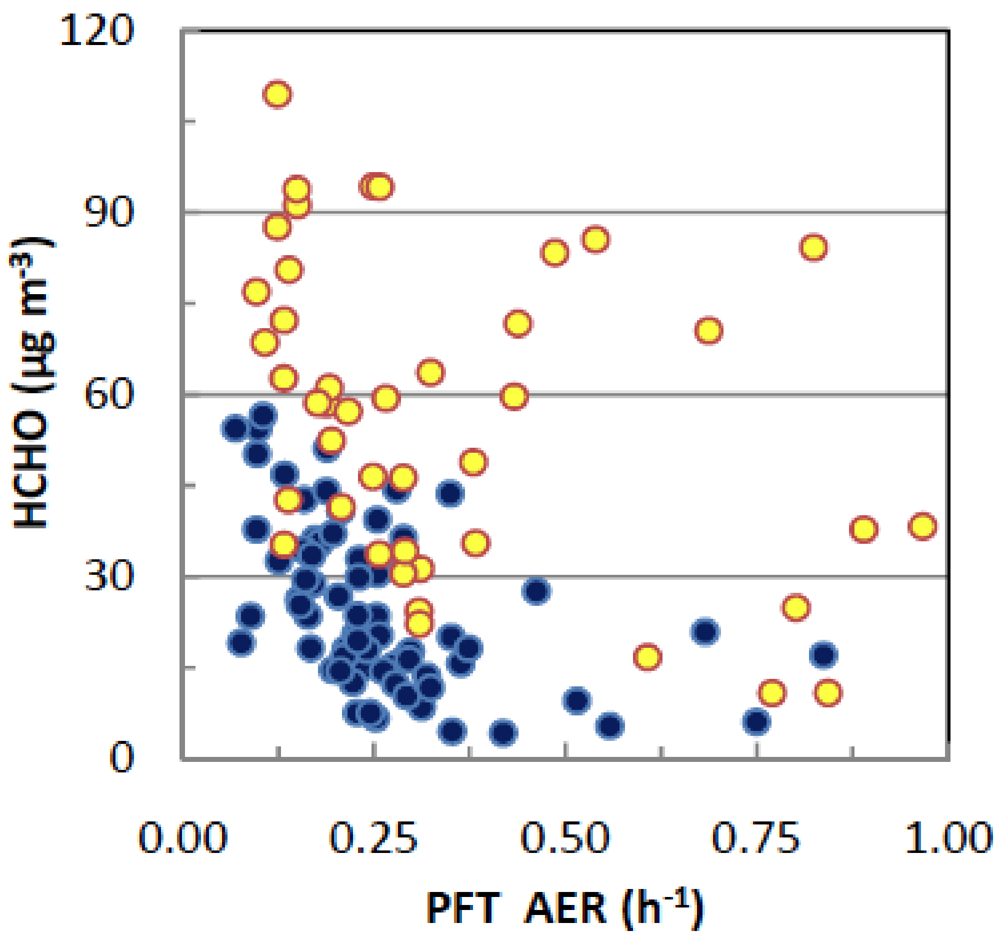
Harvard School of Public Health
1936
1955

150 ft^3	→	20 cfm/person	18.75 ft^2	106 occupants
300 ft^3	→	12 cfm/person	37.5 ft^2	53 occupants

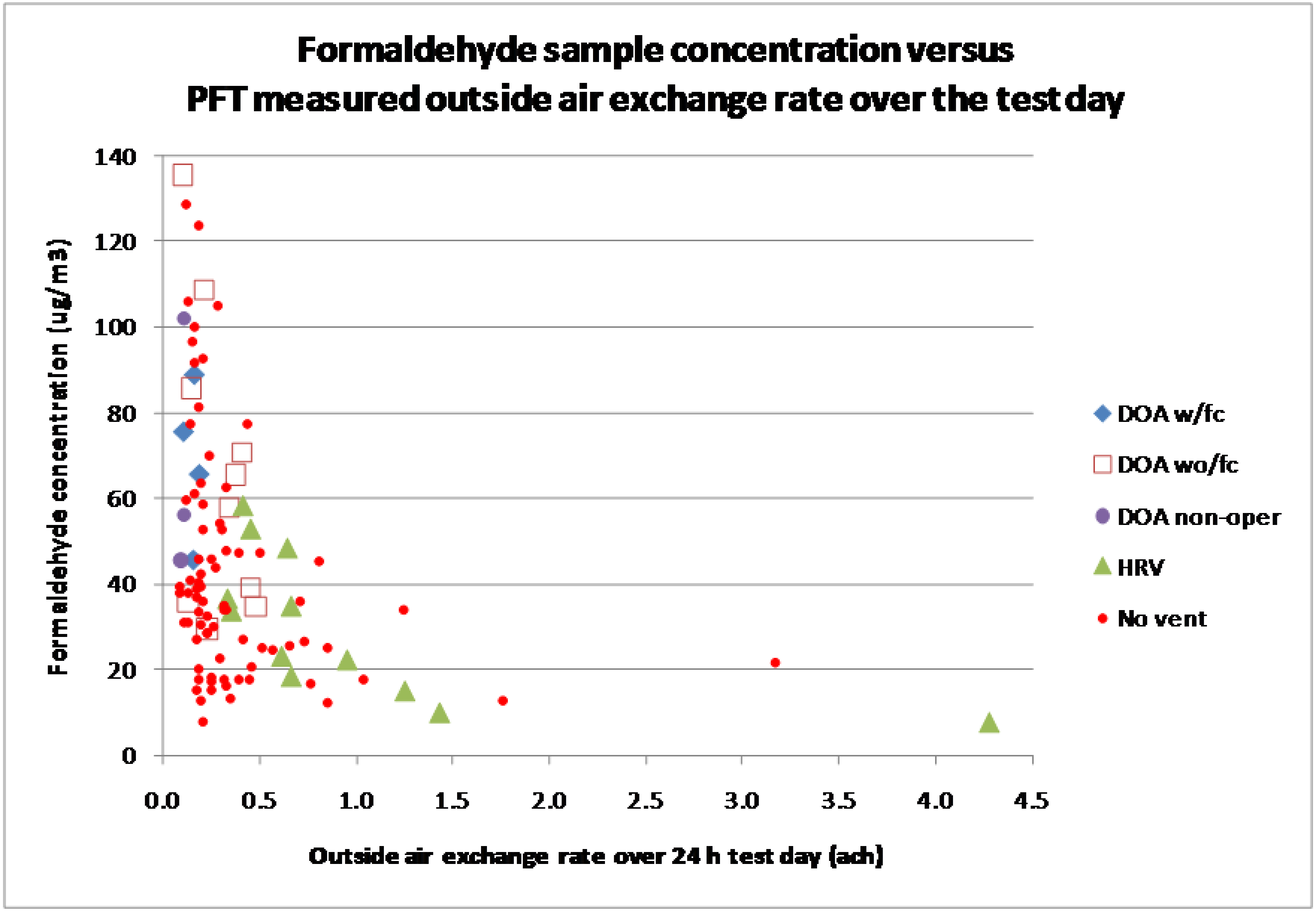
Experiment

470 ft^3	→	59 ft^2
200 ft^3	→	25 ft^2
100 ft^3	→	12 ft^2


8’
6’
6’
8’
45’
45’



Aubin, D., Won, D.Y., Schleibinger, H., 2010


Formaldehyde sample concentration versus
PFT measured outside air exchange rate over the test day
Formaldehyde concentration (ug/m3)
140
120
100
80
60
40
20
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Outside air exchange rate over 24 h test day (ach)
DOA w/fc
DOA wo/fc
DOA non-oper
HRV
No vent

ASHRAE Standard 62.2 calls for 7.5 cfm per person plus 0.03 cfm per square foot of conditioned area

Occupancy is deemed to be the number of bedrooms plus one

ASHRAE Standard 62.2 calls for 7.5 cfm per person plus 0.03 cfm per square foot of conditioned area

Occupancy is deemed to be the number of bedrooms plus one

Outcome is often bad – part load humidity problems, dryness problems, energy problems

- IRC 2015 and 2018 calls for 7.5 cfm per person plus 0.01 cfm per square foot of conditioned area
- Occupancy is deemed to be the number of bedrooms plus one

3 Bedroom House – 2,500 ft2

30 cfm plus 75 cfm

105 cfm

3 Bedroom House – 2,500 ft2

30 cfm plus 25 cfm

55 cfm

The Cult of The Blower Door

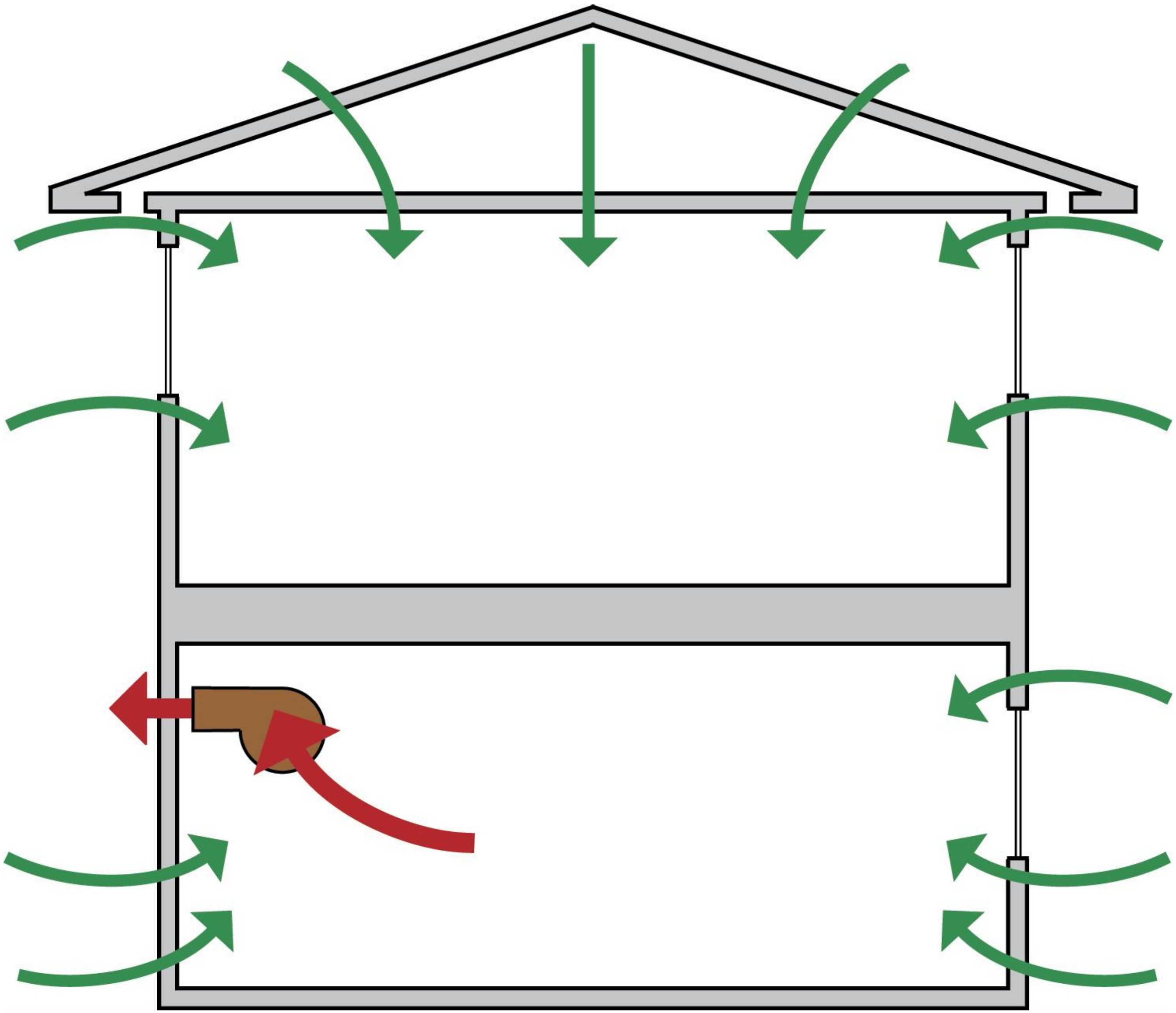
Blower Door Can’t Get You The True ACH

On A Short Term Basis – Hour, Day, Week

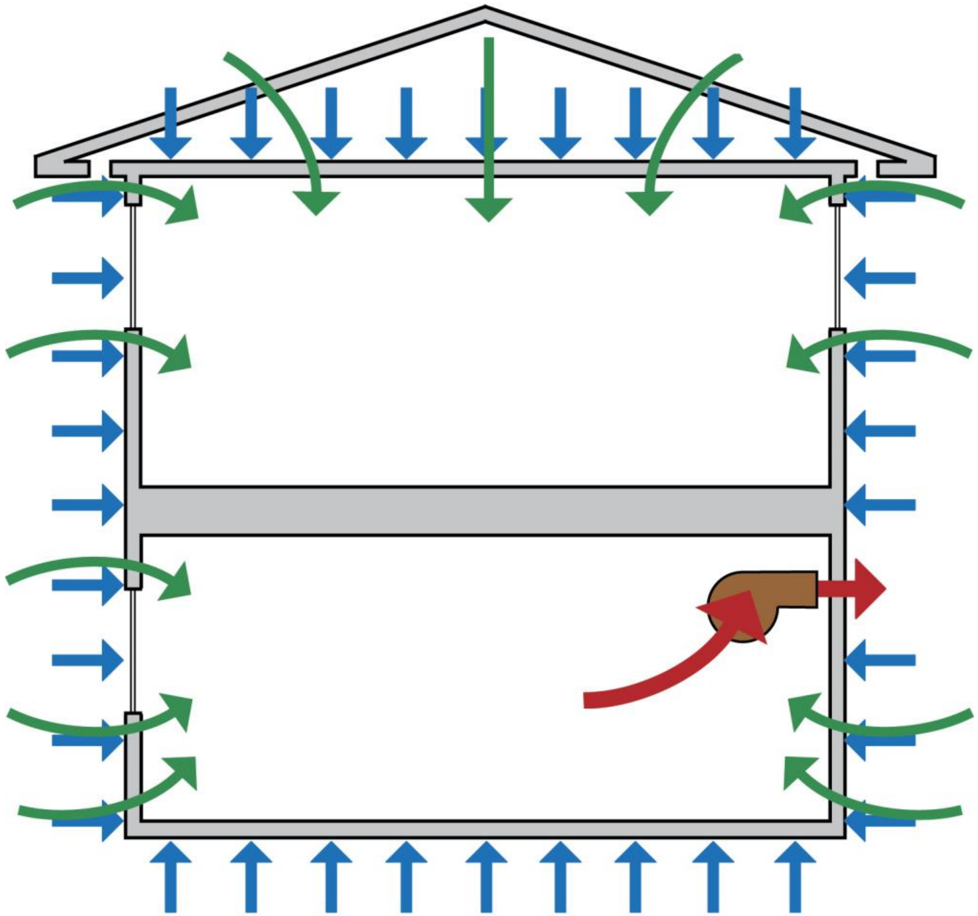
Don’t Know Where The Holes Are

Don’t Know The Type of Holes

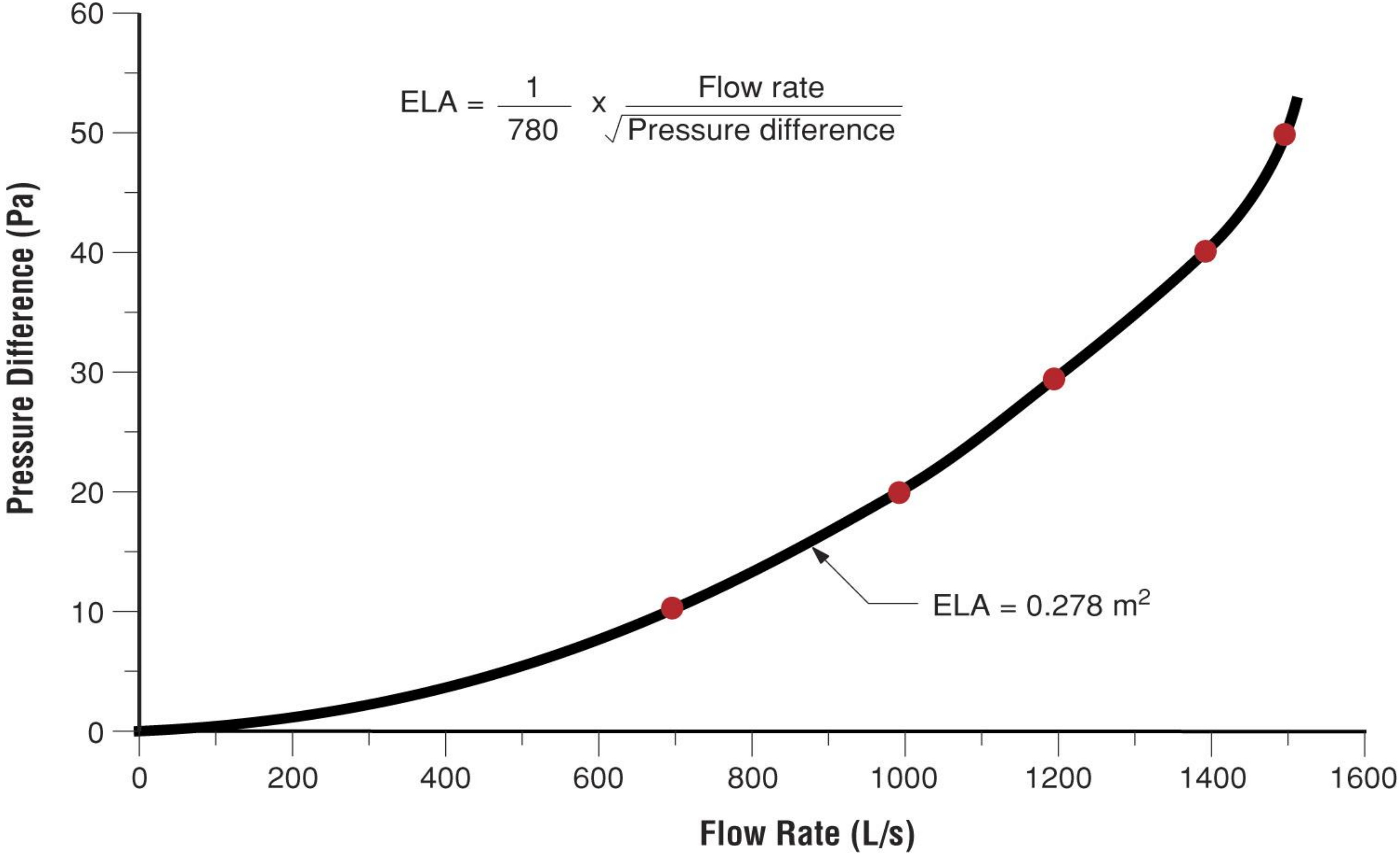
Don’t Know The Pressure Across The Holes



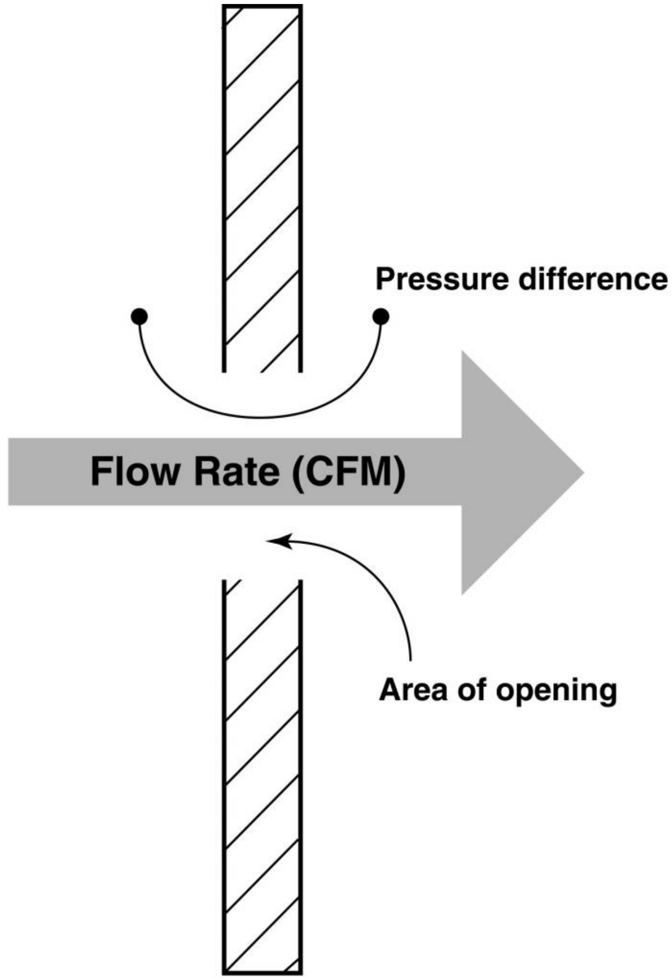
$$\text{ELA} \approx C \times \frac{\text{Rate of flow}}{\sqrt{\text{Pressure difference}}}$$



$$(\text{Meters})^2 \approx \frac{1}{780} \times \frac{\text{Litres per second}}{\sqrt{\text{Pascals}}}$$



$$ELA = \frac{1}{780} \times \frac{\text{Flow rate}}{\sqrt{\text{Pressure difference}}}$$
ELA = 0.278 m^2
Pressure Difference (Pa)
Flow Rate (L/s)
0
10
20
30
40
50
60
0
200
400
600
800
1000
1200
1400
1600


Pressure difference
Flow Rate (CFM)
Area of opening

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

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

Bernoulli

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

Darcy

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

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

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

Bernoulli

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

Darcy

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

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

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

Kronval "an engineer"

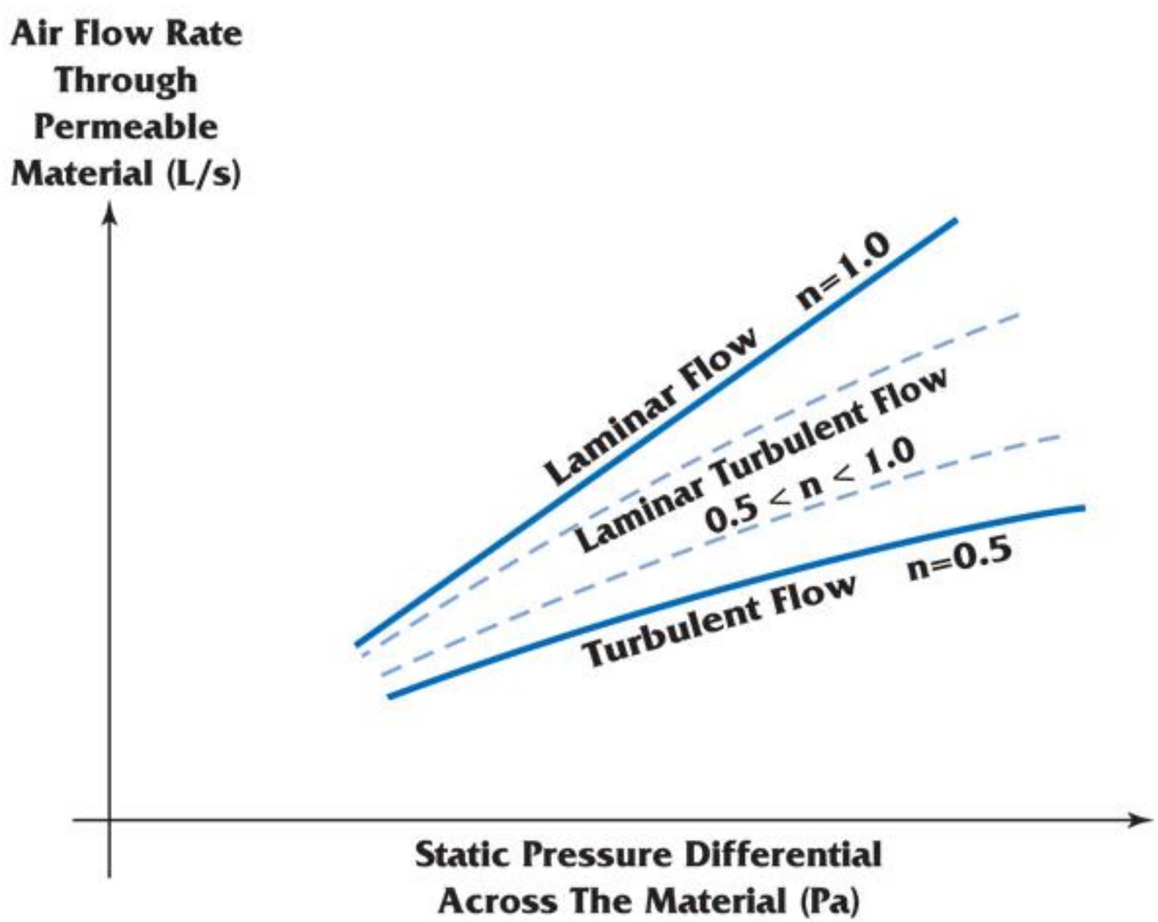
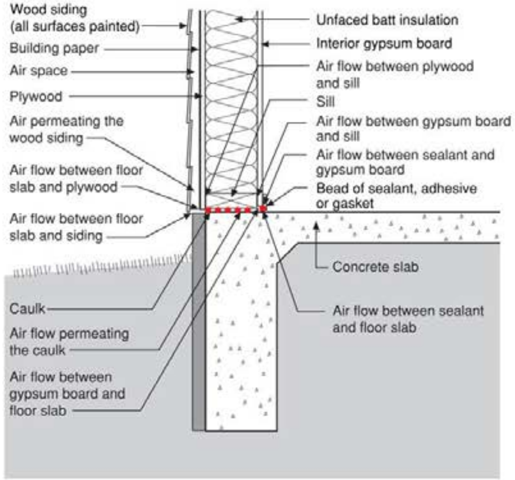
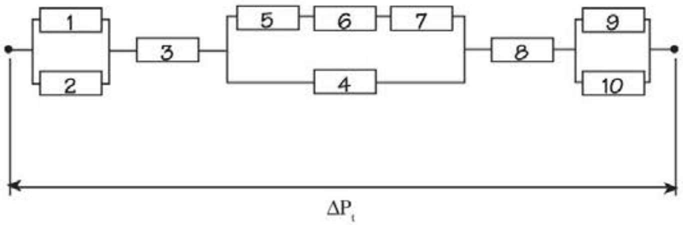


Figure 2.5
Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)



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)

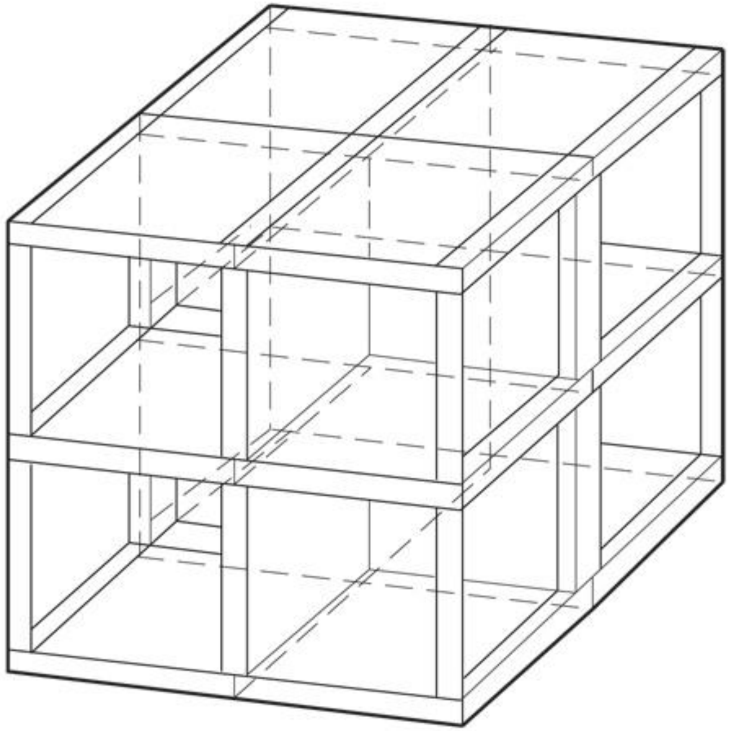
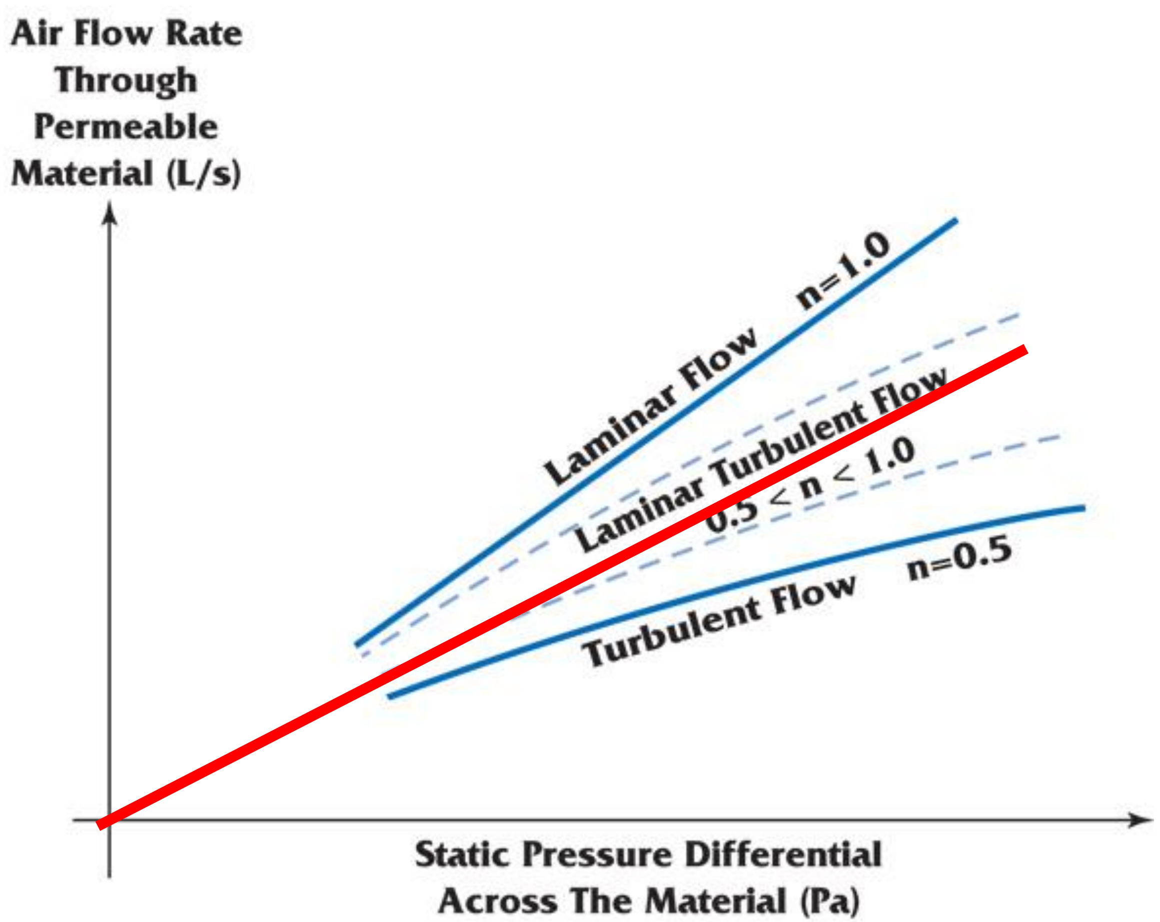


Figure 2.11
Three Dimensional Multi-Layer Multi-Cell Analogue



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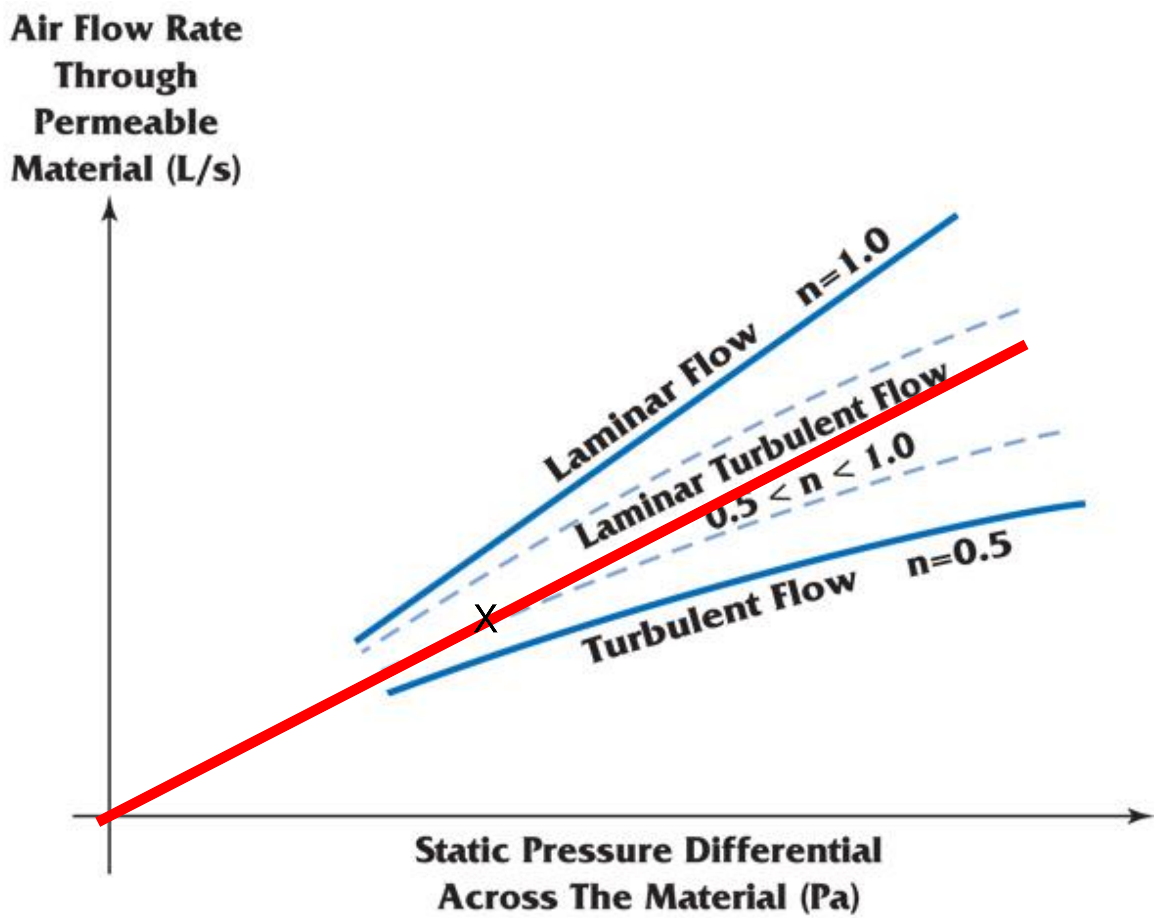

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Q = f (Dp) » k (Dp)^{b}

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

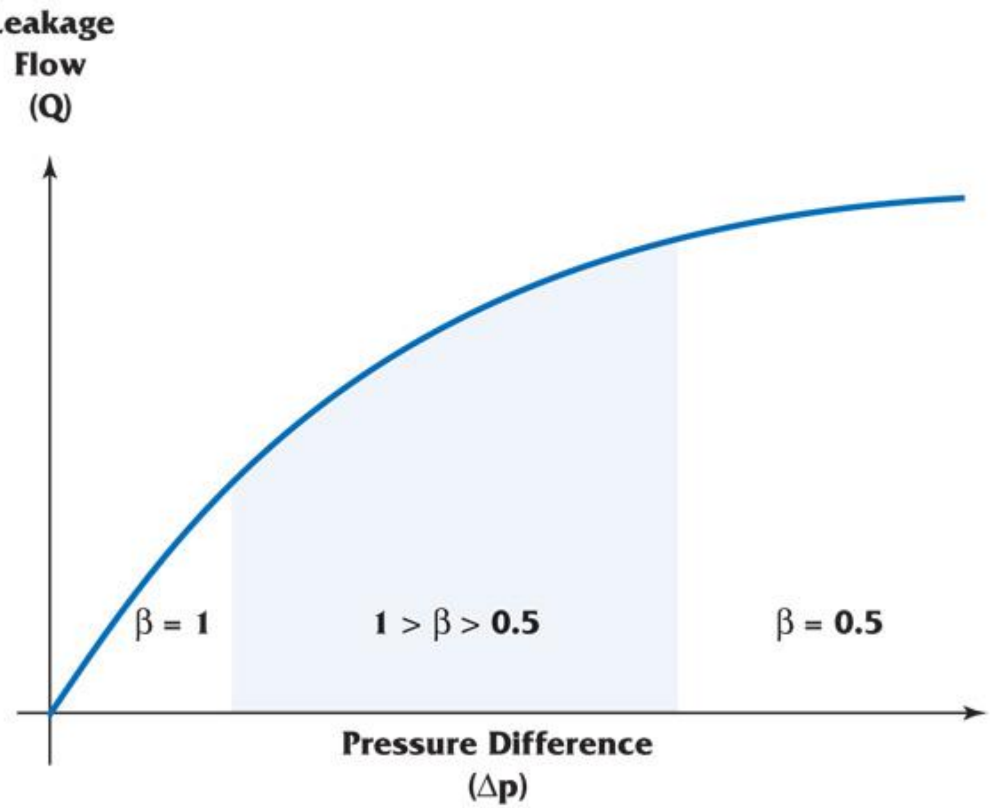


Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)

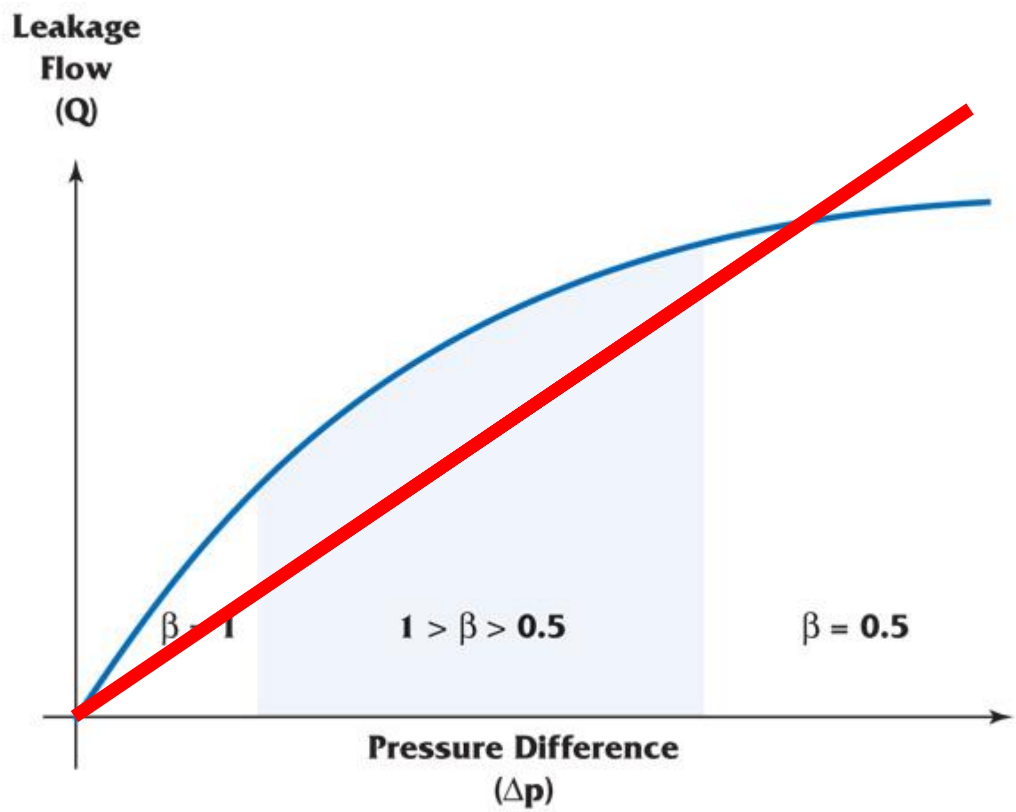
$$\mathbf{Q = f\ (Dp)\ » \ k\ (Dp)^{b}}$$

Q = air flow, volume/unit of time

D**p** = pressure difference

k = coefficient

b = exponent in approximate leakage function



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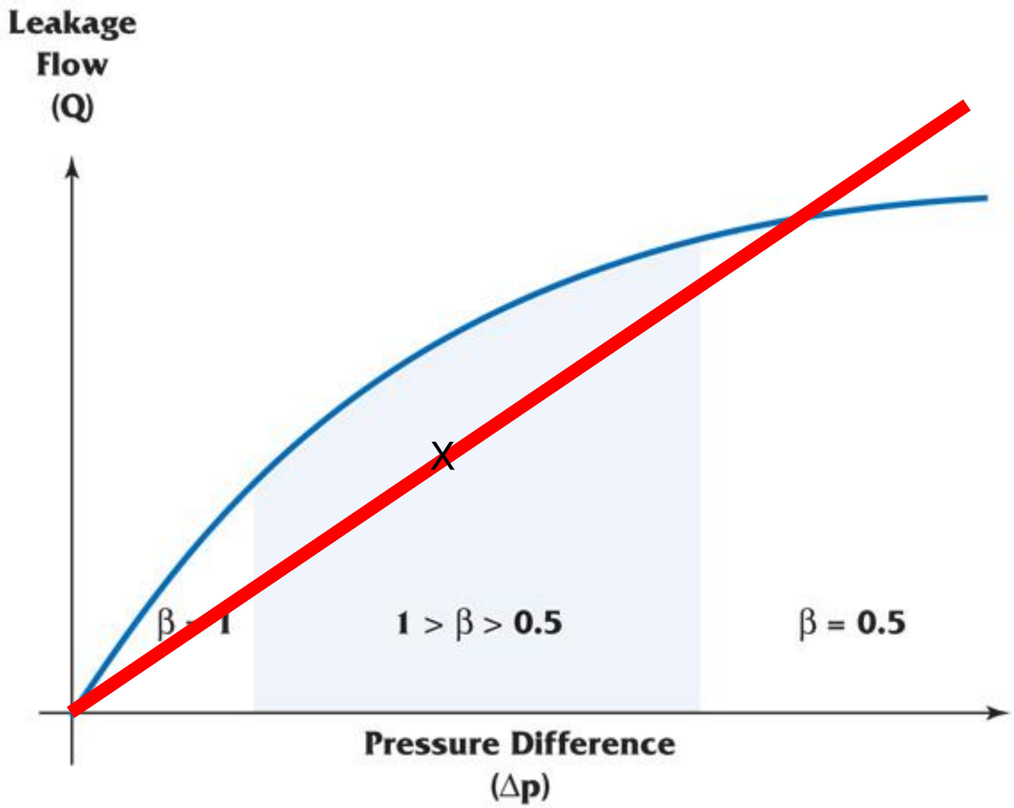

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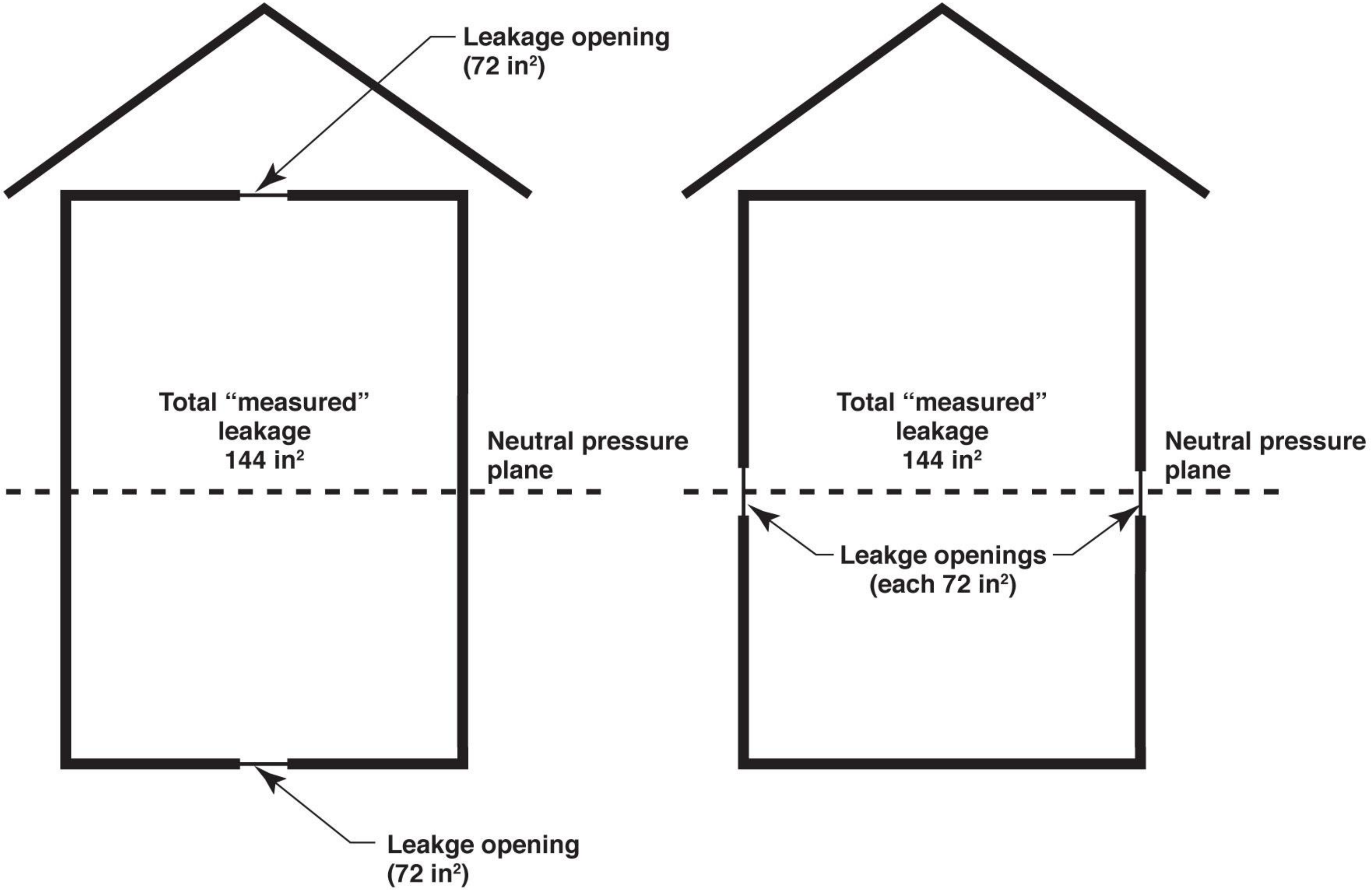


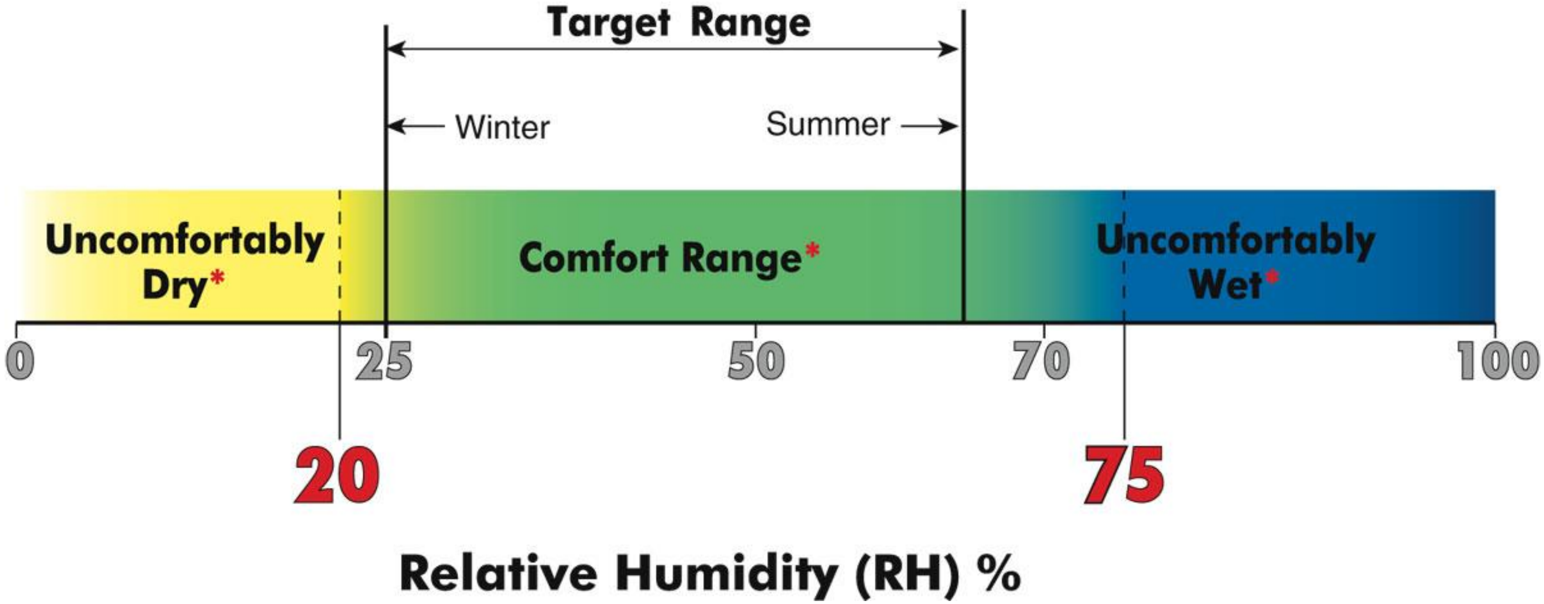
Leakage area

Dilution Is Not The Solution To Indoor Pollution

Source Control

Dilution For People

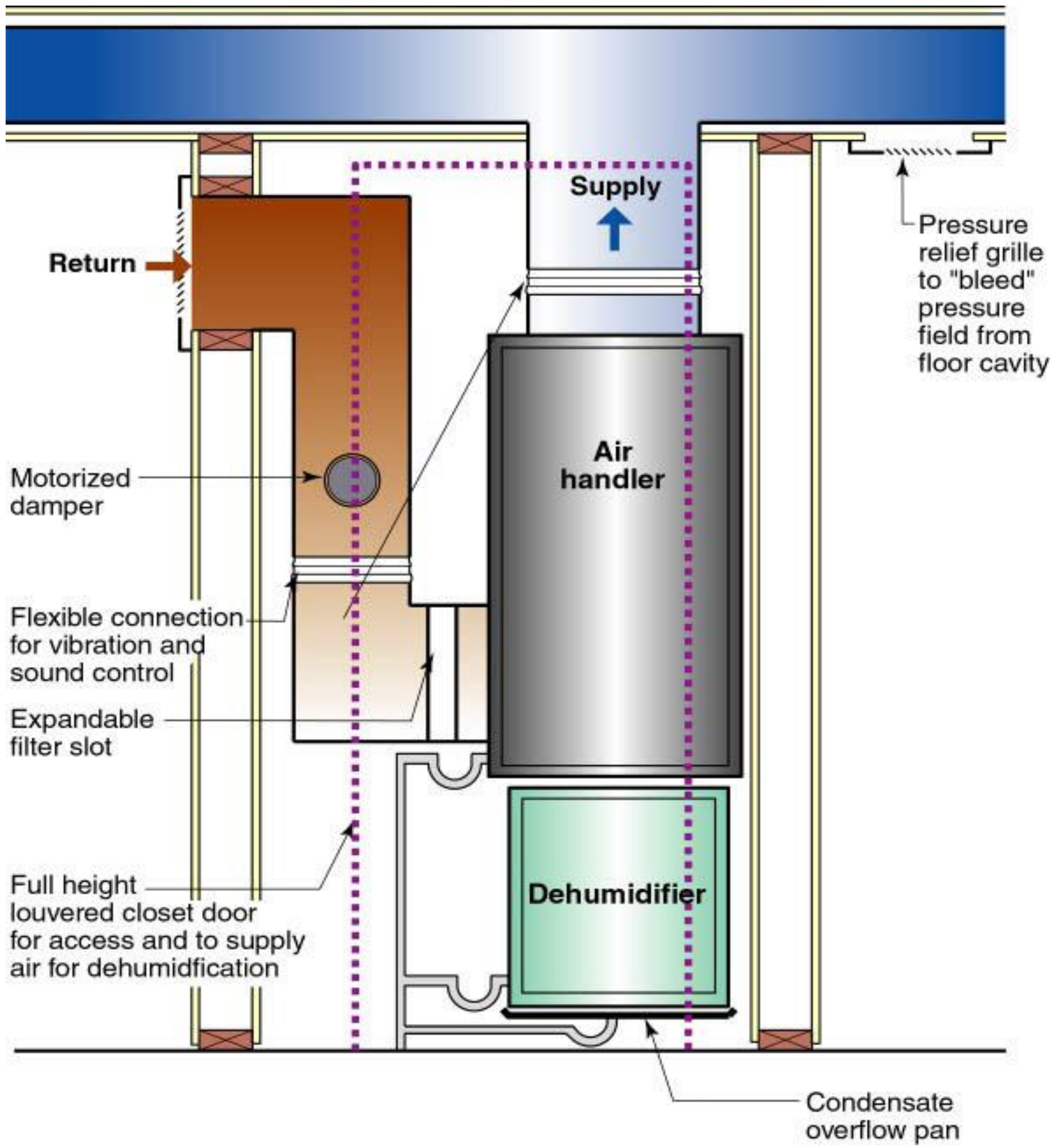
Source Control For The Building


Target Range
Winter
Summer
Uncomfortably Dry*
Comfort Range*
Uncomfortably Wet*
0
25
50
70
100
20
75
Relative Humidity (RH) %

Recommended Range of Relative Humidity

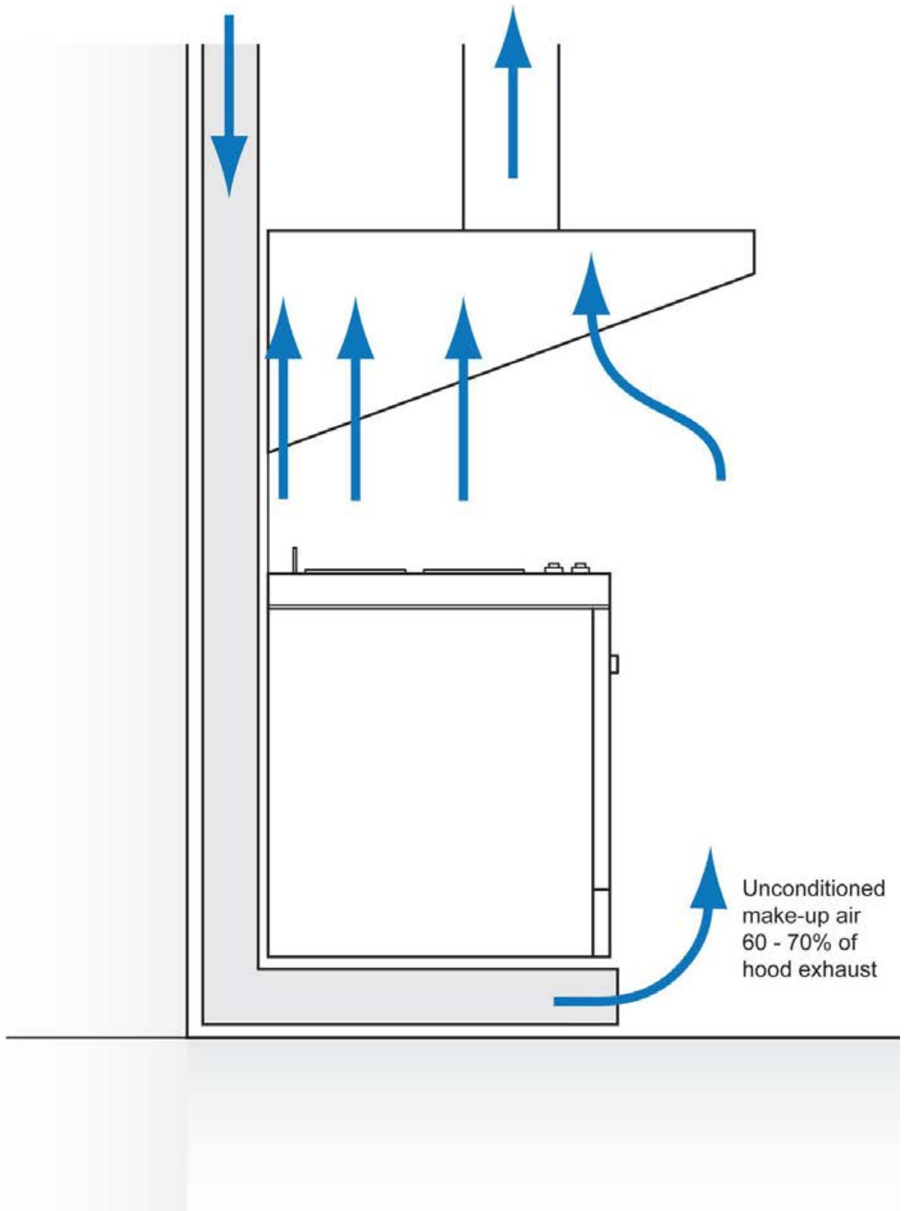
Above 25 percent during winter

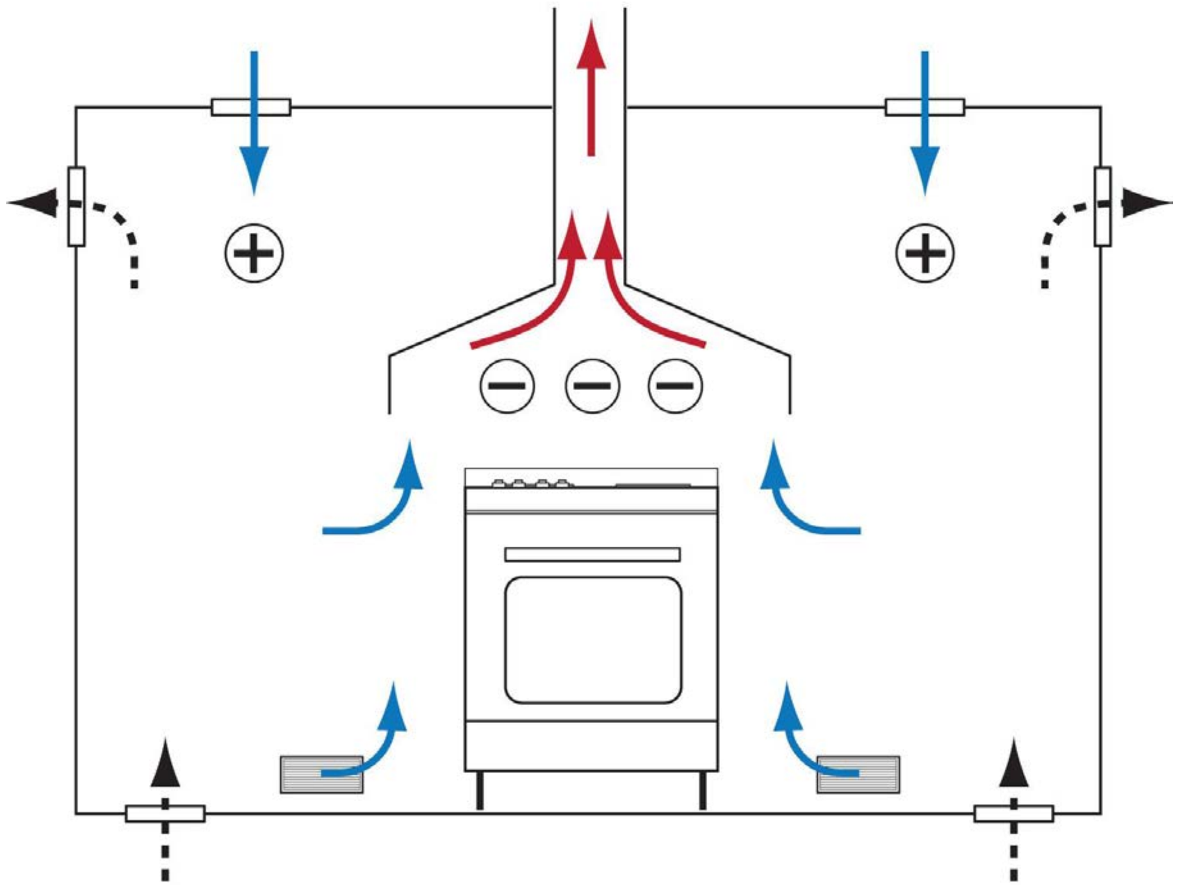
Below 70 percent during summer

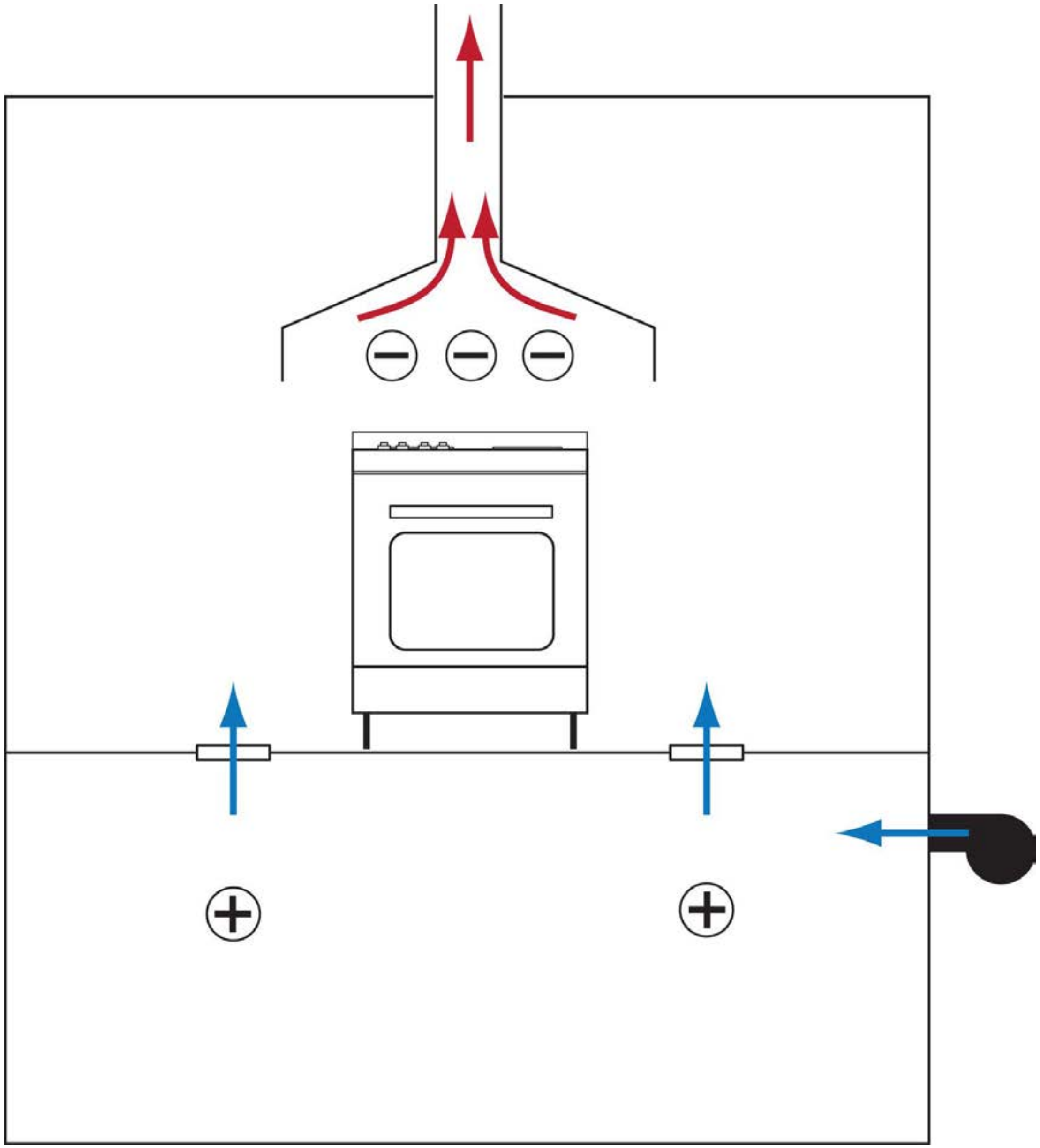

Supply
Pressure relief grille to "bleed" pressure field from floor cavity
Return
Air handler
Motorized damper
Flexible connection for vibration and sound control
Expandable filter slot
Dehumidifier
Full height louvered closet door for access and to supply air for dehumidfication
Condensate overflow pan

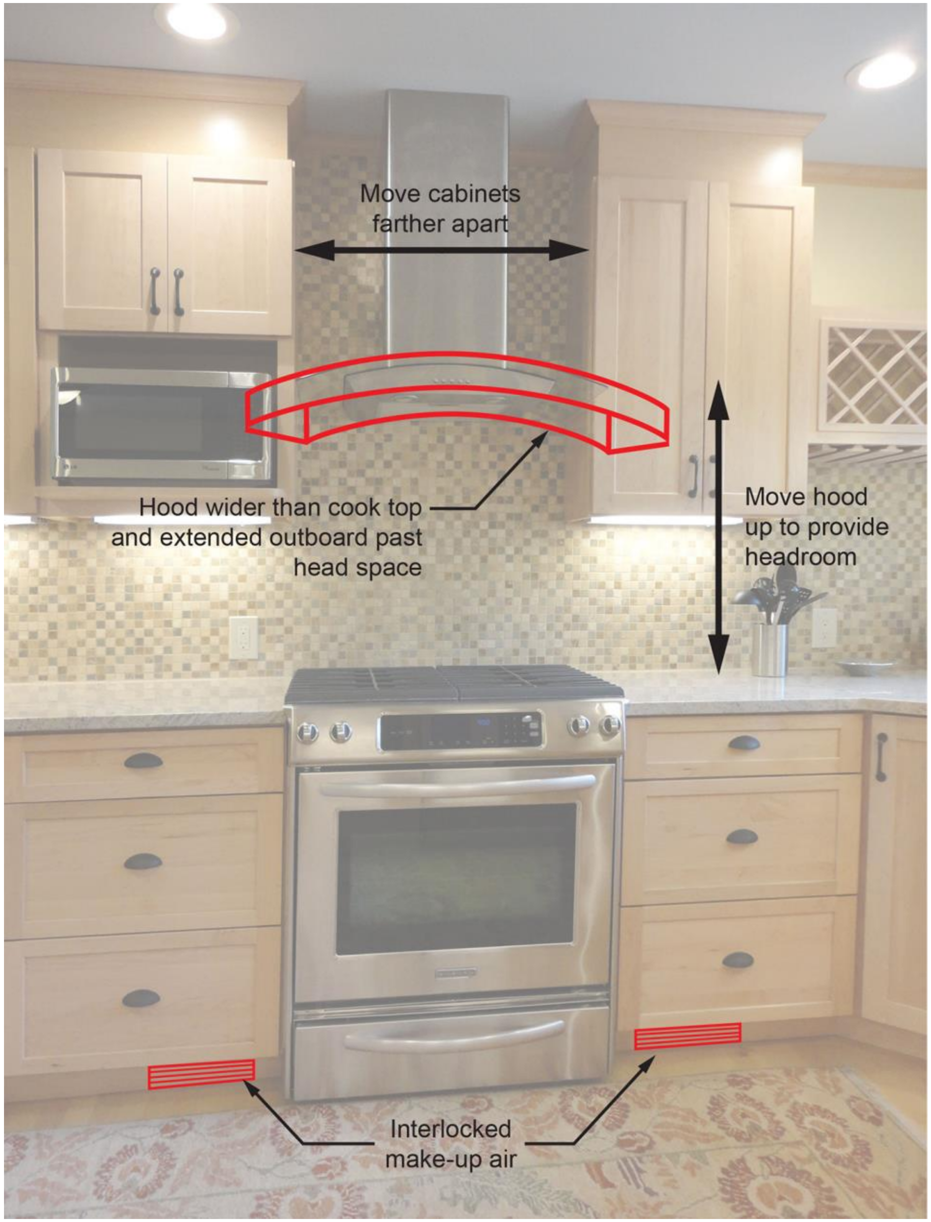

MAXIMUM
Wood's

Kitchen Exhaust Hoods


Unconditioned
make-up air
60 - 70% of
hood exhaust





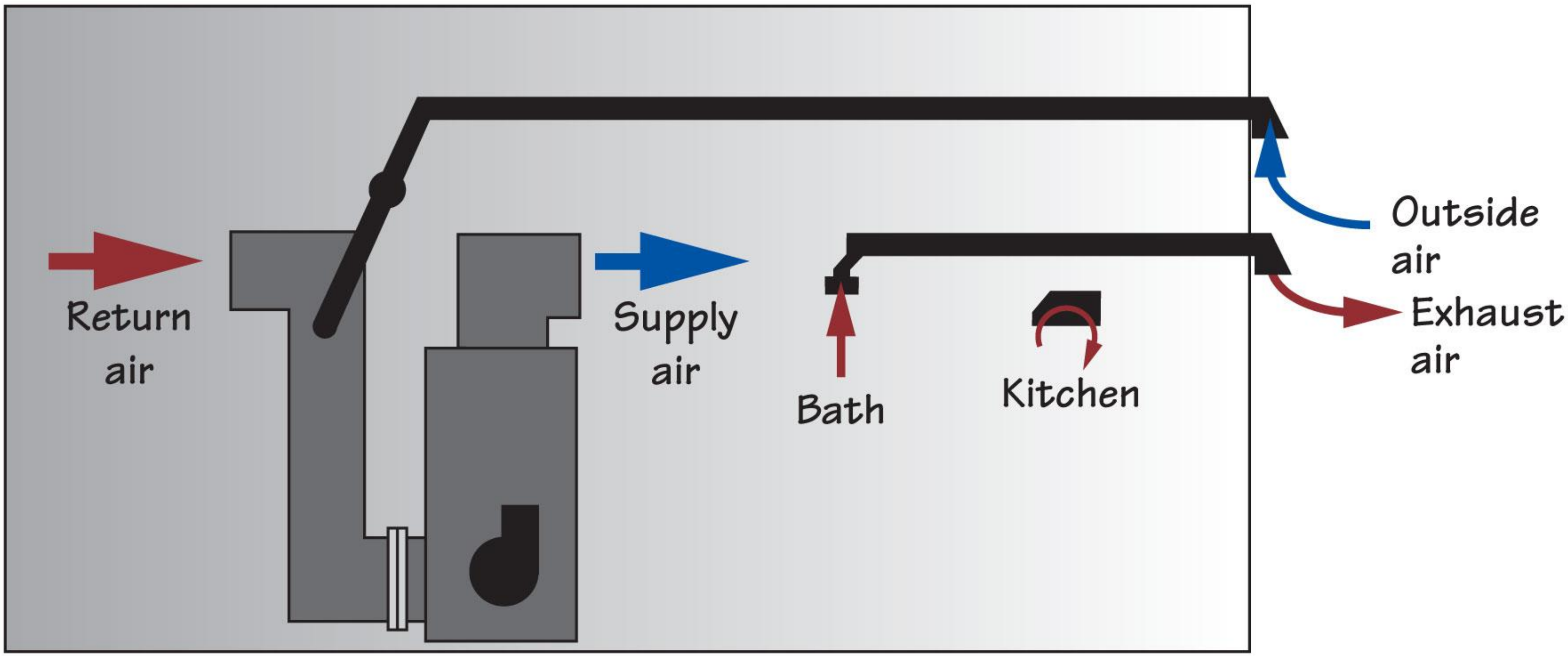

Move cabinets farther apart
Hood wider than cook top and extended outboard past head space
Move hood up to provide headroom
Interlocked make-up air

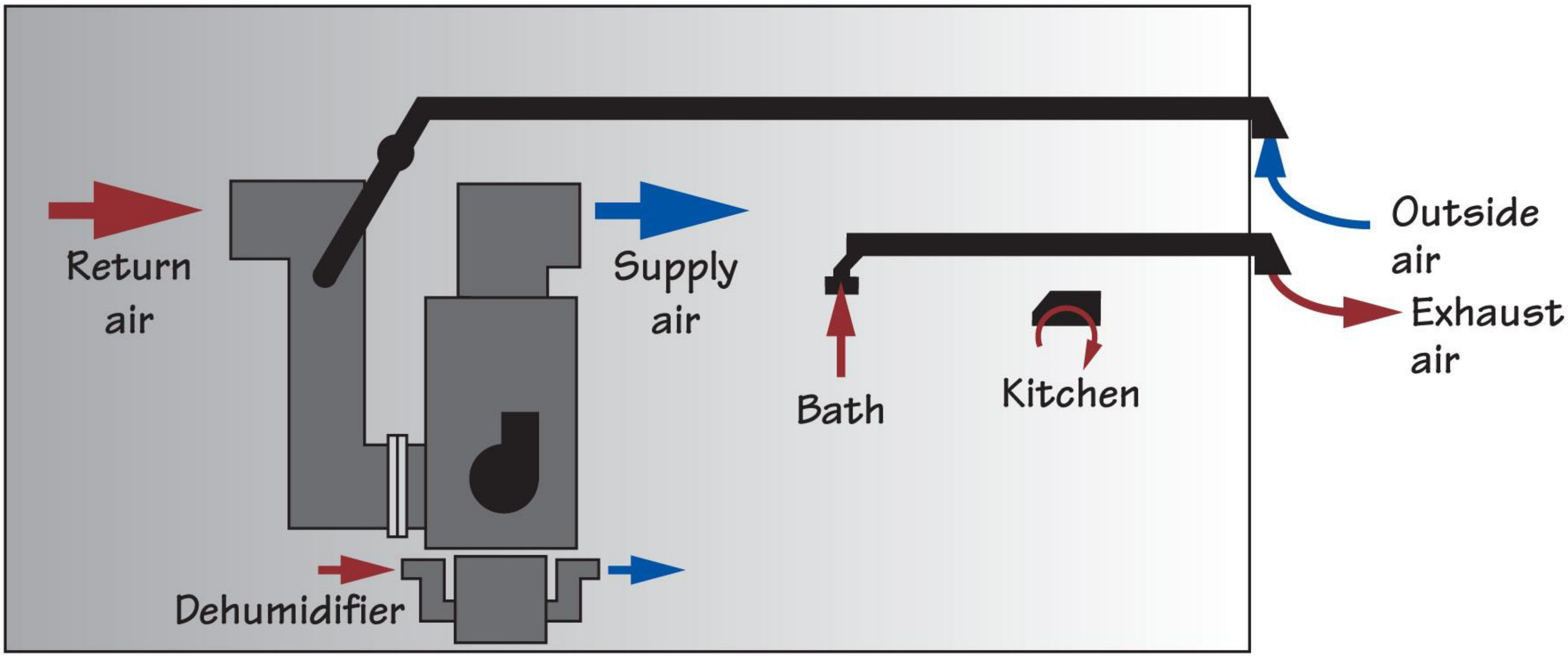
Clothes Dryers

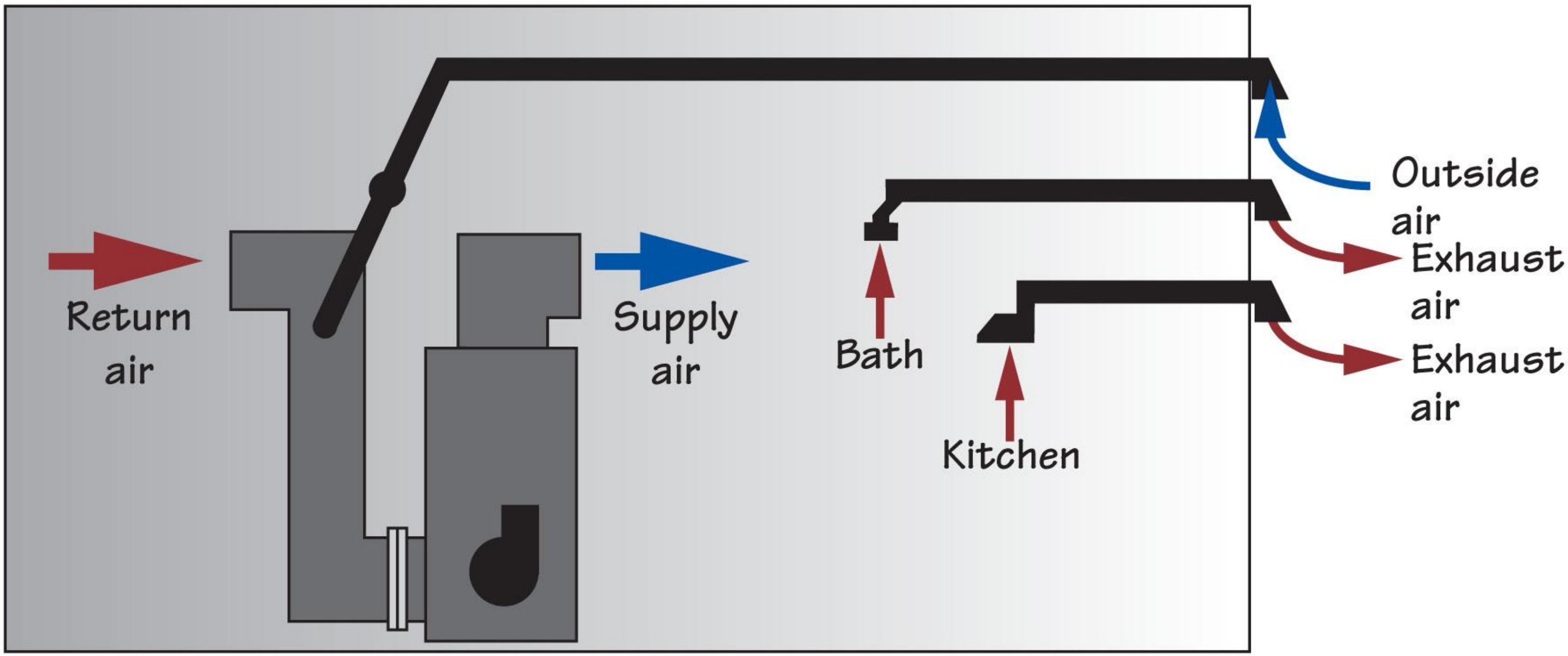

ASKO
ASKO
ENERGUIDE
209 kWh

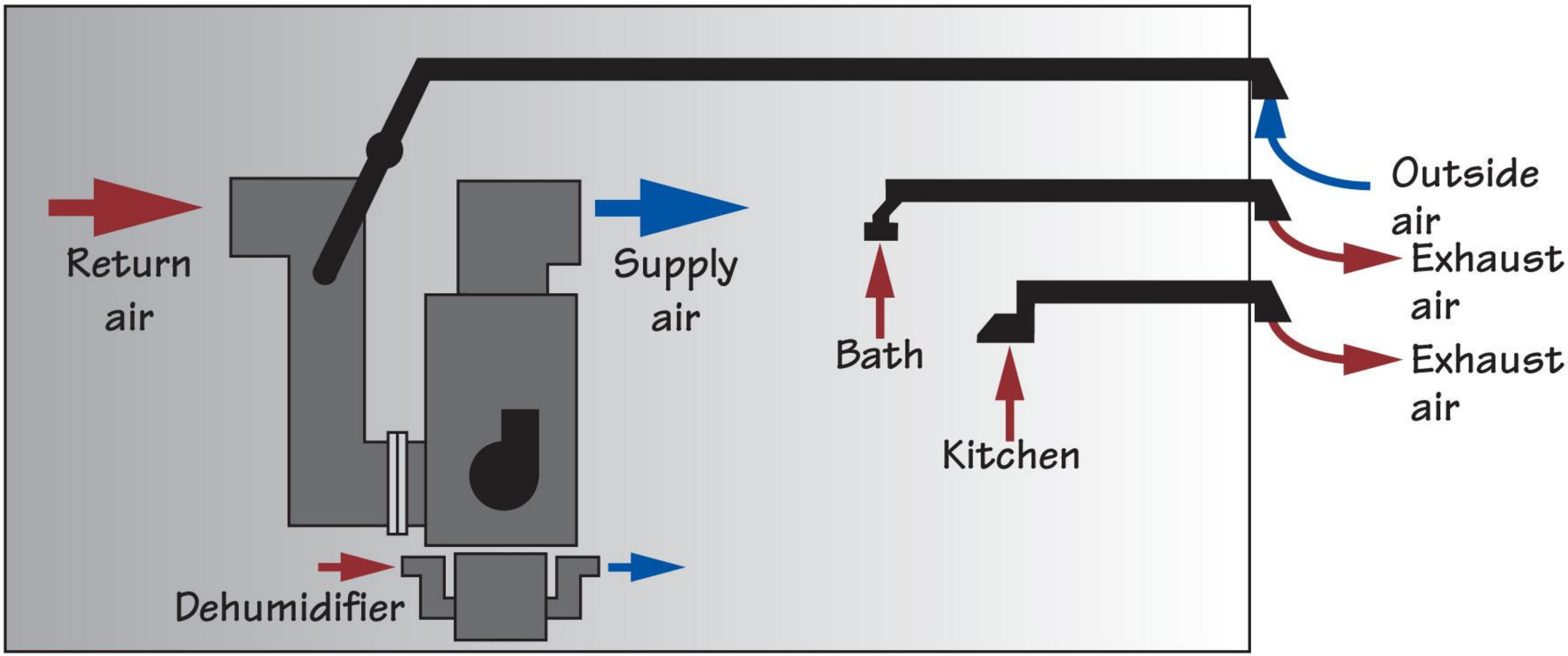
Fireplaces

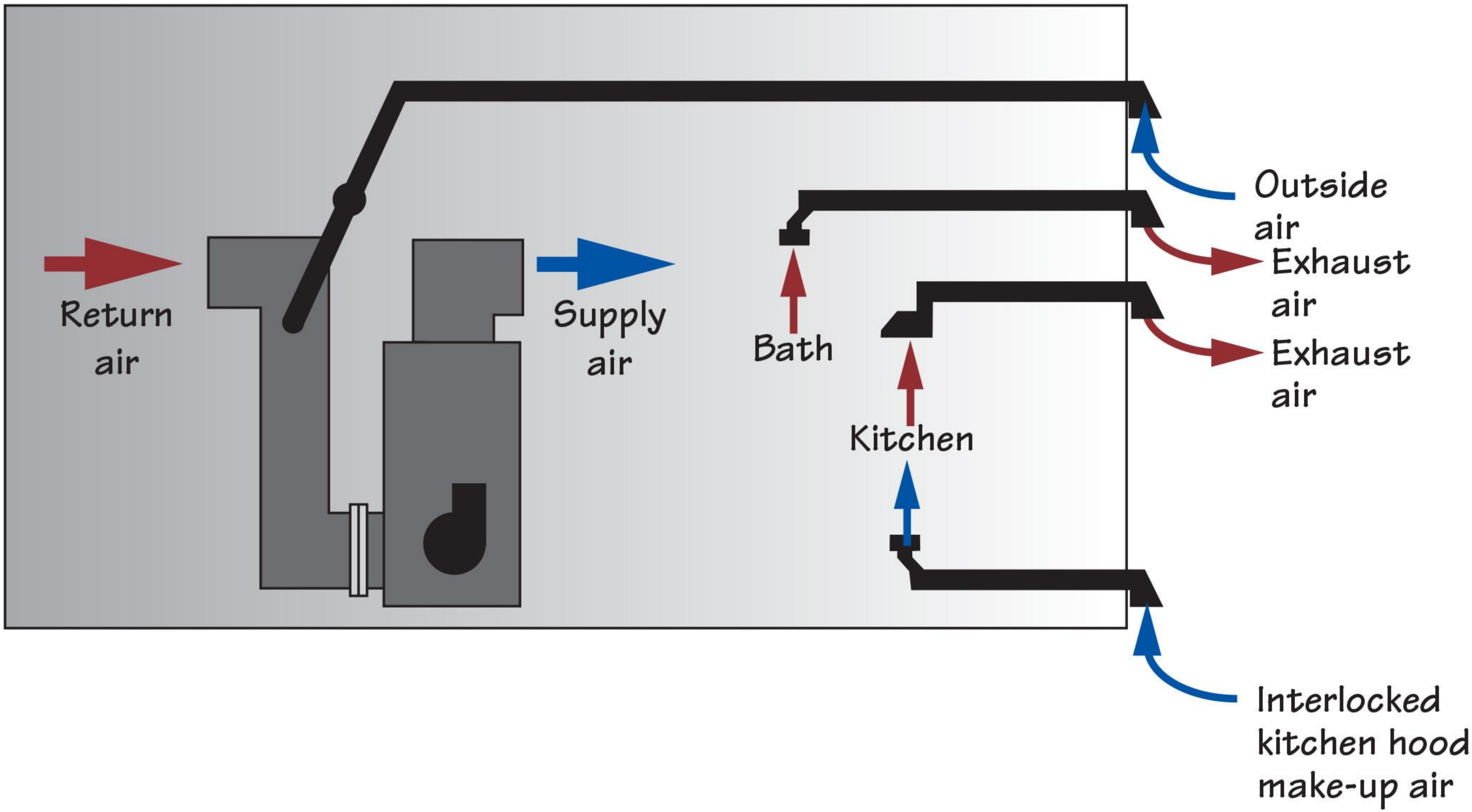
Approaches

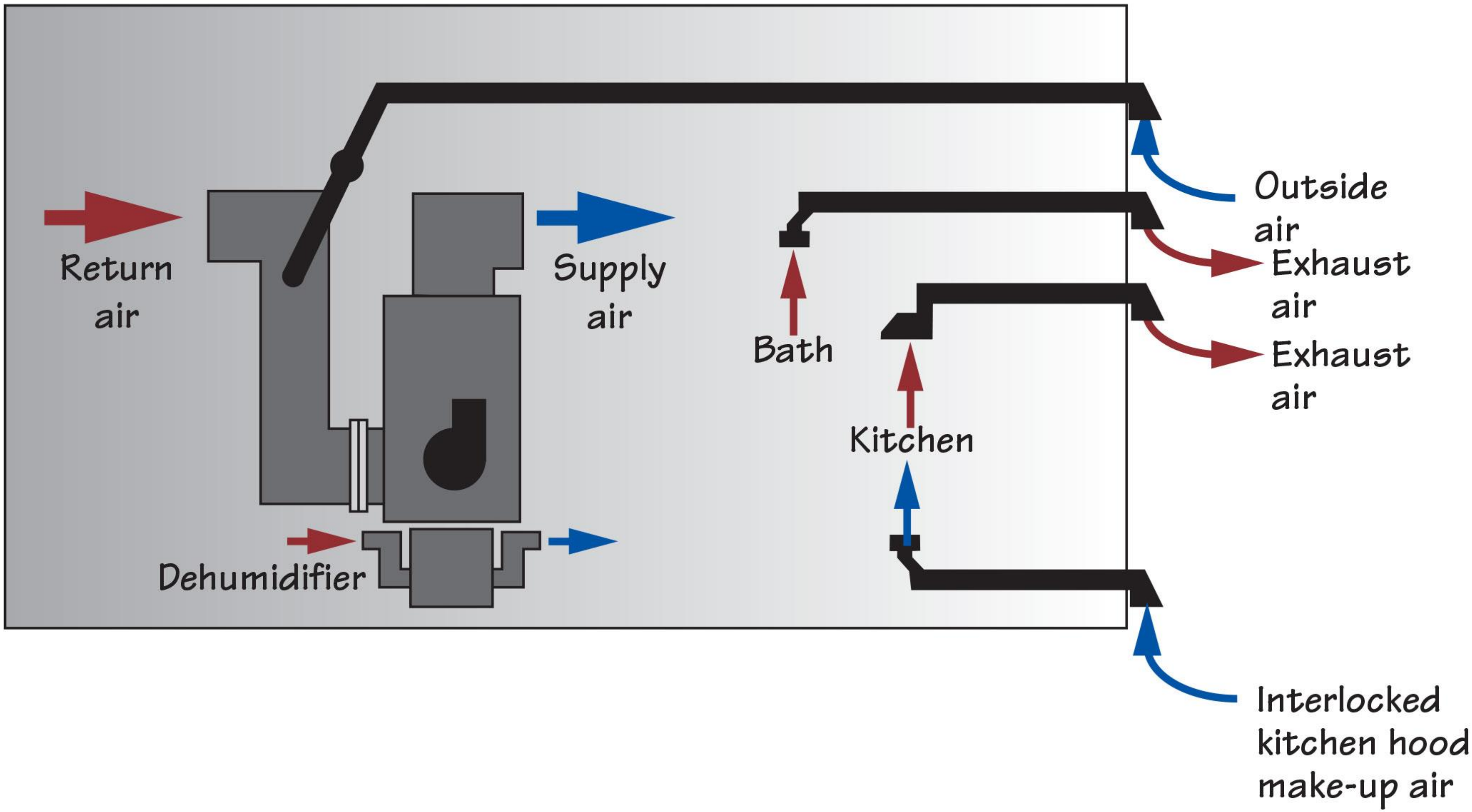

Return
air
Supply
air
Bath
Kitchen
Outside
air
Exhaust
air

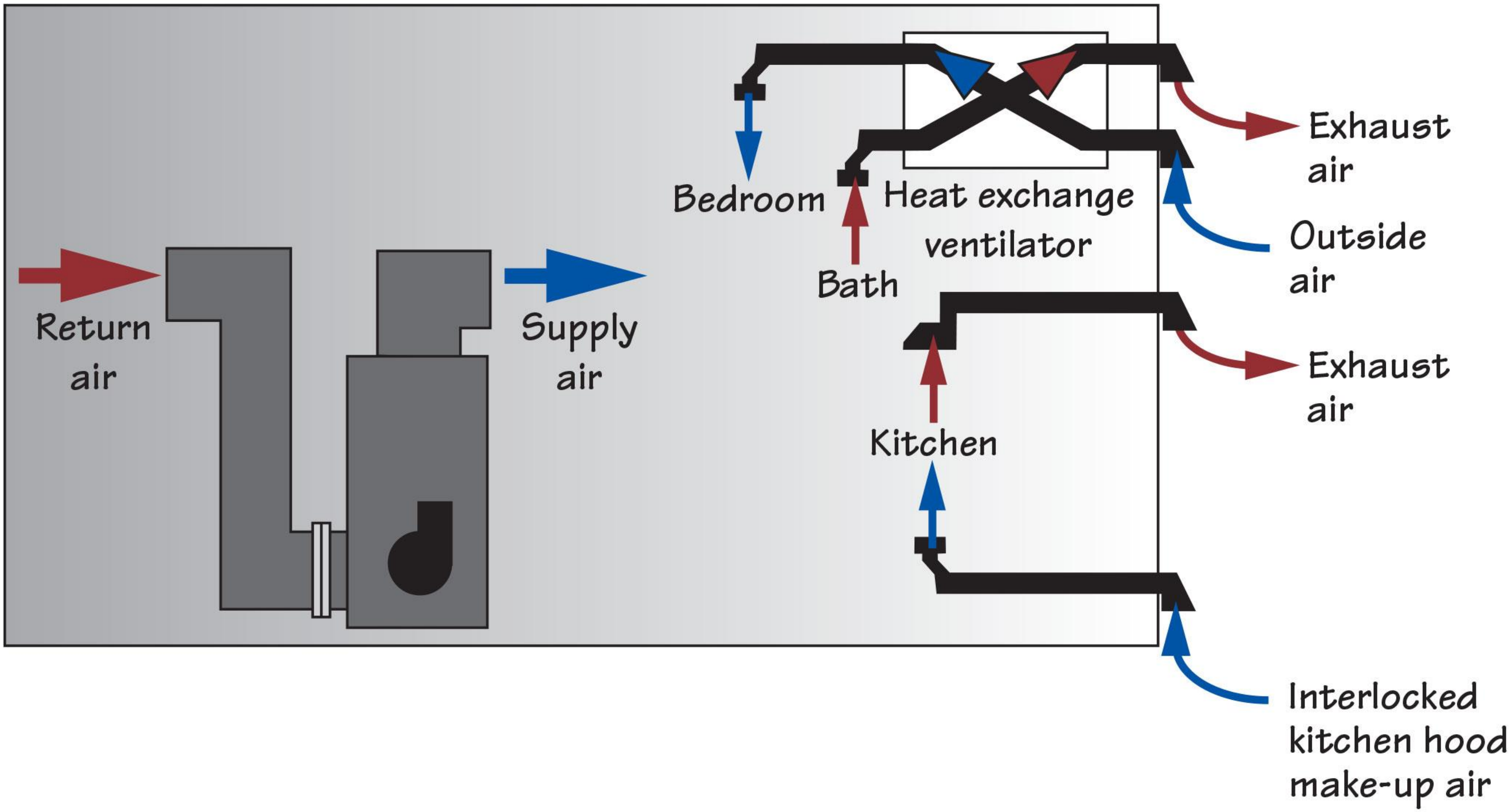

Return
air
Supply
air
Outside
air
Exhaust
air
Bath
Kitchen
Dehumidifier

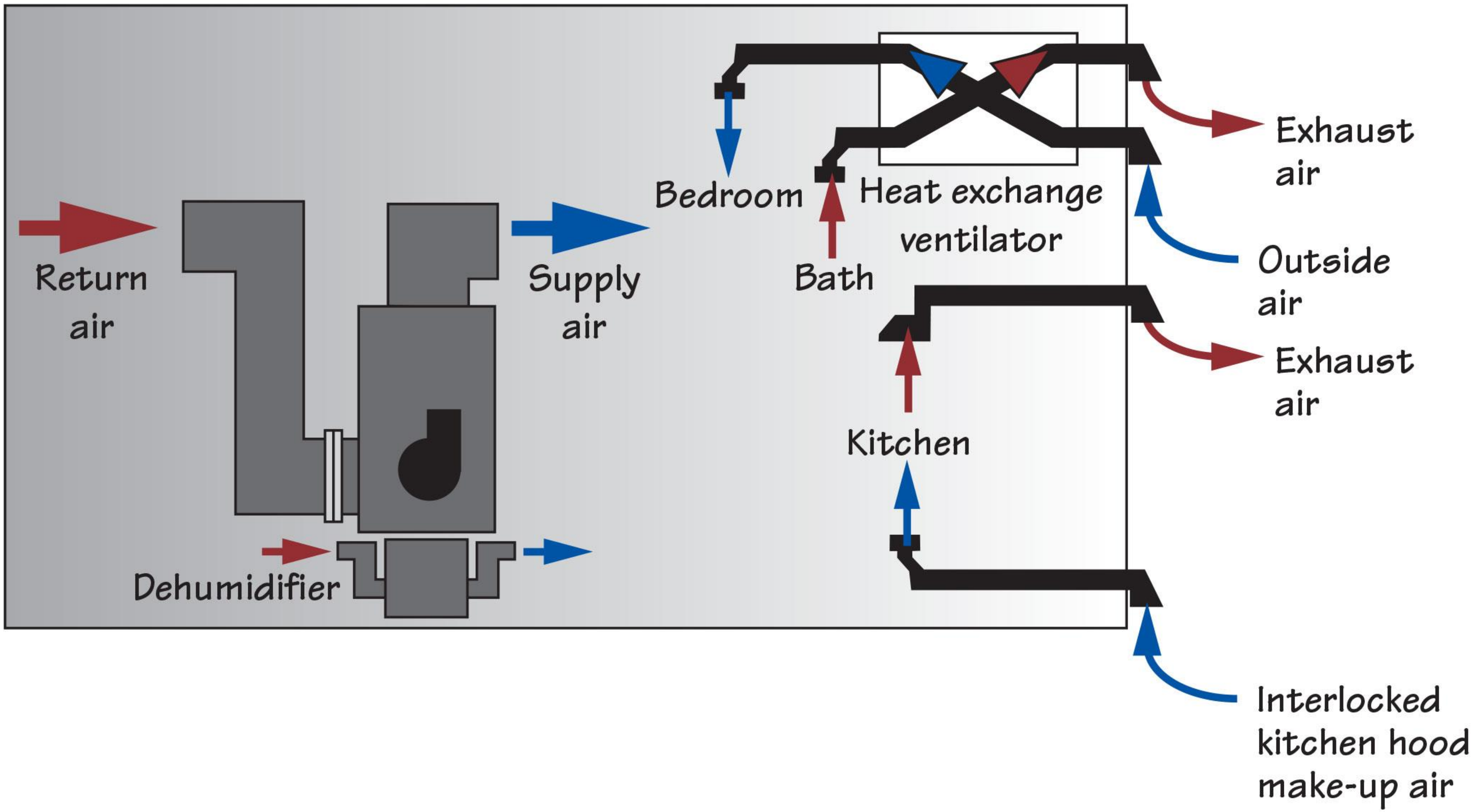

Return
air
Supply
air
Bath
Kitchen
Outside
air
Exhaust
air
Exhaust
air


Return air
Supply air
Dehumidifier
Bath
Kitchen
Outside air
Exhaust air
Exhaust air

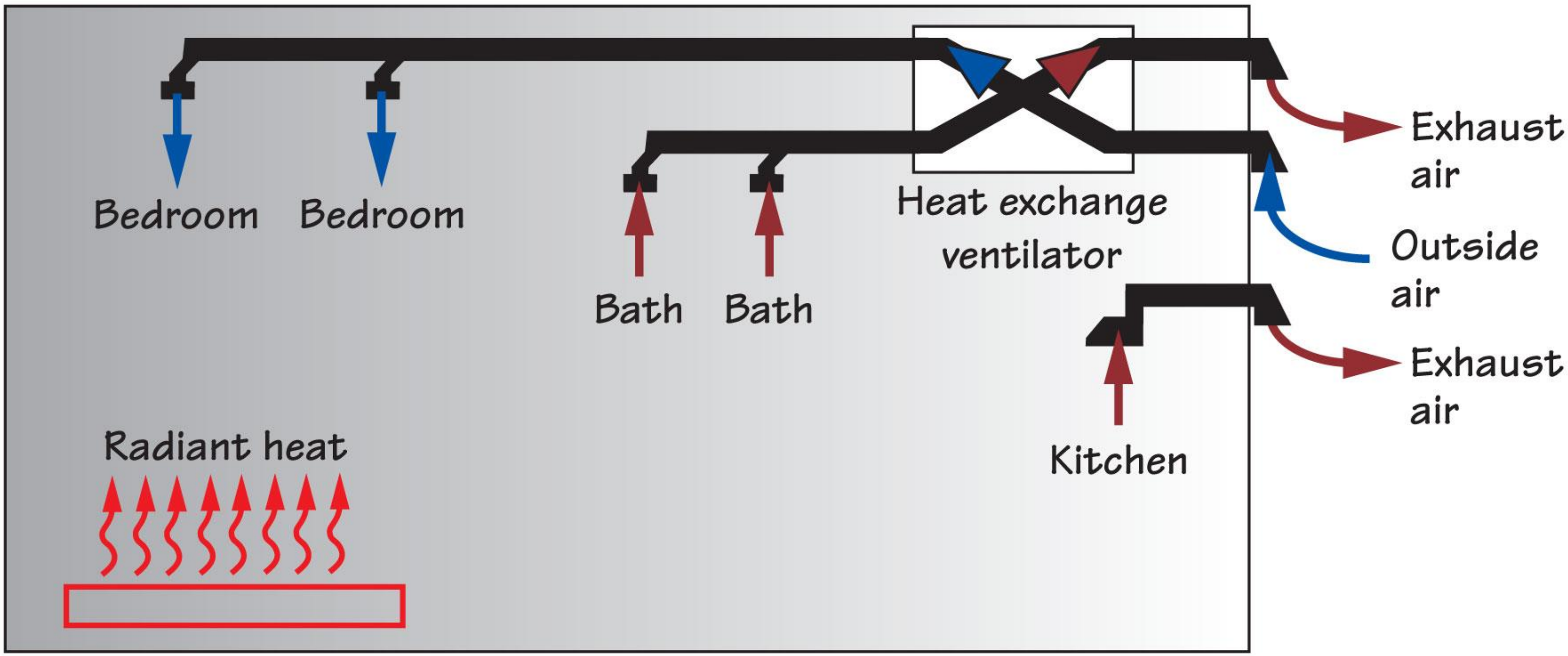

Outside air
Return air
Supply air
Bath
Exhaust air
Exhaust air
Kitchen
Interlocked kitchen hood make-up air

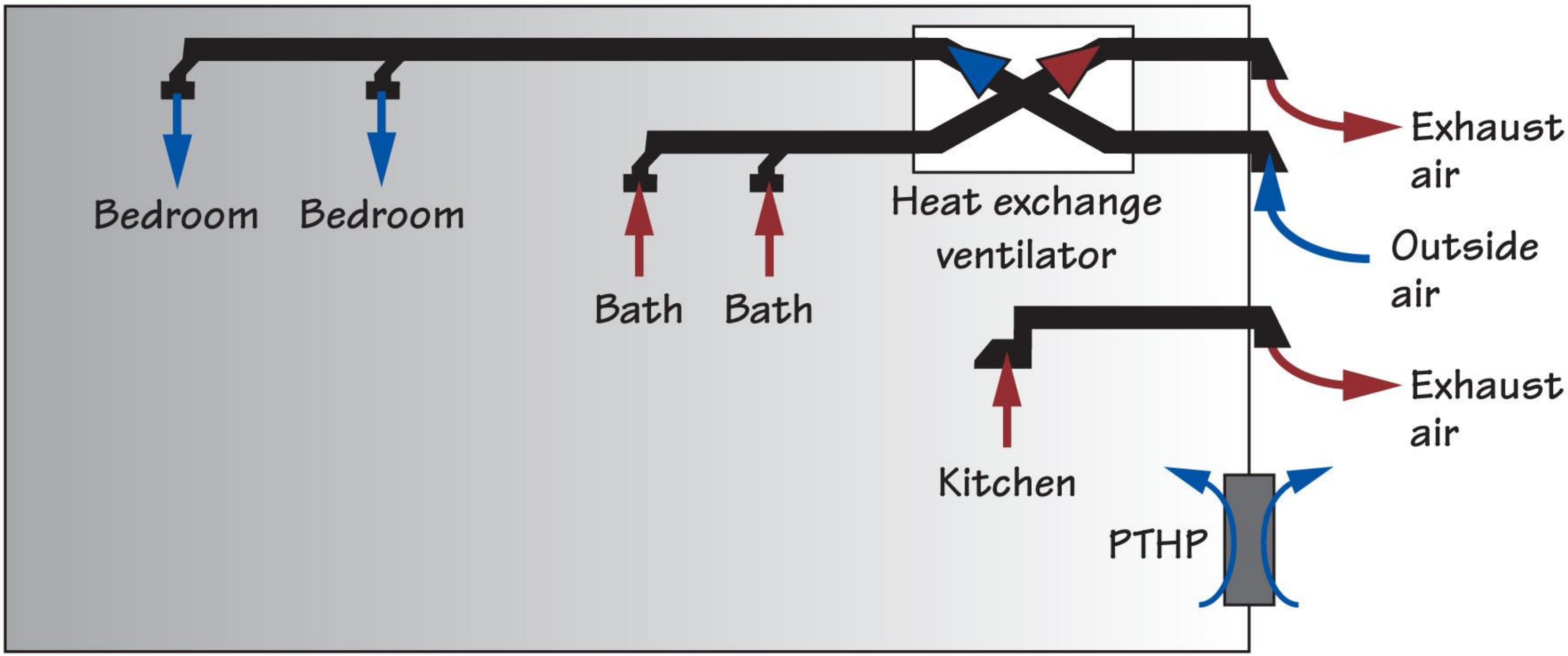

Outside
air
Exhaust
air
Exhaust
air
Return
air
Supply
air
Bath
Kitchen
Dehumidifier
Interlocked
kitchen hood
make-up air

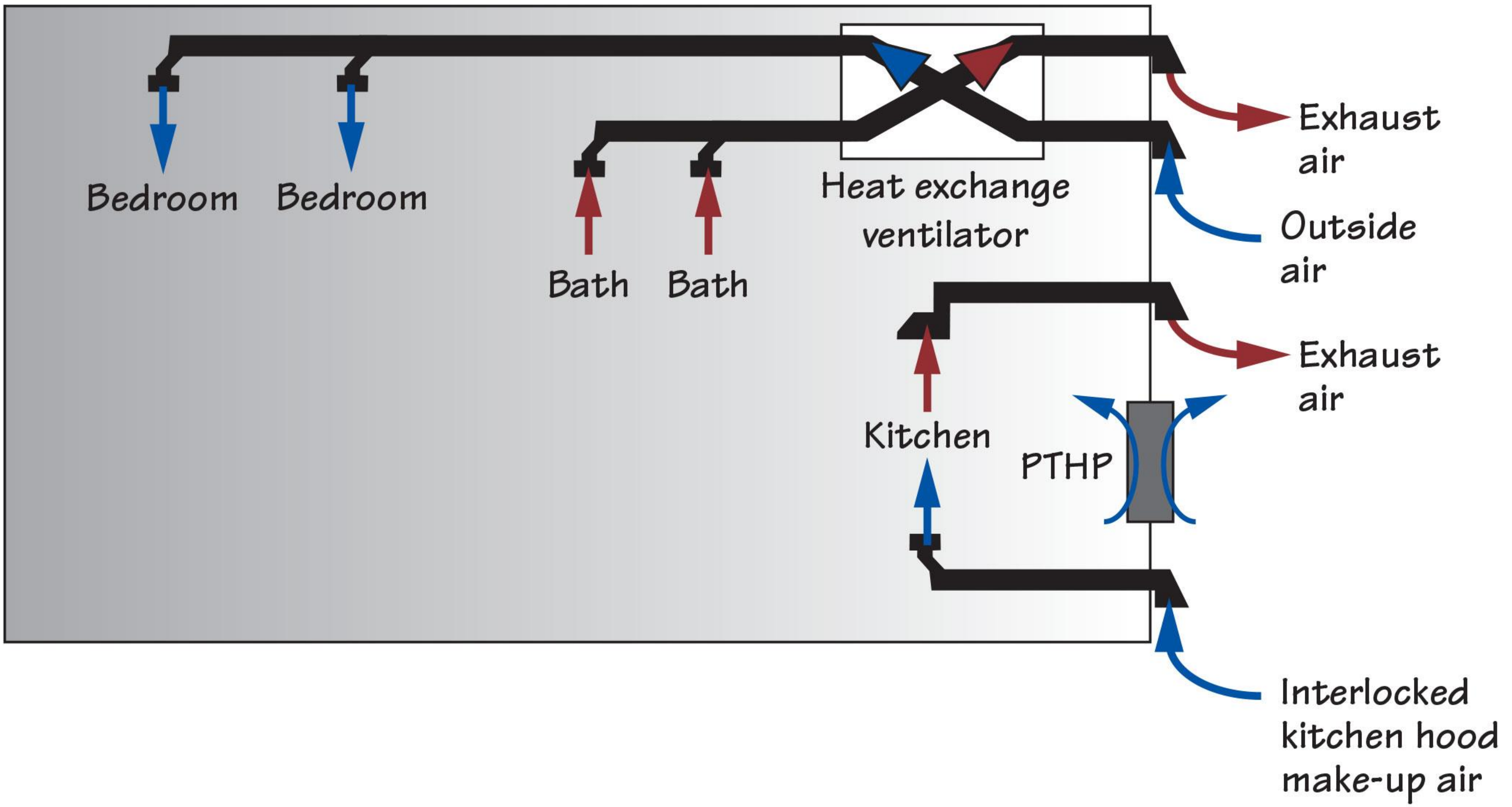

Exhaust air
Outside air
Bedroom
Heat exchange ventilator
Bath
Return air
Supply air
Exhaust air
Kitchen
Interlocked kitchen hood make-up air

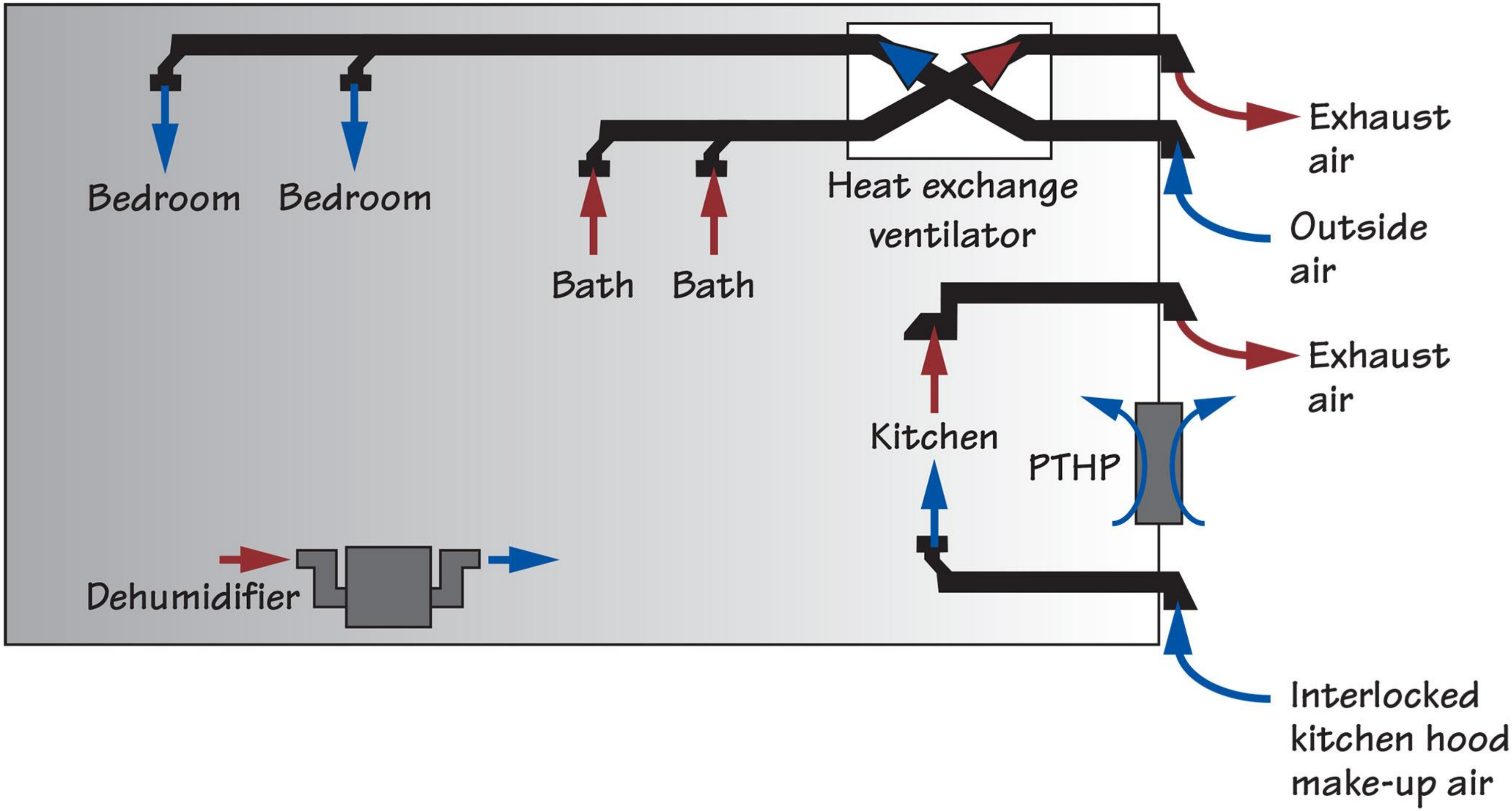


Return air
Supply air
Dehumidifier
Bedroom
Bath
Heat exchange ventilator
Kitchen
Exhaust air
Outside air
Exhaust air
Interlocked kitchen hood make-up air

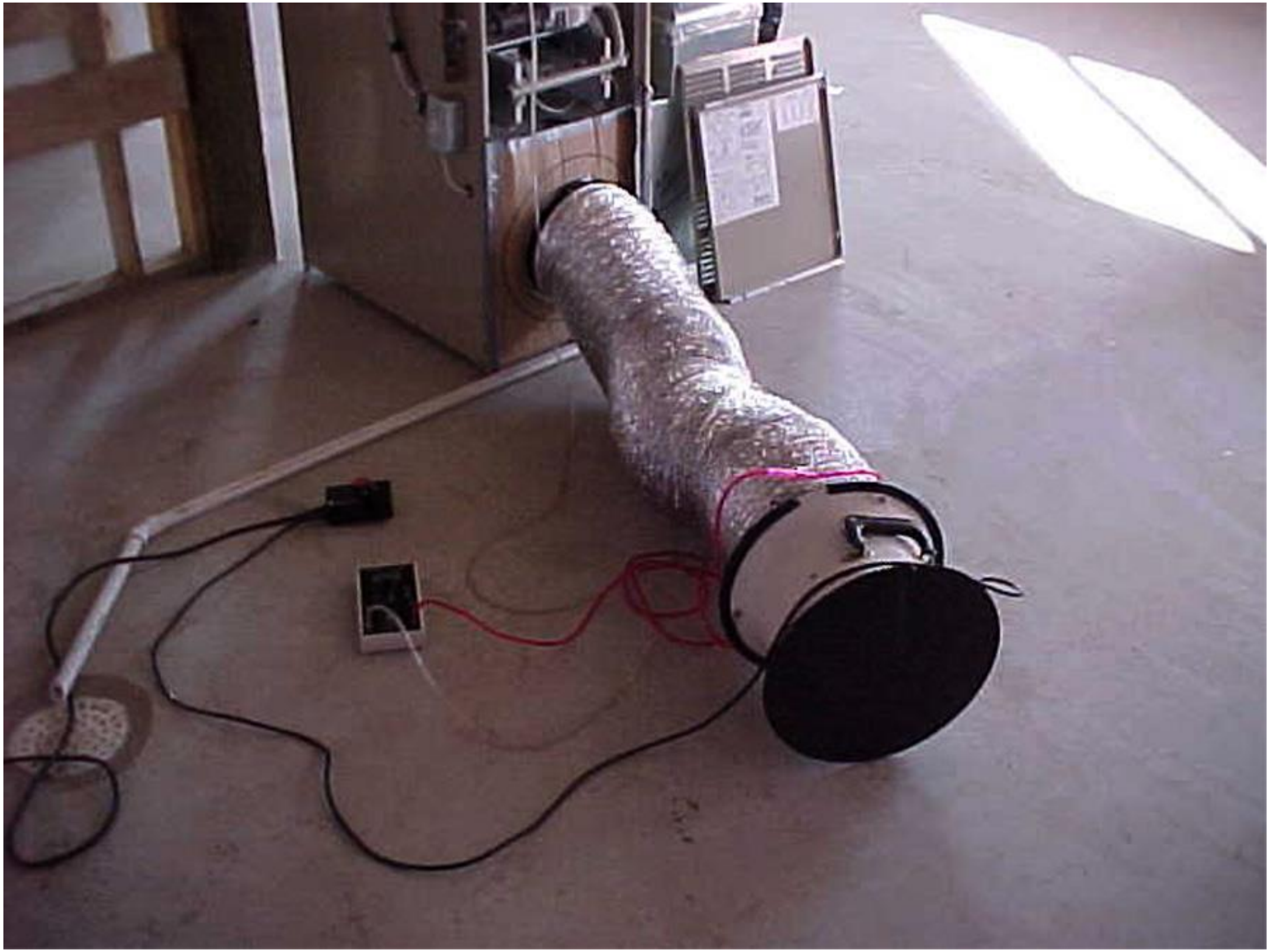

Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
Radiant heat


Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
PTHP

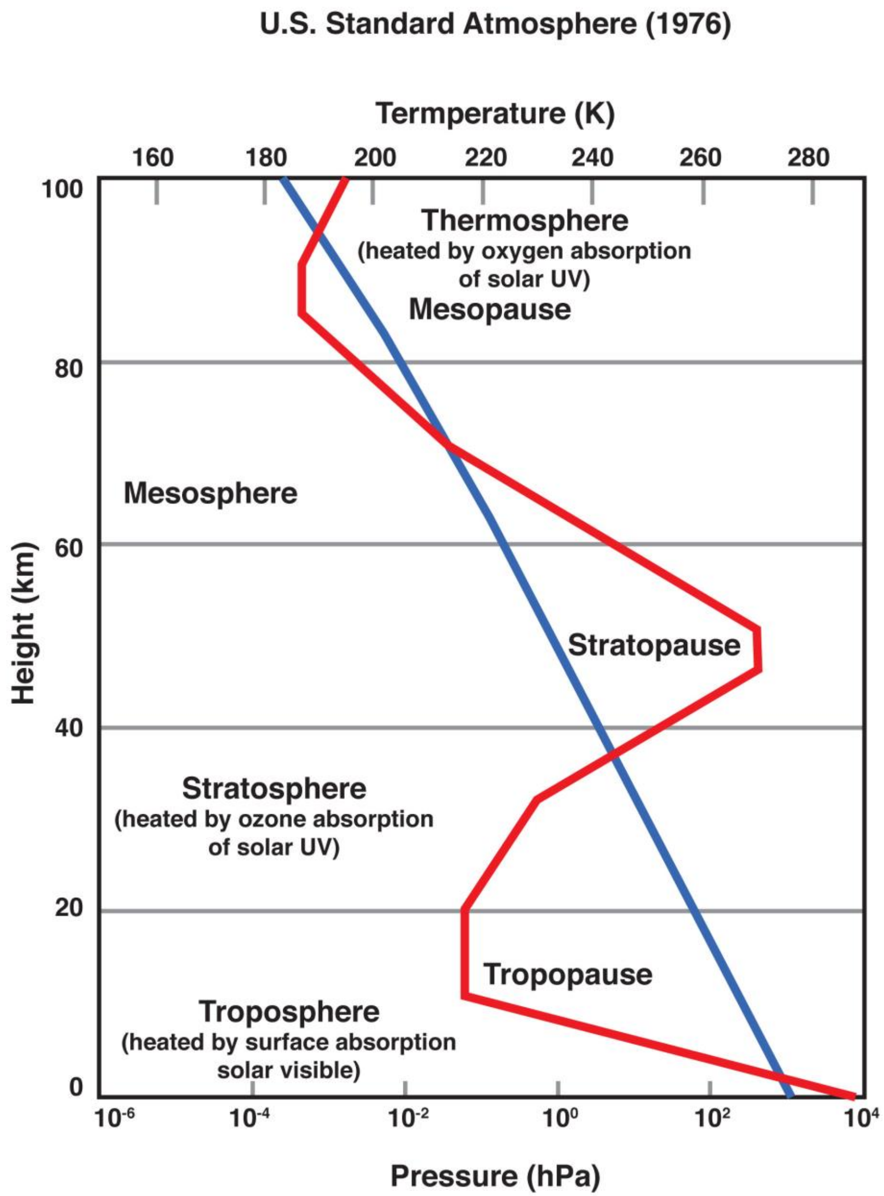

Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
PTHP
Interlocked kitchen hood make-up air



Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
PTHP
Dehumidifier
Interlocked kitchen hood make-up air



Lapse Rate


U.S. Standard Atmosphere (1976)
Termperature (K)
160
180
200
220
240
260
280
100
80
60
40
20
0
Height (km)
Thermosphere
(heated by oxygen absorption
of solar UV)
Mesopause
Mesosphere
Stratopause
Stratosphere
(heated by ozone absorption
of solar UV)
Tropopause
Troposphere
(heated by surface absorption
solar visible)
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Pressure (hPa)

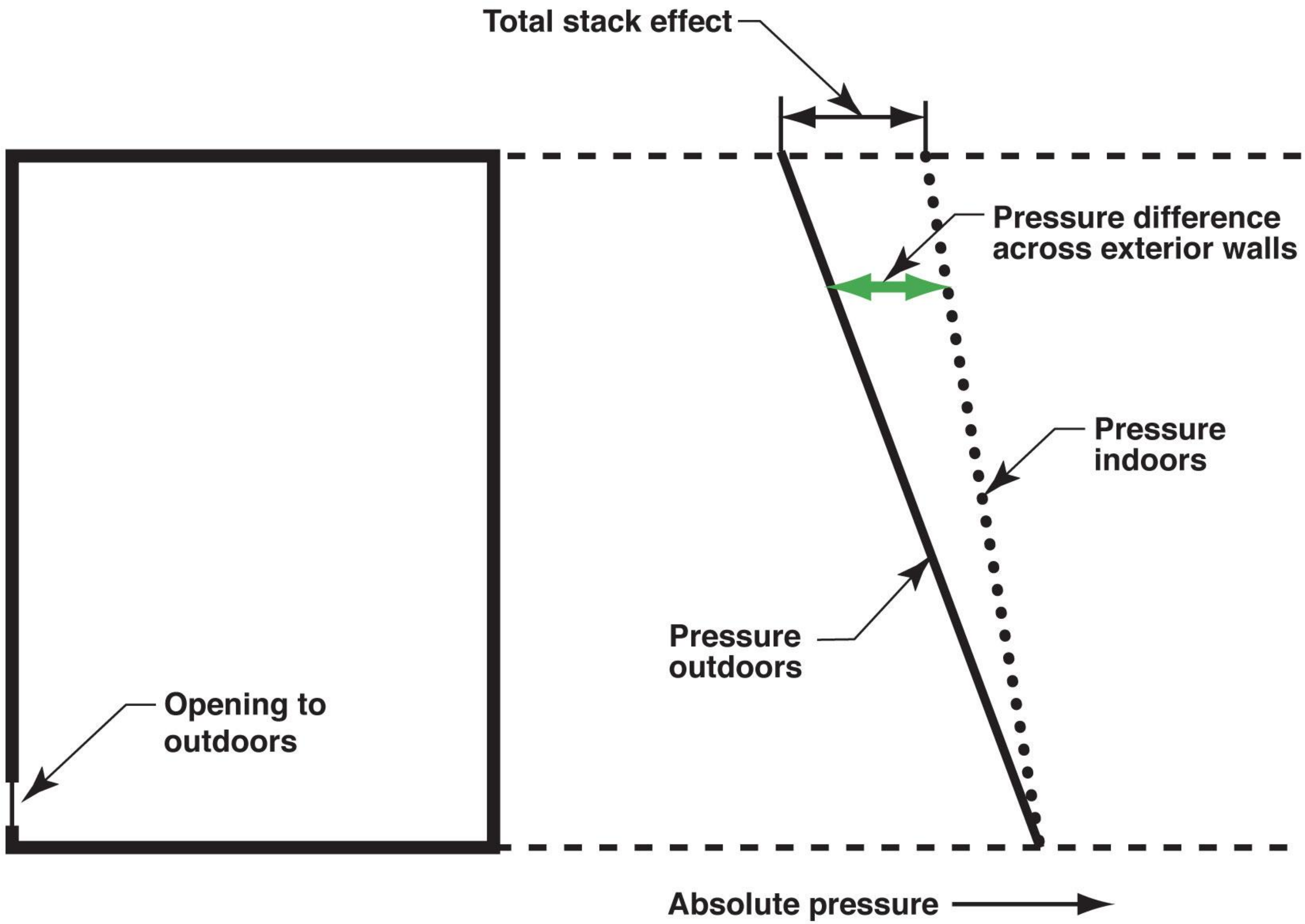


Figure 11.1: Building with no internal separations with opening at the bottom (Adapted from G.O. Handegord, 1998)

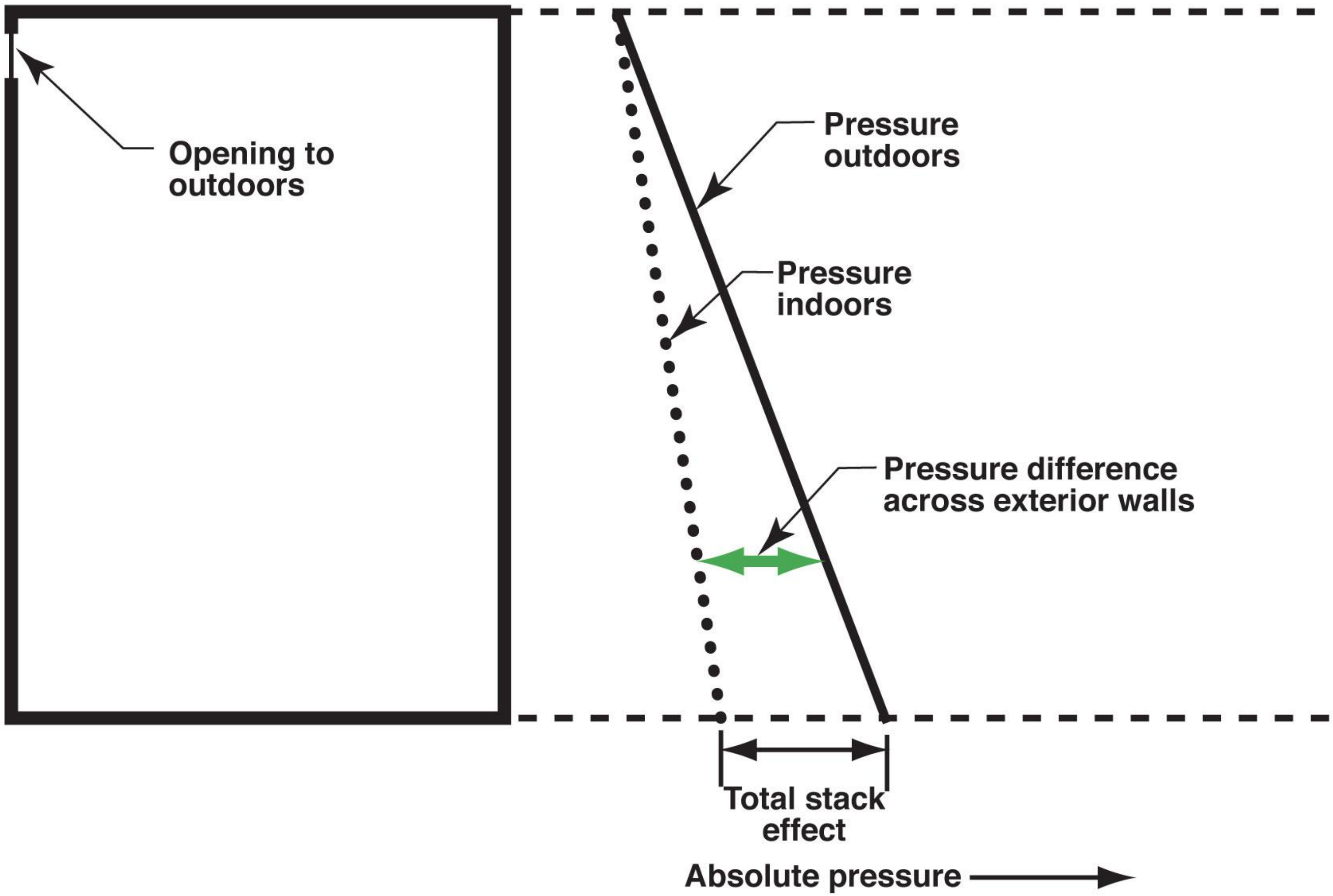


Figure 11.2: Building with no internal separations with opening at the top (Adapted from G.O. Handegord, 1998)

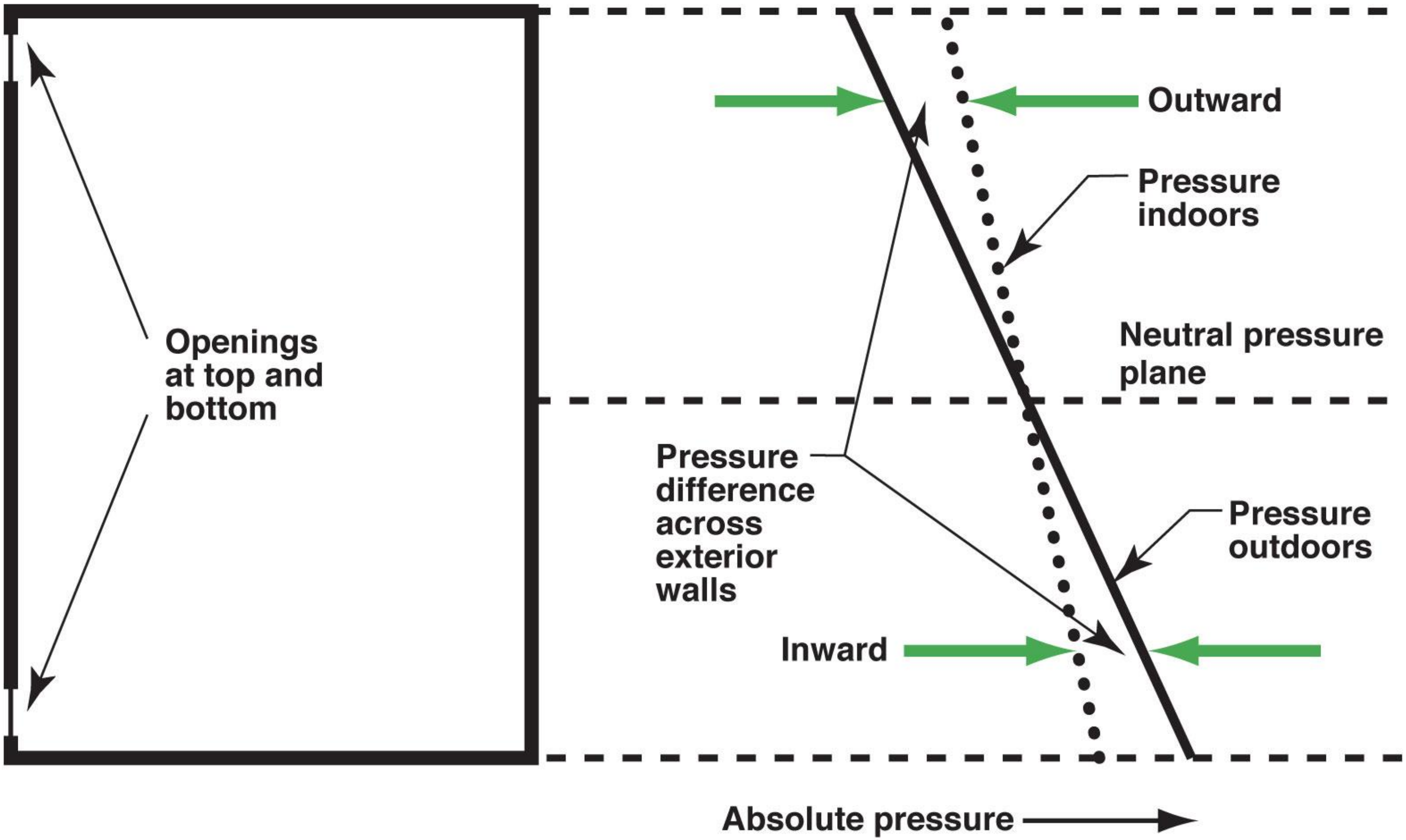


Figure 11.3: Building with no internal separations with openings at top and bottom (Adapted from G.O. Handegord, 1998)

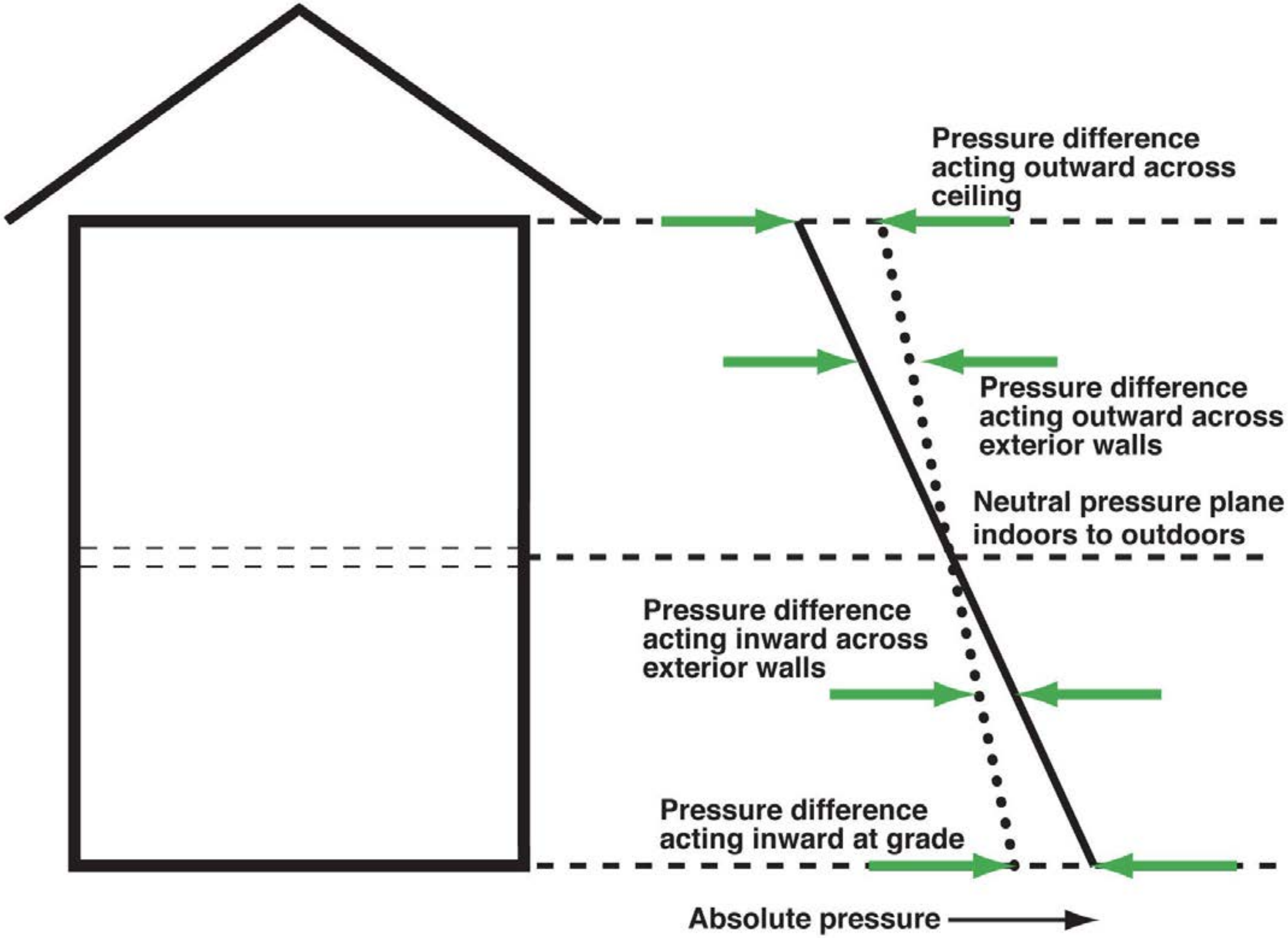


Figure 11.4: Basic two storey house with vented attic
(Adapted from G.O. Handegord, 1998)


POMPIERS NO. 3

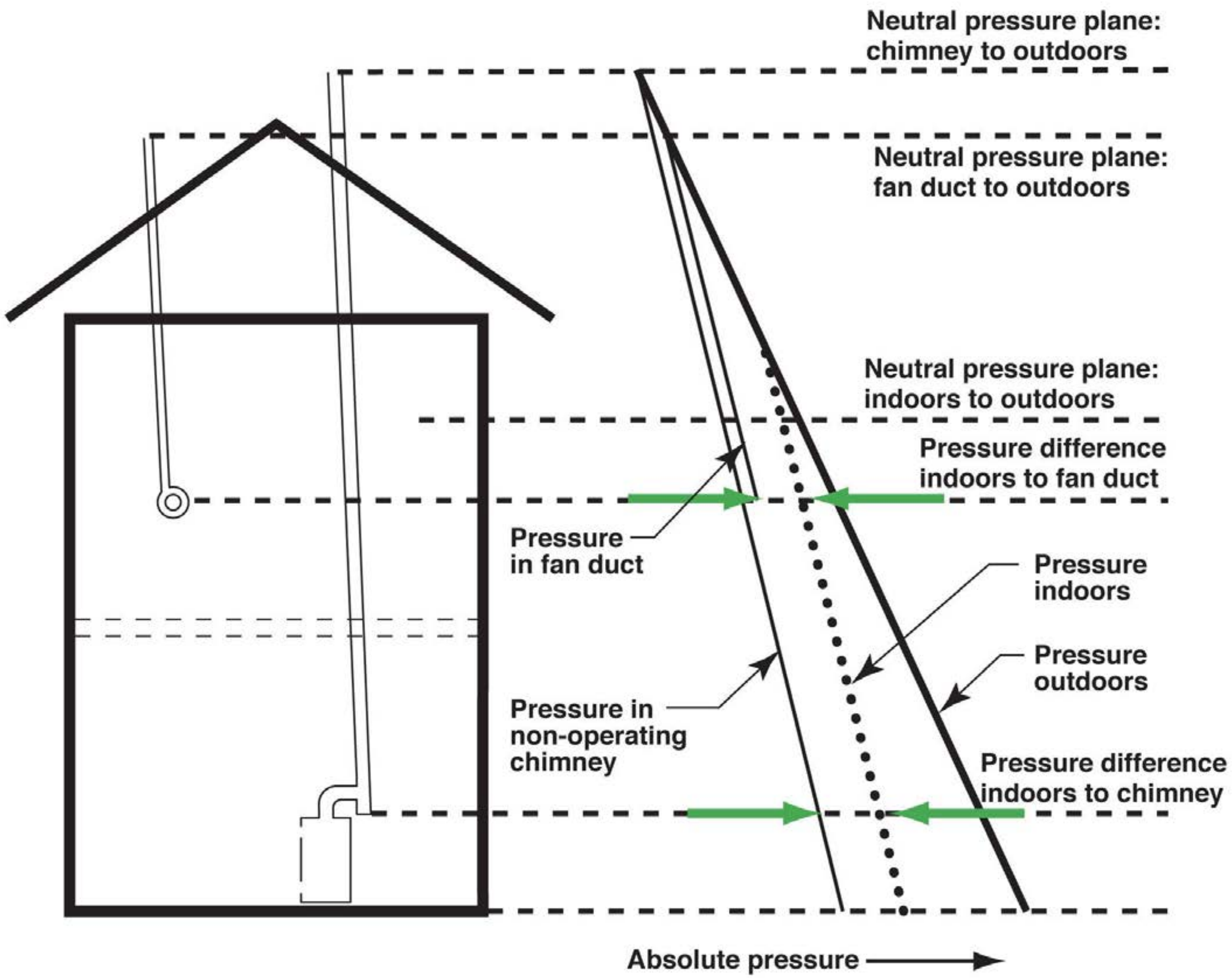


Figure 11.5: Two storey house with non-operating chimney and exhaust fan (Adapted from G.O. Handegord, 1998)

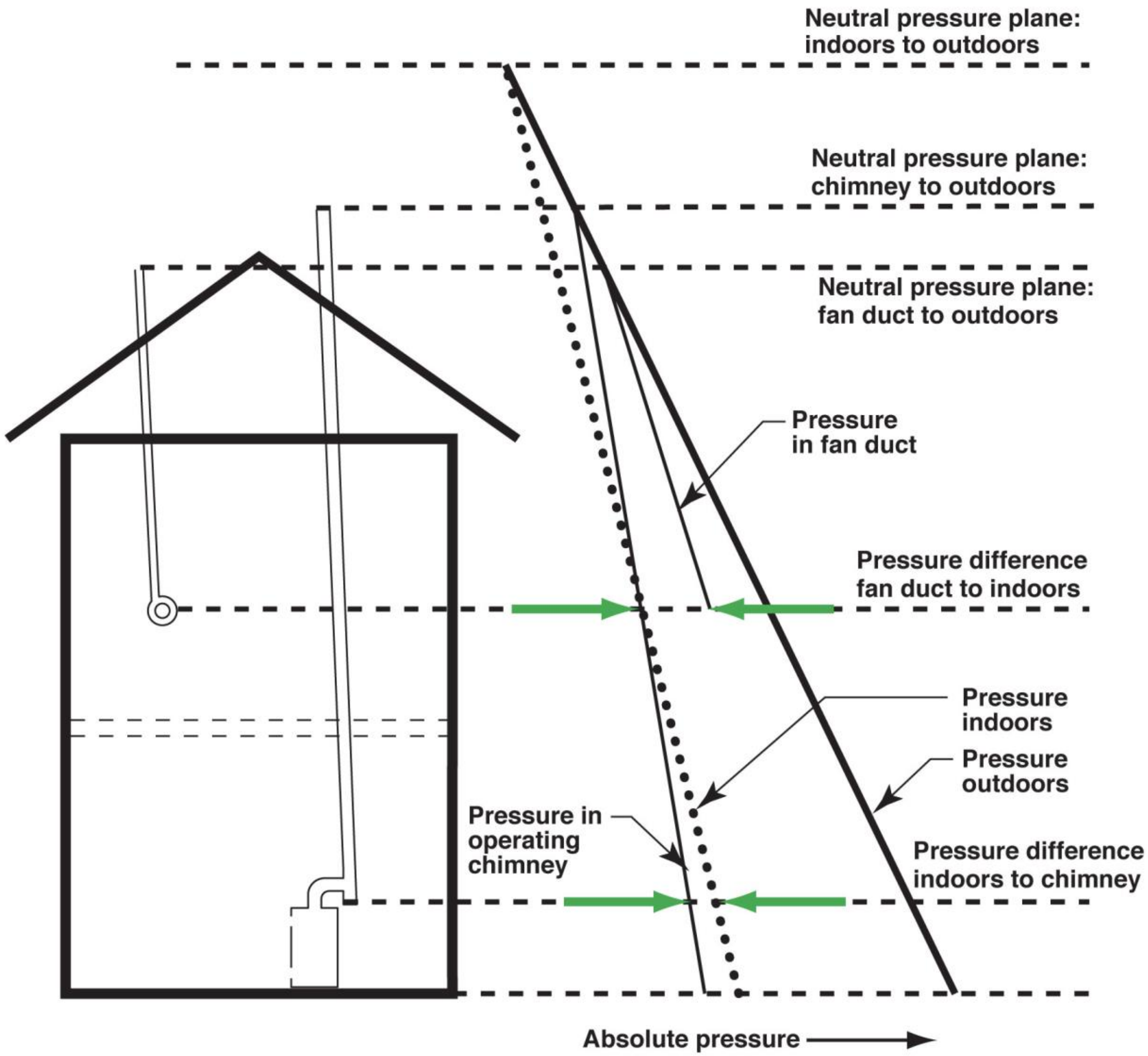
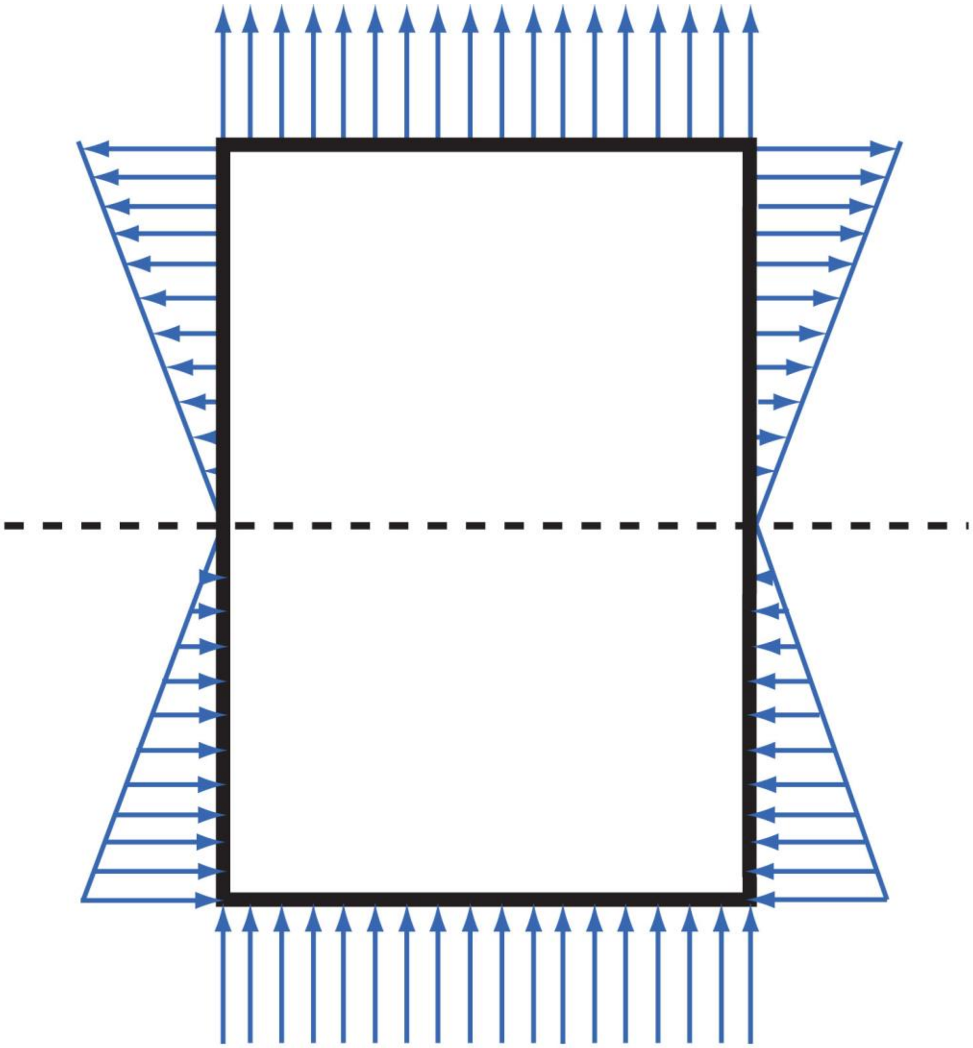
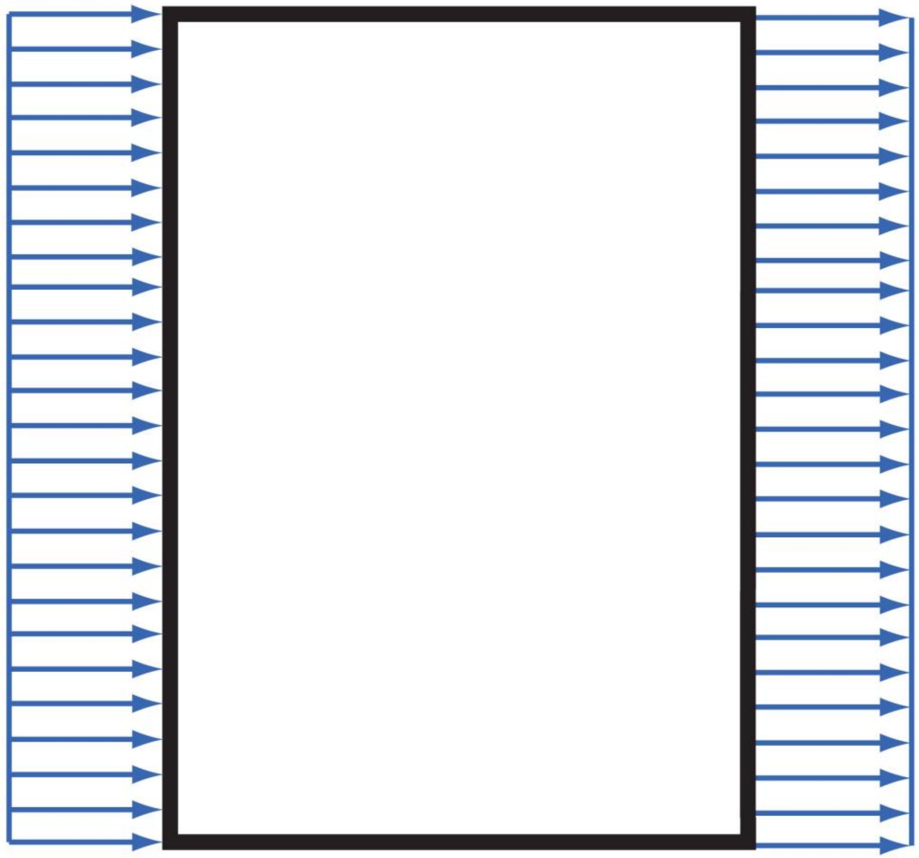


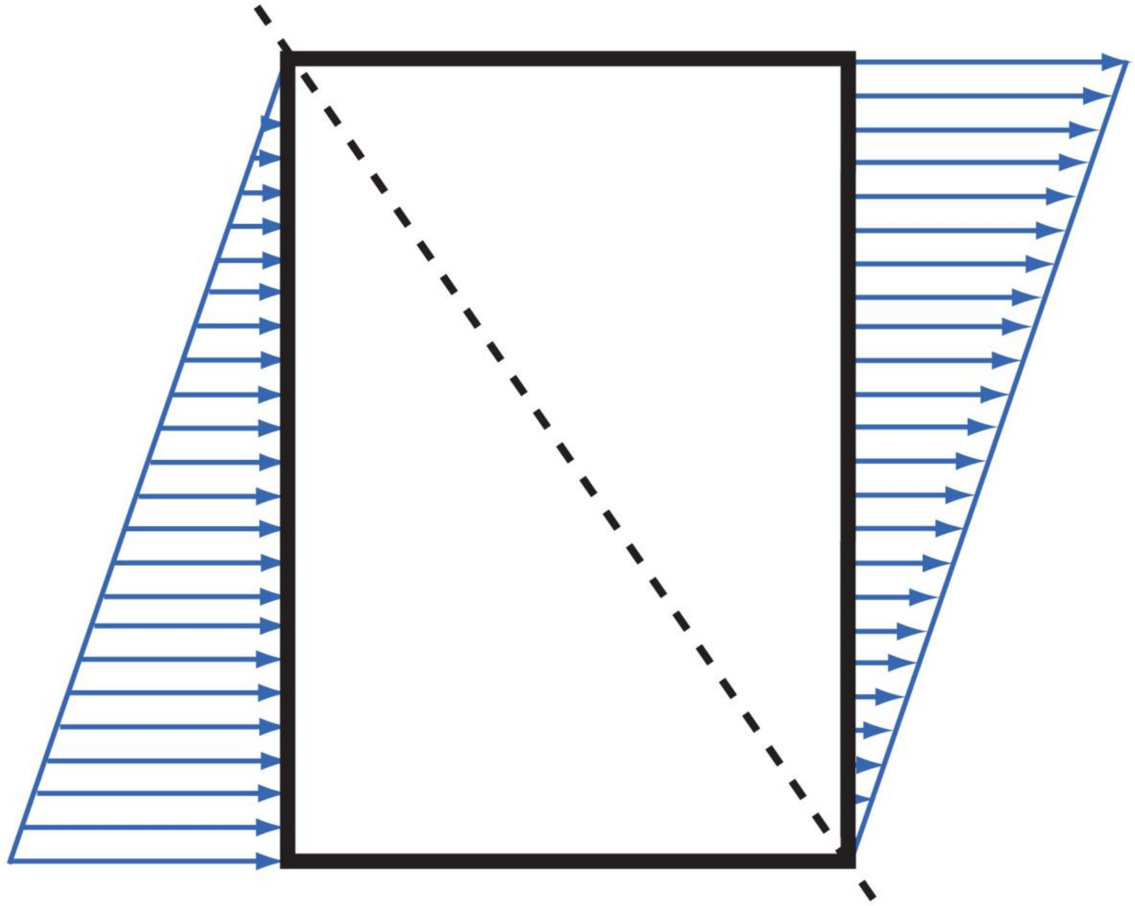
Figure 11.6: Two storey house with operating chimney (Adapted from G.O. Handegord, 1998)



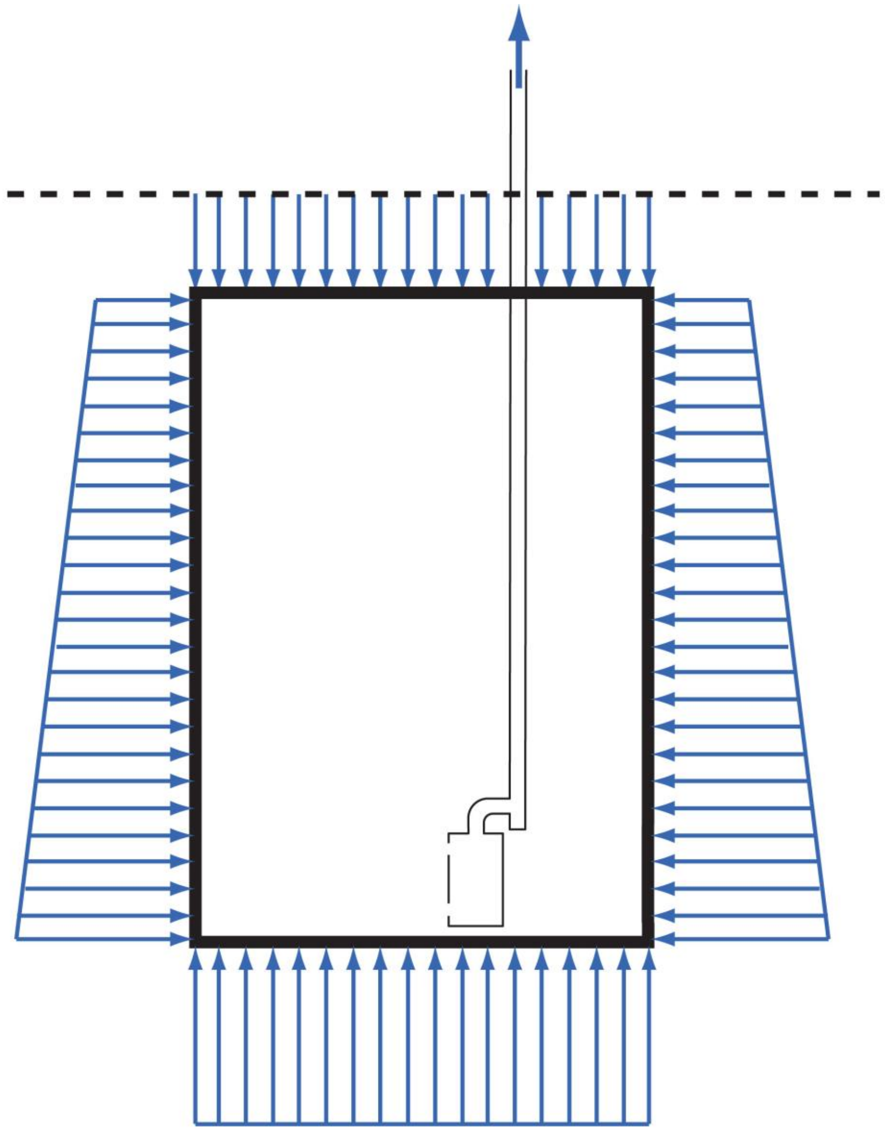
Stack effect



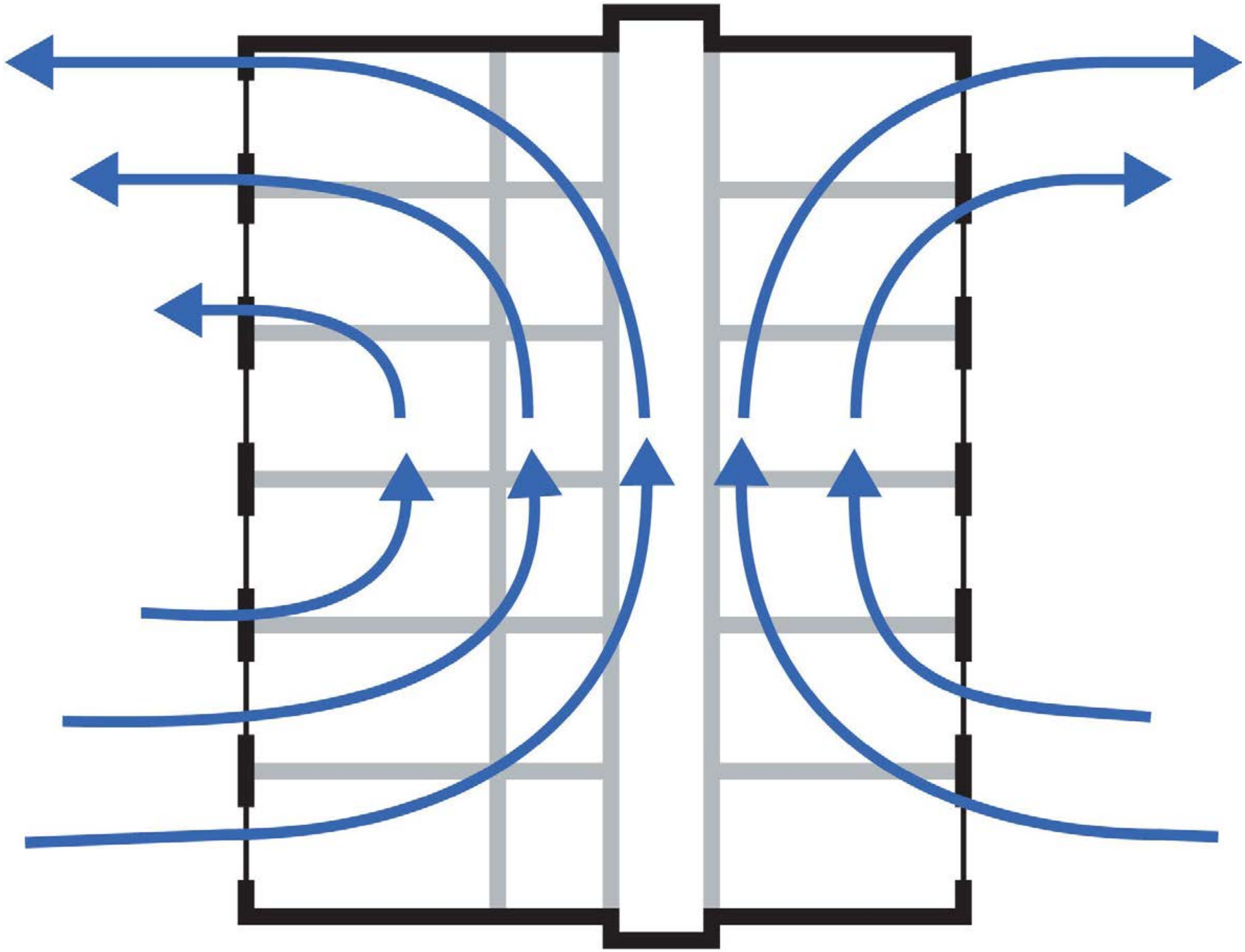
Wind

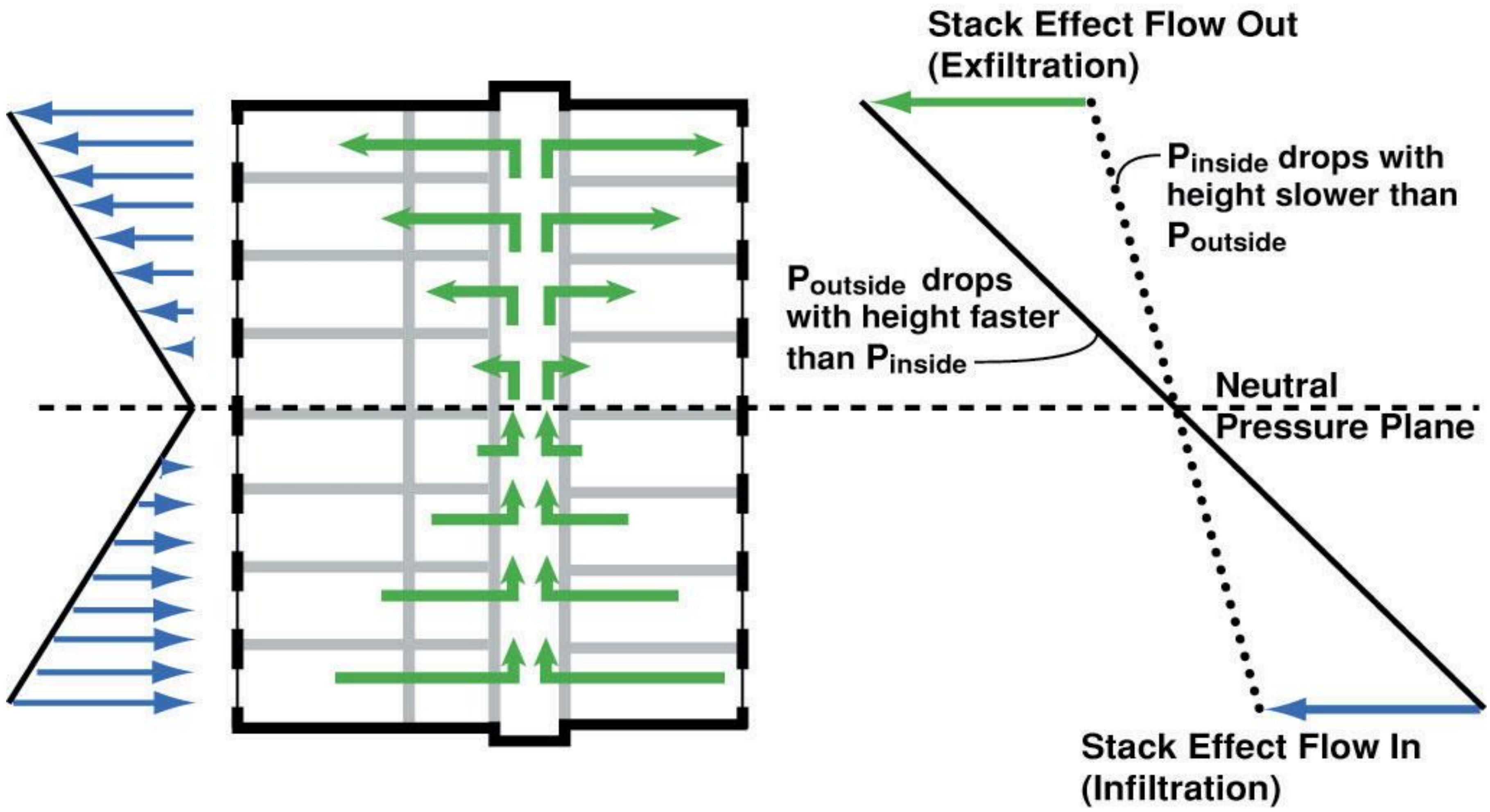


Stack effect and wind



Chimney effect





Stack Effect Flow Out
(Exfiltration)
P_{inside} drops with height slower than P_{outside}
P_{outside} drops with height faster than P_{inside}
Neutral Pressure Plane
Stack Effect Flow In
(Infiltration)

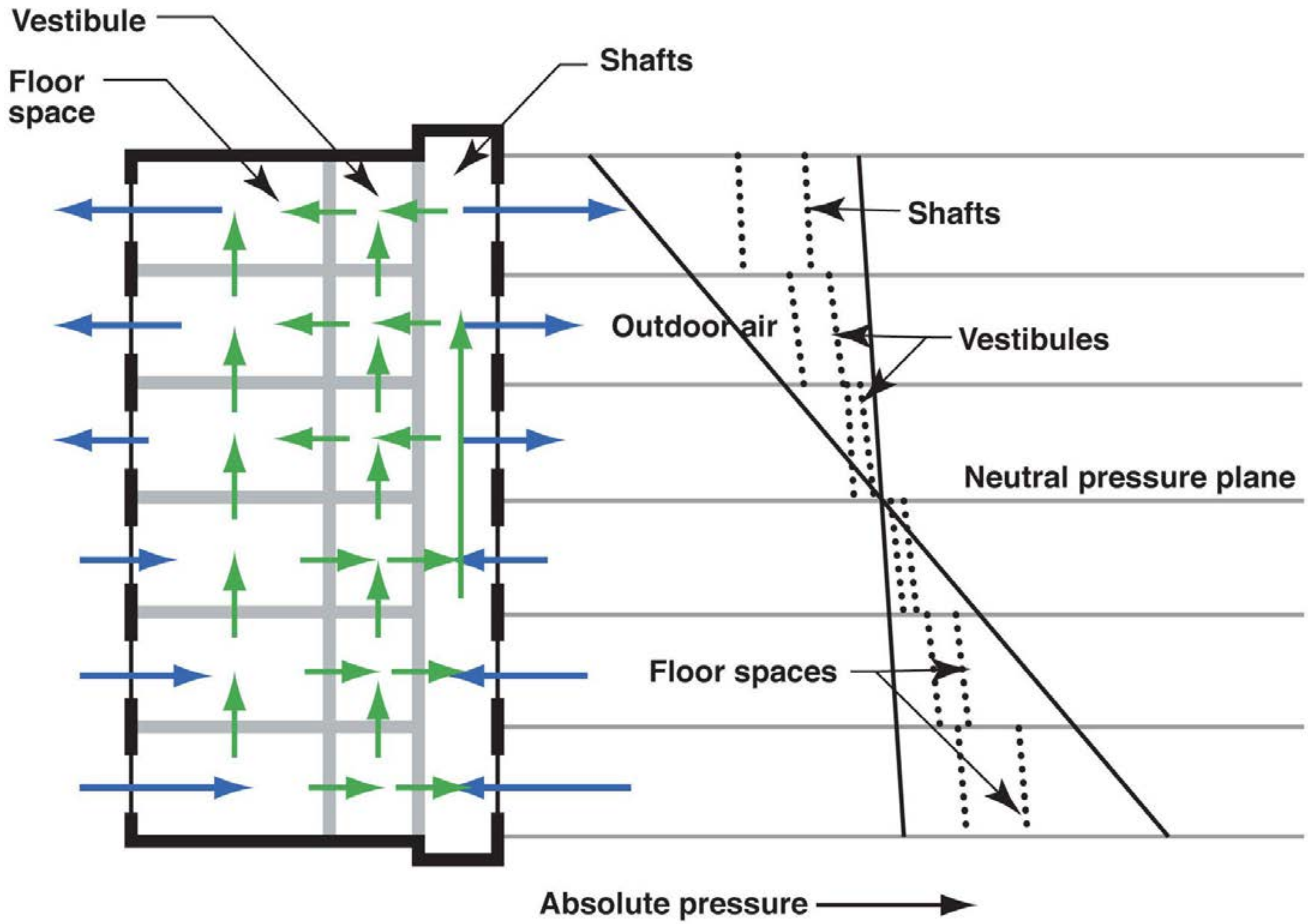


Figure 11.8: Stack effect pressures in high rise office building
(Adapted from G.O. Handegord, 1998)

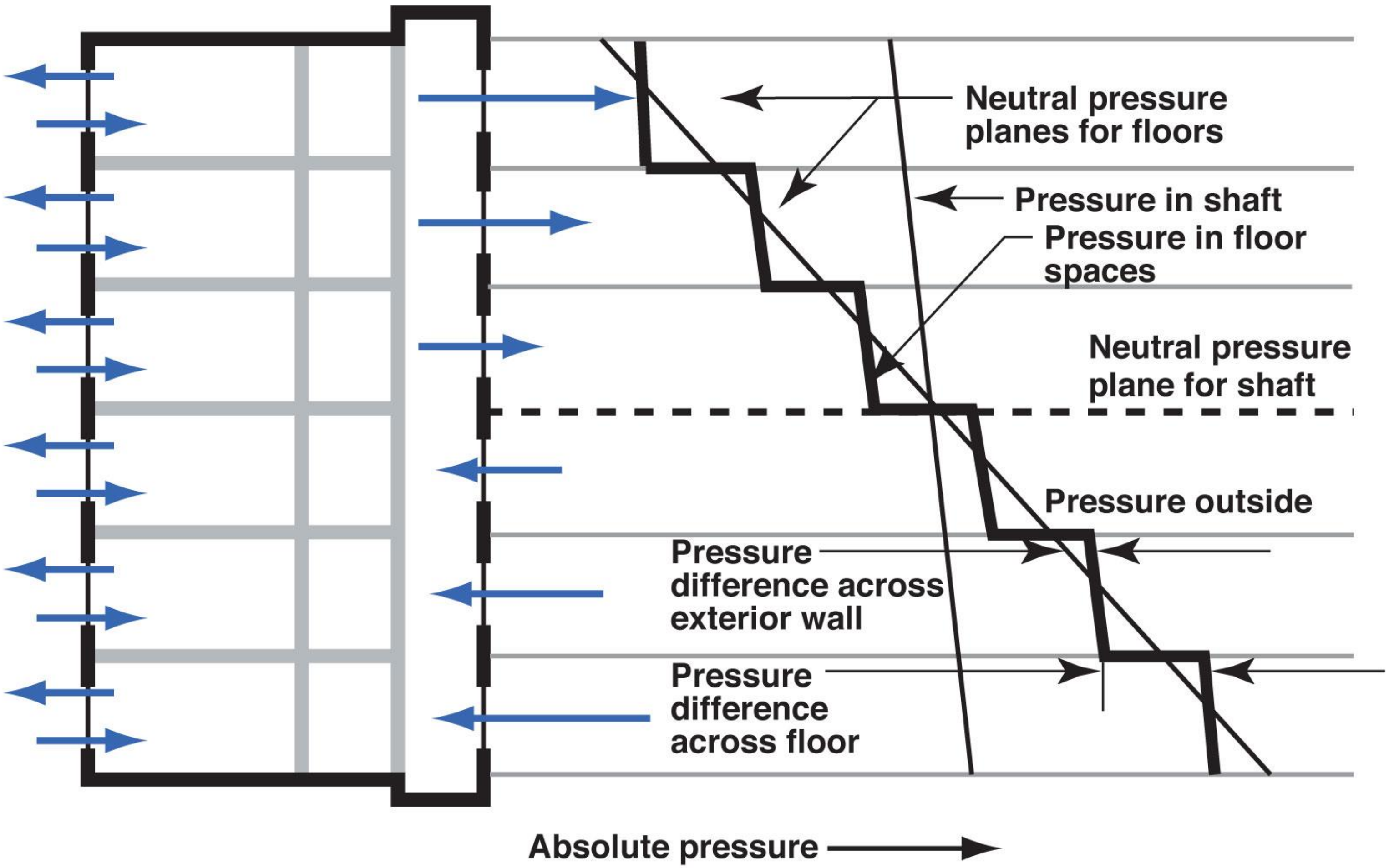


Figure 11.9: Multi-storey building with floor spaces isolated from vertical shafts (Adapted from G.O. Handegord, 1998)

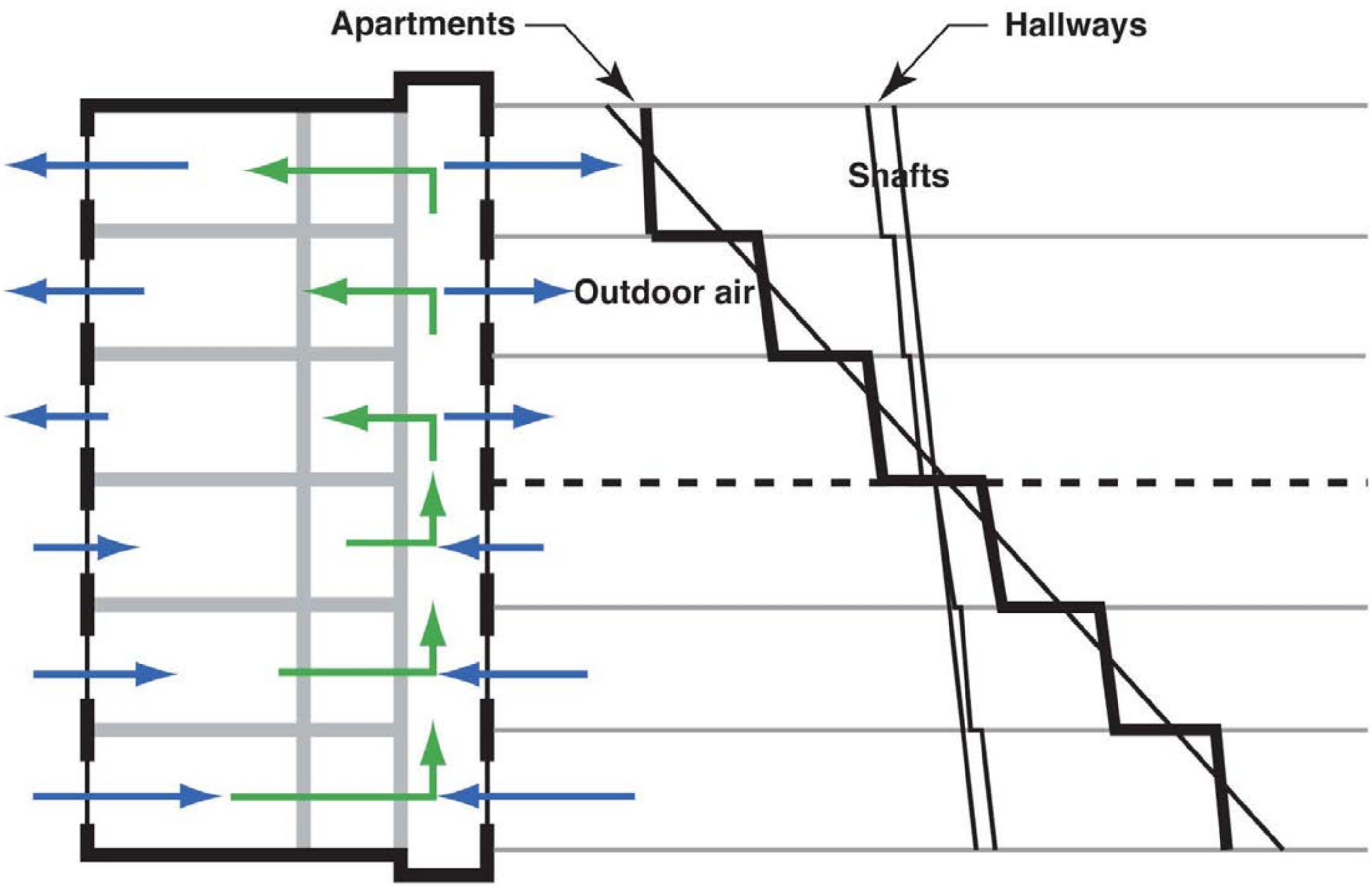
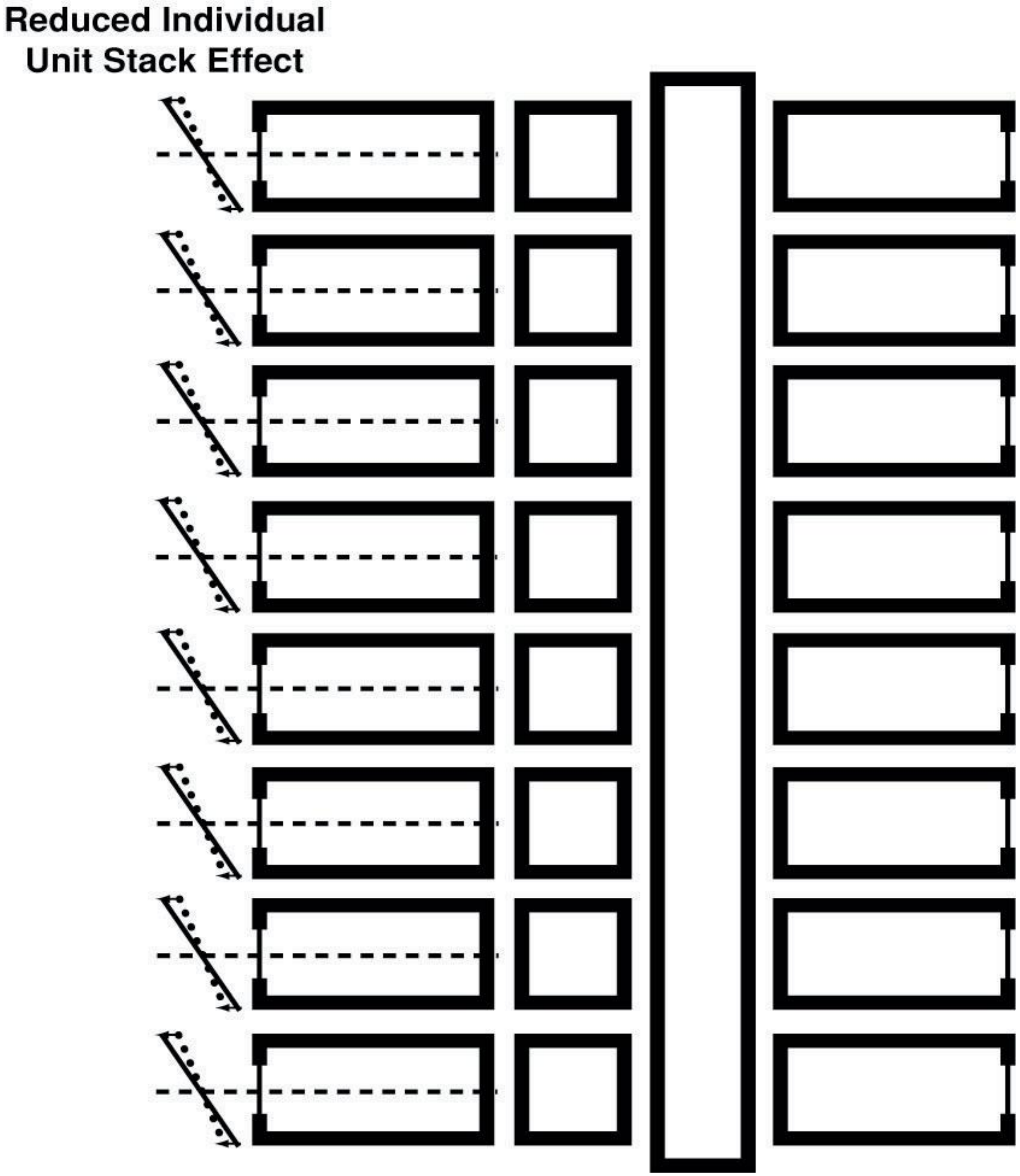
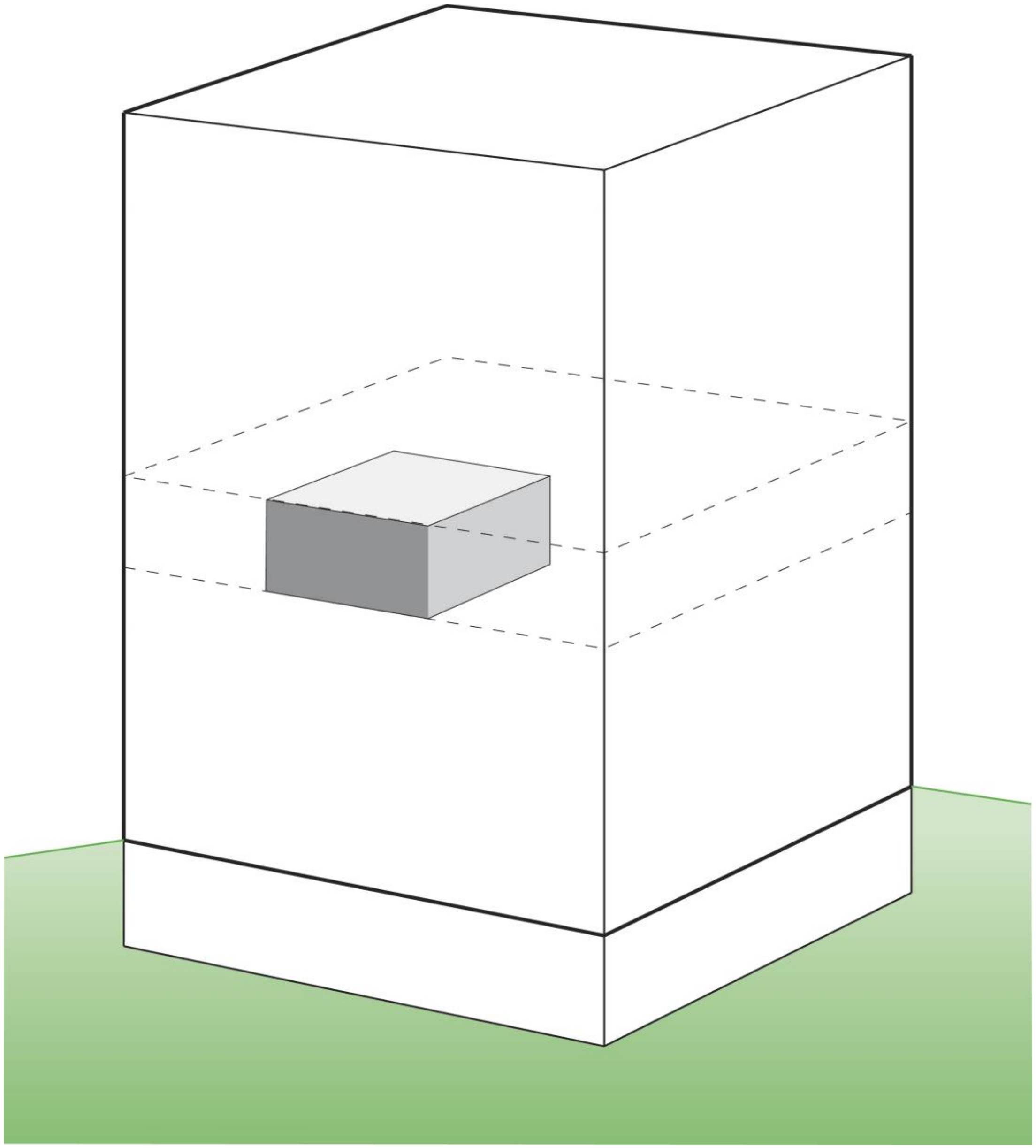
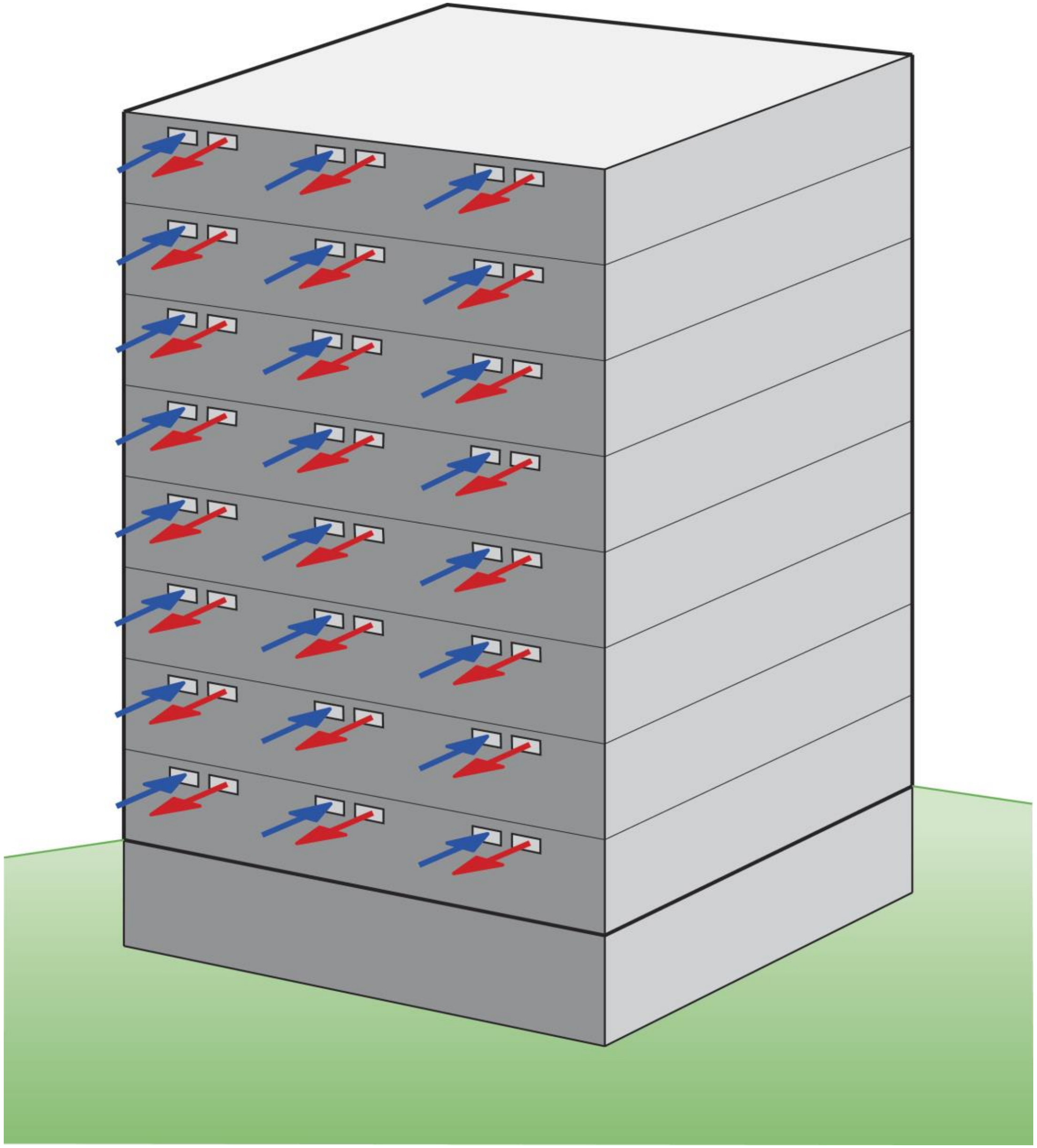
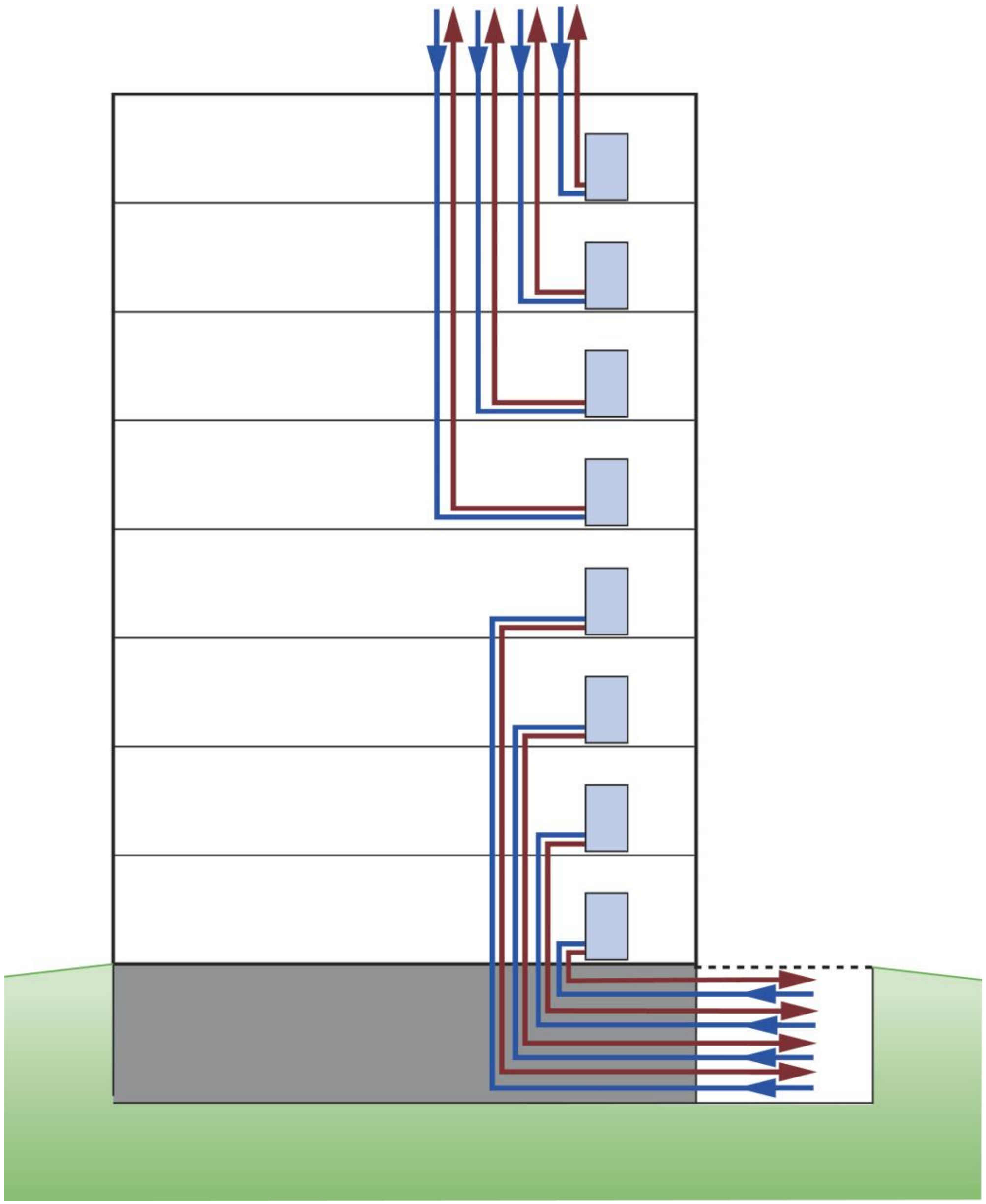


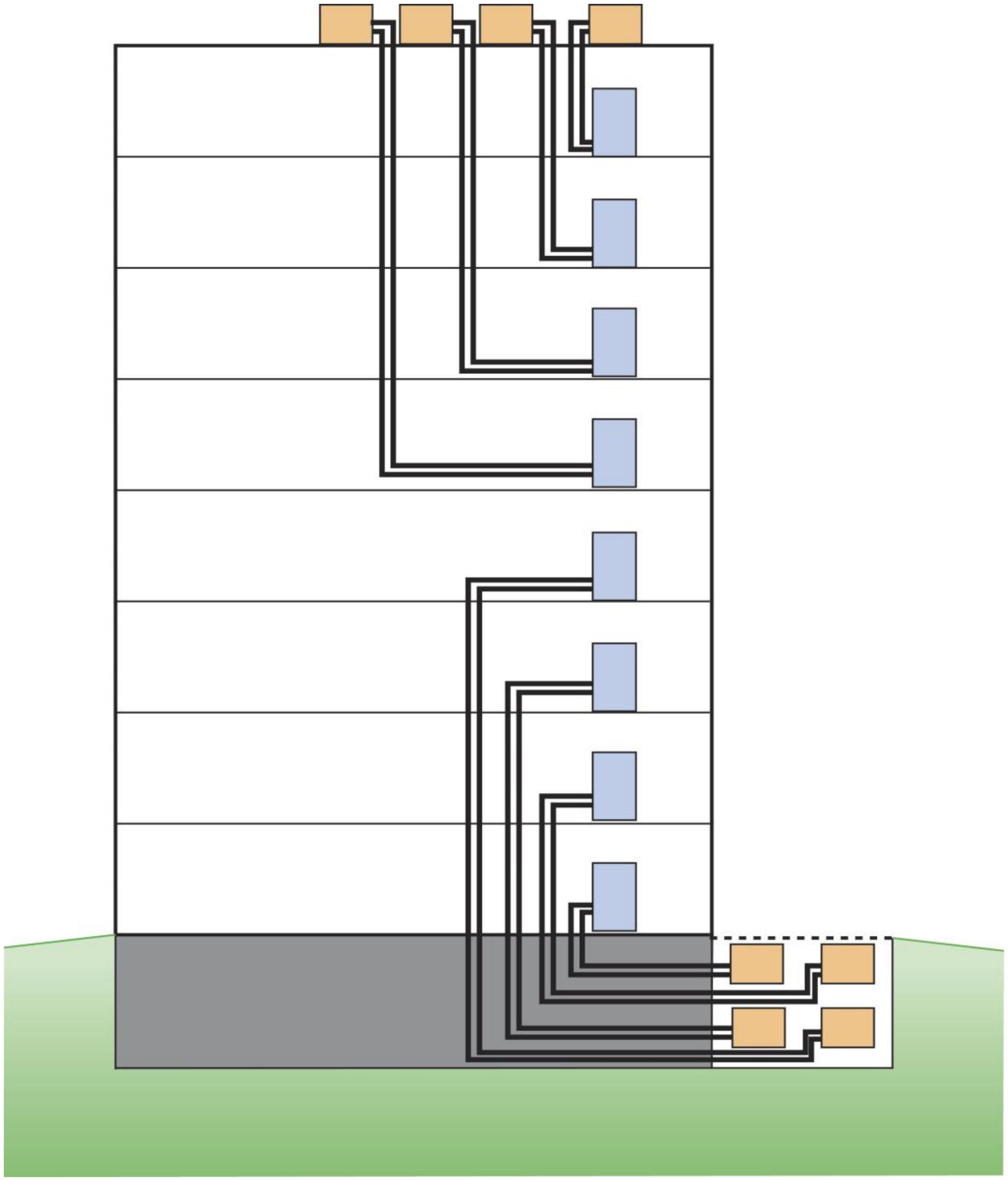
Figure 11.12: Apartment building with tighter apartment entry doors (Adapted from G.O. Handegord, 1998)

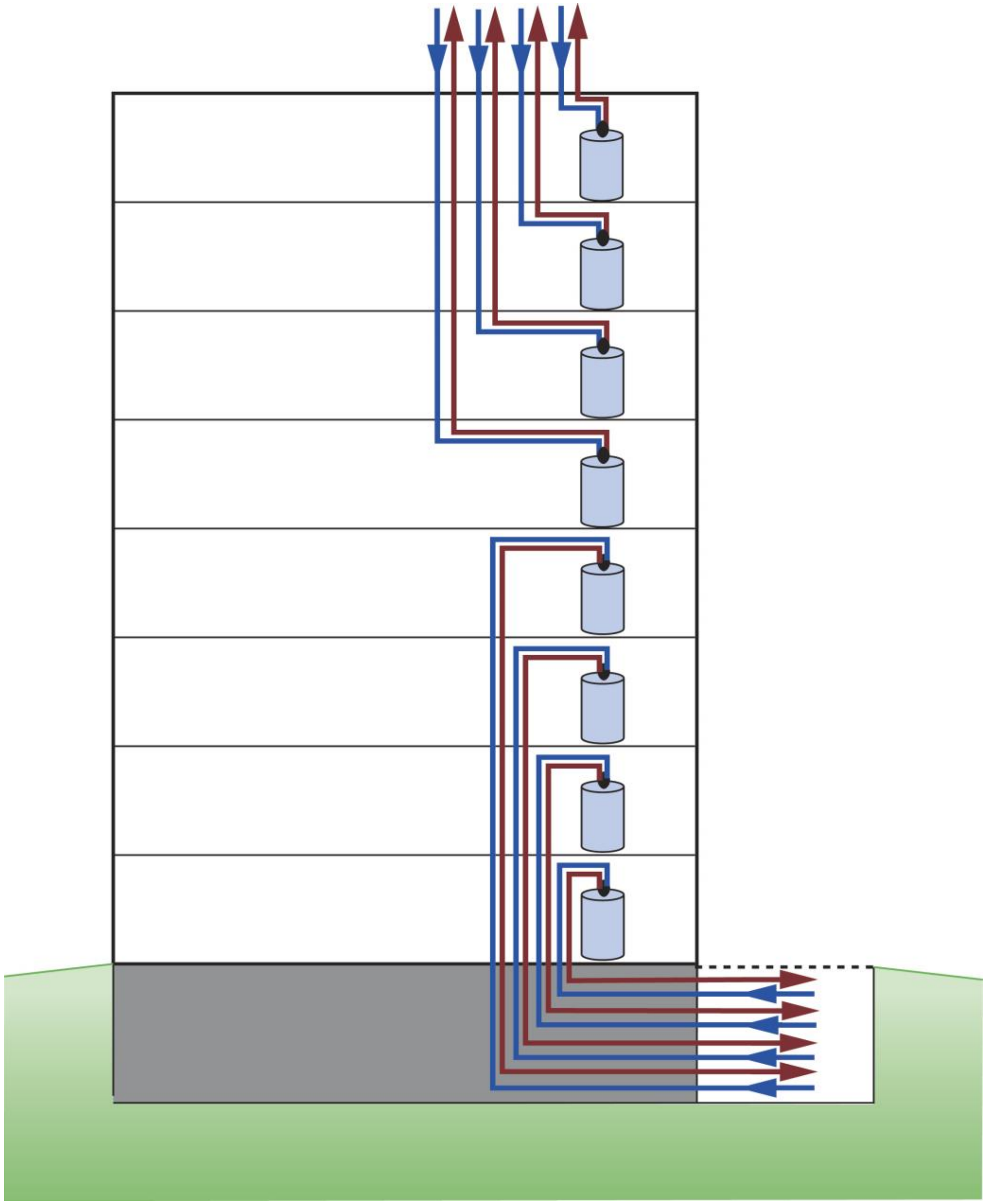

Reduced Individual
Unit Stack Effect












HOT WATER


YORK
YORK


Goodman
Goodman
Goodman


EASTERN EASTERN
939
ANJAC FASHION BLDGS
Carrier
Carrier


A.O. Smith
EnergySaver
ENERGYGUIDE
POTABLE WATER
EXPANSION TANK
REGULATOR
8 23 '00

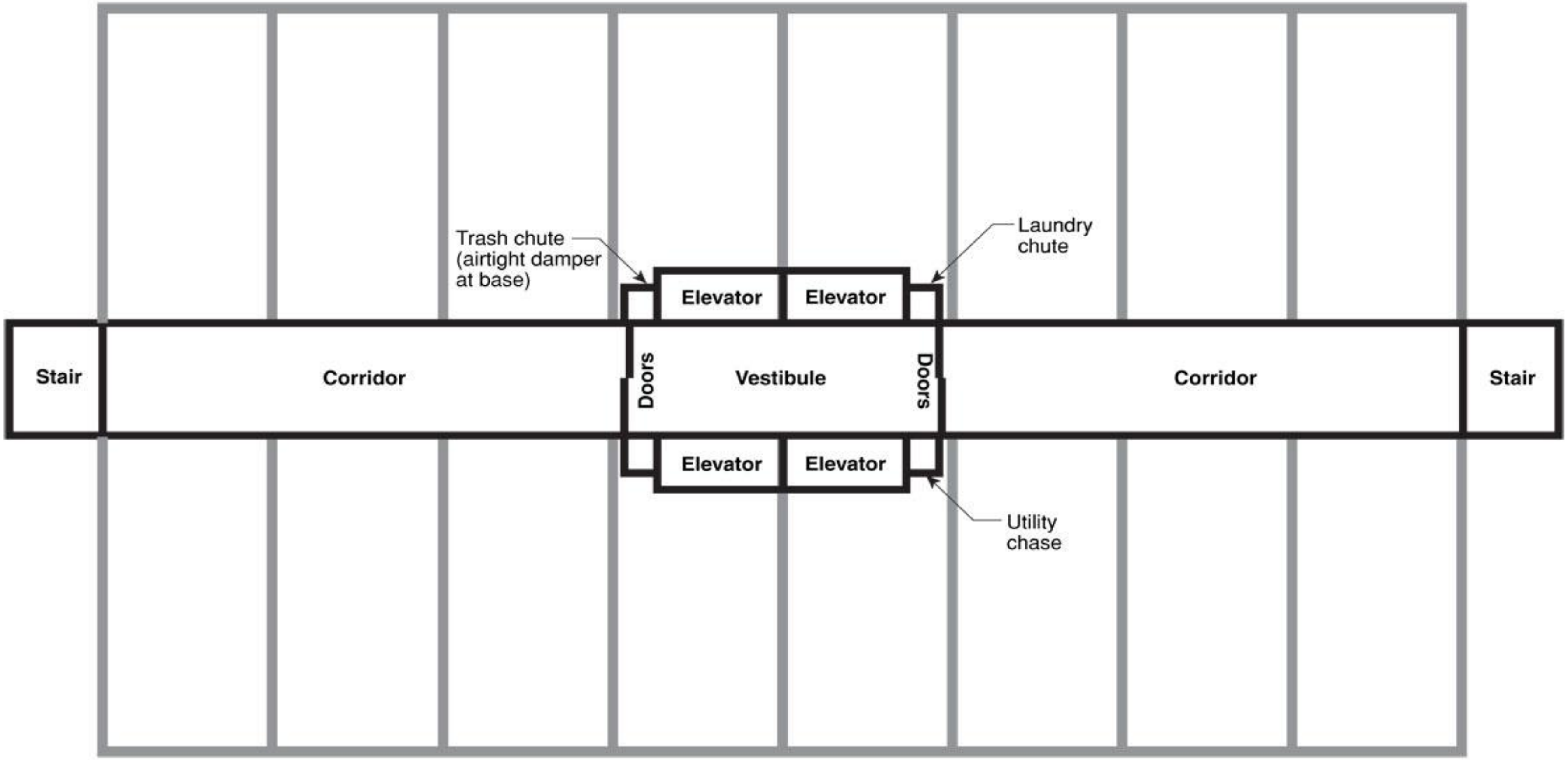

ASKO
ASKO
ENERGUIDE
209 kWh

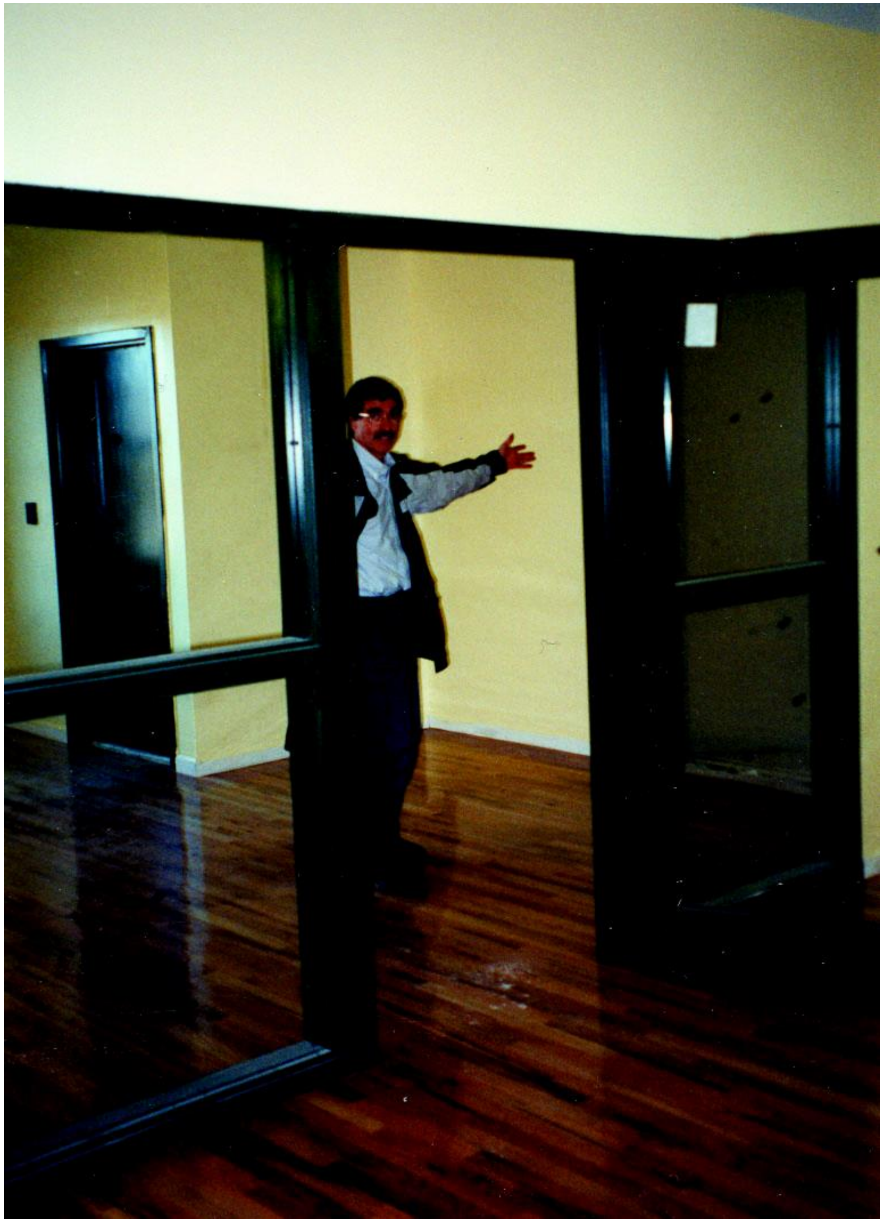

Heating And Air Conditioning

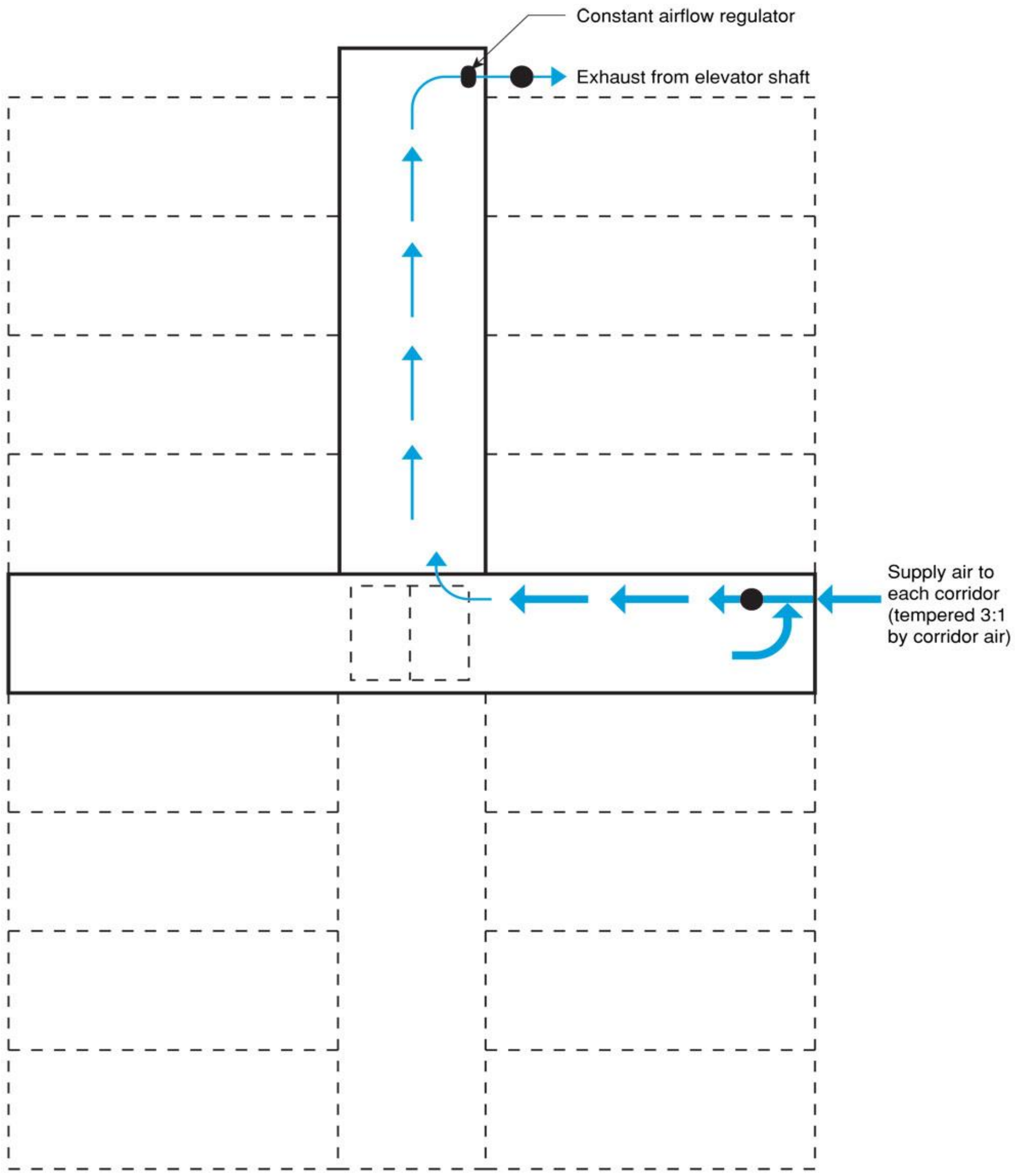

ENERGYGUIDE

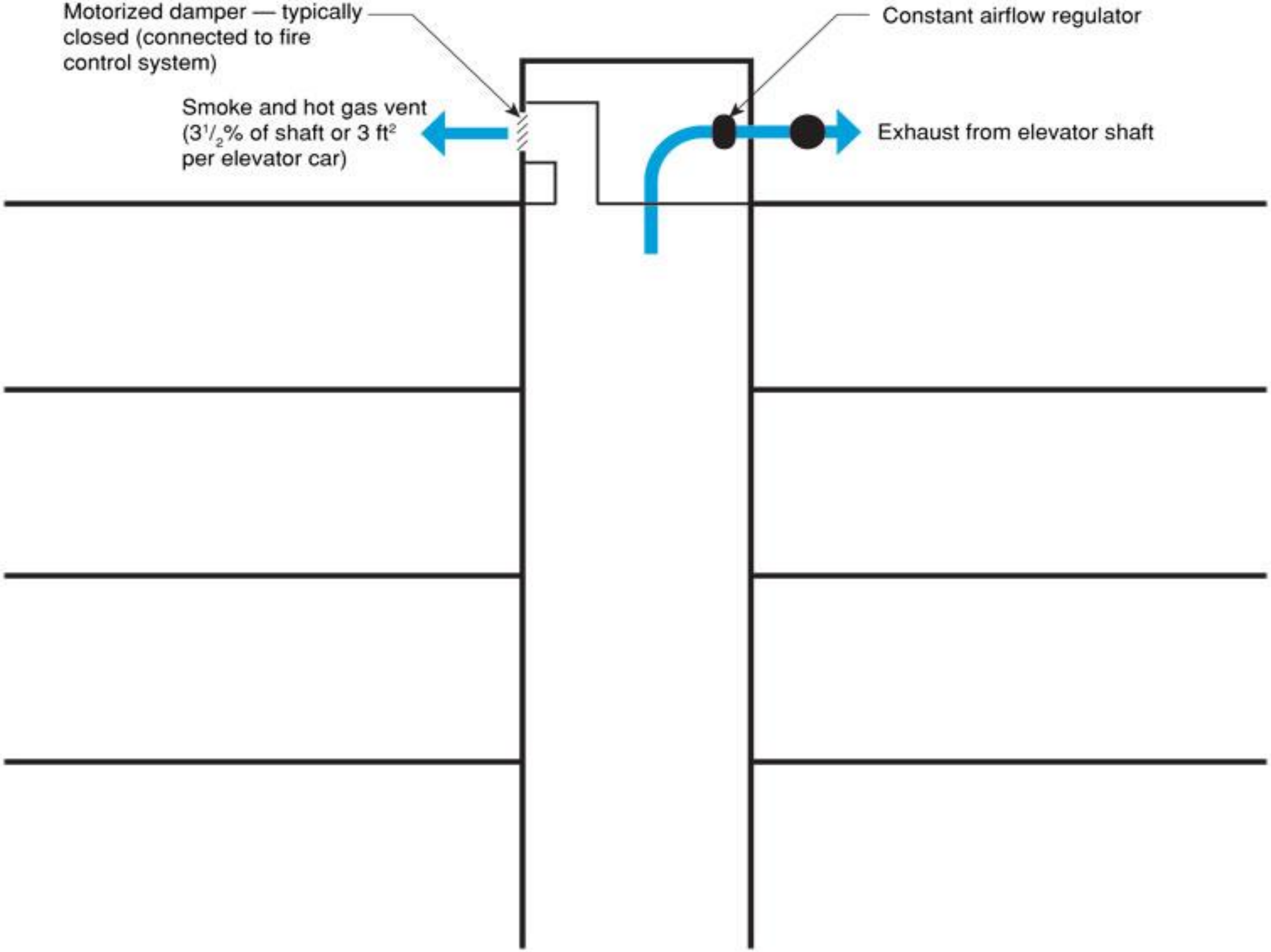

Rheem
EverKleen
Self-Cleansing Water Heaters
ENERGYGUIDE
DANGER

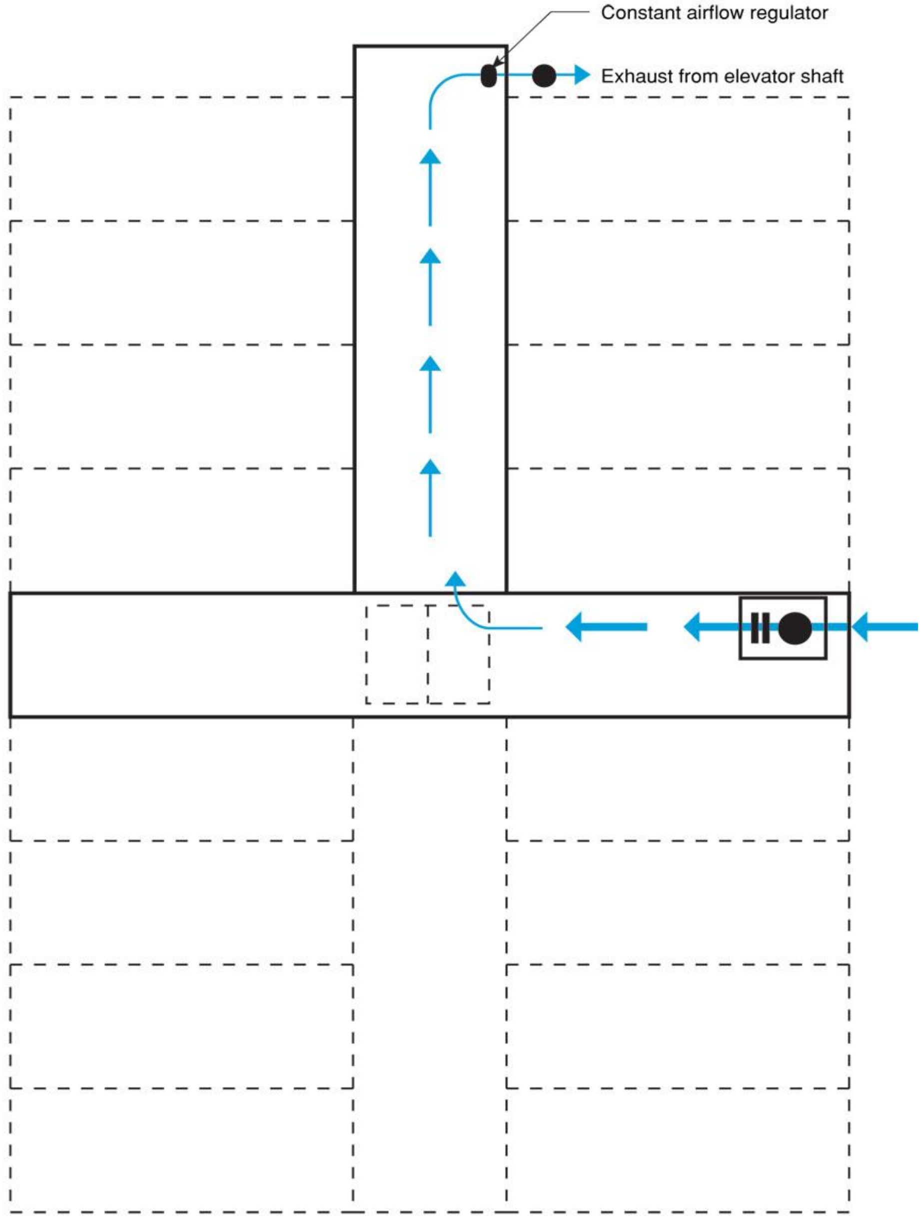

BOSTON
UNIVERSITY

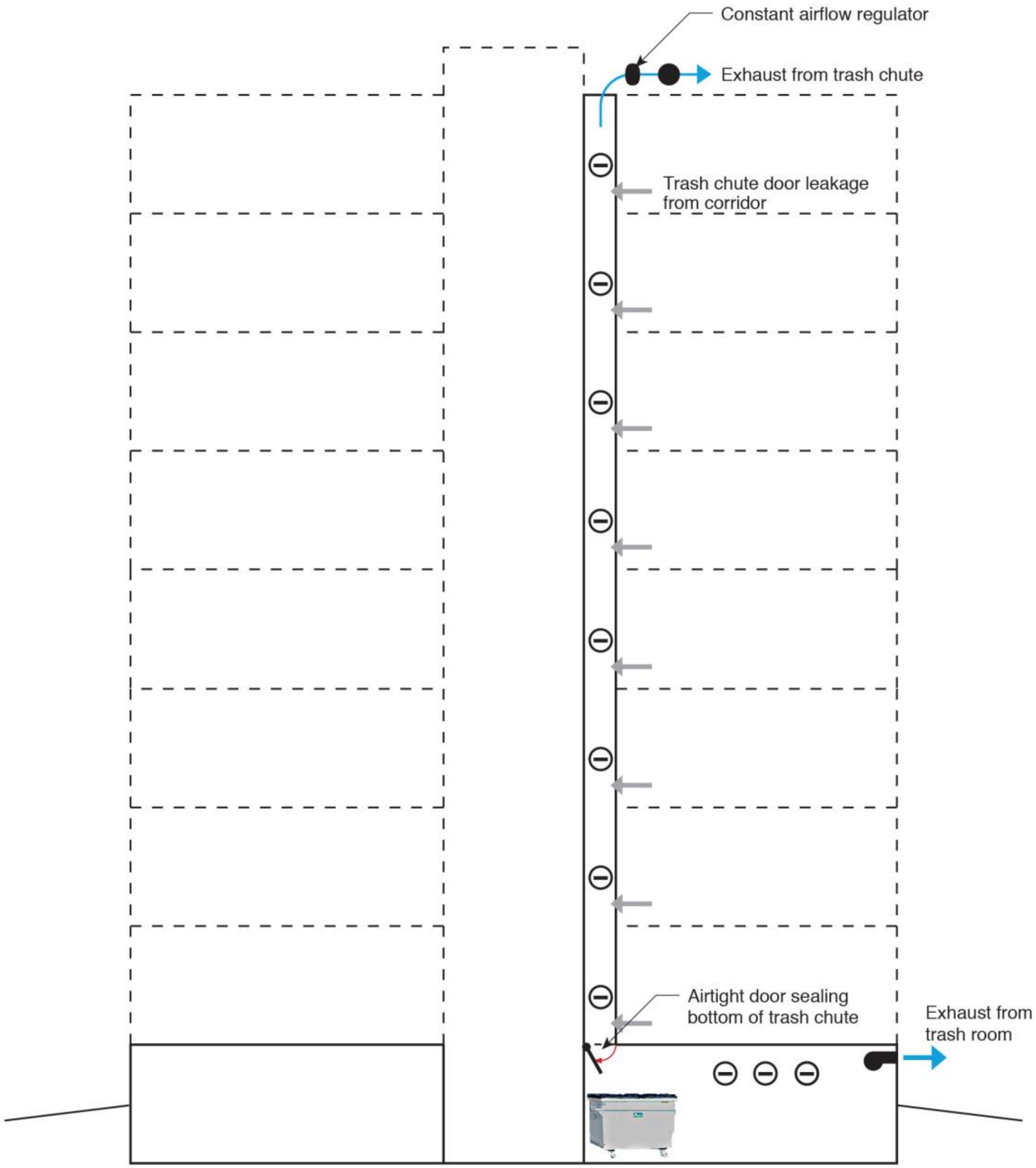

Trash chute
(airtight damper
at base)
Laundry
chute
Elevator
Elevator
Stair
Corridor
Doors
Vestibule
Doors
Corridor
Stair
Elevator
Elevator
Utility
chase

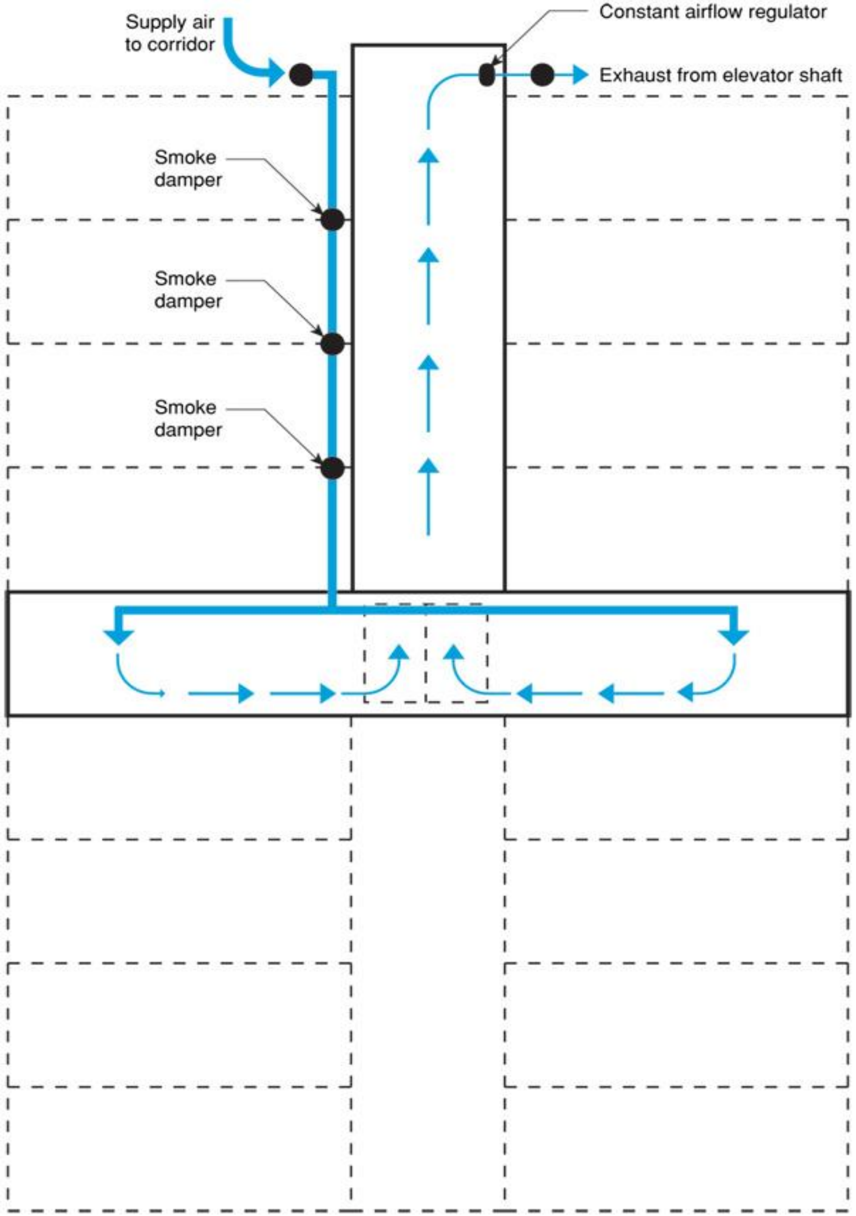


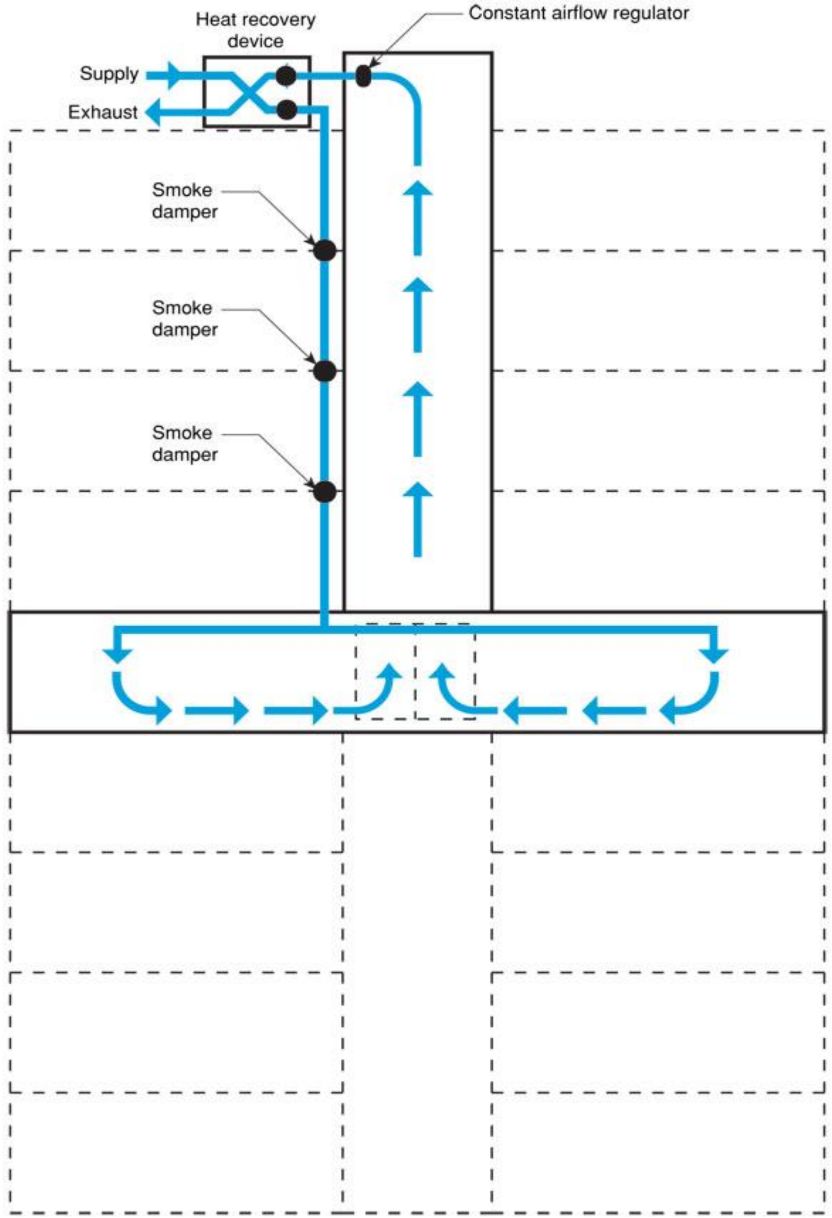

Constant airflow regulator
Exhaust from elevator shaft
Supply air to
each corridor
(tempered 3:1
by corridor air)

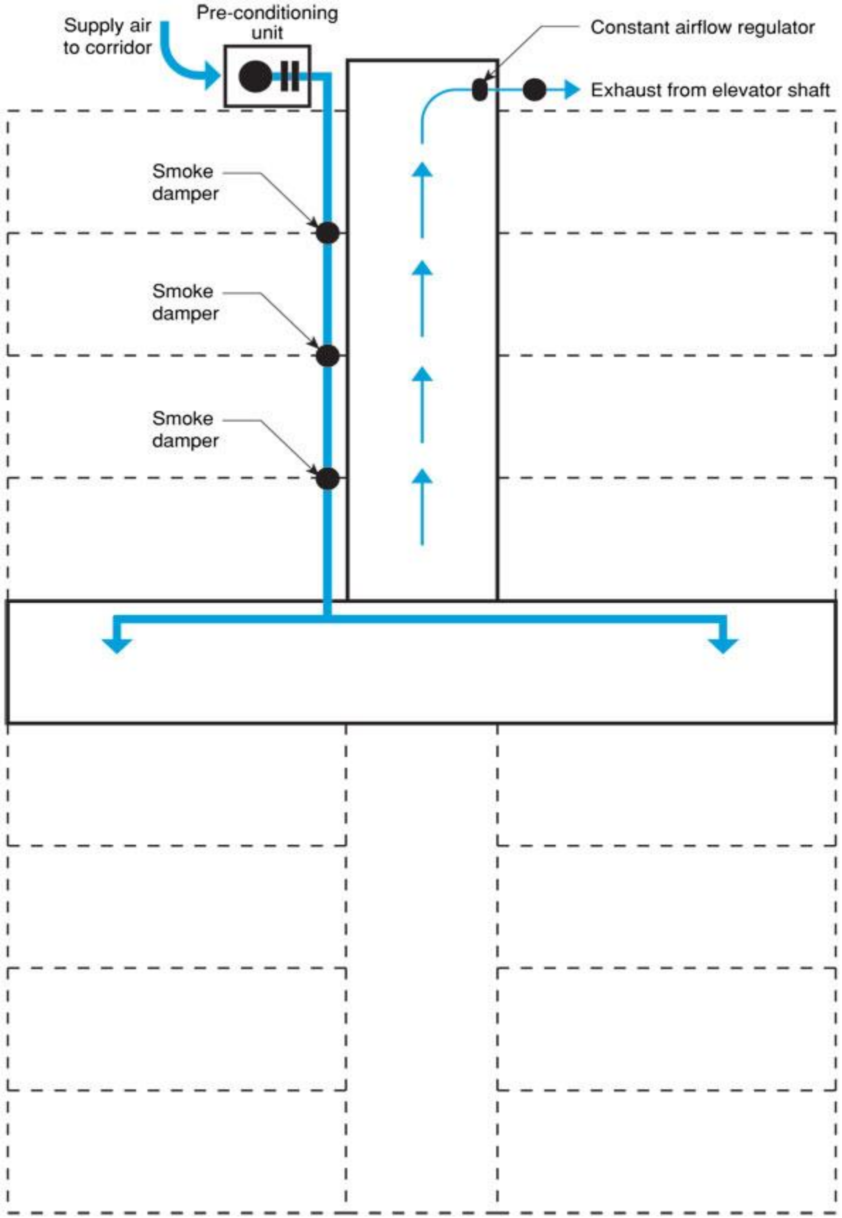

Motorized damper — typically closed (connected to fire control system)
Constant airflow regulator
Smoke and hot gas vent (3 1/2% of shaft or 3 ft² per elevator car)
Exhaust from elevator shaft

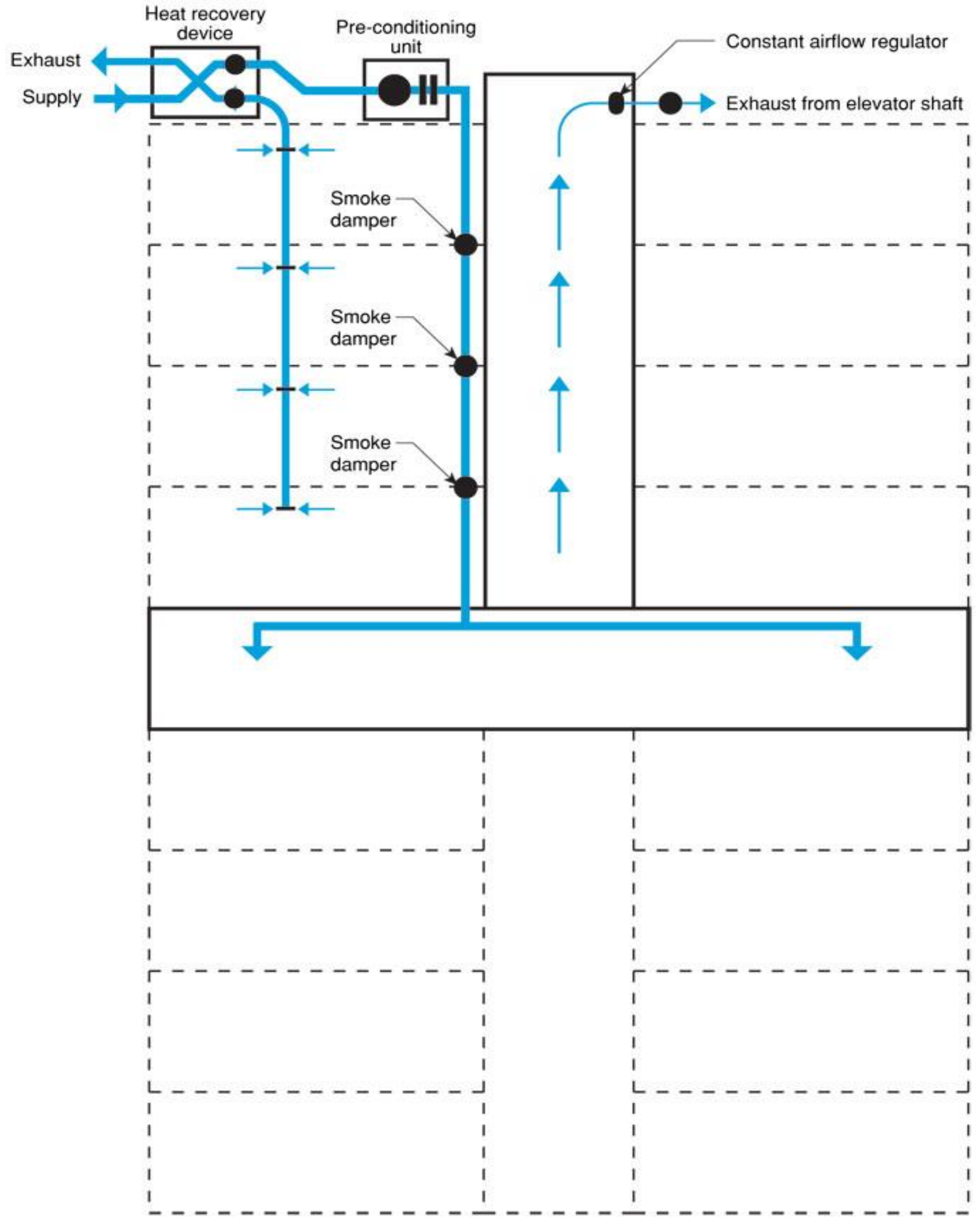

Constant airflow regulator
Exhaust from elevator shaft


Constant airflow regulator
Exhaust from trash chute
Trash chute door leakage from corridor
Airtight door sealing bottom of trash chute
Exhaust from trash room


Supply air
to corridor
Constant airflow regulator
Exhaust from elevator shaft
Smoke
damper
Smoke
damper
Smoke
damper


Heat recovery device
Constant airflow regulator
Supply
Exhaust
Smoke damper
Smoke damper
Smoke damper


Supply air to corridor
Pre-conditioning unit
Constant airflow regulator
Exhaust from elevator shaft
Smoke damper
Smoke damper
Smoke damper


Heat recovery device
Pre-conditioning unit
Constant airflow regulator
Exhaust
Supply
Exhaust from elevator shaft
Smoke damper
Smoke damper
Smoke damper


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

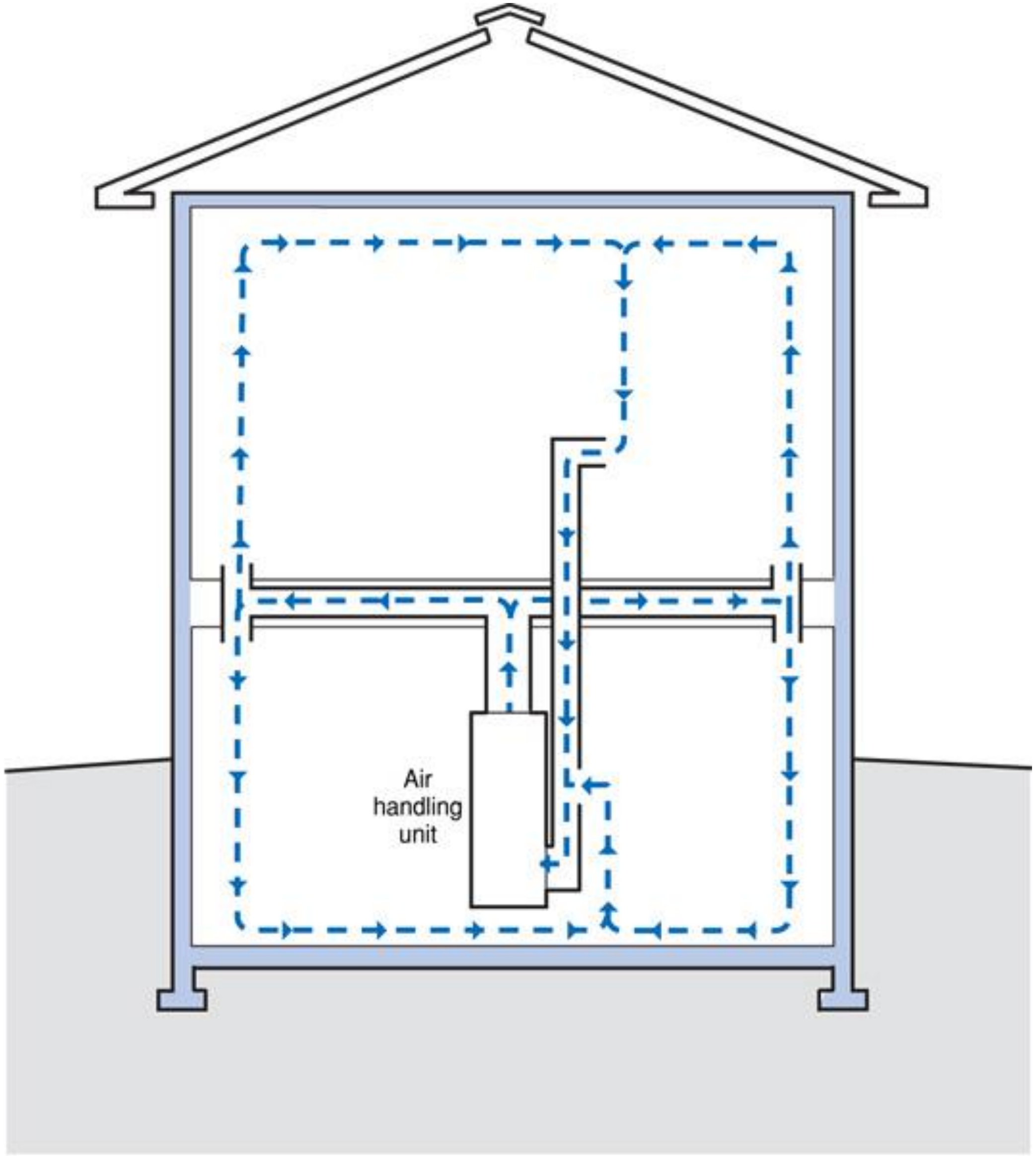
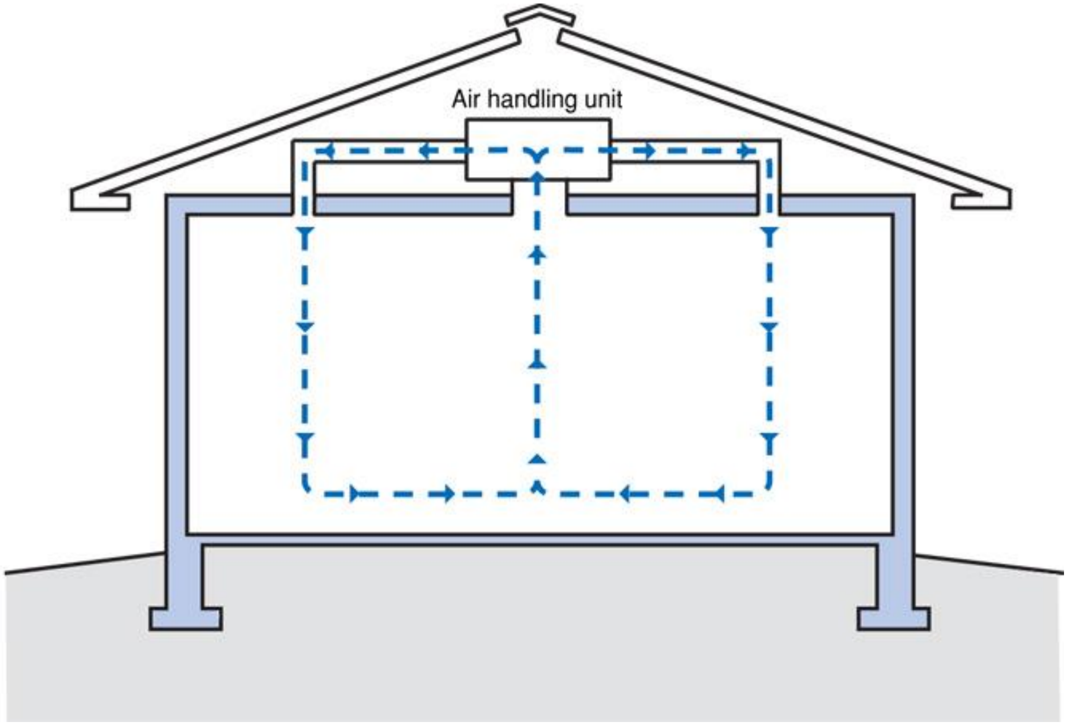


Figure 3.13

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



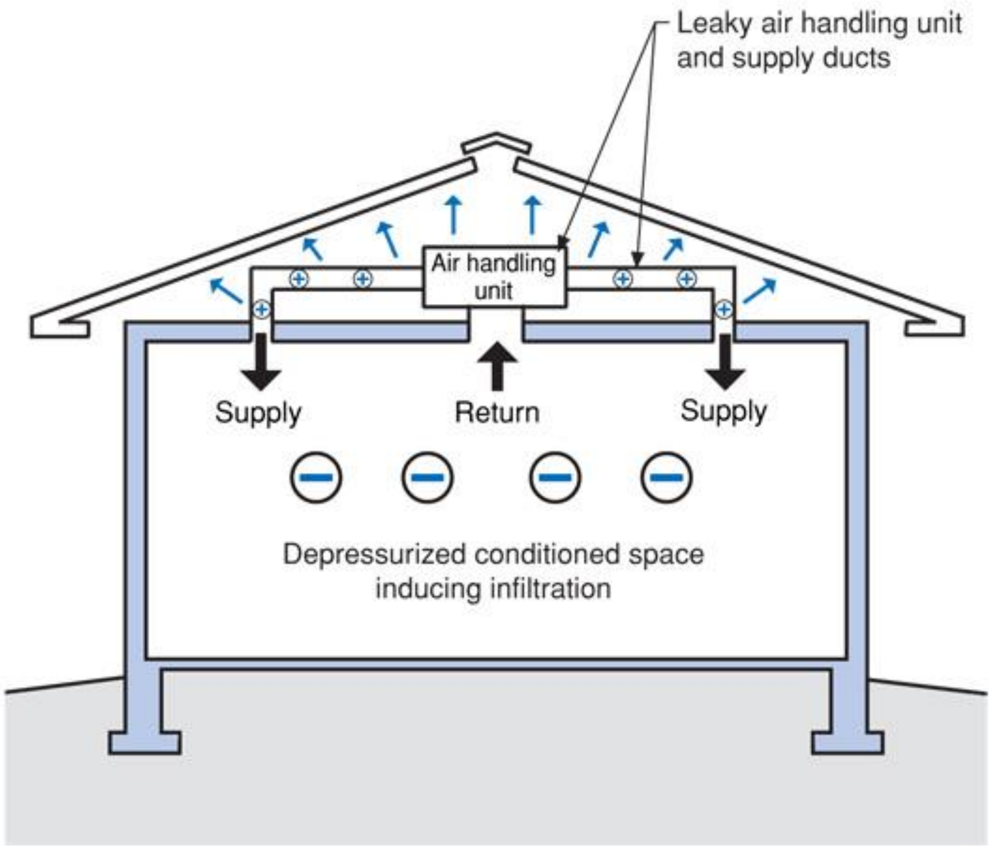


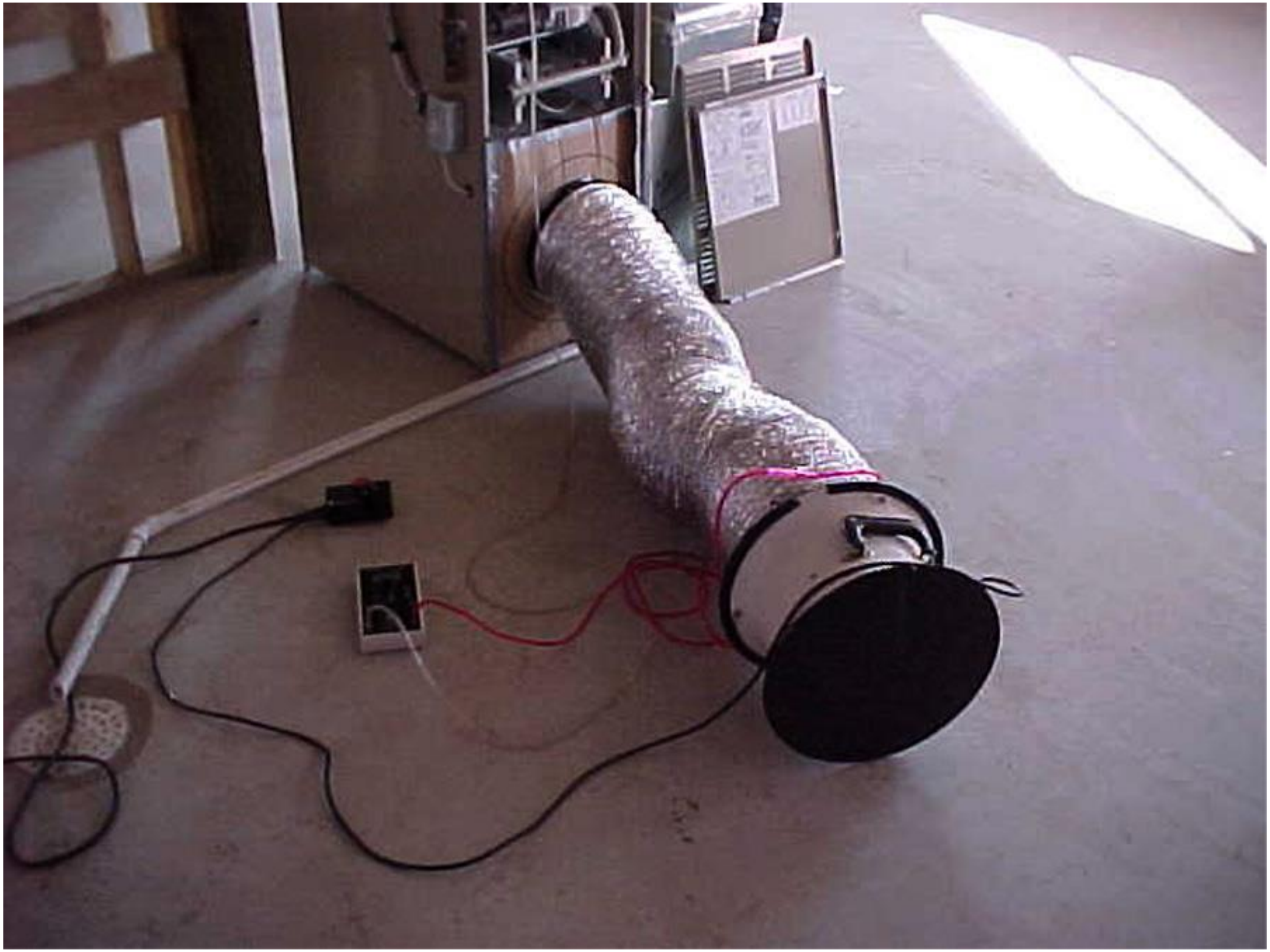
Figure 3.15

Leaky Ductwork and Air Handlers in Vented Attics

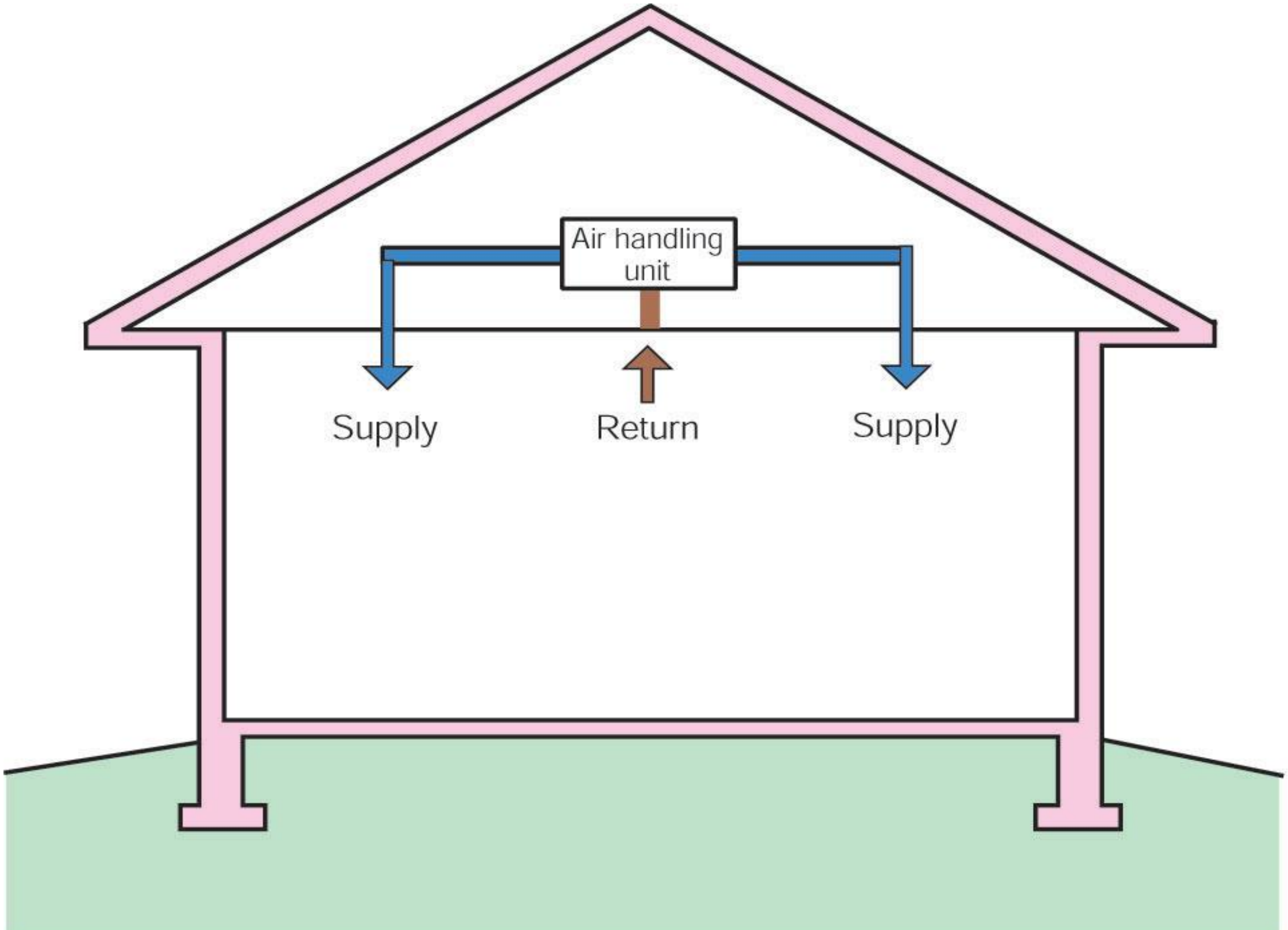
- Supply ductwork and air handler leakage is typically 20% or more of the flow through the system


15

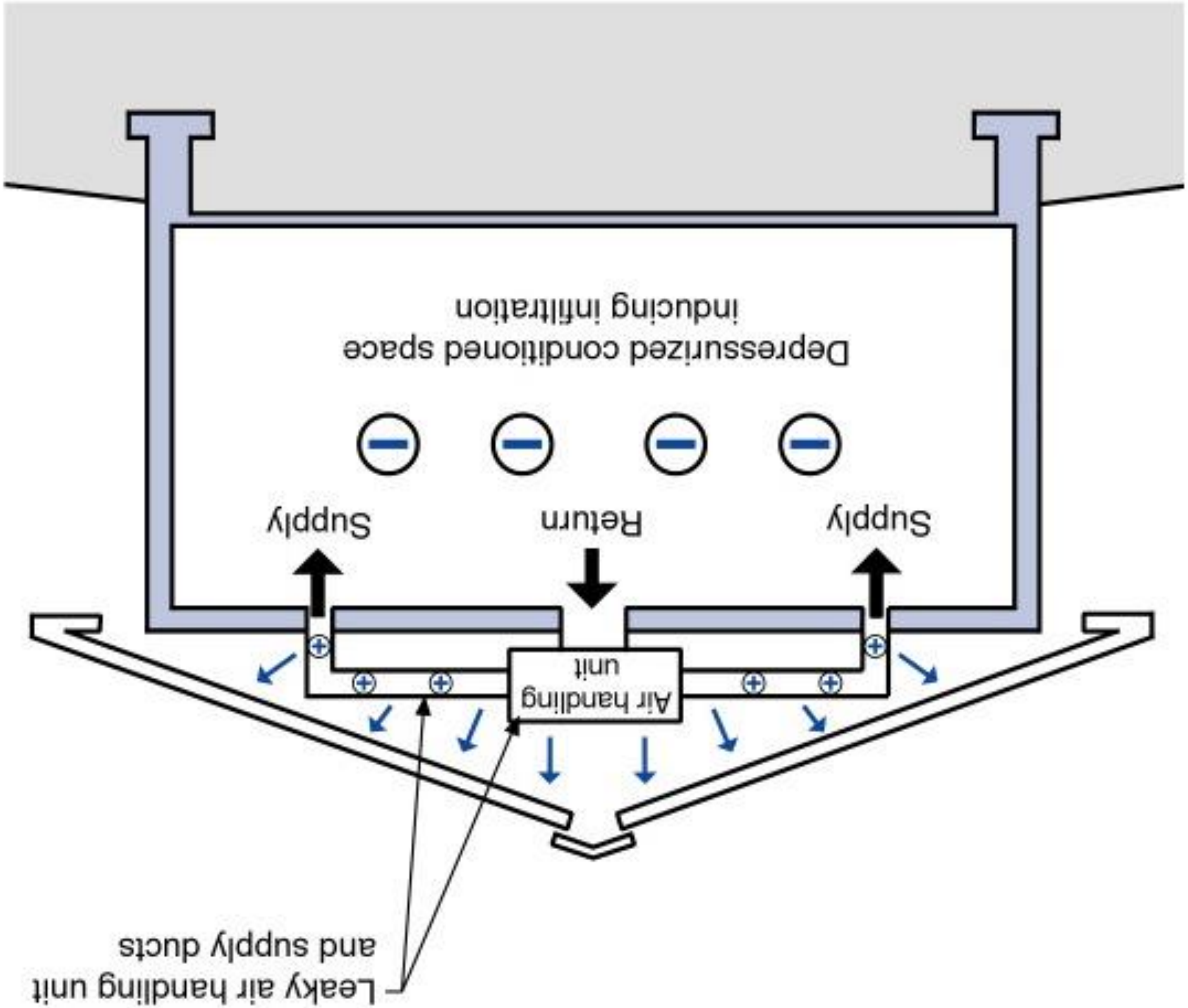

021



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

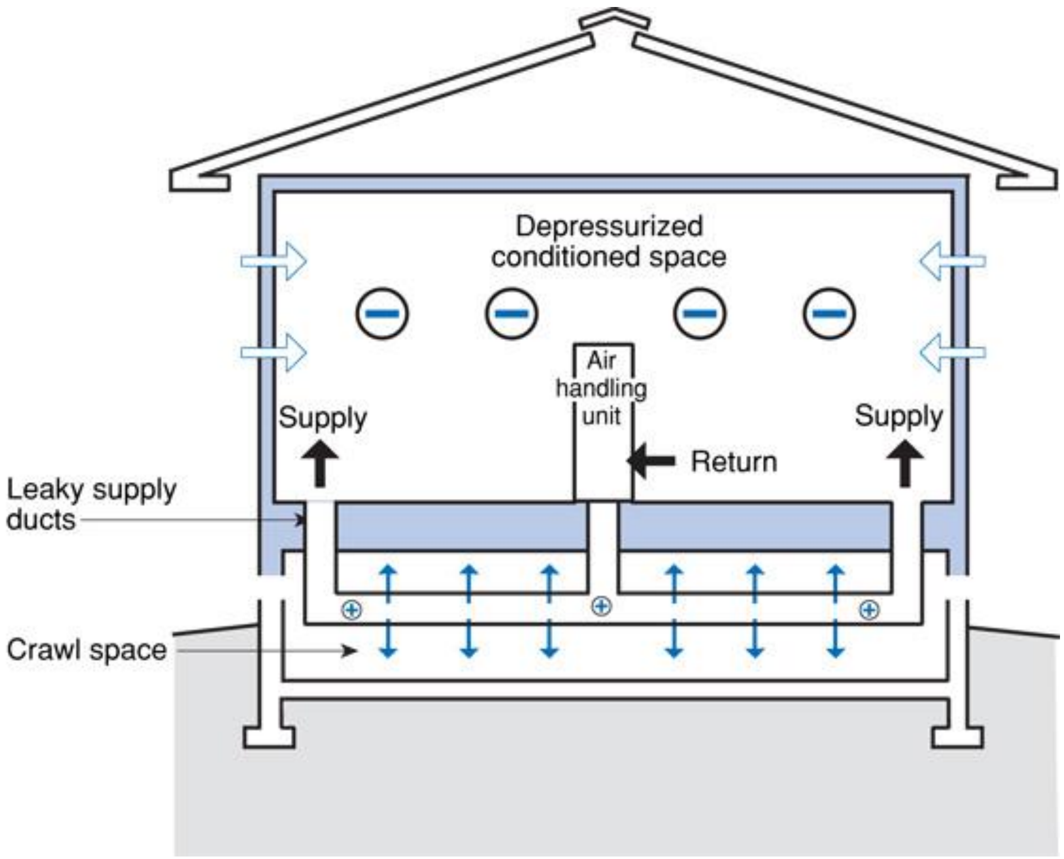
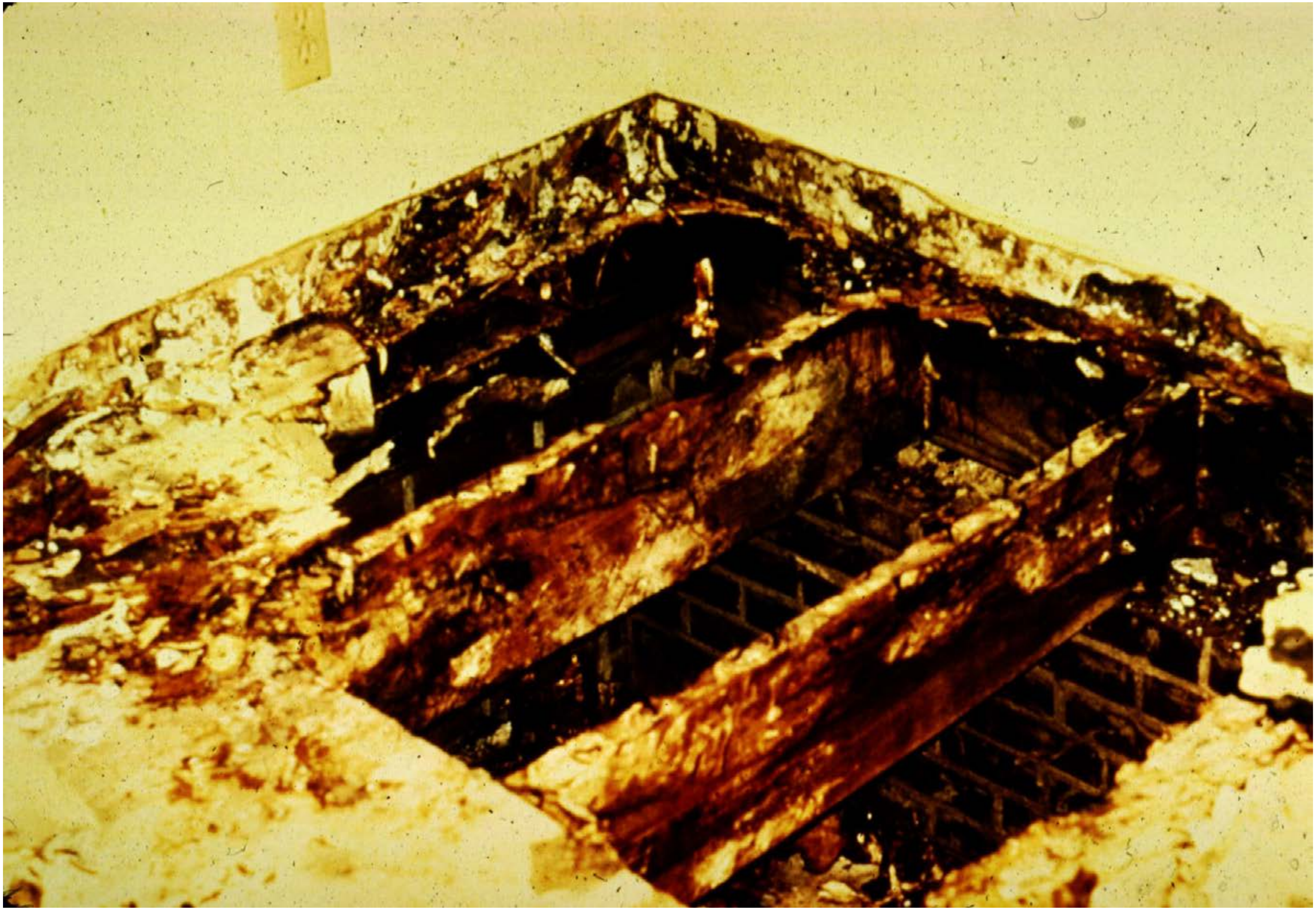


Figure 3.16

Leaky Supply Ductwork in Vented Crawl Space

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



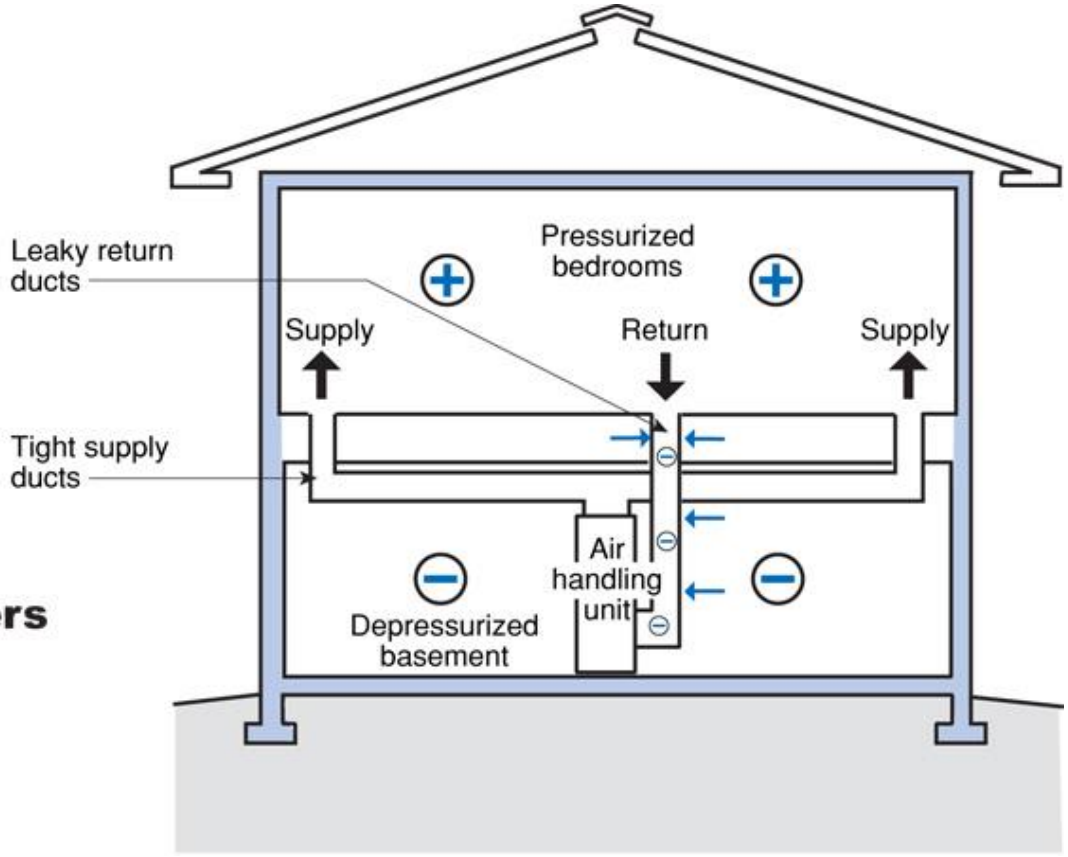
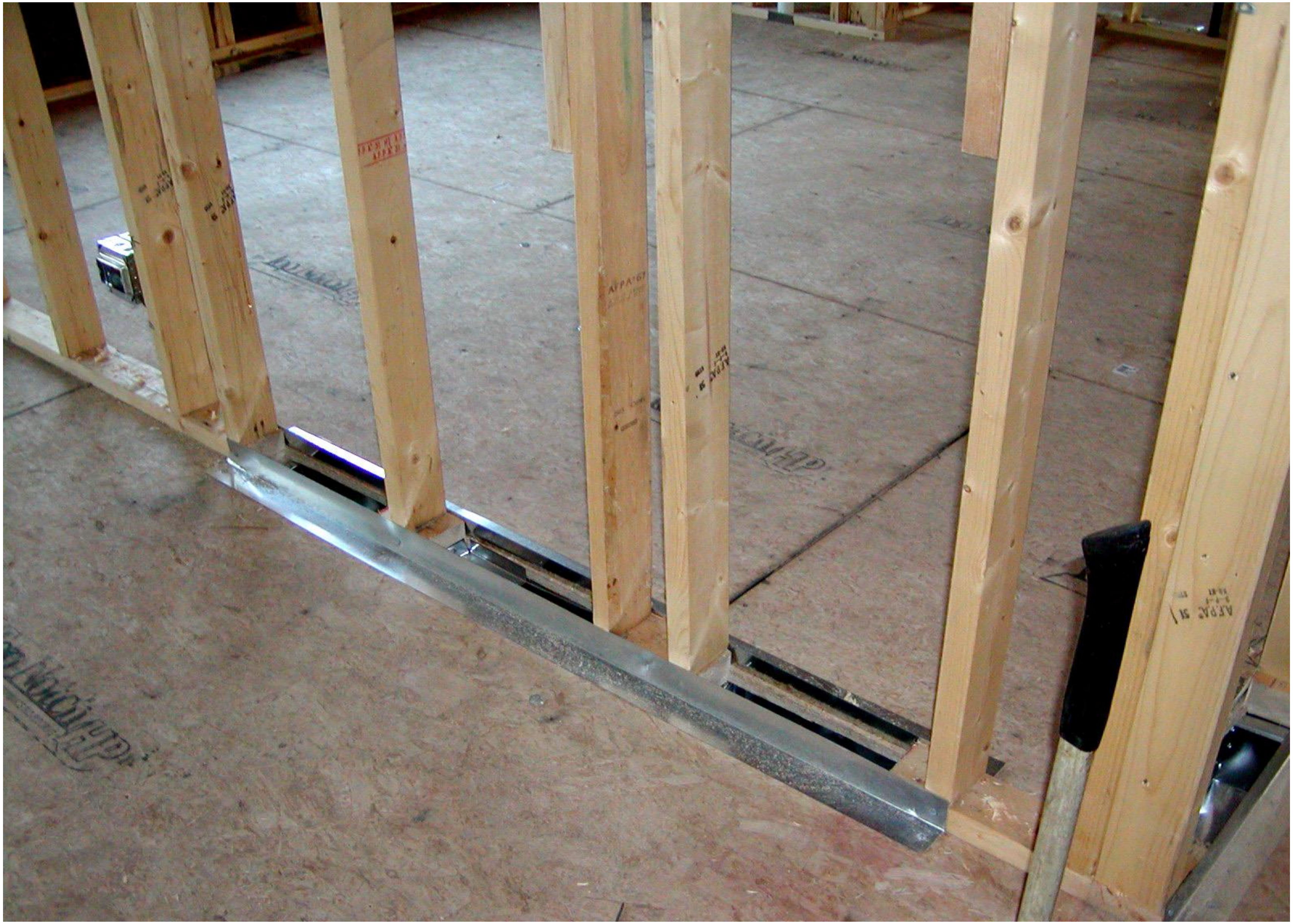
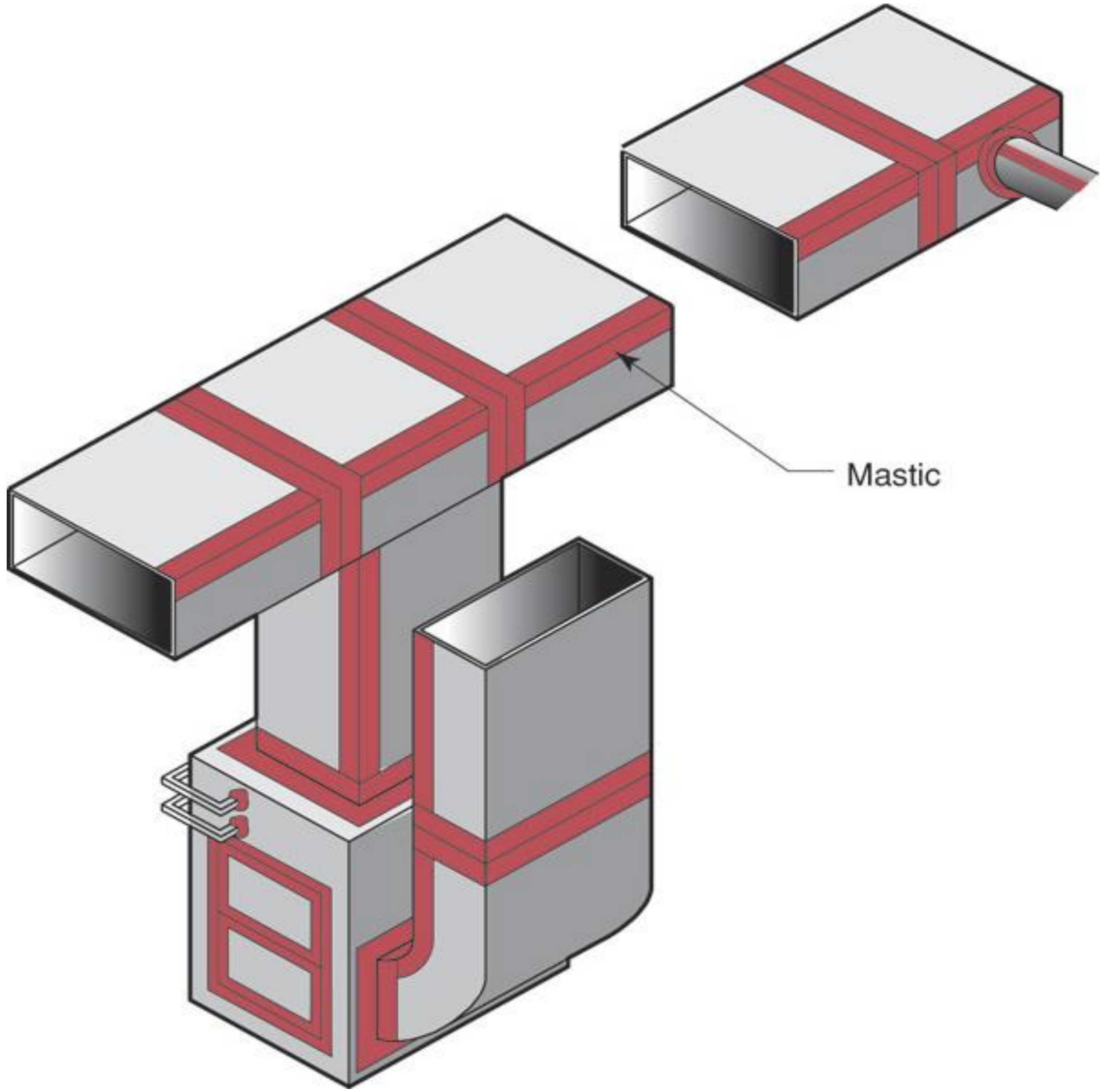


Figure 3.14

Leaky Ductwork and Air Handlers in Basements

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




Mastic

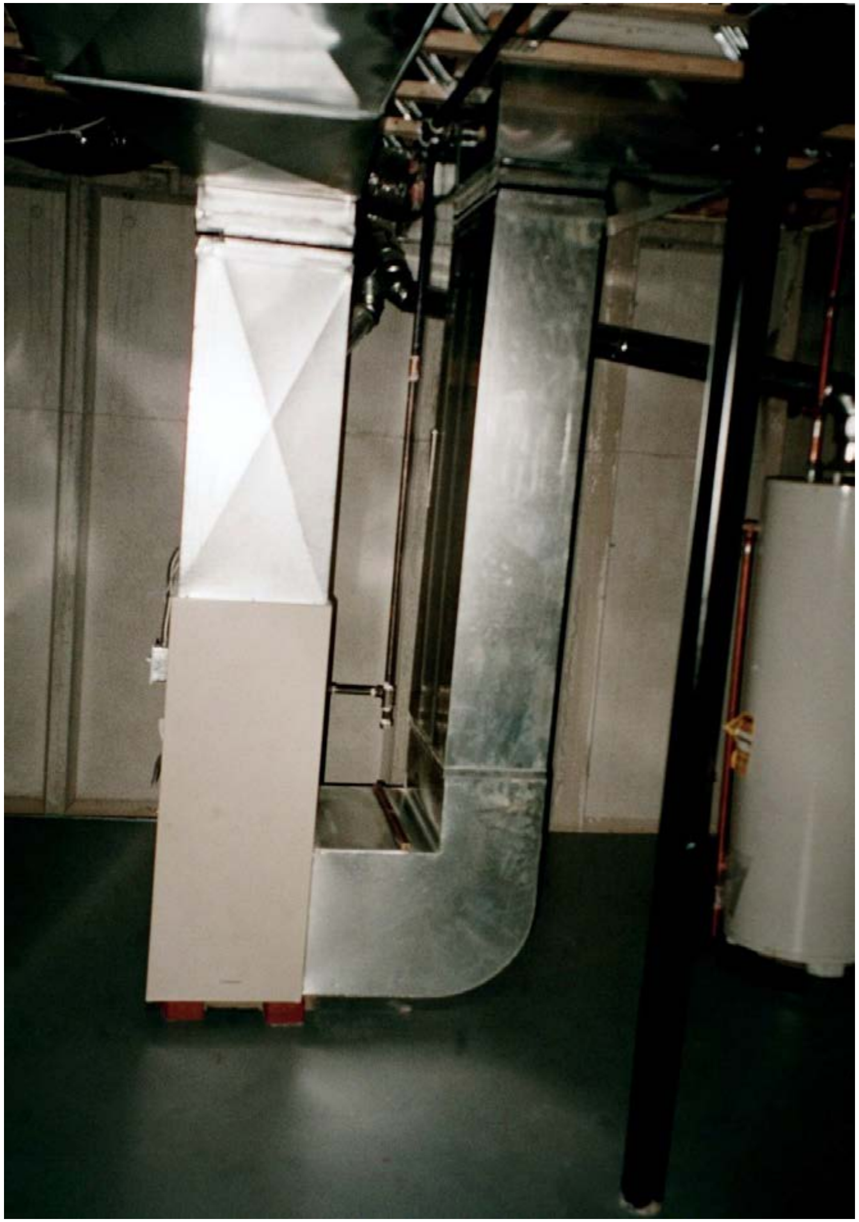
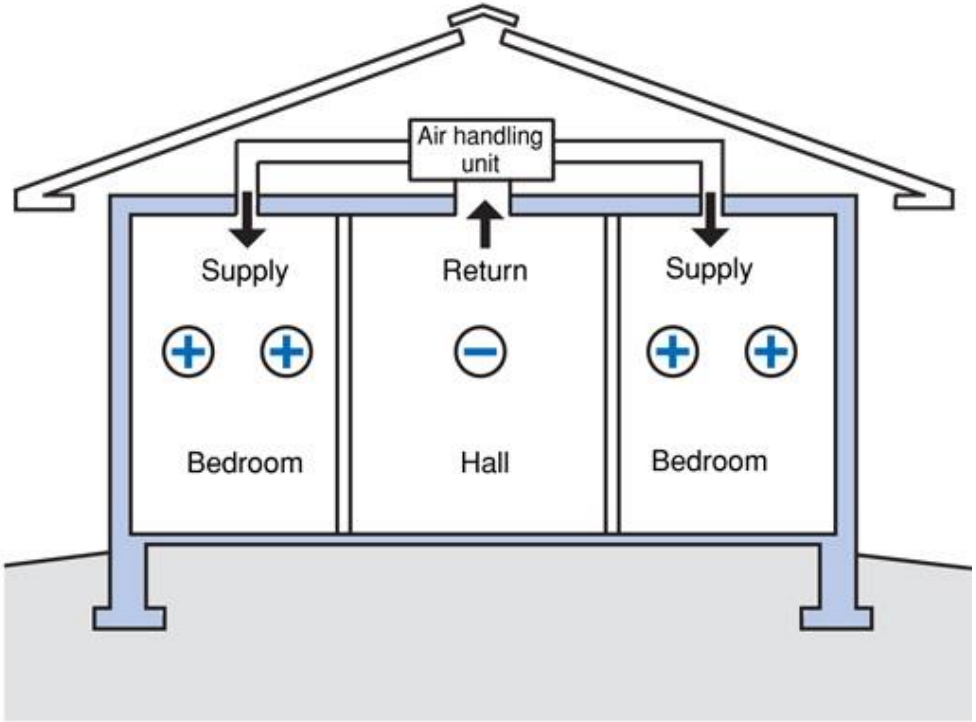
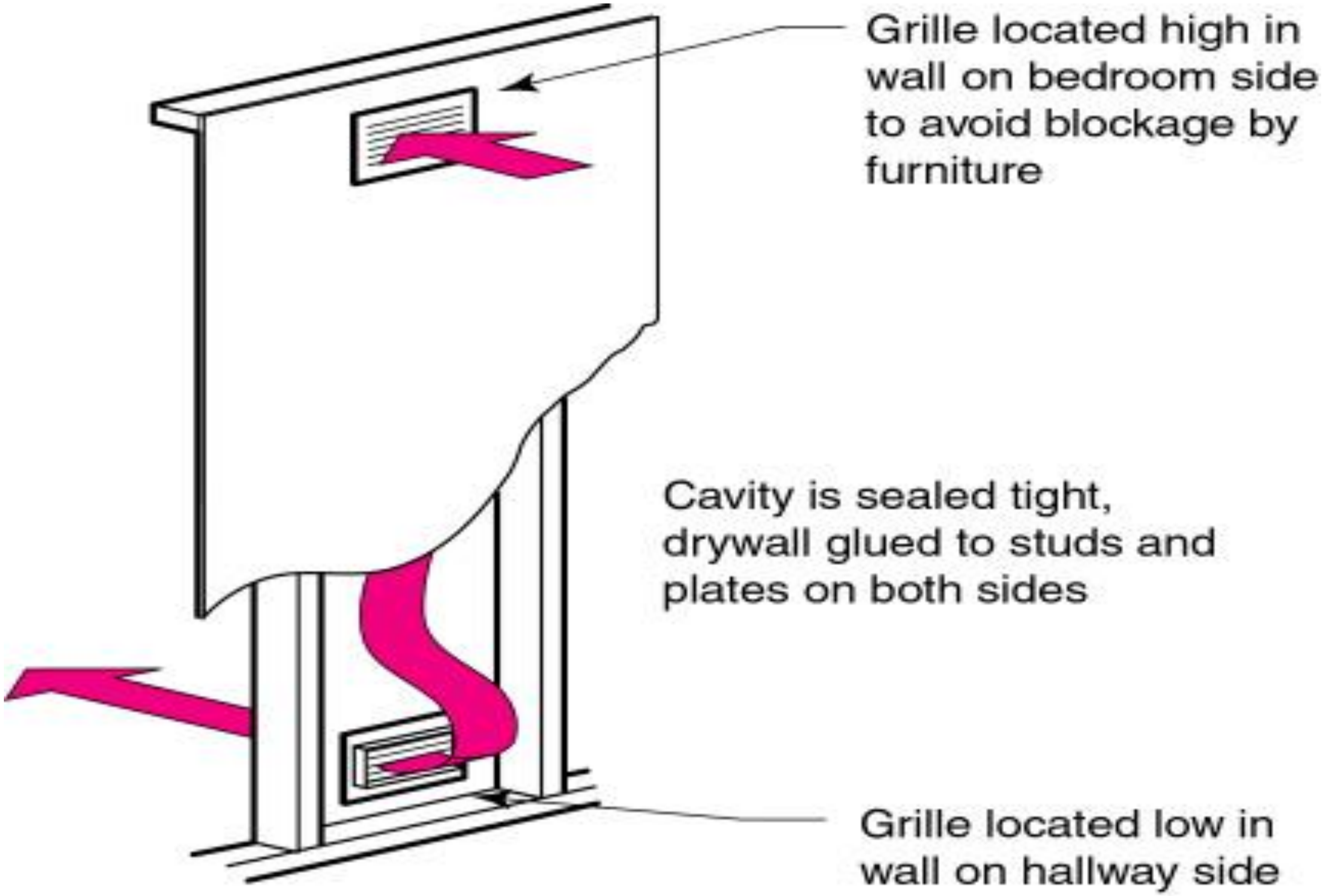


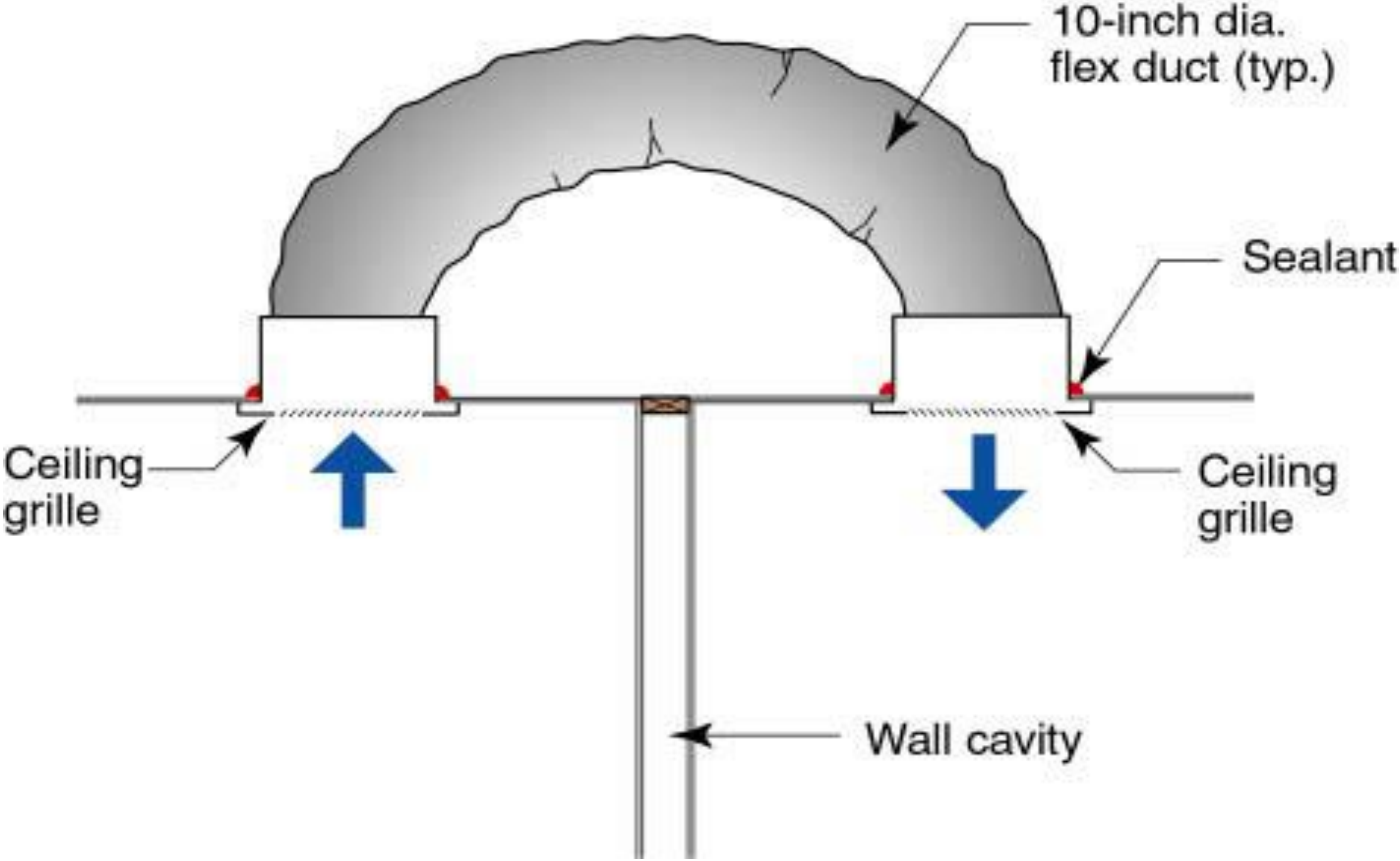
Figure 3.18

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

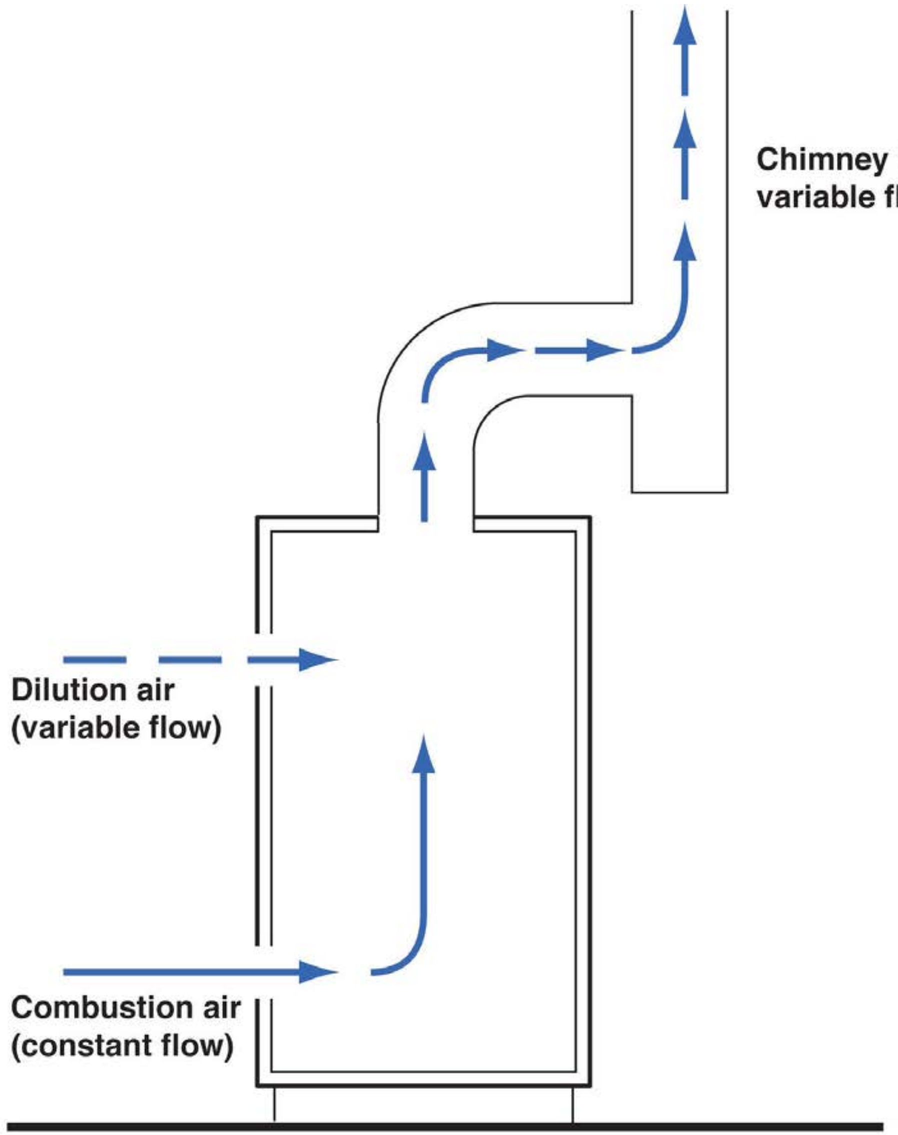



Grille located high in wall on bedroom side to avoid blockage by furniture
Cavity is sealed tight, drywall glued to studs and plates on both sides
Grille located low in wall on hallway side

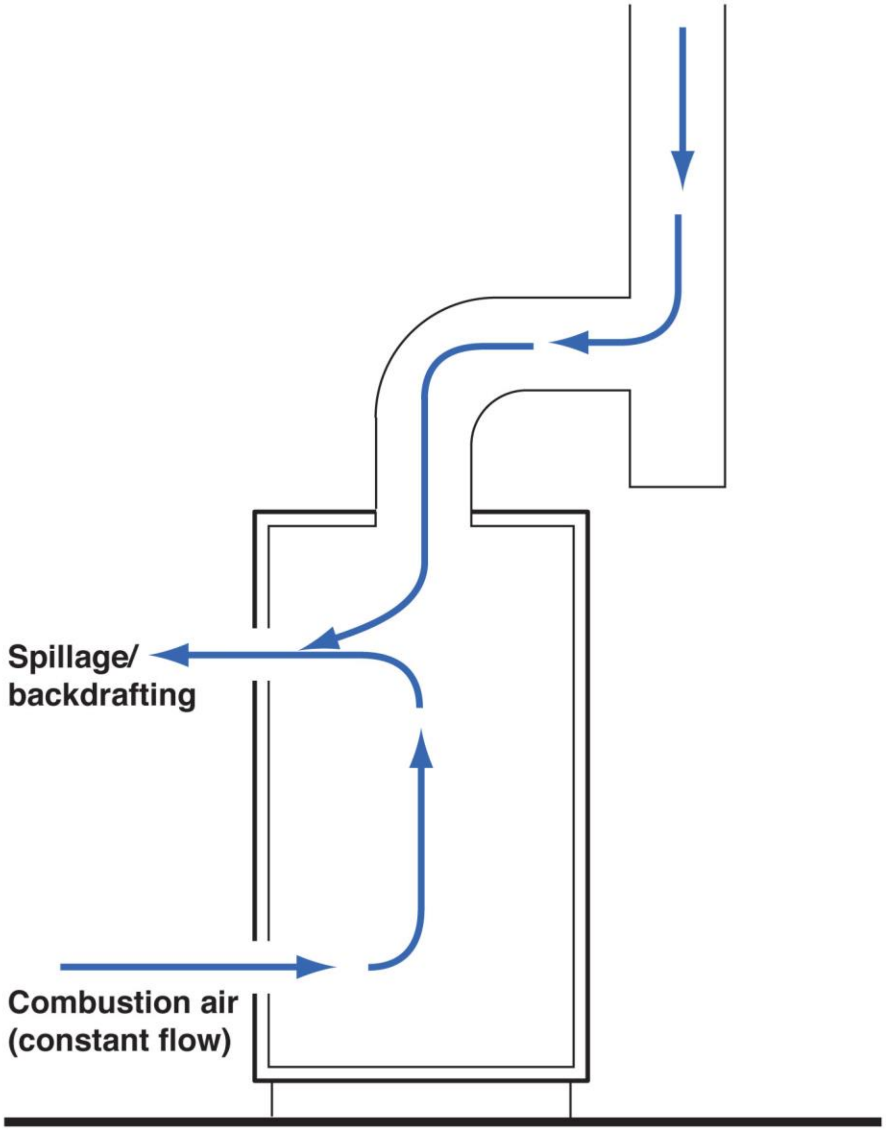

10-inch dia.
flex duct (typ.)
Sealant
Ceiling
grille
Ceiling
grille
Wall cavity


26 9 86

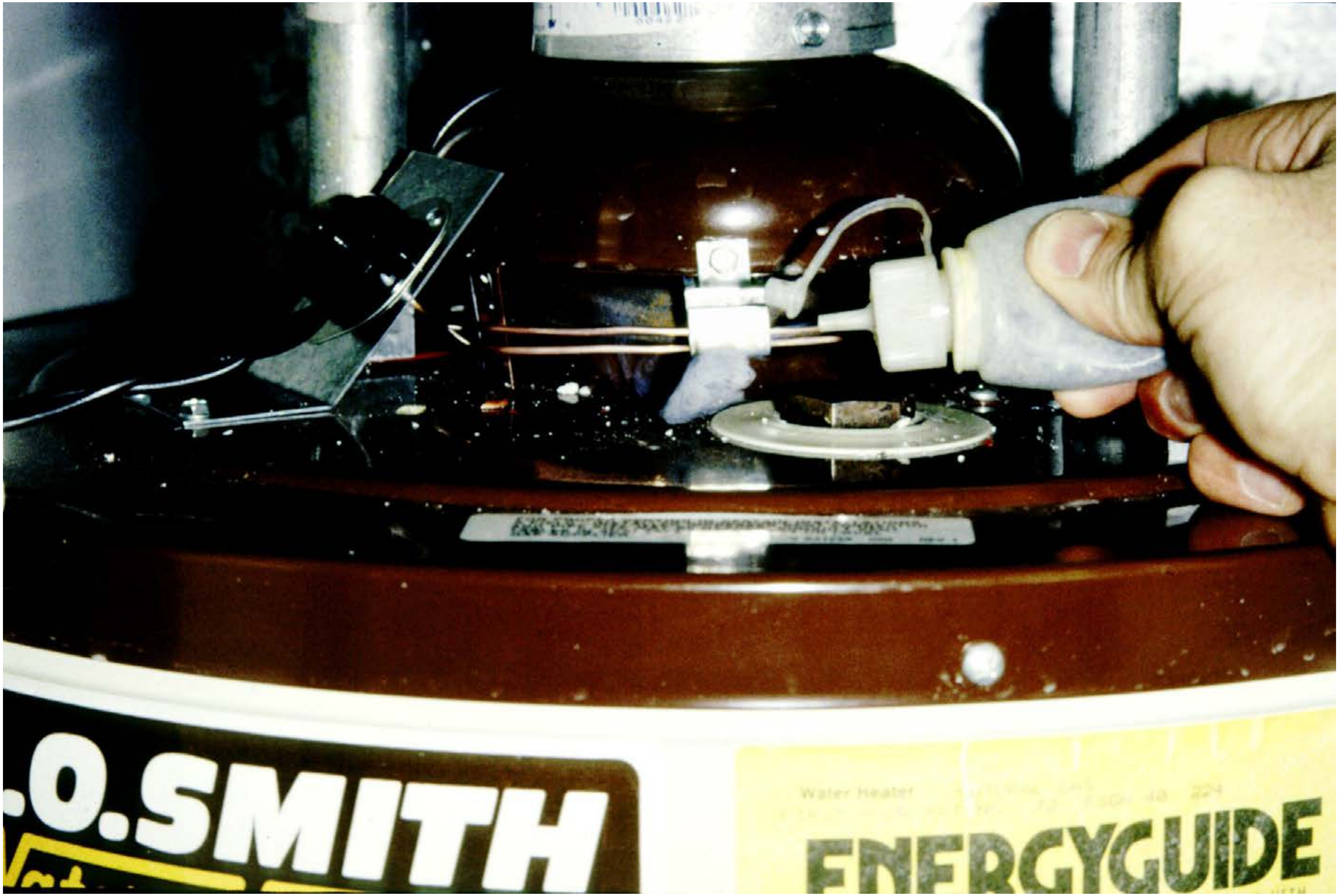

EMERY #3


Chimney (highly variable flow)
Dilution air (variable flow)
Combustion air (constant flow)

Draft hood



Spillage/backdrafting


.O.SMITH
ENERGYGUIDE