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

Building Science

Ventilation

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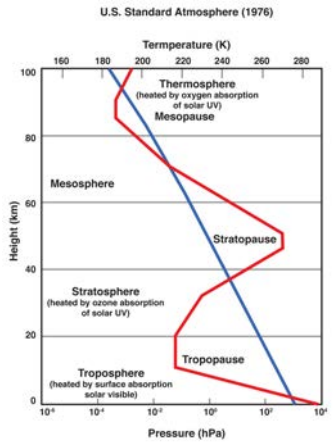
"It isn't what we don't know that gives us trouble, it's what we know that ain't so"

Will Rogers

"There are known knowns. These are things we know. There are known unknowns. There are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know.

Donald Rumsfeld

Lapse Rate



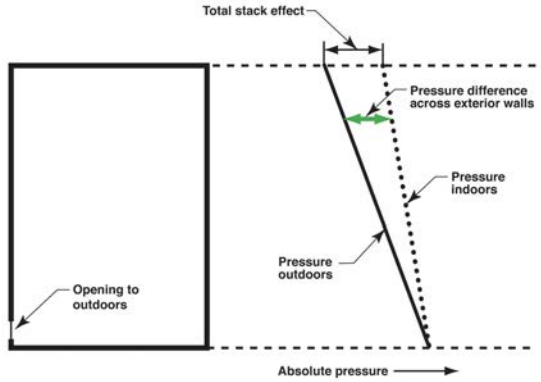


Figure 11.1: Building with no internal separations with opening at the bottom
(Adapted from G.O. Handegord, 1998)

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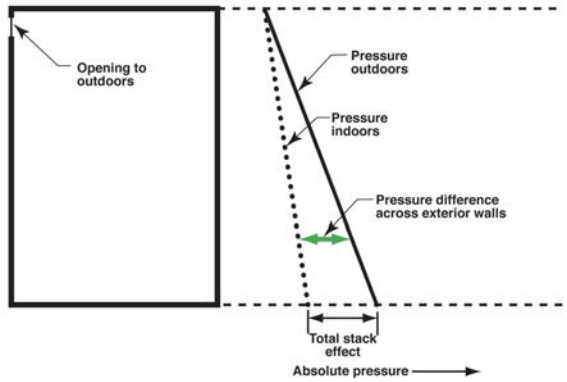

Figure 11.2: Building with no internal separations with opening at the top
(Adapted from G.O. Handegord, 1998)

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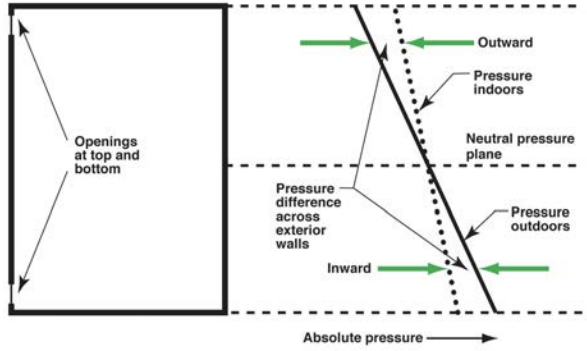

Figure 11.3: Building with no internal separations with openings at top and bottom
(Adapted from G.O. Handegord, 1998)

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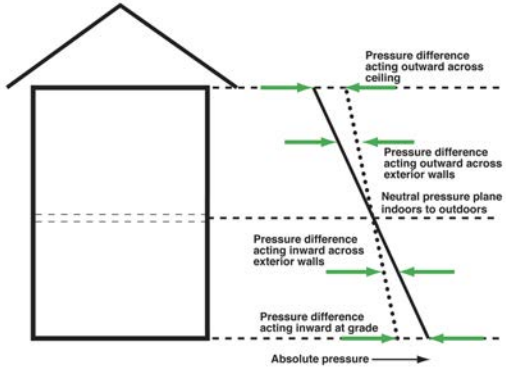

Figure 11.4: Basic two storey house with vented attic
(Adapted from G.O. Handegord, 1998)

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Joseph Lstiburek 10

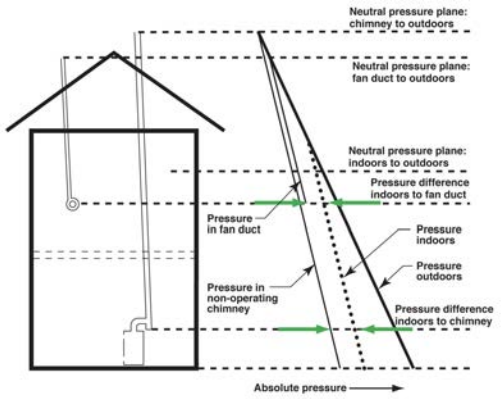

Figure 11.5: Two storey house with non-operating chimney and exhaust fan (Adapted from G.O. Handegord, 1998)

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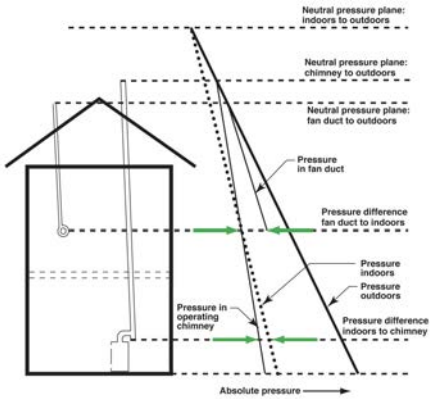

Figure 11.6: Two storey house with operating chimney (Adapted from G.O. Handegord, 1998)

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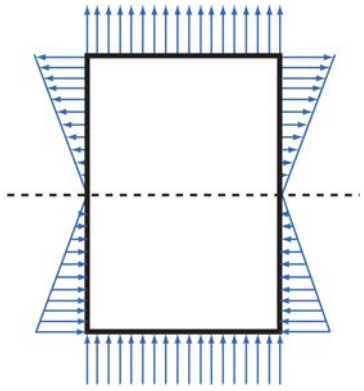

Stack effect

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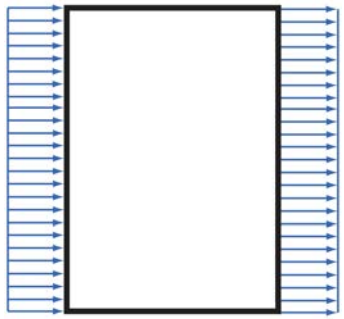

Wind

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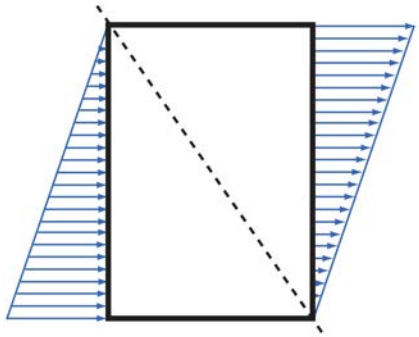

Stack effect and wind

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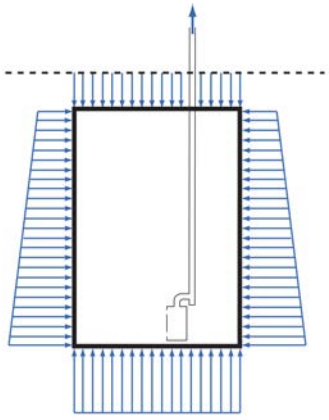

Chimney effect

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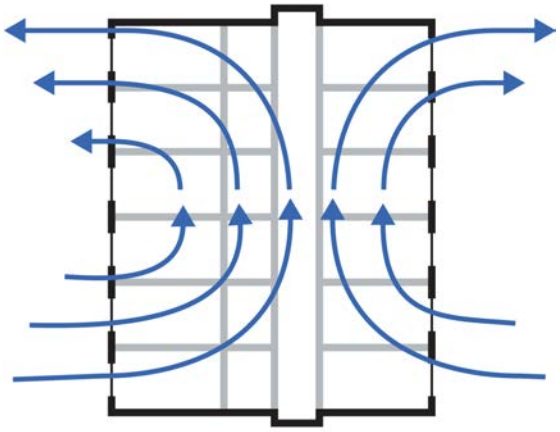

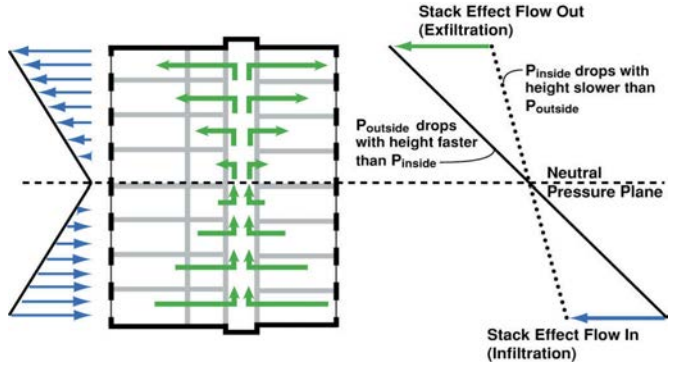

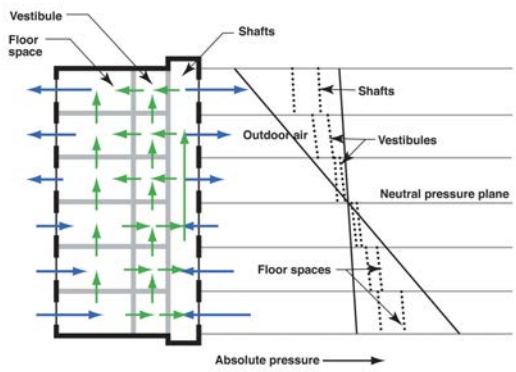

Figure 11.8: Stack effect pressures in high rise office building
(Adapted from G.O. Handegord, 1998)

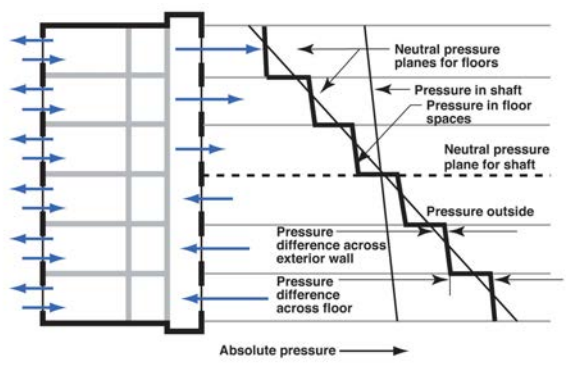

Figure 11.9: Multi-storey building with floor spaces isolated from vertical shafts
(Adapted from G.O. Handegord, 1998)

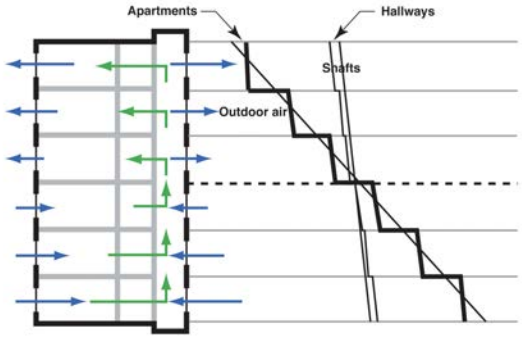

Figure 11.12: Apartment building with tighter apartment entry doors (Adapted from G.O. Handegord, 1998)

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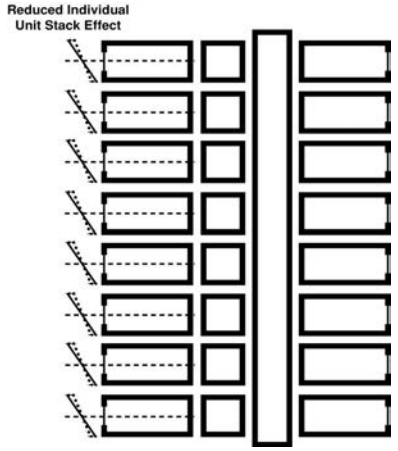

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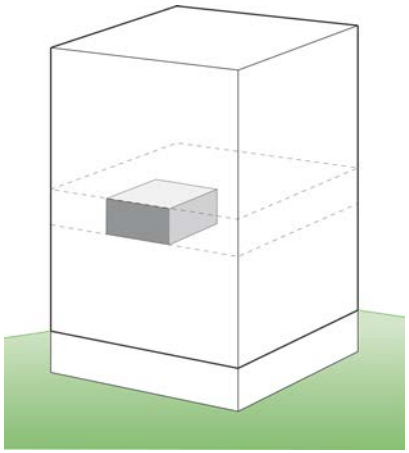

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Figure 3.12
Ductwork and Air Handlers in Basements
- No air pressure differences result in a house with an air handler and ductwork located in a basement if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed

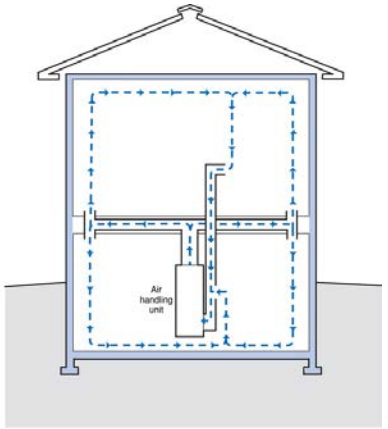


Figure 3.13
Ductwork and Air Handlers in Vented Attics
- No air pressure differences result in a house with an air handler and ductwork located in a vented attic if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed

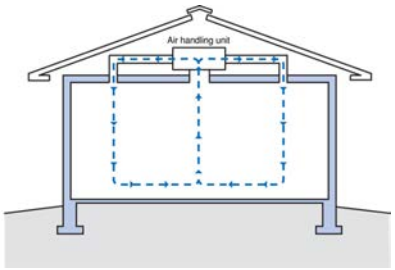
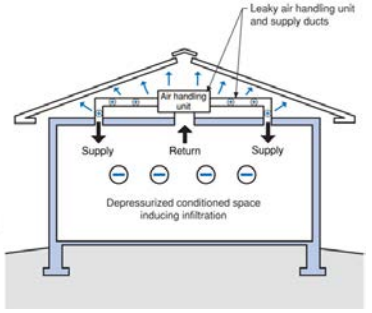


Figure 3.15
Leaky Ductwork and Air Handlers in Vented Attics
- Supply ductwork and air handler leakage is typically 20% or more of the flow through the system



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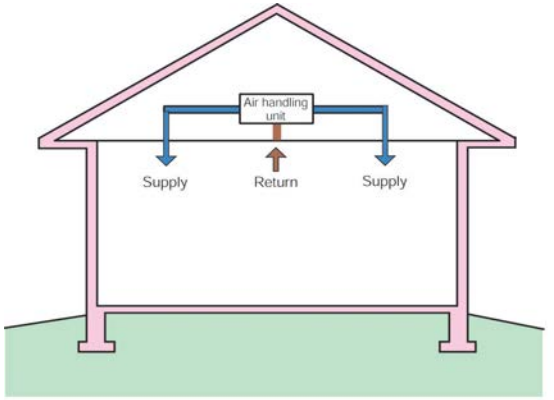
Duct Leakage Should Be Less Than 5% of Rated Flow As

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.

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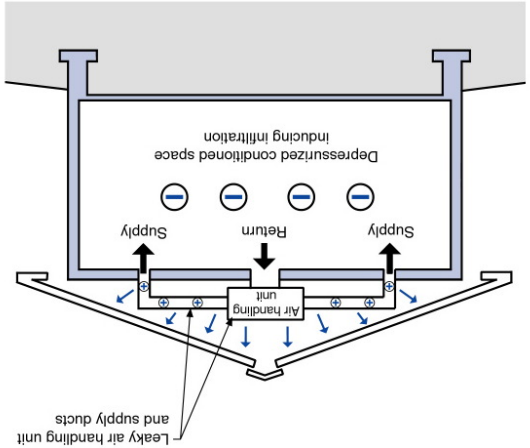

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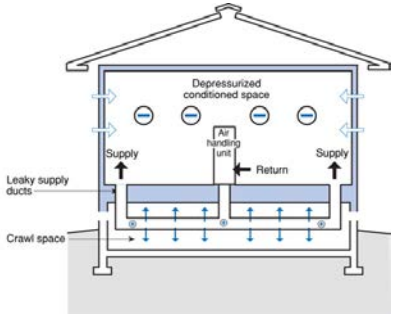
Figure 3.16
Leaky Supply Ductwork in Vented Crawl Space
- Air pressurization pattern with mechanical system ducts in the crawl space



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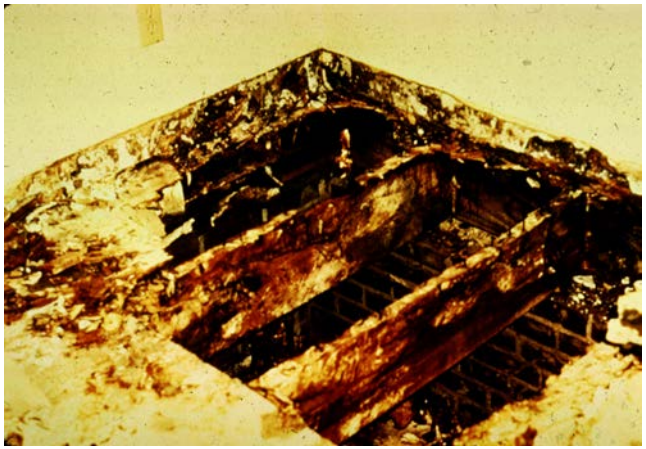

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Joseph Lstiburek – Airflow 44

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Joseph Lstiburek – Airflow 45

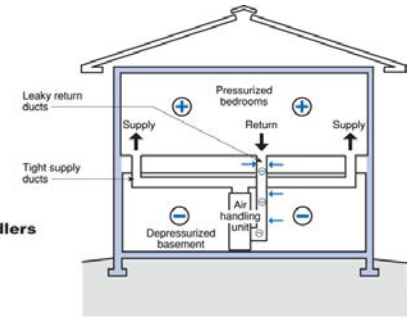

Figure 3.14
Leaky Ductwork and Air Handlers in Basements
- Air pressurization patterns in a house with leaky ductwork in the basement

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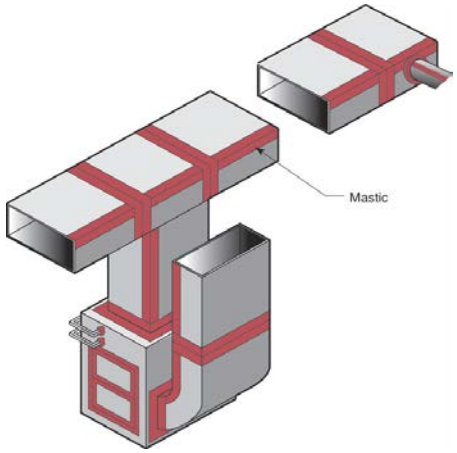
Building Science Corporation Joseph Lstiburek – Airflow 50

Building Science Corporation Joseph Lstiburek – Airflow 51

Building Science Corporation Joseph Lstiburek – Airflow 52



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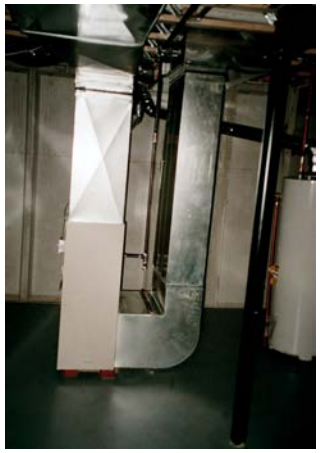

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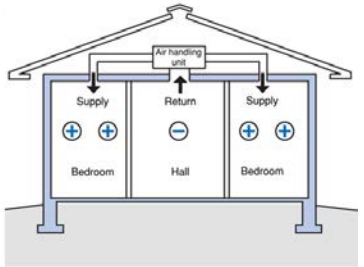
Figure 3.18
Insufficient Return Air Paths

- 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



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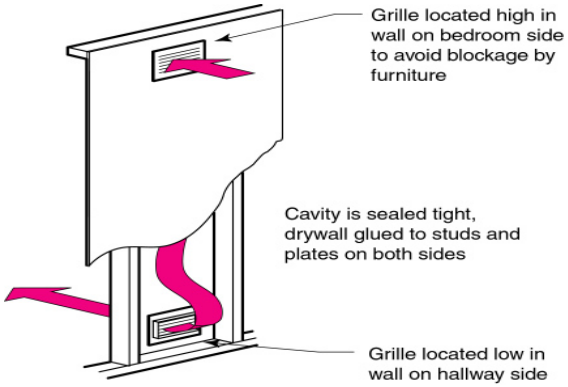

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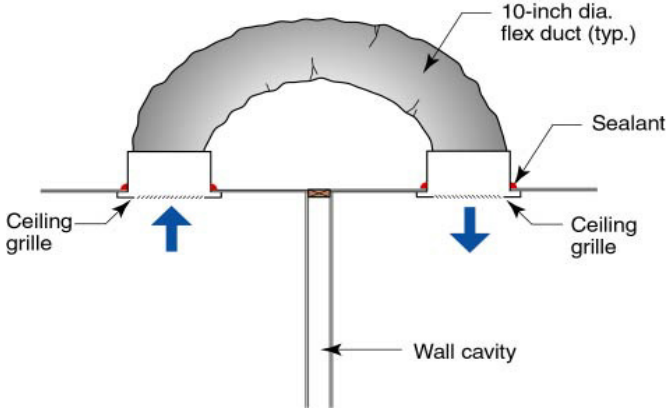
Joseph Lstiburek – Airflow 58



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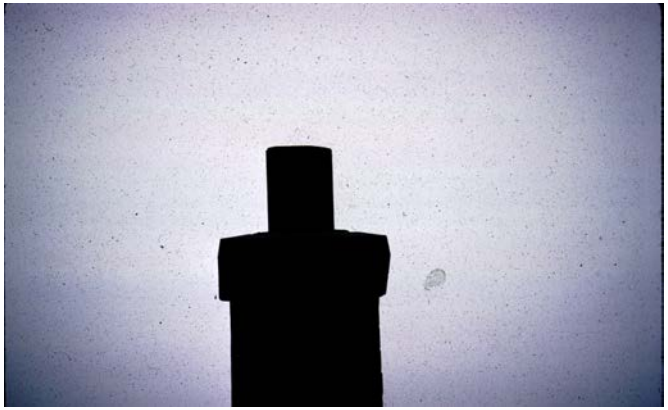
Joseph Lstiburek – Airflow 60



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Joseph Lstiburek – Airflow 62

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Joseph Lstiburek – Airflow 63

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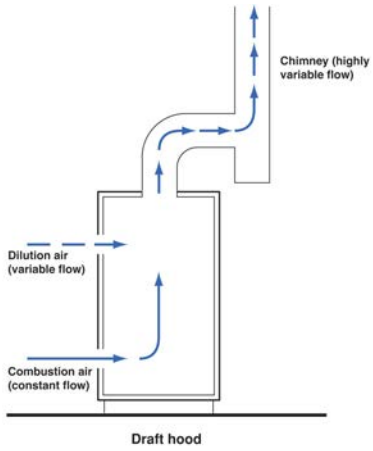
Joseph Lstiburek – Airflow 64



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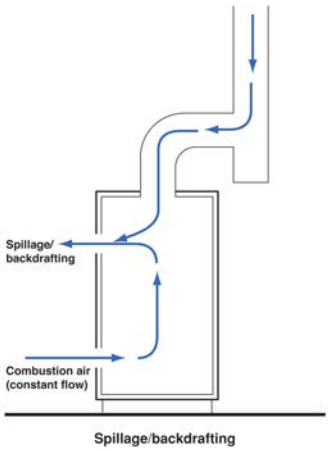

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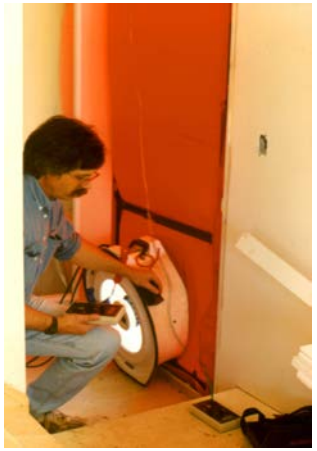
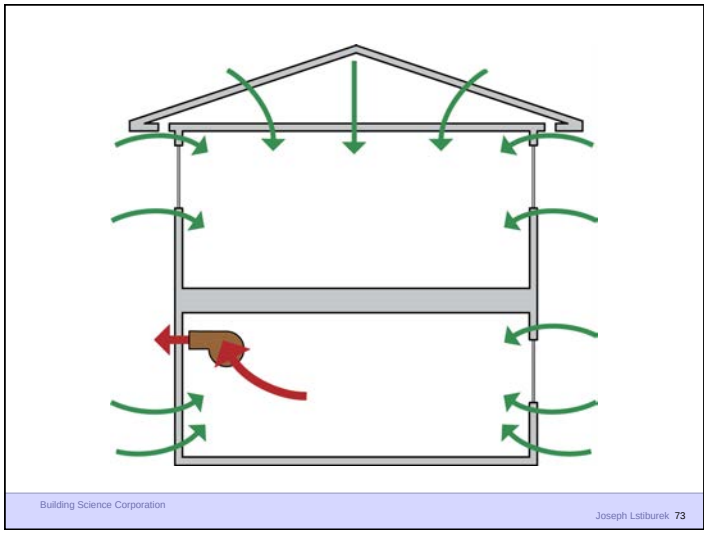
Air Barrier Metrics

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





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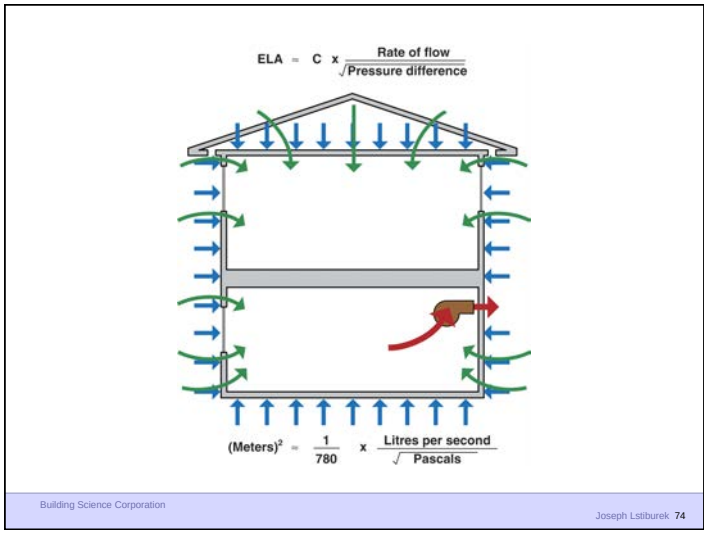

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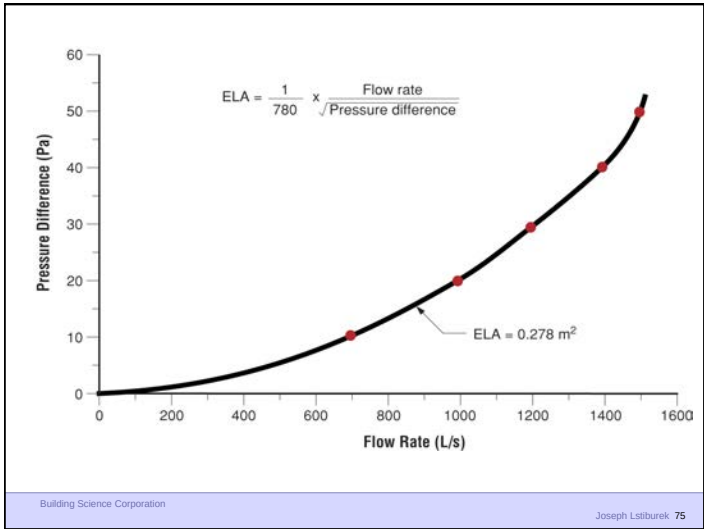

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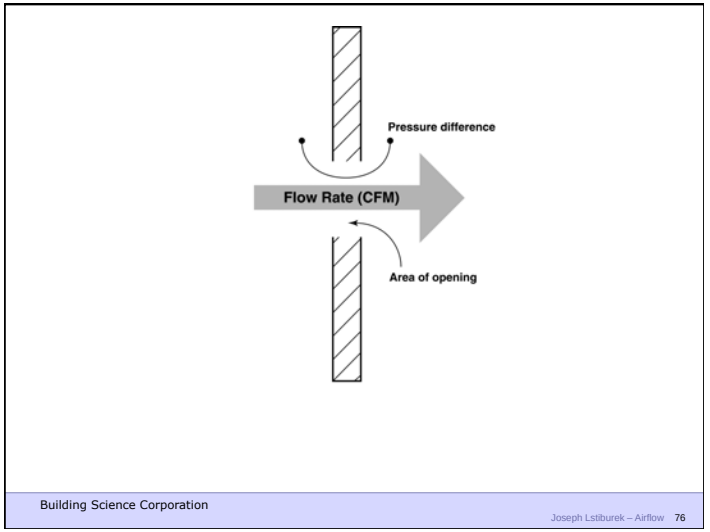

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Flow Through Orifices

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"

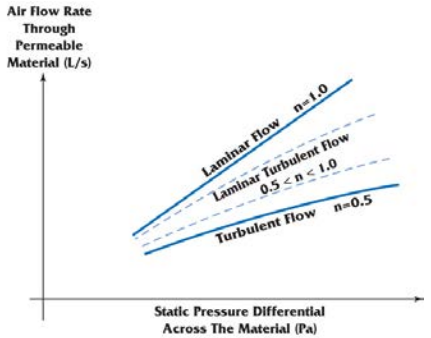
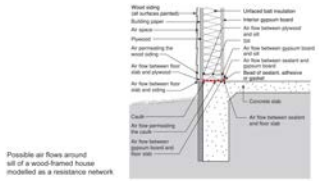
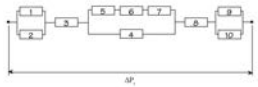


Figure 2.5
Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)



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

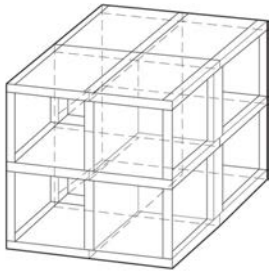
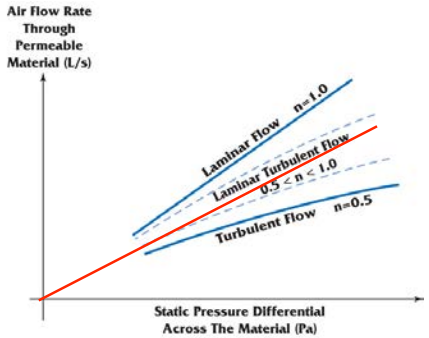


Figure 2.11
Three Dimensional Multi-Layer Multi-Cell Analogue



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Modes of Air Flow
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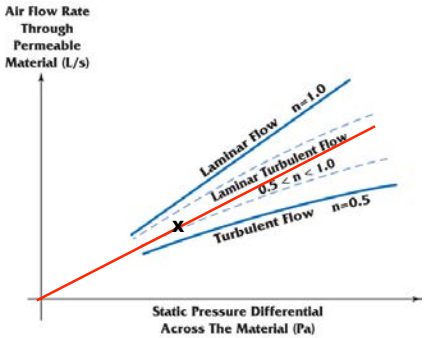

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Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)

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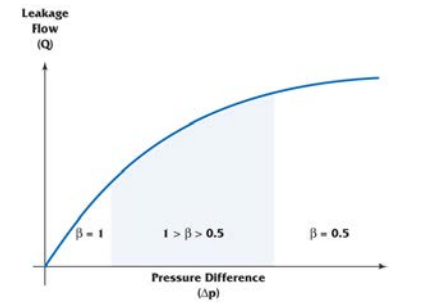

Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)

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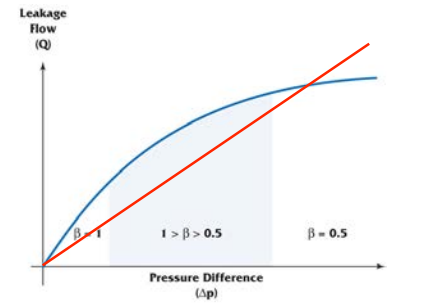

Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)

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Joseph Lstiburek – Airflow 88

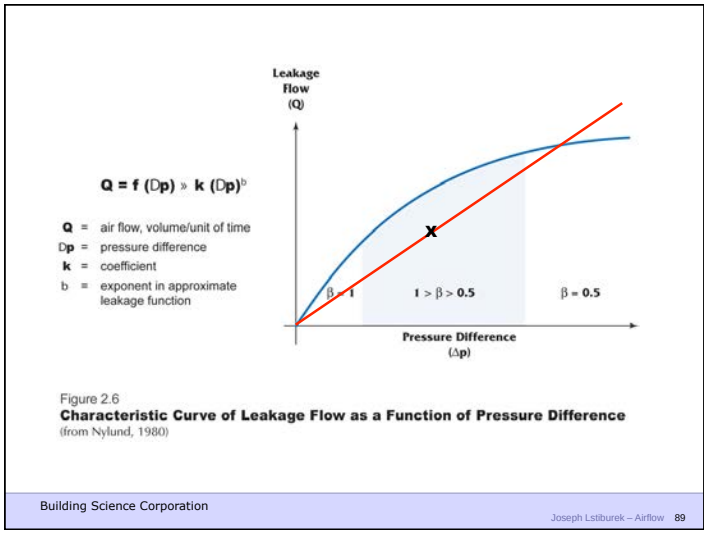
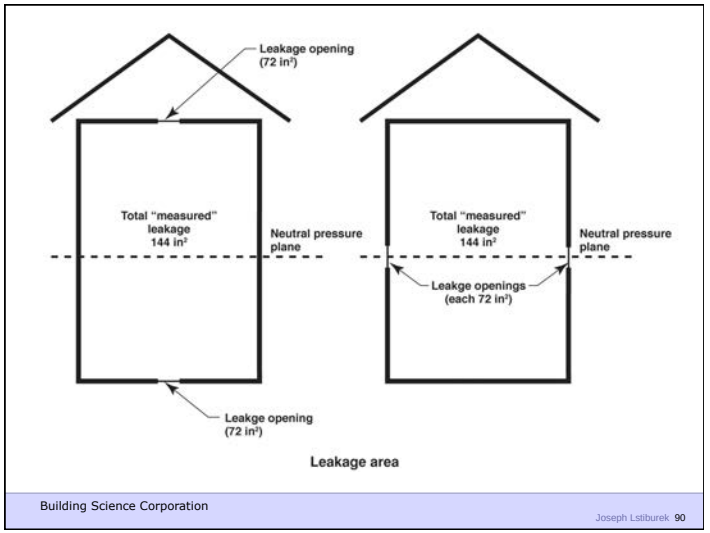


Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)

Building Science Corporation Joseph Lstiburek – Airflow 89



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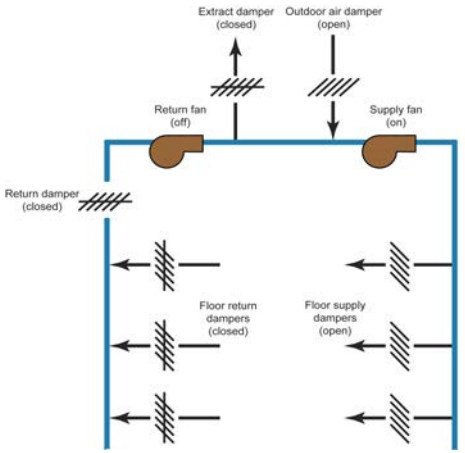
Building Science Corporation
Joseph Lstiburek 1

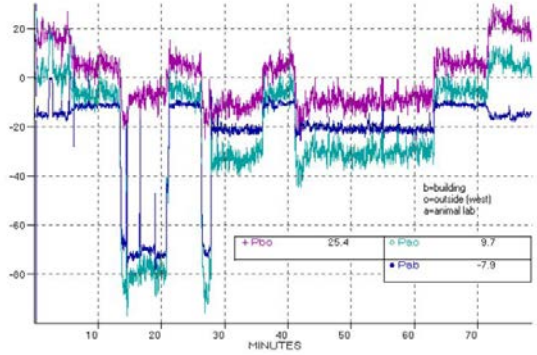
Building Science Corporation
Joseph Lstiburek 2

Building Science Corporation
Joseph Lstiburek 3

Building Science Corporation
Joseph Lstiburek 4


Shriners Hospitals for Crippled Children
Shriners Burns Institute
STOP


Extract damper (closed)
Outdoor air damper (open)
Return fan (off)
Supply fan (on)
Return damper (closed)
Floor return dampers (closed)
Floor supply dampers (open)



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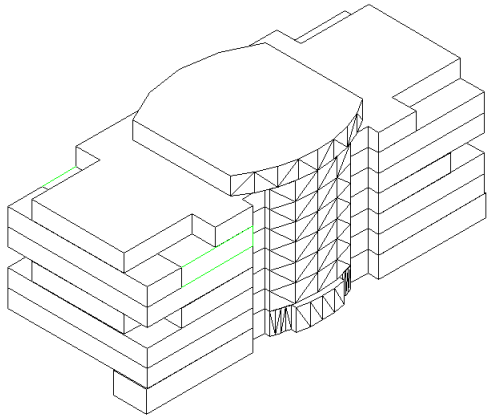

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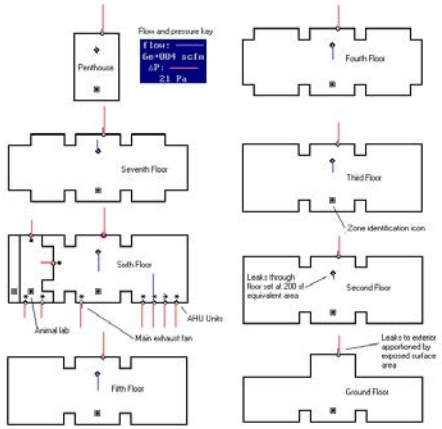
Joseph Lstiburek 10



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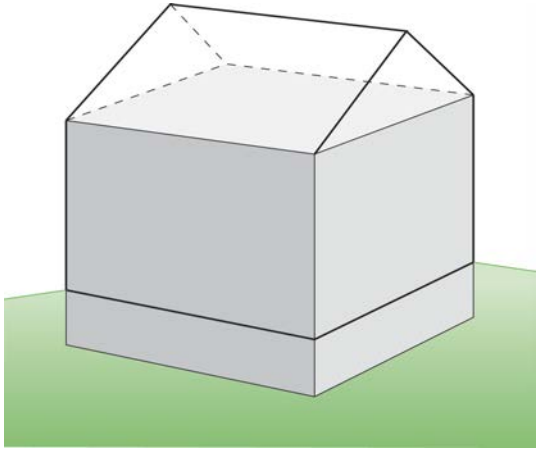
Joseph Lstiburek 11



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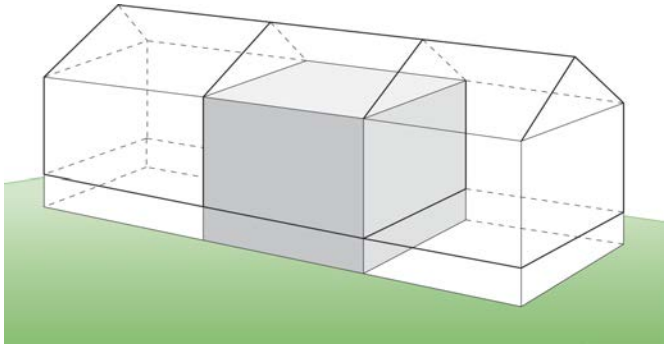
Joseph Lstiburek 12



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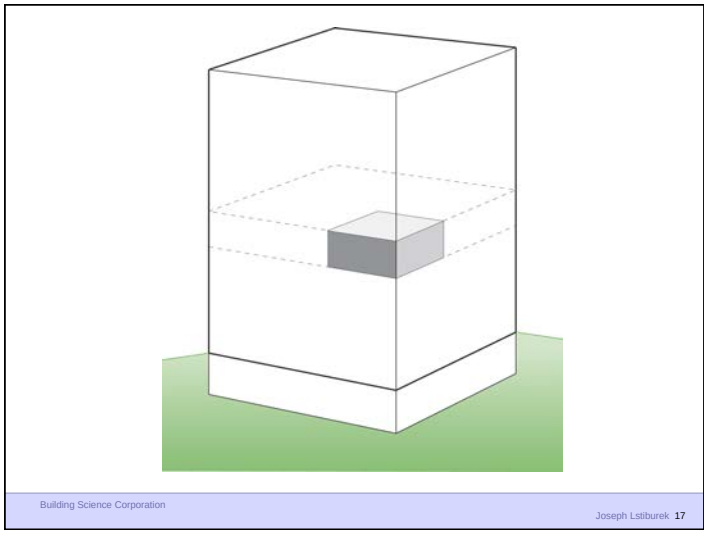
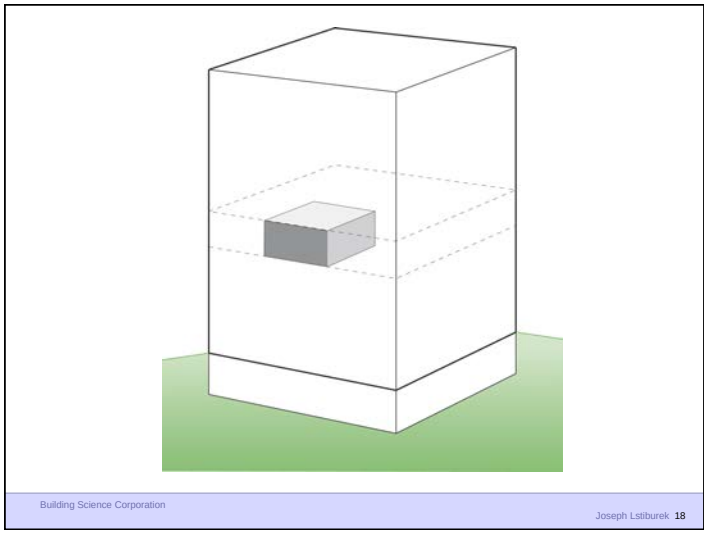
Building Science Corporation Joseph Lstiburek 14

Building Science Corporation Joseph Lstiburek 15

Building Science Corporation Joseph Lstiburek 16





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
	0.35 cfm/ft2 @ 50 Pa
	0.25 cfm/ft2 @ 50 Pa
	0.15 cfm/ft2 @ 50 Pa

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

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Best

As Tight as Possible - with -
Balanced Ventilation
Energy Recovery
Distribution
Source Control - Spot exhaust ventilation
Filtration
Material selection

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Worst

Leaky - with – Nothing
Spot Ventilation in Bathroom/Kitchen
Exhaust Ventilation – with – No Distribution

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Three Types of Controlled Ventilation Systems

Exhaust Ventilation
Supply Ventilation
Balanced Ventilation

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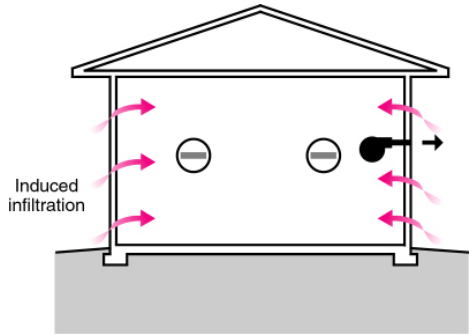

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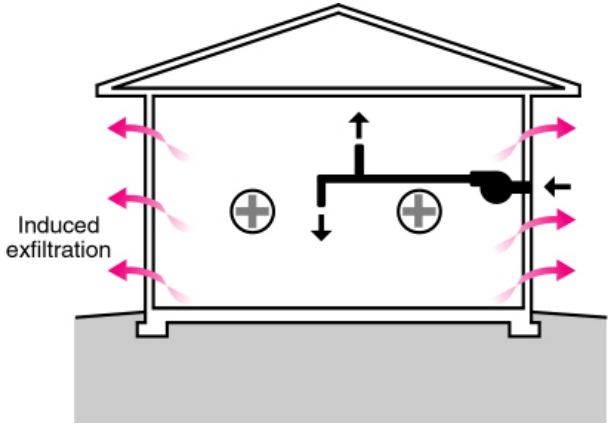
Joseph Lstiburek – HVAC 26



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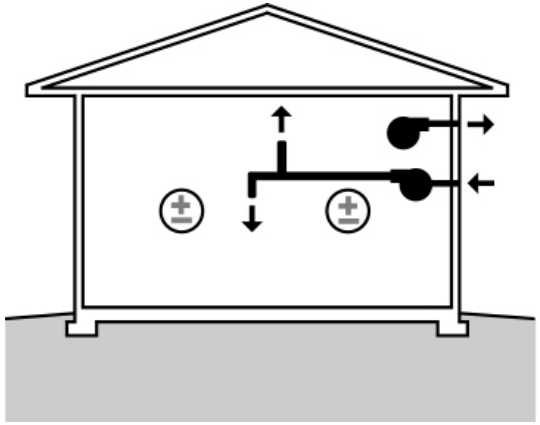
Joseph Lstiburek – HVAC 27



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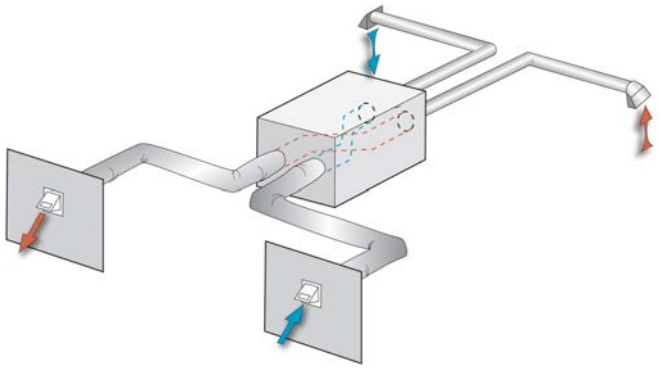
Joseph Lstiburek – HVAC 28



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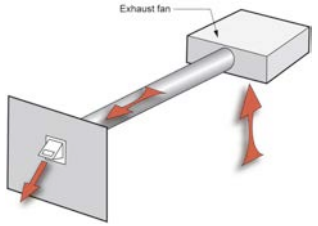
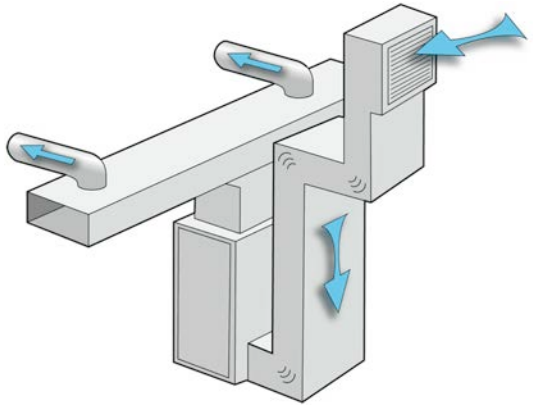
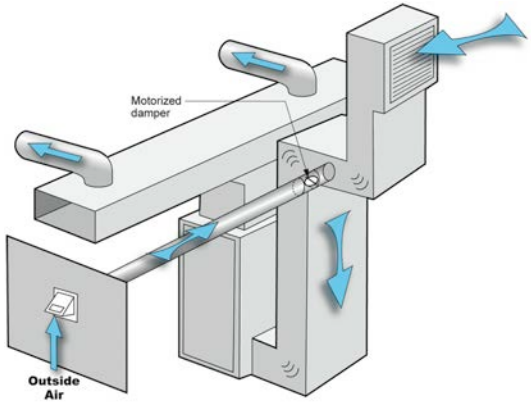


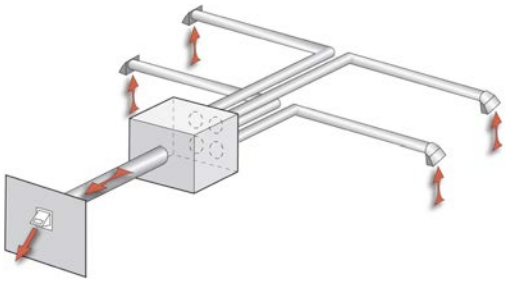
Building Science Corporation Joseph Lstiburek 30



Building Science Corporation Joseph Lstiburek 31



Building Science Corporation Joseph Lstiburek 32



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Cost	Exhaust	$150
	Exhaust + Dist	$200
	Supply + Dist	$200
	Spot + Ex/Sup + Dist	$500
	Balanced/HRV	$1,250

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The Cult of The Blower Door

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Joseph Lstiburek 36

Blower Door Can't Get You The True ACH
On A Short Term Basis – Hour, Day, Week

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Don't Know Where The Holes Are
Don't Know The Type of Holes
Don't Know The Pressure Across The Holes

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Good For Long Term Average If No Big Pressures

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Good For Long Term Average If No Big Pressures
Good For Average Annual Energy Prediction

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Joseph Lstiburek 40

Good For Long Term Average If No Big Pressures

Good For Average Annual Energy Prediction

Not Good For IAQ Unless You Accept Average Annual Exposure As A Metric

Cost of Addressing the Problems Are Less Than The Cost of Testing To See If You Have Problems

Combustion Safety

Indoor Contaminants

Comfort

Energy

Bring Combustion Appliances Up To Code

Control Pressures

Install Controlled Ventilation

Get Rid of Big Holes

Insulate

Code Compliant Combustion Air

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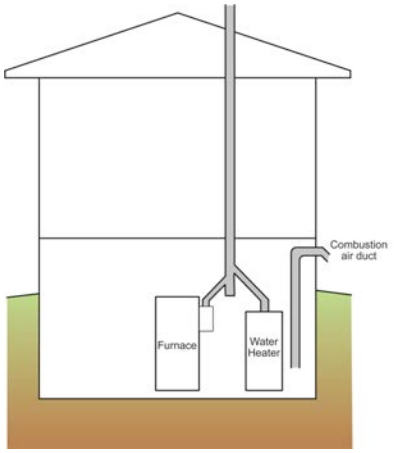

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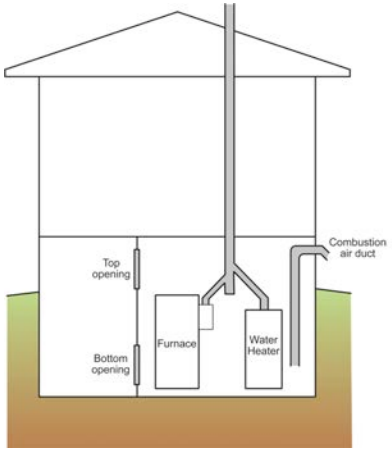
Joseph Lstiburek 46



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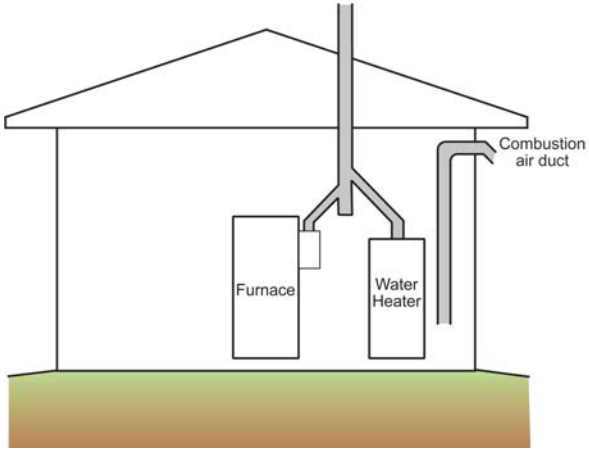
Joseph Lstiburek 47



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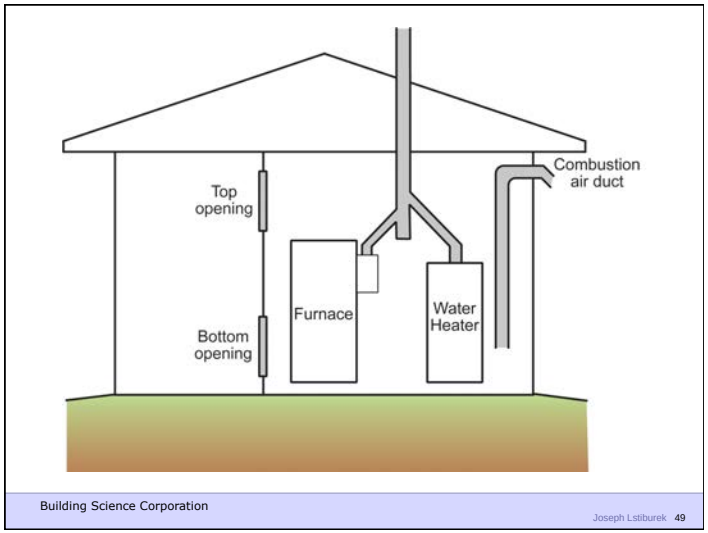
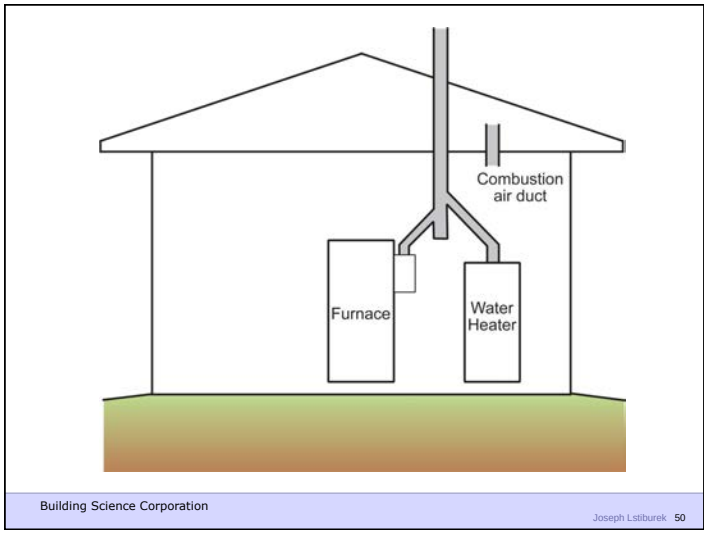
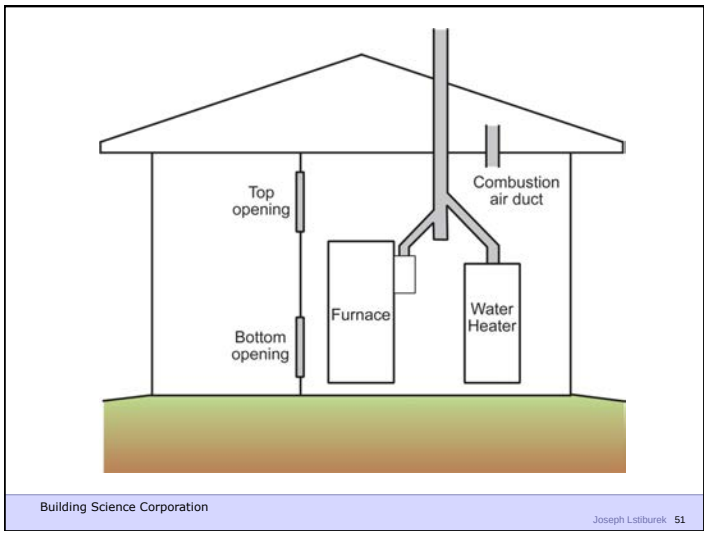
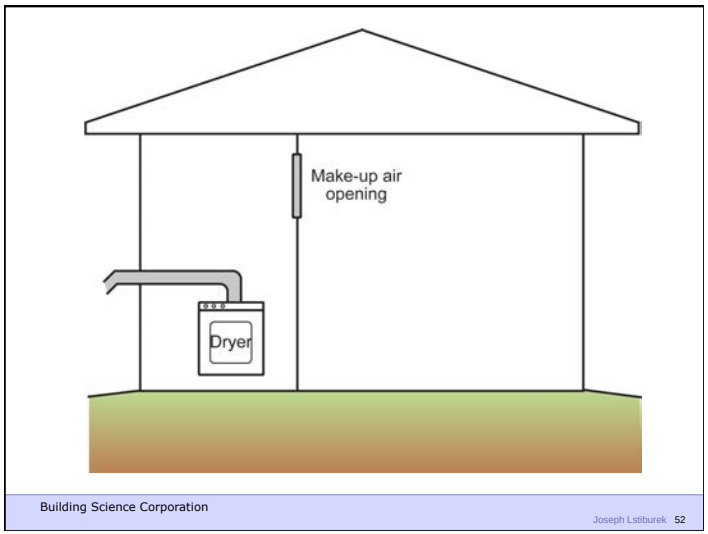
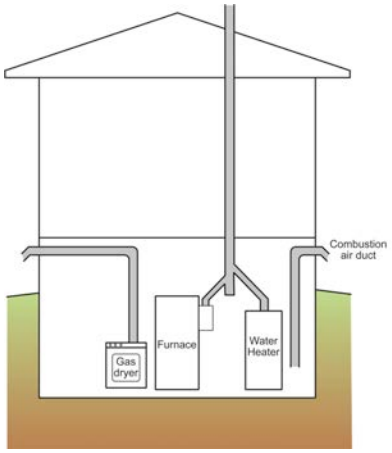
Joseph Lstiburek 48


Top opening
Bottom opening
Furnace
Water Heater
Combustion air duct
Building Science Corporation
Joseph Lstiburek 49

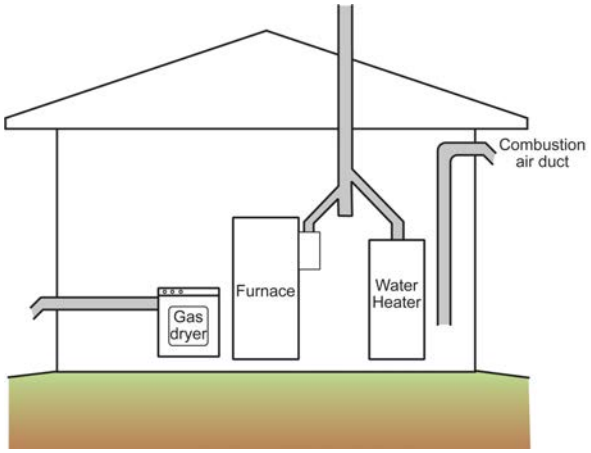

Combustion air duct
Furnace
Water Heater
Building Science Corporation
Joseph Lstiburek 50


Top opening
Bottom opening
Furnace
Water Heater
Combustion air duct
Building Science Corporation
Joseph Lstiburek 51

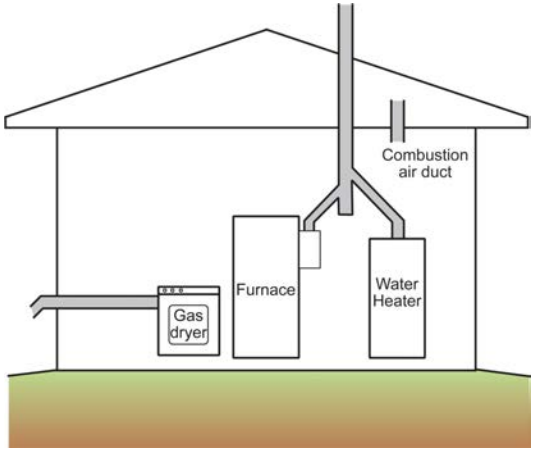

Make-up air opening
Dryer
Building Science Corporation
Joseph Lstiburek 52



Building Science Corporation Joseph Lstiburek 53



Building Science Corporation Joseph Lstiburek 54



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Sealed Combustion Appliances

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Joseph Lstiburek 57

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Joseph Lstiburek 58

Control Pressures

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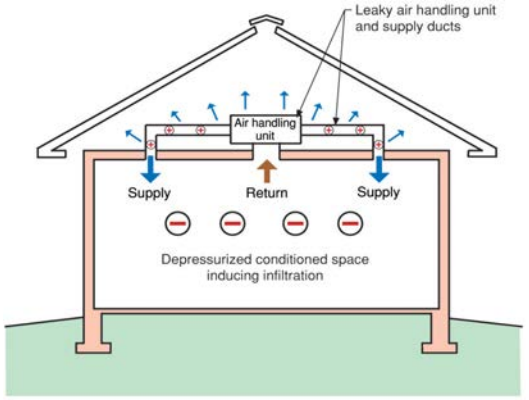
Joseph Lstiburek 59



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

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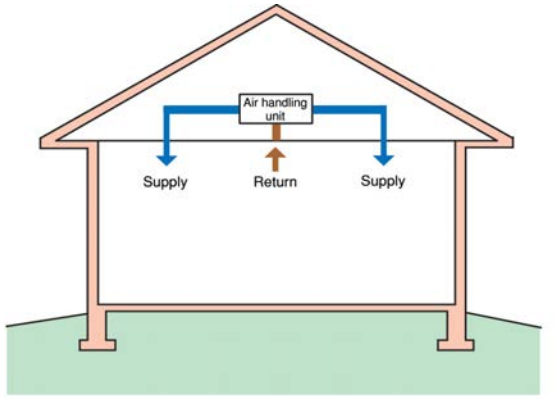
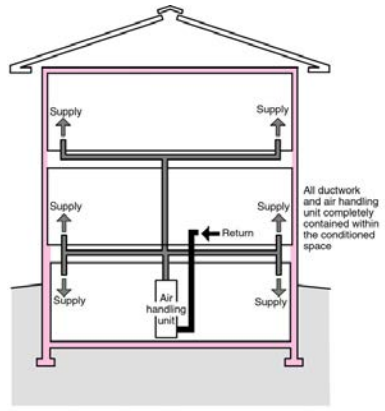
Joseph Lstiburek 60



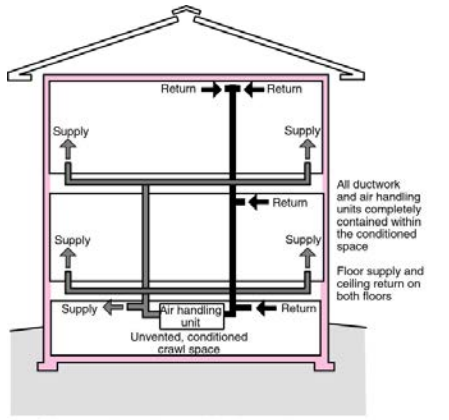
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Building Science Joseph Lstiburek 61



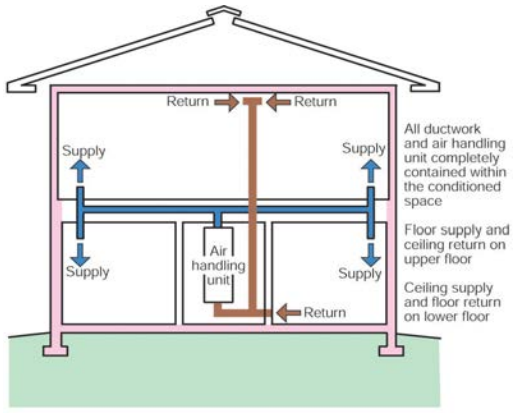
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Building Science Joseph Lstiburek 62



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

Building Science Joseph Lstiburek 63



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

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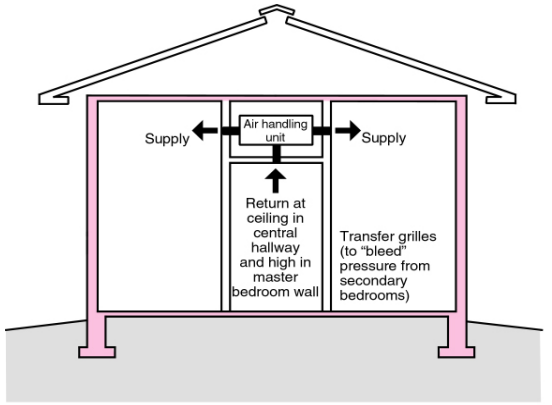
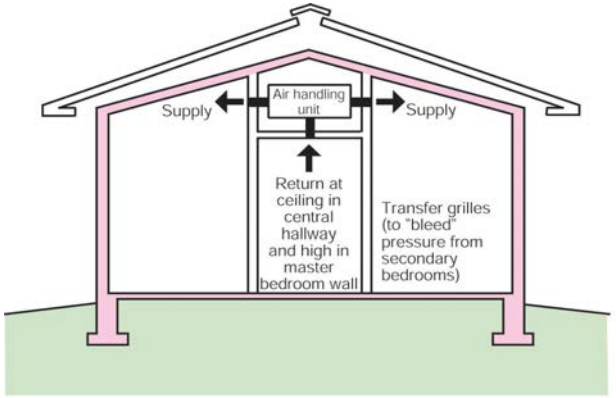
Joseph Lstiburek 65



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

Building Science Corporation
Joseph Lstiburek 66



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

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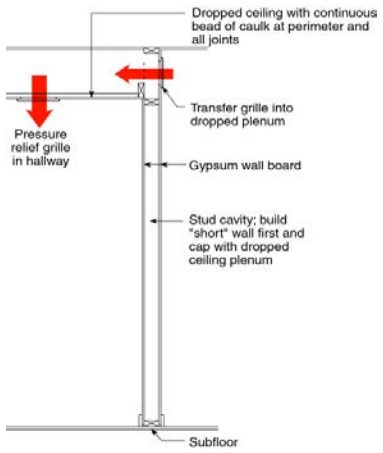
Joseph Lstiburek 68

Building Science Corporation

Joseph Lstiburek 69

Building Science

Joseph Lstiburek 70



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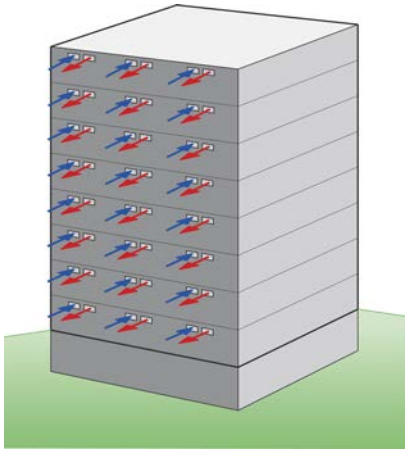
Joseph Lstiburek 71



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Joseph Lstiburek – HVAC 2

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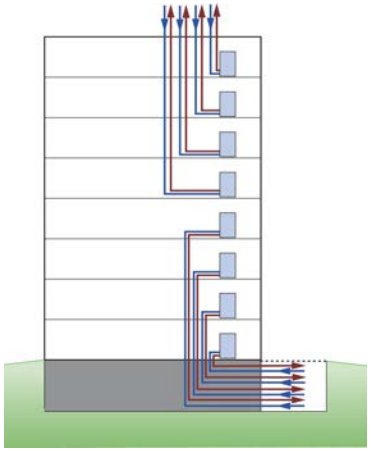
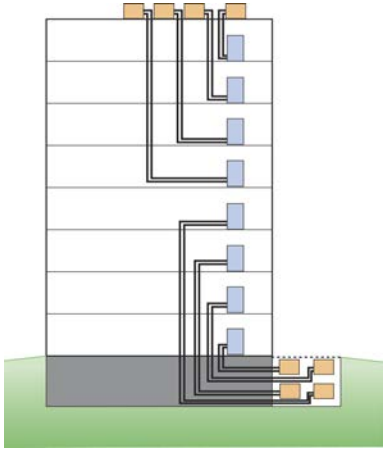
Joseph Lstiburek 3



Building Science Corporation

Joseph Lstiburek – HVAC 4



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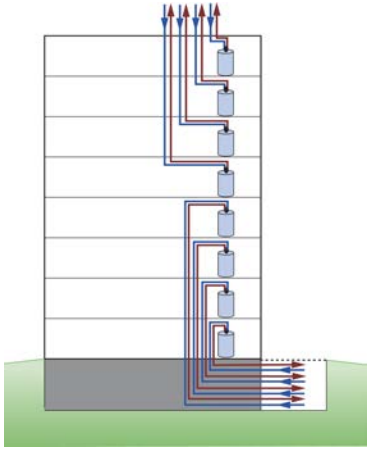
Joseph Lstiburek – HVAC 5



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Joseph Lstiburek – HVAC 6

Building Science Corporation

Joseph Lstiburek – HVAC 7

Building Science Corporation

Joseph Lstiburek – HVAC 8

Building Science Corporation

Joseph Lstiburek – HVAC 9

Building Science Corporation

Joseph Lstiburek – HVAC 10

Building Science Corporation

Joseph Lstiburek – HVAC 11

Building Science Corporation

Joseph Lstiburek – HVAC 12

Building Science Corporation

Joseph Lstiburek 13

Building Science Corporation

Joseph Lstiburek – HVAC 14

Building Science Corporation

Joseph Lstiburek – HVAC 15

Building Science Corporation

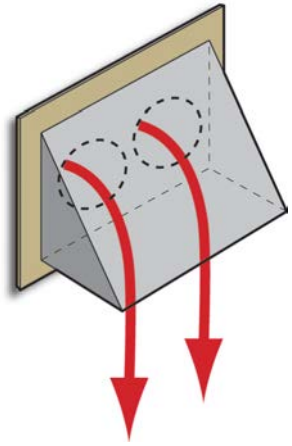
Joseph Lstiburek – HVAC 16

Building Science Corporation

Joseph Lstiburek – HVAC 17

Building Science Corporation

Joseph Lstiburek – HVAC 18



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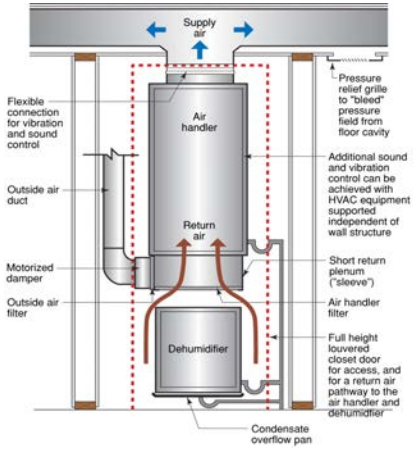
Joseph Lstiburek – HVAC 19



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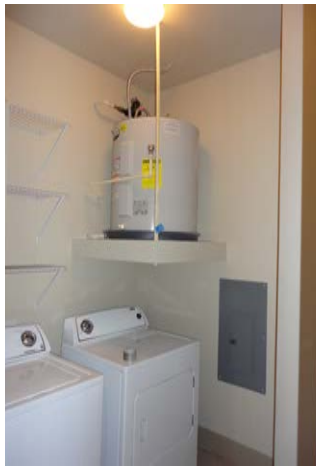
Joseph Lstiburek – HVAC 20



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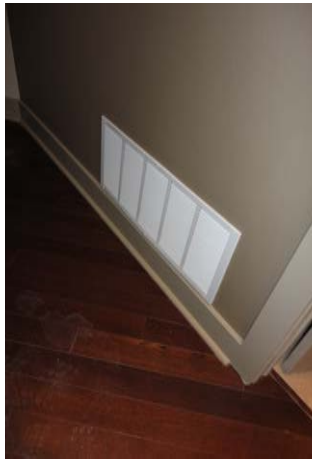

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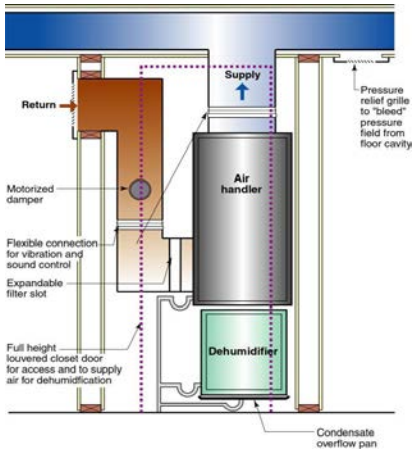
Joseph Lstiburek 22



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Joseph Lstiburek – HVAC 23

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Joseph Lstiburek – HVAC 24

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Joseph Lstiburek – HVAC 25

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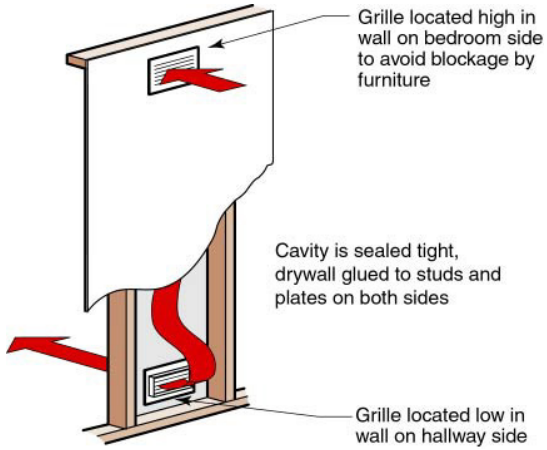
Joseph Lstiburek – HVAC 26



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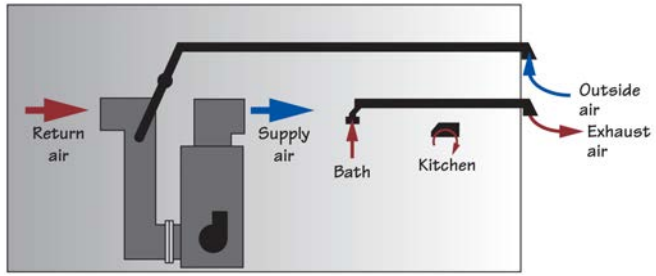
Joseph Lstiburek – HVAC 27



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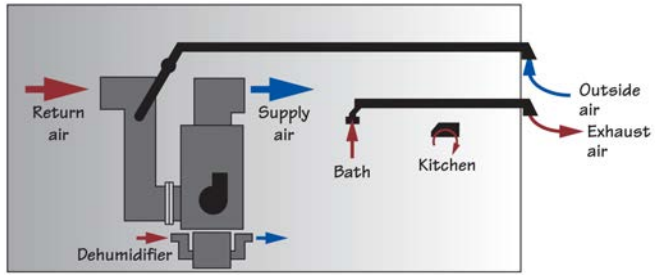
Joseph Lstiburek 28



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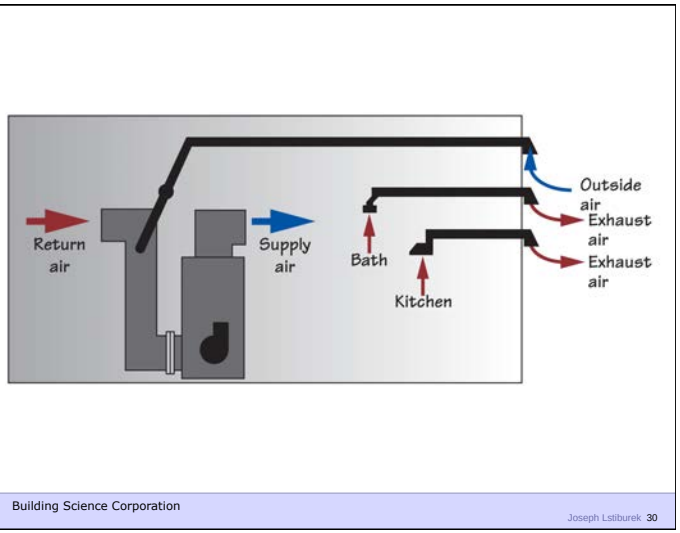
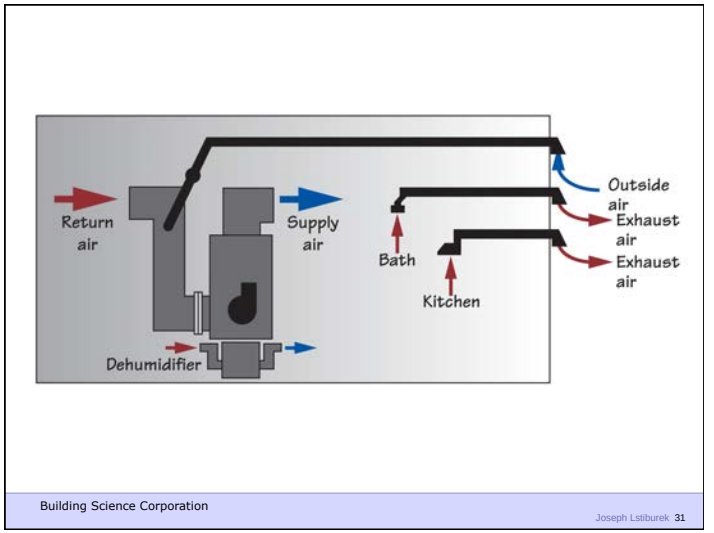
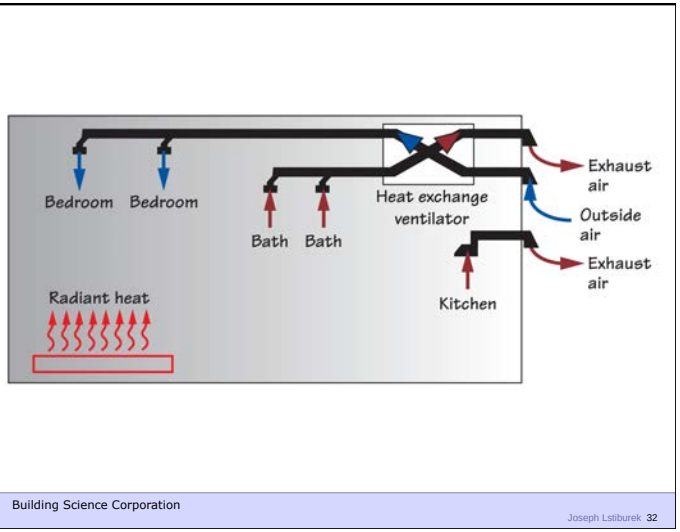
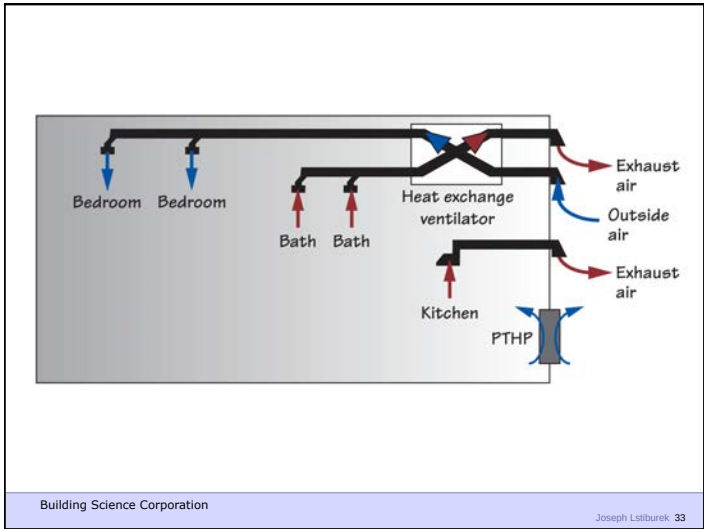
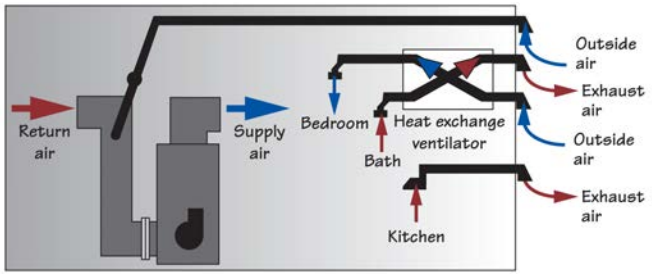

Return air
Supply air
Bath
Kitchen
Outside air
Exhaust air
Exhaust air
Building Science Corporation
Joseph Lstiburek 30


Return air
Supply air
Bath
Kitchen
Outside air
Exhaust air
Exhaust air
Dehumidifier
Building Science Corporation
Joseph Lstiburek 31


Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
Radiant heat
Building Science Corporation
Joseph Lstiburek 32


Bedroom
Bedroom
Bath
Bath
Heat exchange ventilator
Exhaust air
Outside air
Exhaust air
Kitchen
PTHP
Building Science Corporation
Joseph Lstiburek 33



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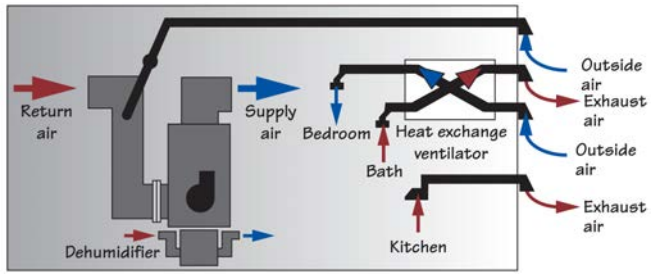

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Building Science Corporation
Joseph Lstiburek 36

Building Science Corporation
Joseph Lstiburek 37

Building Science Corporation Joseph Lstiburek 38

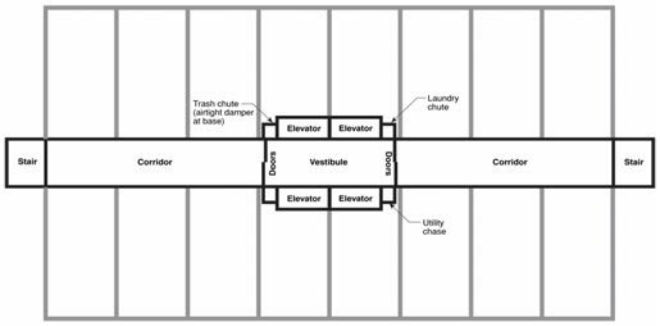
Building Science Corporation Joseph Lstiburek 39

Building Science Corporation Joseph Lstiburek 40

Building Science Corporation Joseph Lstiburek 41

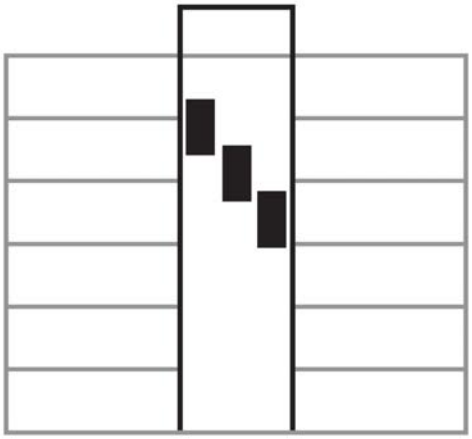
Building Science Corporation
Joseph Lstiburek 42

Building Science Corporation
Joseph Lstiburek – HVAC 43



Building Science Corporation
Joseph Lstiburek – HVAC 44

Building Science Corporation
Joseph Lstiburek – HVAC 45



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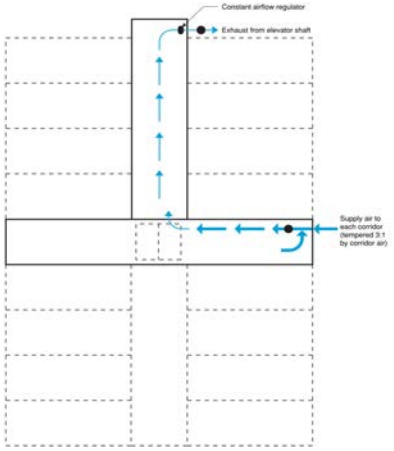
Joseph Lstiburek – HVAC 46



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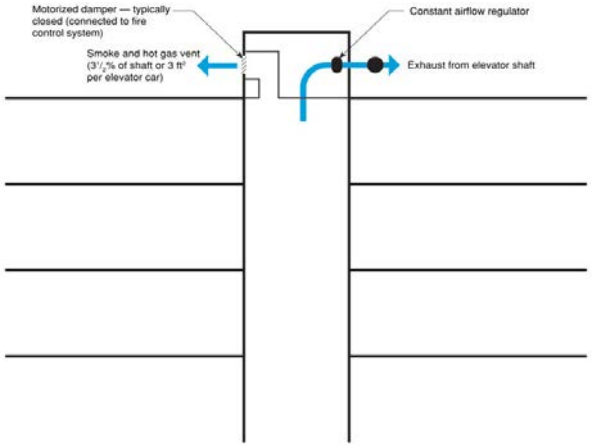
Joseph Lstiburek – HVAC 47



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Joseph Lstiburek – HVAC 48

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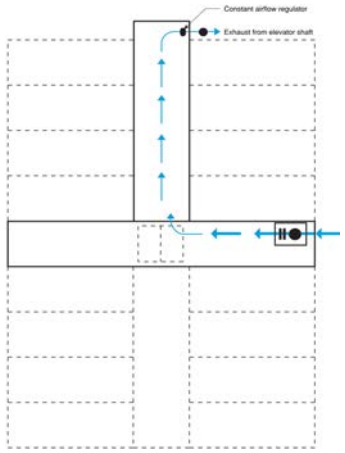
Joseph Lstiburek – HVAC 49



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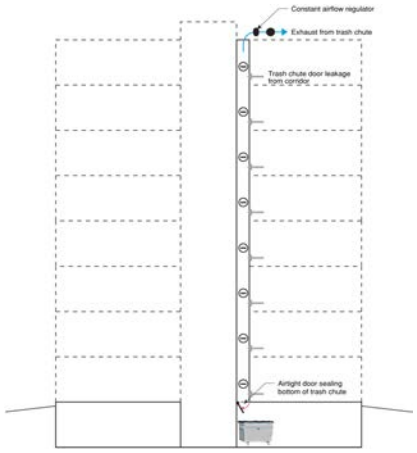
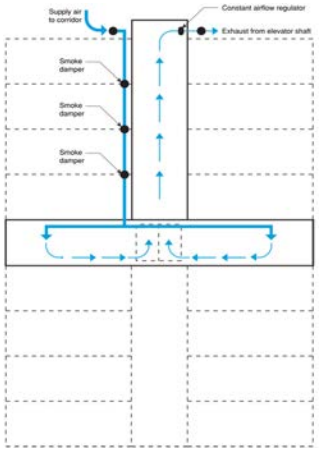
Joseph Lstiburek – HVAC 50



Building Science Corporation
Joseph Lstiburek – HVAC 51

Building Science Corporation
Joseph Lstiburek 52



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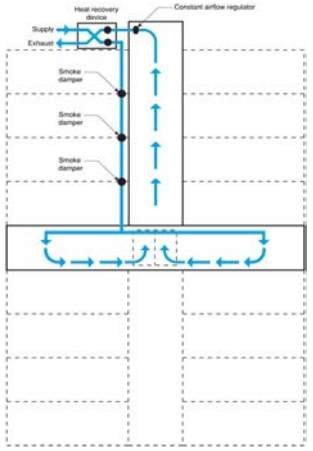
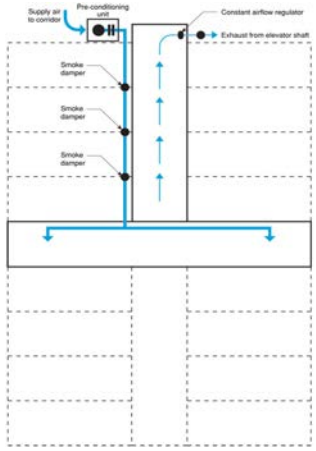
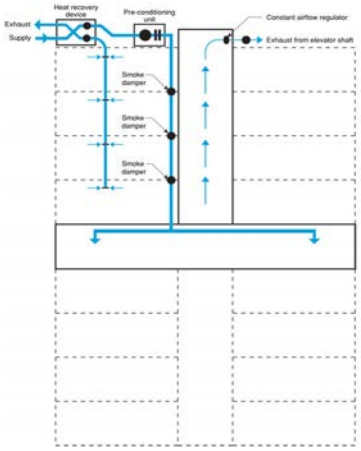
Joseph Lstiburek – HVAC 53



Building Science Corporation
Joseph Lstiburek – HVAC 54



Building Science Corporation
Joseph Lstiburek – HVAC 55



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Building Science Corporation
Joseph Lstiburek – HVAC 57

Building Science Corporation Joseph Lstiburek 58

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Building Science Corporation Joseph Lstiburek 59

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Building Science Corporation Joseph Lstiburek 60

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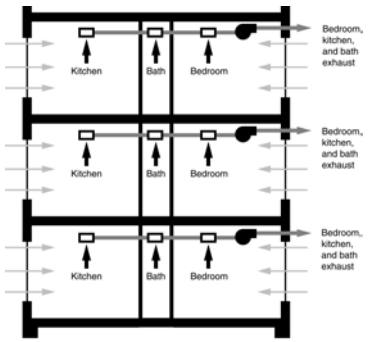
Building Science Corporation Joseph Lstiburek 61



Distributed Ventilation

- Individual unit exhaust ventilation fan exhausts [during occupancy] from each bedroom, bathroom, and kitchen
- Operation of system is time of occupancy sensitive — on only when occupied

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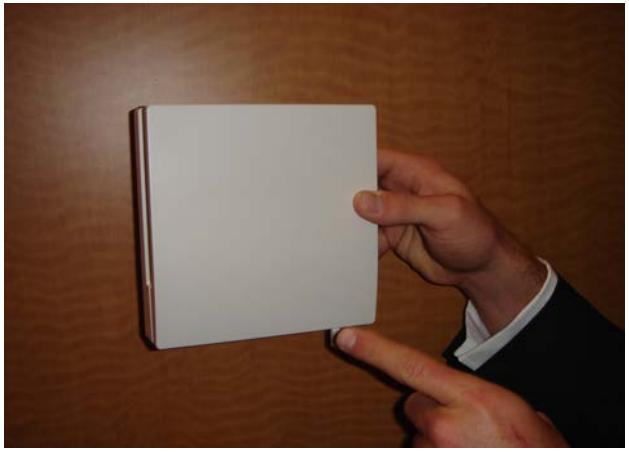
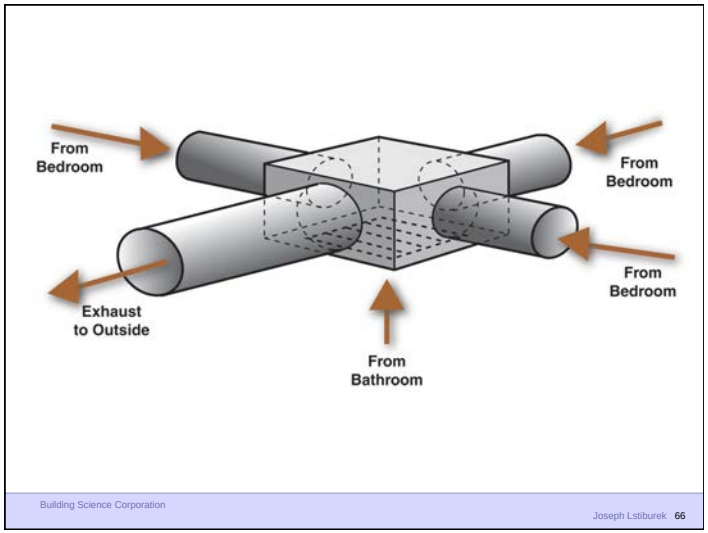
Building Science Corporation Joseph Lstiburek 63

Building Science Corporation Joseph Lstiburek 64



Building Science Corporation Joseph Lstiburek 65


From
Bedroom
From
Bedroom
From
Bedroom
Exhaust
to Outside
From
Bathroom
Building Science Corporation
Joseph Lstiburek 66

Ventilation Rates Are Based on Odor Control

Ventilation Rates Are Based on Odor Control

Health Science Basis for Ventilation Rates is Extremely Limited

Ventilation Rates Are Based on Odor Control

Health Science Basis for Ventilation Rates is Extremely Limited

Almost Nothing Cited Applies to Housing

Ventilation Rates Are Based on Odor Control

Health Science Basis for Ventilation Rates is Extremely Limited

Almost Nothing Cited Applies to Housing

The Applicable Studies Focus on Dampness

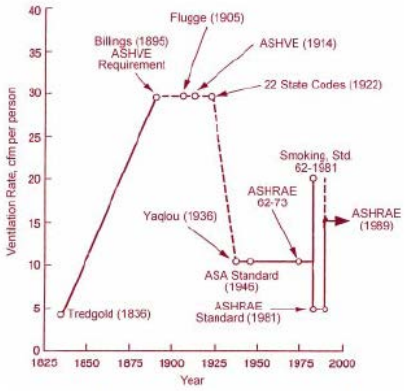


Figure 1: Minimum ventilating rate history.

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House

2,000 ft²
3 bedrooms
8 ft. ceiling
Volume: 16,000 ft³

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

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House

2,000 ft²
3 bedrooms
8 ft. ceiling
Volume: 16,000 ft³

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

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

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Office

Occupant Density

15/1000 ft² (67 ft²/person)	62 - 89	15 cfm/person
5/1000 ft² (200 ft²/person)	62.1 - 2007	17 cfm/person

Correctional Facility Cell

Occupant Density

20/1000 ft² (48 ft²/person)	62.1 – 2007	10 cfm/person

C.P. Yaglou

Harvard School of Public Health
1936
1955

150 ft^3 → 20 cfm/person approx 4x4x8

300 ft^3 → 12 cfm/person approx 6x6x8

C.P. Yaglou

Harvard School of Public Health
1936
1955

150 ft^3 → 20 cfm/person 18.75 ft^2 106 occupants

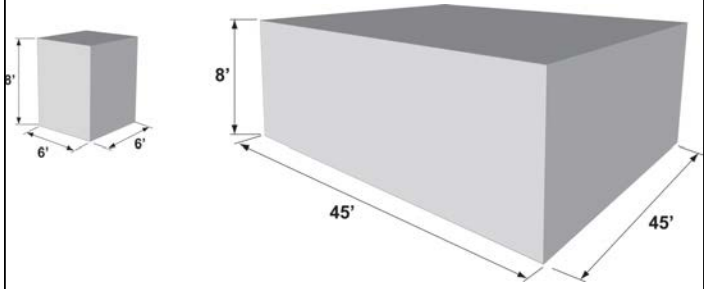
300 ft^3 → 12 cfm/person 37.5 ft^2 53 occupants

Experiment

470 ft^3 → 59 ft^2

200 ft^3 → 25 ft^2

100 ft^3 → 12 ft^2



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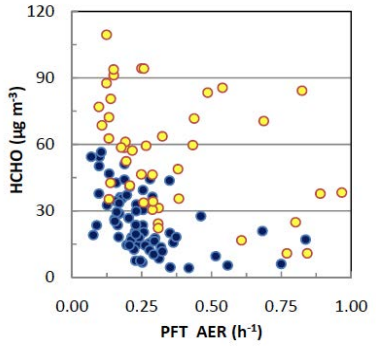

Aubin, D., Won, D.Y., Schleibinger, H., 2010

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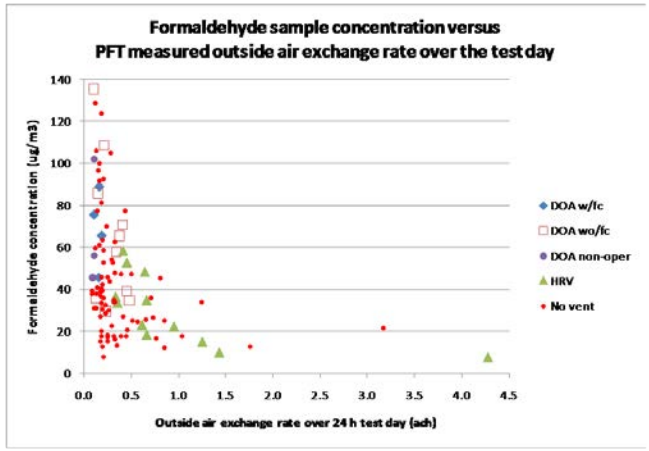


Dilution is Not The Solution To Indoor Pollution

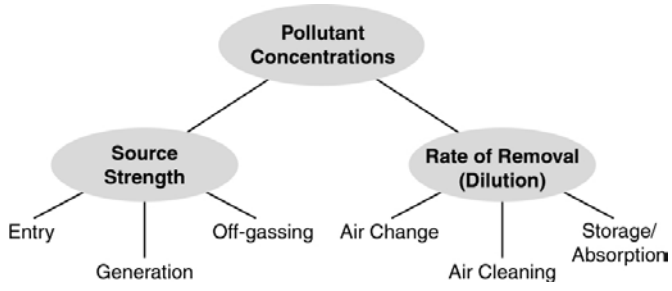


Table 1. Summary of the air changes rates measured during the winter 2009-10 season in Quebec City

Method	ACH (h^{-1})	ACH standard deviation (h^{-1})	number of measurements
SF_6 tracer decay	0.27	0.12	77
perflurocarbon tracer	0.32	0.22	37
blower door at 50 Pa	4.16	2.64	63

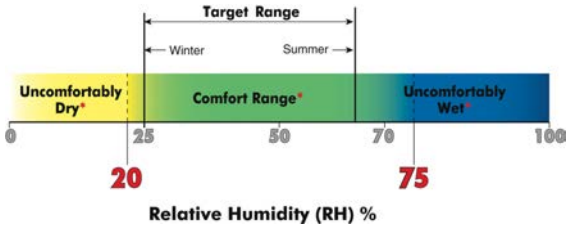
ASHRAE Standard 62.2 calls for 7.5 cfm per person plus 0.03 cfm per square foot of conditioned area

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

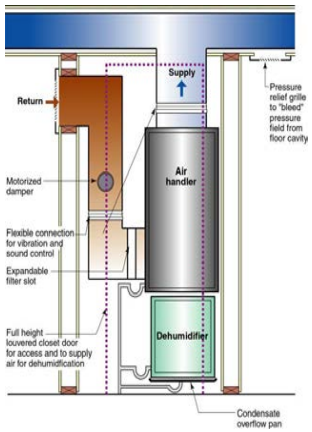
Outcome is often bad – part load humidity problems, dryness problems, energy problems



Recommended Range of Relative Humidity

Above 25 percent during winter

Below 70 percent during summer



Barriers – Technology Dehumidification

Barriers – Cost Exhaust $150
Exhaust + Dist $200
Supply + Dist $200
Spot + Ex/Sup + Dist $500
Balanced/ER $1,250
Dehumidification $250 to $1,250

- Tracer gas test of a production 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

Example Results of Tracer Gas Testing

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

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

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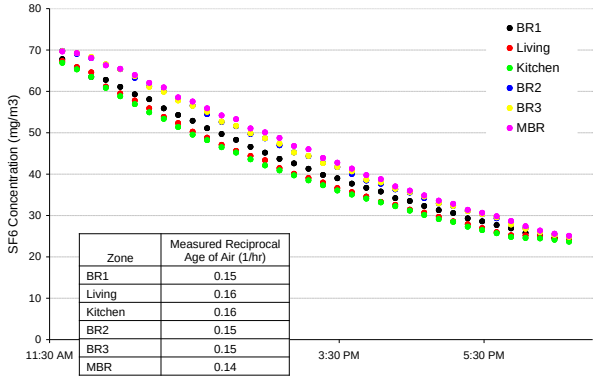
Example Results of Tracer Gas Testing

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, 33% Mixing



Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.15
Living	0.16
Kitchen	0.16
BR2	0.15
BR3	0.15
MBR	0.14

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Example Results of Tracer Gas Testing

CFI, 100% of 62.2 Rate, Doors Closed, 33% Mixing

Zone	Measured Reciprocal Age of Air (1/hr)
BR1	0.20
Living	0.19
Kitchen	0.20
BR2	0.20
BR3	0.20
MBR	0.19

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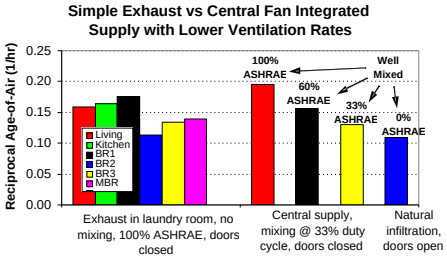
Conclusions From Tracer Gas Testing

- Mixing is very important to whole-house and individual zone pollutant decay rate
- Supply ventilation is slightly more effective than exhaust ventilation, even with mixing
- The location of a single-point ventilation system affects the performance



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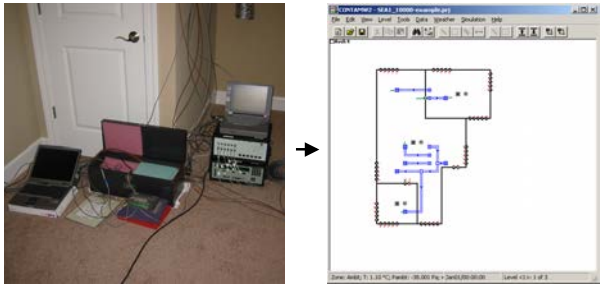
Tuned CONTAM Model



Computer modeling used to replicate field testing (tune the model) and predict performance of systems not tested in the field

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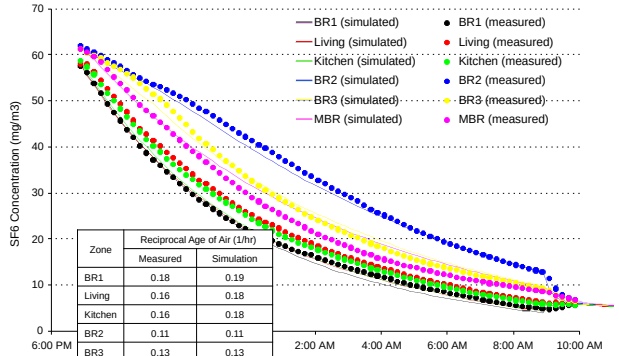
Example Results of Tuned CONTAM Model

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, 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

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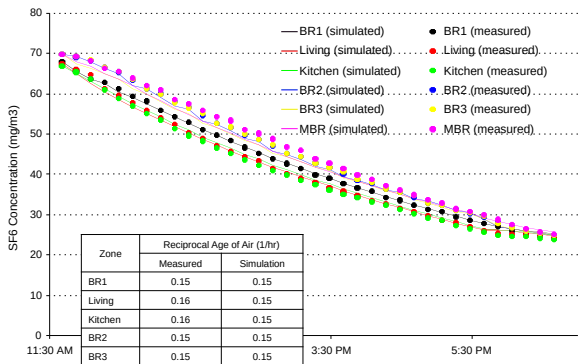
Example Results of Tuned CONTAM Model

Laundry Exhaust, 100% of 62.2 Rate, Doors Closed, 33% Mixing



Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.15	0.15
Living	0.16	0.15
Kitchen	0.16	0.15
BR2	0.15	0.15
BR3	0.15	0.15
MBR	0.14	0.15

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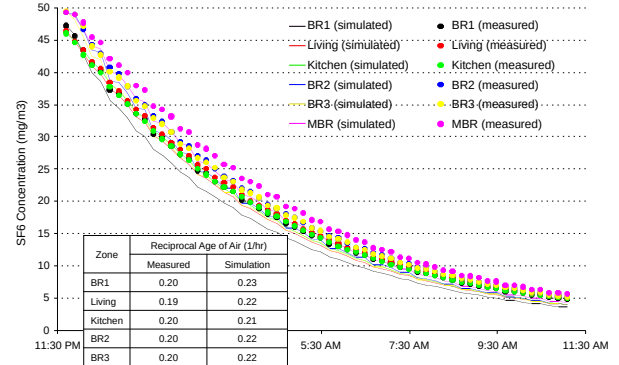
Example Results of Tuned CONTAM Model

CFI, 100% of 62.2 Rate, Doors Closed, 33% Mixing



Zone	Reciprocal Age of Air (1/hr)	
	Measured	Simulation
BR1	0.20	0.23
Living	0.19	0.22
Kitchen	0.20	0.21
BR2	0.20	0.22
BR3	0.20	0.22
MBR	0.19	0.21

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Tuned CONTAM Model Applied to Other Systems

Systems Evaluated & Compared:

1. Exhaust ventilation, without central duct system
2. Supply ventilation, without central duct system
3. Exhaust ventilation, with central ducts, standard Tstat
4. Exhaust ventilation, with central ducts, Tstat with timer
5. Supply ventilation, with central ducts, Tstat with timer
6. Fully ducted balanced ventilation system, without central duct system

Q(v) = Ventilation Rate

Q(fan) = Q(v) • C(s)

C(s) = System Coefficient

Airflow Ratios—All Simulations

System Type	Range	Approximate Median
Fully ducted balanced ventilation system, with or without central duct system	1.0	1.0
Non-fully ducted balanced ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	0.9 to 1.1	1.0
Supply ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.7	1.25
Exhaust ventilation, with central duct system, and central air handler unit controlled to a minimum runtime of at least 10 minutes per hour	1.1 to 1.9	1.25
Exhaust ventilation, with central duct system, and central air handler unit not controlled to a minimum runtime of at least 10 minutes per hour	1.0 to 1.8	1.5
Supply ventilation, without central duct system	1.4 to 1.9	1.75
Exhaust ventilation, without central duct system	1.3 to 2.6	2.0

BSC 01 - 2013 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

Occupant Rate + Building Rate

Q(v) = Fan Flow Rate

Q(fan) = Q(v) • C(s)
C(s) = System Coefficient

Table 4.1

System Coefficient based on system type[1]

System Type	Distributed	Not Distributed
Balanced	1.0	1.25
Not Balanced	1.25	1.5

[1] Where there is whole-building air mixing of at least 70% recirculation turnover each hour, the system coefficient may be reduced by 0.25.

BSC 01-2013

Ventilation for New Low-Rise Residential Building

2,000 ft²
3 bedrooms

20 cfm + 30 cfm = 50 cfm

Mixed, Distributed, Balanced (MDB)
37.5 cfm

Not Mixed, Not Distributed, Not Balanced
75 cfm

House

2,000 ft²
3 bedrooms
8 ft. ceiling
Volume: 16,000 ft³

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

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
BSC 01 - 2013	7.5 cfm/person + 0.01 (MBD)	37 cfm 75 cfm