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

Building Science

Ventilation

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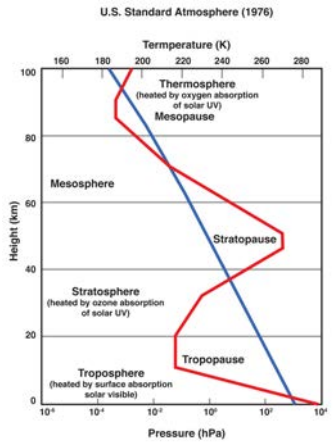
"It isn't what we don't know that gives us trouble, it's what we know that ain't so"

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



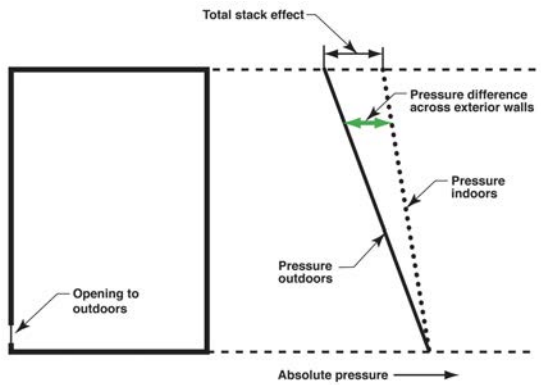


Figure 11.1: Building with no internal separations with opening at the bottom (Adapted from G.O. Handegord, 1998)

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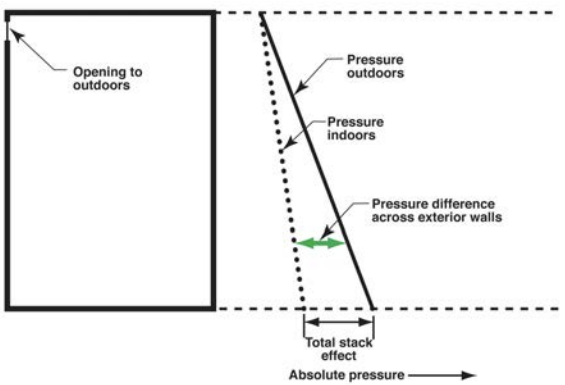

Figure 11.2: Building with no internal separations with opening at the top (Adapted from G.O. Handegord, 1998)

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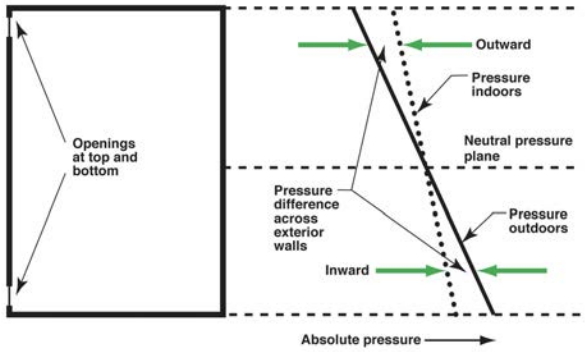

Figure 11.3: Building with no internal separations with openings at top and bottom (Adapted from G.O. Handegord, 1998)

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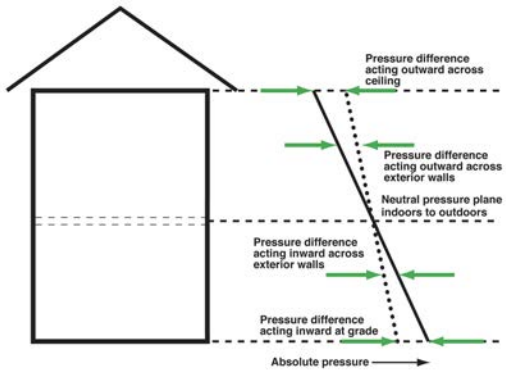

Figure 11.4: Basic two storey house with vented attic (Adapted from G.O. Handegord, 1998)

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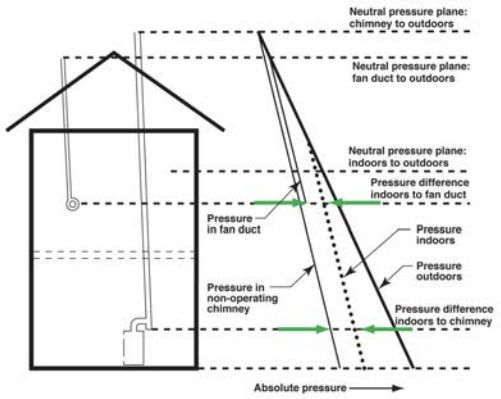

Figure 11.5: Two storey house with non-operating chimney and exhaust fan (Adapted from G.O. Handegord, 1998)

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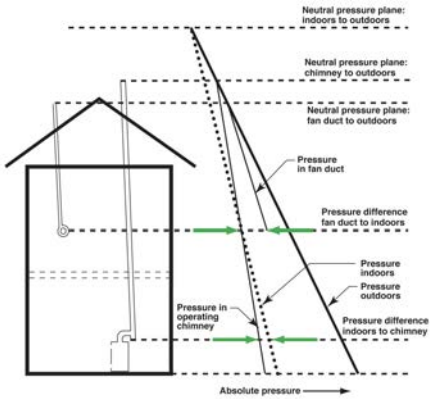

Figure 11.6: Two storey house with operating chimney (Adapted from G.O. Handegord, 1998)

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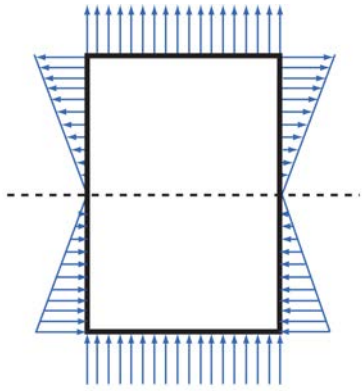

Stack effect

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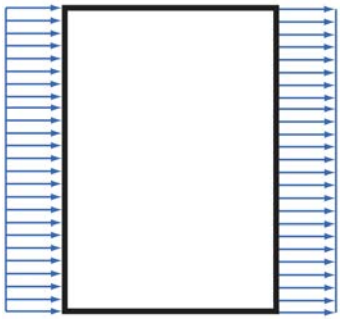

Wind

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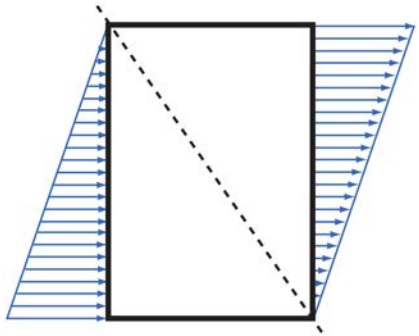

Stack effect and wind

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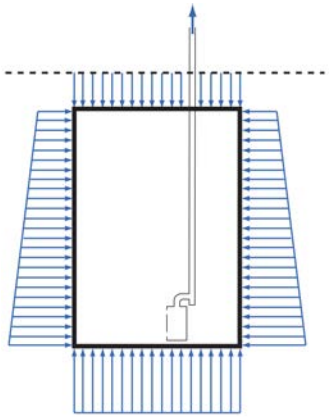

Chimney effect

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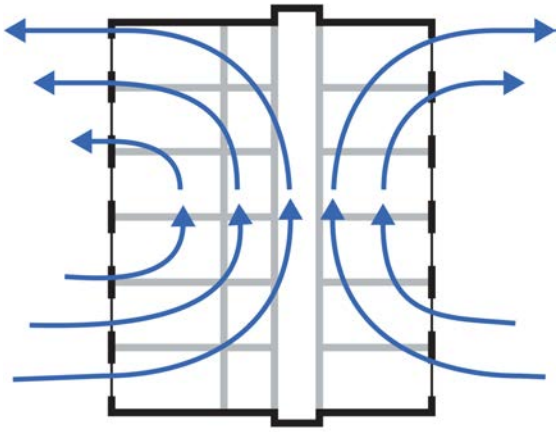
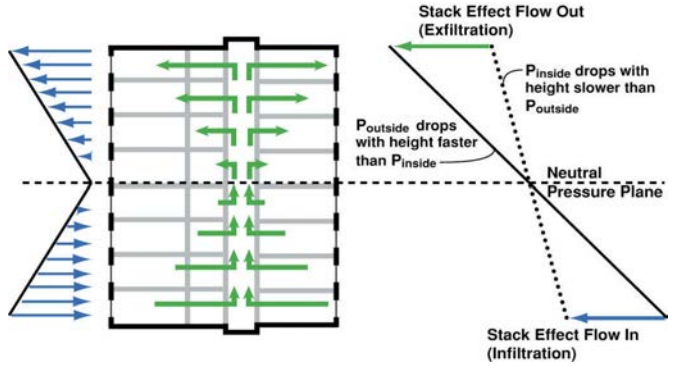




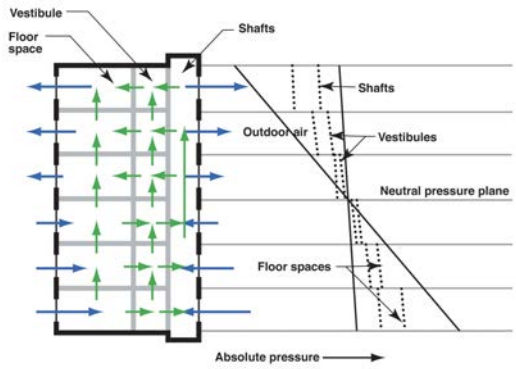


Figure 11.8: Stack effect pressures in high rise office building
(Adapted from G.O. Handegord, 1998)

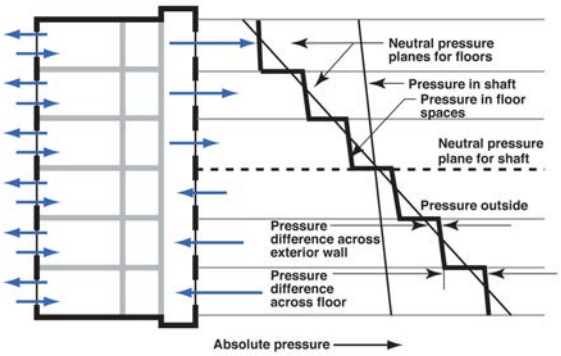


Figure 11.9: Multi-storey building with floor spaces isolated from vertical shafts
(Adapted from G.O. Handegord, 1998)

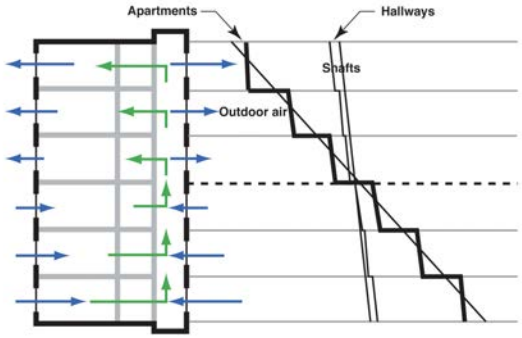
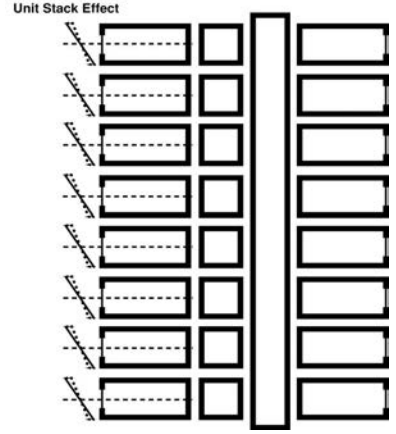
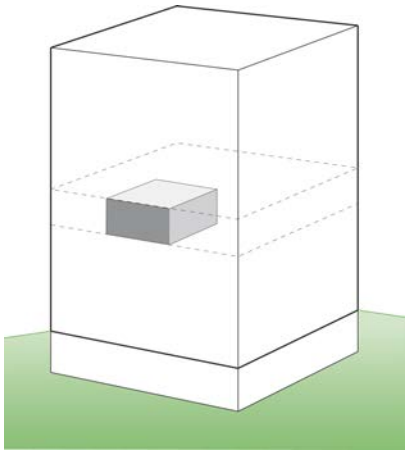


Figure 11.12: Apartment building with tighter apartment entry doors (Adapted from G.O. Handegord, 1998)





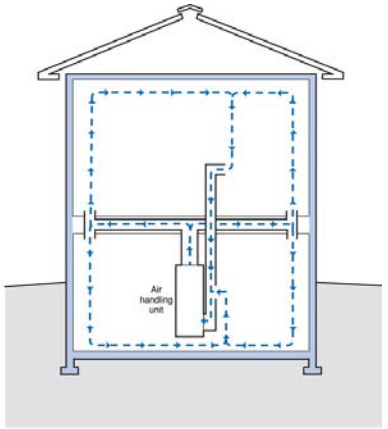


Figure 3.12
Ductwork and Air Handlers in Basements
- No air pressure differences result in a house with an air handler and ductwork located in a basement if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed

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

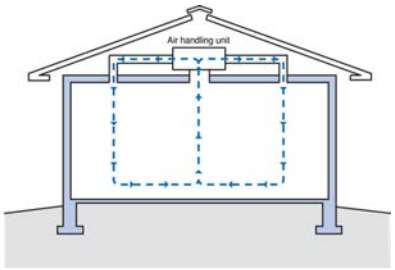
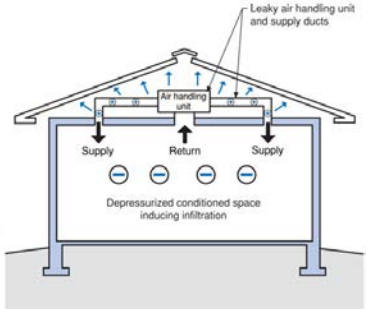


Figure 3.15
Leaky Ductwork and Air Handlers in Vented Attics
- Supply ductwork and air handler leakage is typically 20% or more of the flow through the system



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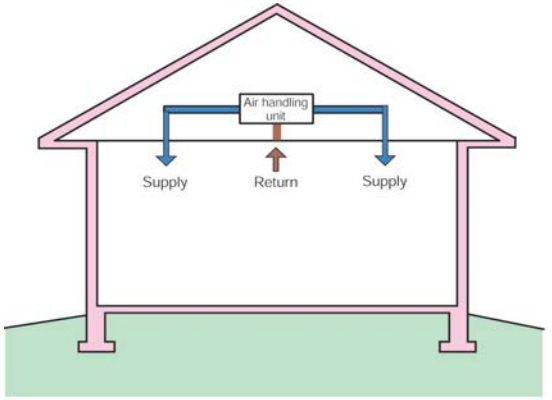
Duct Leakage Should Be Less Than 5% of Rated Flow As

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.

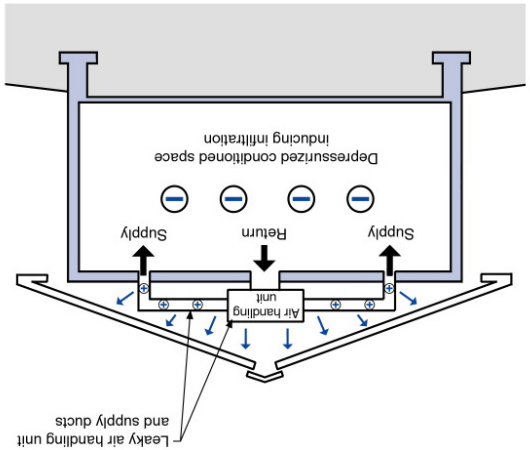
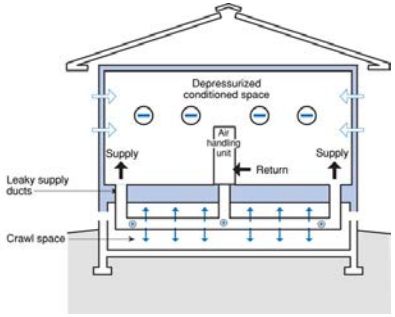


Figure 3.16
Leaky Supply Ductwork in Vented Crawl Space
- Air pressurization pattern with mechanical system ducts in the crawl space



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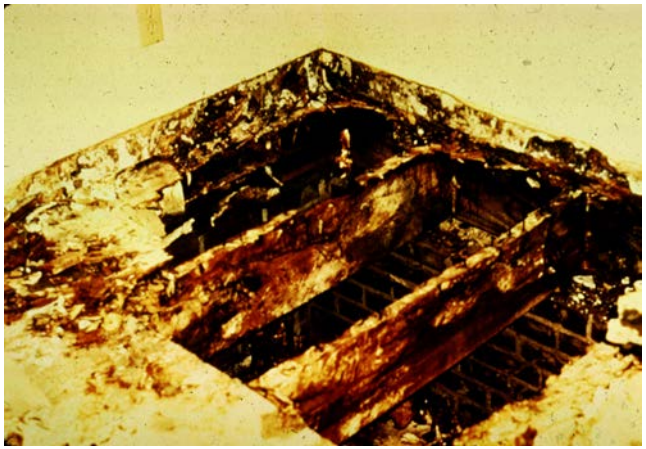
Joseph Lstiburek – Airflow 42



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Joseph Lstiburek – Airflow 44

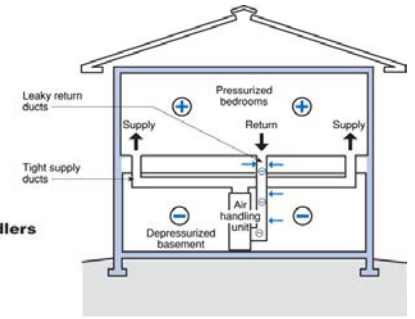

Figure 3.14
Leaky Ductwork and Air Handlers in Basements
- Air pressurization patterns in a house with leaky ductwork in the basement

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Joseph Lstiburek – Airflow 50

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Joseph Lstiburek – Airflow 51

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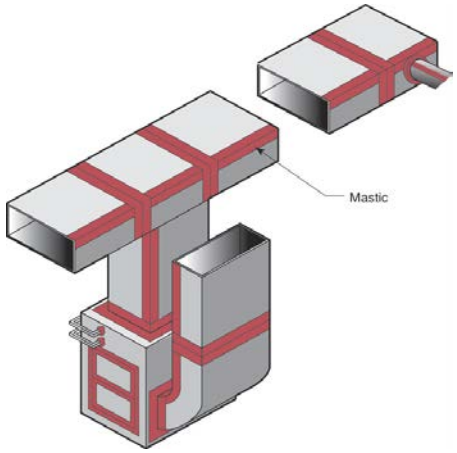
Joseph Lstiburek – Airflow 52



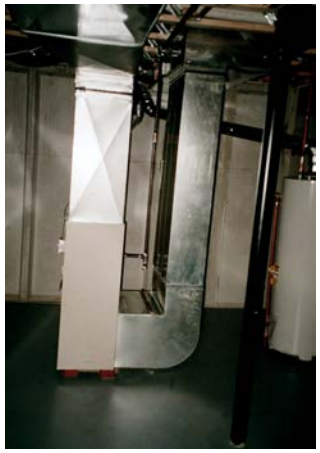
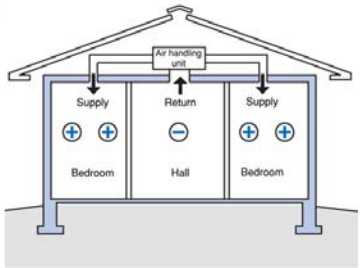
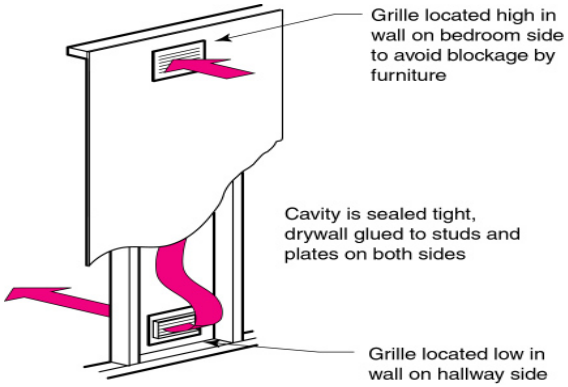


Figure 3.18
Insufficient Return Air Paths

- 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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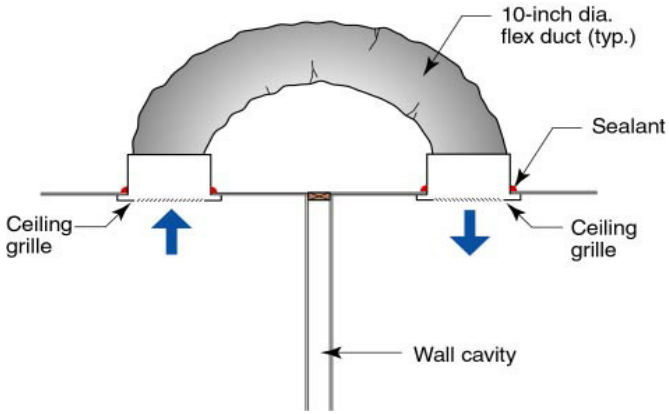
Joseph Lstiburek – Airflow 58



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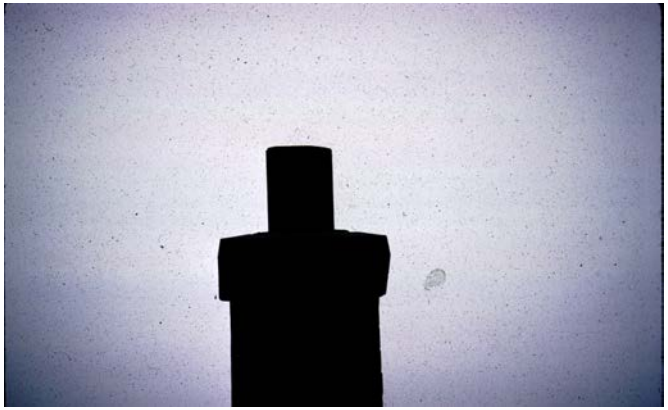
Joseph Lstiburek – Airflow 60



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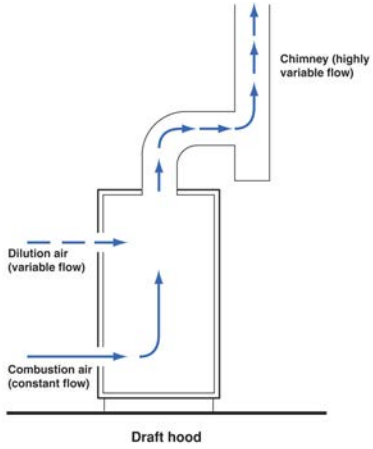
Joseph Lstiburek – Airflow 62

Building Science Corporation

Joseph Lstiburek – Airflow 63

Building Science Corporation

Joseph Lstiburek – Airflow 64



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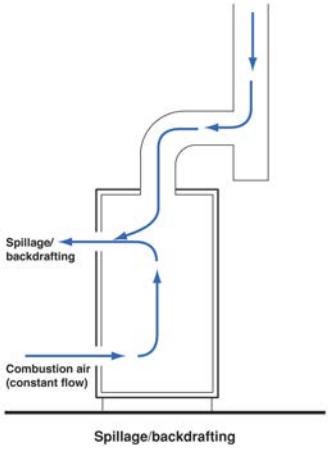

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Joseph Lstiburek – Airflow 67

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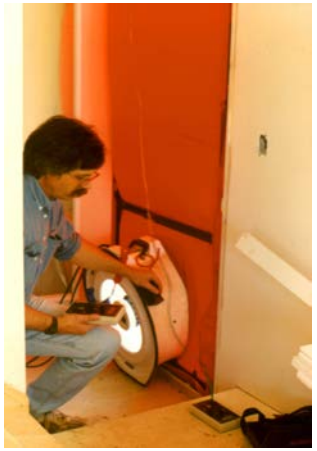
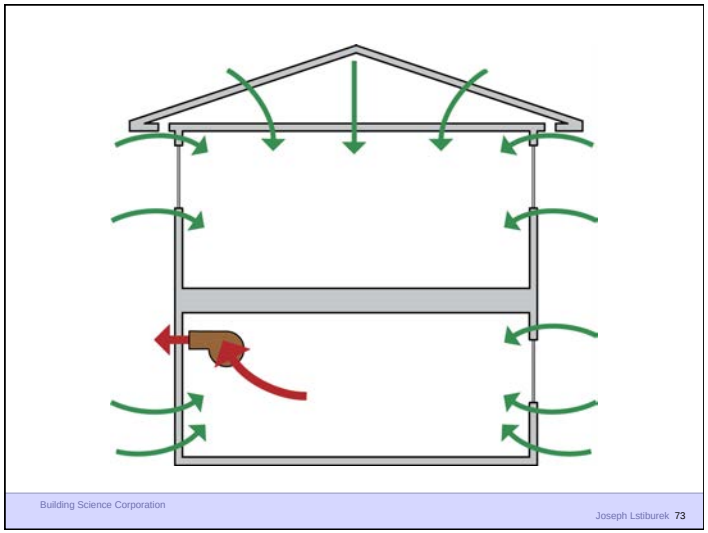
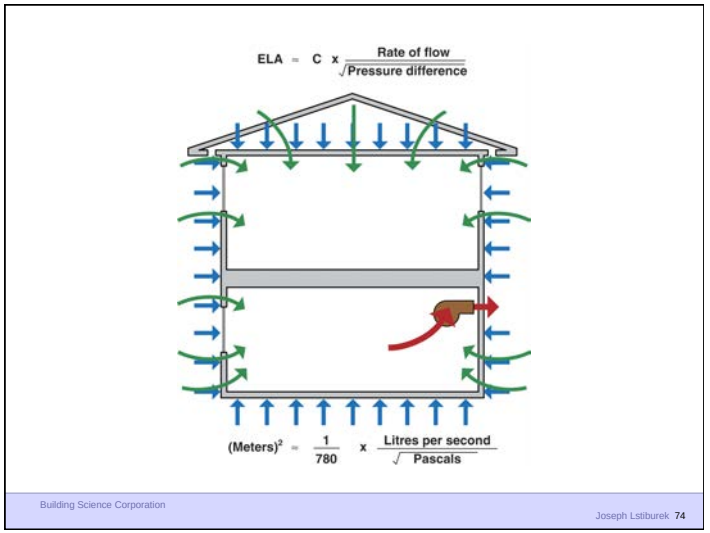
Joseph Lstiburek – Airflow 68

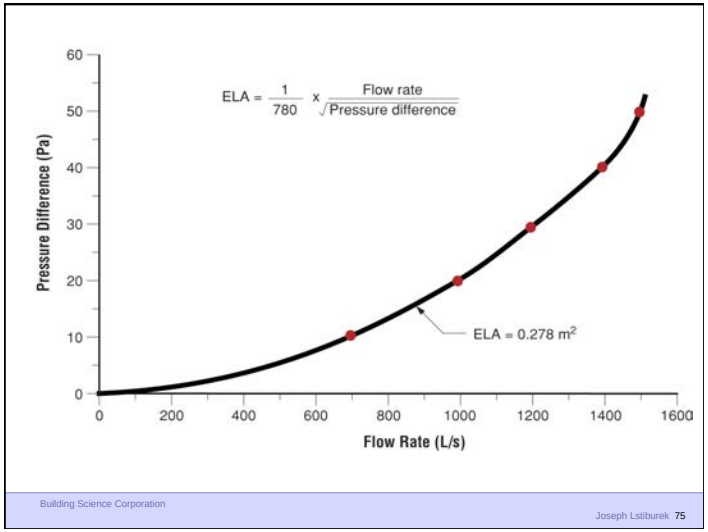
Air Barrier Metrics

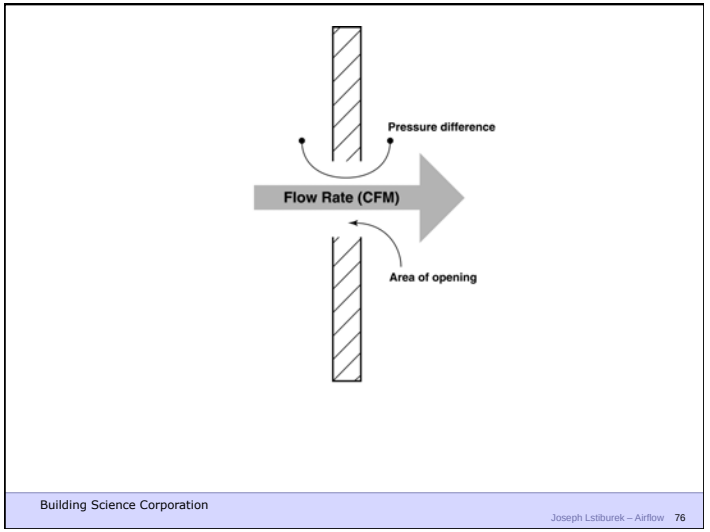
Material 0.02 l/(s-m2)@75 Pa
Assembly 0.20 l/(s-m2)@75 Pa
Enclosure 2.00 l/(s-m2)@75 Pa






ELA = C x Rate of flow / √Pressure difference
(Meters)² = 1/780 x Litres per second / √ Pascals


ELA = 1/780 x Flow rate / √Pressure difference
Pressure Difference (Pa)
Flow Rate (L/s)
ELA = 0.278 m²
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"

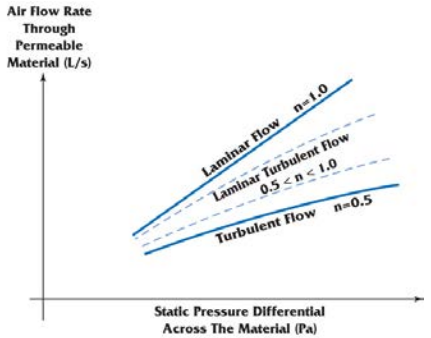
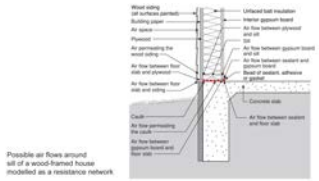
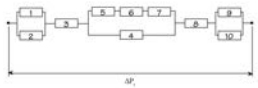


Figure 2.5
Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)





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

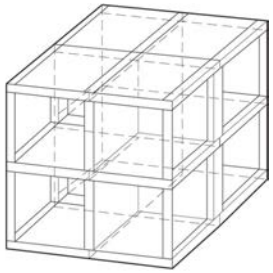


Figure 2.11
Three Dimensional Multi-Layer Multi-Cell Analogue

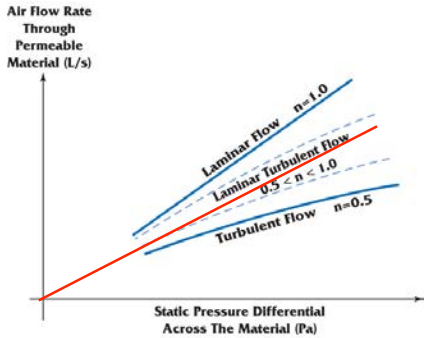


Figure 2.5
Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)

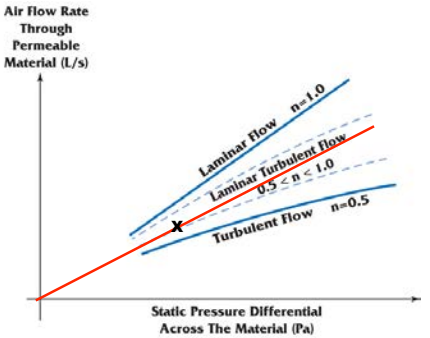


Figure 2.5
Modes of Air Flow
(from Bumbaru, Jutras and Patenaude, 1988)

$Q = f(\Delta p) \approx k(\Delta p)^b$

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

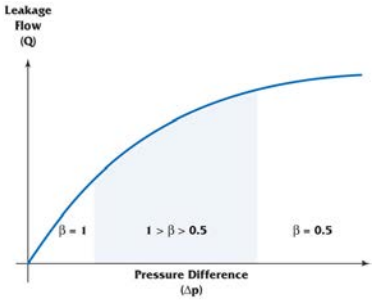


Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)

$Q = f(\Delta p) \approx k(\Delta p)^b$

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

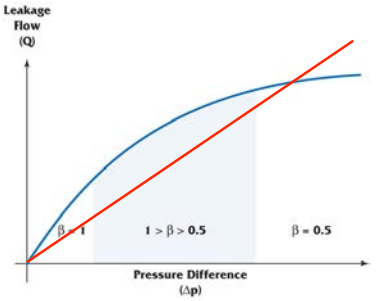


Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)

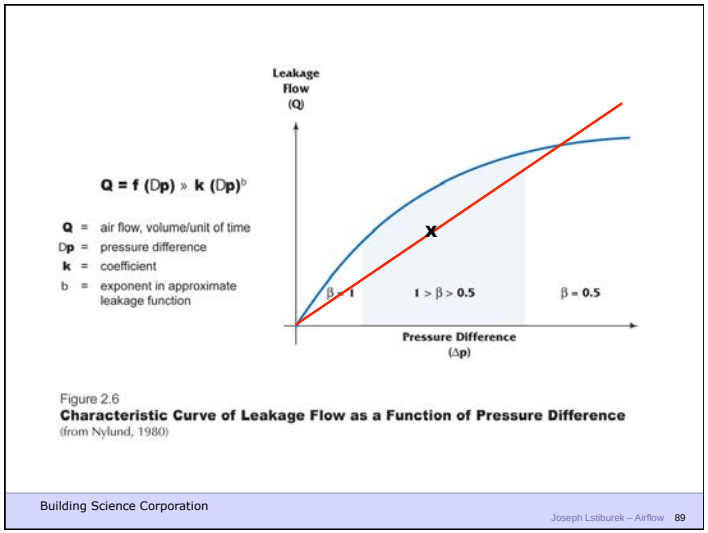


Figure 2.6
Characteristic Curve of Leakage Flow as a Function of Pressure Difference
(from Nylund, 1980)

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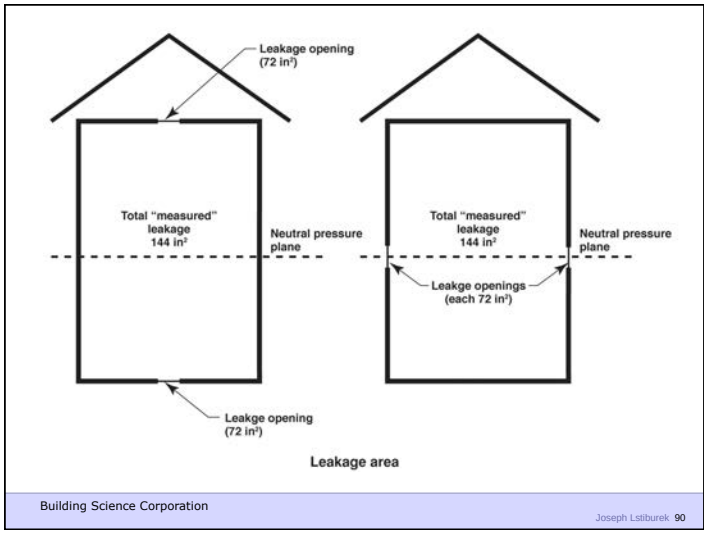

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Joseph Lstiburek 1

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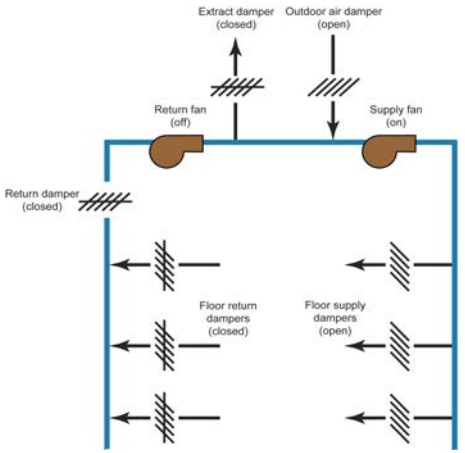
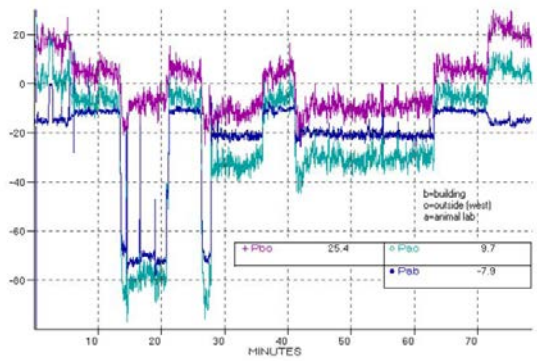
Joseph Lstiburek 2

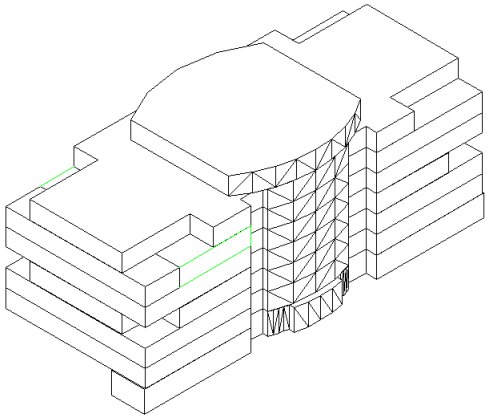
Building Science Corporation
Joseph Lstiburek 3

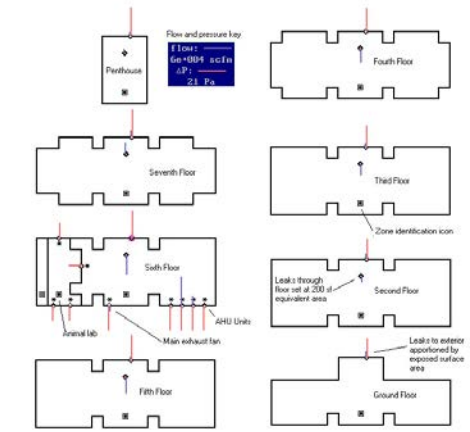
Building Science Corporation
Joseph Lstiburek 4

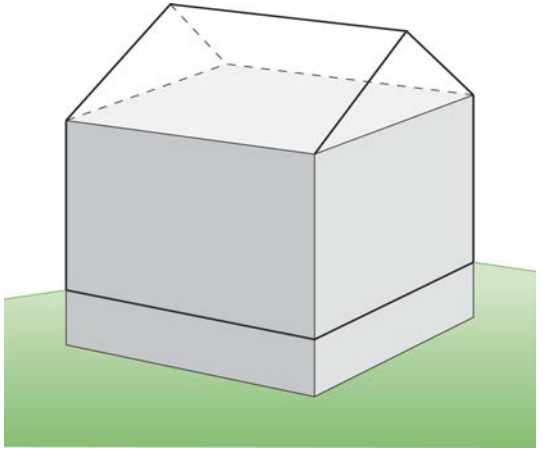
Shriners Hospitals for Crippled Children
Burns Institute
STOP

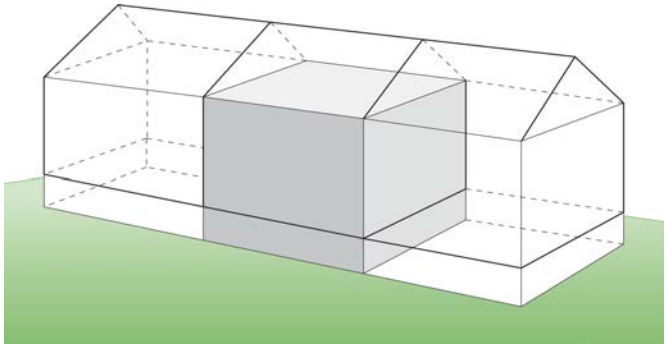

Extract damper (closed)
Outdoor air damper (open)
Return fan (off)
Supply fan (on)
Return damper (closed)
Floor return dampers (closed)
Floor supply dampers (open)

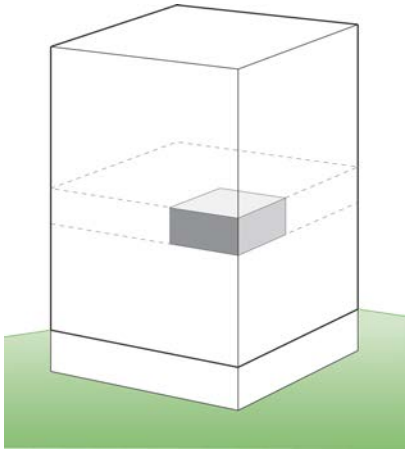

20
0
-20
-40
-60
-80
10
20
30
40
50
60
70
MINUTES
b=building
o=outside (west)
a=animal lab
+ Pbo 25.4
Pao 9.7
Pab -7.9

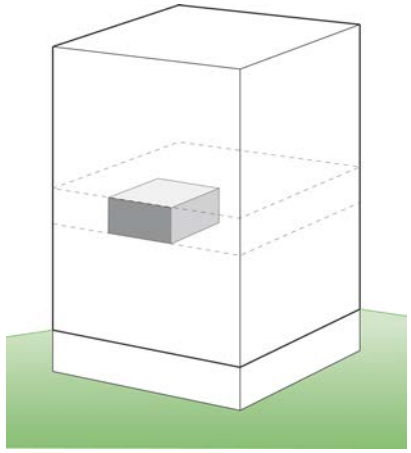



Flow and pressure key
flow:
6e+004 scfm
ΔP:
21 Pa
Penthouse
Seventh Floor
Sixth Floor
Animal lab
AHU Units
Main exhaust fan
Fifth Floor
Fourth Floor
Third Floor
Zone identification icon
Leaks through floor set at 200 sf equivalent area
Second Floor
Leaks to exterior apportioned by exposed surface area
Ground Floor









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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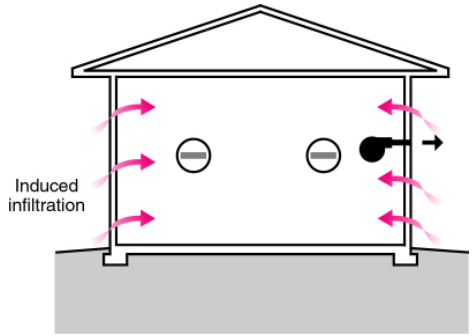
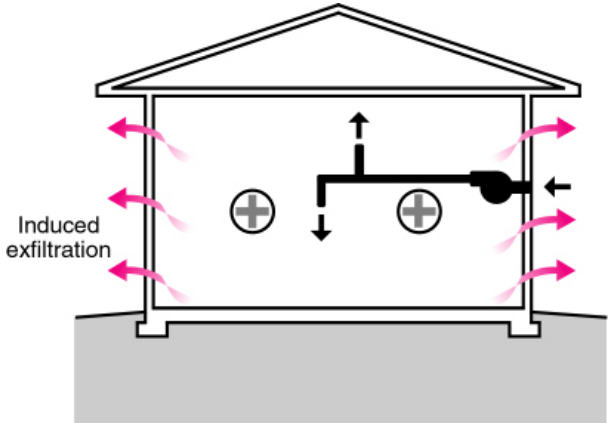
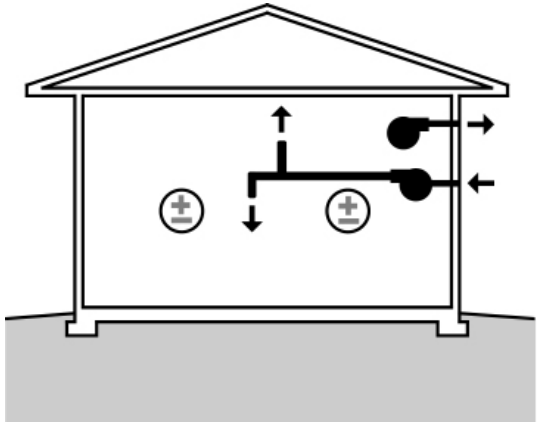
Joseph Lstiburek 24

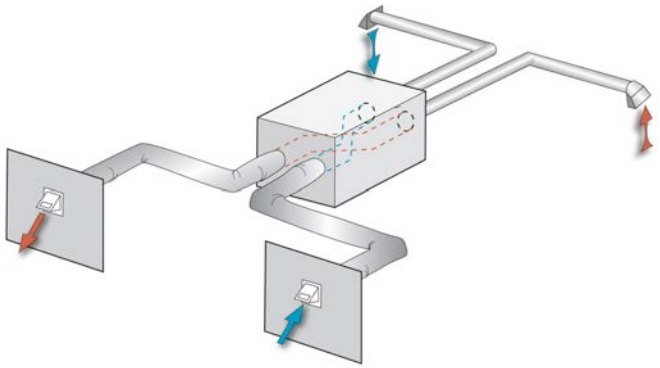
Three Types of Controlled Ventilation Systems

Exhaust Ventilation
Supply Ventilation
Balanced Ventilation









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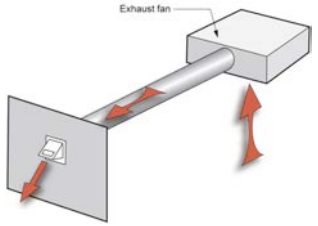

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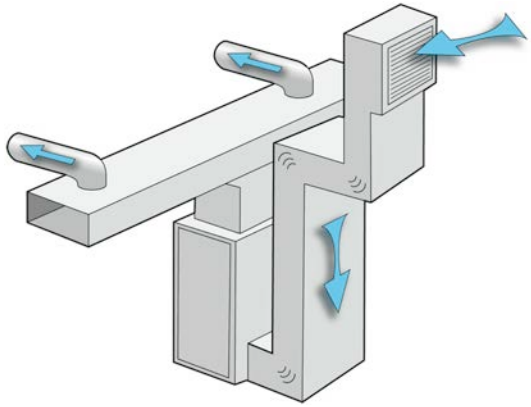
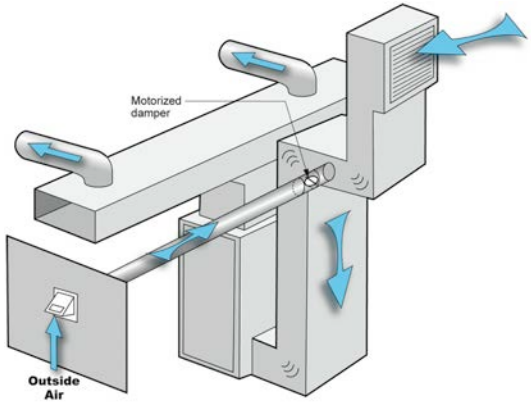
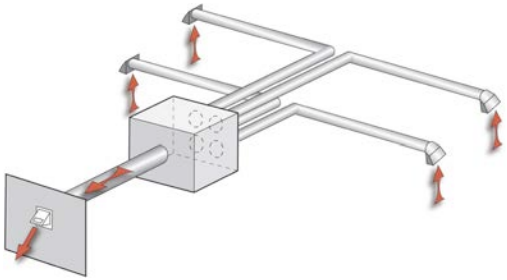


Building Science Corporation Joseph Lstiburek 31



Building Science Corporation Joseph Lstiburek 32



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

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

Good For Long Term Average If No Big Pressures

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

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

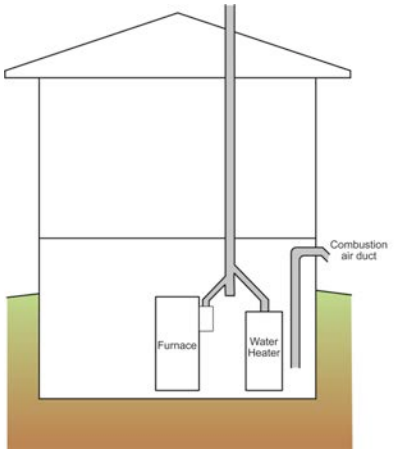
Control Pressures

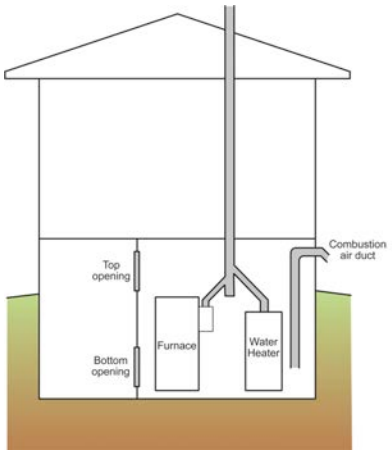
Install Controlled Ventilation

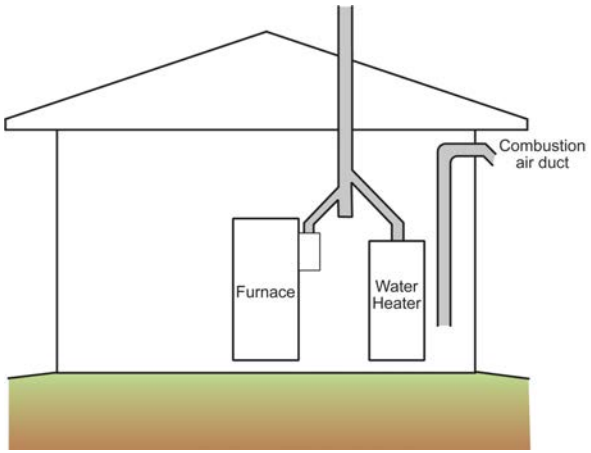
Get Rid of Big Holes

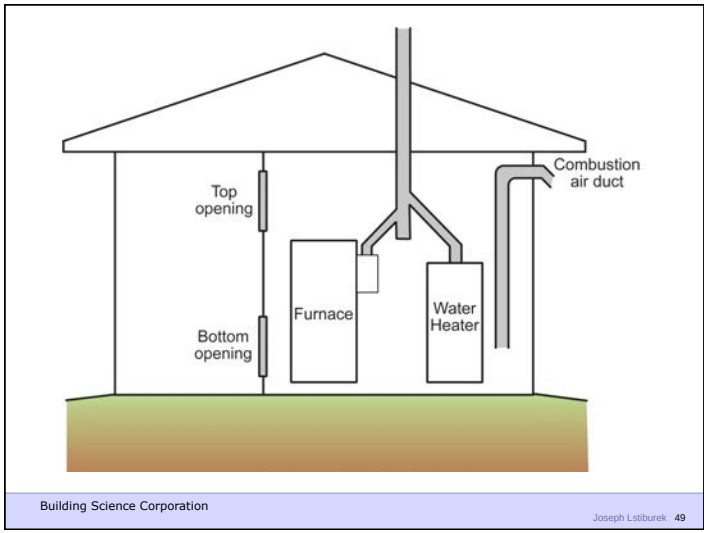
Insulate

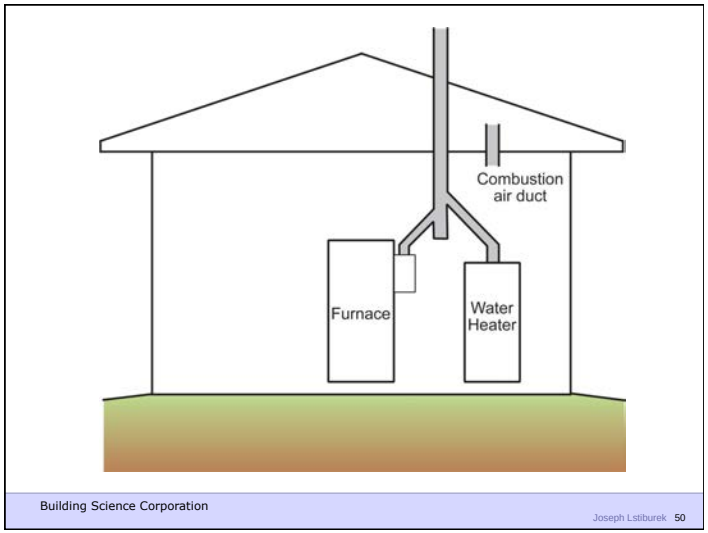
Code Compliant Combustion Air

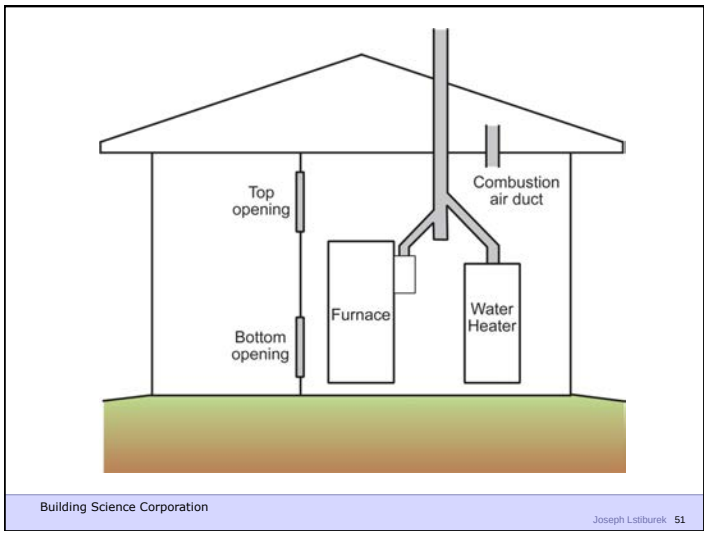


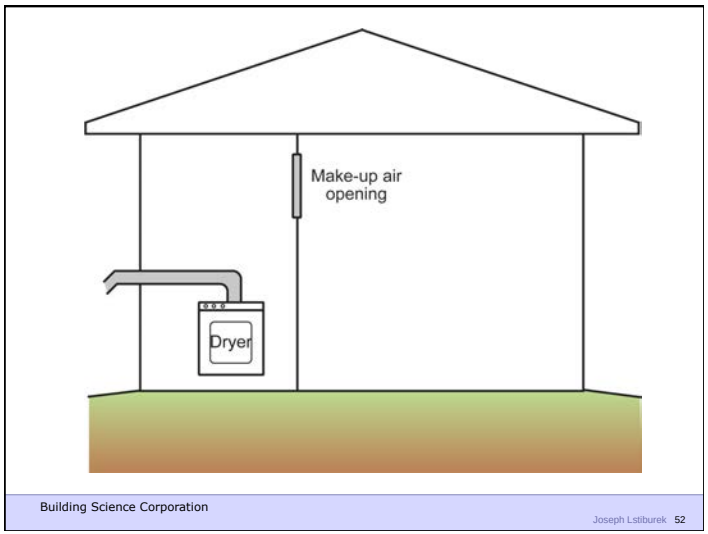


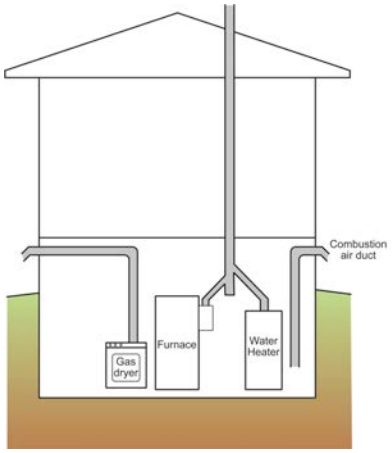



Top
opening
Bottom
opening
Furnace
Water
Heater
Combustion
air duct
Building Science Corporation
Joseph Lstiburek 49


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



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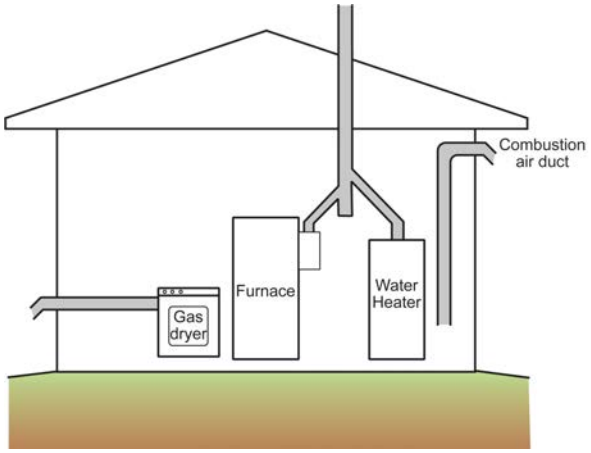
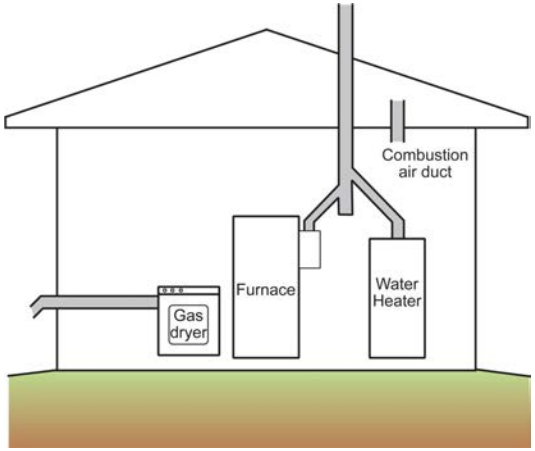


Building Science Corporation
Joseph Lstiburek 54



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Sealed Combustion Appliances

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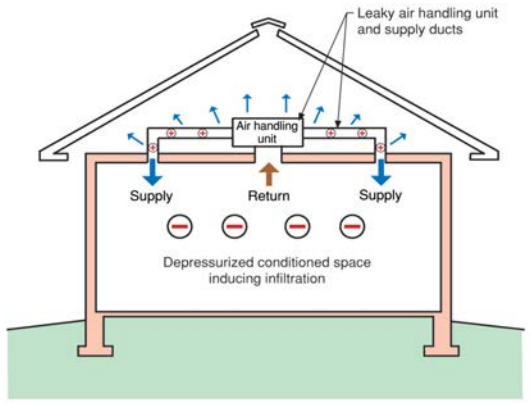
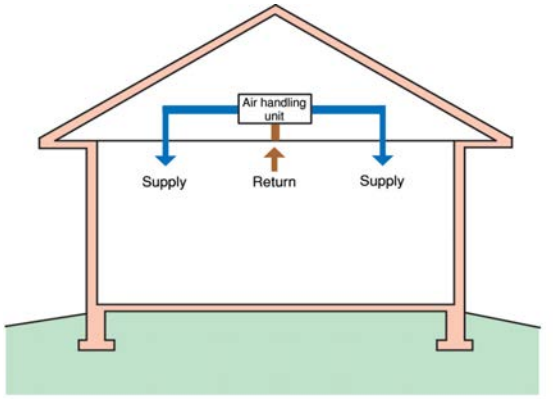
Joseph Lstiburek 56

Control Pressures

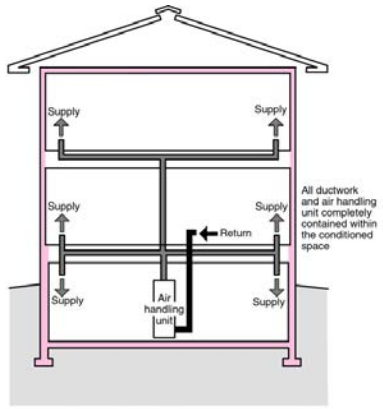


Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.



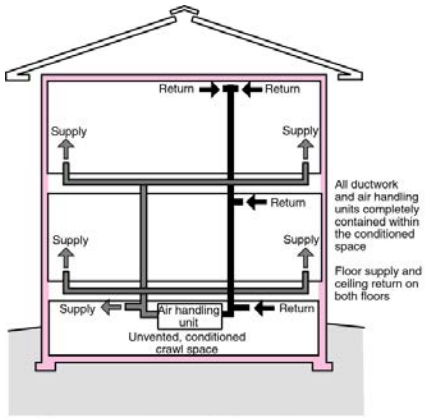
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Building Science Joseph Lstiburek 61



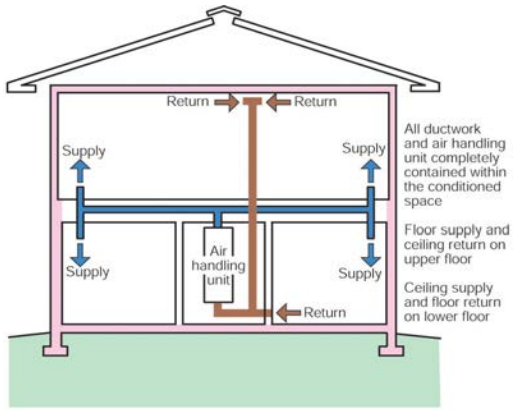
Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

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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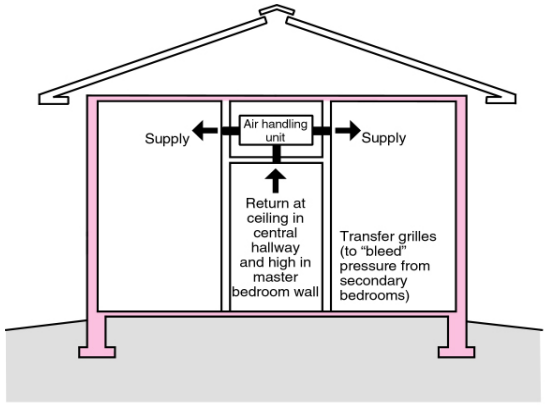
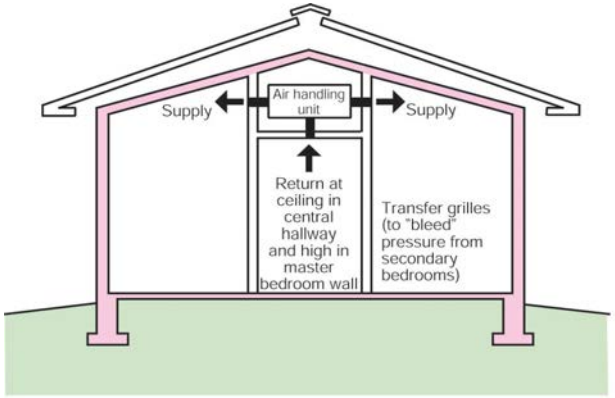
Joseph Lstiburek 65



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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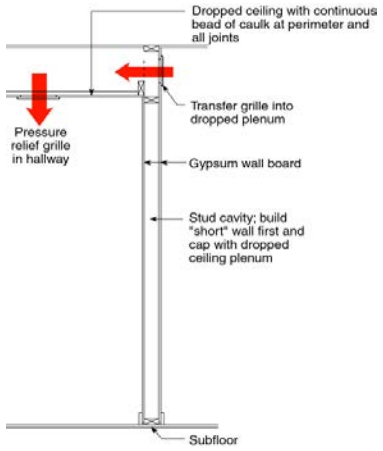
Building Science Corporation
Joseph Lstiburek 68

Building Science Corporation

Joseph Lstiburek 69

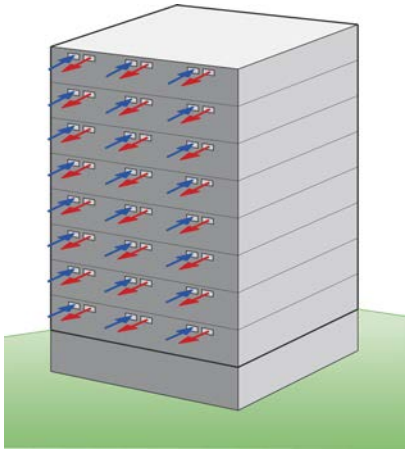
Building Science

Joseph Lstiburek 70



Building Science

Joseph Lstiburek 71



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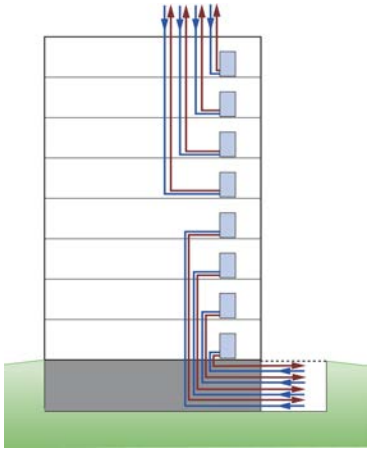
Joseph Lstiburek – HVAC 2

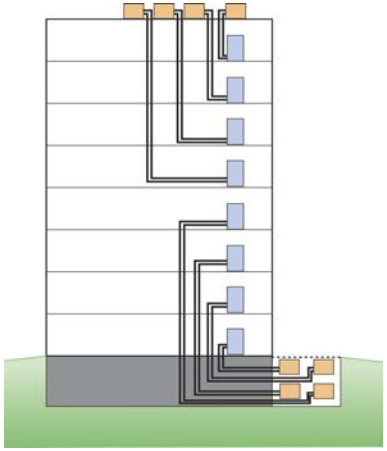
Building Science Corporation

Joseph Lstiburek 3



Building Science Corporation

Joseph Lstiburek – HVAC 4



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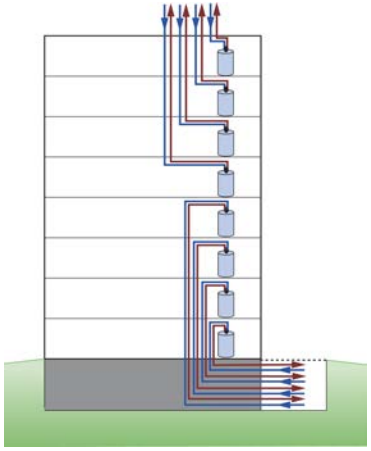
Joseph Lstiburek – HVAC 5



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Joseph Lstiburek – HVAC 6

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Joseph Lstiburek – HVAC 7

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Joseph Lstiburek – HVAC 8

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Joseph Lstiburek – HVAC 9

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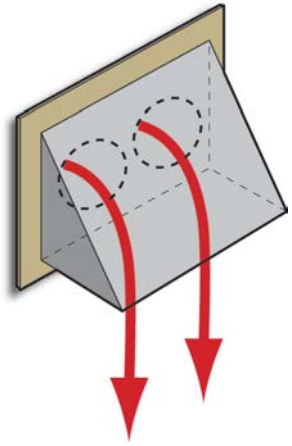
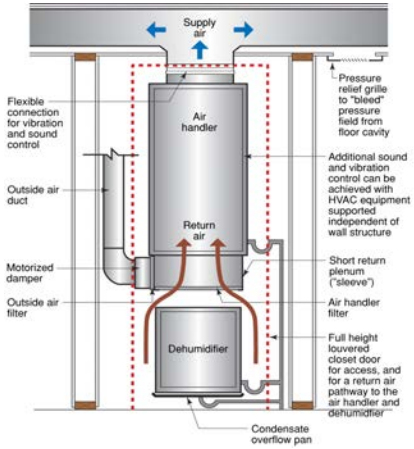
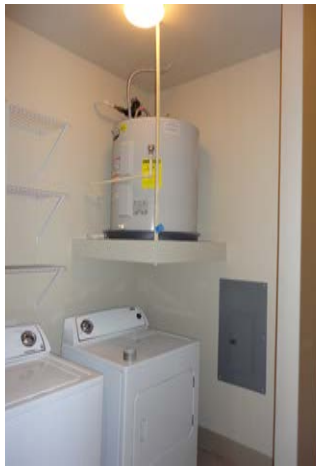
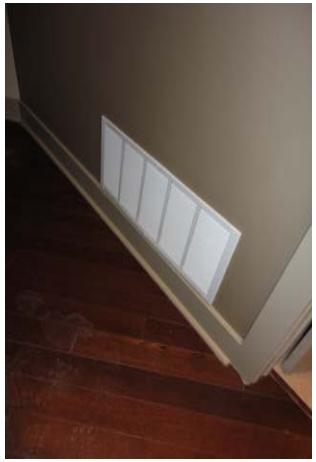



Supply air
Flexible connection for vibration and sound control
Outside air duct
Motorized damper
Outside air filter
Air handler
Return air
Dehumidifier
Pressure relief grille to "bleed" pressure field from floor cavity
Additional sound and vibration control can be achieved with HVAC equipment supported independent of wall structure
Short return plenum ("sleeve")
Air handler filter
Full height louvered closet door for access, and for a return air pathway to the air handler and dehumidifier
Condensate overflow pan





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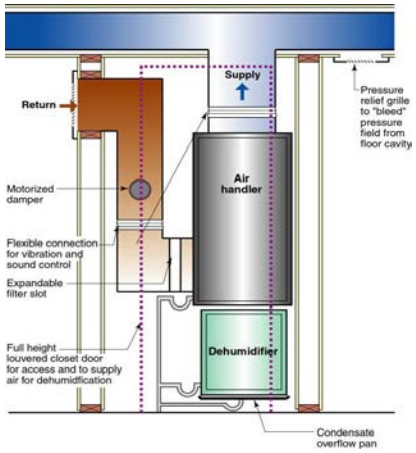

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Joseph Lstiburek – HVAC 23

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Joseph Lstiburek – HVAC 24

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Joseph Lstiburek – HVAC 25

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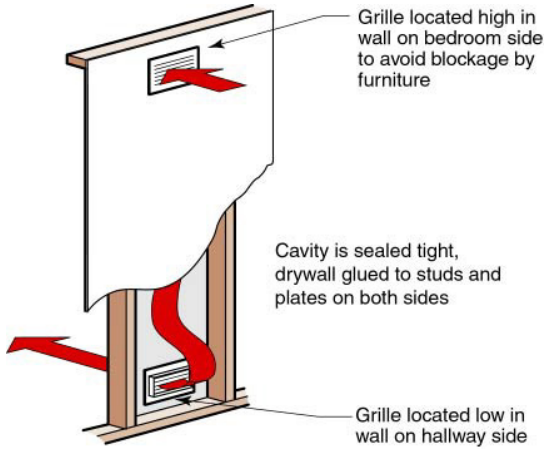

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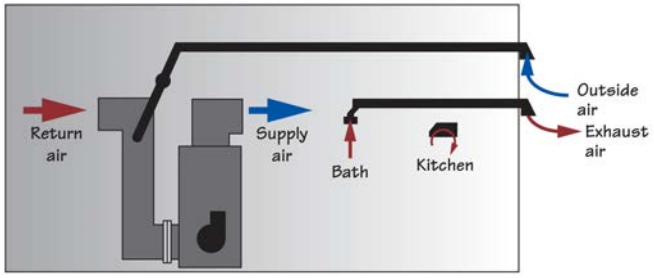

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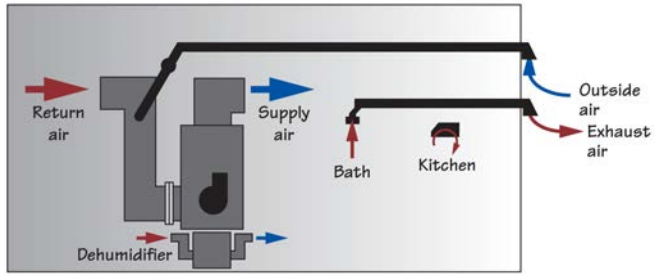

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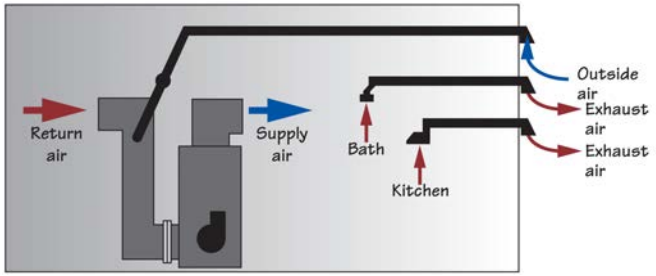
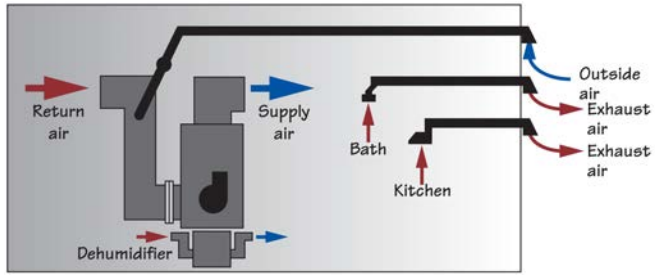
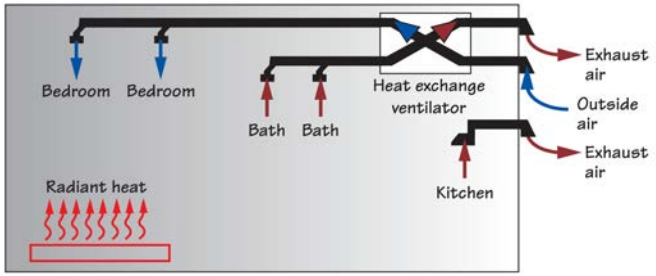


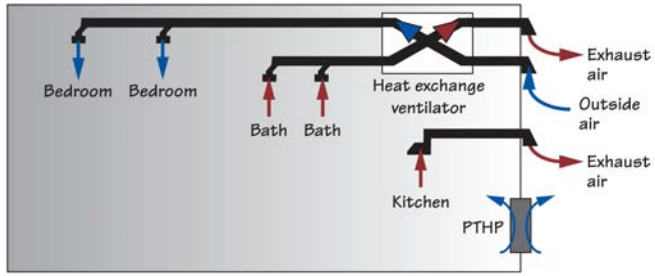
Building Science Corporation Joseph Lstiburek 30



Building Science Corporation Joseph Lstiburek 31



Building Science Corporation Joseph Lstiburek 32



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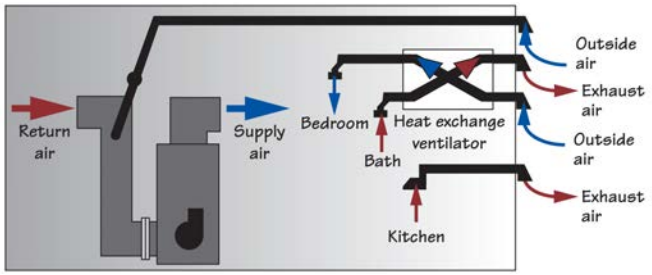

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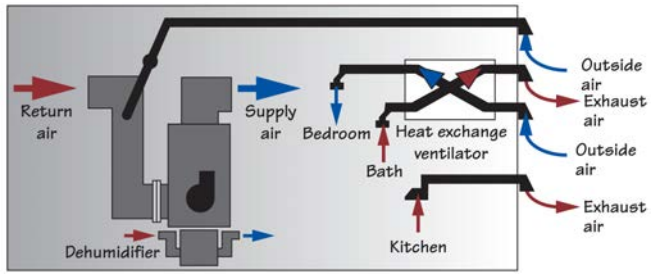
Joseph Lstiburek 34



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Joseph Lstiburek 36

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Joseph Lstiburek 37

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Joseph Lstiburek 38

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Joseph Lstiburek 39

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Joseph Lstiburek 40

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Joseph Lstiburek 41

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Joseph Lstiburek 42

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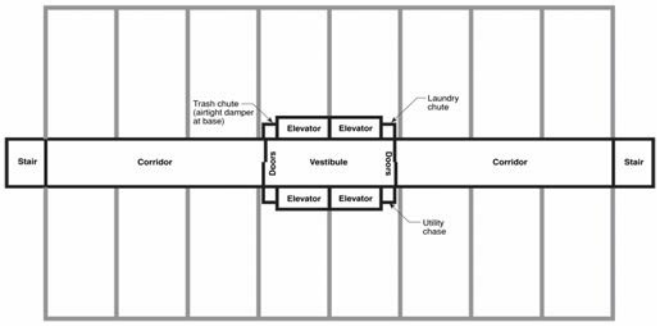
Joseph Lstiburek – HVAC 43



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Joseph Lstiburek – HVAC 44

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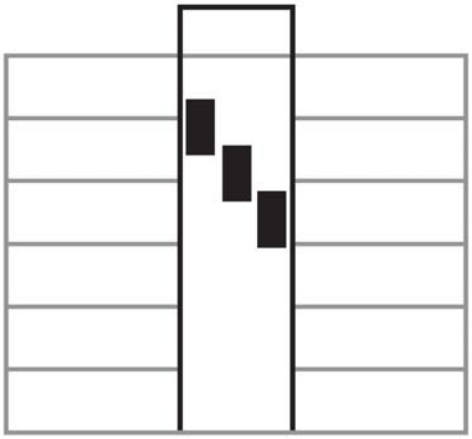
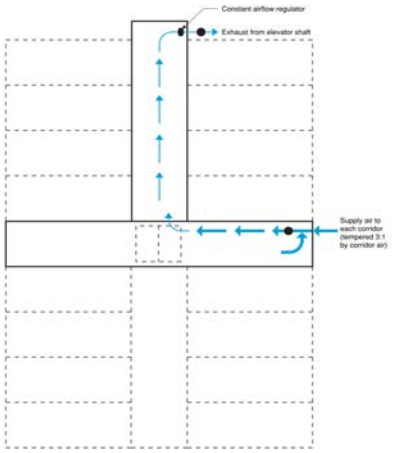
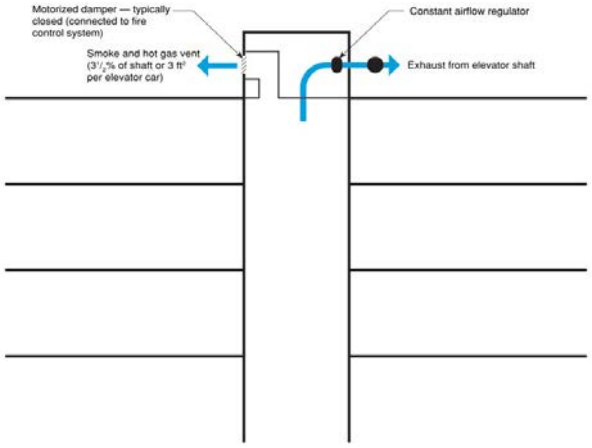
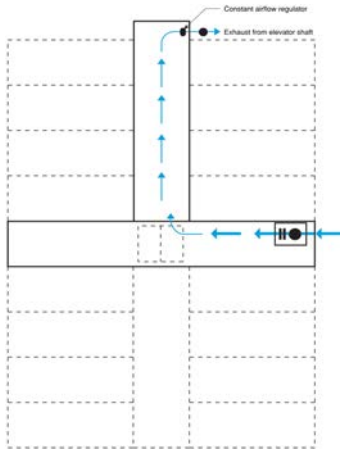
Joseph Lstiburek – HVAC 45




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)
Smoke and hot gas vent (3½% of shaft or 3 ft² per elevator car)
Constant airflow regulator
Exhaust from elevator shaft



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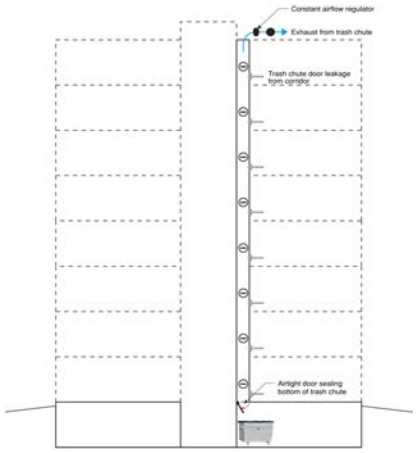
Joseph Lstiburek – HVAC 50



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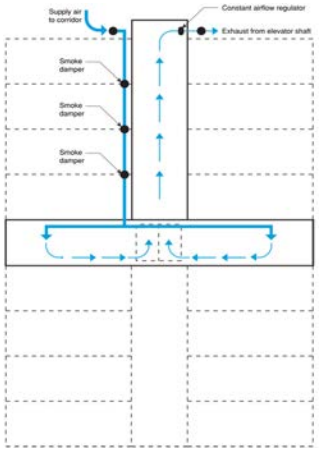
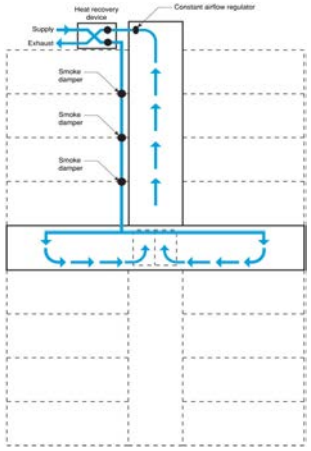
Joseph Lstiburek – HVAC 51

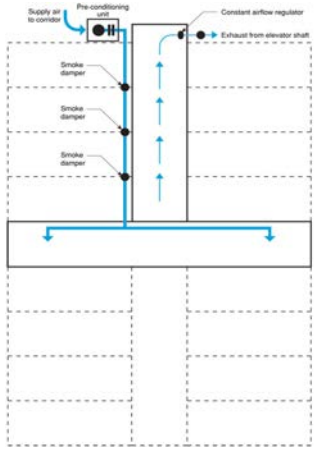
Building Science Corporation
Joseph Lstiburek 52



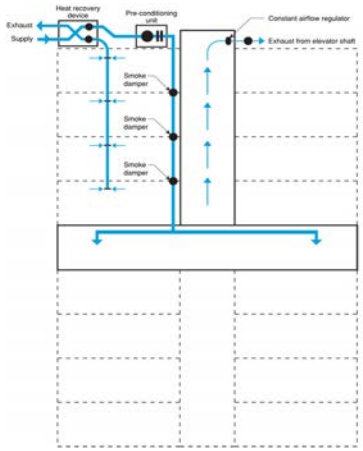
Building Science Corporation
Joseph Lstiburek – HVAC 53



Building Science Corporation
Joseph Lstiburek – HVAC 54



Building Science Corporation
Joseph Lstiburek – HVAC 55



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Joseph Lstiburek – HVAC 56

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Joseph Lstiburek – HVAC 57

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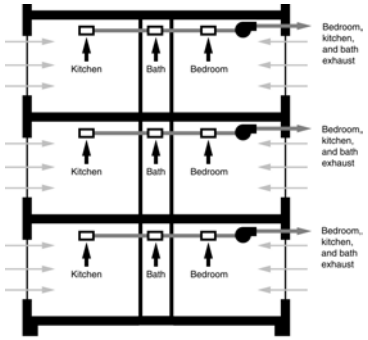


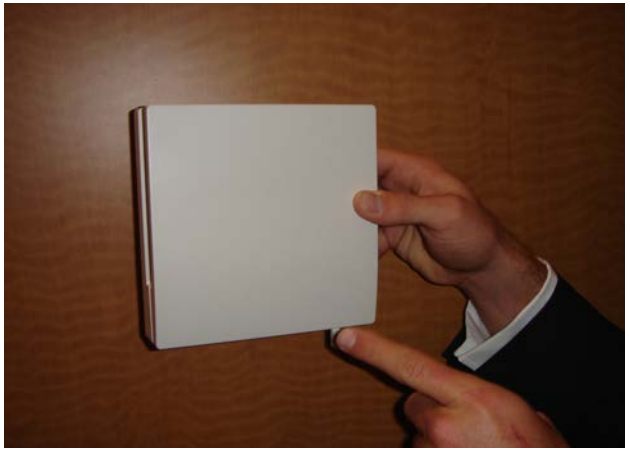
Distributed Ventilation

- 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

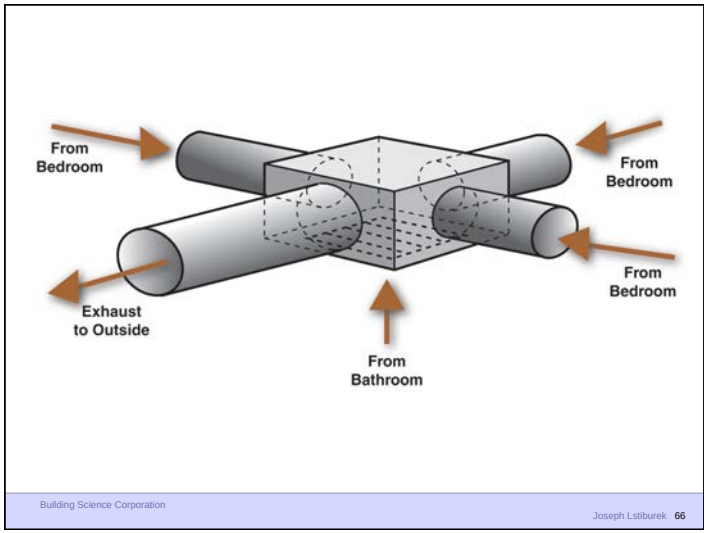
Building Science Corporation Joseph Lstiburek 62

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
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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

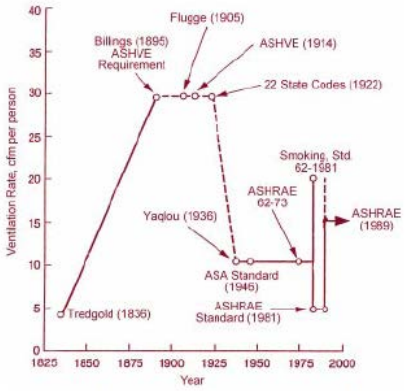

Figure 1: Minimum ventilating rate history.

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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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Joseph Lstiburek 7

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

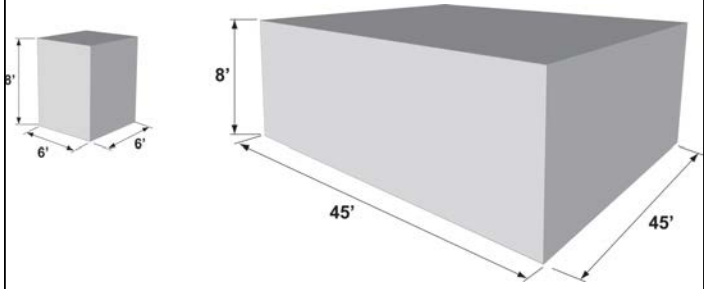
300 ft^3 → 12 cfm/person 37.5 ft^2 53 occupants

Experiment

470 ft^3 → 59 ft^2

200 ft^3 → 25 ft^2

100 ft^3 → 12 ft^2



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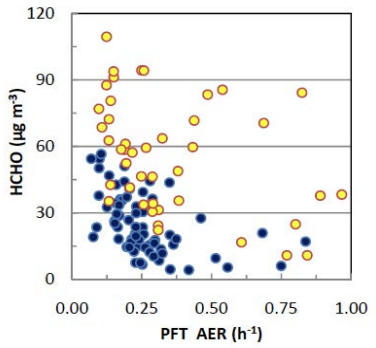

Aubin, D., Won, D.Y., Schleibinger, H., 2010

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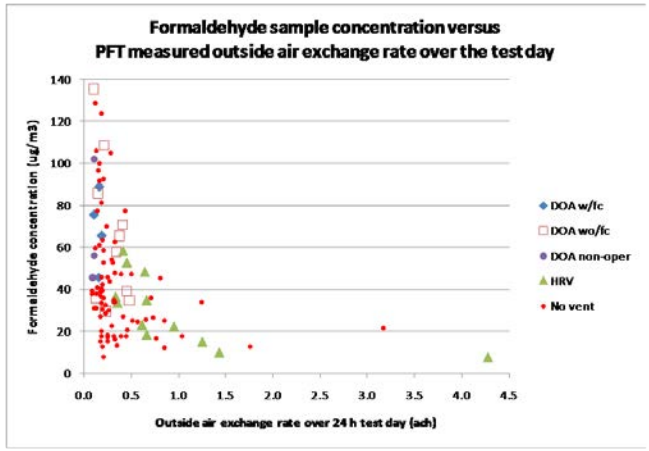


Dilution is Not The Solution To Indoor Pollution

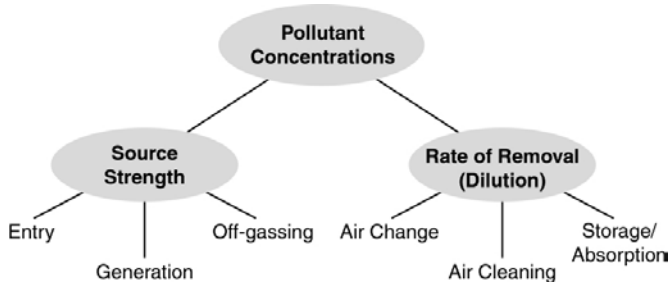


Table 1. Summary of the air changes rates measured during the winter 2009-10 season in Quebec City

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

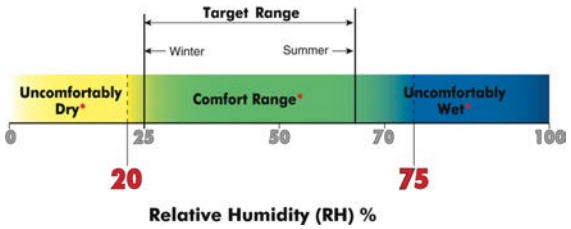
ASHRAE Standard 62.2 calls for 7.5 cfm per person plus 0.03 cfm per square foot of conditioned area

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

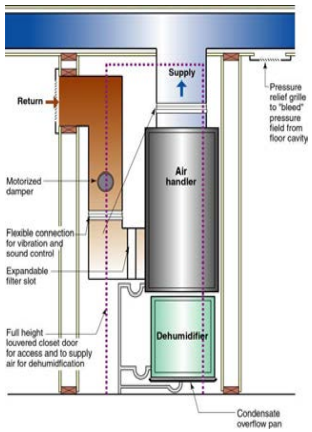
Outcome is often bad – part load humidity problems, dryness problems, energy problems



Recommended Range of Relative Humidity

Above 25 percent during winter

Below 70 percent during summer



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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

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- 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

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Floor Plan - 2 Story House

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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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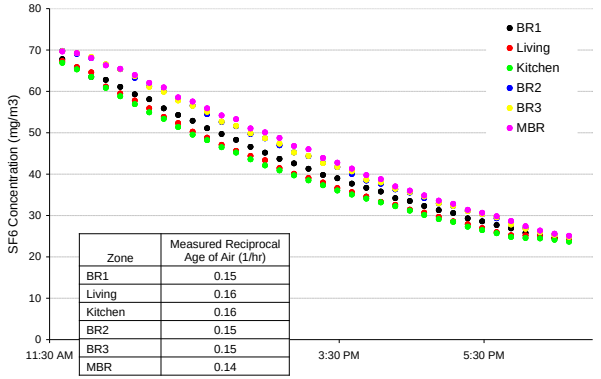
Example Results of Tracer Gas Testing

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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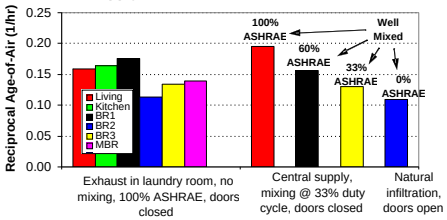
Conclusions From Tracer Gas Testing

- 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

Simple Exhaust vs Central Fan Integrated Supply with Lower Ventilation Rates



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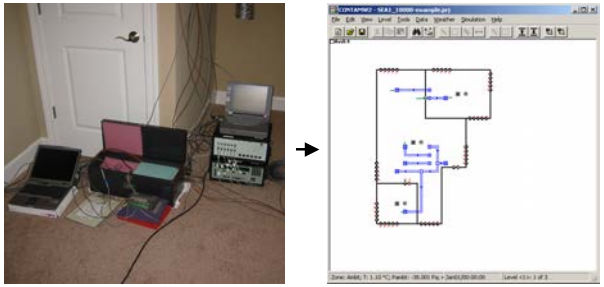
Tuned CONTAM Model



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

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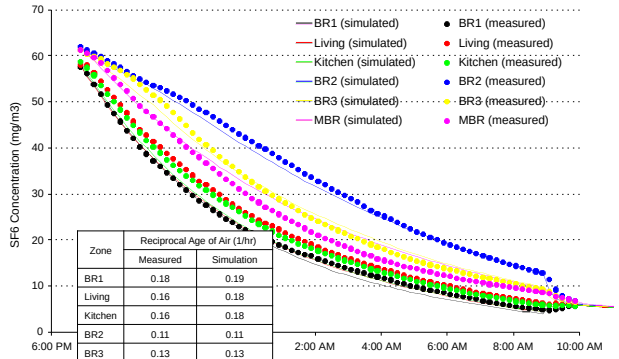
Example Results of Tuned CONTAM Model

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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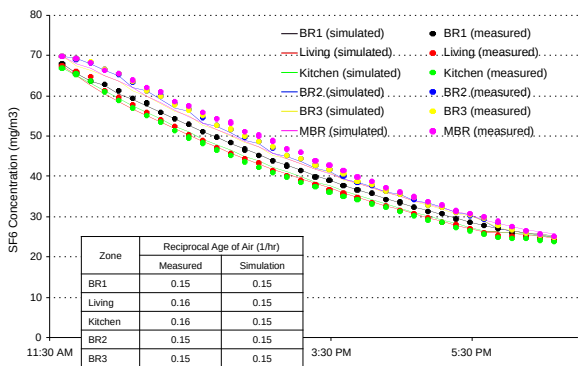
Example Results of Tuned CONTAM Model

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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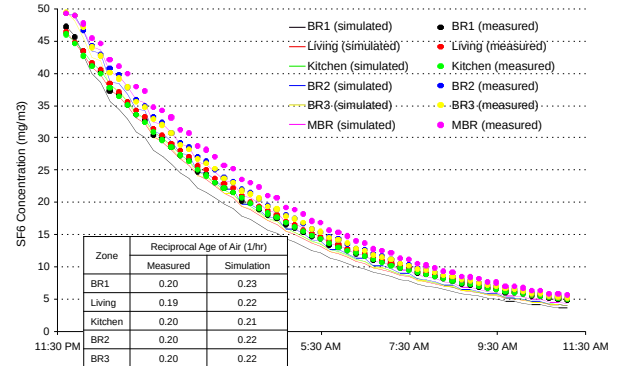
Example Results of Tuned CONTAM Model

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