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

Building Science

Adventures In Building Science

www.buildingscience.com

What is a Building?

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A Building is an Environmental Separator

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

Damage Functions

Damage Functions
Water
Heat
Ultra Violet Radiation

The Three Biggest Problems In Buildings Are Water, Water and Water…

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80 Percent of all Construction Problems are Related to Water

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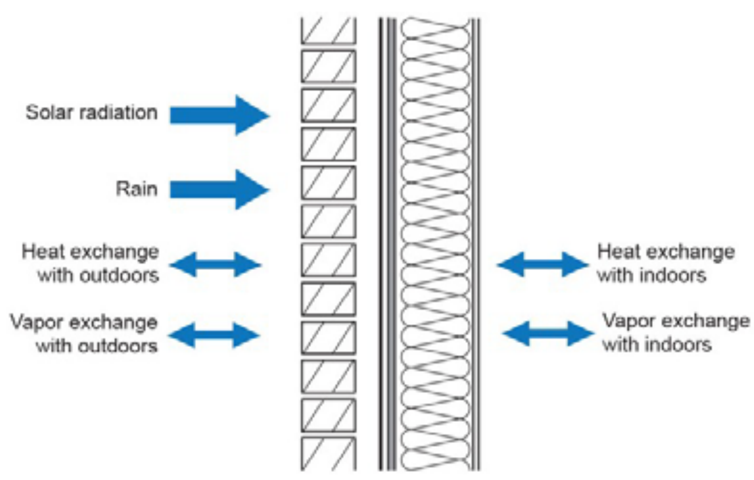
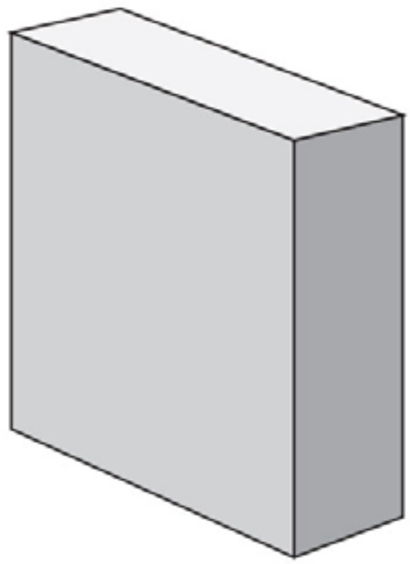
Heat
Air
Moisture

HAM

Hygrothermal Analysis





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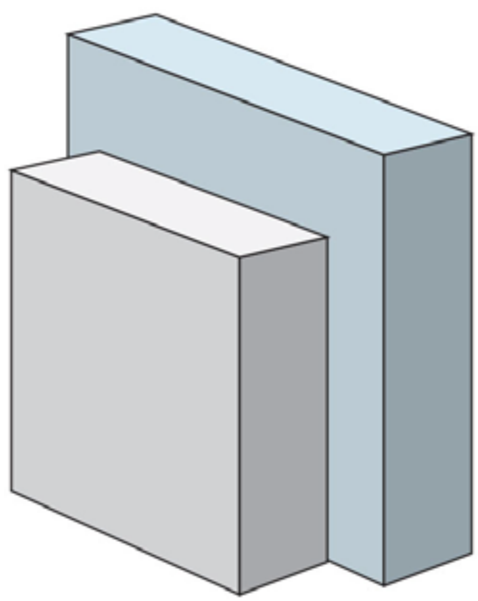

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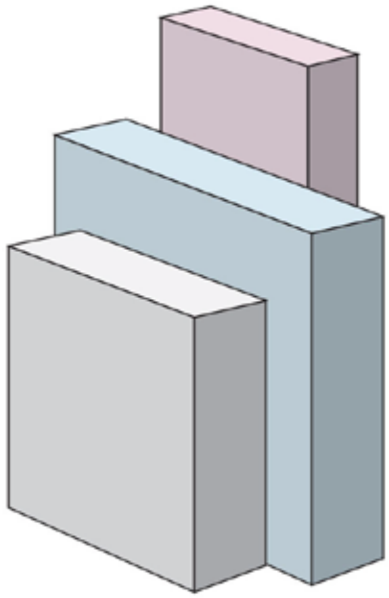
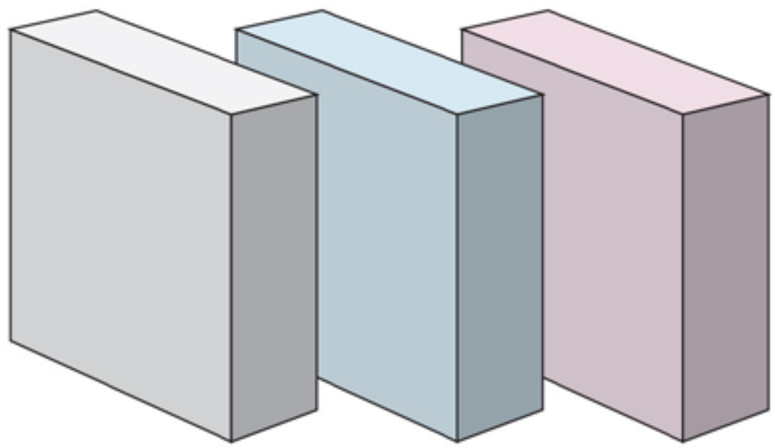


Rain and Airflow Missing



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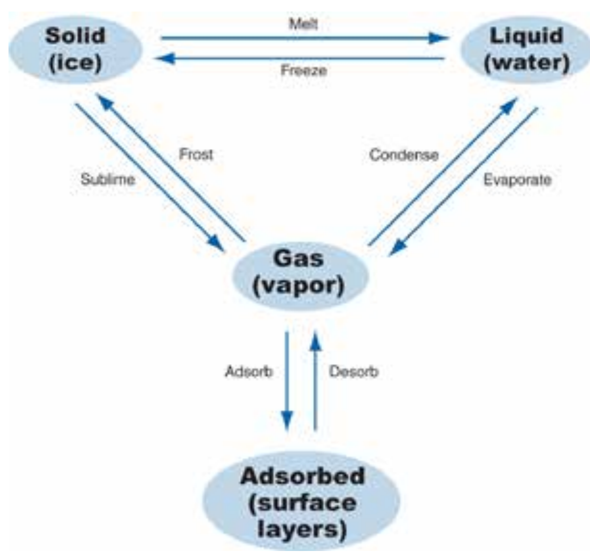

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Moisture Transport in Porous Media

Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration

Recall That Rain and Airflow Are Missing

Moisture Transport in Assemblies

Phase	Transport Process	Driving Potential
Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration
	Gravitational Flow	Height
	Surface Tension	Surface Energy
	Momentum	Kinetic Energy
	Convective Flow	Air Pressure

Laws of Thermodynamics

Zeroth Law – Equal Systems
First Law - Conservation of Energy
Second Law - Entropy
Third Law – Absolute Zero

2nd Law of Thermodynamics

In an isolated system, a process can occur only if it increases the total entropy of the system

Rudolf Clausius

Heat Flow Is From Warm To Cold

Moisture Flow Is From Warm To Cold

Moisture Flow Is From More To Less

Air Flow Is From A Higher Pressure to a Lower Pressure

Gravity Acts Down

Moisture Flow Is From Warm To Cold
Moisture Flow Is From More To Less

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Moisture Flow Is From Warm To Cold
Moisture Flow Is From More To Less

Thermal Gradient – Thermal Diffusion
Concentration Gradient – Molecular Diffusion

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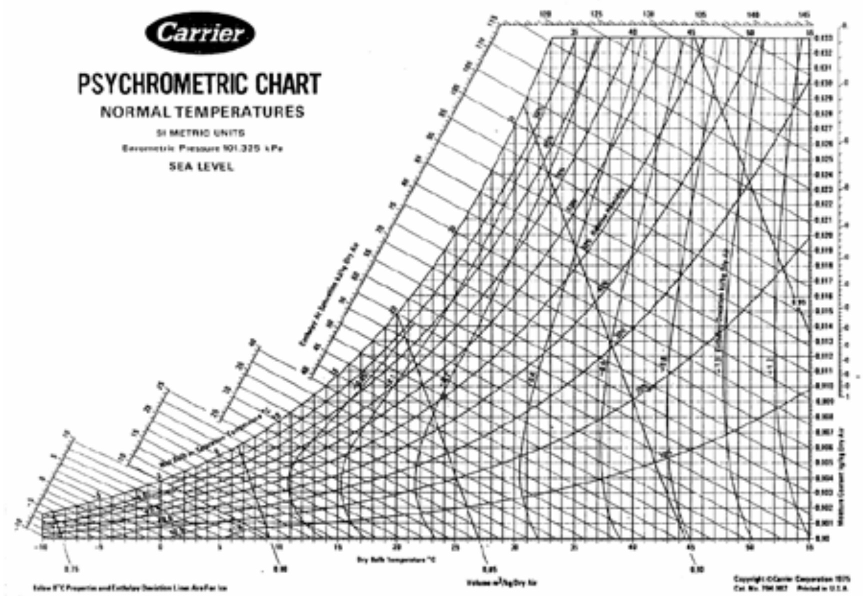
Moisture Flow Is From Warm To Cold
Moisture Flow Is From More To Less

Thermal Gradient – Thermal Diffusion
Concentration Gradient – Molecular Diffusion

Vapor Diffusion

Thermodynamic Potential



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Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure

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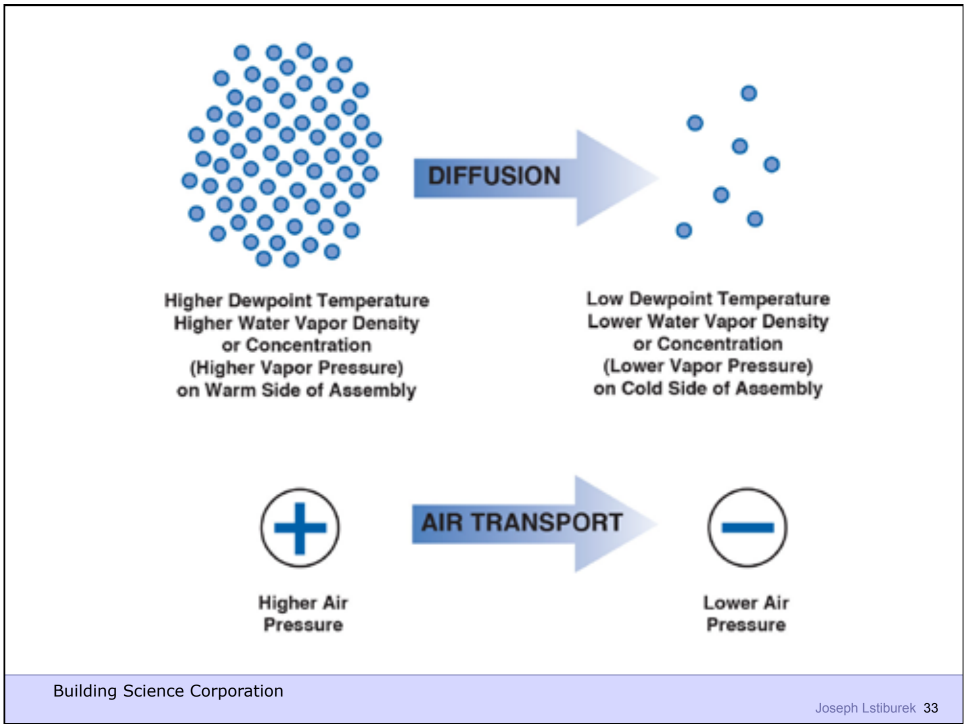

DIFFUSION
Higher Dewpoint Temperature
Higher Water Vapor Density
or Concentration
(Higher Vapor Pressure)
on Warm Side of Assembly
Low Dewpoint Temperature
Lower Water Vapor Density
or Concentration
(Lower Vapor Pressure)
on Cold Side of Assembly
AIR TRANSPORT
Higher Air
Pressure
Lower Air
Pressure
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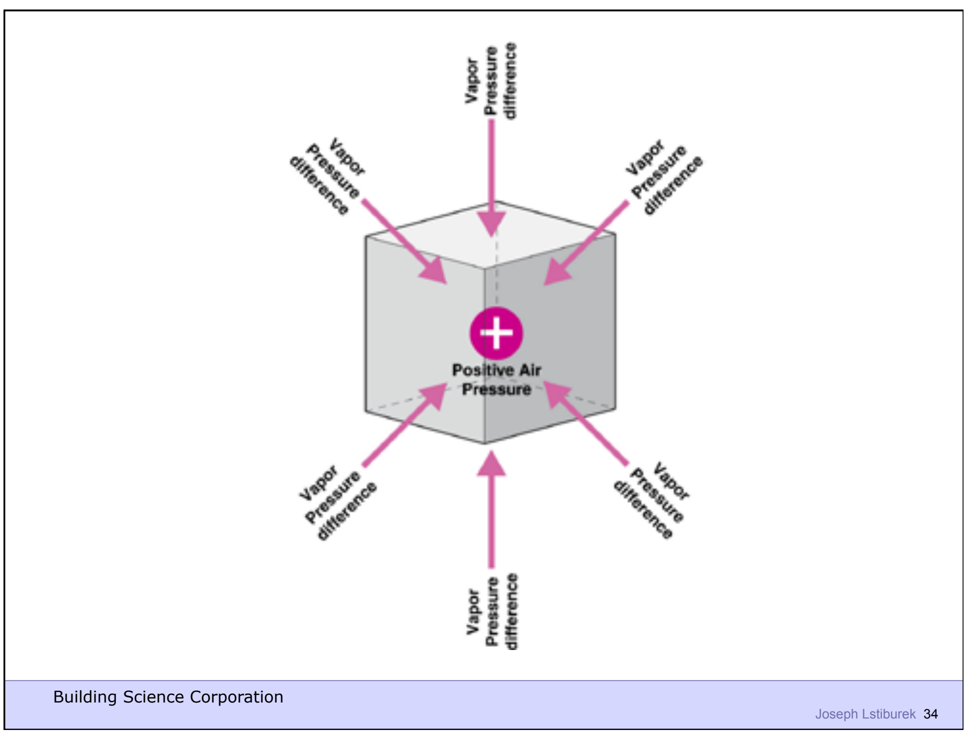

Vapor Pressure difference
Vapor Pressure difference
Vapor Pressure difference
Positive Air Pressure
Vapor Pressure difference
Vapor Pressure difference
Vapor Pressure difference
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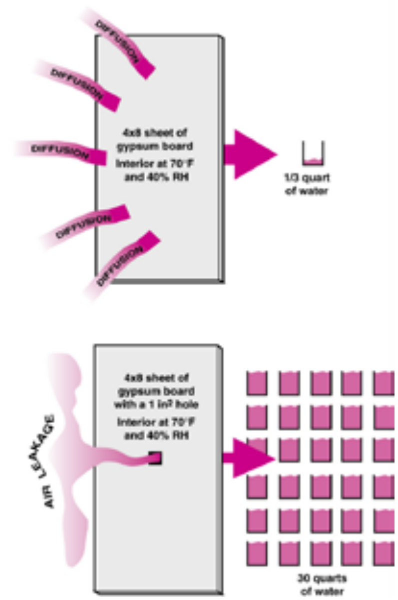

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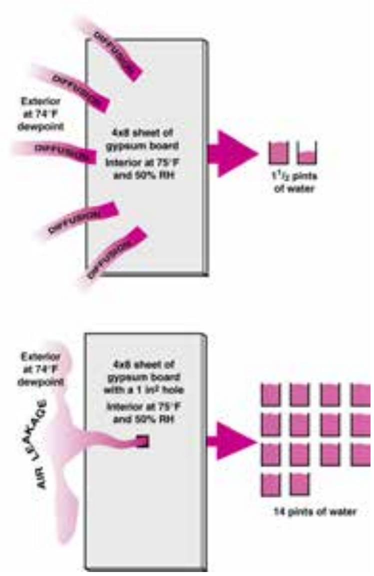

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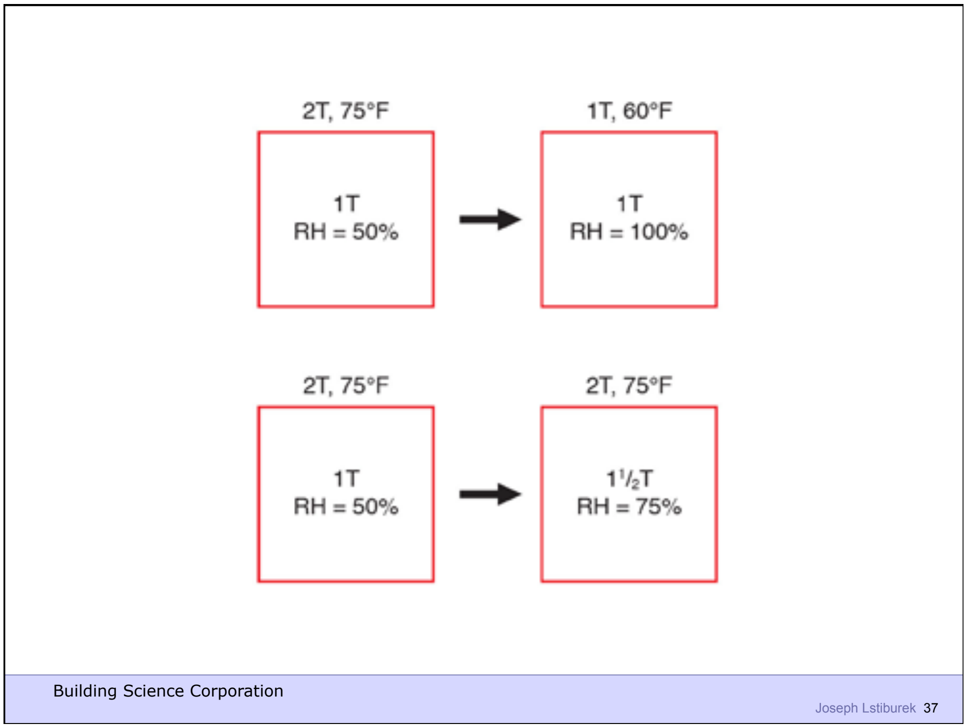
2T, 75°F
1T
RH = 50%
1T, 60°F
1T
RH = 100%
2T, 75°F
1T
RH = 50%
2T, 75°F
1½T
RH = 75%
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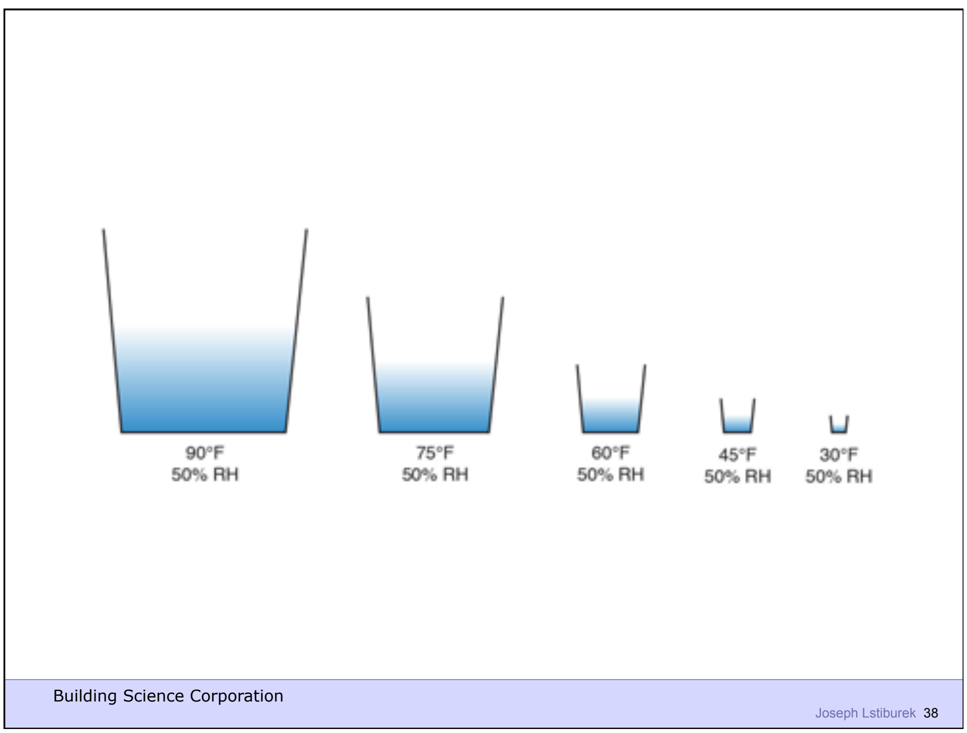
90°F
50% RH
75°F
50% RH
60°F
50% RH
45°F
50% RH
30°F
50% RH
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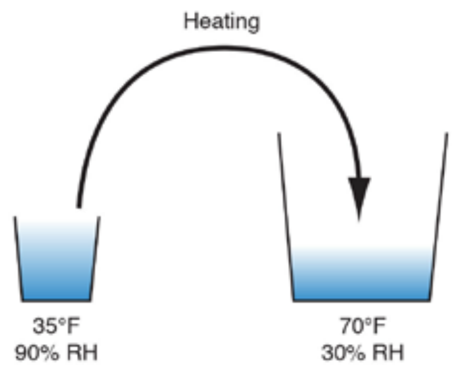

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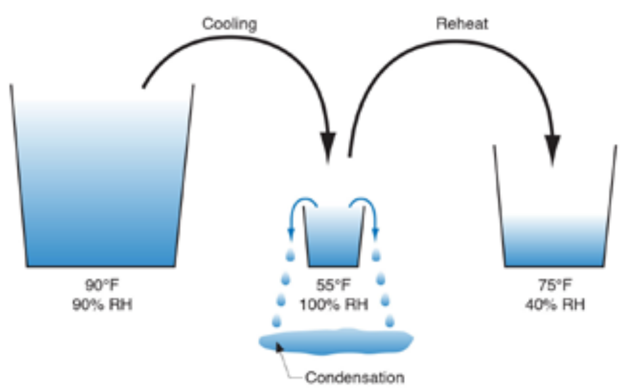

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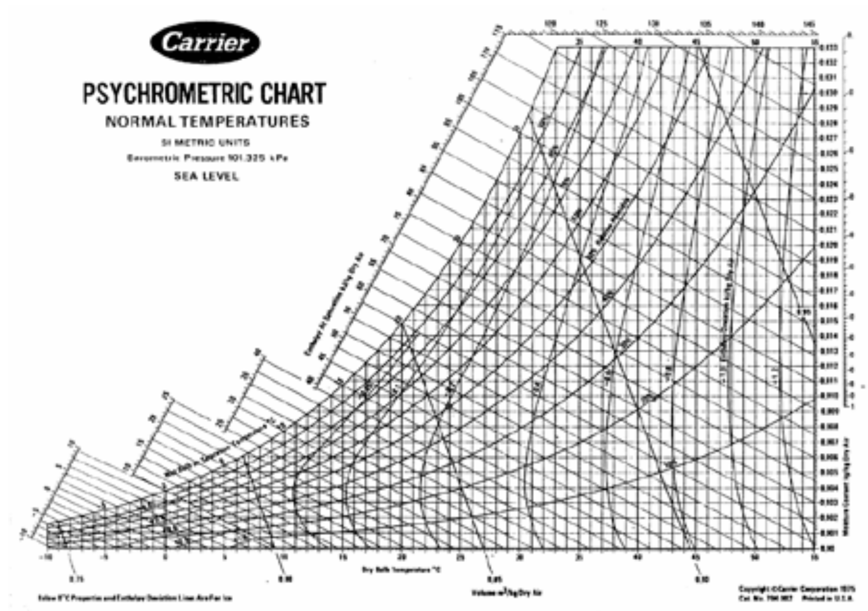

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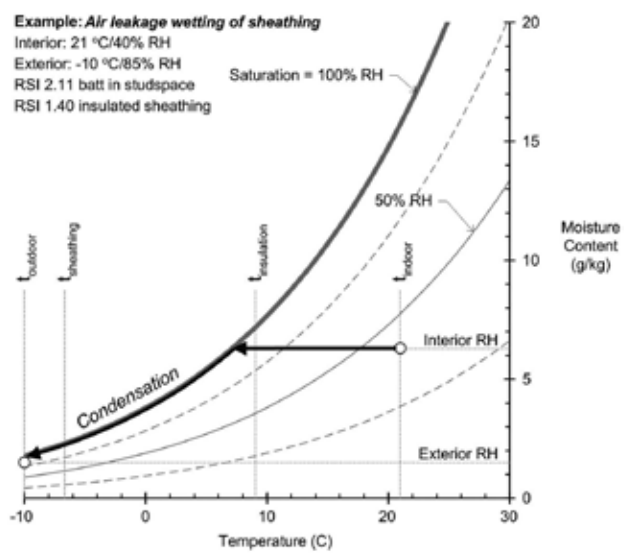

Cooling and condensation

From Straube & Burnett, 2005

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Water Molecules

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Size Matters

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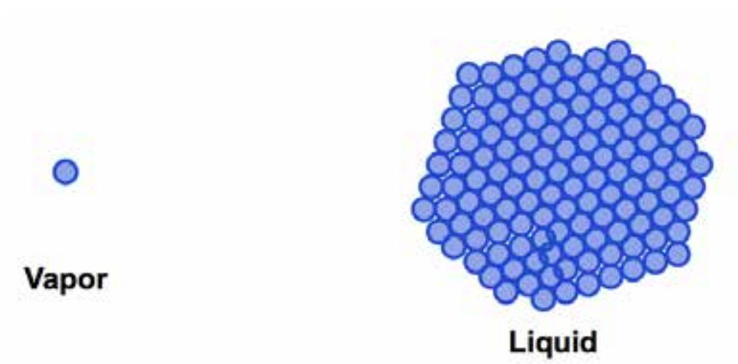

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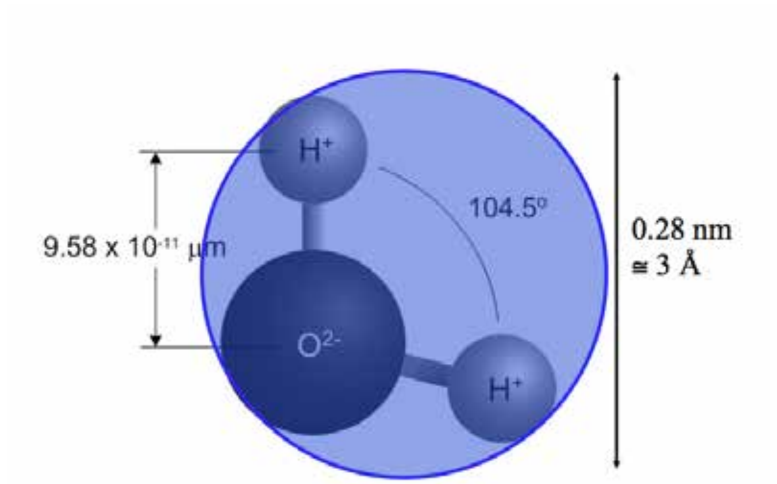

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Polar Molecule

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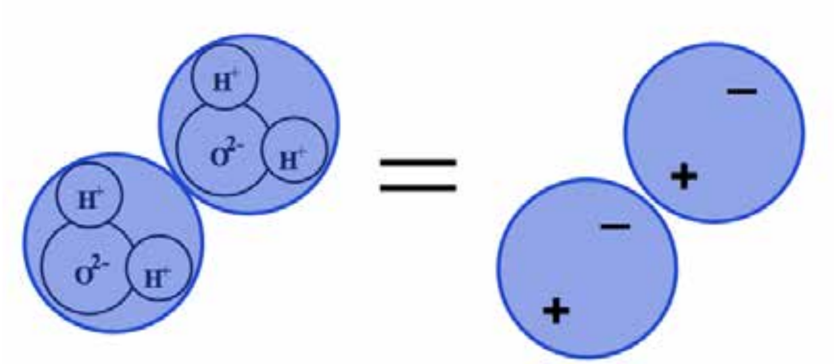

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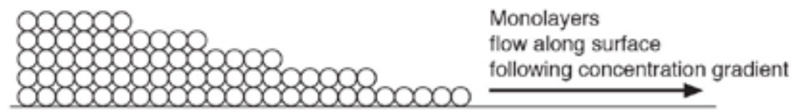
Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration



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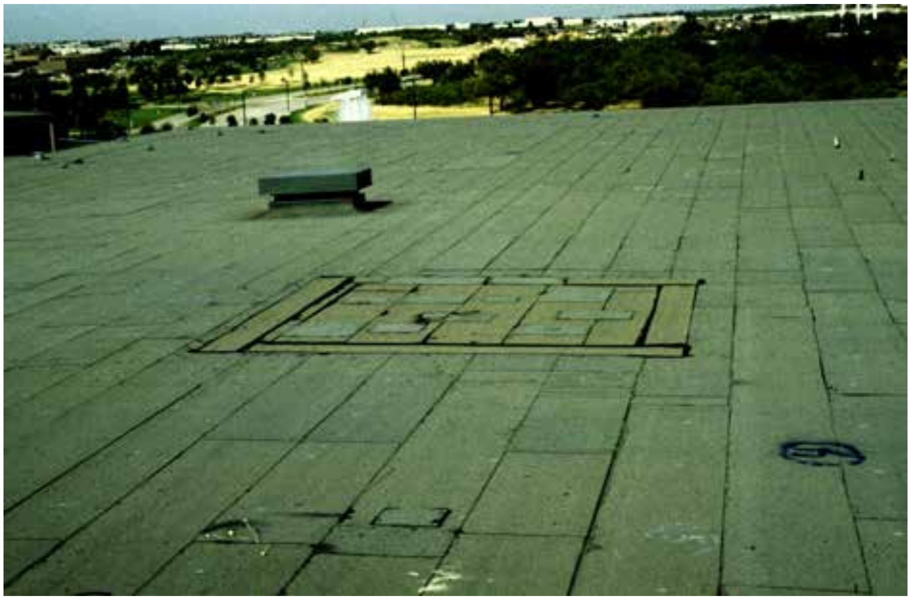

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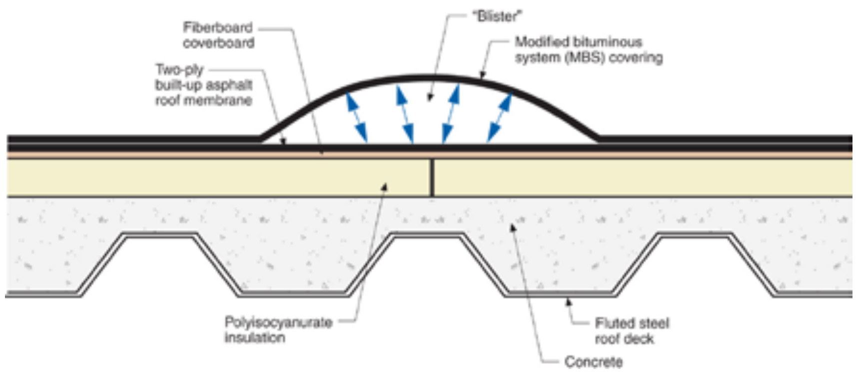

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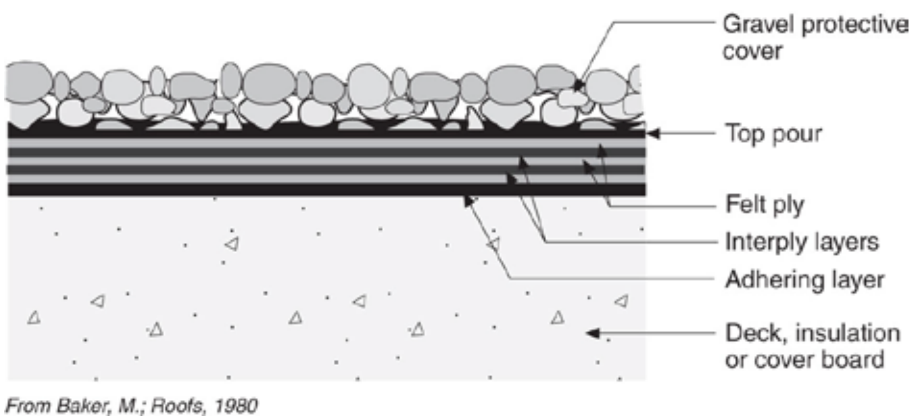

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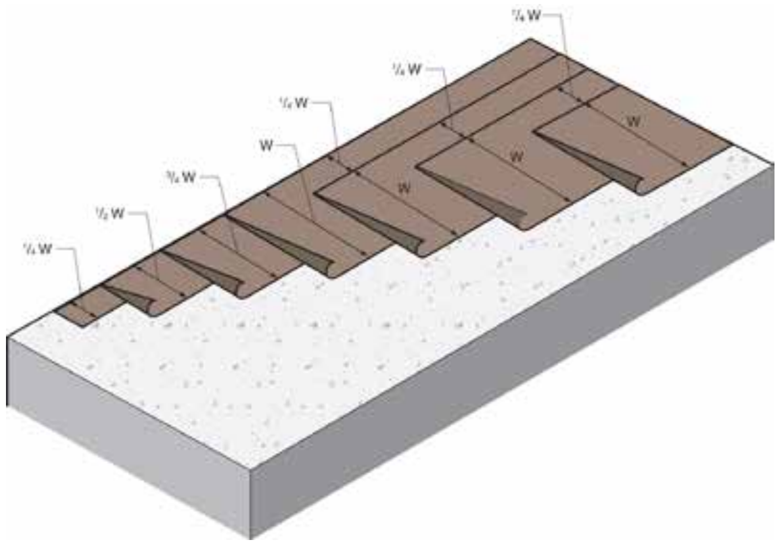

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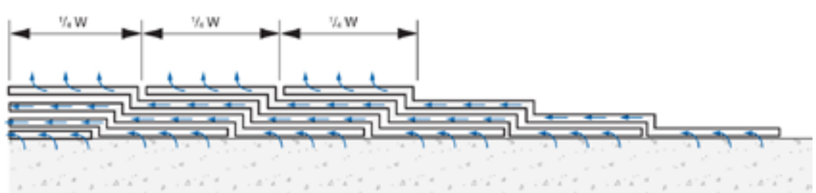

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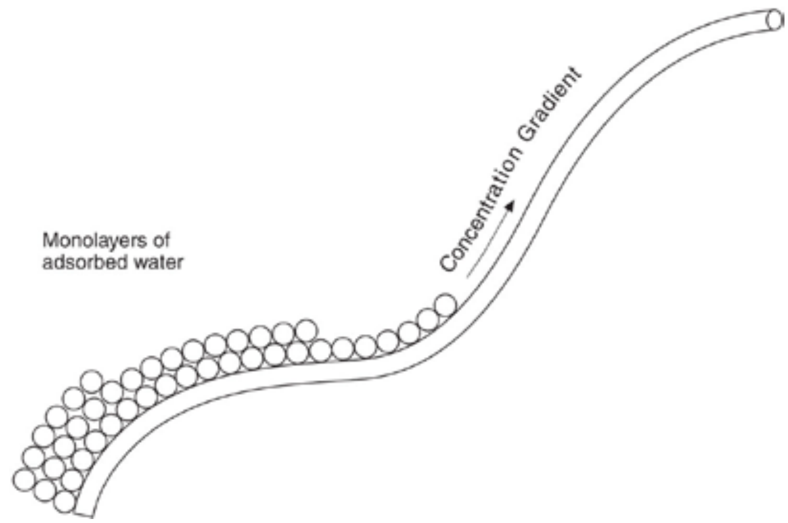

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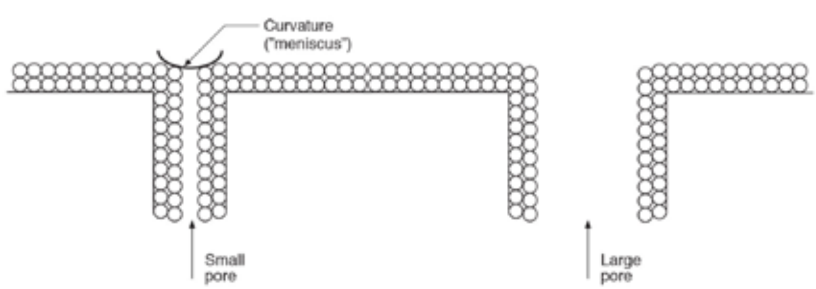

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Vapor	Diffusion Convective Flow	Vapor Concentration Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure

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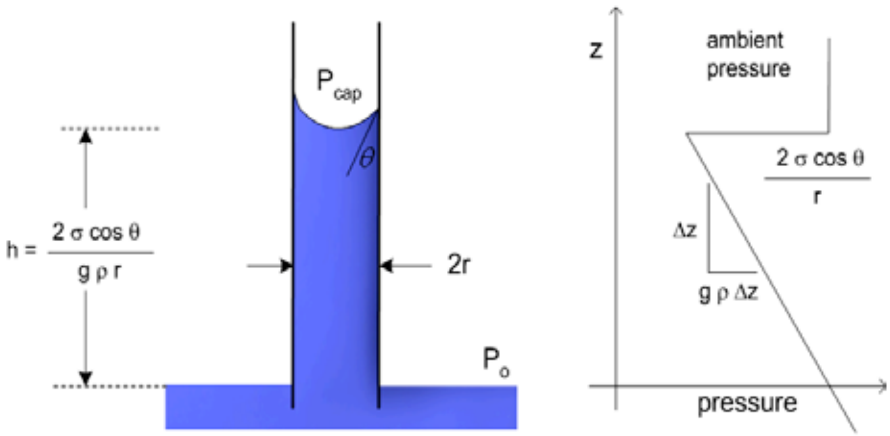
Calculating capillary rise



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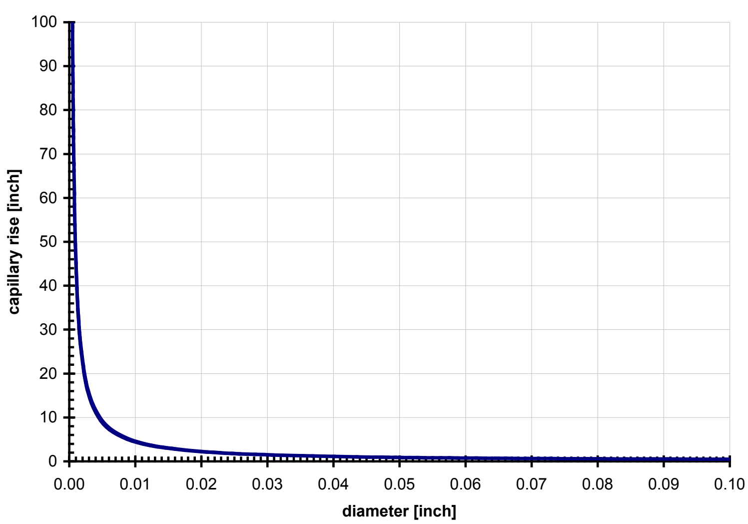
Capillary rise versus diameter



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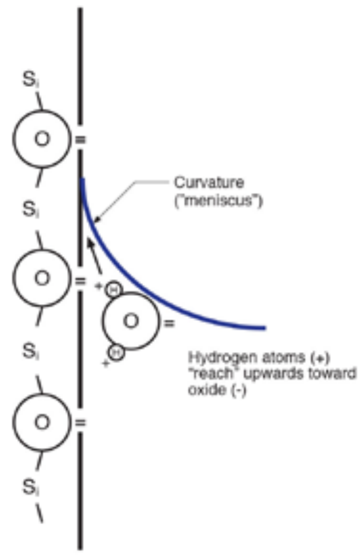

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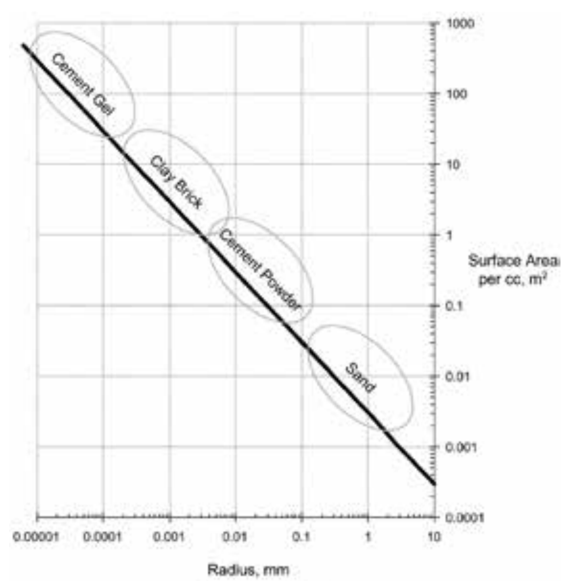

Surface area vs. particle size
From Straube & Burnett, 2005

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

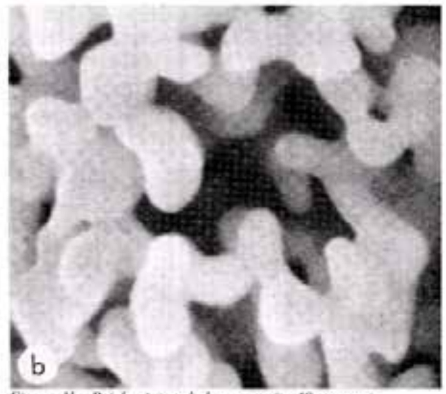

Figure 1b. Brick, sintered clay, porosity 40 per cent.

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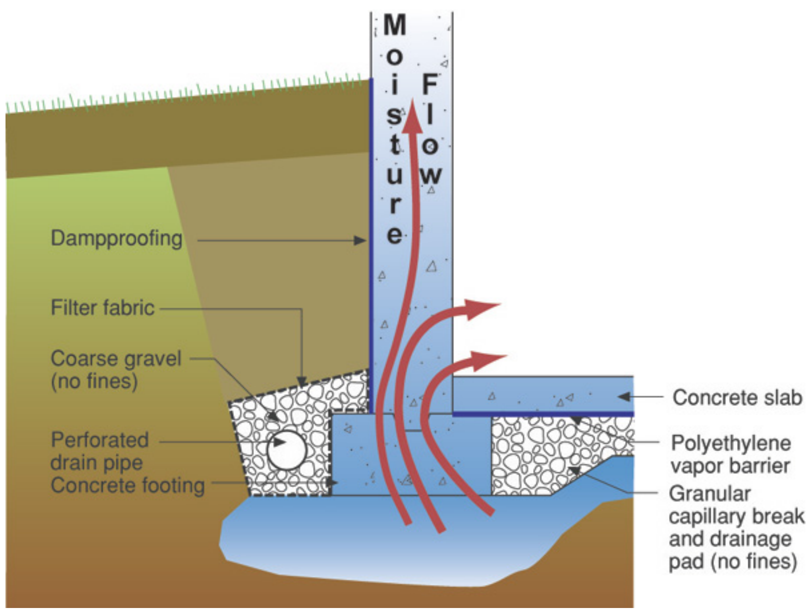

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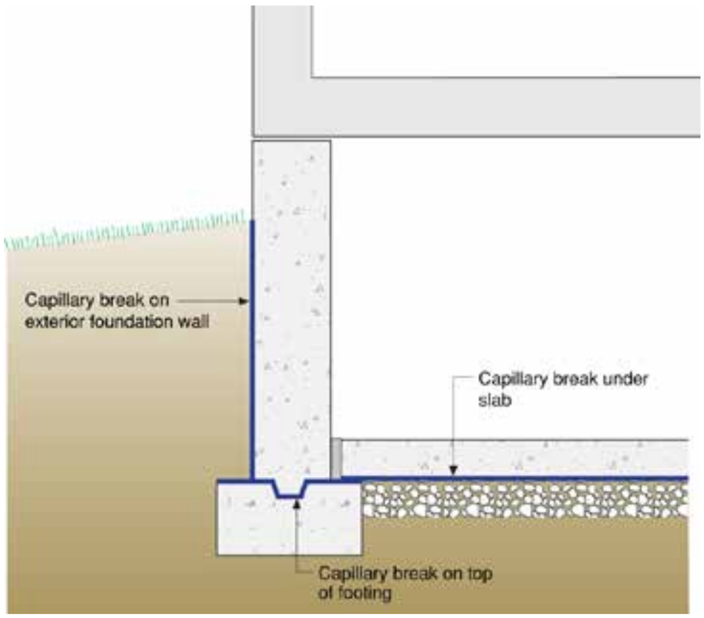

Vapor	Diffusion Convective Flow	Vapor Concentration Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow Osmosis	Suction Pressure Solute Concentration

Capillarity + Salt = Osmosis

- Mineral salts carried in solution by capillary water
- When water evaporates from a surface the salts left behind form crystals in process called efflorescence
- When water evaporated beneath a surface the salts crystallize within the pore structure of the material in called sub-efflorescence
- The salt crystallization causes expansive forces that can exceed the cohesive strength of the material leading to spalling

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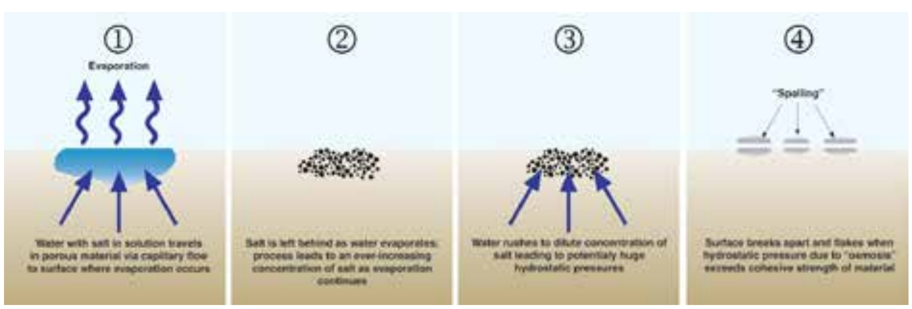

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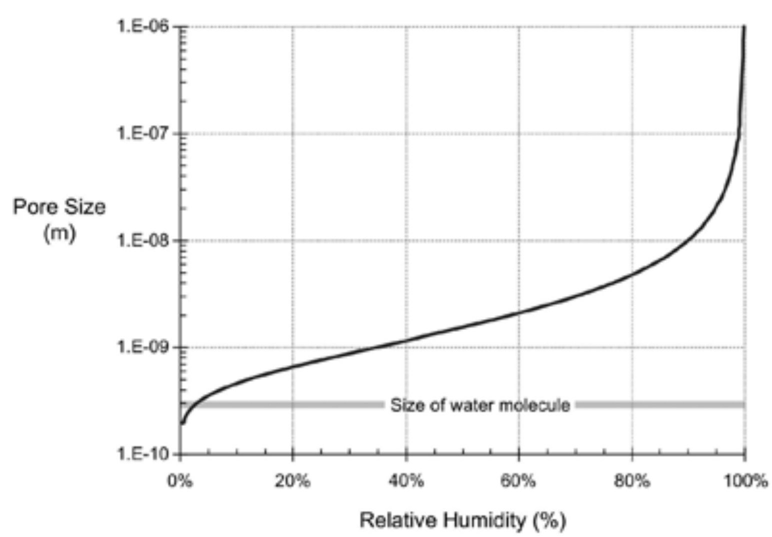
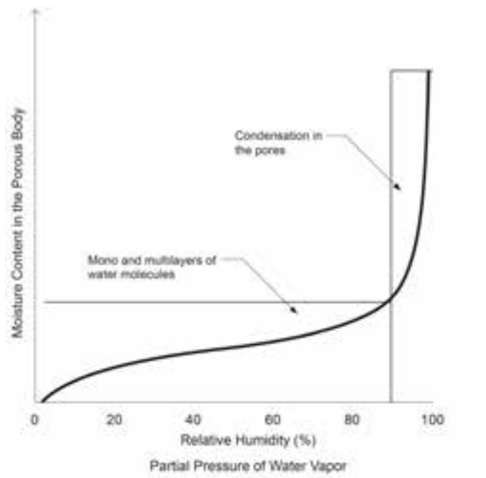
Pressures

• Diffusion Vapor Pressure	3 to 5 psi
• Capillary Pressure	300 to 500 psi
• Osmosis Pressure	3,000 to 5,000 psi

Combined Flows



Ambient relative humidity at which capillary condensation is predicted to occur by the Kelvin equation
From Straube & Burnett, 2005



Change in the storage of moisture in a porous building material as the partial pressure of water vapor in the ambient air increases from zero to full saturation value at a given temperature.

Sorption Curve
From M.K. Kumaran, ASTM MNL 18-2nd Edition, Moisture Control in Buildings, 2009

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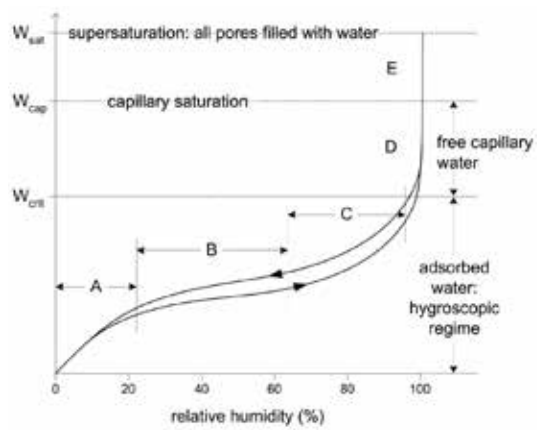

A: Single-layer of adsorbed molecules
B: Multiple layers of adsorbed molecules
C: Interconnected layers (internal capillary condensation
D: Free water in Pores, capillary suction
E: Supersaturated Regime

Regimes of moisture storage in a hygroscopic porous material
From Straube & Burnett, 2005

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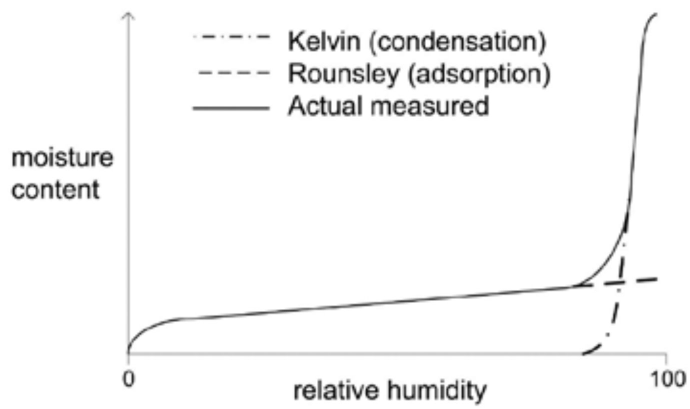

Typical predicted sorption isotherm according to Kelvin equation and modified BET theory

From Straube & Burnett, 2005

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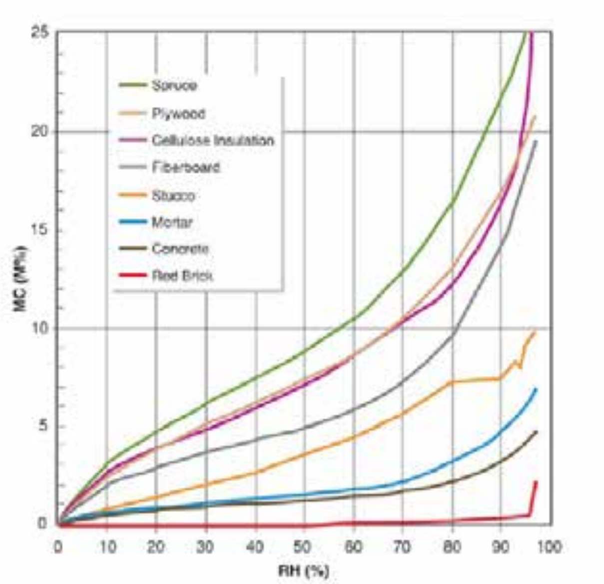

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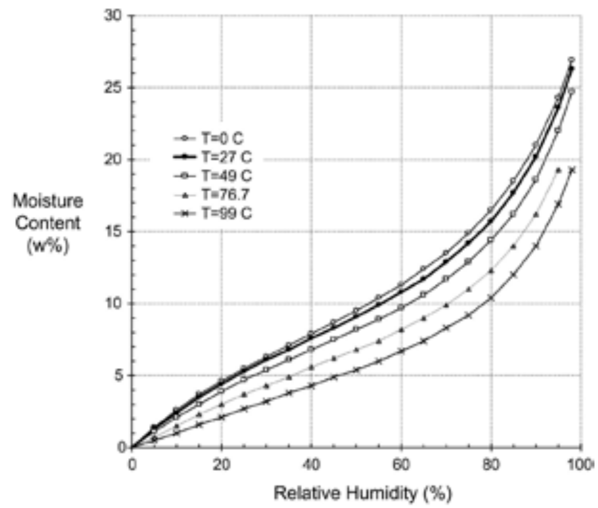

Average sorption isotherm for wood as a function of temperature
From Straube & Burnett, 2005

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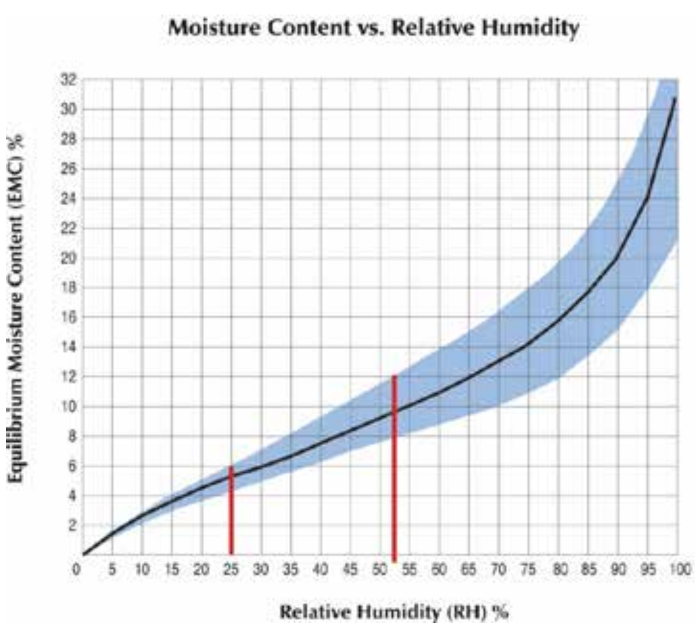

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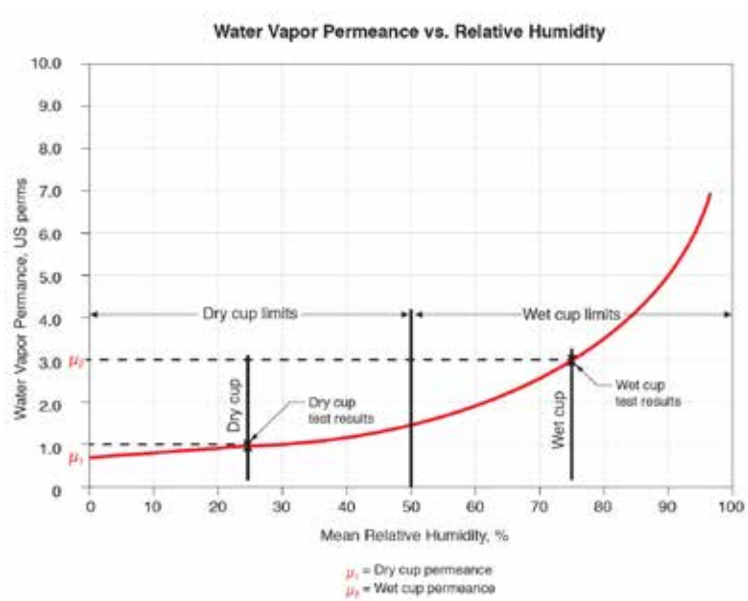

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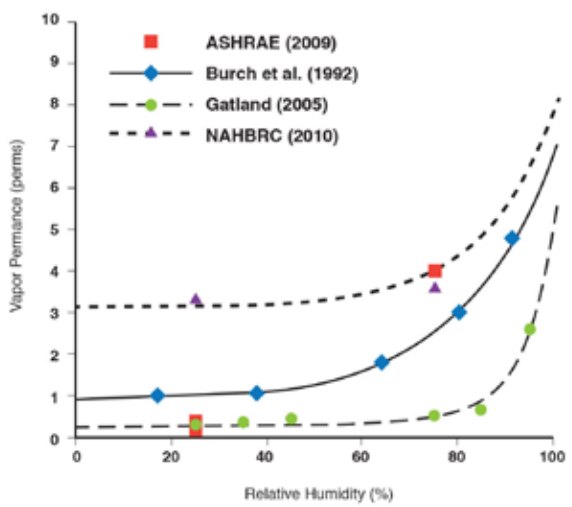

Kraft facing permeance as a function of humidity (Glass 2013)

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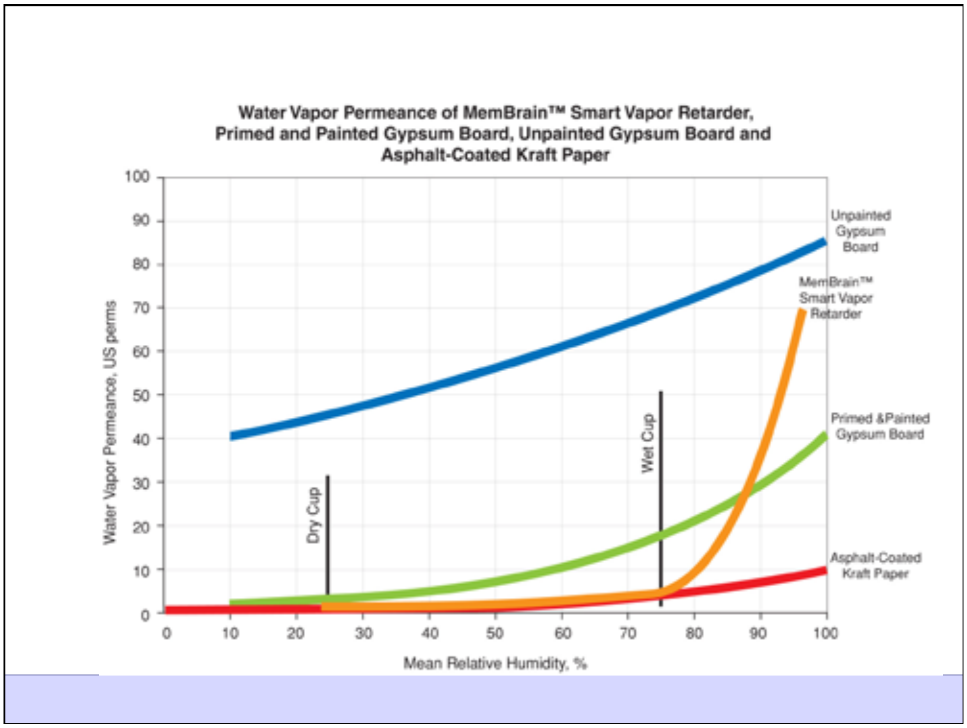
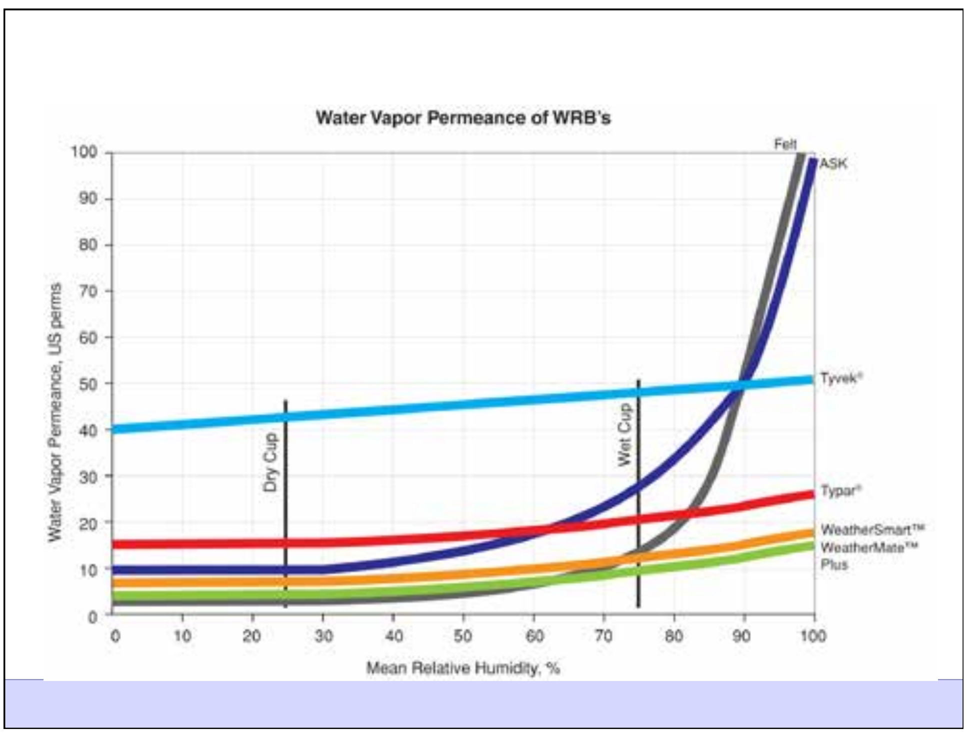
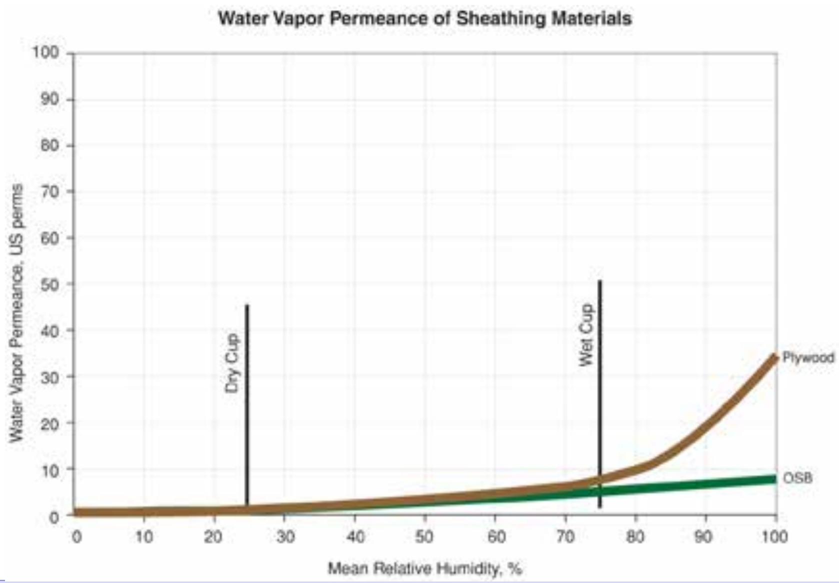
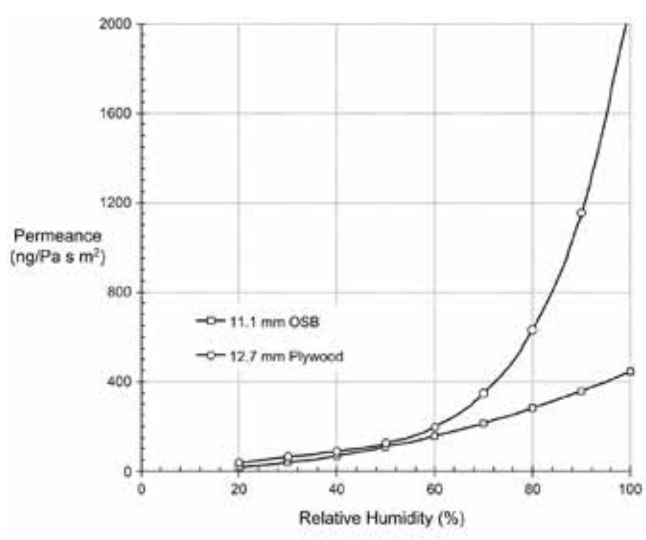

Water Vapor Permeance of MemBrain™ Smart Vapor Retarder, Primed and Painted Gypsum Board, Unpainted Gypsum Board and Asphalt-Coated Kraft Paper
Water Vapor Permeance, US perms
Mean Relative Humidity, %
Dry Cup
Wet Cup
Unpainted Gypsum Board
MemBrain™ Smart Vapor Retarder
Primed &Painted Gypsum Board
Asphalt-Coated Kraft Paper


Water Vapor Permeance of WRB's
Water Vapor Permeance, US perms
Mean Relative Humidity, %
Dry Cup
Wet Cup
Felt
ASK
Tyvek®
Typar®
WeatherSmart™
WeatherMate™ Plus





Vapor permeability test results for wood-based products as a function of RH
[Kumaran *et al* 2002]
From Straube & Burnett, 2005

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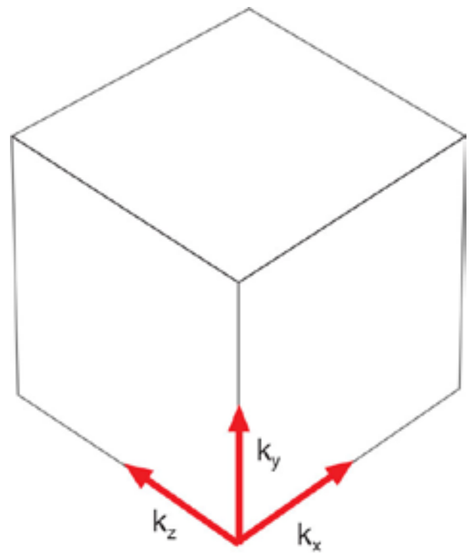

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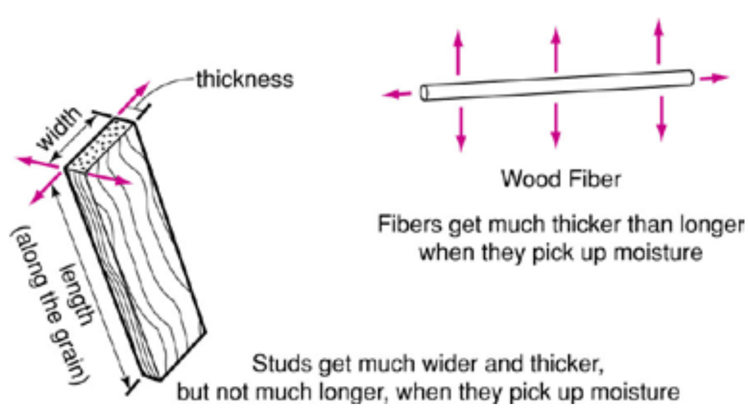

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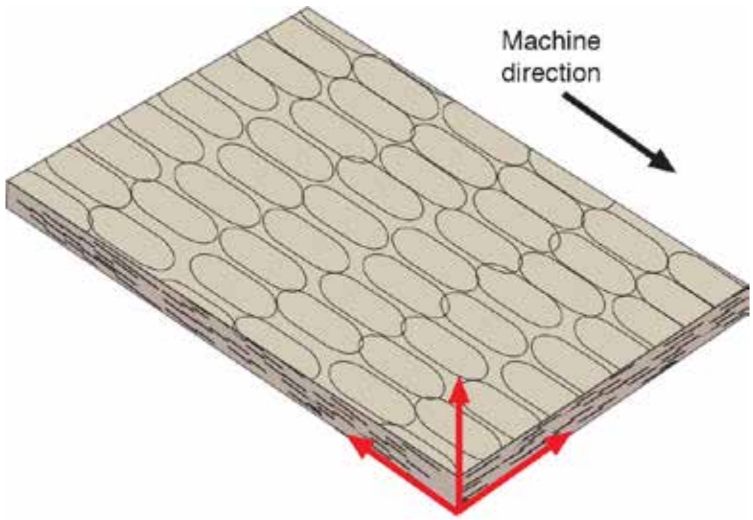

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Still More Combined Flows

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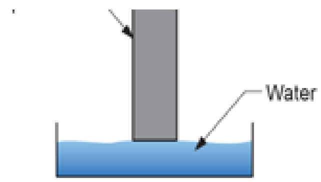

Schematic drawing of the transient moisture transport process that is used to determine the liquid diffusivity of porous building materials. All four longitudinal surfaces of the test specimen are coated with water vapor resistant epoxy resin and one of the open-end surfaces is in contact with water while the other is open to the ambient air.

Determining Liquid Diffusivity of Porous Building Materials

From M.K. Kumaran, ASTM MNL 18-2nd Edition,

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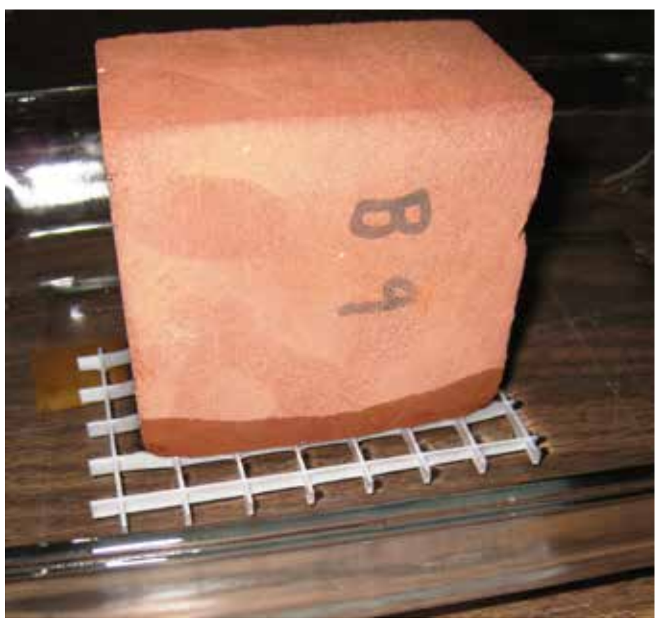

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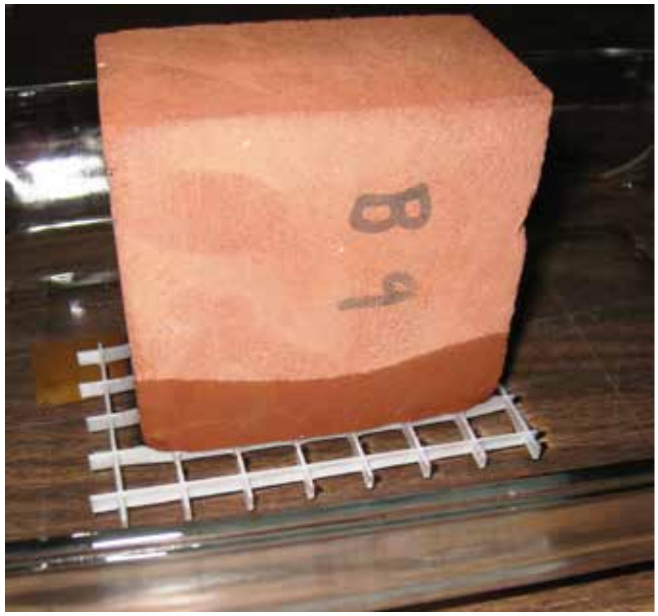
Joseph Lstiburek 98



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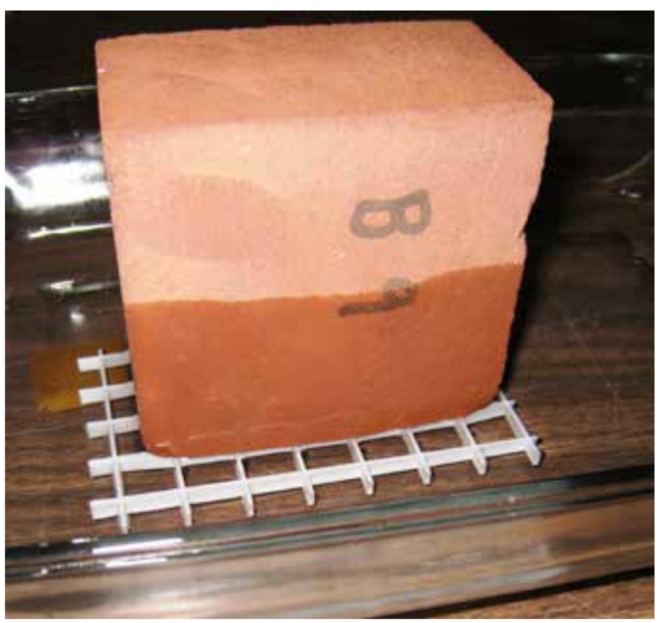

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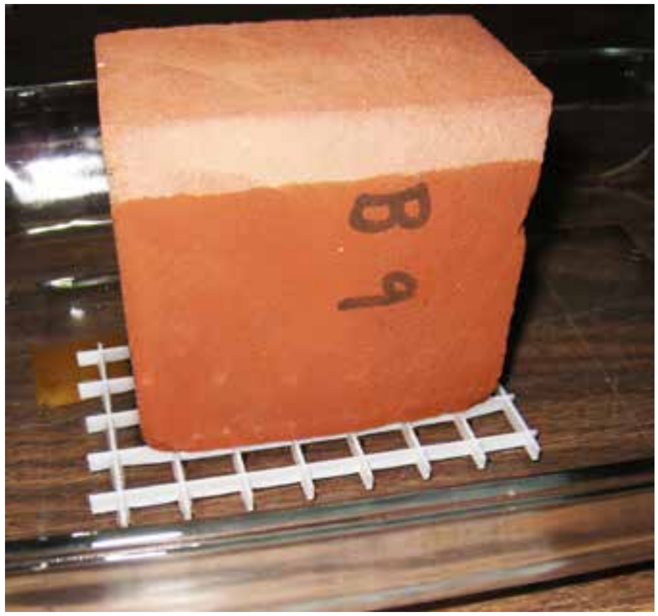
Joseph Lstiburek 100



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Joseph Lstiburek 102

How Does Wetting Occur?

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- "non-wetable" surface
- water repellant surface
- hygrophobic surface
- water more attracted to itself than to surface
- surface energy of water greater than surface energy of surface
- water "beads up"
- "greasy" surface
- high contact angle "θ"

- "wetable" surface
- non-water repellant surface
- hygroscobic surface
- water more attracted to surface than itself
- surface energy of surface greater than surface energy of water
- water "spreads out"
- "non-greasy" surface
- low contact angle "θ"

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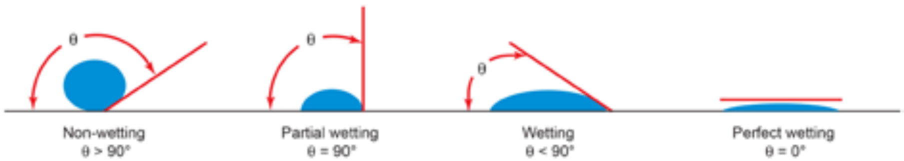

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Joseph Lstiburek 106

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Joseph Lstiburek 107

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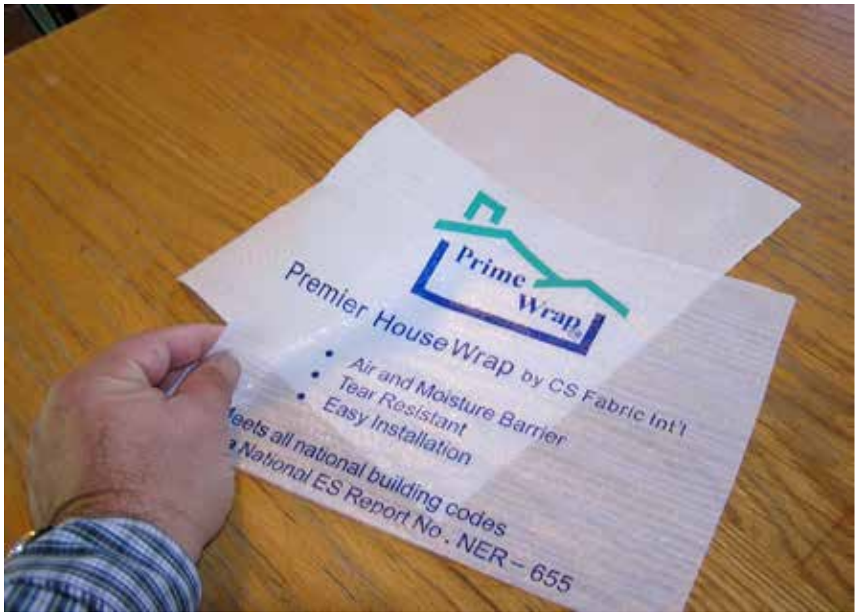
Joseph Lstiburek 108



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Joseph Lstiburek 110

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Joseph Lstiburek 111

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Joseph Lstiburek 112

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Joseph Lstiburek 113

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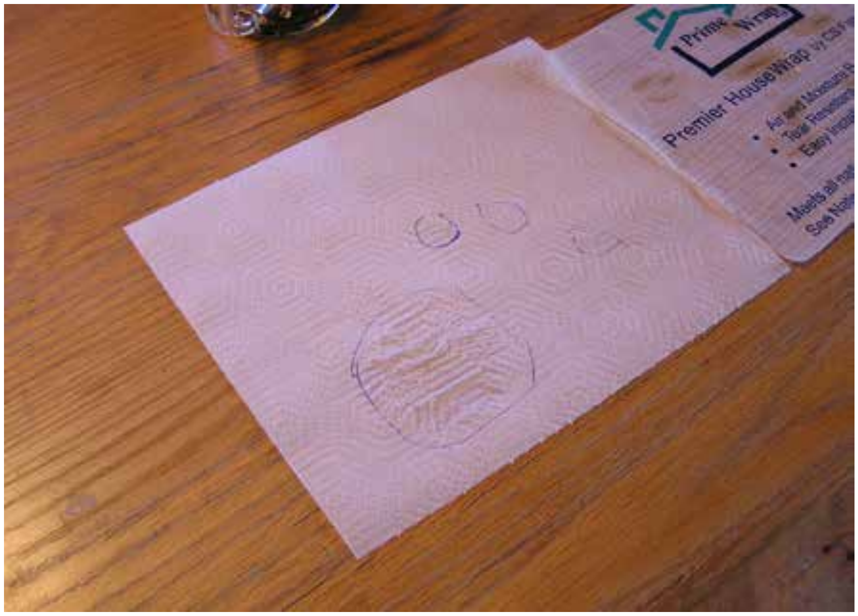
Joseph Lstiburek 114



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Joseph Lstiburek – Rain Control 116

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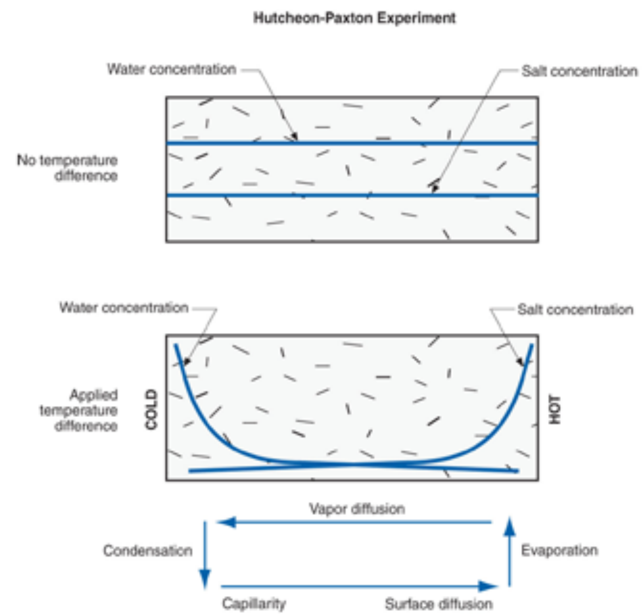
	Surface Energy
Water (20 C)	73 dynes/cm
Water (100 C)	59 dynes/cm
Epoxy	46 dynes/cm
Polyethylene	31 dynes/cm
Soapy water	30 dynes/cm
Paraffin wax	25 dynes/cm
Silicone	24 dynes/cm
Teflon	18 dynes/cm

More Combined Flows



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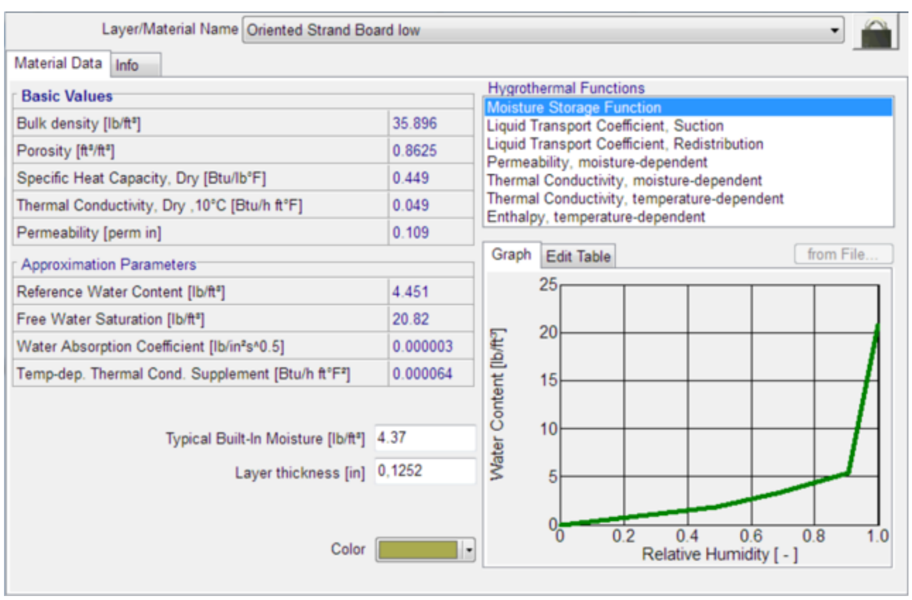

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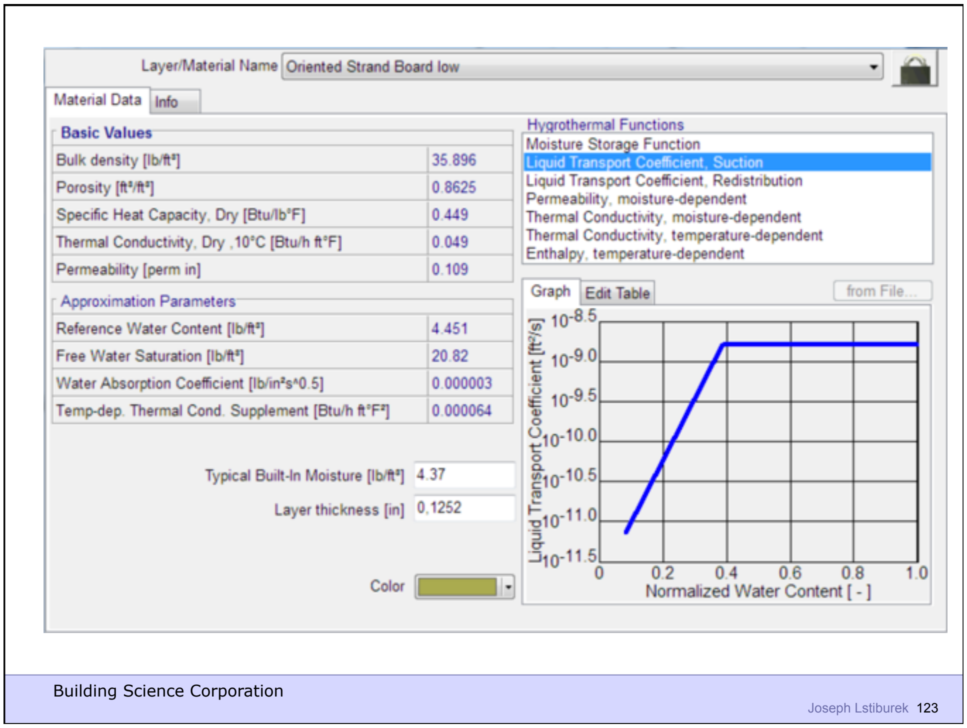
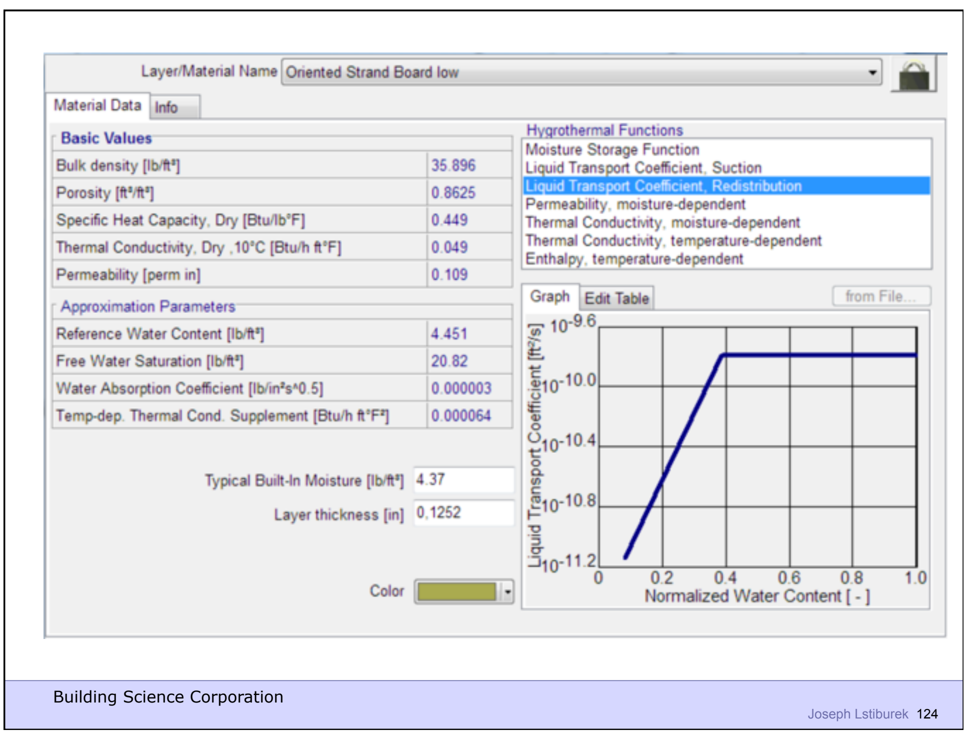
Joseph Lstiburek 122


Layer/Material Name
Oriented Strand Board low
Material Data
Info
Basic Values
Bulk density [lb/ft³] 35.896
Porosity [ft³/ft³] 0.8625
Specific Heat Capacity, Dry [Btu/lb°F] 0.449
Thermal Conductivity, Dry ,10°C [Btu/h ft°F] 0.049
Permeability [perm in] 0.109
Approximation Parameters
Reference Water Content [lb/ft³] 4.451
Free Water Saturation [lb/ft³] 20.82
Water Absorption Coefficient [lb/in²s^0.5] 0.000003
Temp-dep. Thermal Cond. Supplement [Btu/h ft°F²] 0.000064
Typical Built-In Moisture [lb/ft³] 4.37
Layer thickness [in] 0.1252
Color
Hygrothermal Functions
Moisture Storage Function
Liquid Transport Coefficient, Suction
Liquid Transport Coefficient, Redistribution
Permeability, moisture-dependent
Thermal Conductivity, moisture-dependent
Thermal Conductivity, temperature-dependent
Enthalpy, temperature-dependent
Graph
Edit Table
from File...
Liquid Transport Coefficient [ft²/s]
10-8.5
10-9.0
10-9.5
10-10.0
10-10.5
10-11.0
10-11.5
0 0.2 0.4 0.6 0.8 1.0
Normalized Water Content [-]
Building Science Corporation
Joseph Lstiburek 123


Layer/Material Name
Oriented Strand Board low
Material Data
Info
Basic Values
Bulk density [lb/ft³] 35.896
Porosity [ft³/ft³] 0.8625
Specific Heat Capacity, Dry [Btu/lb°F] 0.449
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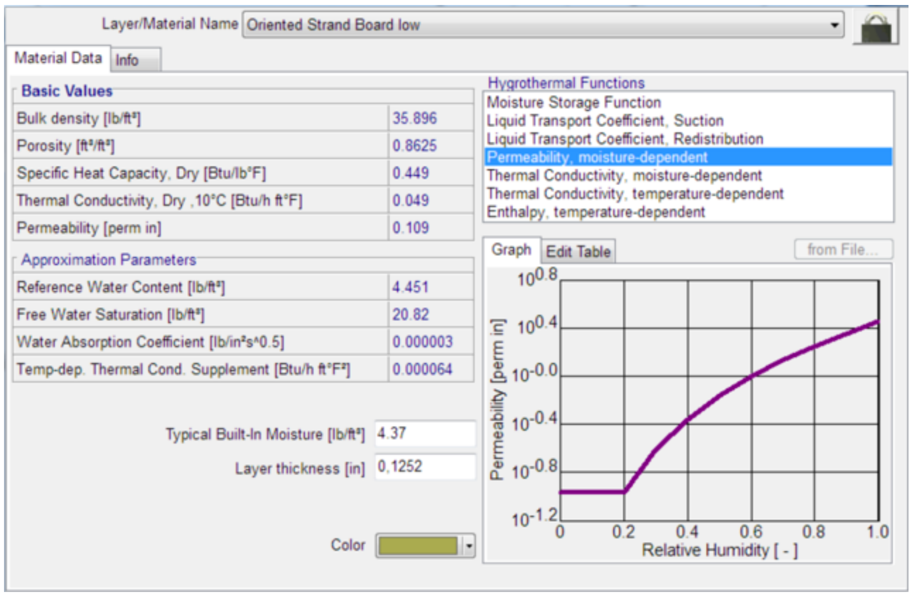
Thermal Conductivity, moisture-dependent
Thermal Conductivity, temperature-dependent
Enthalpy, temperature-dependent
Graph
Edit Table
from File...
Liquid Transport Coefficient [ft²/s]
10-9.6
10-10.0
10-10.4
10-10.8
10-11.2
0 0.2 0.4 0.6 0.8 1.0
Normalized Water Content [-]
Building Science Corporation
Joseph Lstiburek 124



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When Phases Change

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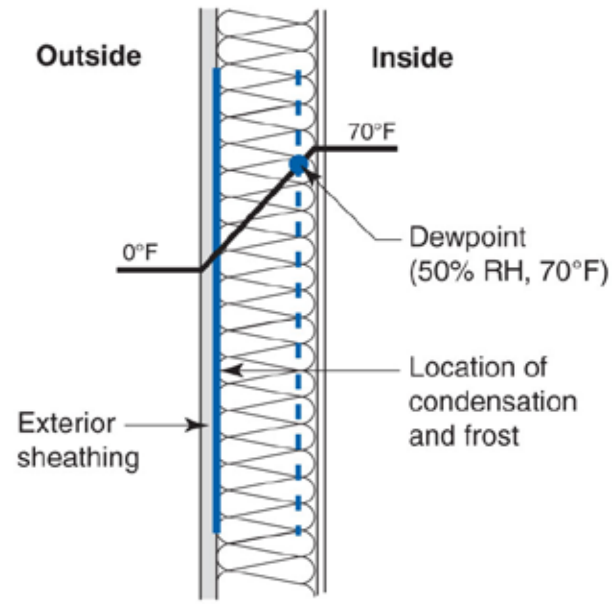
Joseph Lstiburek 126



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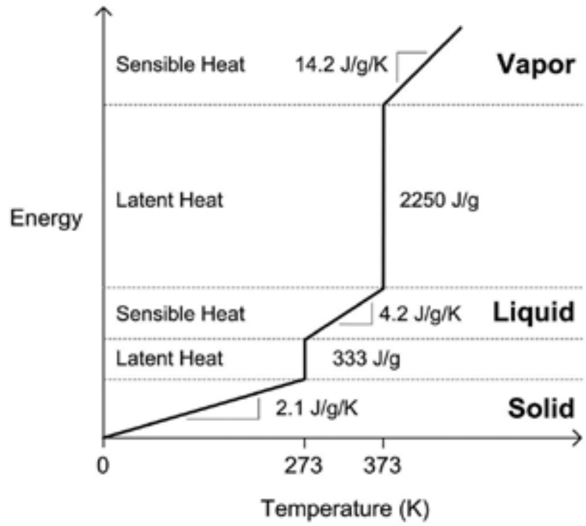
Joseph Lstiburek 128



Simple linearized energy-temperature relation for water
From Straube & Burnett, 2005

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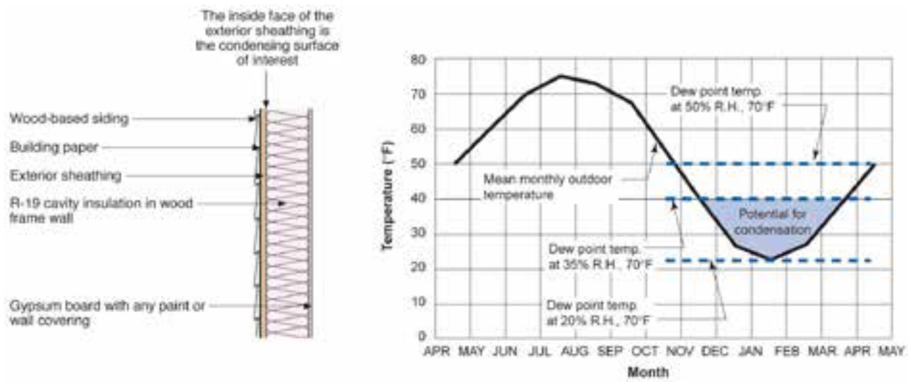

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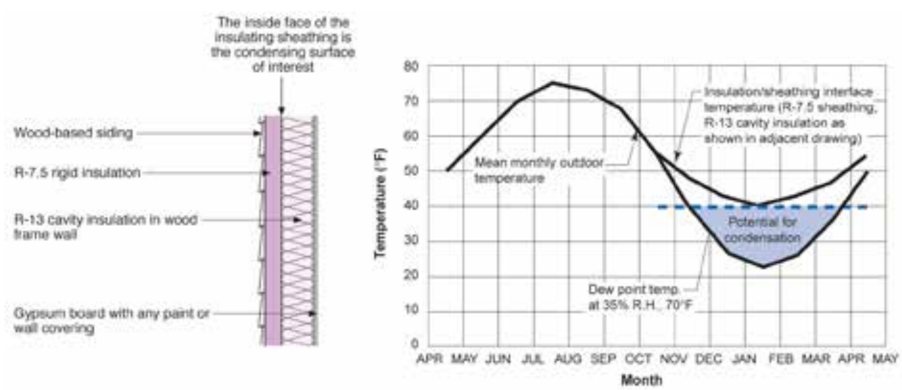
Joseph Lstiburek 131



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Joseph Lstiburek 132

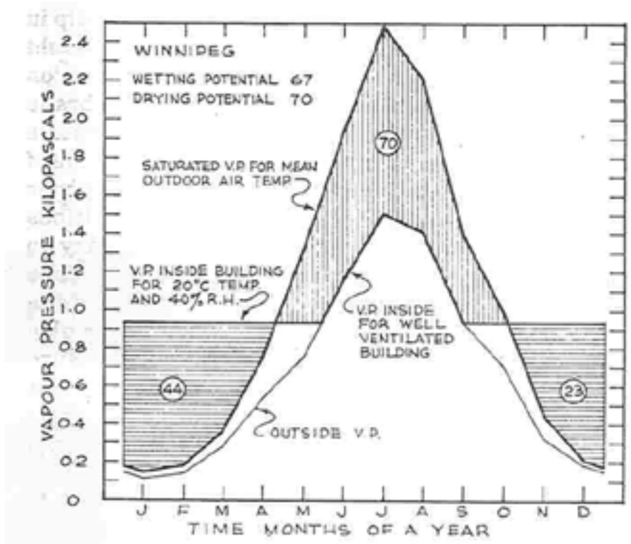
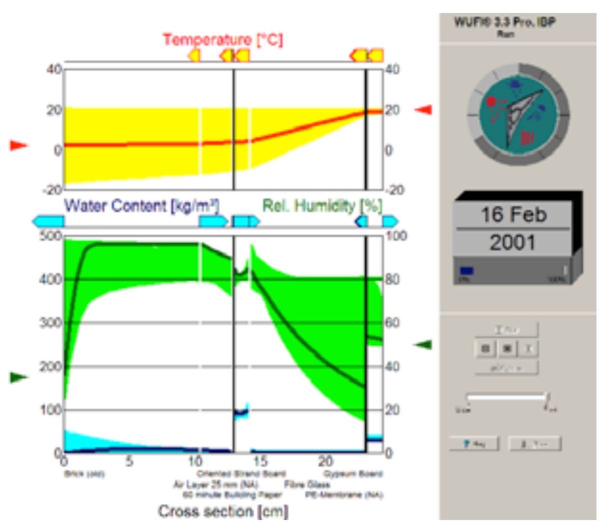


Figure 8-7. Outside vapour pressure, saturated vapour pressure and inside vapour pressure for Winnipeg.

133



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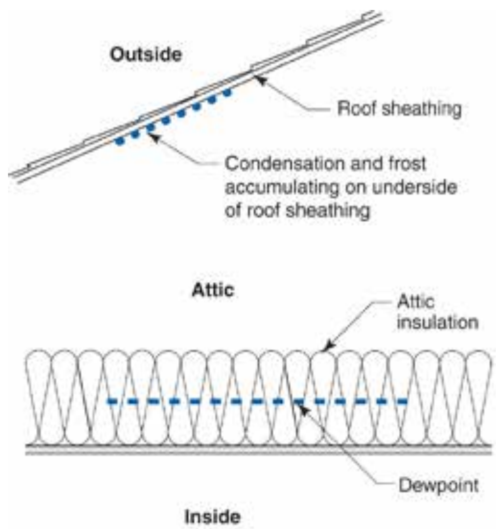

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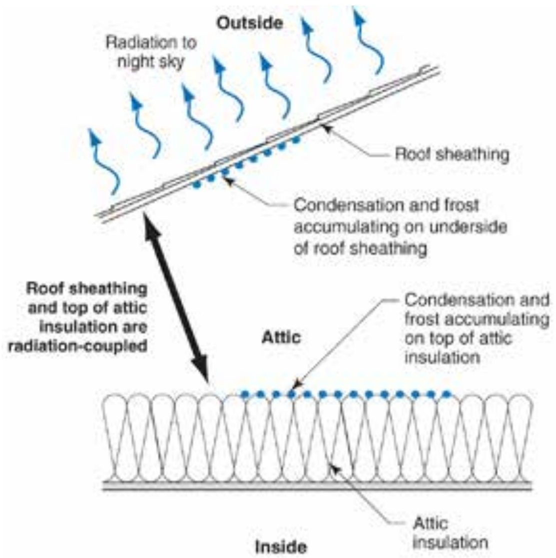

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Joseph Lstiburek 139

Revisiting Convective Flow

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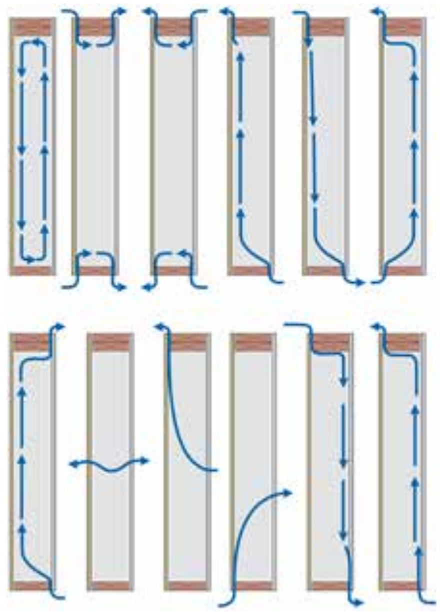
Joseph Lstiburek 140



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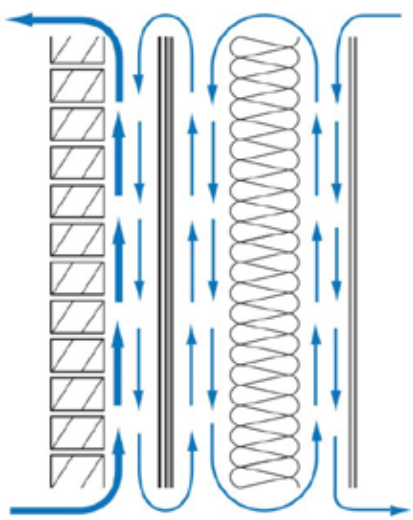
Joseph Lstiburek 141



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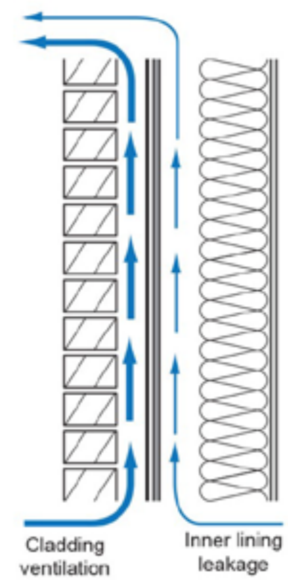
Joseph Lstiburek 142



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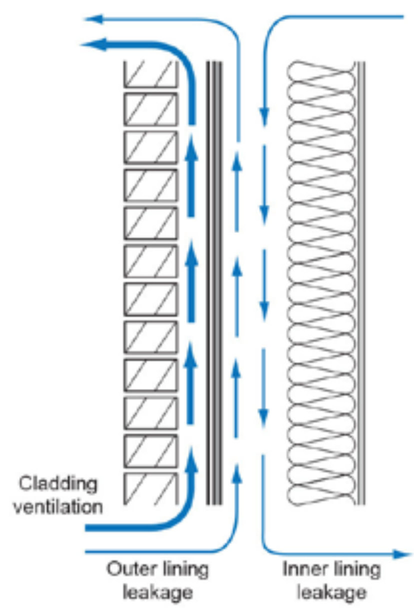

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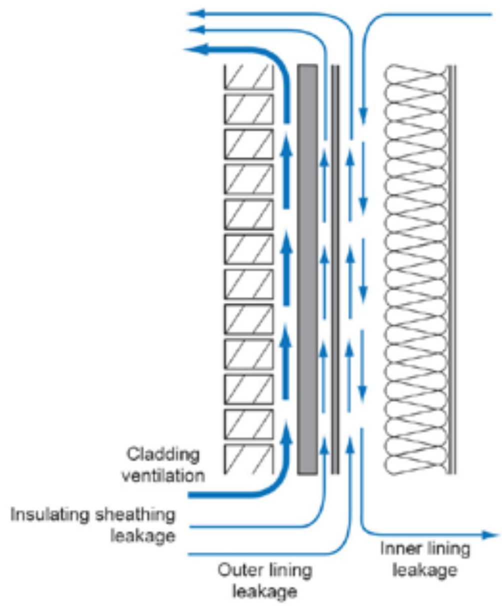
Joseph Lstiburek 144



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Cladding Ventilation/ Sheathing Ventilation

	Flow Rate	Gap	ACH
Wood Siding	0.1 cfm/sf	3/16"	20
Vinyl Siding	0.5 cfm/sf	3/16"	200
Brick Veneer	0.15 cfm/sf	1"	10
Stucco (vented)	0.1 cfm/sf	3/8"	10
Stucco (direct applied)	none	none	0
Sheathing flanking flow	0.05 cfm/sf	3/16"	10

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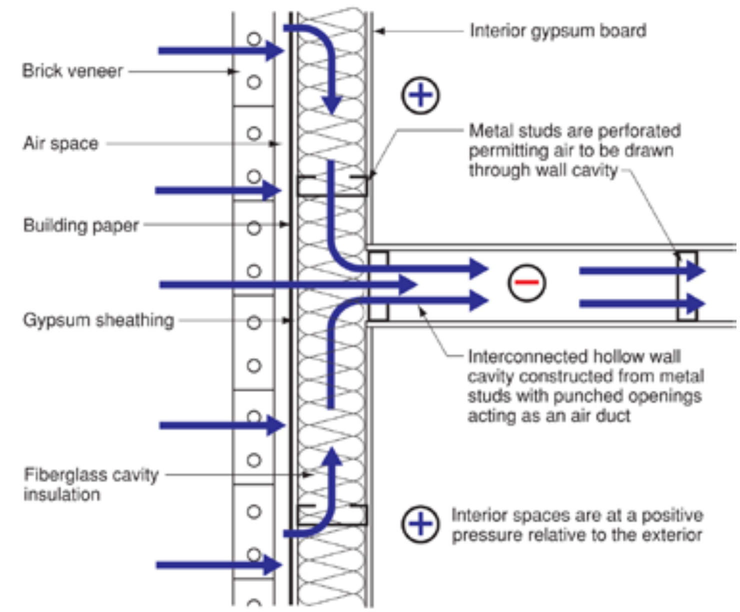

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Interior Load – Exterior Load

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Joseph Lstiburek 148

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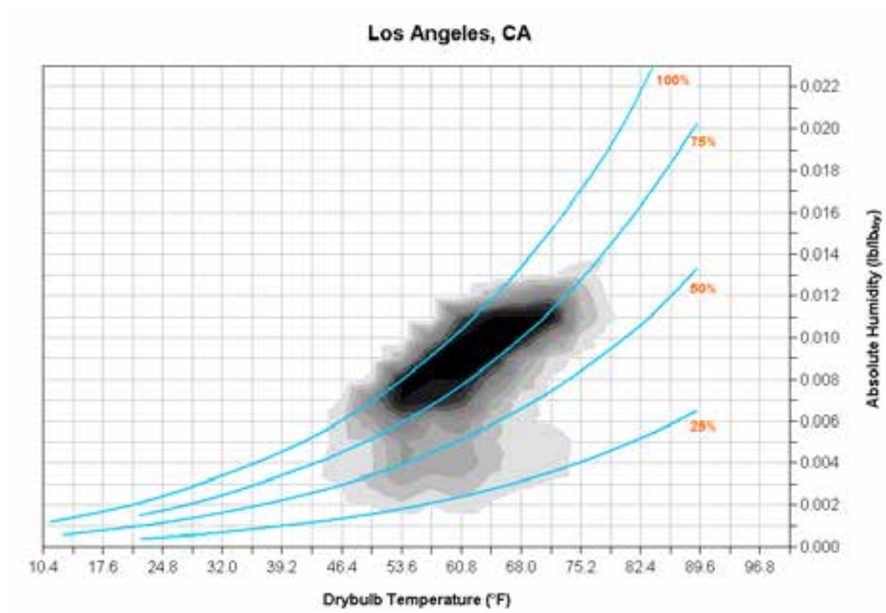
Joseph Lstiburek 149



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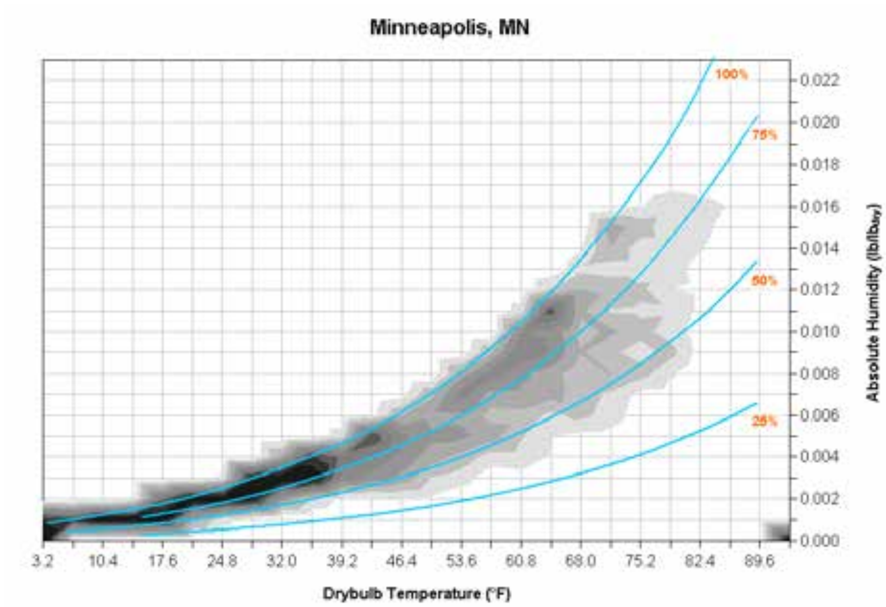
Joseph Lstiburek 150



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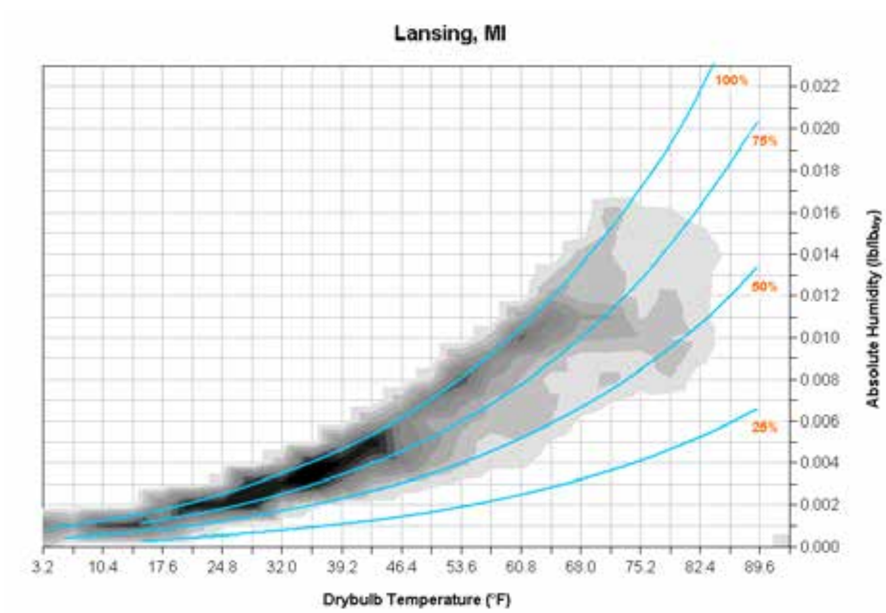
Joseph Lstiburek 151



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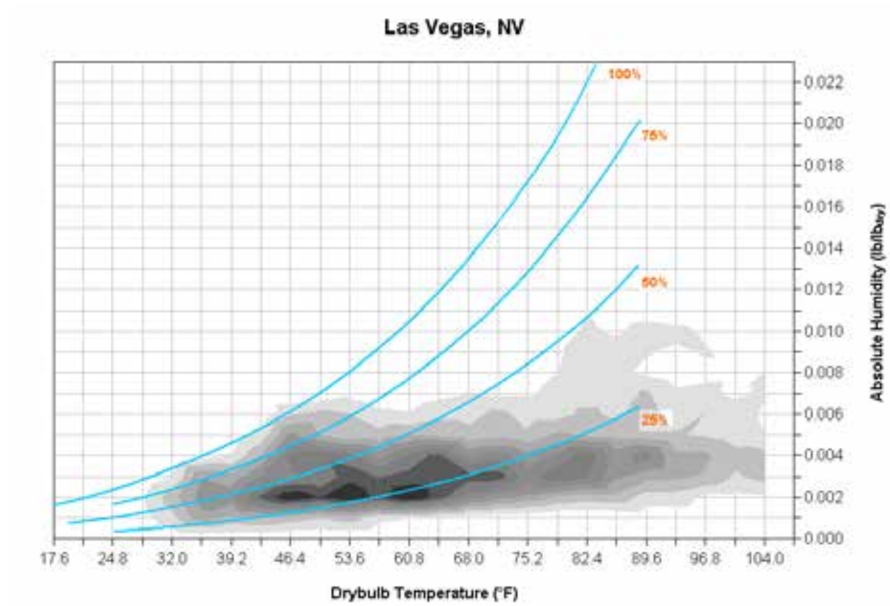
Joseph Lstiburek 152



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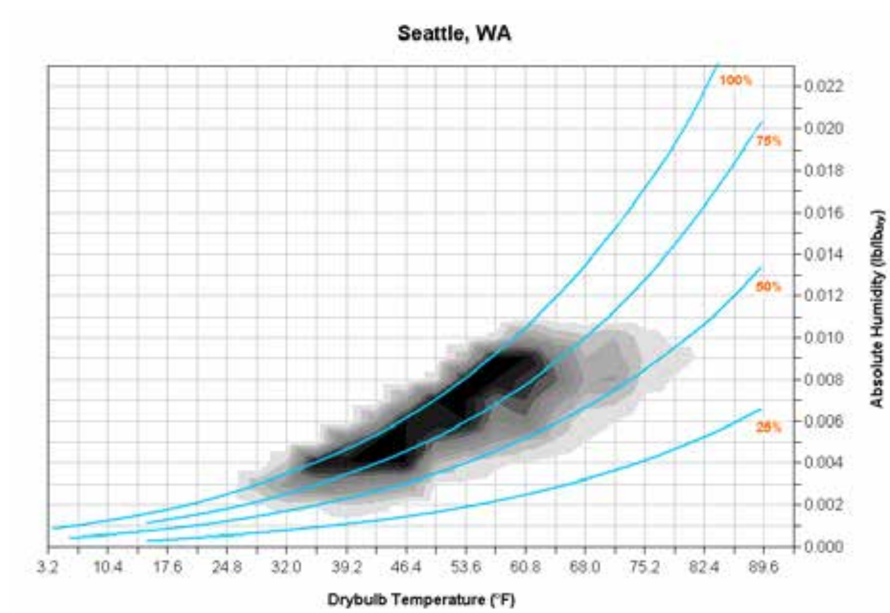
Joseph Lstiburek 153



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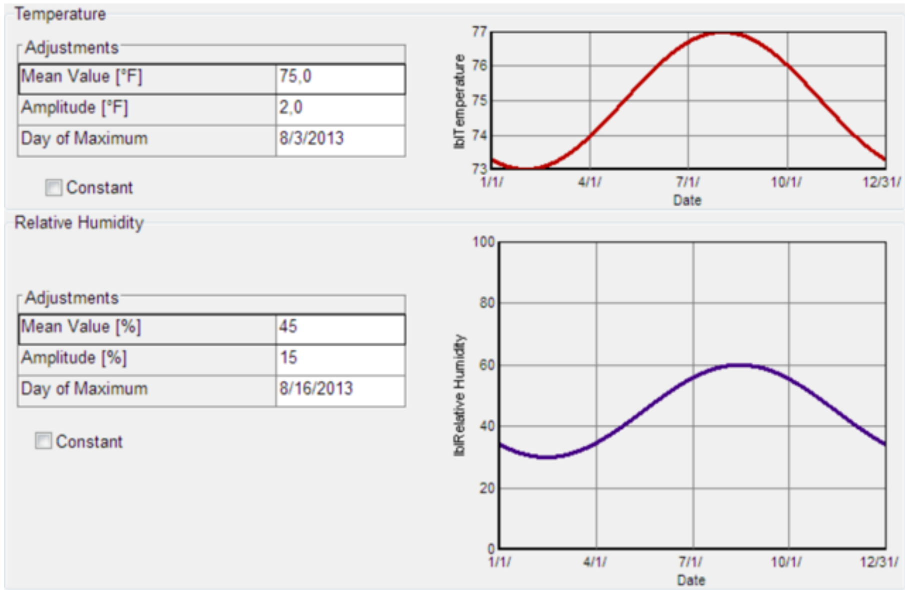
Joseph Lstiburek 154



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Don’t Do Stupid Things

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Joseph Lstiburek 156

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Joseph Lstiburek 157

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Joseph Lstiburek 158

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Joseph Lstiburek 159

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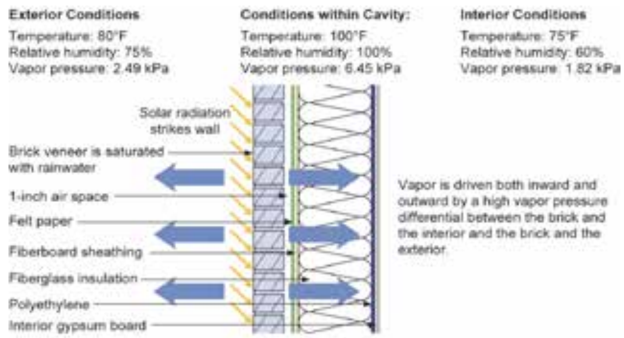
Joseph Lstiburek 160



- It is not a good idea to install a vapor barrier (polyethylene) on the inside of an air conditioned assembly. Vinyl wall coverings and foil-backed batt cavity insulation should also be avoided.
- Vapor permeable exterior sheathings, housewraps or building papers should not be used with absorptive claddings such as brick veneers unless a ventilated cavity is provided in conjunction with high inward drying potentials (i.e. no interior polyethylene vapor barriers).
- Failure will occur when brick is installed over a frame wall constructed with felt paper, fiberboard sheathing and an interior polyethylene vapor barrier. Kraft-faced fiberglass batts should be used in place of unfaced batts and a polyethylene vapor barrier. OSB, plywood or foam sheathing should be used in place of the fiberboard sheathing.
- Similar problems occur with stucco.

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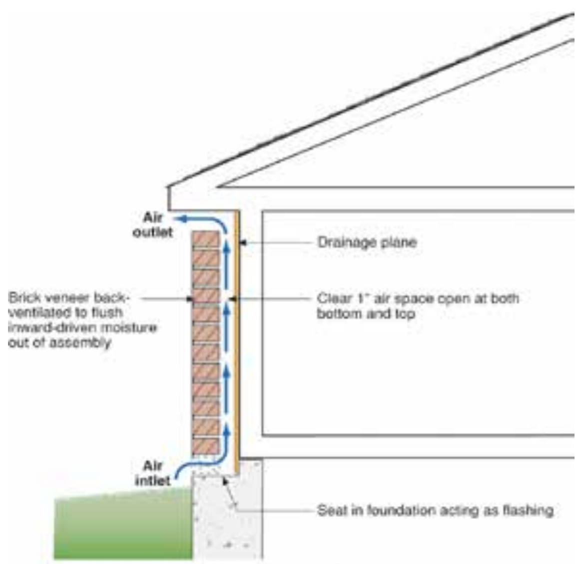

- To effectively uncouple a brick veneer from a wall system by using back ventilation, a clear cavity must be provided along with both air inlets at the bottom and air outlets at the top

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Joseph Lstiburek 163

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Joseph Lstiburek 164

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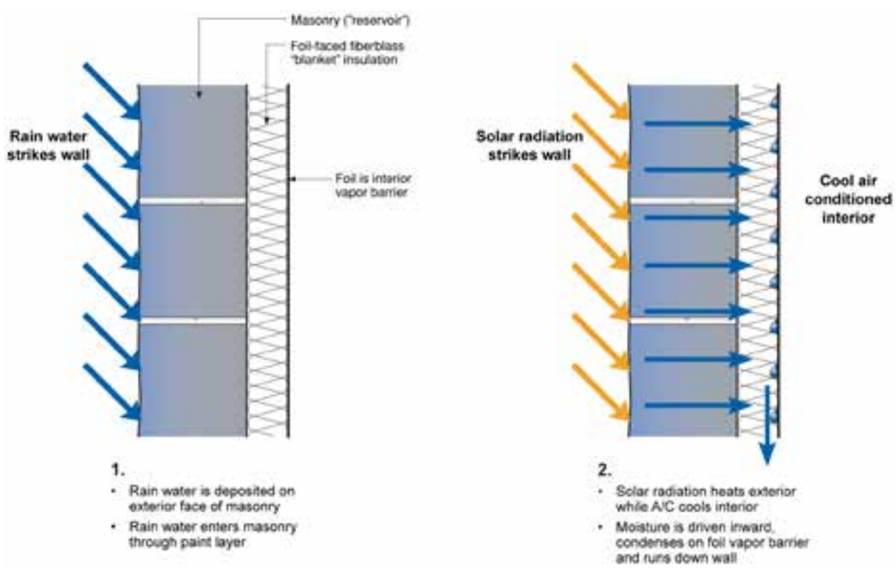
Joseph Lstiburek 165



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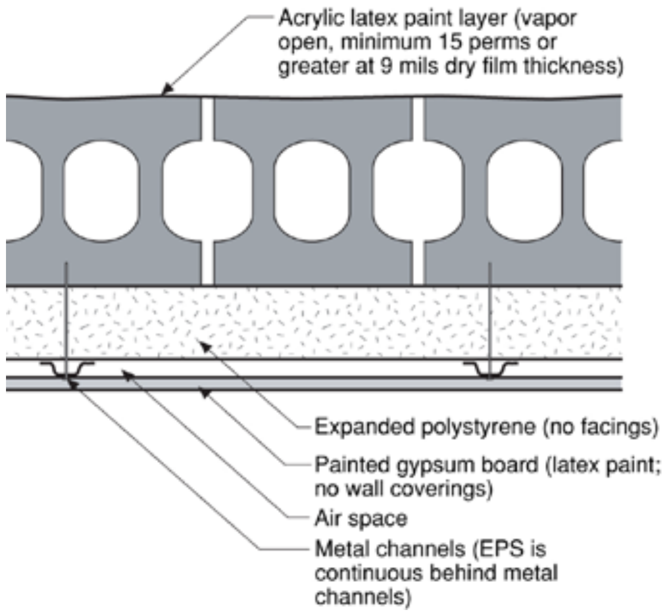

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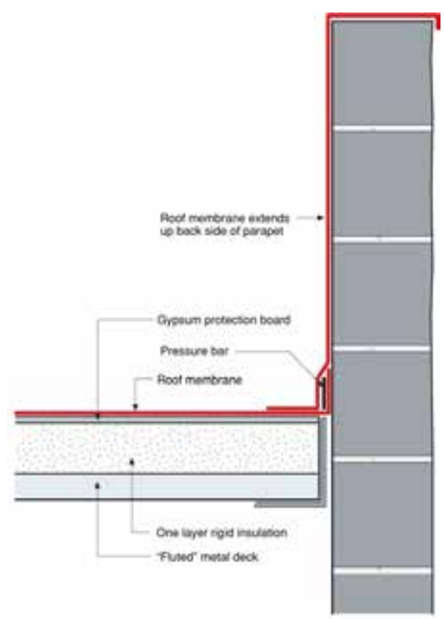
Joseph Lstiburek 167



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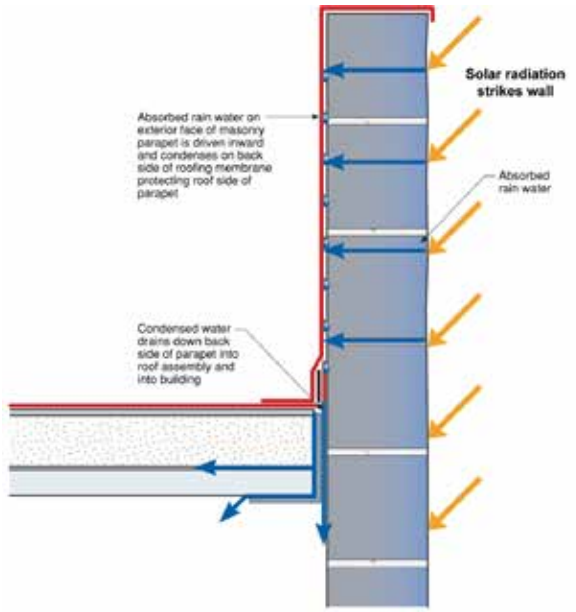
Joseph Lstiburek 168



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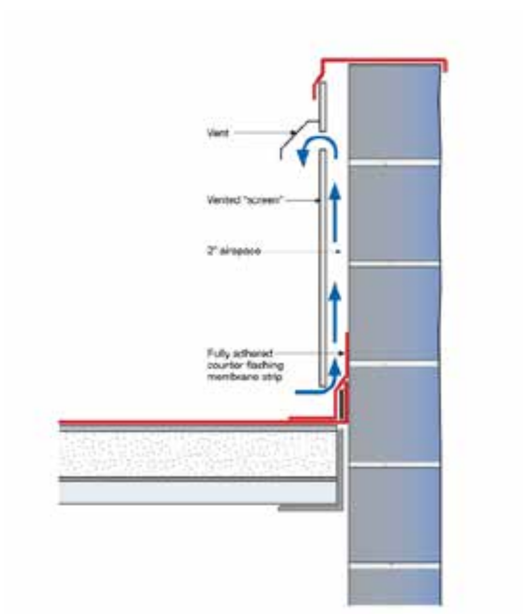
Joseph Lstiburek 169



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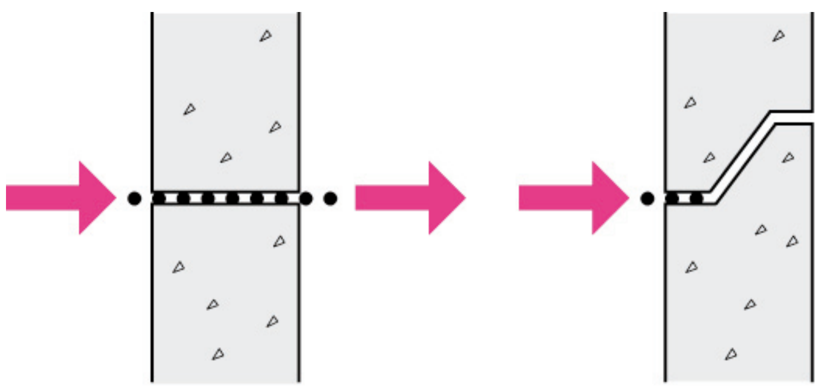
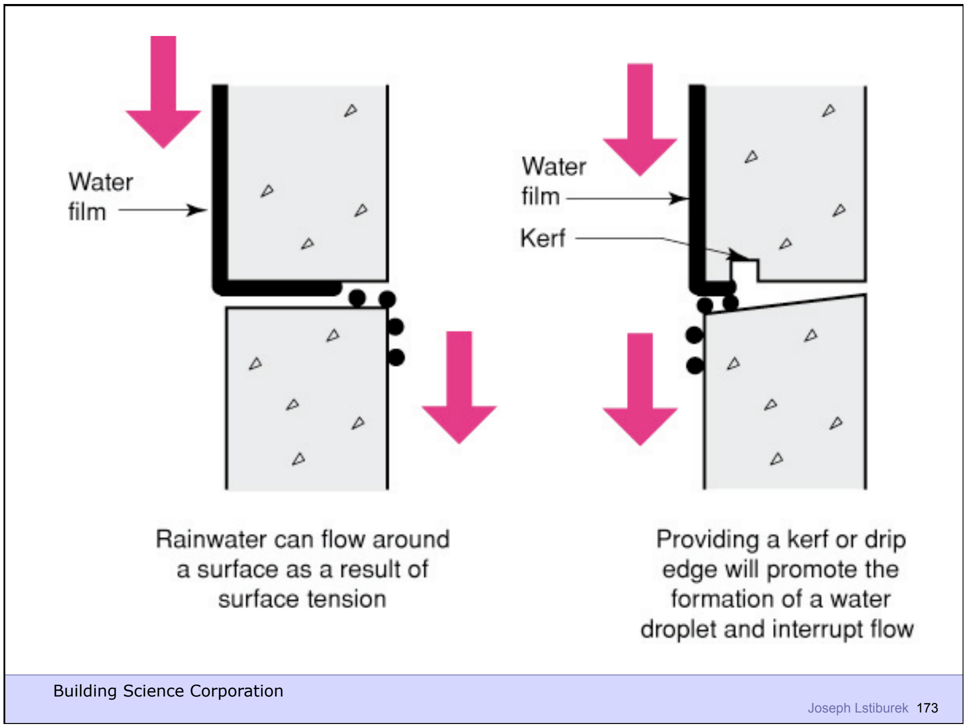
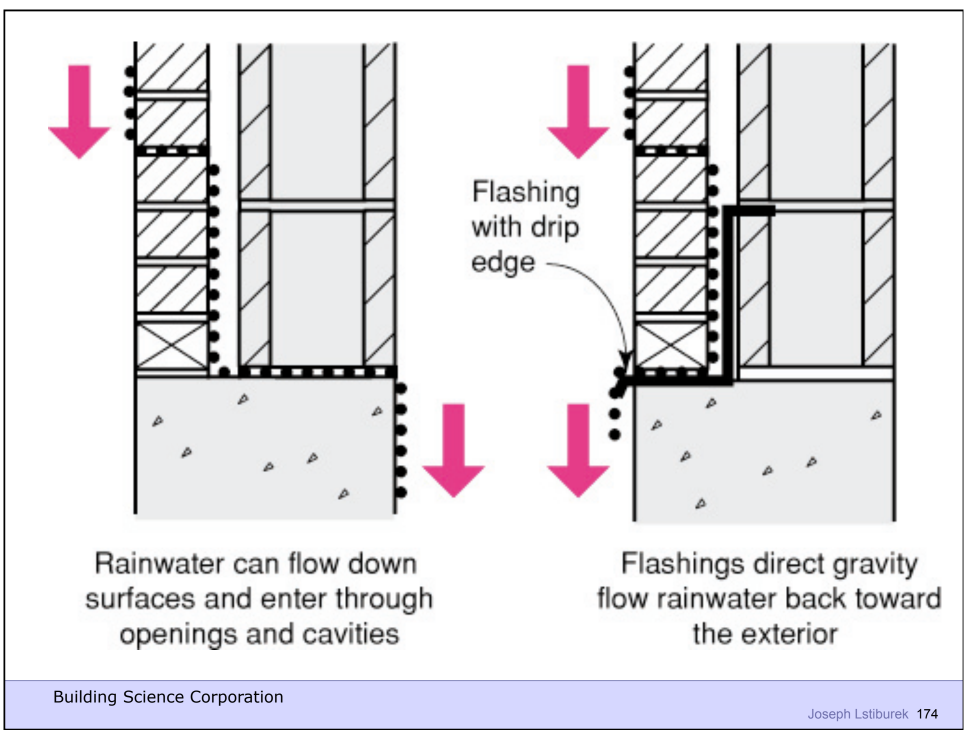
Rain	Gravitational Flow	Height
	Surface Tension	Surface Energy
	Momentum	Kinetic Energy
	Convective Flow	Air Pressure



Rain droplets can be carried through a wall by their own momentum

Rain entry by momentum can be prevented by designing wall systems with no straight through openings


Water
film
Water
film
Kerf
Rainwater can flow around a surface as a result of surface tension
Providing a kerf or drip edge will promote the formation of a water droplet and interrupt flow
Building Science Corporation
Joseph Lstiburek 173


Flashing
with drip
edge
Rainwater can flow down surfaces and enter through openings and cavities
Flashings direct gravity flow rainwater back toward the exterior
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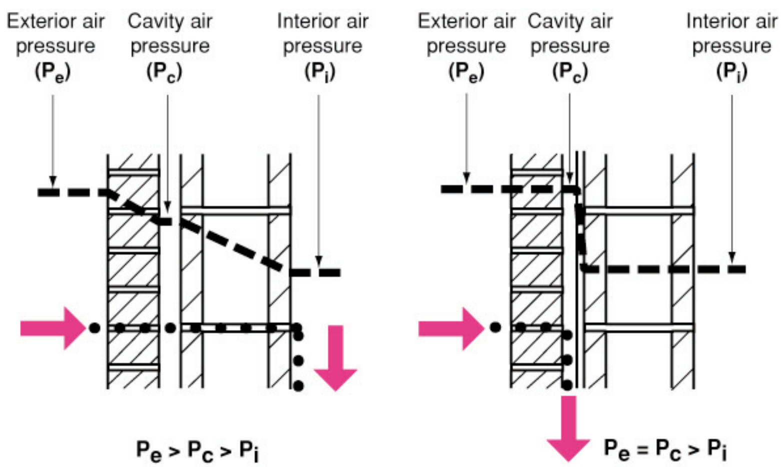
Joseph Lstiburek 174



Driven by air pressure differences, rain droplets are drawn through wall openings from the exterior to the interior

By creating pressure equalization or pressure moderation between the exterior and cavity air, air pressure is diminished as a driving force for rain entry

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When We Talk About Rain We Also Include Capillary Flow

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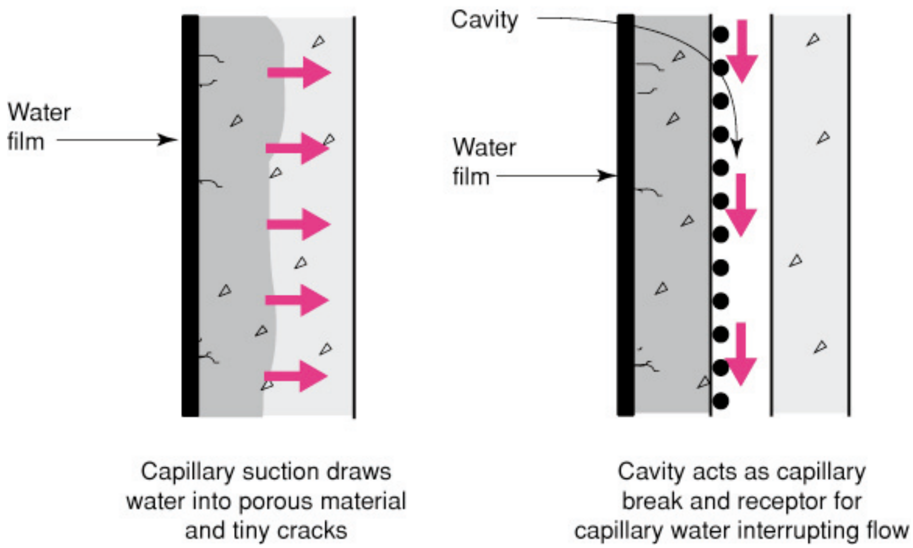

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All We Have To Figure Out Is How Much Hits The Wall

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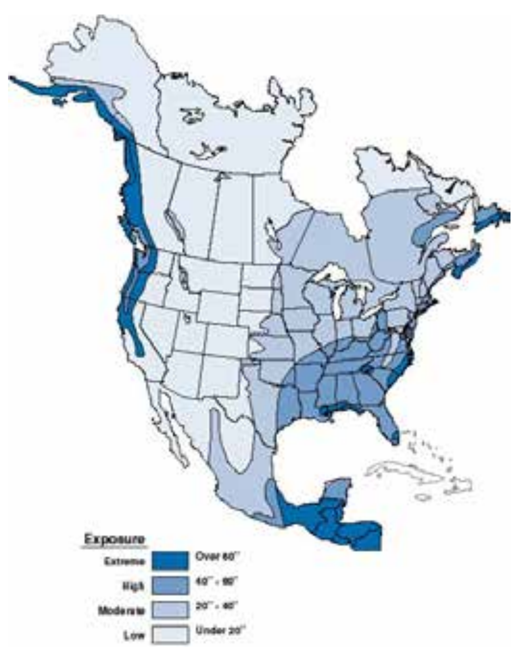
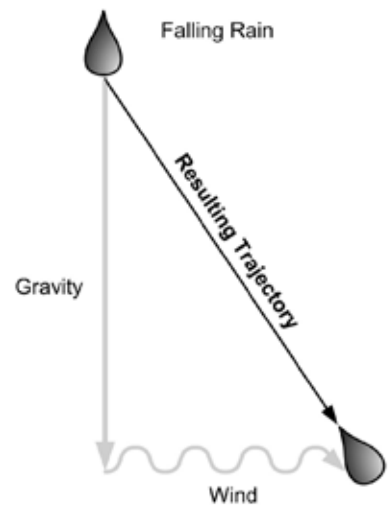
Joseph Lstiburek 178

All We Have To Figure Out Is How Much Hits The Wall

We Need Straube and Kuenzel





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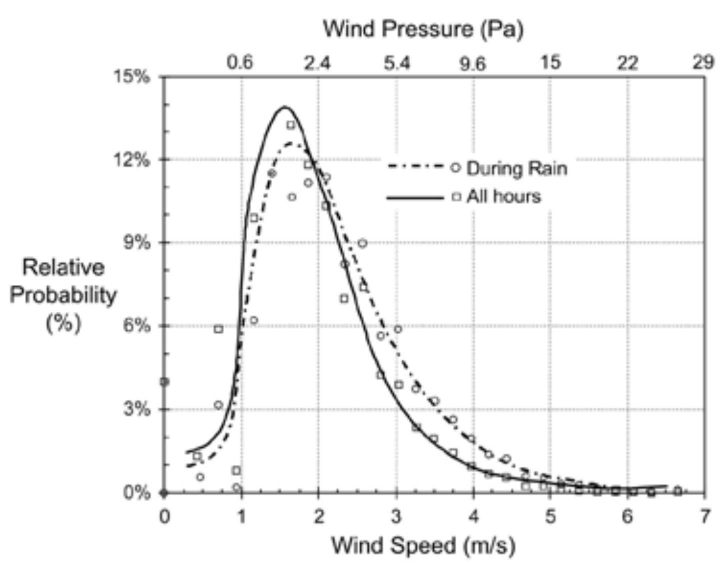

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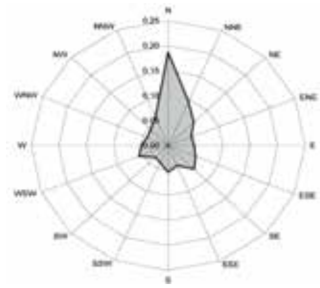
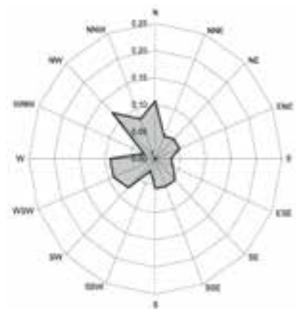
Joseph Lstiburek 182





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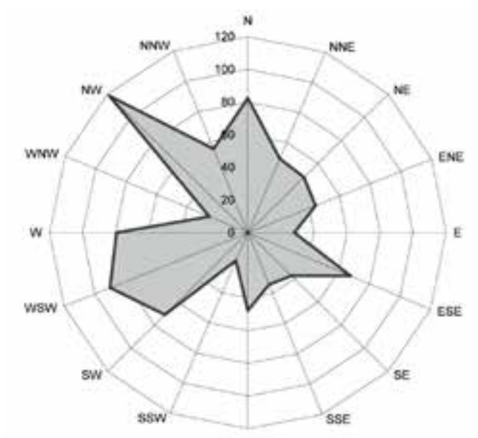
Joseph Lstiburek 183



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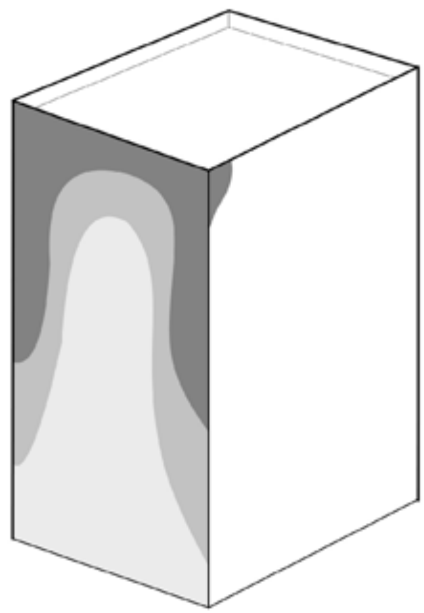
Joseph Lstiburek 184



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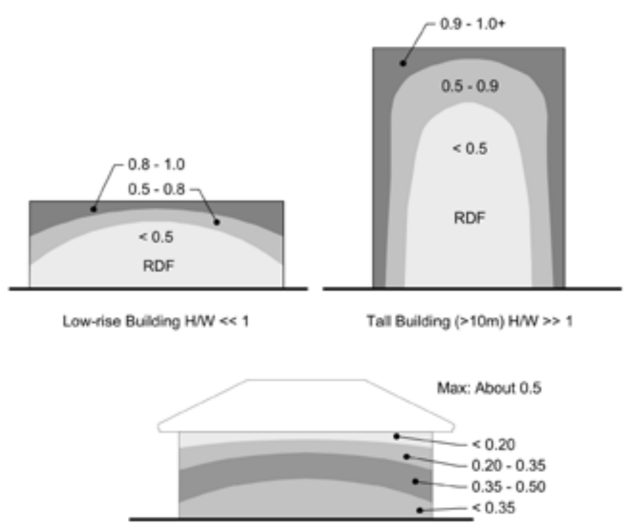
Joseph Lstiburek 185



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We use Straube/Kuenzel to determine how much rain water impinges on the wall.

We assume 30% bounces off

70% stays on the wall.

The 70% that stays on the wall is addressed by liquid conductivity (capillary flow) and vapor diffusion.

We assume 1% of the 70% penetrates to the back side of the cladding.

We further assume that 1% of the 1% gets past the water control layer into the sheathing.

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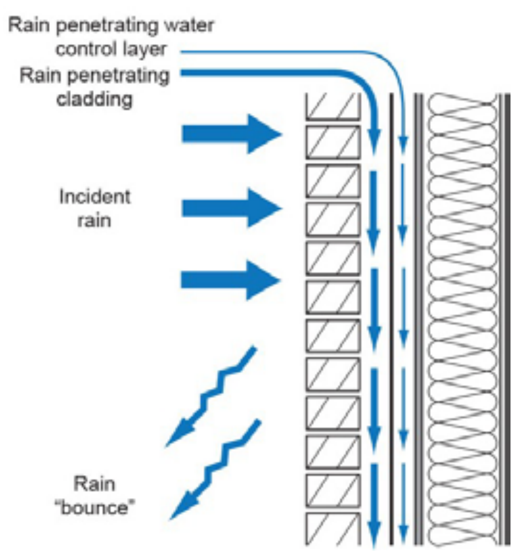

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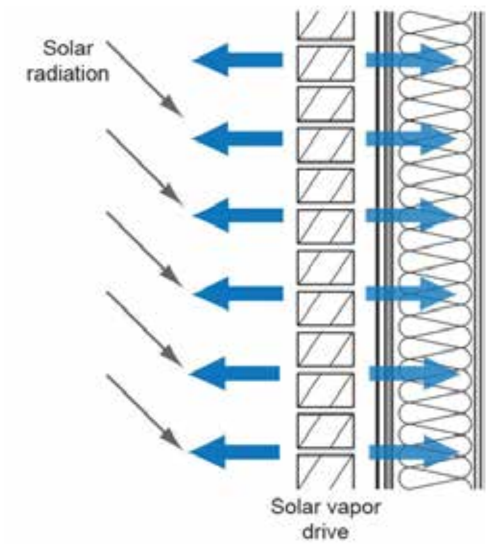
Joseph Lstiburek 188



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Joseph Lstiburek 189

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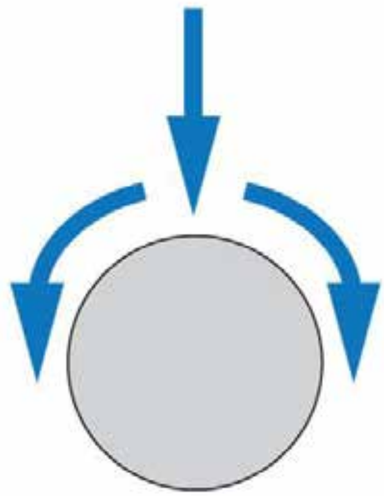
Joseph Lstiburek 190



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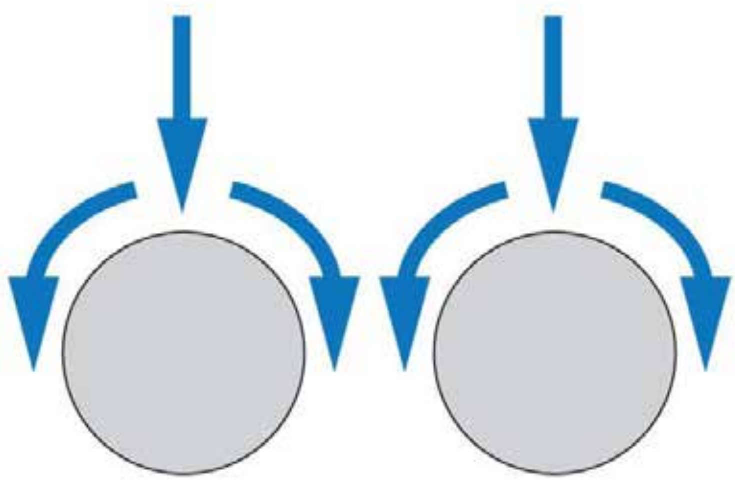
Joseph Lstiburek 191



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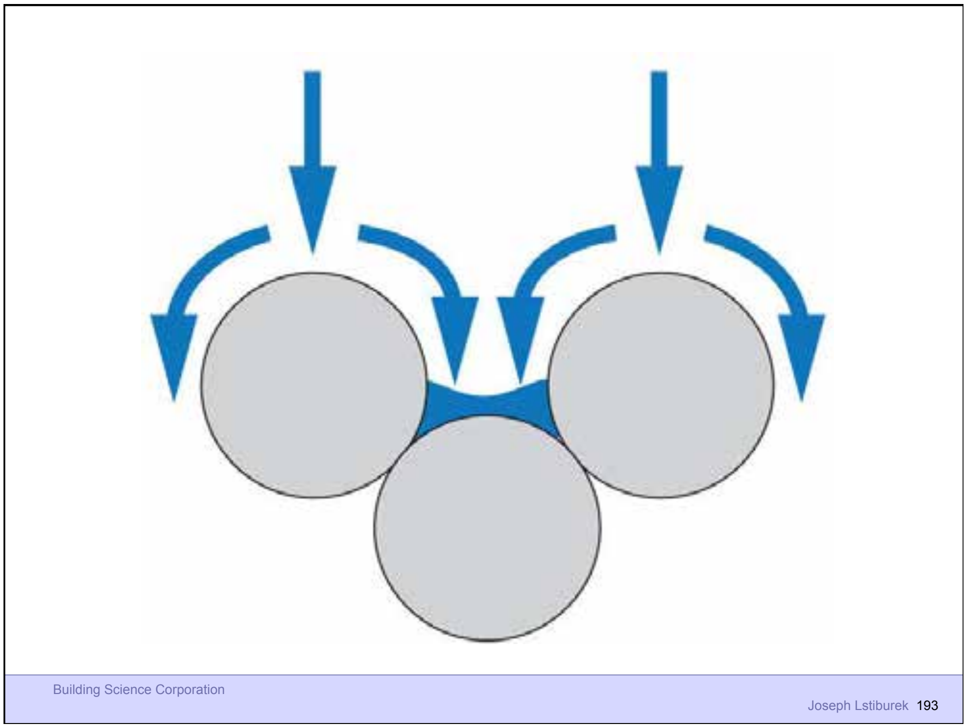
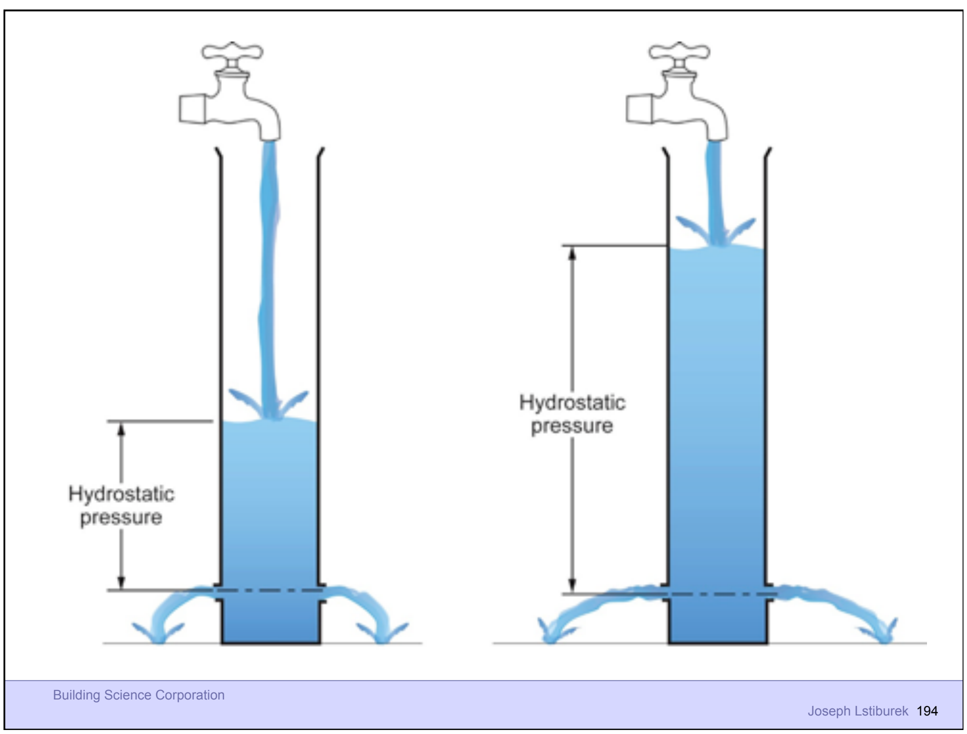
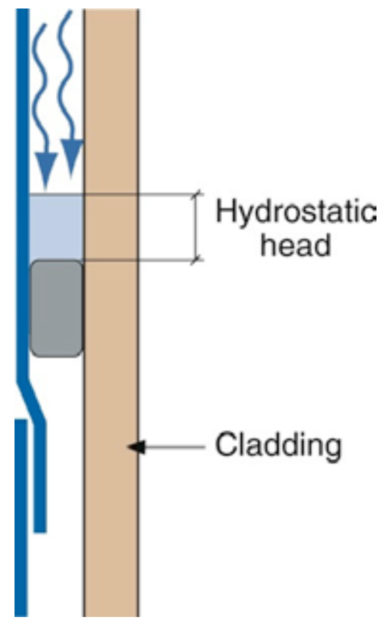
Joseph Lstiburek 192


Building Science Corporation
Joseph Lstiburek 193


Hydrostatic pressure
Hydrostatic pressure
Building Science Corporation
Joseph Lstiburek 194



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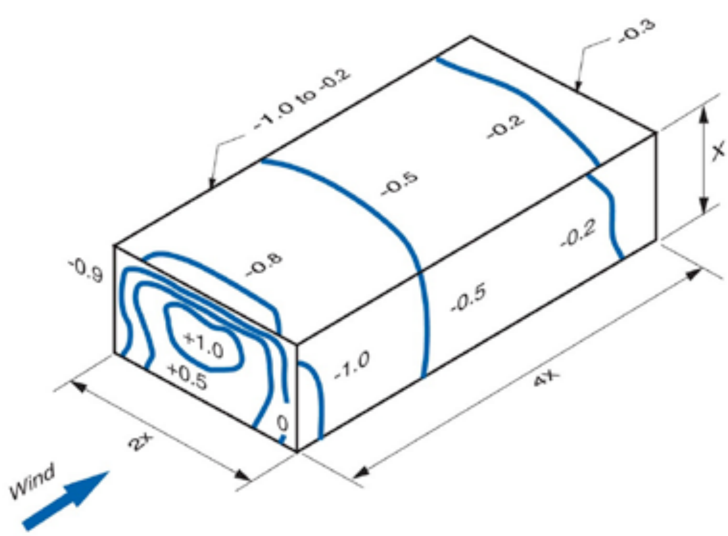
Joseph Lstiburek 195



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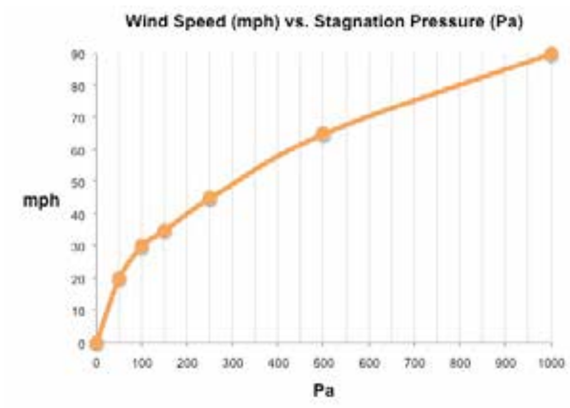
Pascals	mph
50 Pa =	20 mph
100 Pa =	30 mph
150 Pa =	35 mph
250 Pa =	45 mph
500 Pa =	65 mph
1,000 Pa =	90 mph



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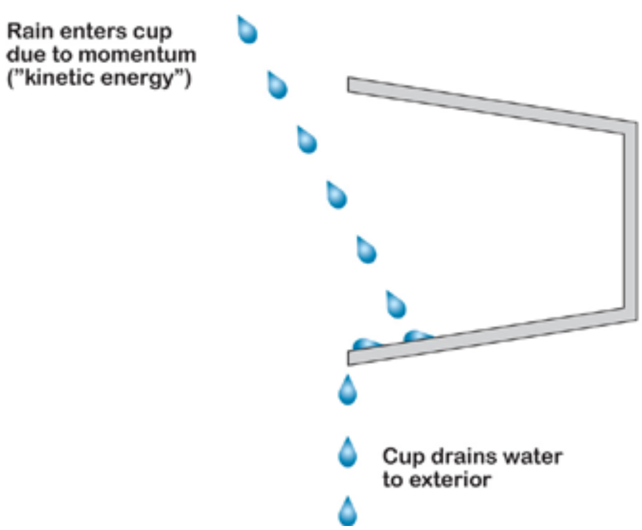
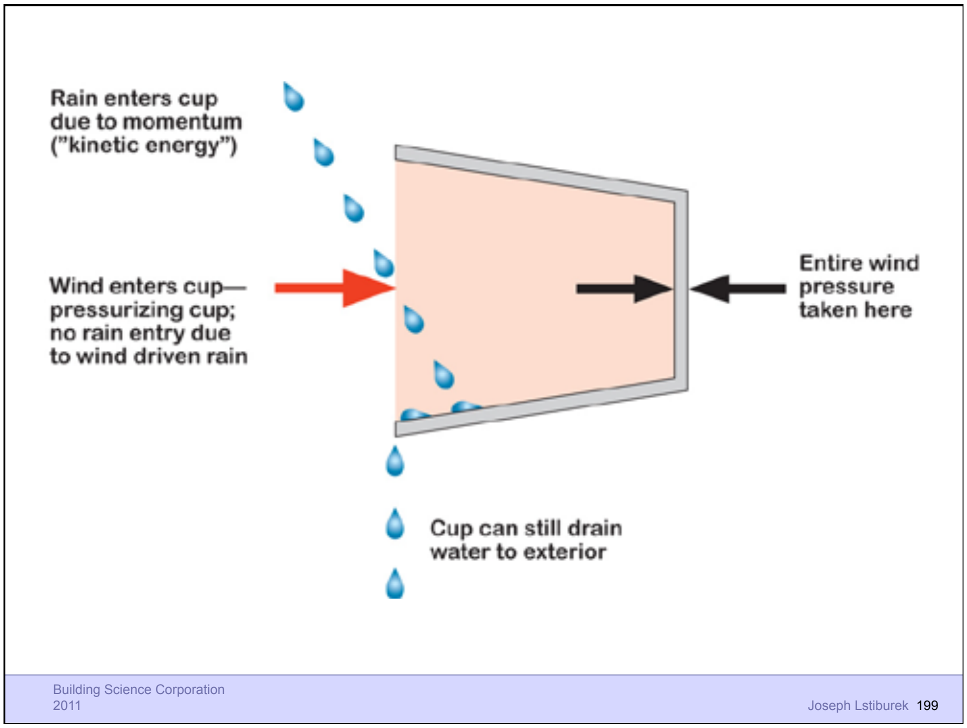
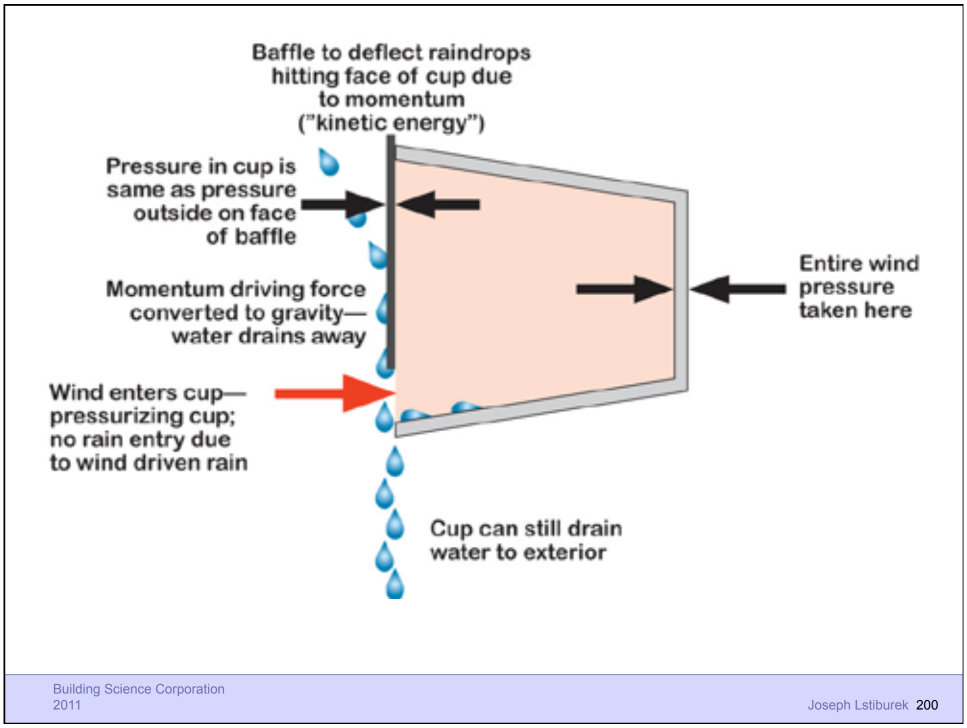
Joseph Lstiburek 197

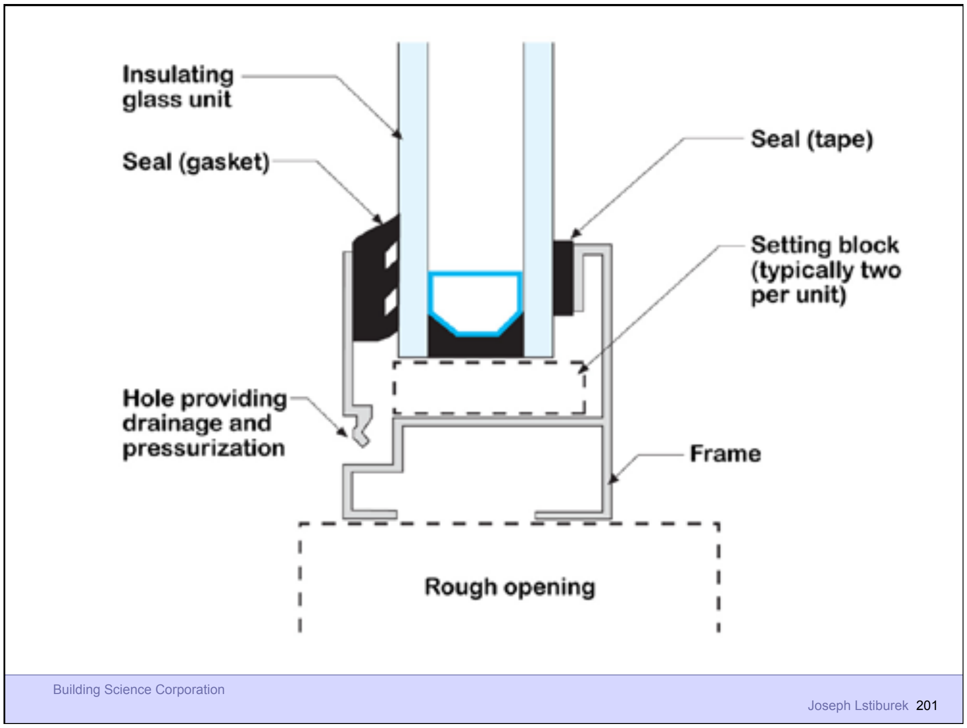


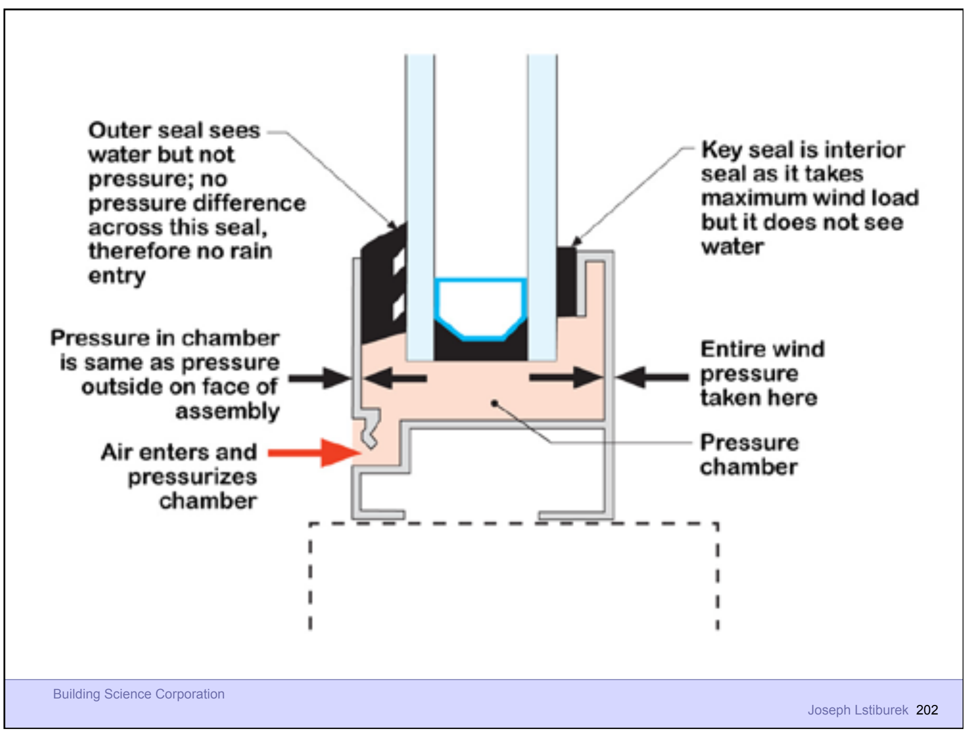
Building Science Corporation
2011

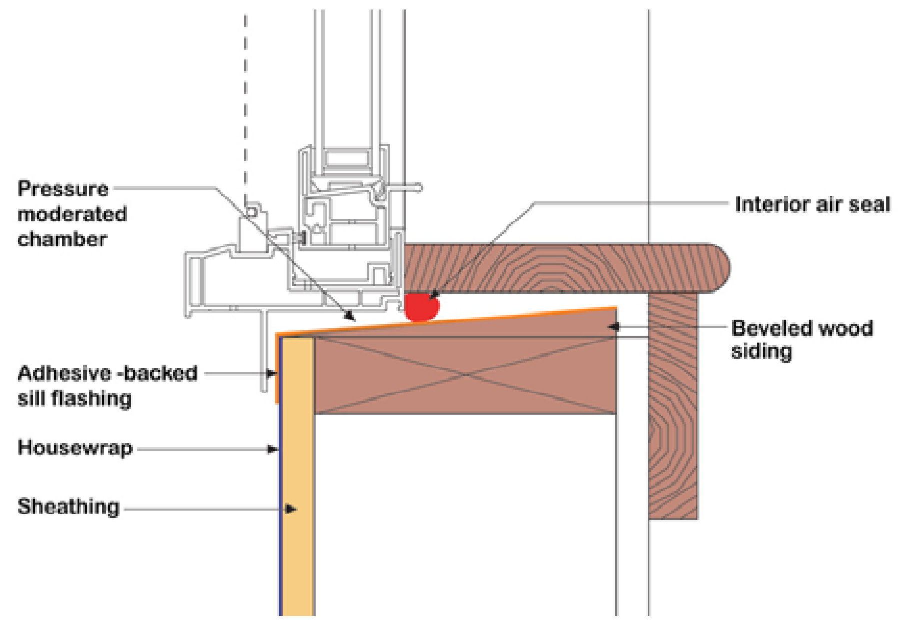
Joseph Lstiburek 198


Rain enters cup due to momentum ("kinetic energy")
Wind enters cup—pressurizing cup; no rain entry due to wind driven rain
Entire wind pressure taken here
Cup can still drain water to exterior
Building Science Corporation 2011
Joseph Lstiburek 199


Baffle to deflect raindrops hitting face of cup due to momentum ("kinetic energy")
Pressure in cup is same as pressure outside on face of baffle
Momentum driving force converted to gravity—water drains away
Wind enters cup—pressurizing cup; no rain entry due to wind driven rain
Entire wind pressure taken here
Cup can still drain water to exterior
Building Science Corporation 2011
Joseph Lstiburek 200


Insulating glass unit
Seal (gasket)
Seal (tape)
Setting block (typically two per unit)
Hole providing drainage and pressurization
Frame
Rough opening
Building Science Corporation
Joseph Lstiburek 201


Outer seal sees water but not pressure; no pressure difference across this seal, therefore no rain entry
Key seal is interior seal as it takes maximum wind load but it does not see water
Pressure in chamber is same as pressure outside on face of assembly
Entire wind pressure taken here
Air enters and pressurizes chamber
Pressure chamber
Building Science Corporation
Joseph Lstiburek 202



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Joseph Lstiburek 203

Building Science Corporation

Joseph Lstiburek 204

Building Science Corporation

Joseph Lstiburek 205

Building Science Corporation

Joseph Lstiburek 206

Building Science Corporation

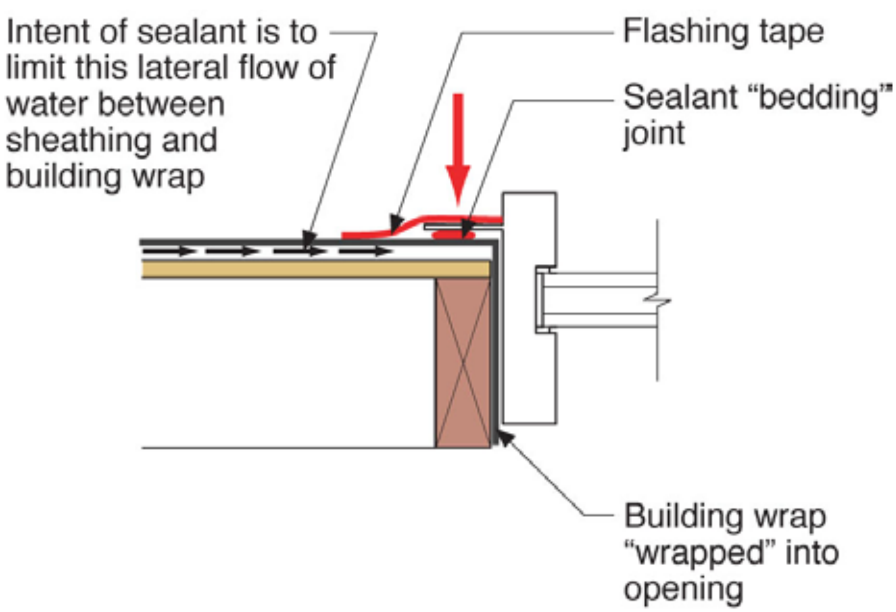
Joseph Lstiburek 207

Building Science Corporation

Joseph Lstiburek 208

Building Science Corporation

Joseph Lstiburek 209



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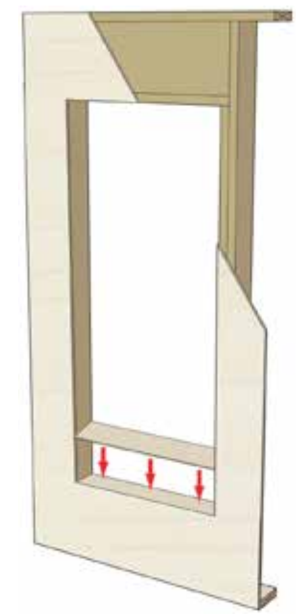
Joseph Lstiburek 210



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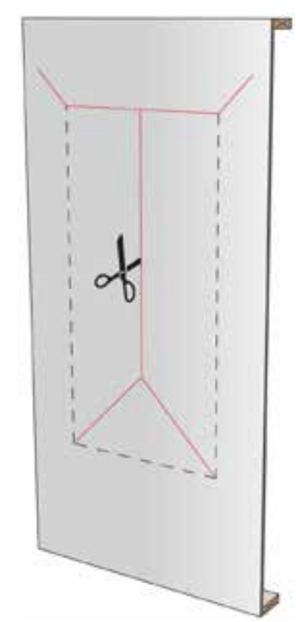
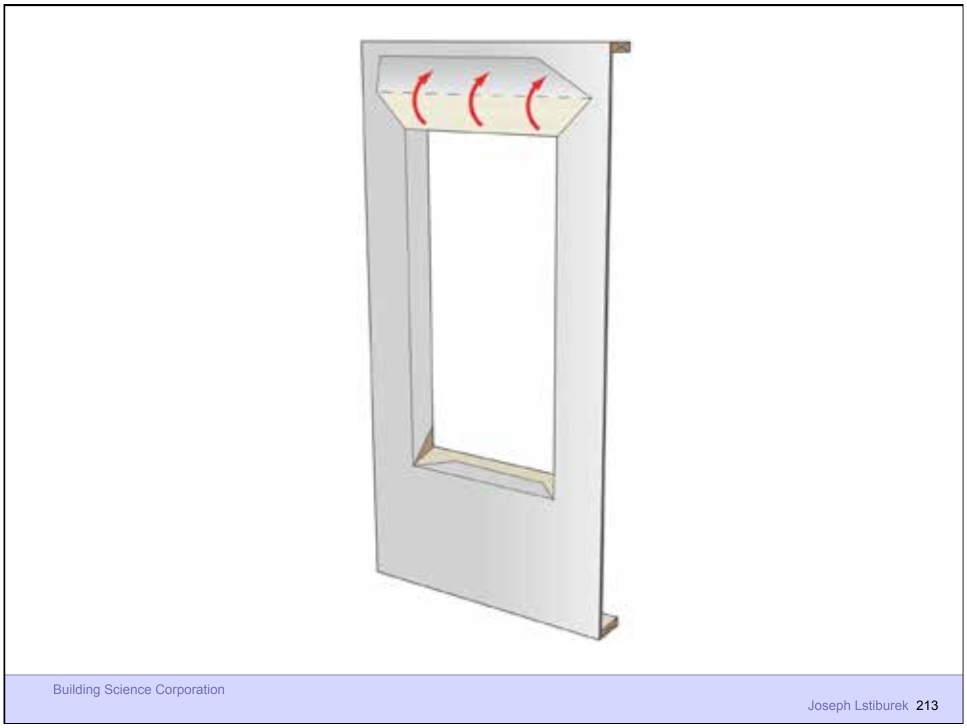
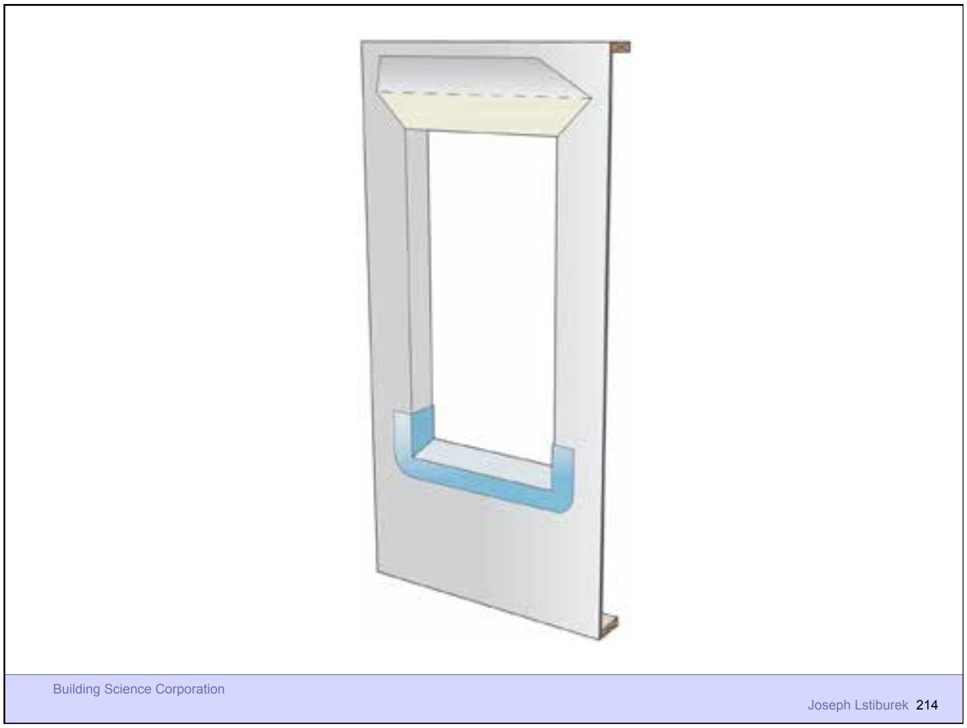
Joseph Lstiburek 211

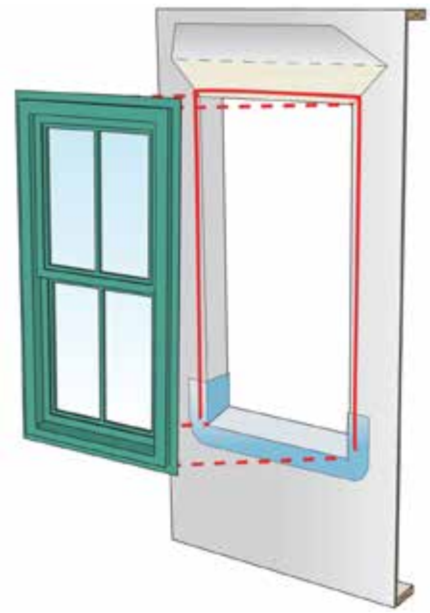


Building Science Corporation

Joseph Lstiburek 212


Building Science Corporation
Joseph Lstiburek 213


Building Science Corporation
Joseph Lstiburek 214



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Joseph Lstiburek 216

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Joseph Lstiburek 217

Building Science Corporation

Joseph Lstiburek 218

Building Science Corporation

Joseph Lstiburek 219

Building Science Corporation

Joseph Lstiburek 220

Building Science Corporation

Joseph Lstiburek 221

Building Science Corporation

Joseph Lstiburek 222

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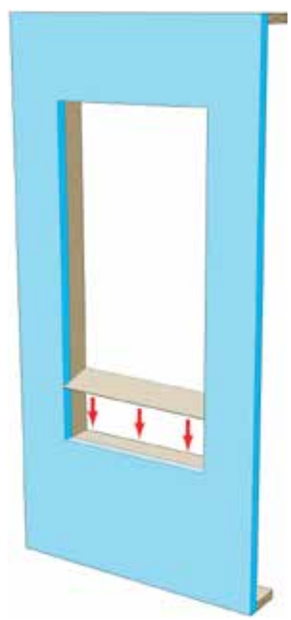
Joseph Lstiburek 223



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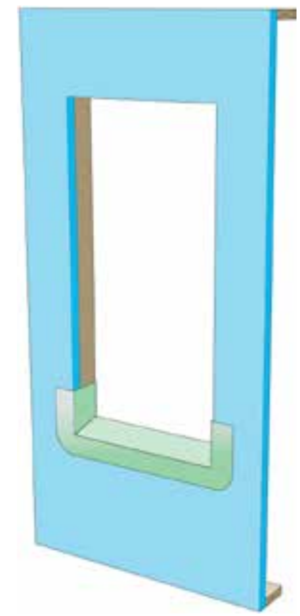
Joseph Lstiburek 224



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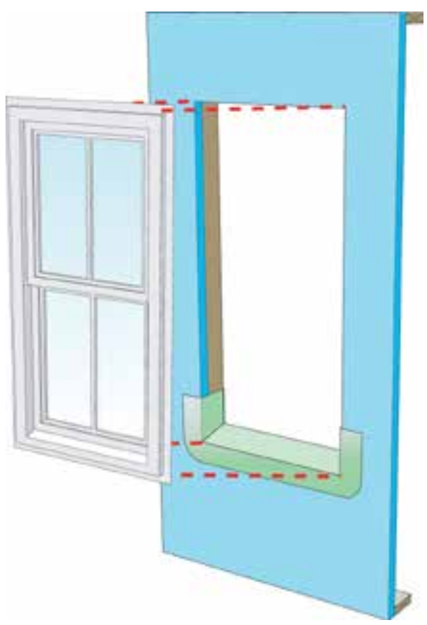
Joseph Lstiburek 225



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Joseph Lstiburek 226

Building Science Corporation

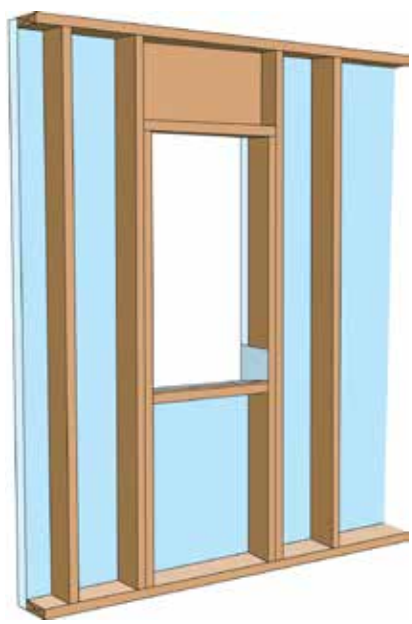
Joseph Lstiburek 227

Building Science Corporation

Joseph Lstiburek 228

Building Science Corporation

Joseph Lstiburek 229



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Building Science Corporation

Joseph Lstiburek 231

Building Science Corporation

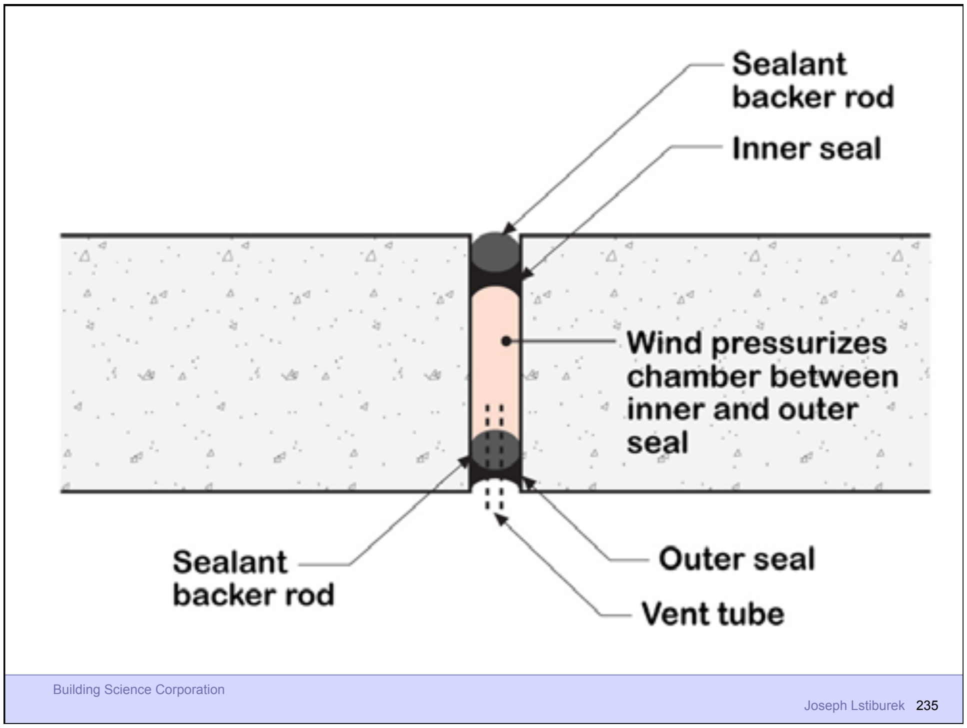
Joseph Lstiburek 232

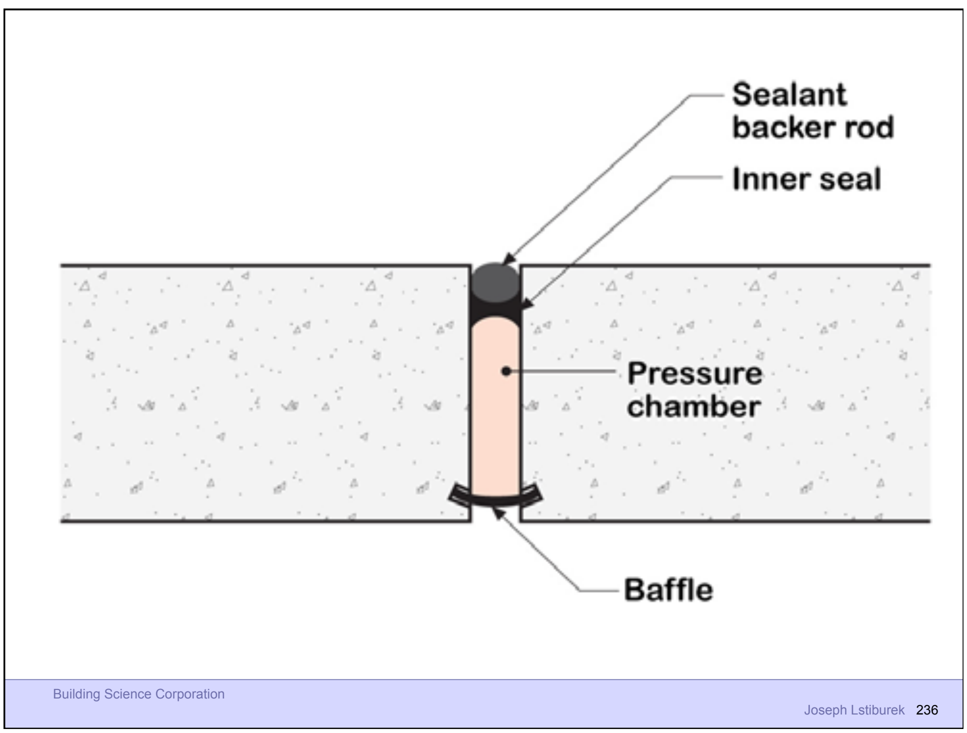
Building Science Corporation

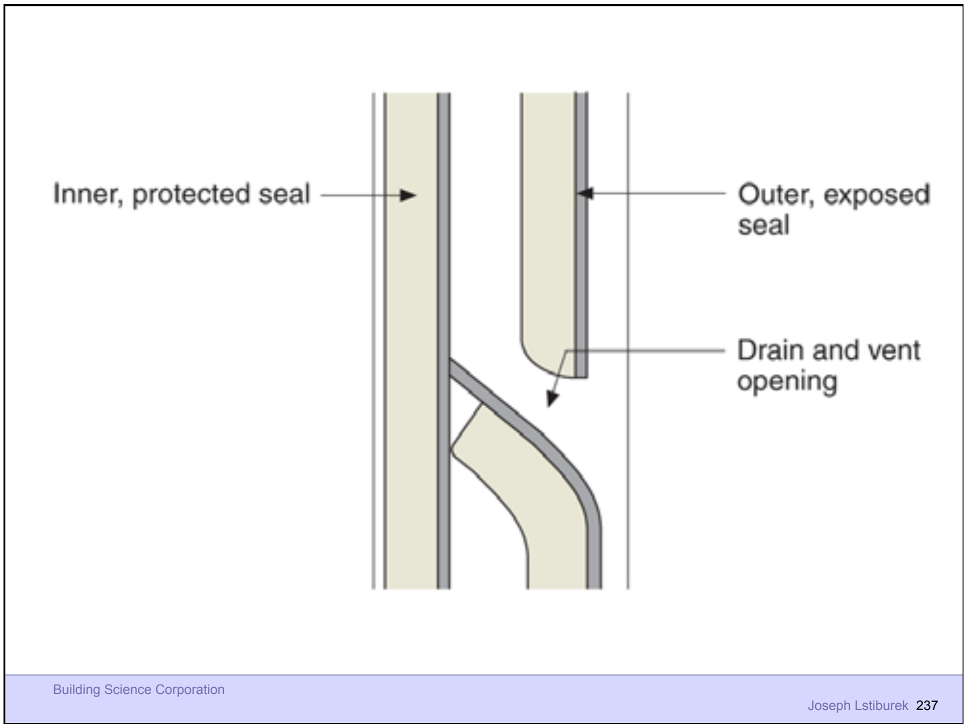
Joseph Lstiburek 233

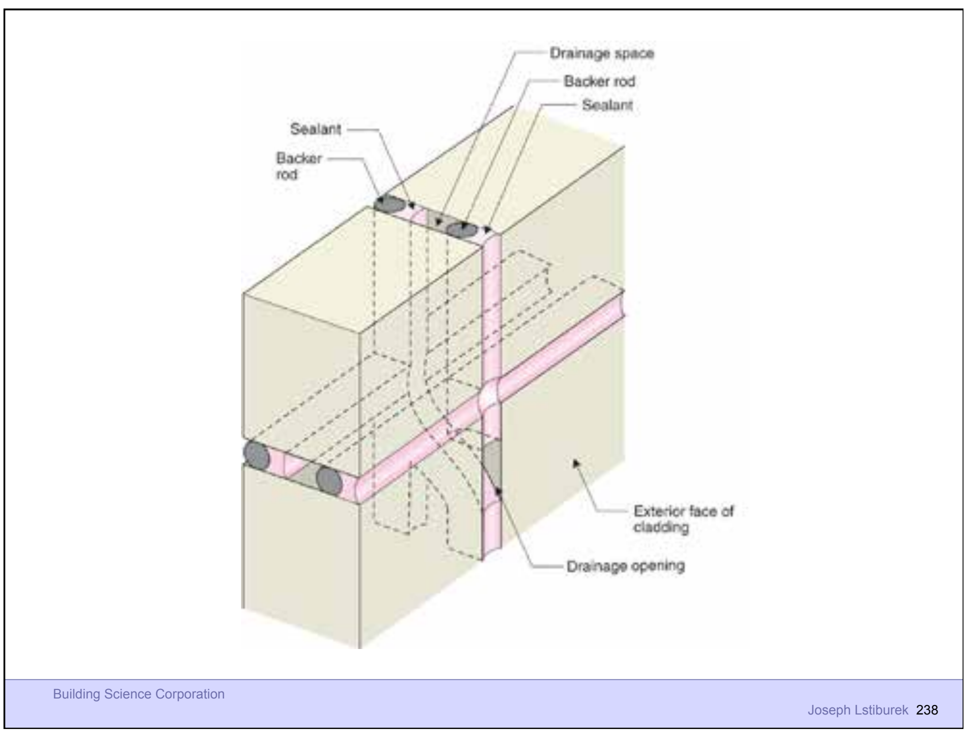
Building Science Corporation

Joseph Lstiburek 234


Sealant
backer rod
Inner seal
Wind pressurizes
chamber between
inner and outer
seal
Sealant
backer rod
Outer seal
Vent tube
Building Science Corporation
Joseph Lstiburek 235


Sealant
backer rod
Inner seal
Pressure
chamber
Baffle
Building Science Corporation
Joseph Lstiburek 236


Inner, protected seal
Outer, exposed seal
Drain and vent opening
Building Science Corporation
Joseph Lstiburek 237


Drainage space
Backer rod
Sealant
Sealant
Backer rod
Exterior face of cladding
Drainage opening
Building Science Corporation
Joseph Lstiburek 238

Interesting Complications

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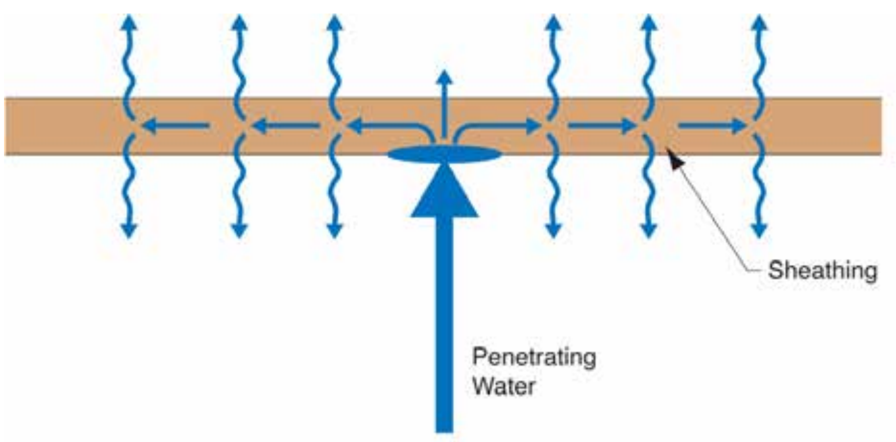
Joseph Lstiburek 239



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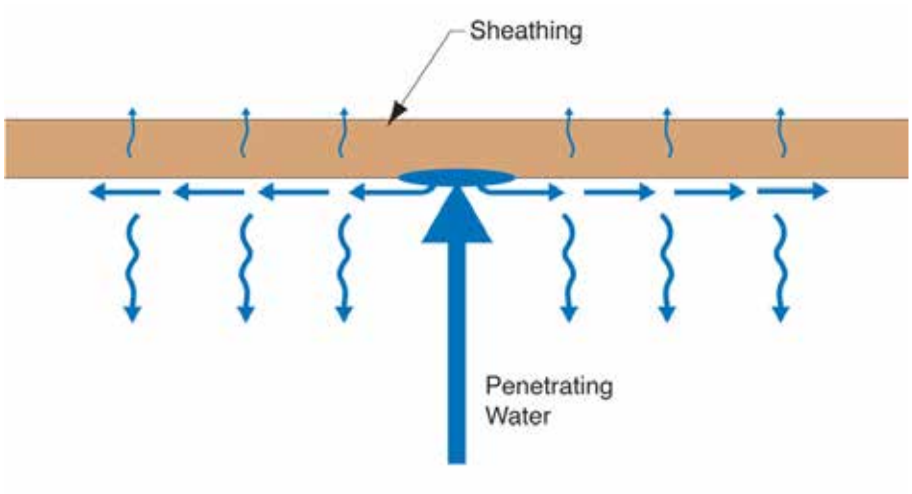
Joseph Lstiburek – Rain Control 240



Building Science Corporation
Joseph Lstiburek – Rain Control 241

Building Science Corporation
Joseph Lstiburek 242

Building Science Corporation

Joseph Lstiburek 243

Building Science Corporation

Joseph Lstiburek 244

Building Science Corporation

Joseph Lstiburek 245

Building Science Corporation

Joseph Lstiburek 246

Building Science Corporation

Joseph Lstiburek 247

Building Science Corporation

Joseph Lstiburek 248

Building Science Corporation

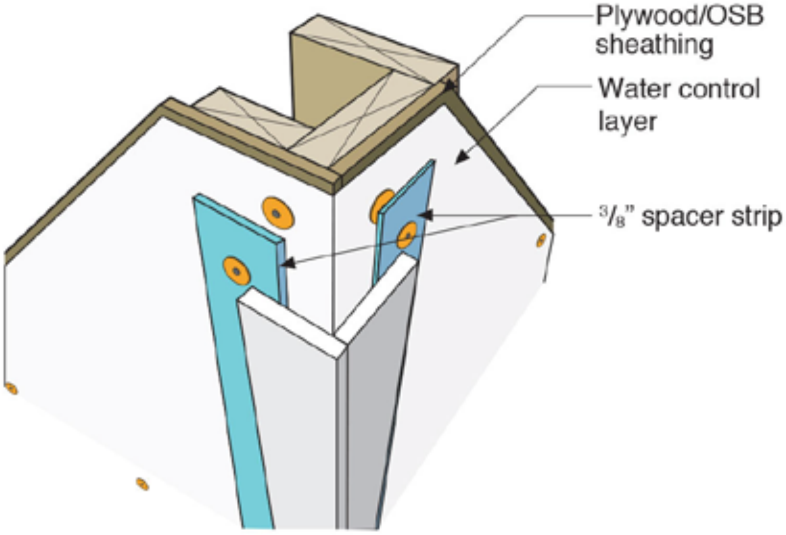
Joseph Lstiburek 249

Building Science Corporation

Joseph Lstiburek – Rain Control 250

Building Science Corporation

Joseph Lstiburek – Rain Control 251



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Joseph Lstiburek 252

Building Science Corporation

Joseph Lstiburek 253

Building Science Corporation

Joseph Lstiburek 254

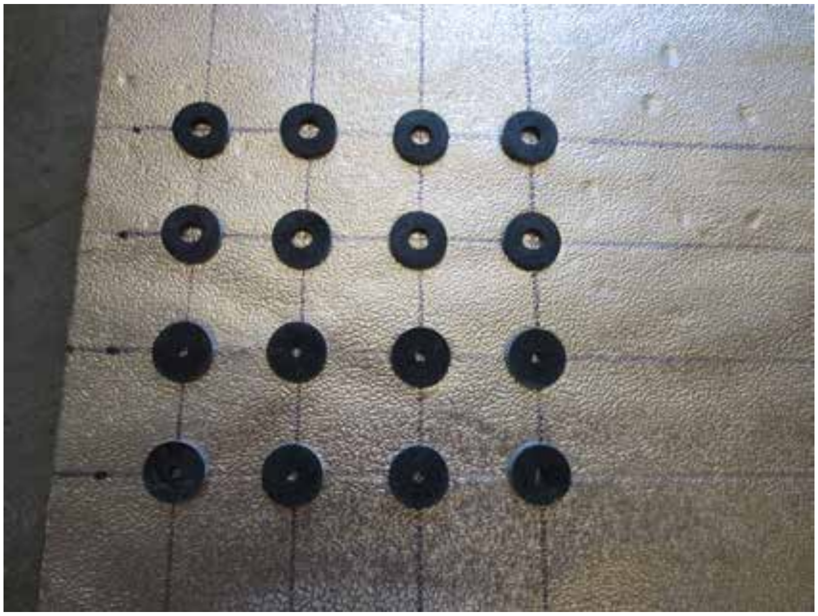
Building Science Corporation

Joseph Lstiburek 255

Rain Screen

Building Science Corporation

Joseph Lstiburek 256



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Joseph Lstiburek 257

Beer Screen?

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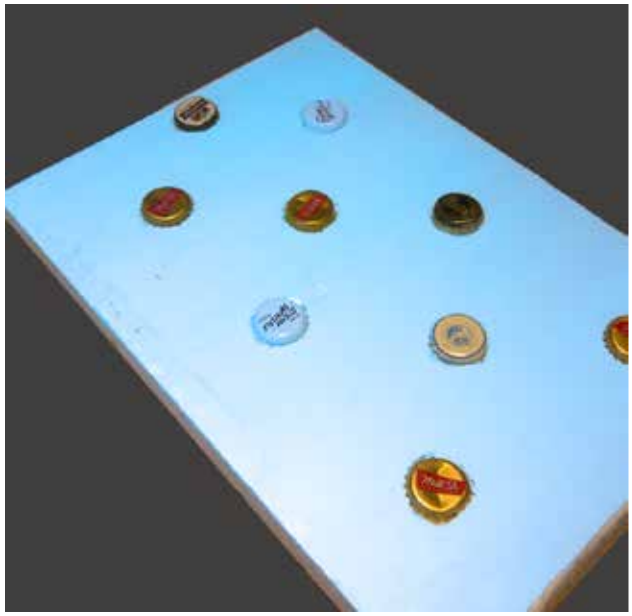
Joseph Lstiburek 258



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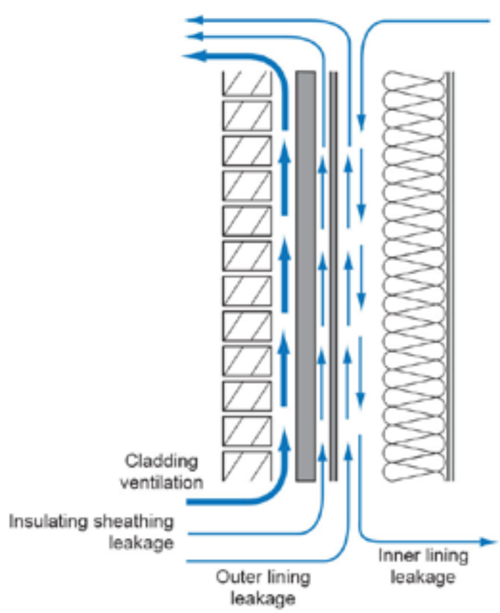
Joseph Lstiburek 259



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Vapor	Diffusion	Vapor Concentration
	Convective Flow	Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure
	Osmosis	Solute Concentration
	Gravitational Flow	Height
	Surface Tension	Surface Energy
	Momentum	Kinetic Energy
	Convective Flow	Air Pressure

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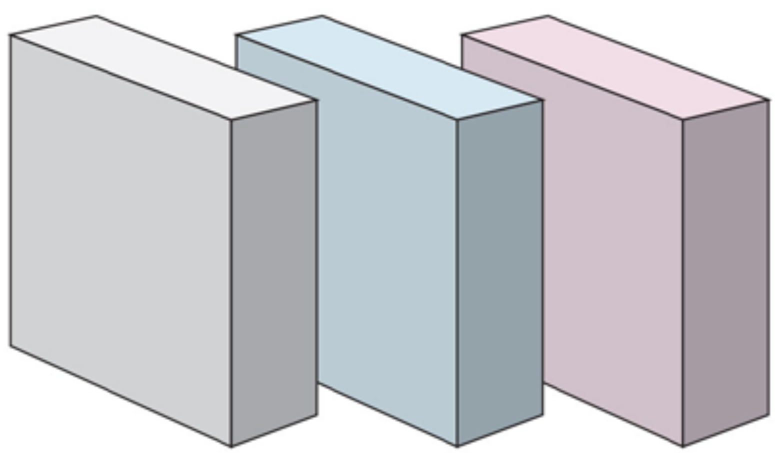
Joseph Lstiburek 261



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Joseph Lstiburek 262