

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

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- 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

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Damage Functions

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Damage Functions
Water
Heat
Ultra Violet Radiation

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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

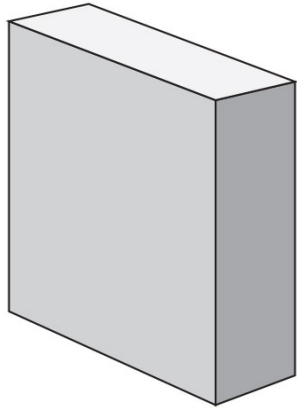
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HAM

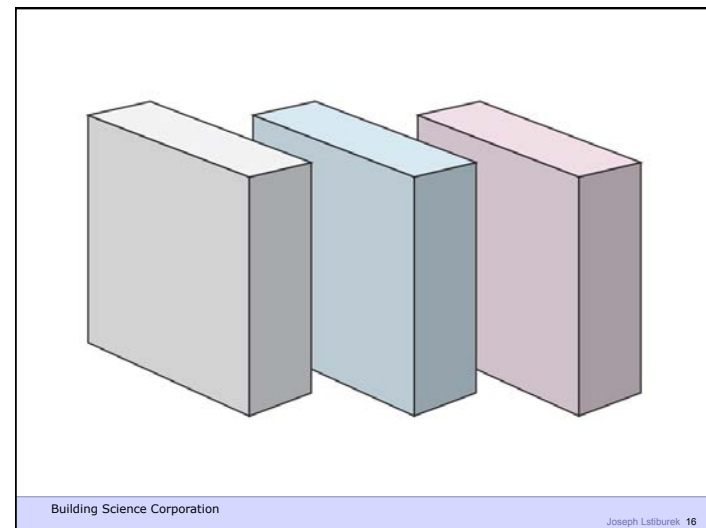
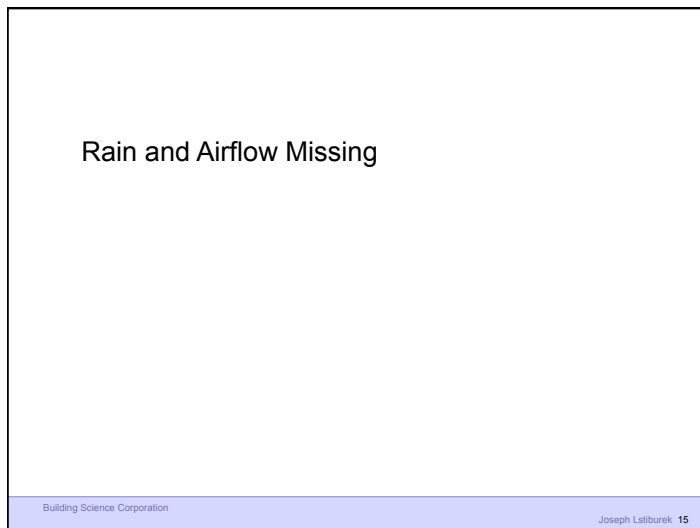
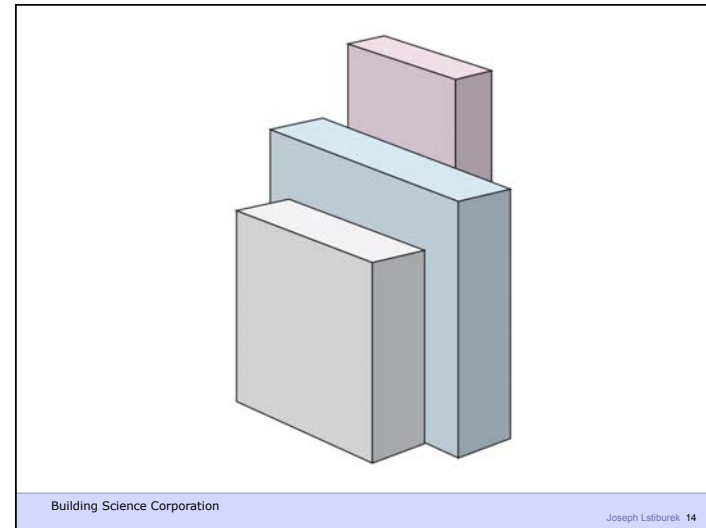
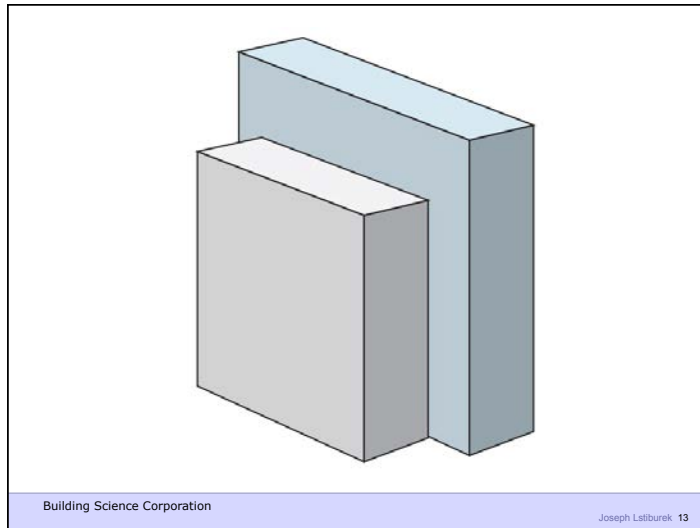
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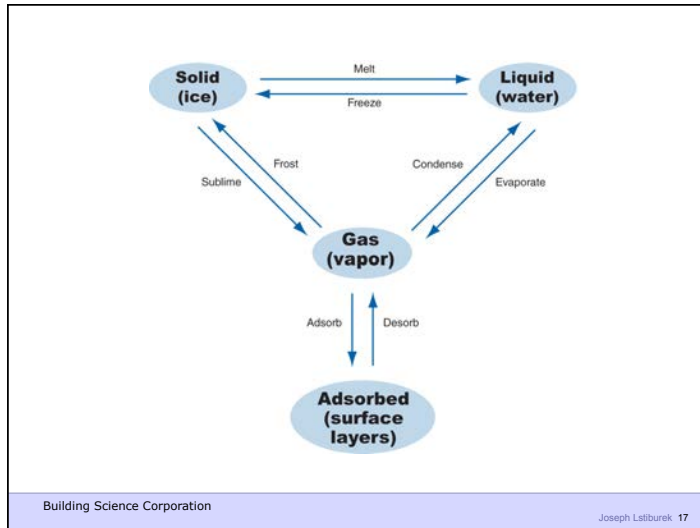
Hygrothermal Analysis

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Moisture Transport in Porous Media

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

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Recall That Rain and Airflow Are Missing

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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

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Laws of Thermodynamics

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

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2nd Law of Thermodynamics

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

Rudolf Clausius

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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

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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

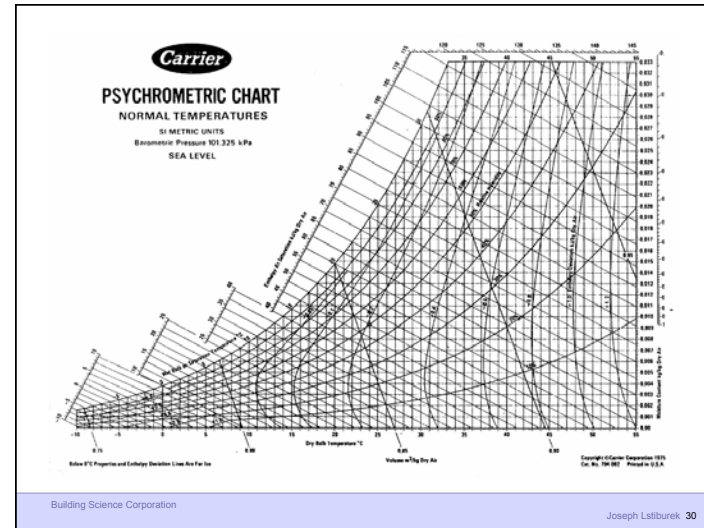
Vapor Diffusion

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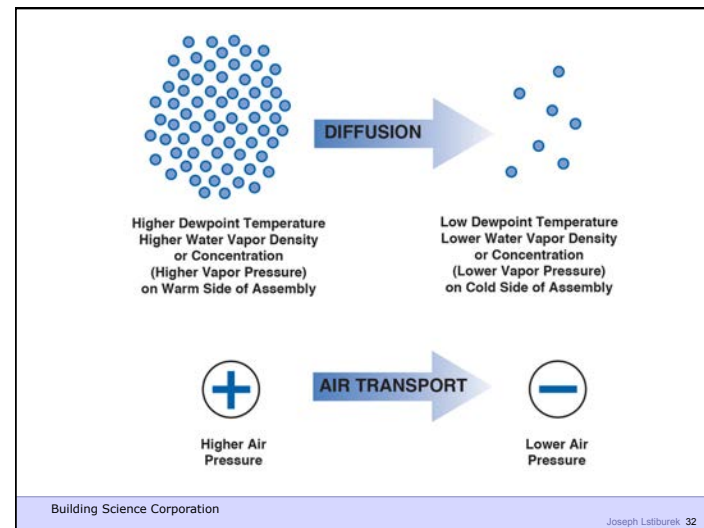
Thermodynamic Potential

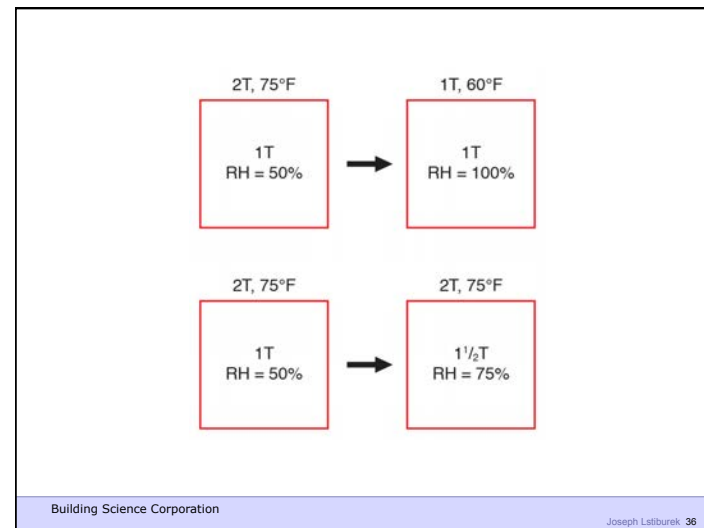
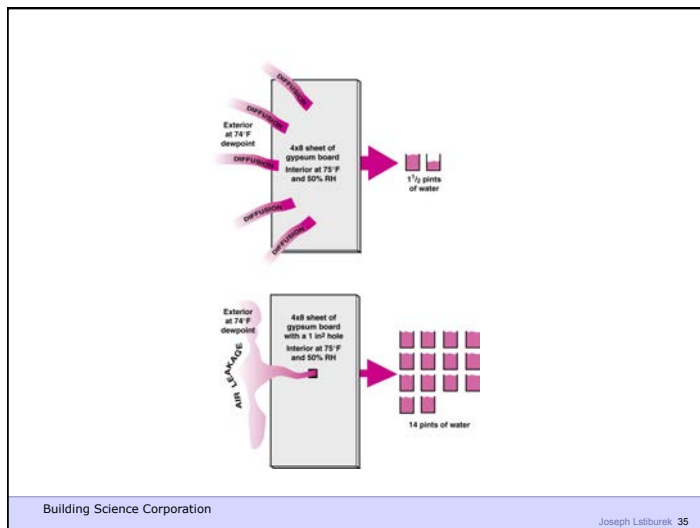
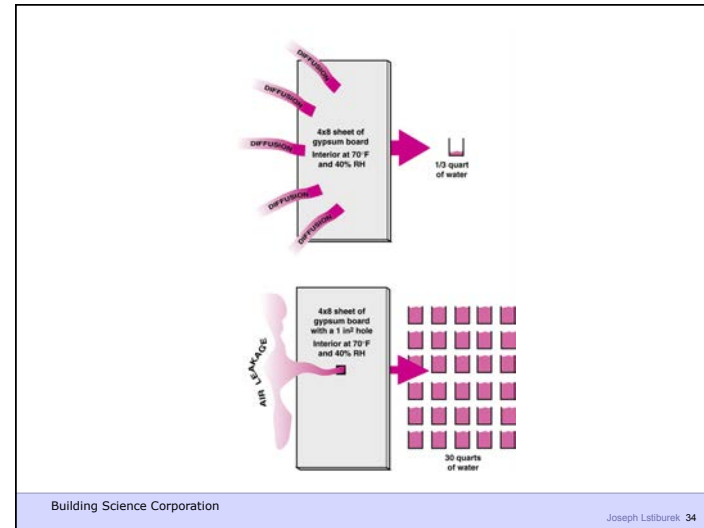
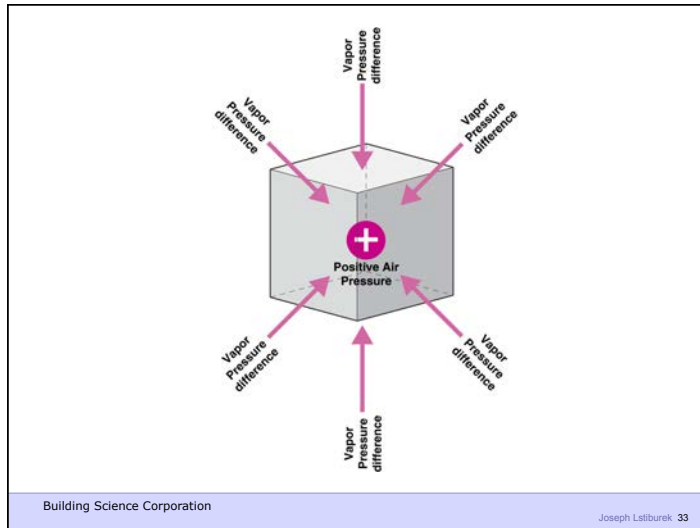
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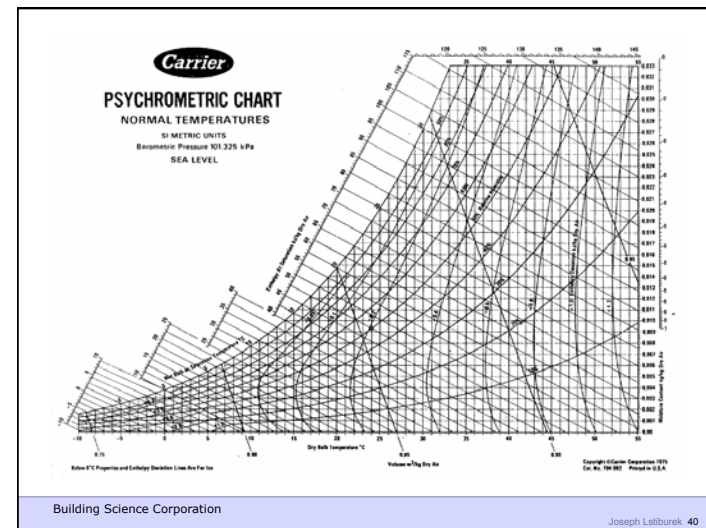
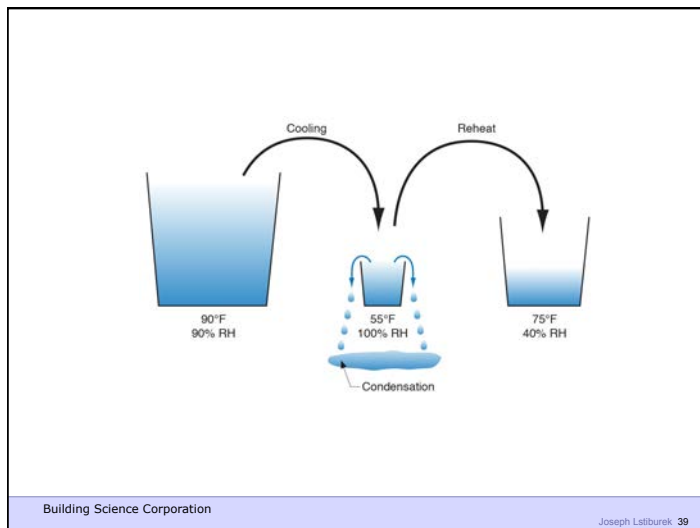
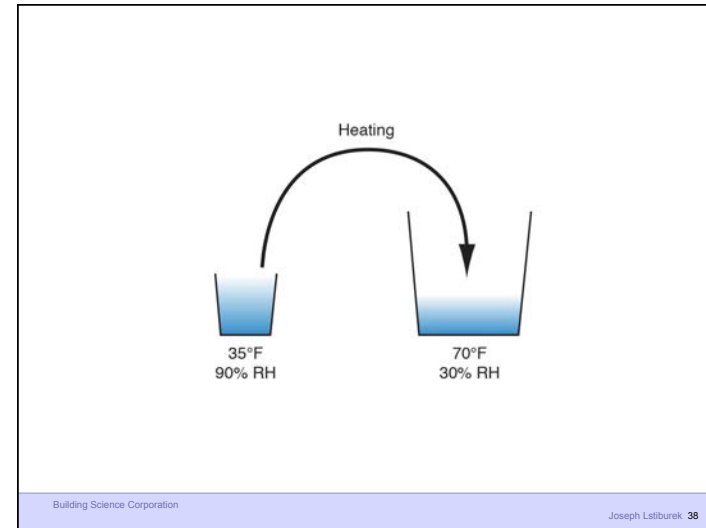
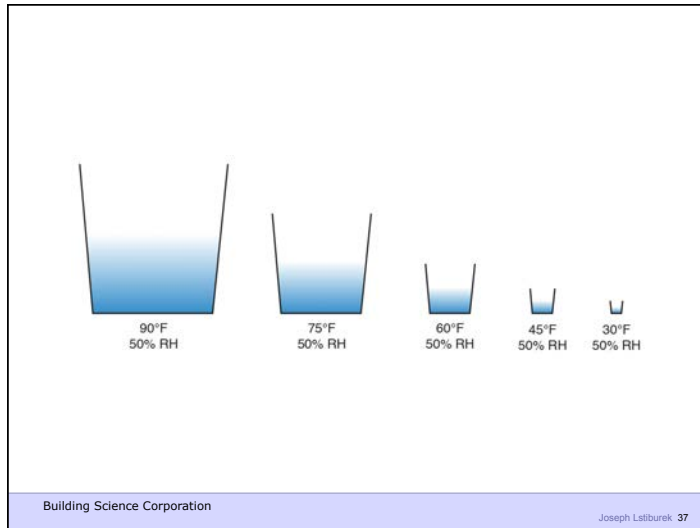


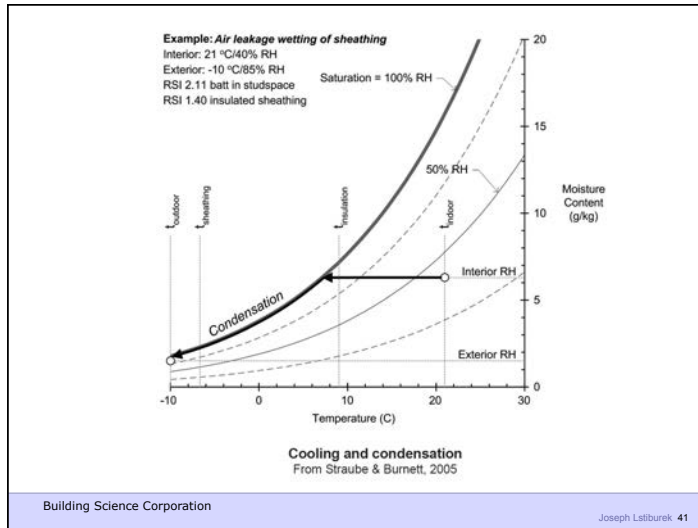
Vapor	Diffusion Convective Flow	Vapor Concentration Air Pressure
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Water Molecules

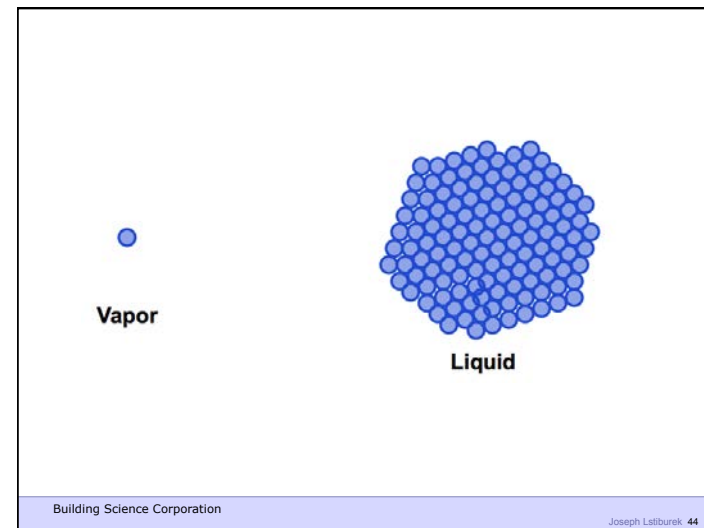
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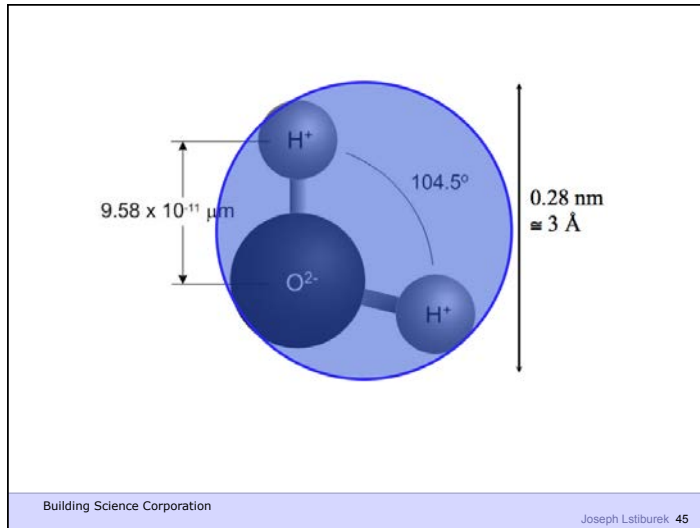
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Size Matters

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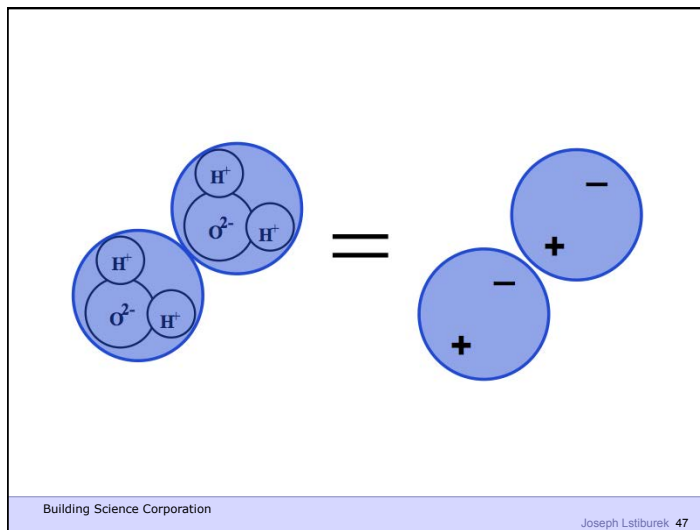
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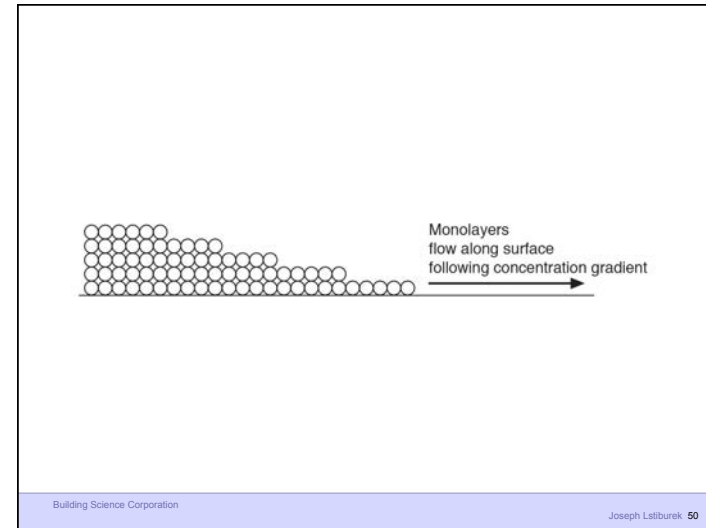
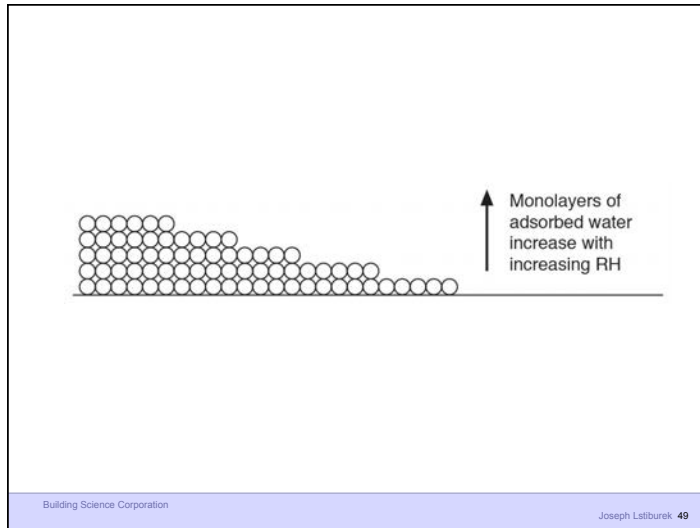
Polar Molecule

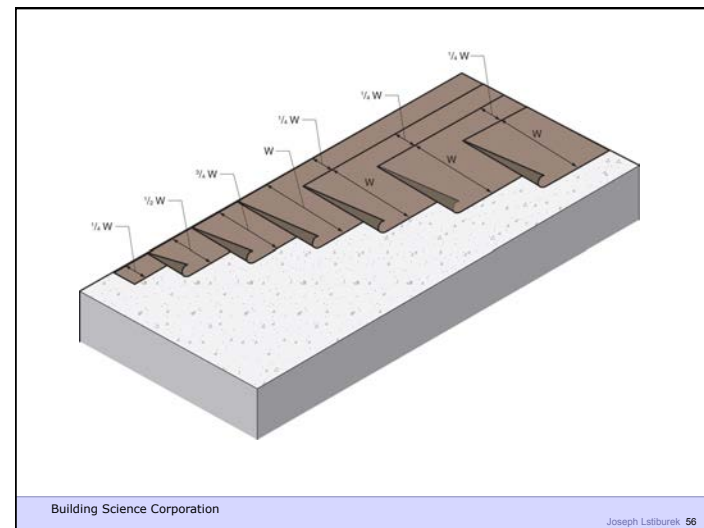
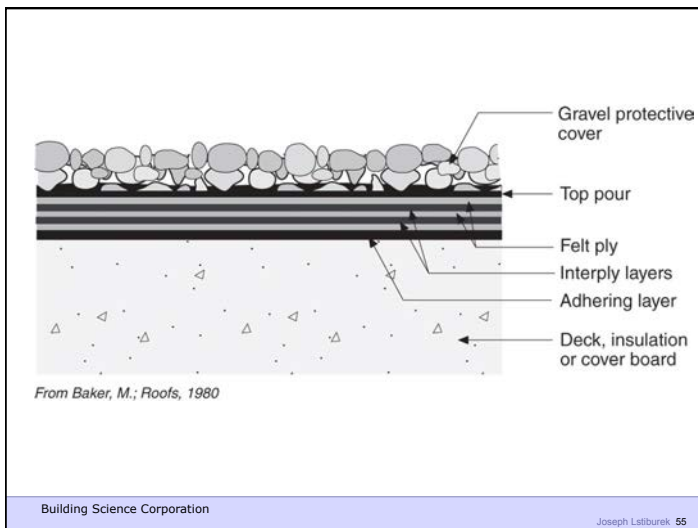
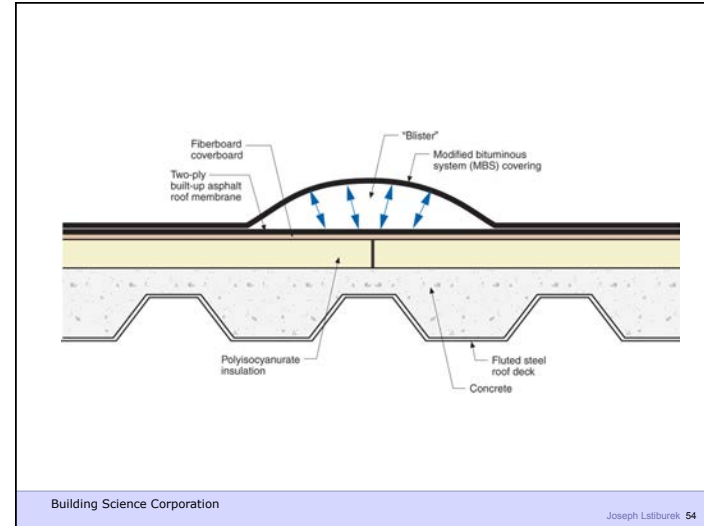
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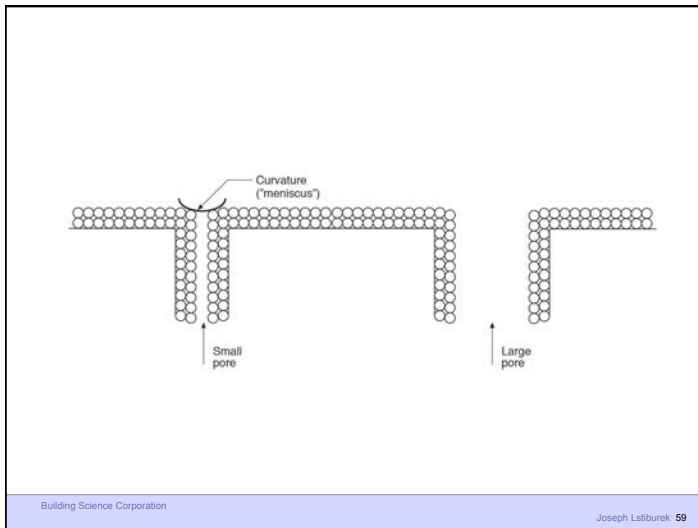
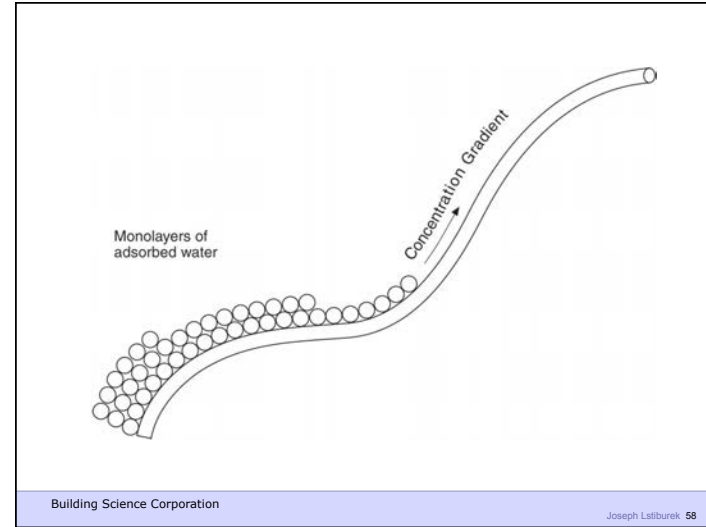
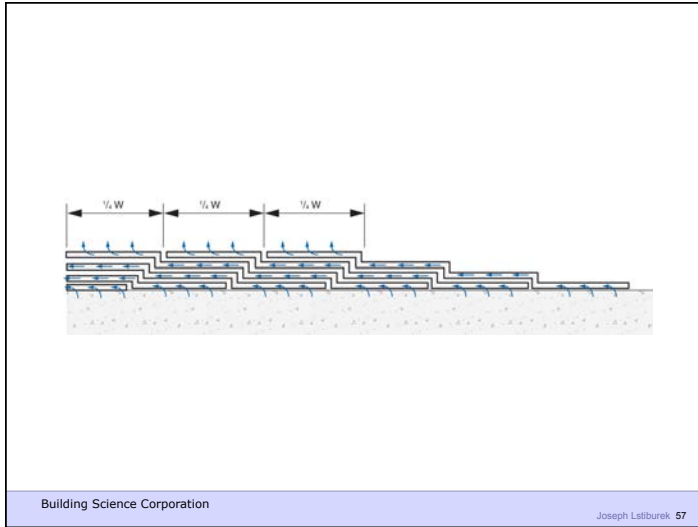


Vapor	Diffusion Convective Flow	Vapor Concentration Air Pressure
Adsorbate	Surface Diffusion	Concentration

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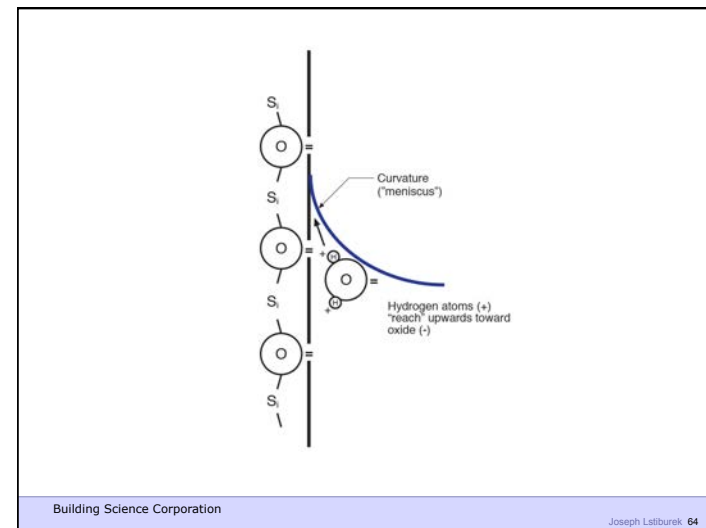
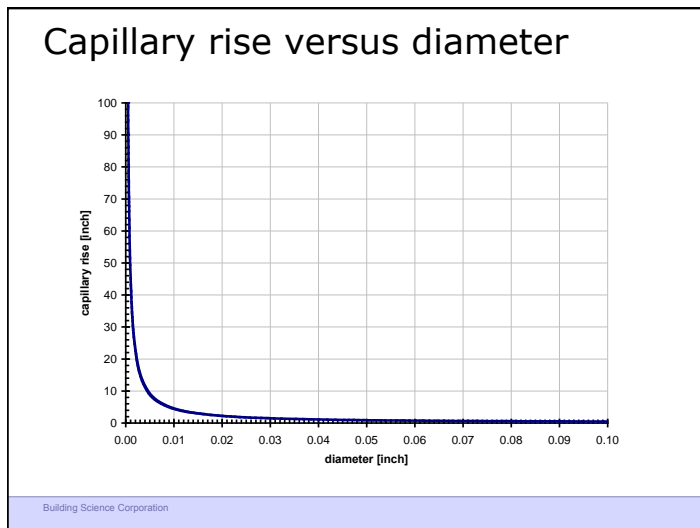
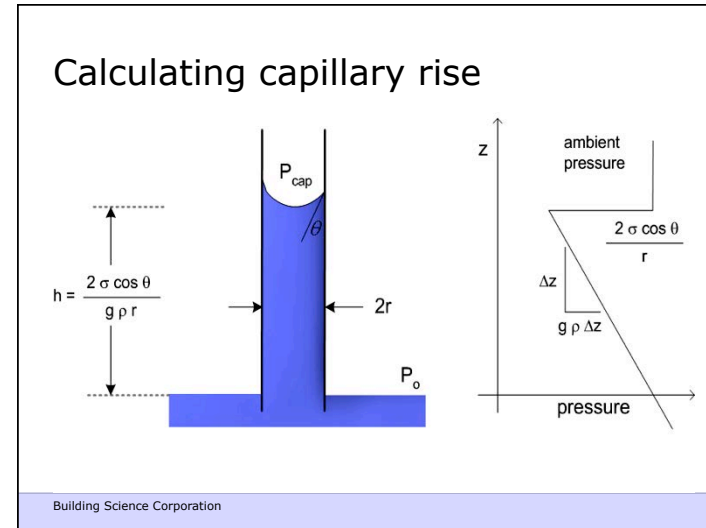


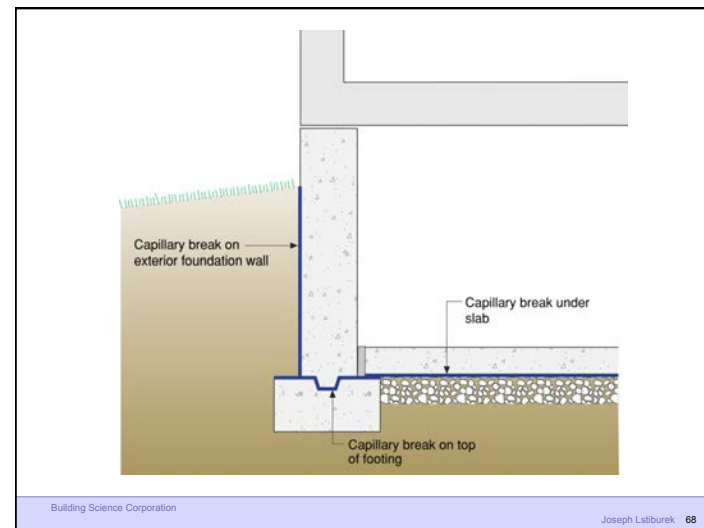
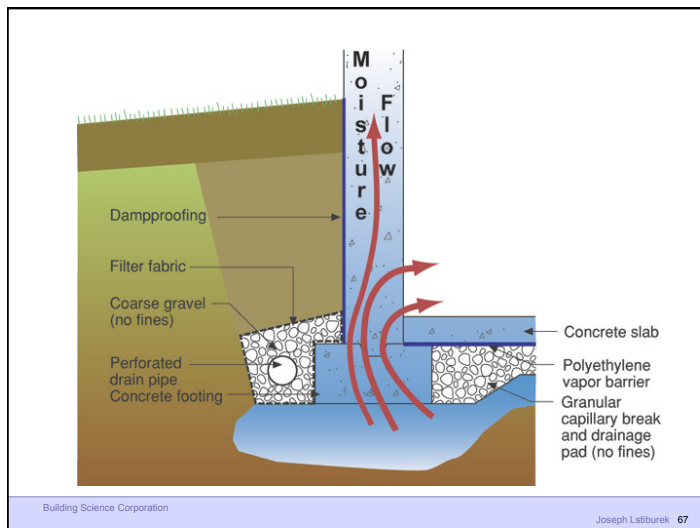
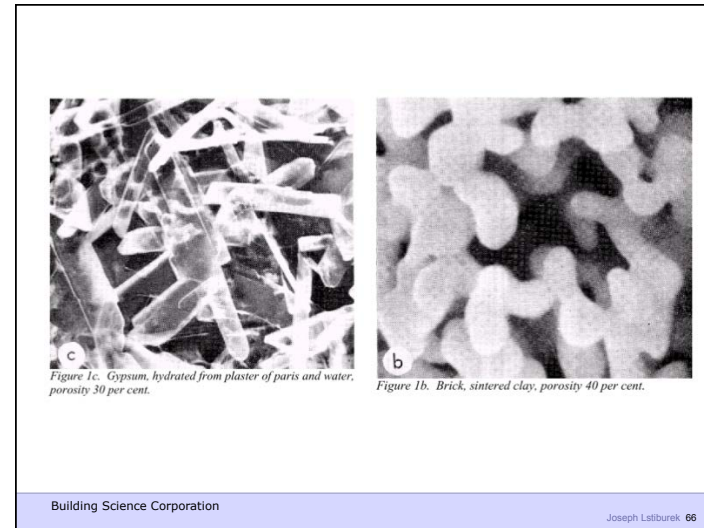
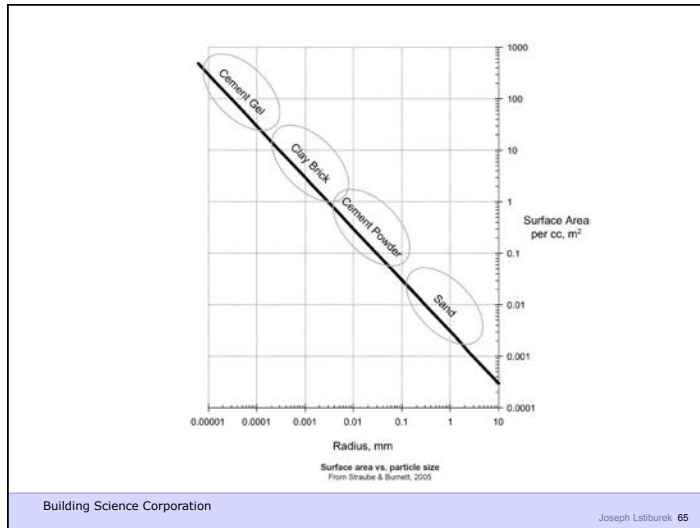




Vapor	Diffusion Convective Flow	Vapor Concentration Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow	Suction Pressure

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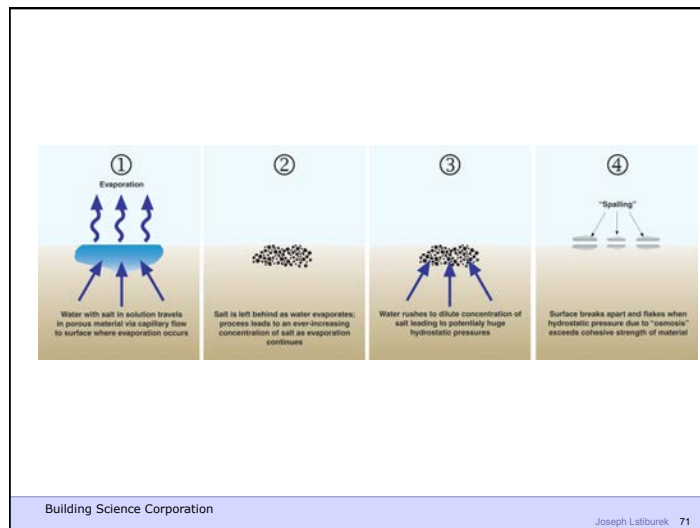
Vapor	Diffusion Convective Flow	Vapor Concentration Air Pressure
Adsorbate	Surface Diffusion	Concentration
Liquid	Capillary Flow Osmosis	Suction Pressure Solute Concentration

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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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Pressures

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

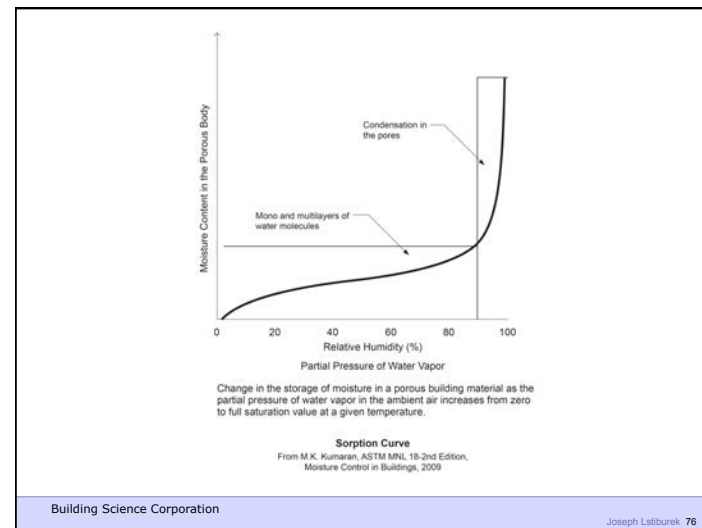
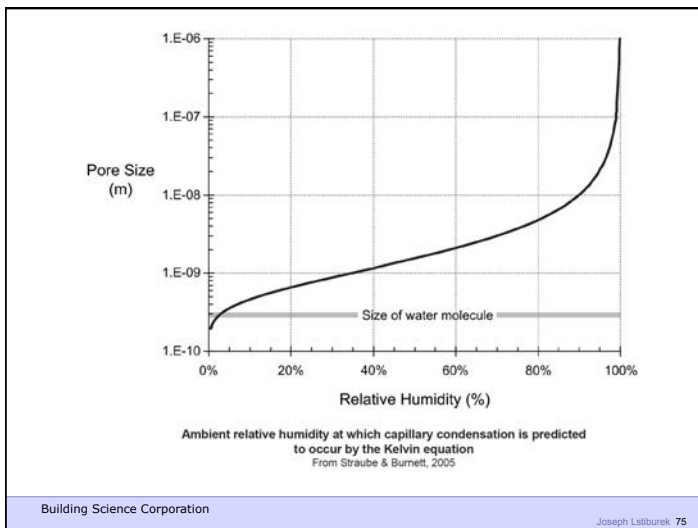
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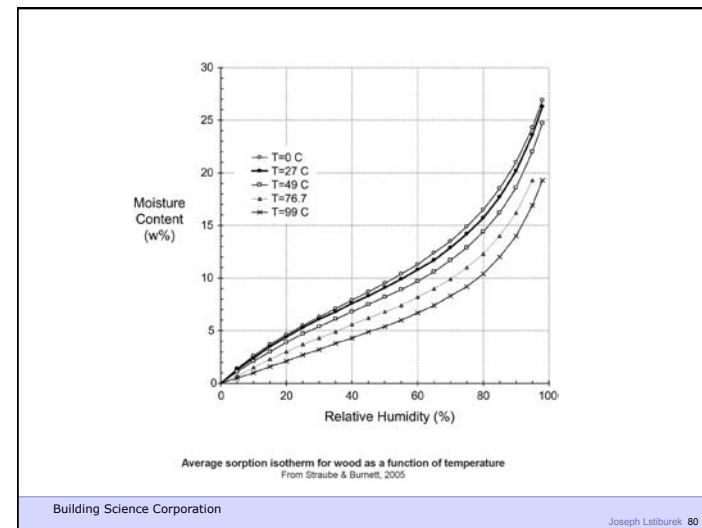
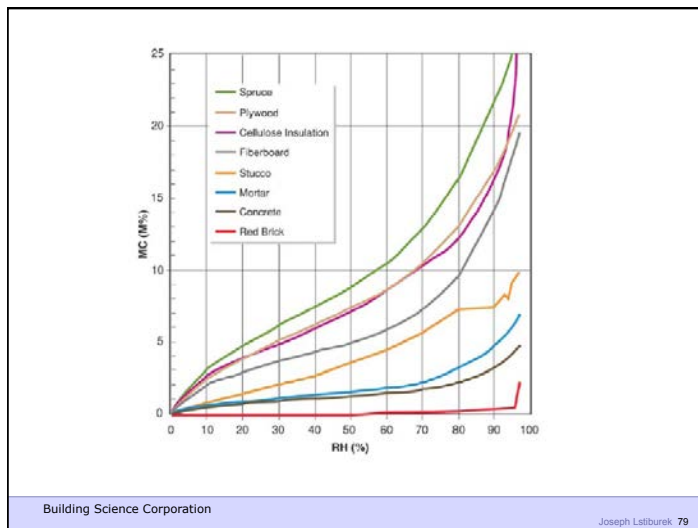
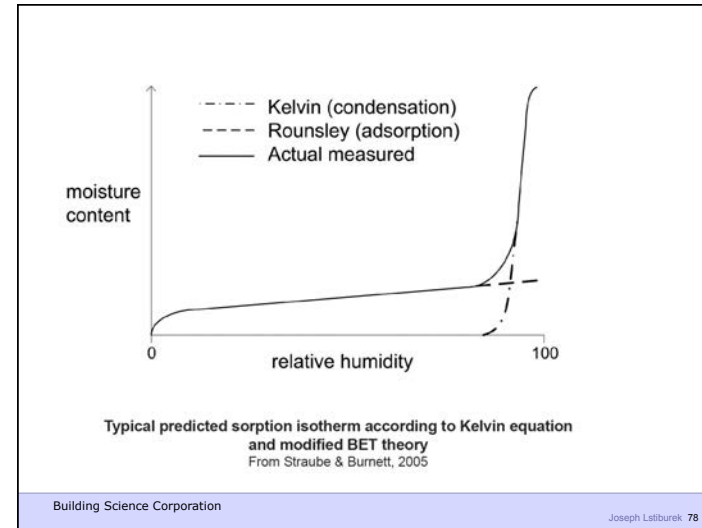
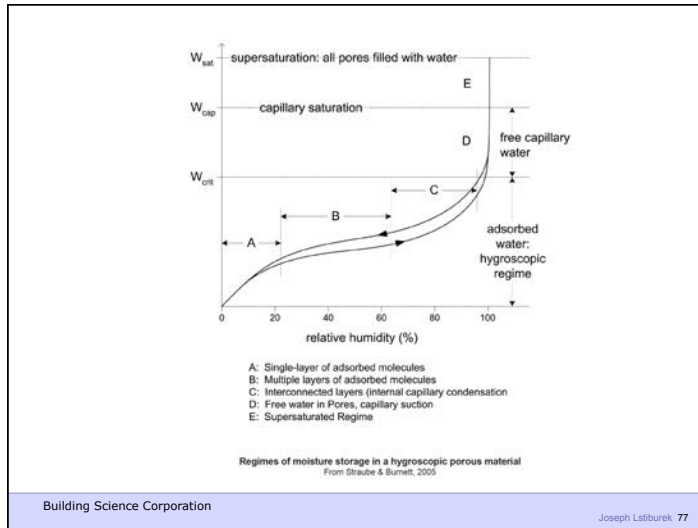


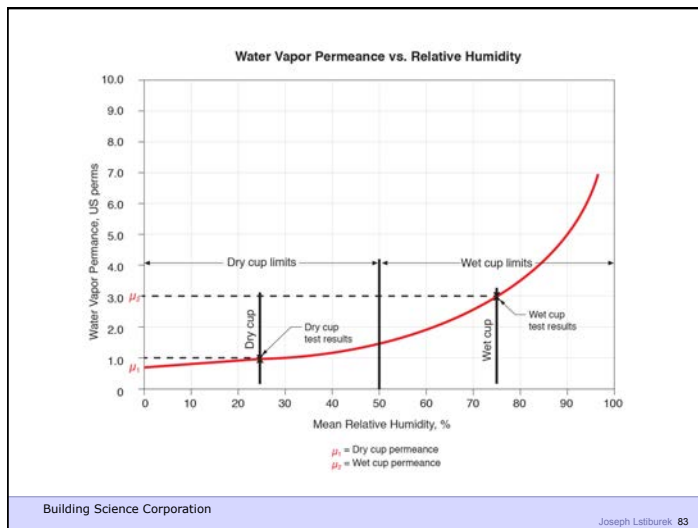
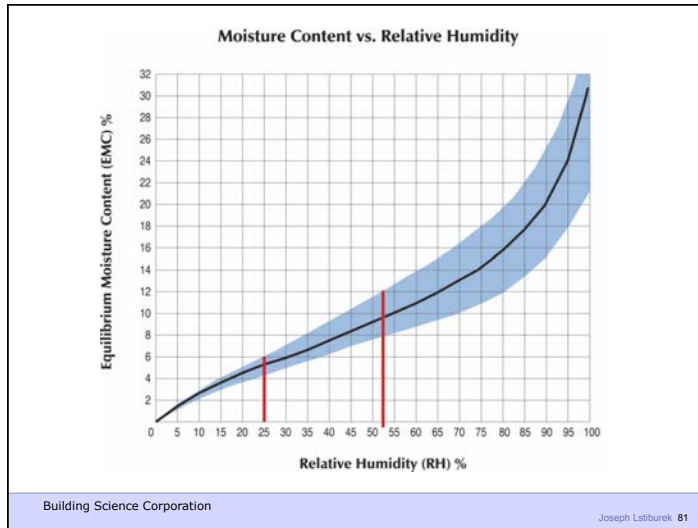
Combined Flows

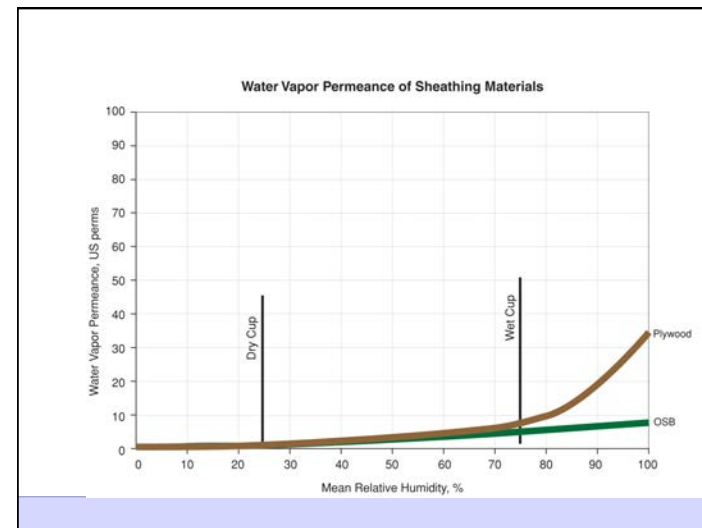
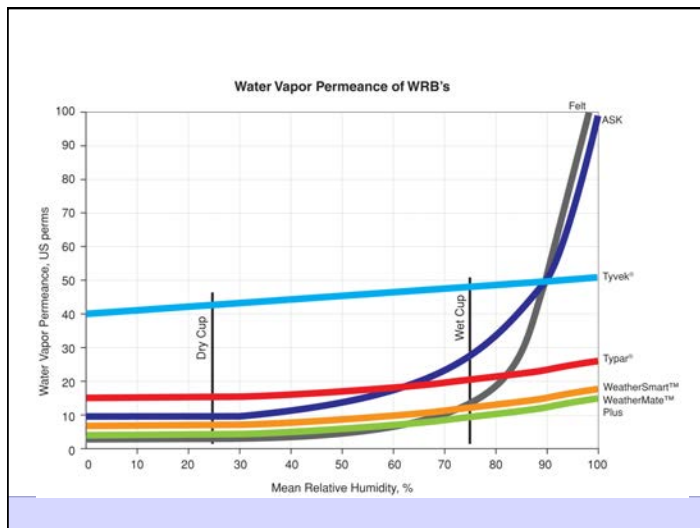
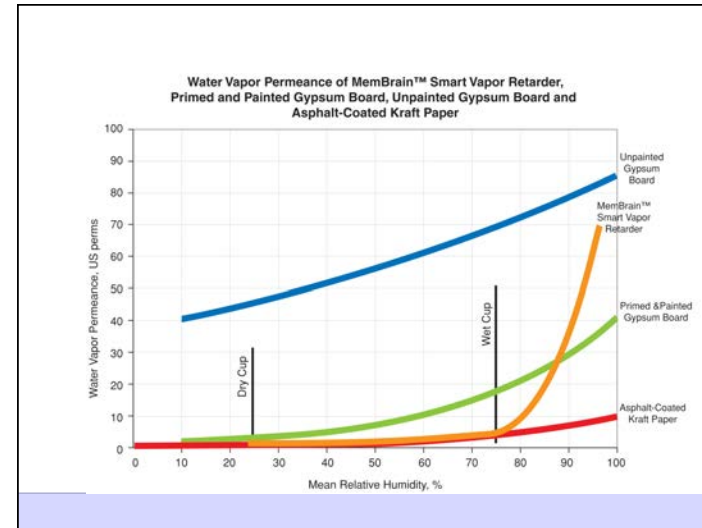
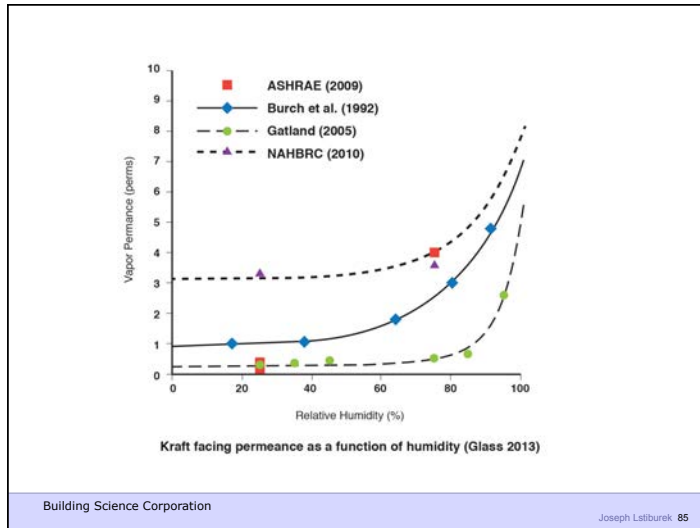
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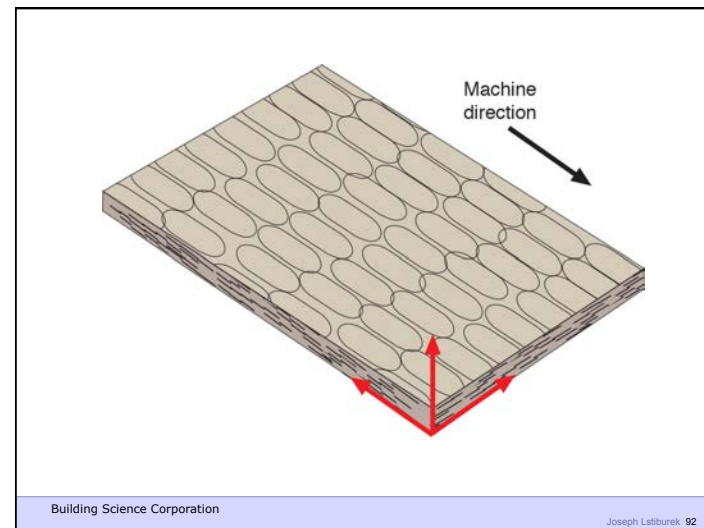
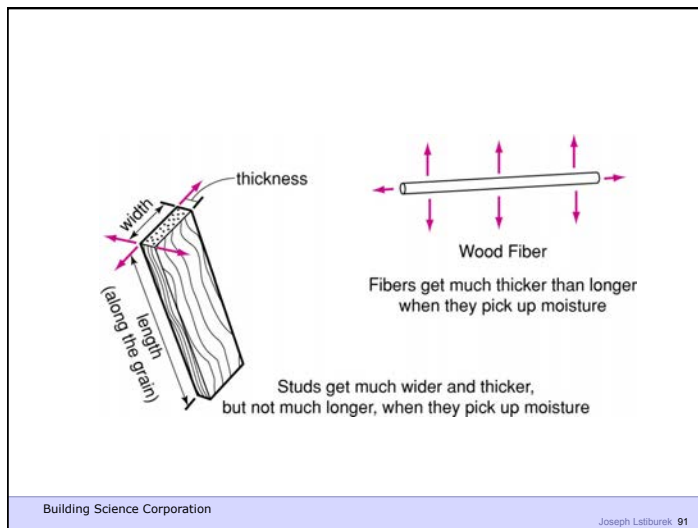
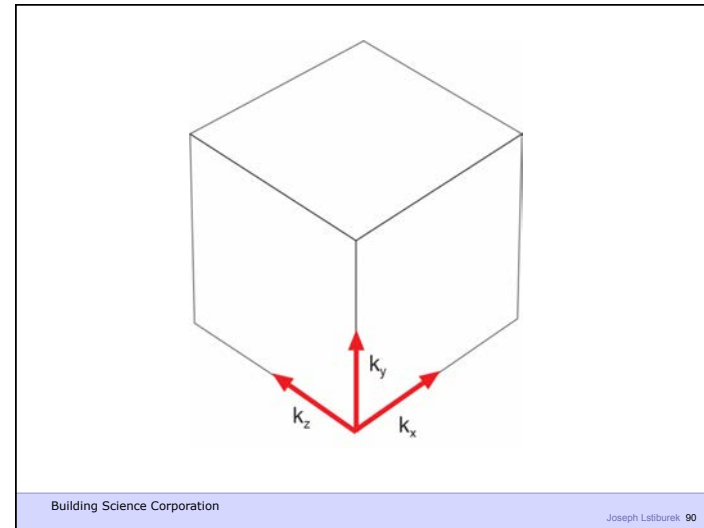
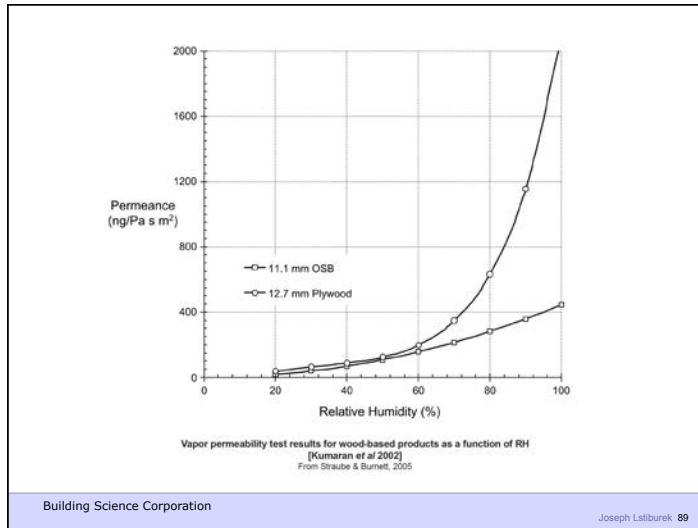
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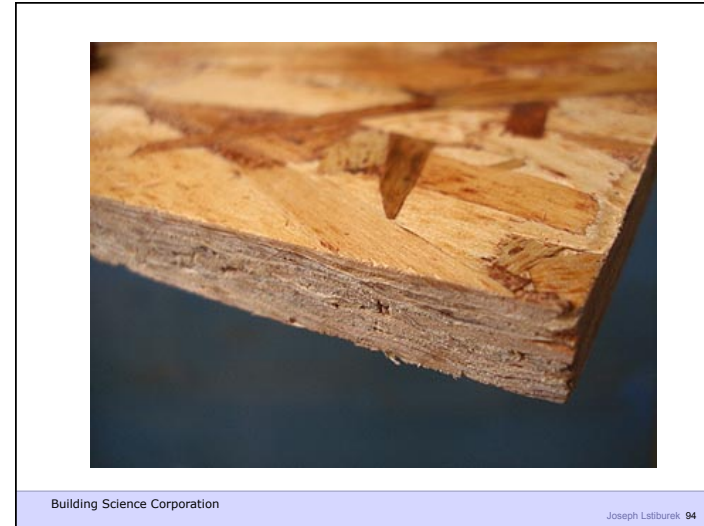
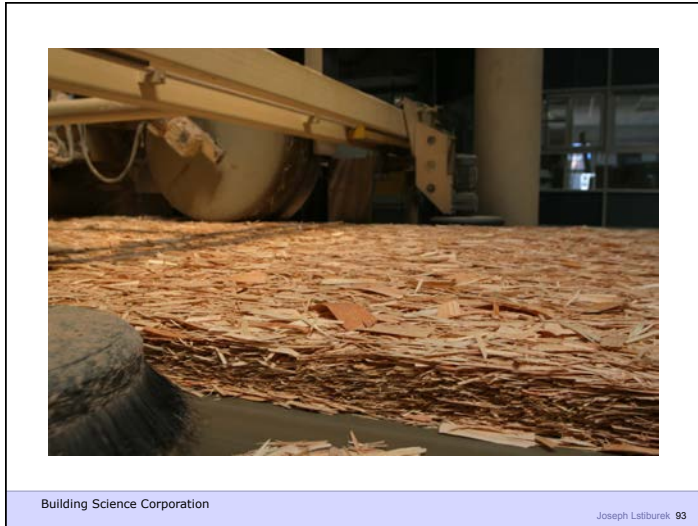






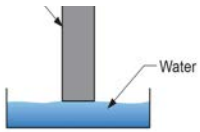






Still More Combined Flows

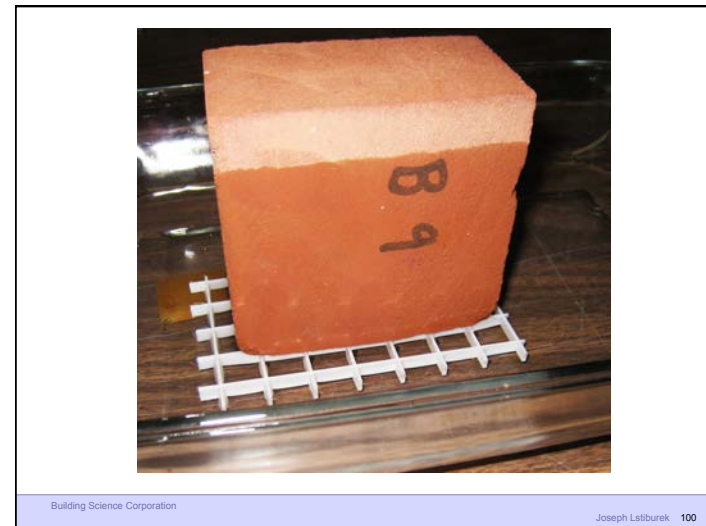
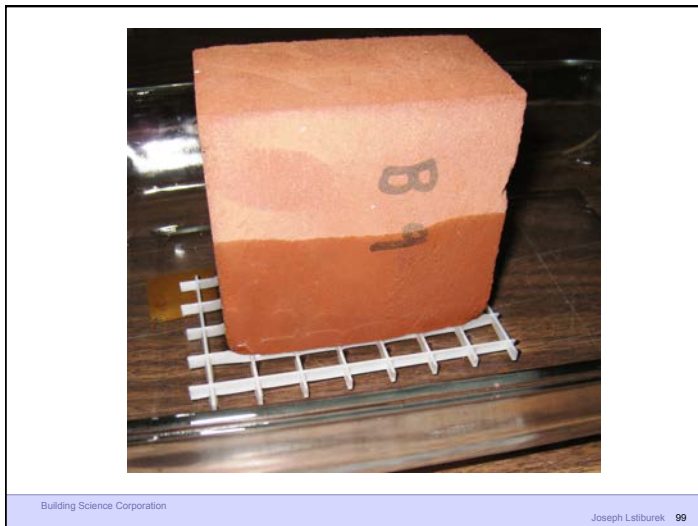
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Schematic drawing of the transient moisture transport process that is used to determine the liquid diffusivity of porous building materials. All four longitudinal surfaces of the test specimen are coated with water vapor resistant epoxy resin and one 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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How Does Wetting Occur?

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- "non-wetable" surface
- water repellent surface
- hydrophobic 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 repellent surface
- hydroscopic 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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Non-wetting
 $\theta > 90^\circ$

Partial wetting
 $\theta = 90^\circ$

Wetting
 $\theta < 90^\circ$

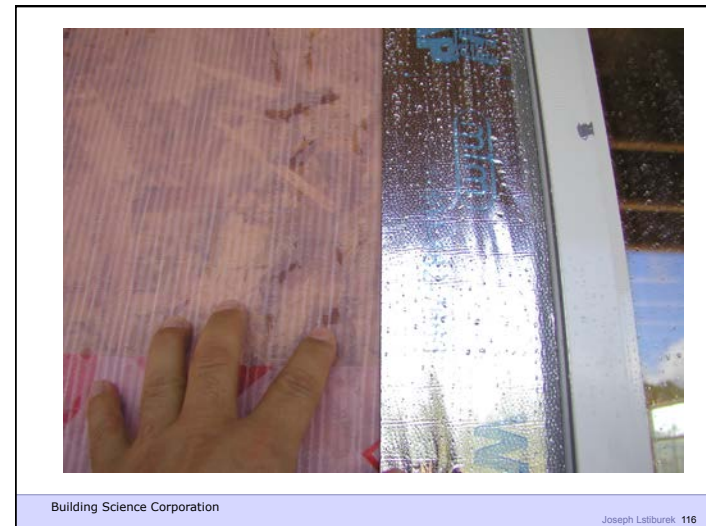
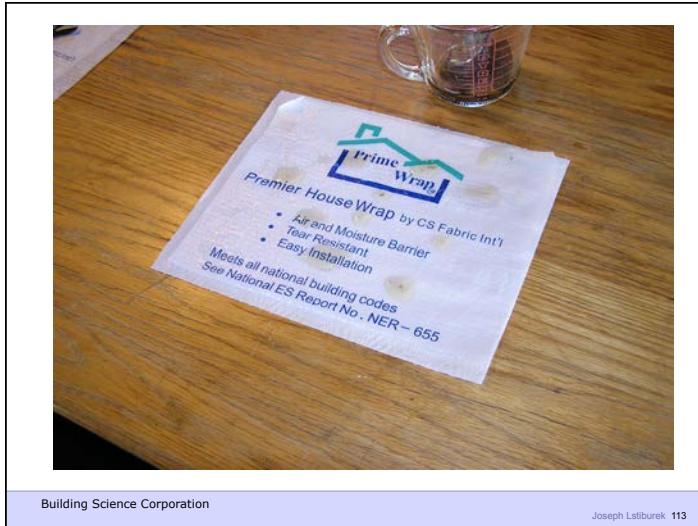
Perfect wetting
 $\theta = 0^\circ$

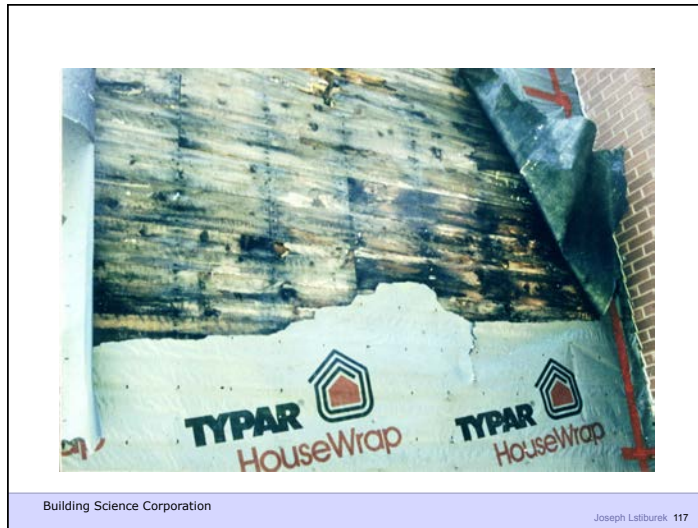
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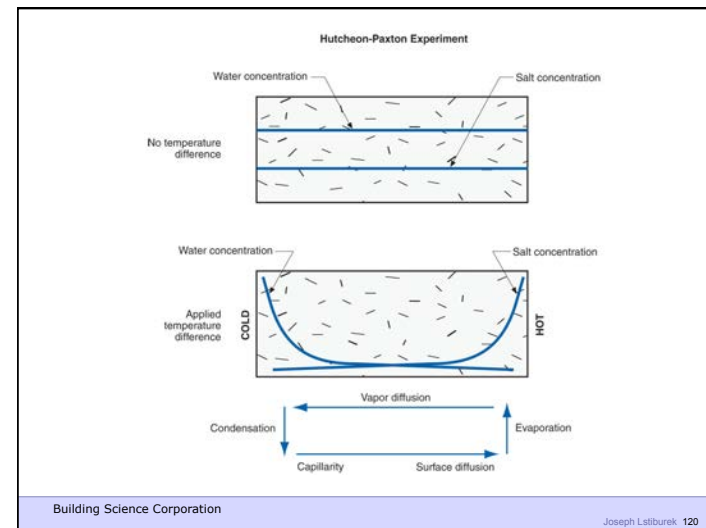


	Surface Energy
Water (20 C)	73 dynes/cm
Water (100 C)	59 dynes/cm
Epoxy	46 dynes/cm
Polyethylene	31 dynes/cm
Soapy water	30 dynes/cm
Paraffin wax	25 dynes/cm
Silicone	24 dynes/cm
Teflon	18 dynes/cm

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More Combined Flows

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Layer/Material Name: Oriented Strand Board low

Material Data Info

Basic Values

Bulk density [lb/ft ³]	35.896
Porosity [ft ³ /ft ³]	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

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

Approximation Parameters

Reference Water Content [lb/ft ³]	4.451
Free Water Saturation [lb/ft ³]	20.82
Water Absorption Coefficient [lb/in ² *0.5]	0.000003
Temp-dep. Thermal Cond. Supplement [Btu/h ft°F]	0.000064

Typical Built-In Moisture [lb/ft³]: 4.37

Layer thickness [in]: 0.1252

Building Science Corporation Joseph Lstiburek 121

Layer/Material Name: Oriented Strand Board low

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Bulk density [lb/ft ³]	35.896
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Building Science Corporation Joseph Lstiburek 122

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Building Science Corporation Joseph Lstiburek 123

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Bulk density [lb/ft ³]	35.896
Porosity [ft ³ /ft ³]	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

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

Approximation Parameters

Reference Water Content [lb/ft ³]	4.451
Free Water Saturation [lb/ft ³]	20.82
Water Absorption Coefficient [lb/in ² *0.5]	0.000003
Temp-dep. Thermal Cond. Supplement [Btu/h ft°F]	0.000064

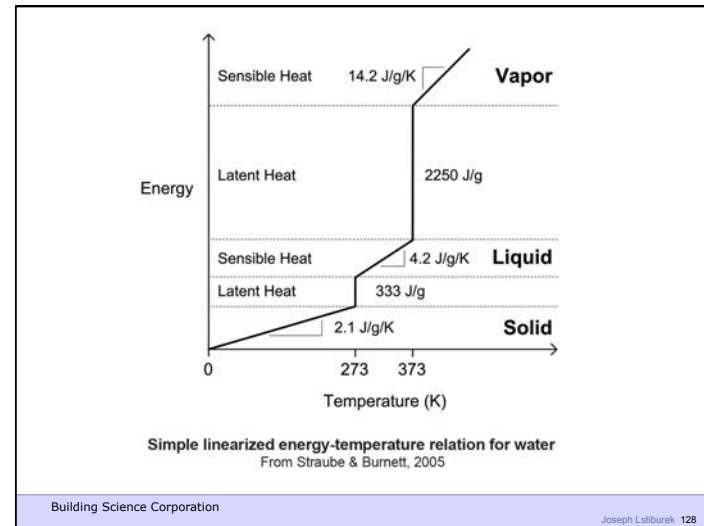
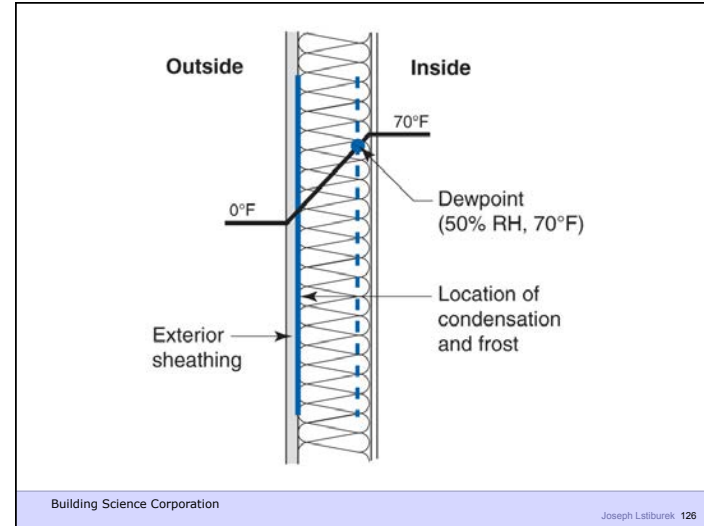
Typical Built-In Moisture [lb/ft³]: 4.37

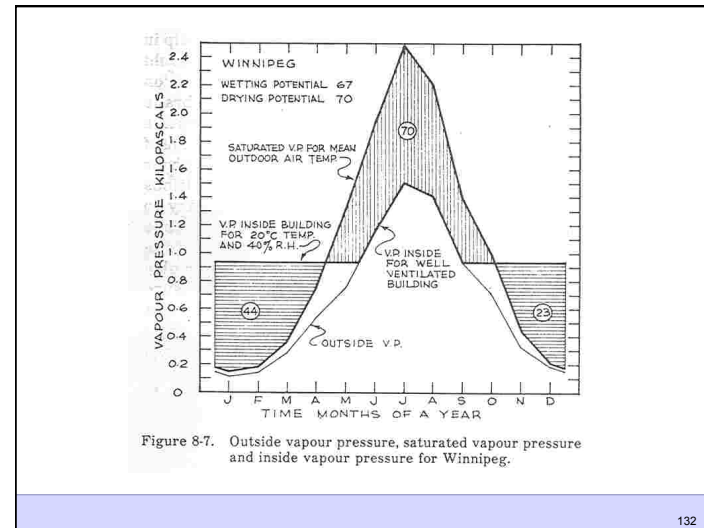
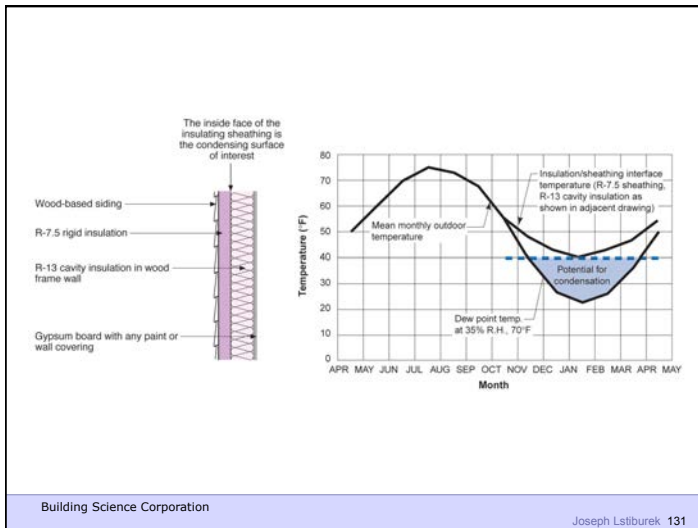
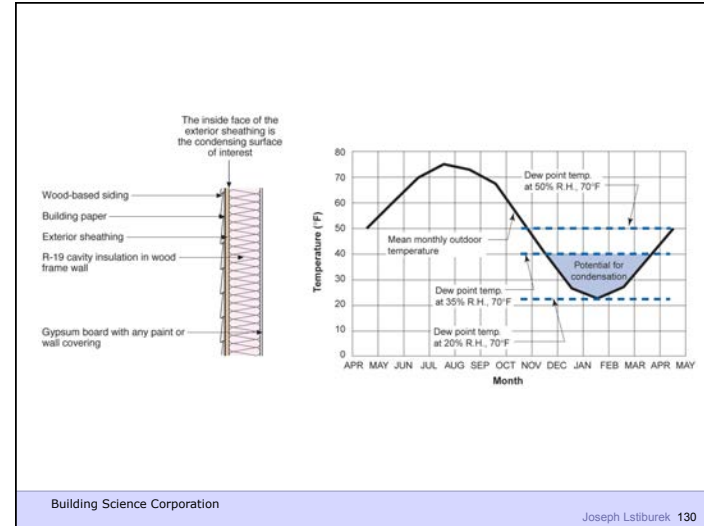
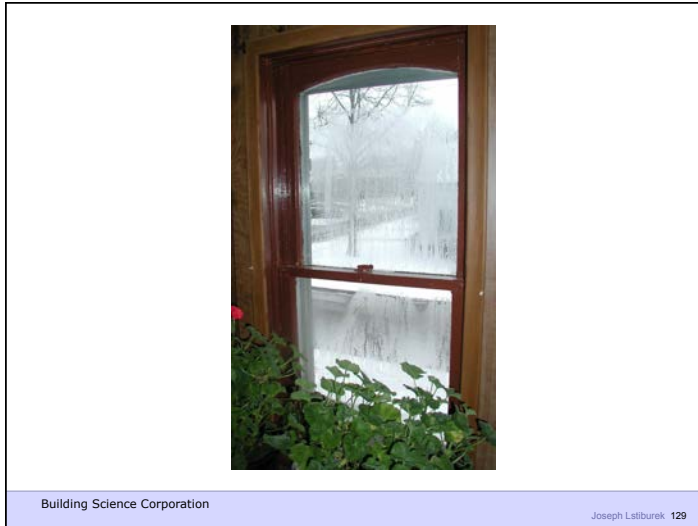
Layer thickness [in]: 0.1252

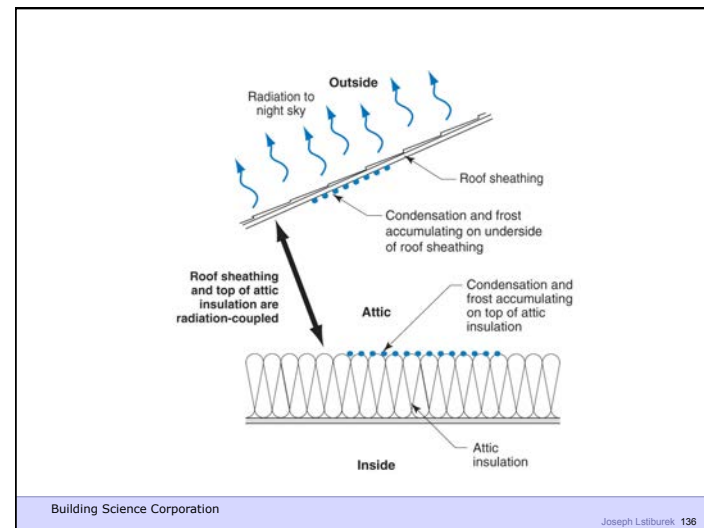
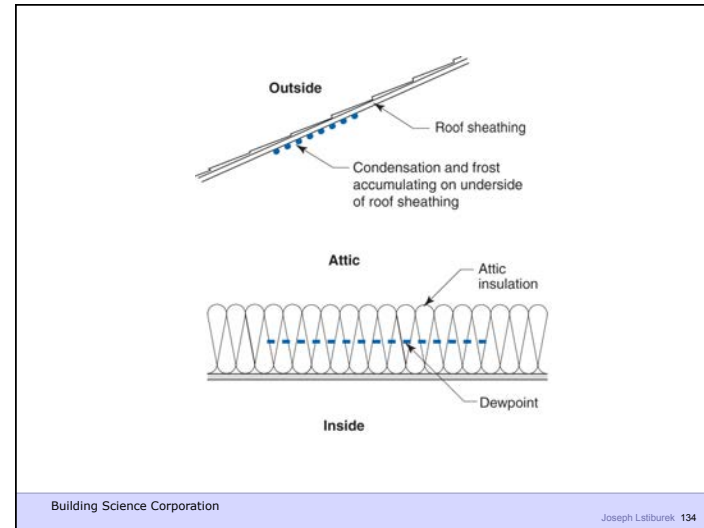
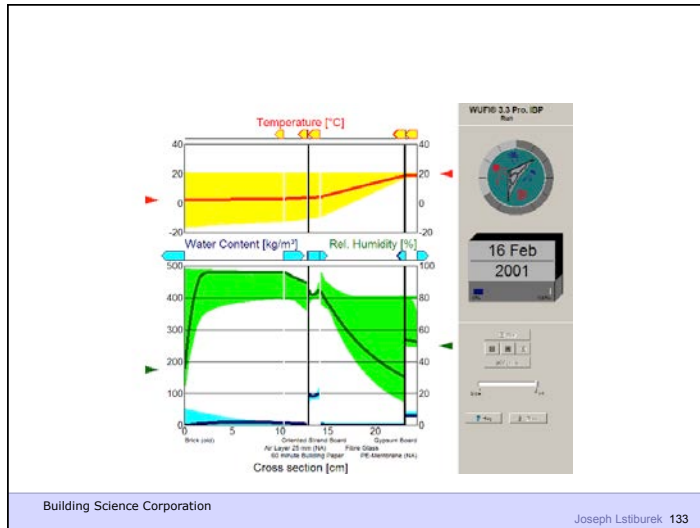
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When Phases Change

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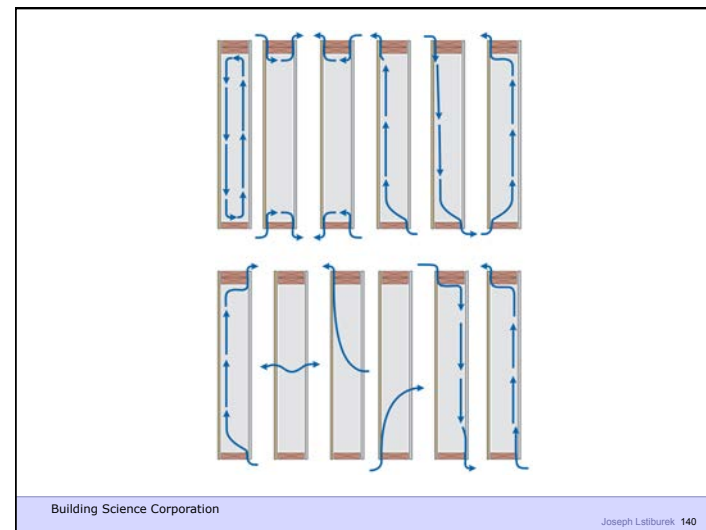


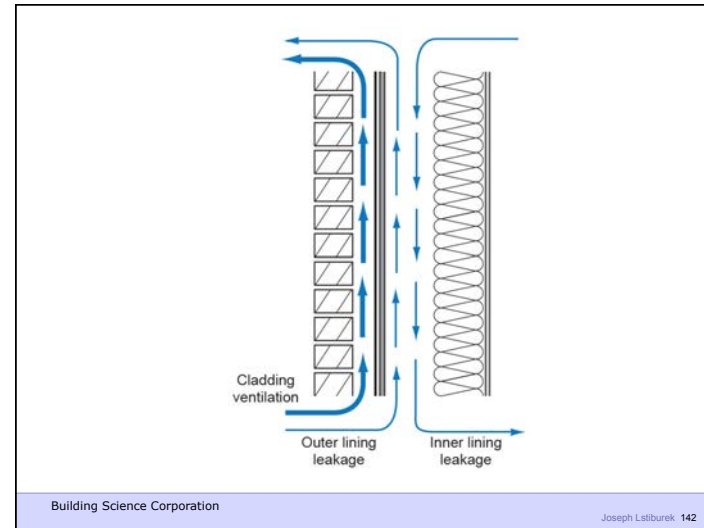
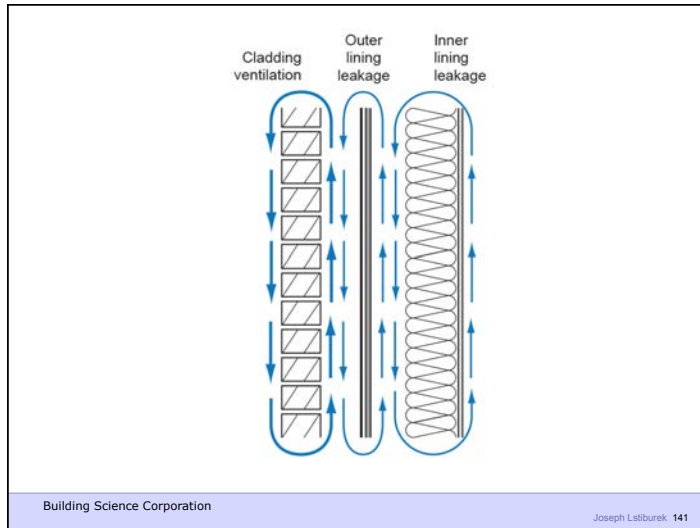




Revisiting Convective Flow

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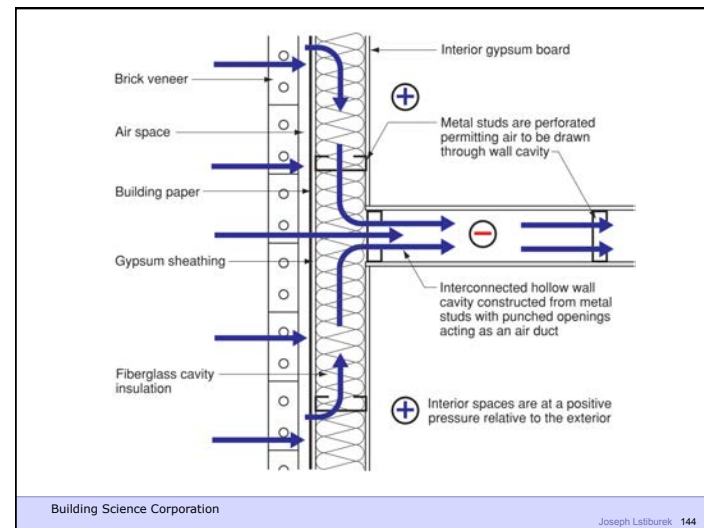




Cladding Ventilation/ Sheathing Ventilation

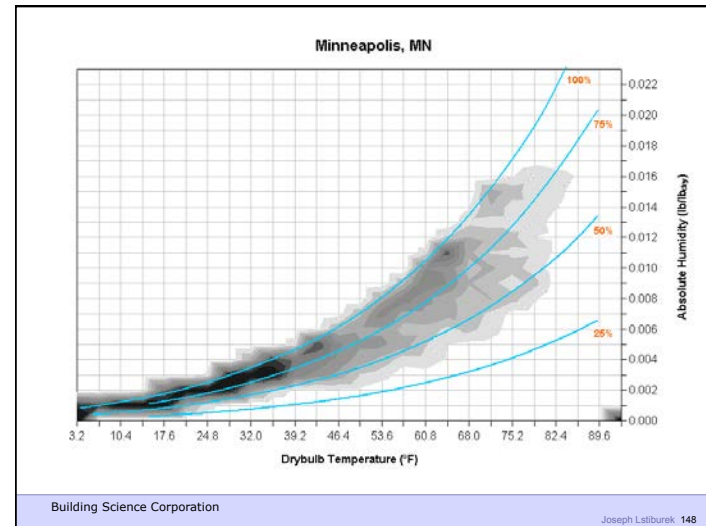
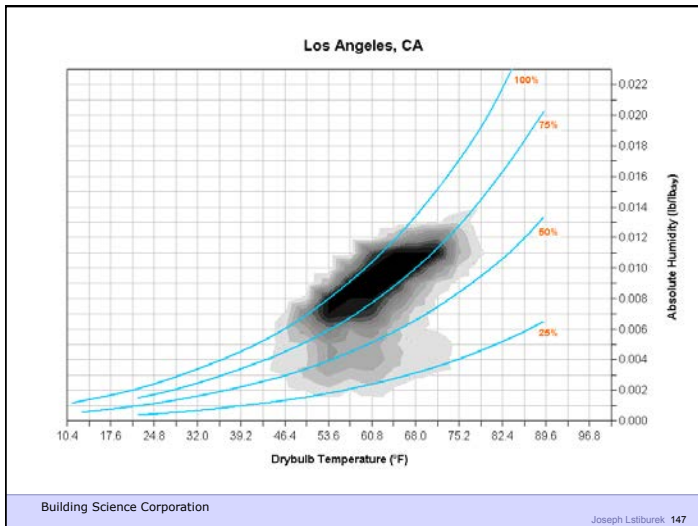
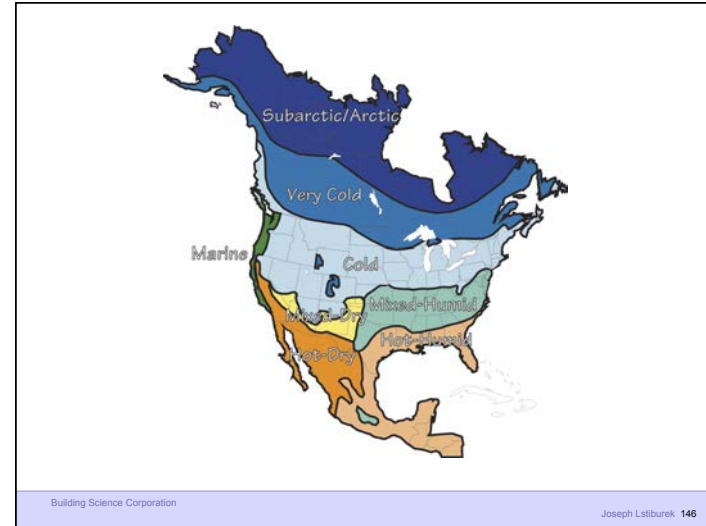
	Flow Rate	Gap	ACH
Wood Siding	0.1 cf _m /sf	3/16"	20
Vinyl Siding	0.5 cf _m /sf	3/16"	200
Brick Veneer	0.15 cf _m /sf	1"	10
Stucco (vented)	0.1 cf _m /sf	3/8"	10
Stucco (direct applied)	none	none	0
Sheathing flanking flow	0.05 cf _m /sf	3/16"	10

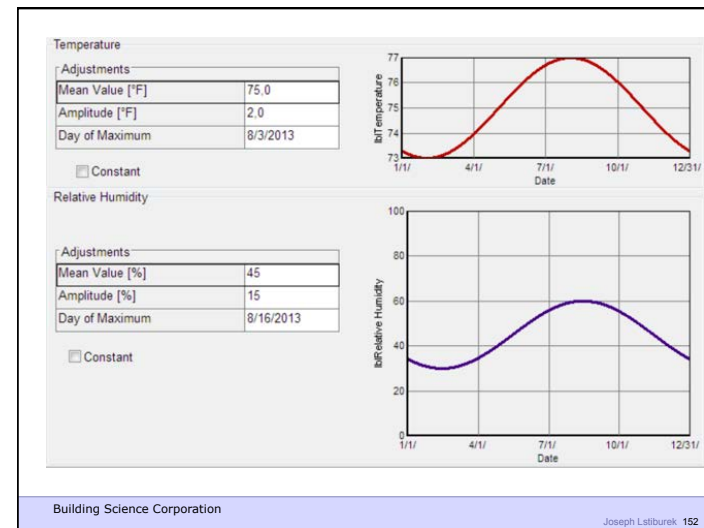
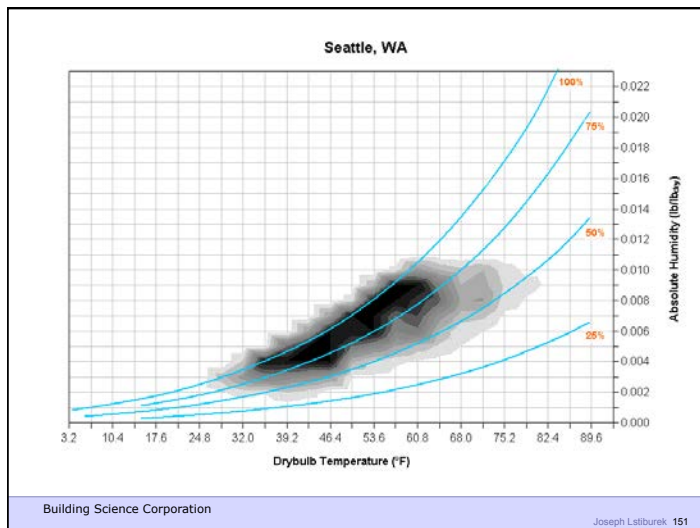
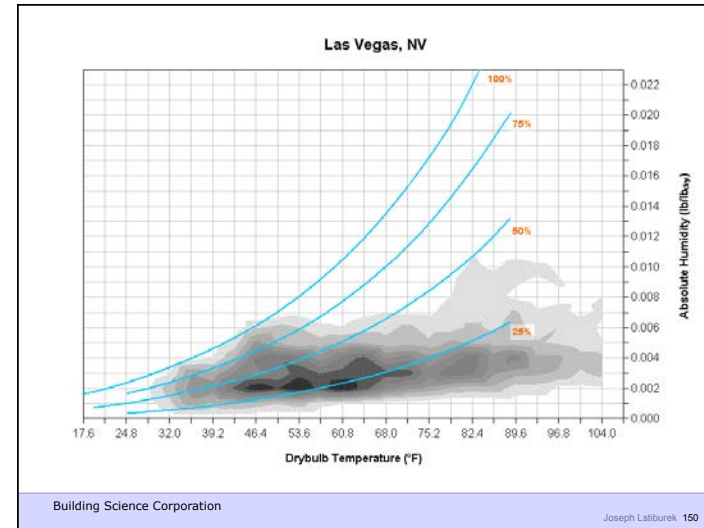
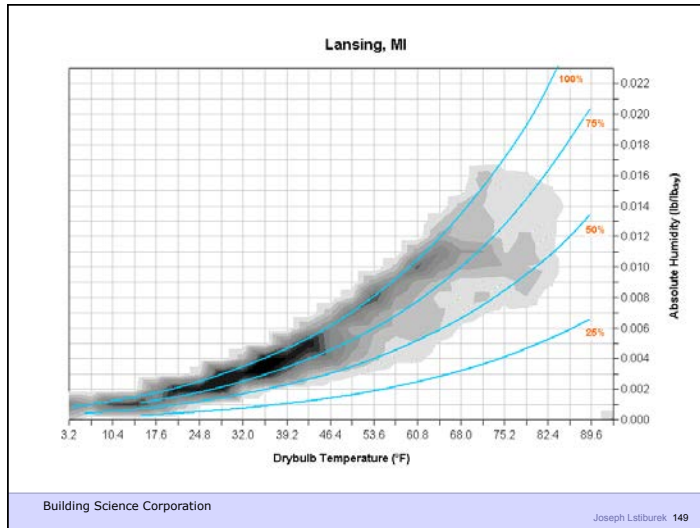
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Interior Load

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Don't Do Stupid Things

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Exterior Conditions	Conditions within Cavity:	Interior Conditions
Temperature: 80°F	Temperature: 100°F	Temperature: 75°F
Relative humidity: 75%	Relative humidity: 100%	Relative humidity: 60%
Vapor pressure: 2.49 kPa	Vapor pressure: 6.45 kPa	Vapor pressure: 1.82 kPa

Solar radiation strikes wall

Brick veneer is saturated with rainwater

1-inch air space

Felt paper

Fiberglass sheathing

Fiberglass insulation

Polyethylene

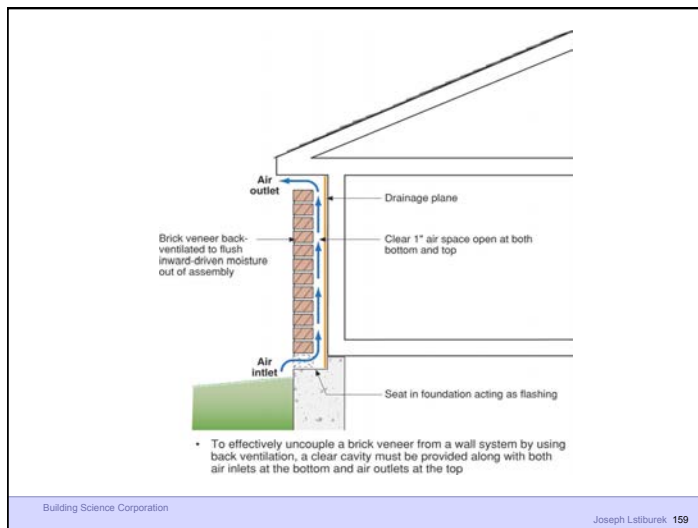
Interior gypsum board

Vapor is driven both inward and outward by a high vapor pressure differential between the brick and the interior and the brick and the exterior.

- 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, fiberglass 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 fiberglass sheathing.
- Similar problems occur with stucco.

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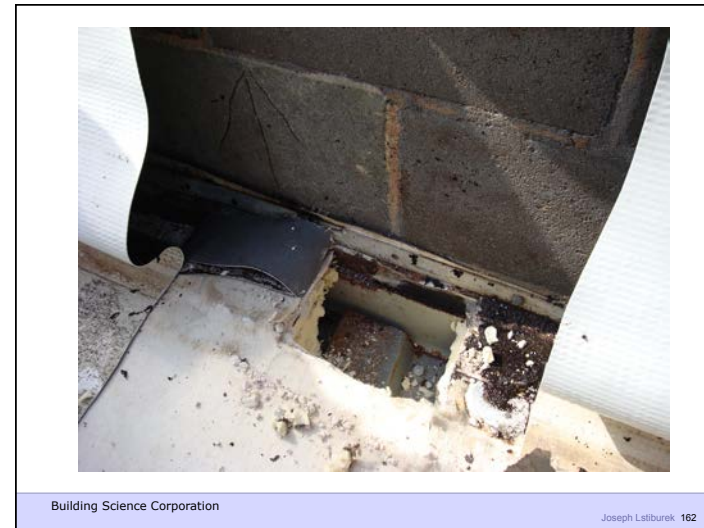
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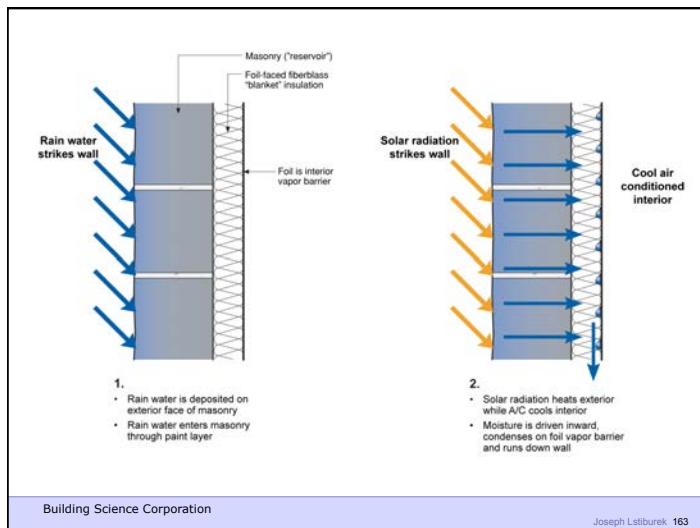
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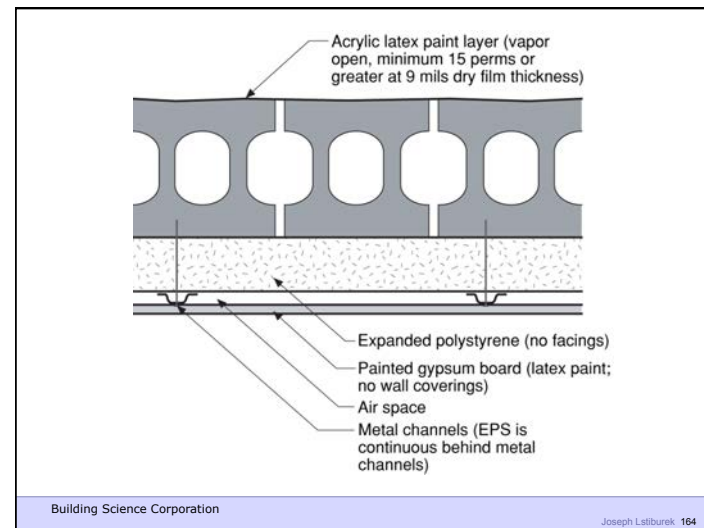
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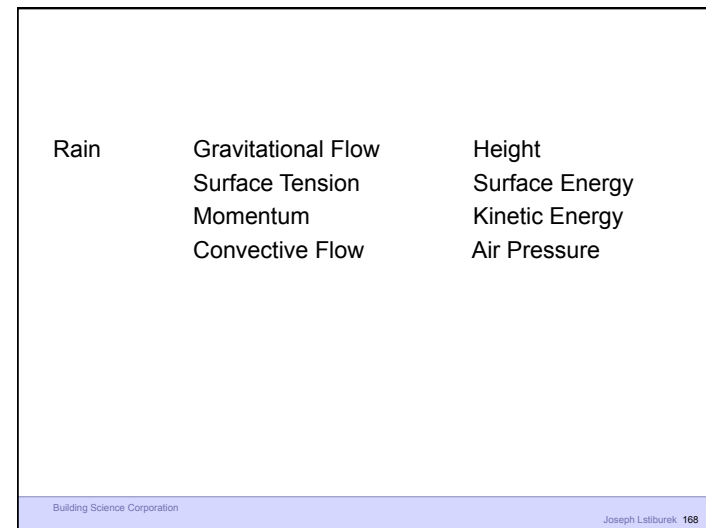
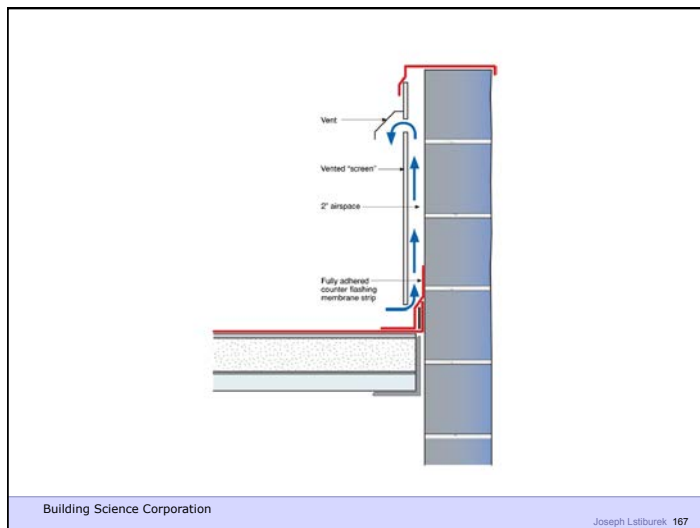
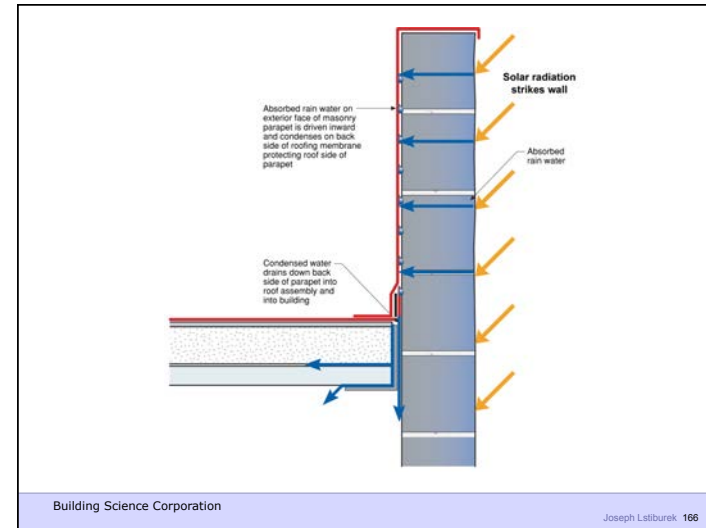
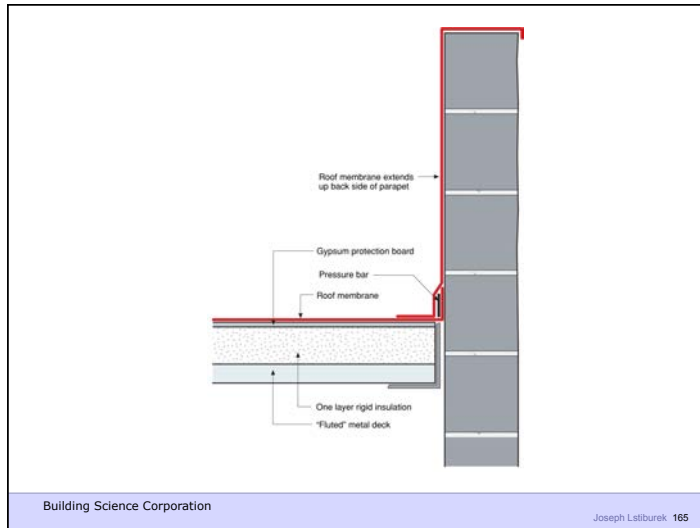
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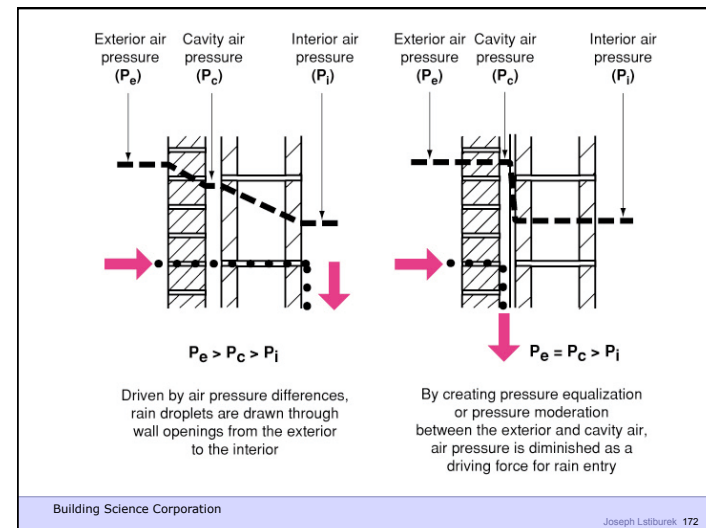
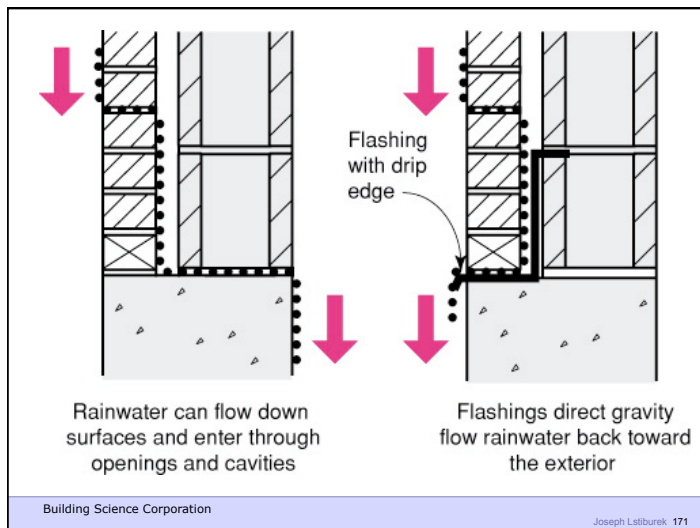
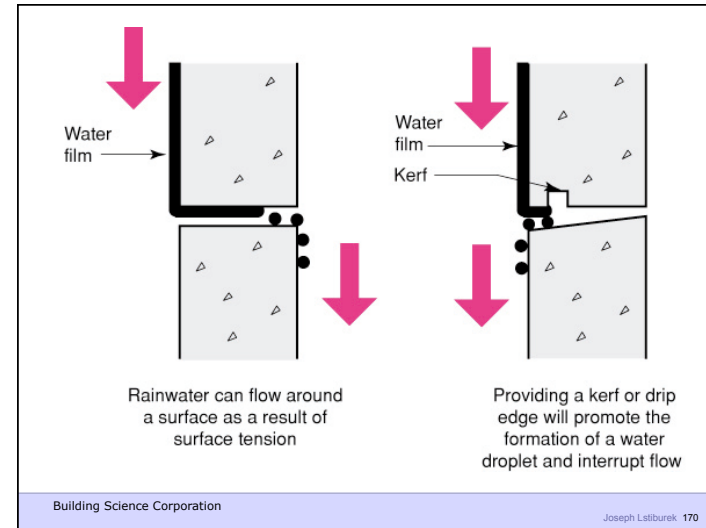
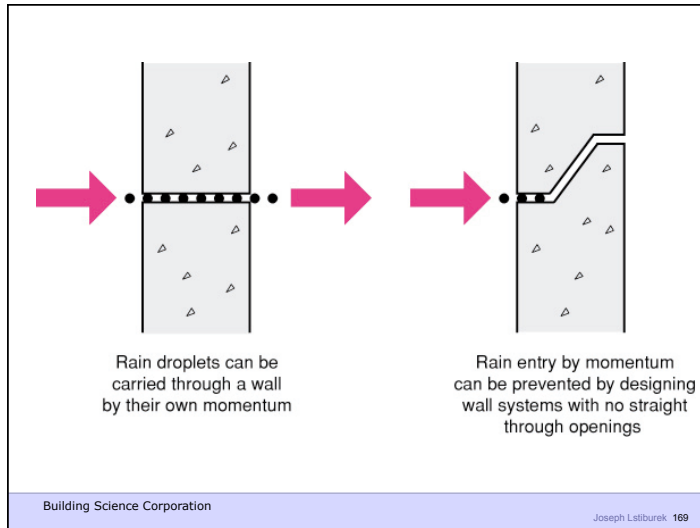
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When We Talk About Rain We Also Include Capillary Flow

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Water film

Water film

Cavity

Capillary suction draws water into porous material and tiny cracks

Cavity acts as capillary break and receptor for capillary water interrupting flow

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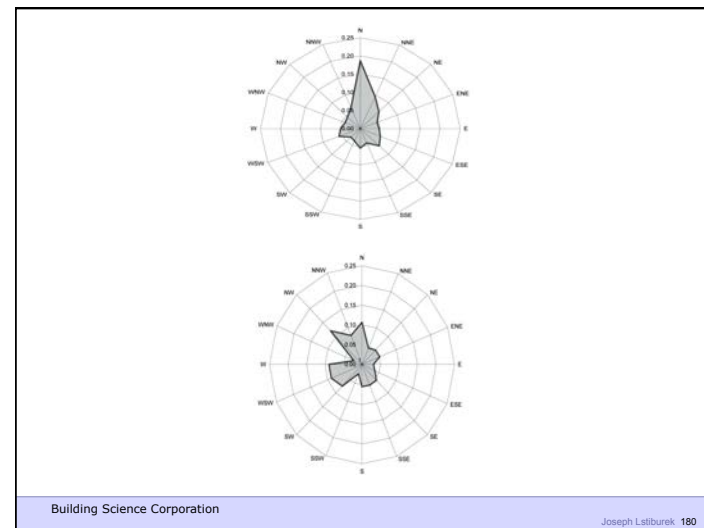
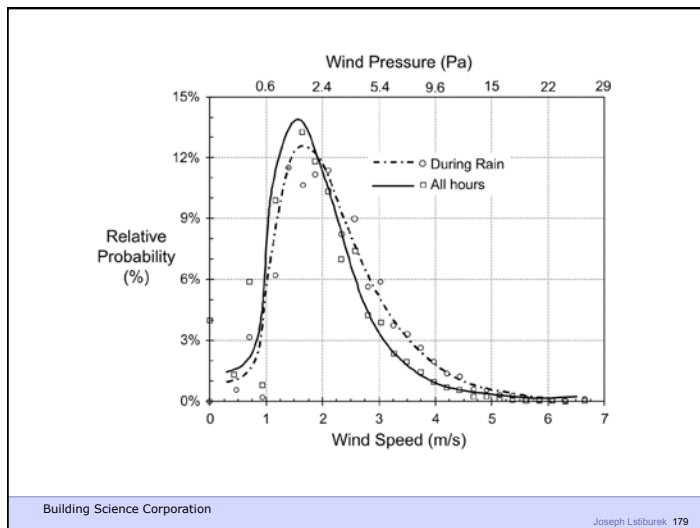
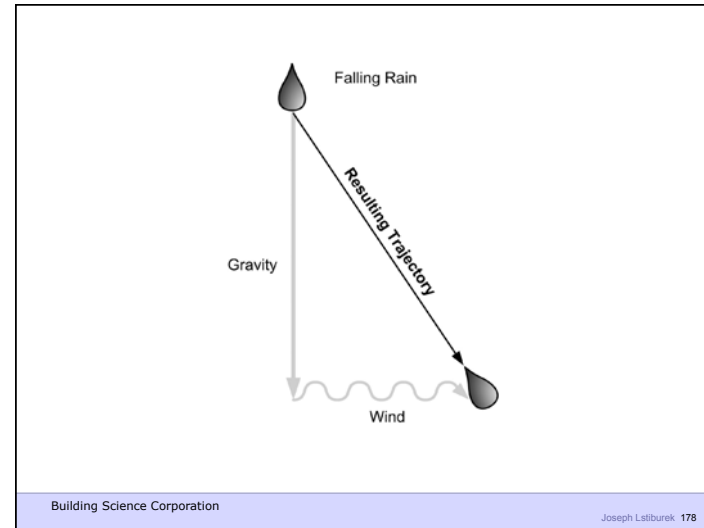
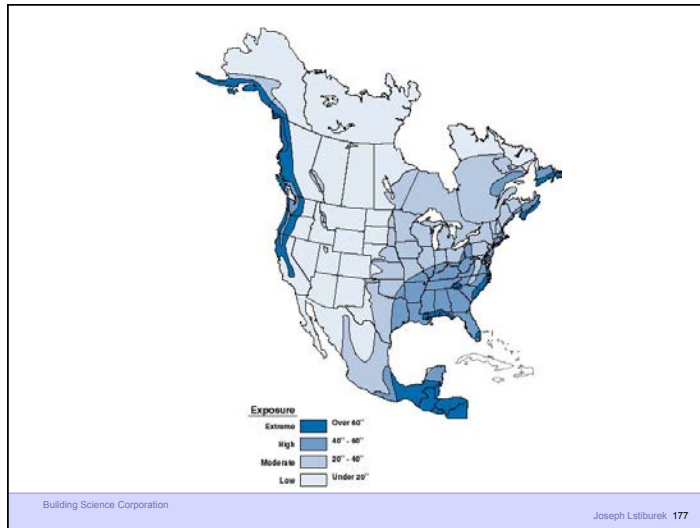
All We Have To Figure Out Is How Much Hits The Wall

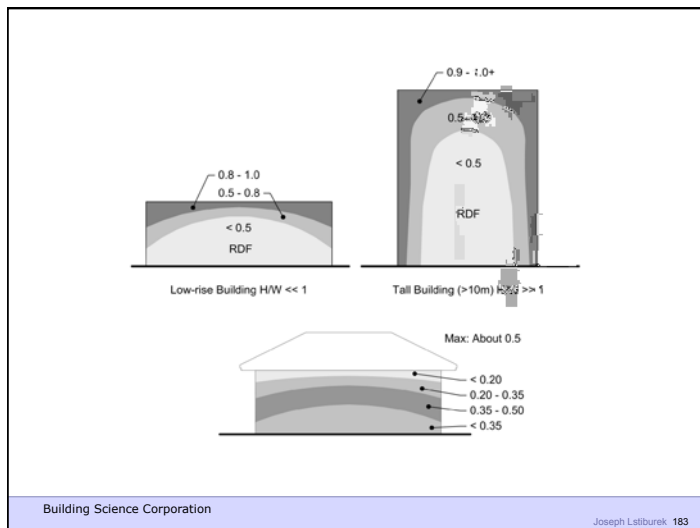
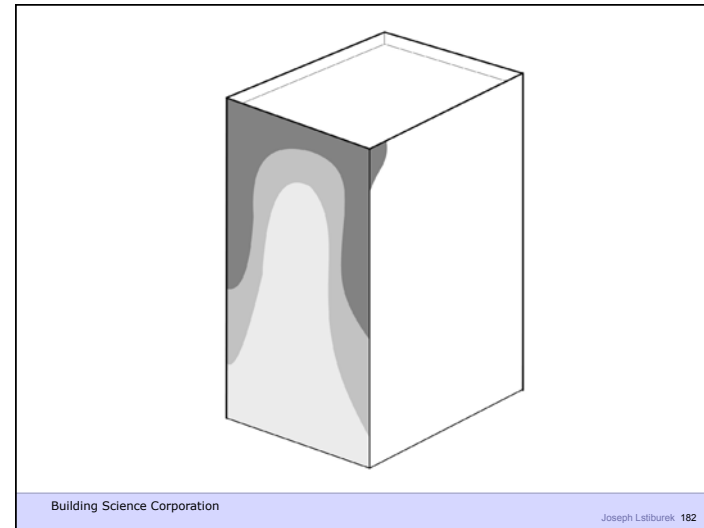
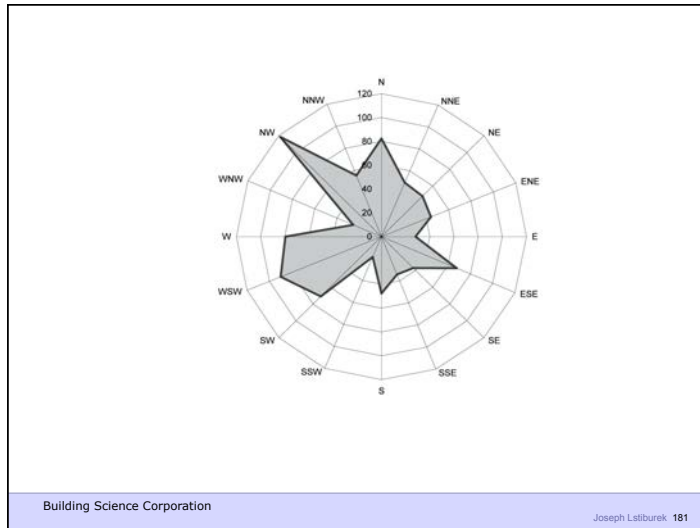
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All We Have To Figure Out Is How Much Hits The Wall

We Need Straube and Kuenzel

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

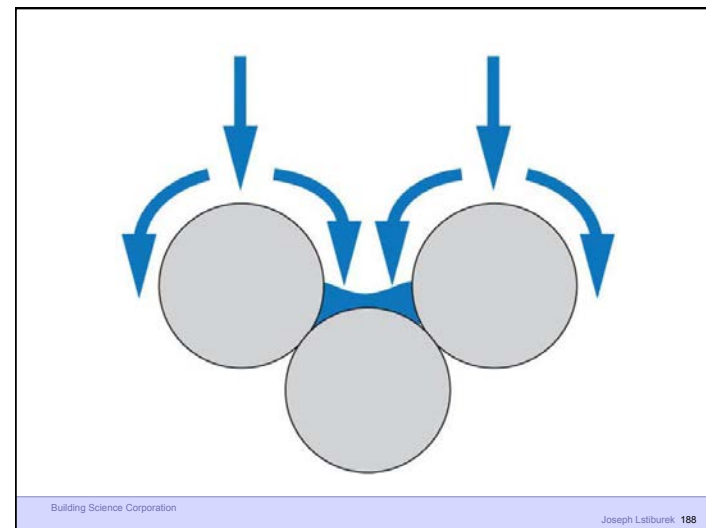
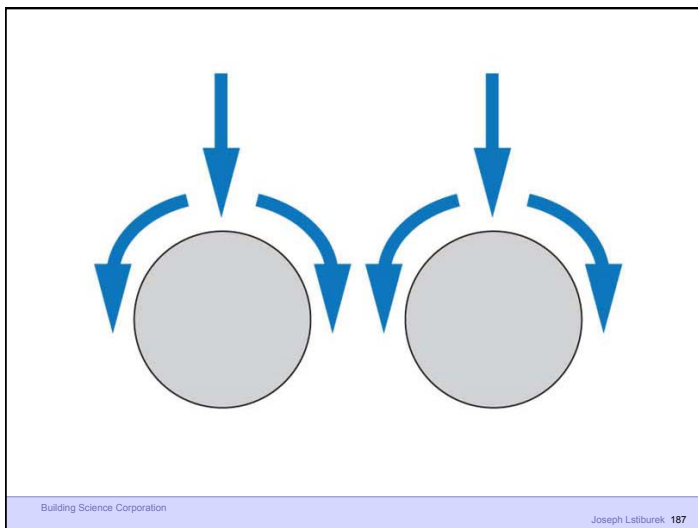
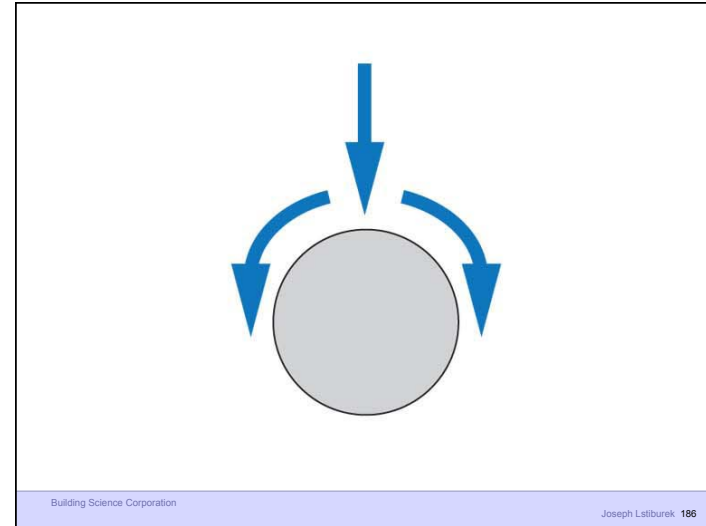
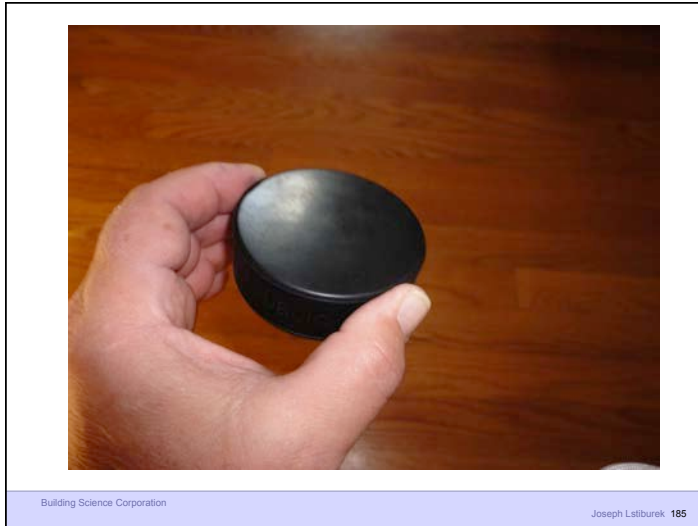
We assume 30% bounces off
70% stays on the wall.

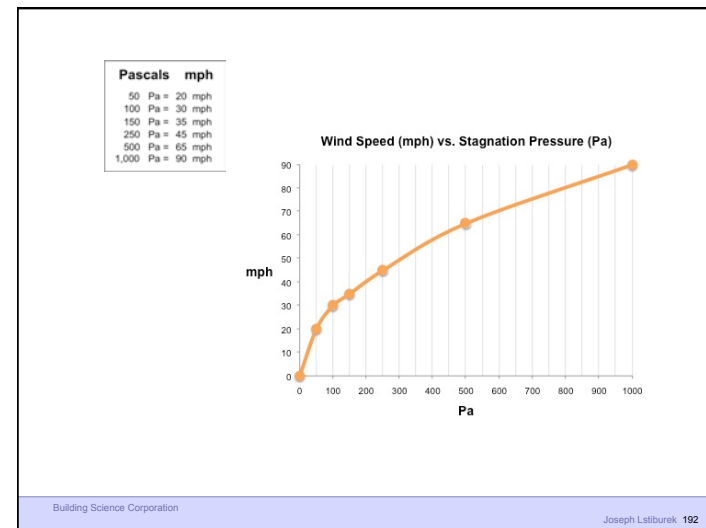
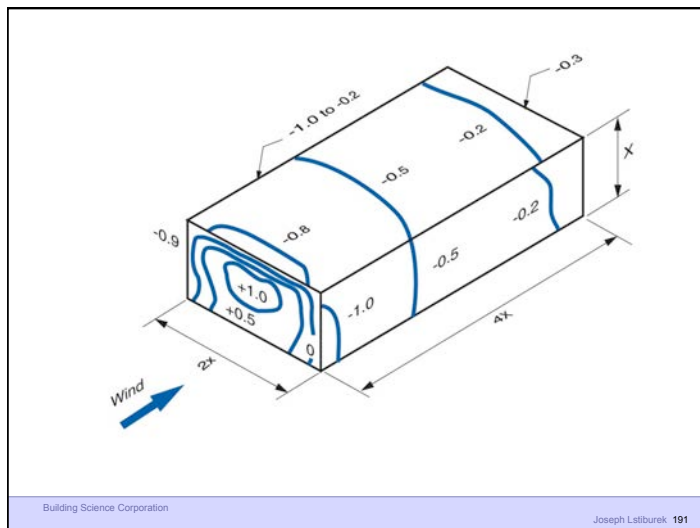
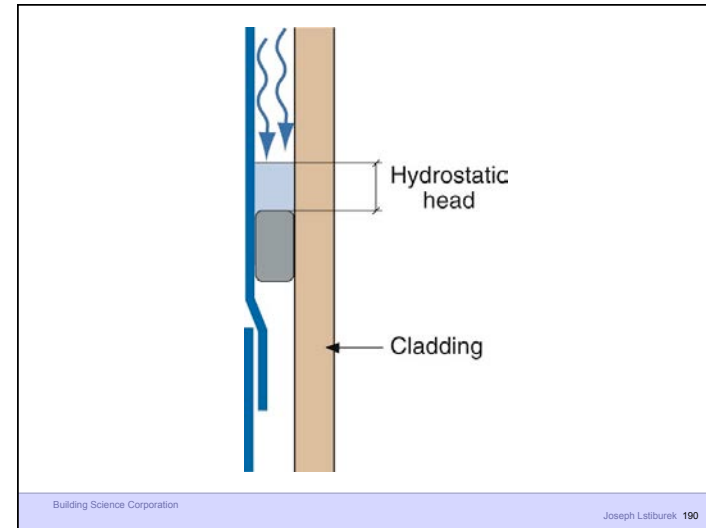
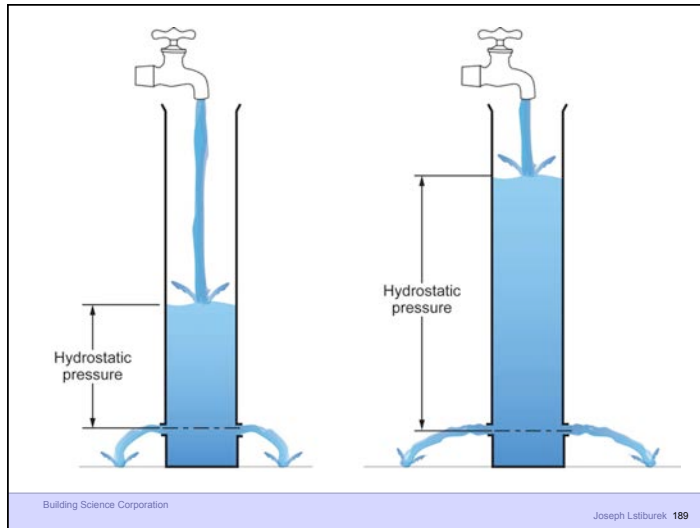
The 70% that stays on the wall is addressed by liquid conductivity (capillary flow) and vapor diffusion.

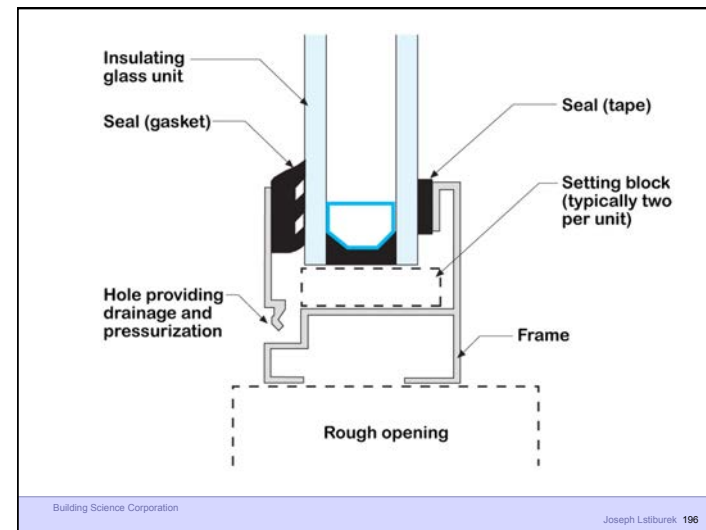
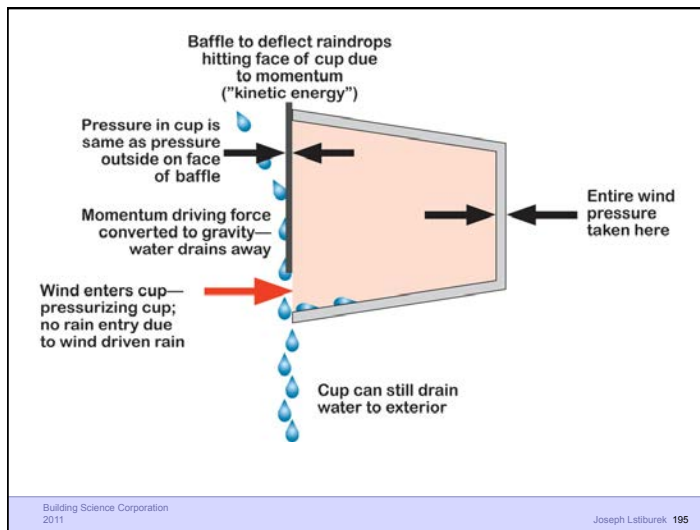
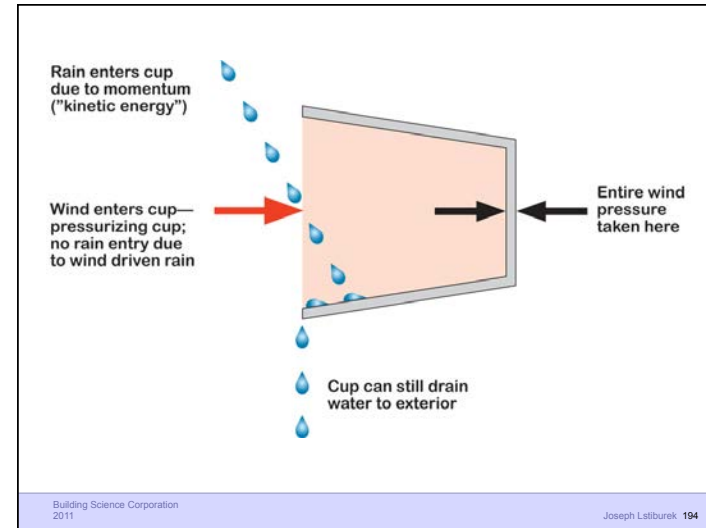
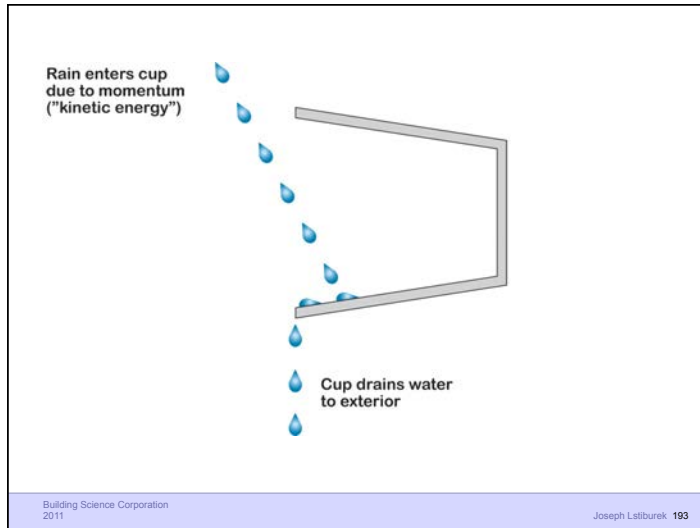
We assume 1% of the 70% penetrates to the back side of the cladding.

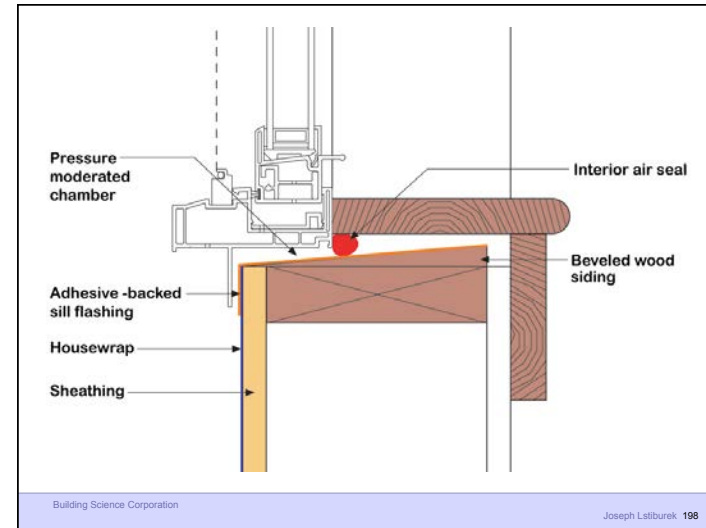
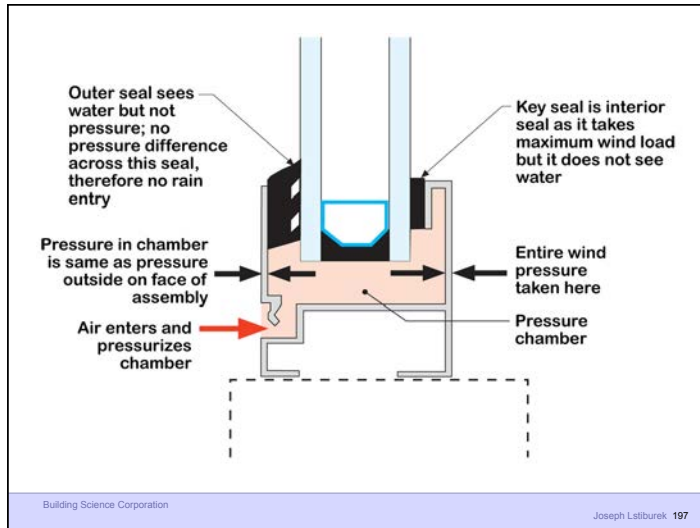
We further assume that 1% of the 1% gets past the water control layer into the sheathing.

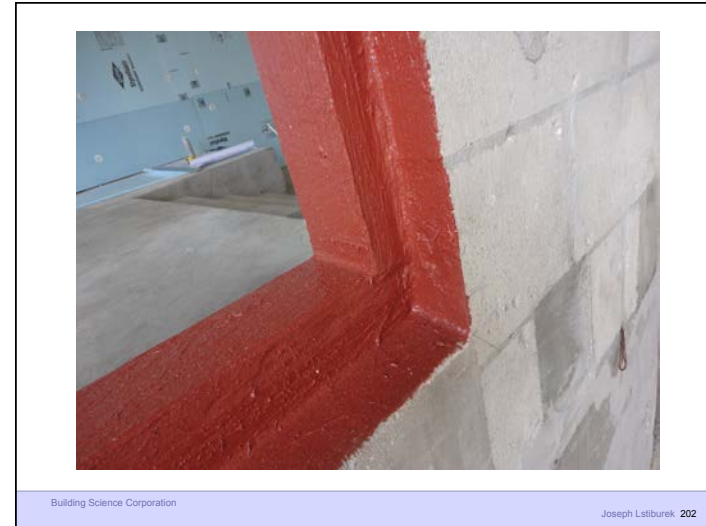
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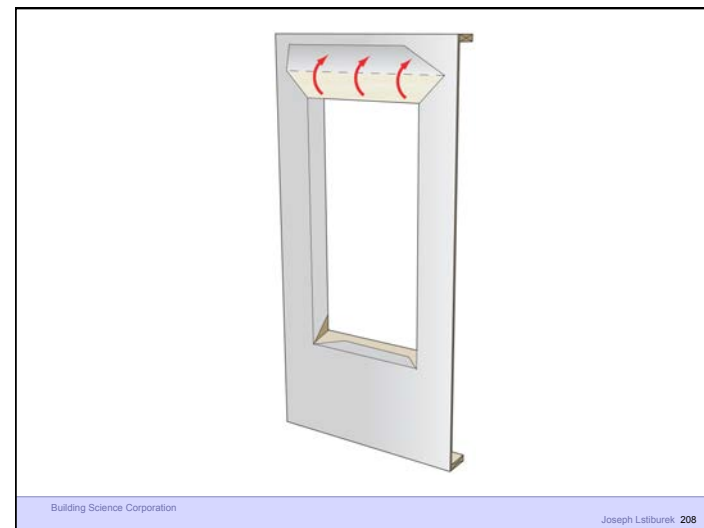
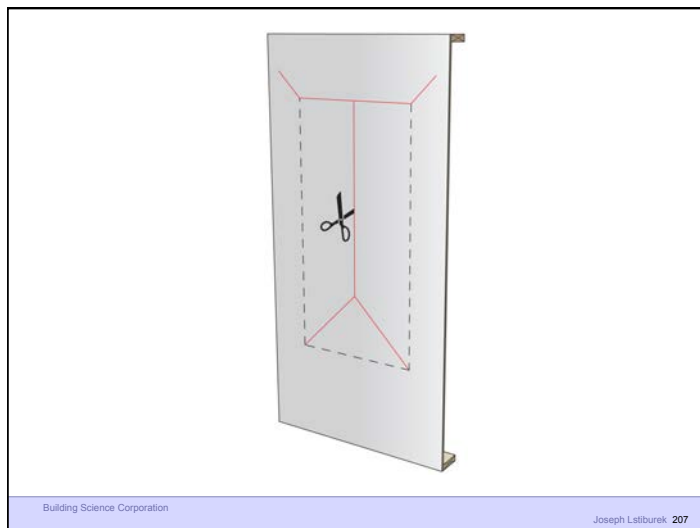
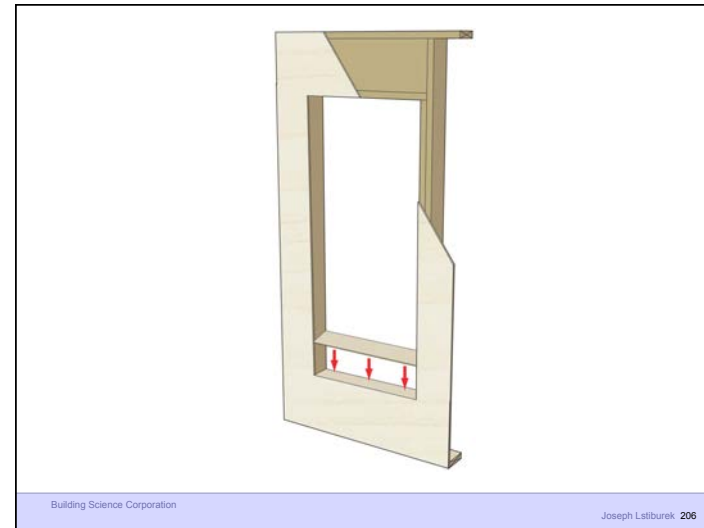
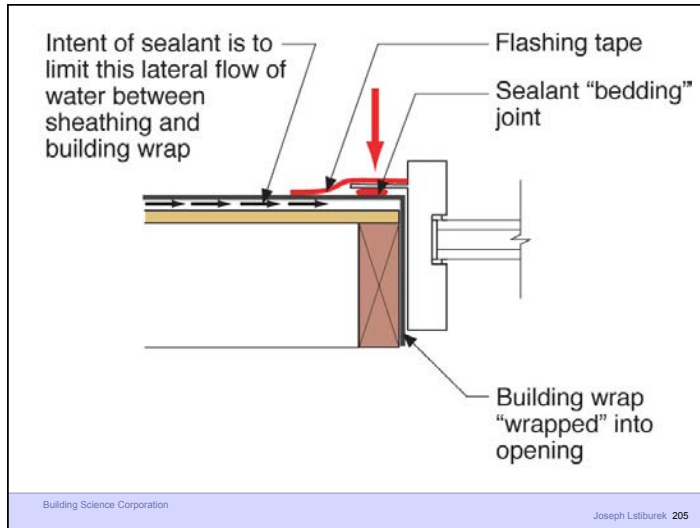


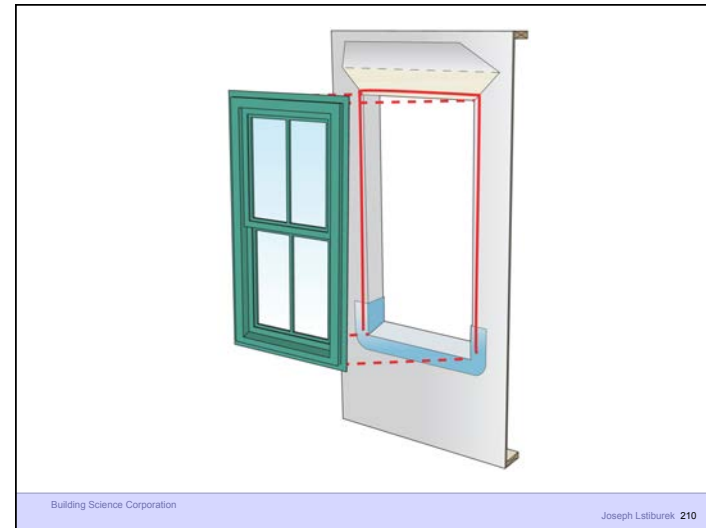
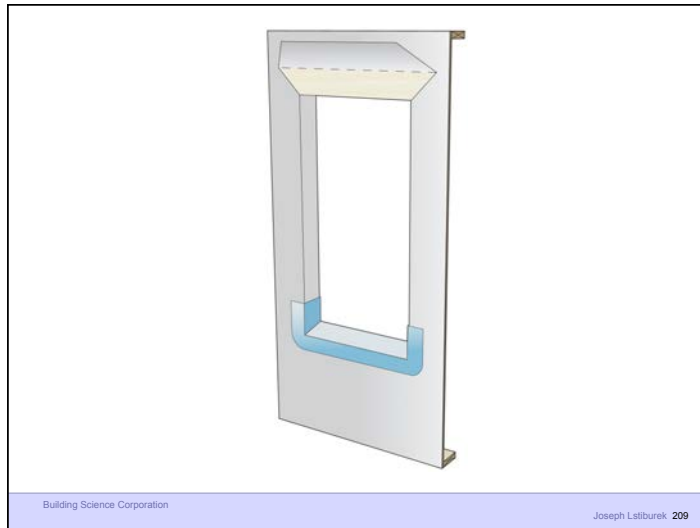




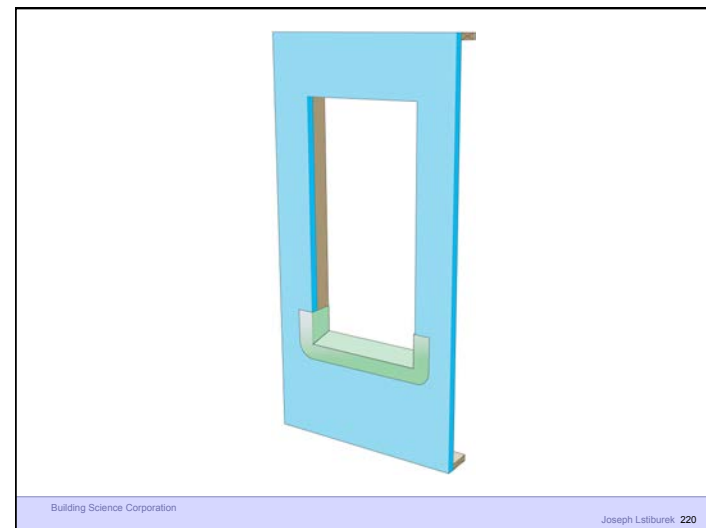
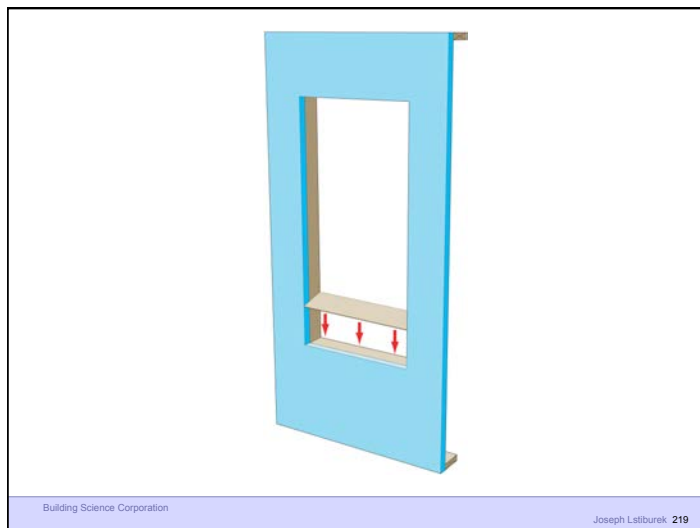
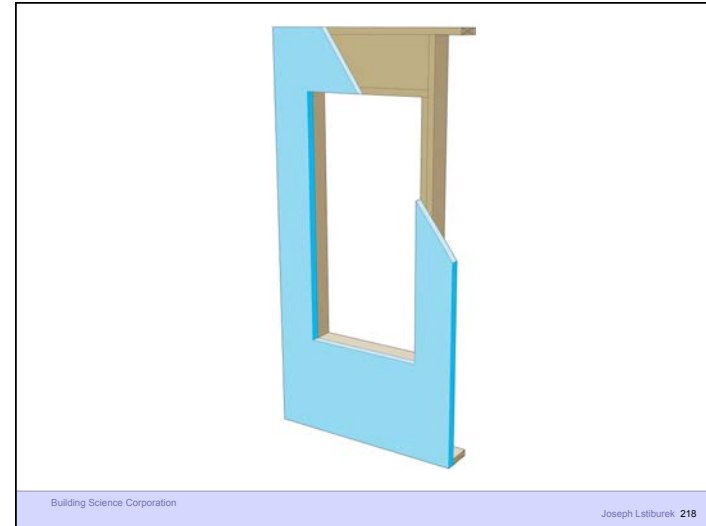


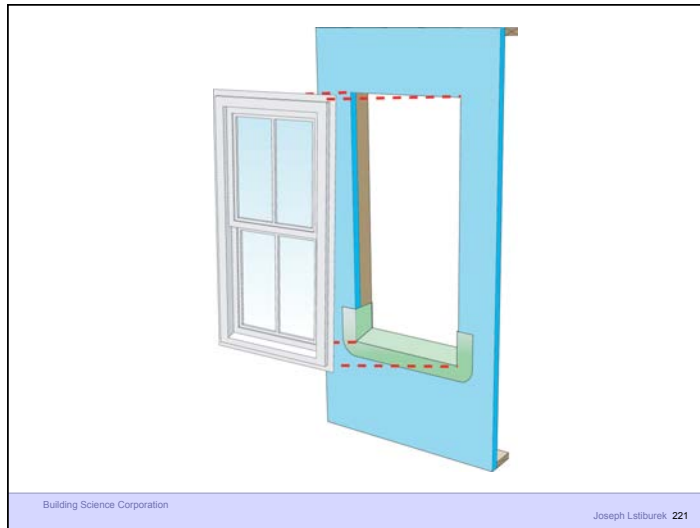


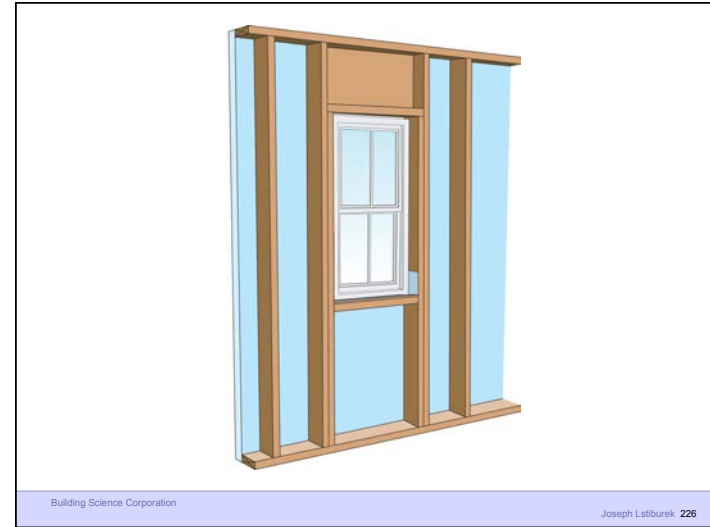
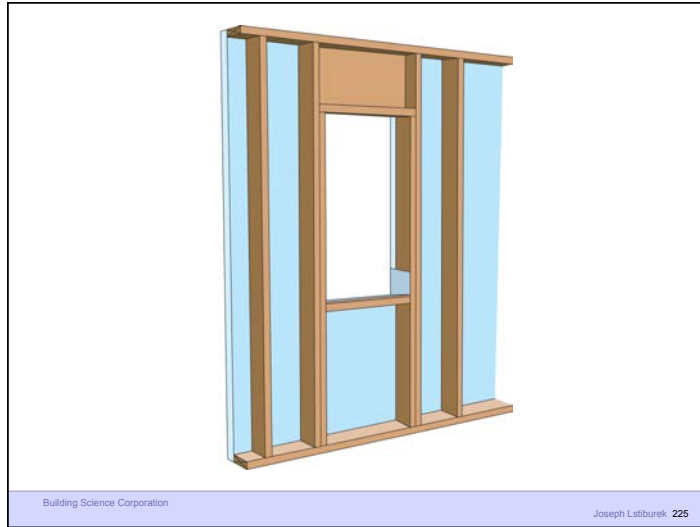


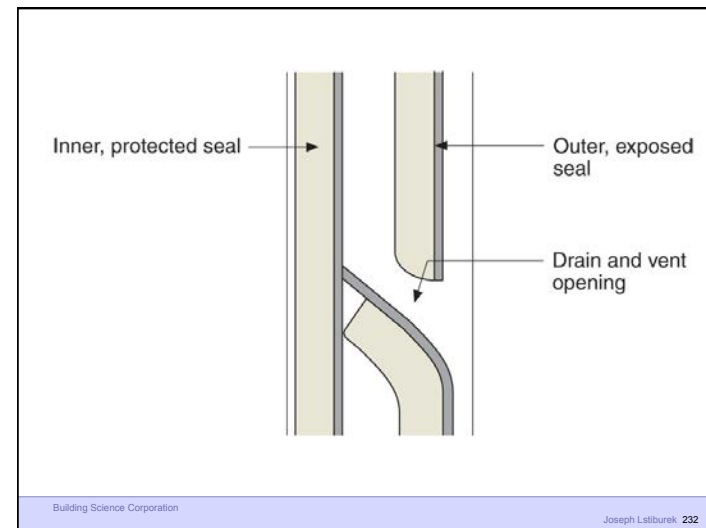
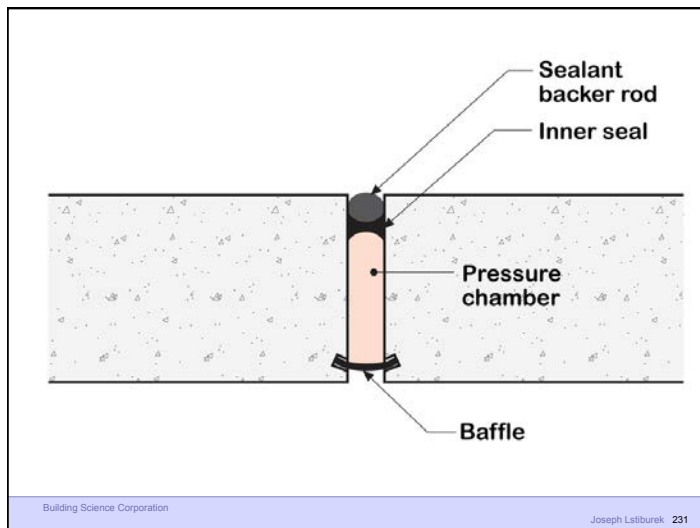
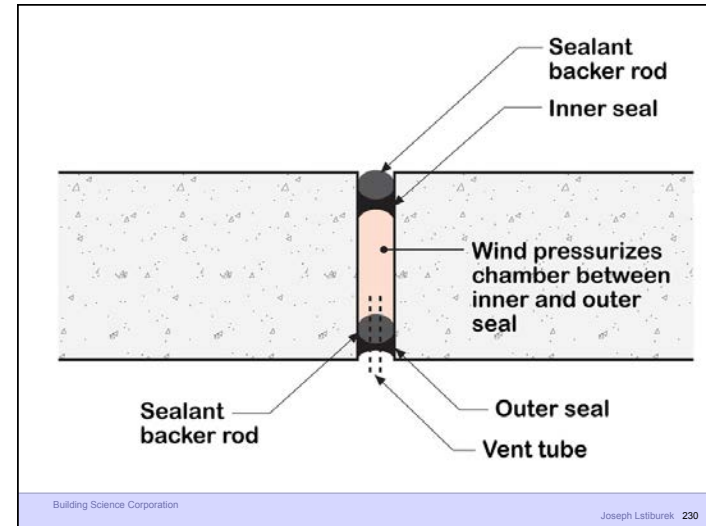


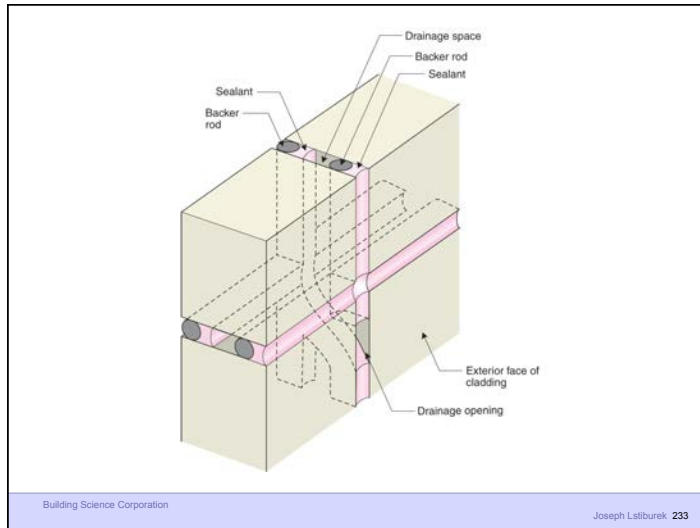






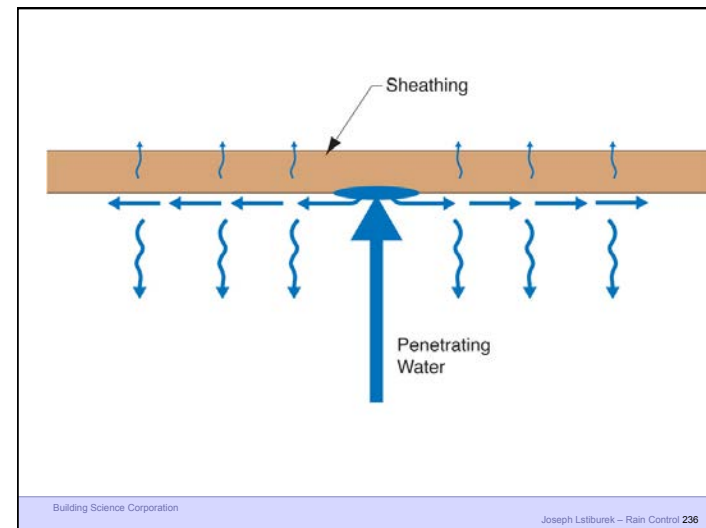
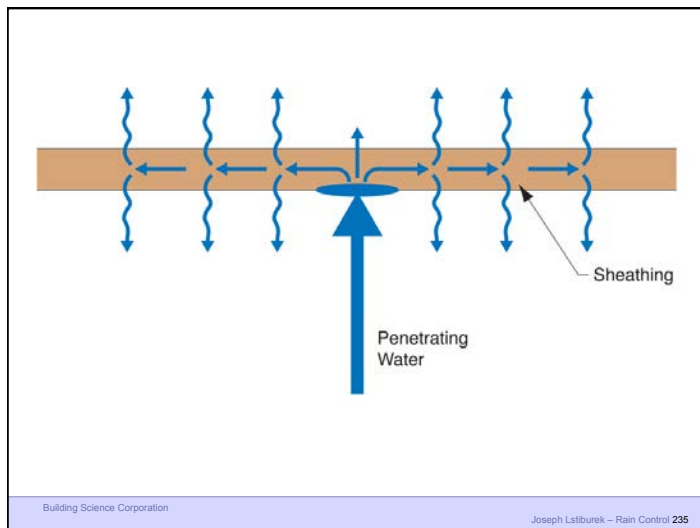


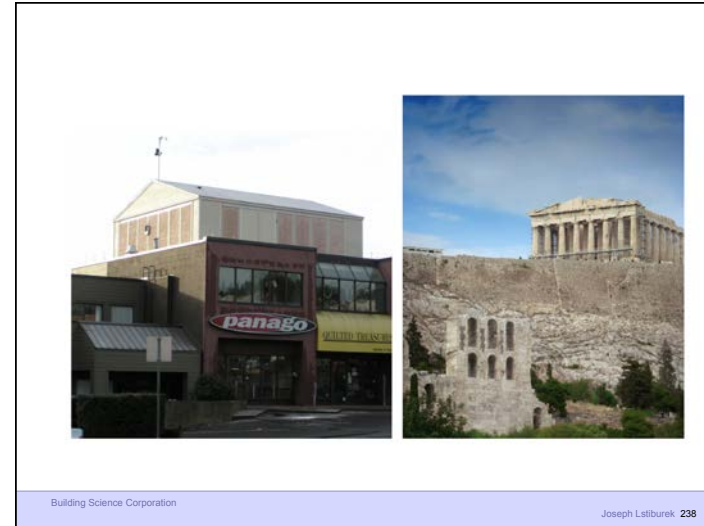
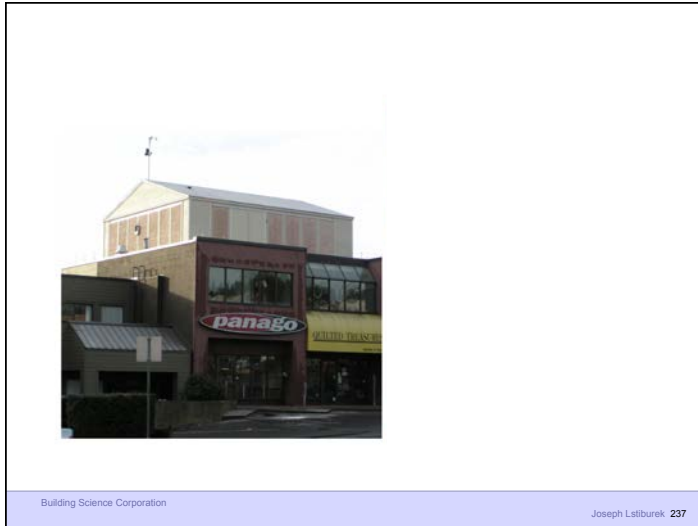


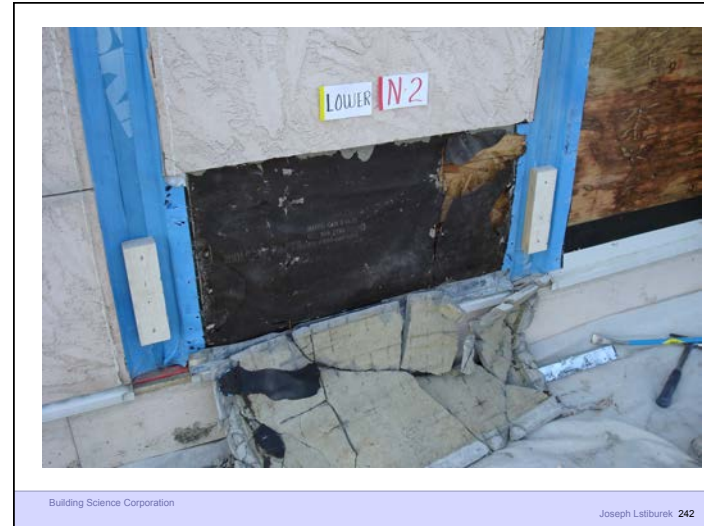
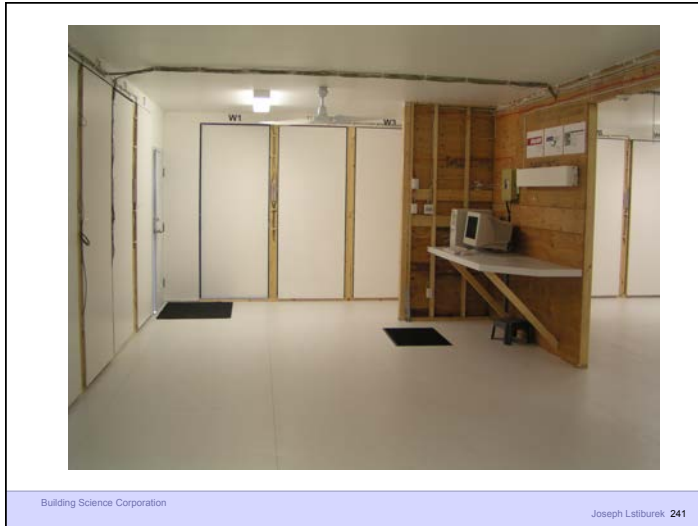


Interesting Complications

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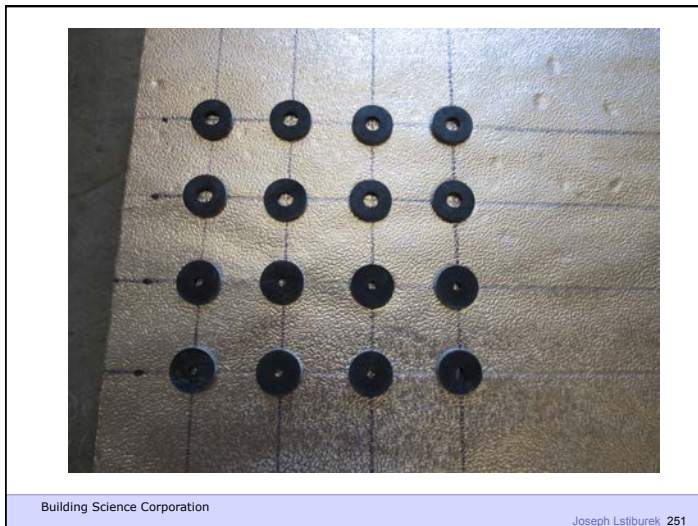






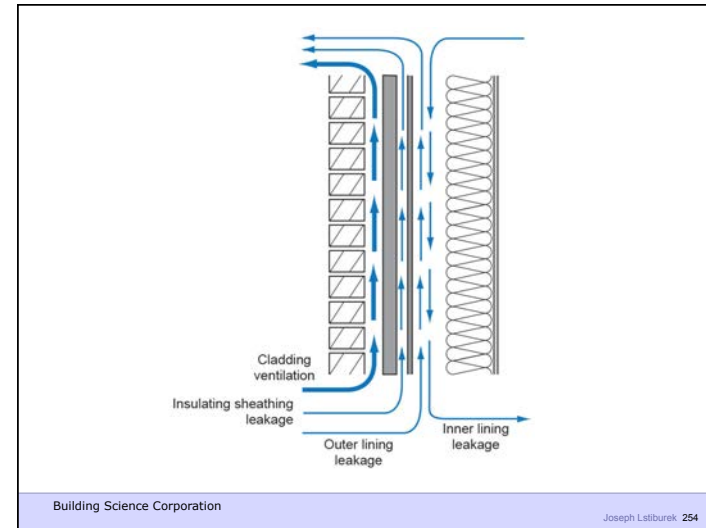
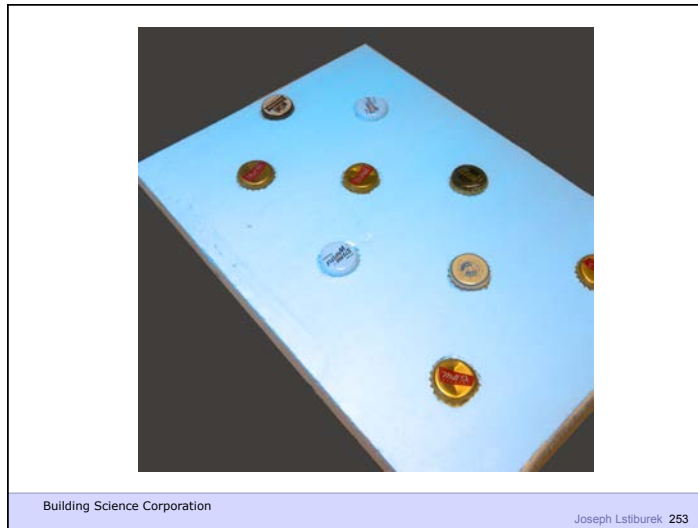
Rain Screen

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Beer Screen?

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

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