Insulation and Beyond:

Building Enclosures for Comfort, Efficiency, Health and Durability

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www.civil.uwaterloo.ca/beg

University of Waterloo

BEG
Building Engineering Group

Overview

- Houses and Multis
- General principles apply
- Insulation
- Air tightness
- Windows & Radiation

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Why control heat flow?

- Occupant Comfort
- Energy Savings
- Control surface and interstitial condensation
- Save duct and heating plant costs (Capitol)
- Meet Codes and specs

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Heat & Temperature

- Heat
  - A form of energy (like Light & Sound)
- Temperature
  - A measure of the amount of thermal energy
- Heat Flow
  - From more to less energy

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Heat Flow

- Always moves from more to less
- Rate of flow depends on
  - Temperature Difference
  - Material Properties
  - Type & Mode of Heat Flow

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Heat Flow

- Mode of Heat Flow
  - Conduction
  - Convection
  - Radiation
- Type of Heat flow
  - steady-state or dynamic
  - one-, two- or three-dimensional
  - We usually use 1-D static!

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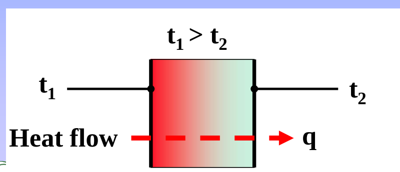
Conduction

- Heat Flow by direct contact
- Vibrating molecules
- Most important for solids



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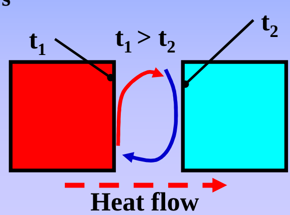
Natural Convection

- Heat Flow by bulk movement of molecules
- Most important for liquids and gases
- Critical for surface heat transfer (e.g convectors, "radiant floors"
- Windows



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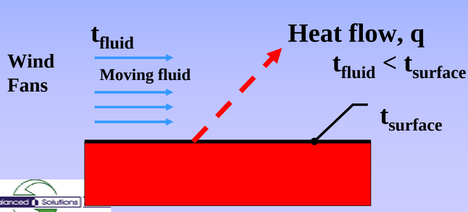
Forced Convection

- E.g. air flow (forced air furnace)
- Also heat flow from solid to liquid or gas



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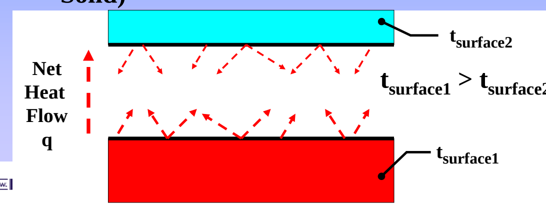
Radiation

- Heat flow by electromagnetic waves
- Heat radiates from *all* materials, e.g. campfire
- Passes through gases and vacuum (NOT Solid)



www.

Radiation

- Important for surfaces, air spaces, voids
  - e.g. Thermos bottle
- Key for low-e Windows
- Foil faced insulation, radiant barriers only work when facing an air space
- Radiation within *pores* important for high void insulation (e.g., glass batt)
- Emissivity is the measure

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How to Control Heat Flow?

- Insulation to control conduction
- Air tightening to control convection
- Solar control to control radiation
- Systems assessment needed!
  - Insulate? Air tighten? Shade? Mass? Windows?

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Heat flow through materials

- Low density materials insulate better!
- Past – relied on high density (but thick) structural materials to control heat, air, and moisture flow
  - Wood R 1.200 /inch
  - Clay Straw R 0.700 /inch
  - Old brick R 0.180 / inch
  - Concrete R 0.070 /inch
  - Steel R 0.004 / inch

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Past Heat Flow Control

- In the past
  - Energy costs were less important (1945-75)
  - Comfort standards less demanding
  - Building materials & finishes were more resistant to condensation & mold
- Today and tomorrow
  - Better heat flow control required
  - More environmental concerns

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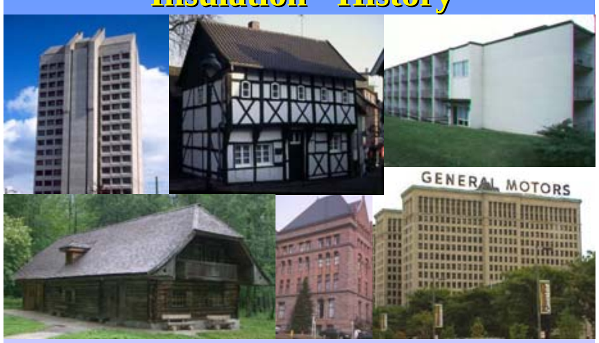
Insulation - History



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How much insulation?

- Comfort & moisture –
  - <u>True</u> RSI 2/R10 is often enough, but …..
- Energy
  - As much as practical
- Practical constraints likely the limit
  - How much space available?
- Increased insulation changes HVAC capital as well as operating!

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Calculating Heat Flow

- Conduction
  - $q = k/l\ A(T_1 - T_2)$
  - k = f(T, MC, density, time?)
- Convection
  - E.g. $q = 1.42\ (\Delta T/L)^{0.25} A(\Delta T)$
  - Typical C_{equiv}=2 to 20 W m²K
- Radiation
  - E.g. $q = F_e A_1 \sigma (T_1^4 - T_2^4)$
  - $Fe = 1/(1/\varepsilon_1 + 1/\varepsilon_2)$

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Calculating Heat Flow

$$Q = \frac{k}{l} A(T_1 - T_2) = UA(\Delta T)$$

- Where
  - Q = heat flow rate (Btu per hr, W = J/s)
  - A = area that the heat is flowing through (m²)
  - ΔT = temperature difference across layer (°C)
  - U = conductance of the layer (W/m²K)
  - k = thermal conductivity (W/mk)
  - l = length of flow path (m)

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Conductance

- A *layer* property
- Expresses how easily heat can flow through a layer of the material

U	=	k/l	=	1/R
Conductance	=	Conductivity / Thickness	=	1 / Resistance

- R-Value is an expression of how well a layer of the material resists heat flow

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Thermal Conductivity

- A material property
- Measure heat flow through a unit thickness and unit area of material under a unit temperature difference
- Heat flow Btu/h, J/s
- Area sq ft, sq m
- Thickness ft, m

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Materials

- Thermal conductivity (& resistance) varies with
  - material type (conduction, radiation)
  - density and pore structure
  - moisture content
  - temperature difference
- Combination of insulation of air + material
- *Still* air is about R6/inch (k=0.024 W/mK)
- Only gas fills (e.g. HCFC) can improve this
- Nanoporous and low-emissivity promise R20/inch

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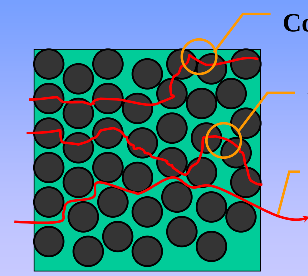
Materials



Hypothetical porous material

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Materials

- High conductivity and high density
  - e.g. wood R1/inch and 40 pcf (600 kg/m^3)
  - concrete R0.1/inch and 140 pcf (2200 kg/m^3)
- Low conductivity and low density
  - e.g. glass batt R3.5/inch and 1 pcf (16 kg/m^3)
- Compromise
  - cellulose, R3.5/inch and 3 pcf (48 kg/m^3)

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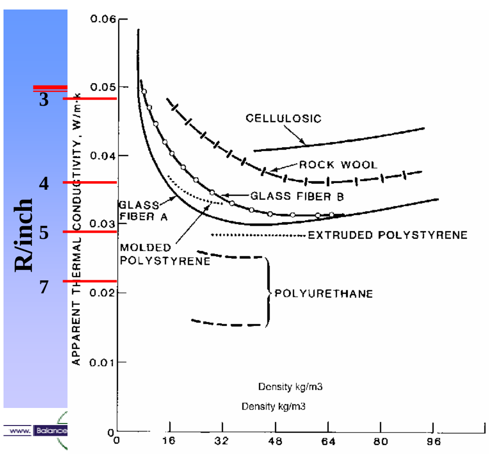

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Fibers

- Mineral Fiber Insulation (vs organic fibers)
  - glass fiber
  - rock fiber } rockwool
  - slag fiber } rockwool
- Glass vs rockwool
  - melts at a much lower temperature
  - has thinner fibers so can use lower density
  - Lower density means more air permeance, less strength, and low volume shipping

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Foams

- Expanded Polystyrene (EPS)
  - R-value of 3.6 to 4.2
- Extruded Polystyrene (XPS)
  - higher R-value, usually 5/inch or higher
  - usually more strength
- Polyisocyanurate (PIC)
  - starts high R-value, then ...
- Polyurethane (PUR)
- Phenolic
- all have fire "issues"

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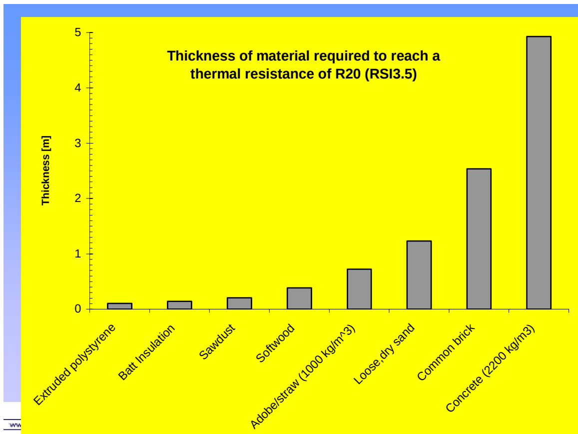

Assemblies

- Building enclosures are typically assemblies of several layers of different materials
- The overall resistance must be calculated

$$R_{tot} = R_1 + R_2 + R_3 \dots$$

- The conductance of the assembly is then

$$U = 1/R_{tot}$$

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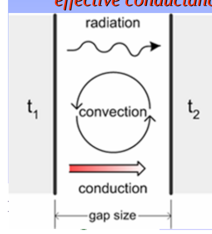
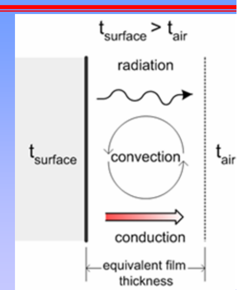
Air Spaces & Surface Films

- All 3 modes of heat transfer play a role
- The effects are lumped into a coefficient, h_o which can be used in the conduction equation as an *effective conductance*





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Air Spaces

- Airspaces are important in windows and old buildings
- Heat flow depends on heat flow *direction* and surface *emissivity*

Situation (poorly vented or sealed)	R/ RSI Value	Conductance
Heat Flow Down (20-100 mm)	1.0 / 0.18	5.5
Heat Flow Across (20-100 mm)	0.96 / 0.17	5.9
Heat Flow Up (20-100 mm)	0.85 / 0.15	6.5
Reflective Airspace (e=0.05)	3.46 / 0.61	1.6

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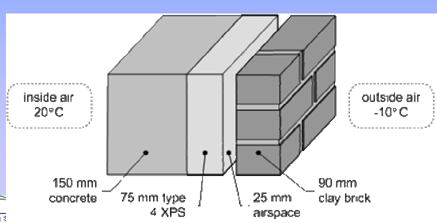
Surface Films

- Surface films are important to define surface temperature of poorly insulated components esp. thermal bridges, windows, old buildings

Surface Position	Flow Direction	Resistance	Conductance
Still Air (e.g. indoors)		**R / RSI**	**[W/m²K]**
Horizontal (i.e. ceilings & floors)	**Upward**	**0.61 / 0.11**	**9.3**
	Downward	**0.93 / 0.16**	**6.1**
Vertical (i.e. walls)	**Horizontal**	**0.68 / 0.12**	**8.3**
Moving Air (e.g. outdoors)			
Stormy 6.7m/s (winter)	**Any**	**0.17 / 0.03**	**34**
Breeze 3.4m/s (summer)	**Any**	**0.25 / 0.04**	**23**
Average Conditions	**Any**	**0.33 / 0.06**	**17**

Calculating Heat Flow through an Assembly

- To calculate assembly, add layers: materials, air gaps and surface films



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Heat Flow Calculations

Layer material	Conductivity	Thickness	Conductance	Resistance
Interior film note 1	N.A.	N.A.	8.3	0.120
Concrete	1.8	0.150	12	0.083
Type 4 XPS	0.029	0.075	0.39	2.56
Air space note 2	N.A.	0.025	N.A.	0.17
Brick	1.3	0.090	14.4	0.069
Exterior film note	N.A.	N.A.	34	0.029
		RSI total		3.04
		Overall co-eff. of heat		0.33

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Gradient Calculation

Layer Material	k (W / m·K)	t [m]	C_i (W / m²·K)	R_i (m²·K /W)	T (°C)	t (°C)
Interior temp						*20*
Interior film note 1	N.A.	N.A.	8.0	0.120	1.58	
						18.4
Concrete	1.8	0.150	12	0.083	1.09	
						17.3
Type 4 XPS	0.029	0.075	0.39	2.56	33.68	
						-16.3
Air space note 2	N.A.	25	N.A.	0.17	2.24	
						-18.59
Brick	1.3	0.090	14.4	0.069	0.91	
						-19.5
Exterior film note 1	N.A.	N.A.	34	0.029	0.38	
Exterior Temp						*-20*
			RSI total	3.04		
			U	0.33		

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But there are Complications

- The actual thermal resistance of an assembly is affected by

1. Thermal Bridges
2. Thermal Mass
3. Air Leakage

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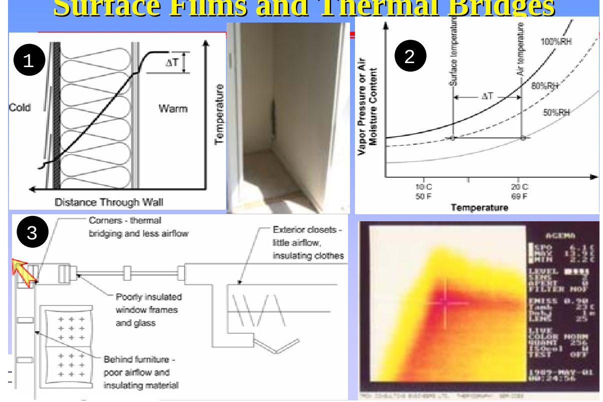
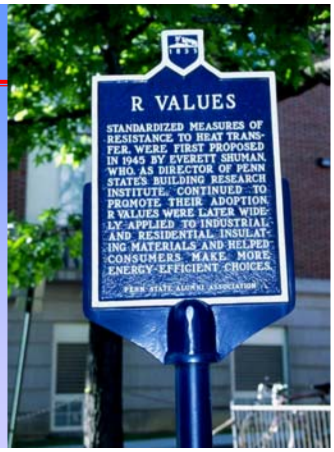
Surface Films and Thermal Bridges



R Values



The Meaning of R-value

- Thermal Resistance
  - R-value
  - Thermal Bridging
- Airtightness
  - about 30 % of energy loss
- Mass
  - smooths peaks and valleys
  - takes advantage of heat within (sun, equipment)
- Buildability / Inspectability
  - do you get what you spec/design?

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R-value

- Gives heat flow as equivalent conductance
  - Rarely includes thermal bridging
  - or three dimensions
- Never intended to include
  - airtightness
  - mass

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Thermal Performance

R-values and *Real* R-values

- Walls are three-dimensional and must be considered as such.
- Simple R-values are inadequate to describe thermal performance of some walls
- Dynamic behaviour and/or three-dimensional details greatly affect energy consumption.

See "Toward a National Opaque Wall Rating Label", by Jeff Christian and Jan Kosny, *Proceedings of Thermal Performance of Exterior Envelope of Buildings VI*, pp. 221-239.

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Different Types of R-values

- Center-of studspace (R_{cs})
  - Typical value given. Calculated between framing members
- Clear-wall (R_{cw})
  - More realistic 2-D. Calculations/tests of a section of wall.
- Whole-wall (R_{ww})
  - Most realistic 3-D steady state. Calculations/tests
  - walls with interfaces, corners and openings, doors windows
- True Energy (R_{te})
  - Includes time effects, e.g., 4-D = "mass effect".
  - Dynamic Whole wall
  - Highly climate and building dependent.

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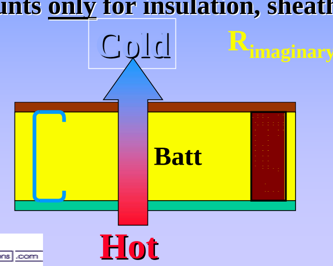
Center of Studspace

- Ignores framing elements
- Accounts only for insulation, sheathing, etc.



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But it's More Than Insulation!

- Thermal bridges provide shortcut for heat through insulation
- Heat passes through the structural members
- Common offenders
  - Floor and balcony slabs
  - Shear walls
  - Window frames
  - Steel studs

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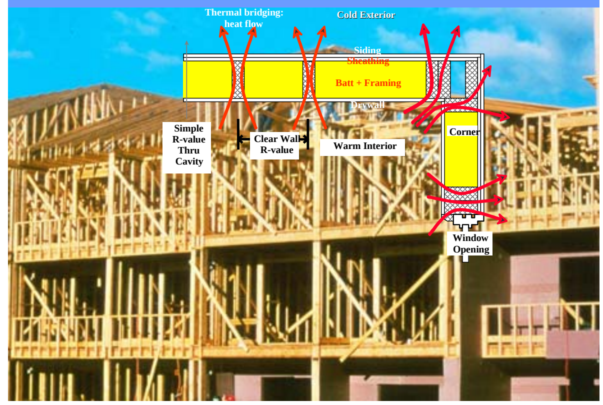
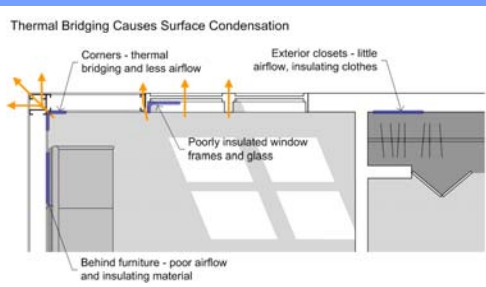
Thermal Bridging



Thermal Bridging: Common Problems



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Solve Thermal Bridging Problems

- Insulate on the inside or outside of thermal bridge
  - Reclad + exterior insulation can solve most thermal bridges
- Outside preferred
- Lower interior RH, add exterior insulation

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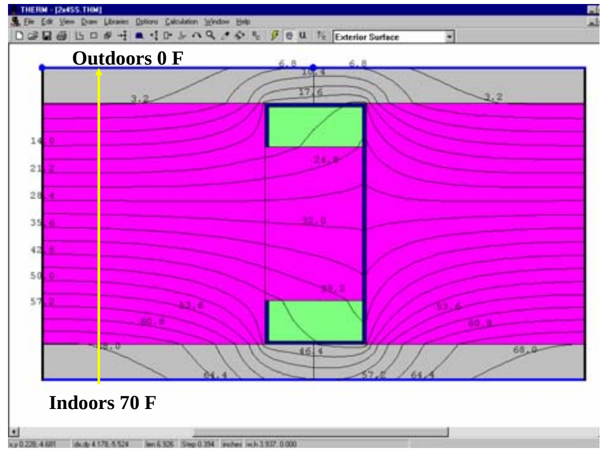
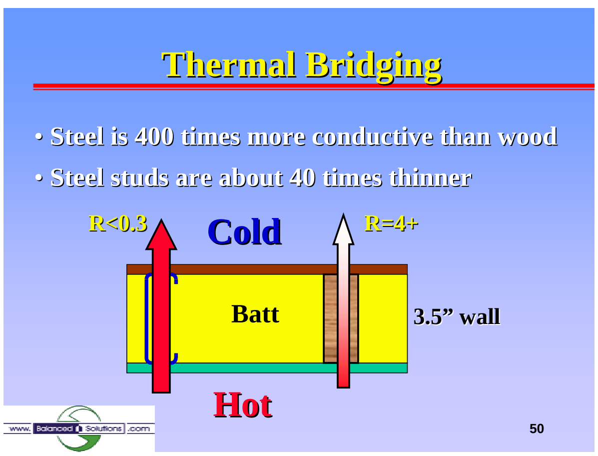
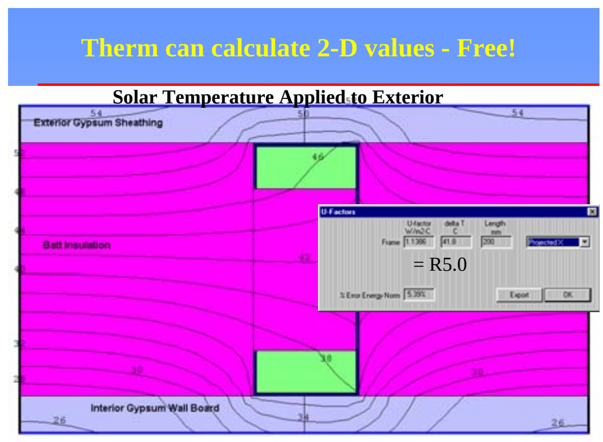


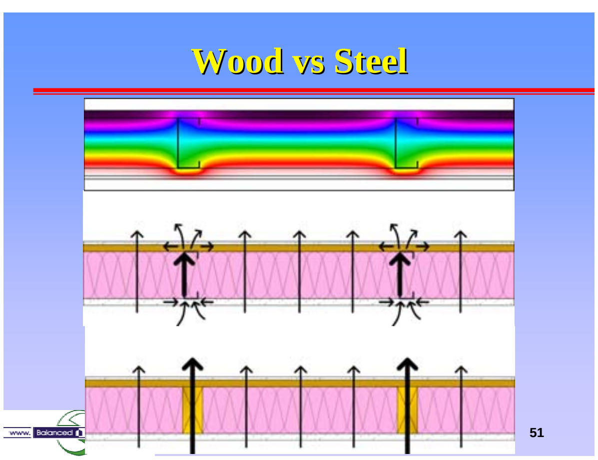
Outdoors 0 F
Indoors 70 F



Thermal Bridging
• Steel is 400 times more conductive than wood
• Steel studs are about 40 times thinner
R<0.3
Cold
R=4+
Batt
3.5" wall
Hot
50



Therm can calculate 2-D values - Free!
Solar Temperature Applied to Exterior
Exterior Gypsum Sheathing
Batt Insulation
= R5.0
Interior Gypsum Wall Board



Wood vs Steel
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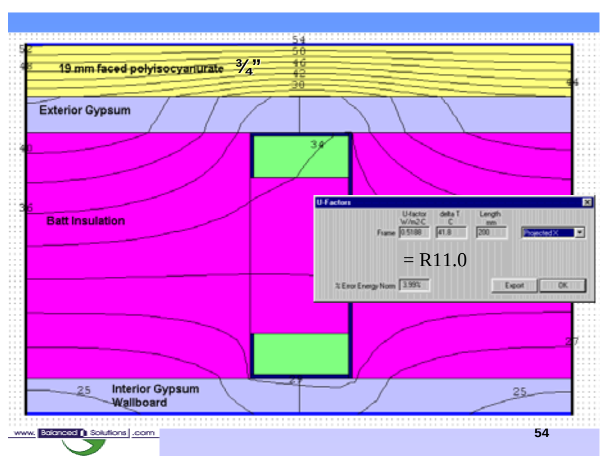

19 mm faced polyisocyanurate ¾"
Exterior Gypsum
Batt Insulation
= R11.0
Interior Gypsum Wallboard
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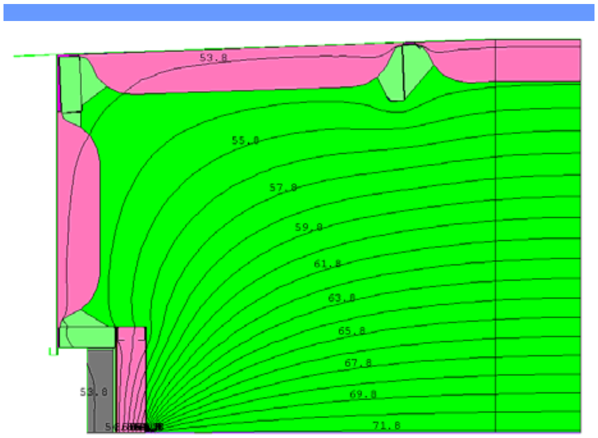
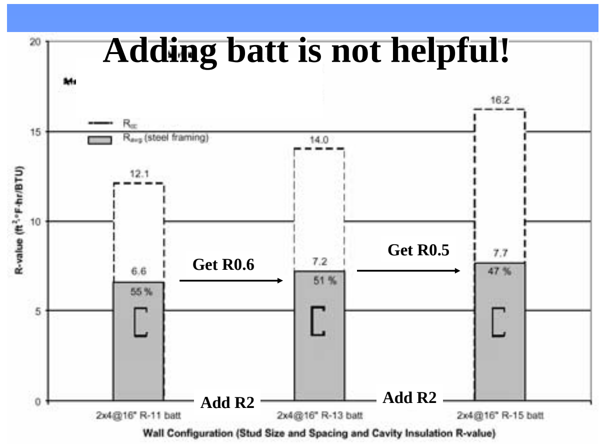
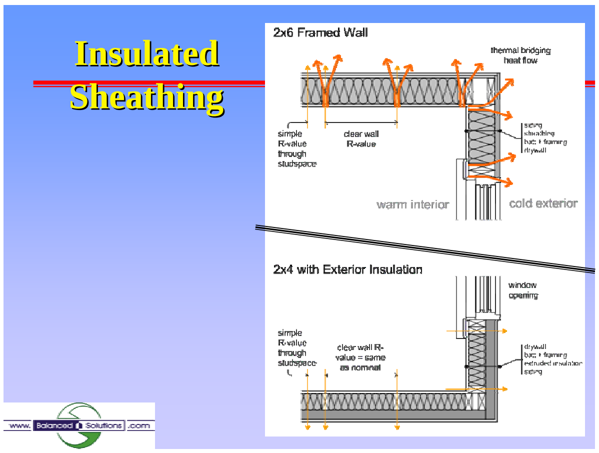
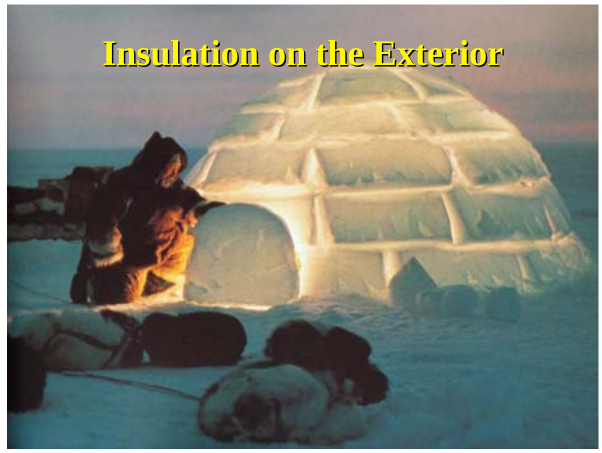
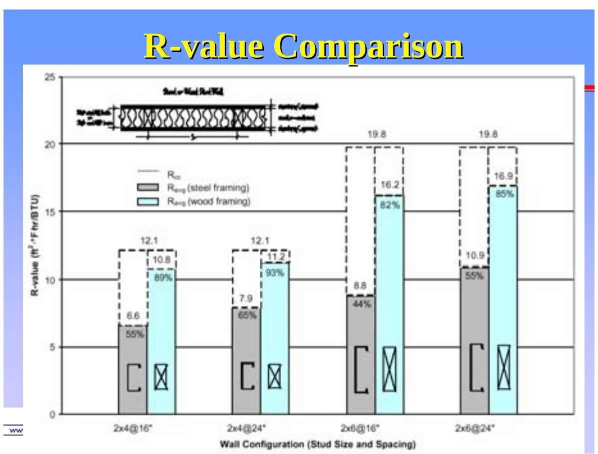

53.8
55.8
57.8
59.8
61.8
63.8
65.8
67.8
69.8
71.8


Adding batt is not helpful!
Get R0.6
Get R0.5
Add R2
Add R2
R-value (ft²·°F·hr/BTU)
Wall Configuration (Stud Size and Spacing and Cavity Insulation R-value)
2x4@16" R-11 batt
2x4@16" R-13 batt
2x4@16" R-15 batt

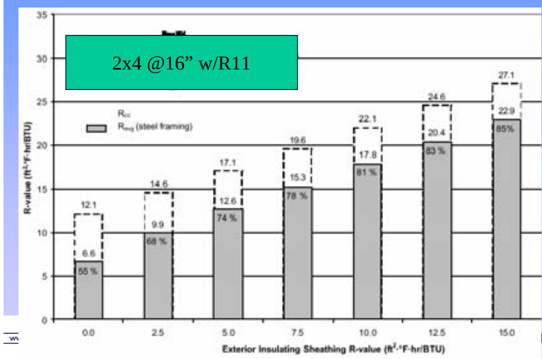

Insulated Sheathing
2x6 Framed Wall
warm interior
cold exterior
2x4 with Exterior Insulation

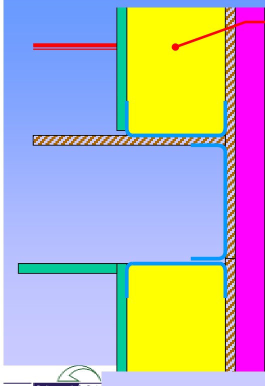

Insulation on the Exterior


R-value Comparison
R-value (ft²·°F·hr/BTU)
Wall Configuration (Stud Size and Spacing)
2x4@16"
2x4@24"
2x6@16"
2x6@24"


All on the exterior

Impact of Insulating Sheathing





E.g. Rim Joists

- Uninsulated Rim Joist
- = thermal nightmare
- Stuffing batts helps little
- Insulated sheathing solves

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Different Types of R-values

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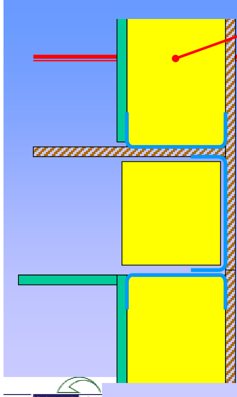

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Typical R-values

Wall Description	Center of cavity $R_{imagine}$	R_{cc}	Clear wall R_{cw}	Whole wall R_{ww}
3.5" SS@16 o.c. R12	12-13	12	7.4	6.1
3.5" SS@16 o.c. R12 + 1" EPS	16-18	16	11.8	9.5
2x6 WS@24 in. o.c., R19 batt	20	19	16.4	13.7
2x4 WS@16 in o.c., R12 batt	12-13	12	10.6	9.6
EPS block forms	15.2	15.2	15.2	15.7
Stressed Skin 6" core	25	25	24.7	21.6

With information from Oak Ridge National Labs

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Codes and R-values

- Implications: traditional framed walls have usually over-reported R-values
- ASHRAE 90.1 uses clear-wall *plus* mass effect
- Most local codes do not consider this

True energy equivalent R-values will vary with climate and building type, but *consumption will always be lower for walls with thermal mass*, and lowest for walls with thermal mass on the inside.

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Data Sources

- Oak Ridge National Labs
  - www.ornl.gov/roofs+walls
- Penn Housing Research Center
  - www.phrc.org Phone 814 865 2341
  - Report #58
- AISI
  - Thermal Design Guide for Exterior Walls

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Summary Heat Flow

- Heat flow *can* be simple
- Airflow and thermal bridges make it complex
- Radiation is poorly understood and may be important for certain applications

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