Building Science

Heat Flow & Insulation

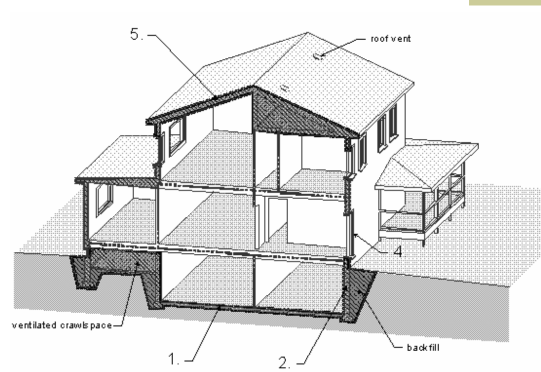
To Date

- Previously,
  - Why Building Science
  - What do Buildings do?
- Last week
  - Site, shape, size, orientation

The Building Enclosure

- The part of the building that physically ***separates*** the ***interior*** and ***exterior*** environments.
- Includes all of the parts that make up the wall, window, roof, floor, etc… from the innermost to the outermost layer.
- Functions – Control, Support, Finish (sometimes distribute)

Building Enclosure Components



Building Enclosure Functions

- Basic Functions
  - Support
  - Control
  - Finish
  - Distribute (sometimes)

Control:

Heat
Air
Vapour
Rain
Sound
Fire
Insects
Access

Control - Mass and Energy Flows

Overview

- Heat
  - modes of heat transport
- Insulation
  - how insulation works
  - impact of deficiencies esp. air flow

Why Insulate?

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

Heat & Temperature

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

Heat Flow

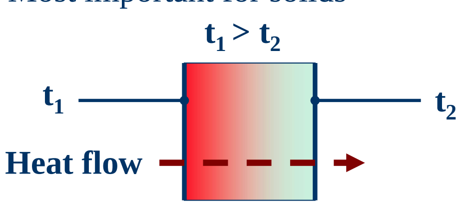
- Always moves from more to less
- Rate of flow depends on:
  - **Temperature Difference**
  - **Material Properties**
  - **Type & Mode**

Heat Flow

- Type of Heat flow
  - steady-state or dynamic
  - one-, two- or three-dimensional
- Mode of Heat Flow
  - **Conduction**
  - **Convection**
  - **Radiation**

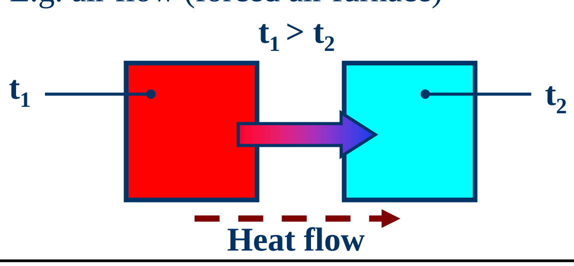
Conduction

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



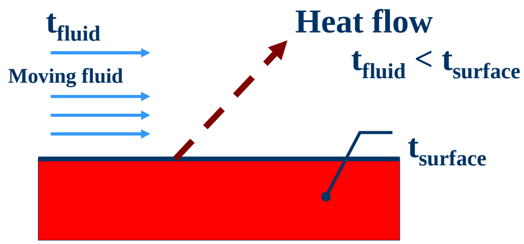
Convection

- Heat Flow by bulk movement of molecules
- Most important for liquids and gases
- E.g. air flow (forced air furnace)



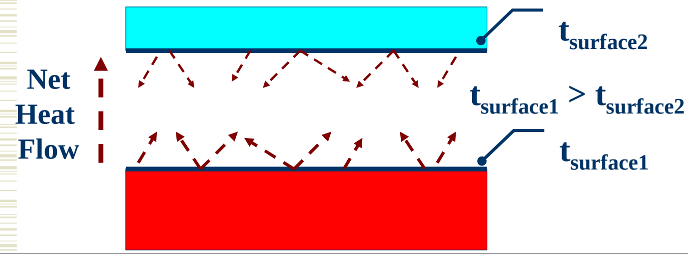
Convection

- Also heat flow from solid to liquid or gas
- Critical for surface heat transfer (e.g radiators)



Radiation

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



Radiation

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

Calculating Heat Flow

- Conduction
  - $q = UA(T_1 - T_2)$ ⟸ ***All we need for most***
- Convection
  - E.g. $q = 1.42(\Delta T/L)^{0.25}A(\Delta T)$
- Radiation
  - E.g. $q = \varepsilon_1\varepsilon_2 A_1 \sigma(T_1^4 - T_2^4)$

Calculating Heat Flow

$q = UA(T_1 - T_2) = UA(\Delta T)$

- Where
  - q = heat flow rate (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)

Conductance?

- Conductance is a layer property
- Expresses how easily heat can flow through a layer of the material

U = k/*l* = 1/R

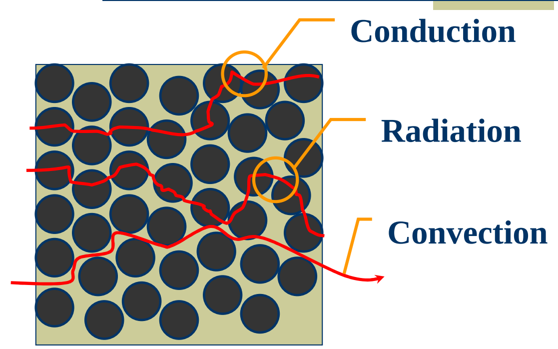
Conductance = Conductivity / Thickness = 1 / Resistance

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

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
- Only gas fills (e.g. HCFC) can improve this

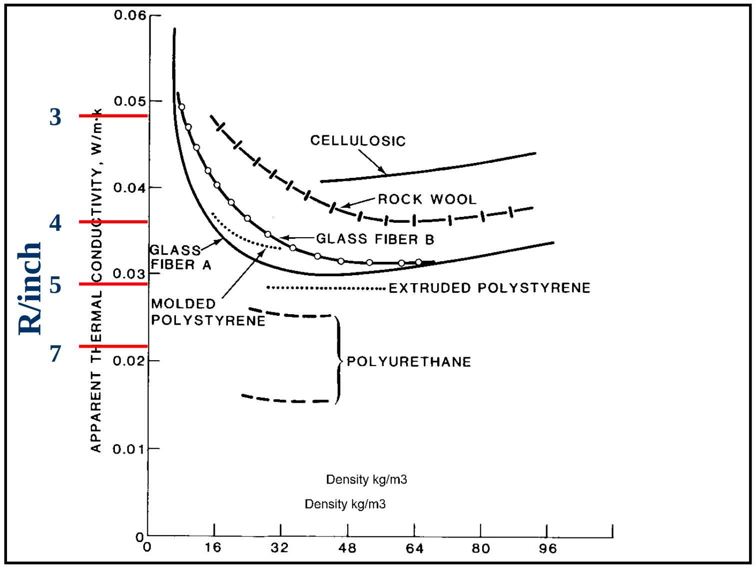
Materials



Hypothetical porous material

Materials

- High conductivity and high density
  - e.g. wood R1/inch and 45 pcf
  - versus concrete R0.1/inch and 140 pcf
- Low conductivity and low density
  - e.g. glass batt R3.5/inch and 1 pcf
- Compromise
  - cellulose, R3.5/inch and 3 pcf

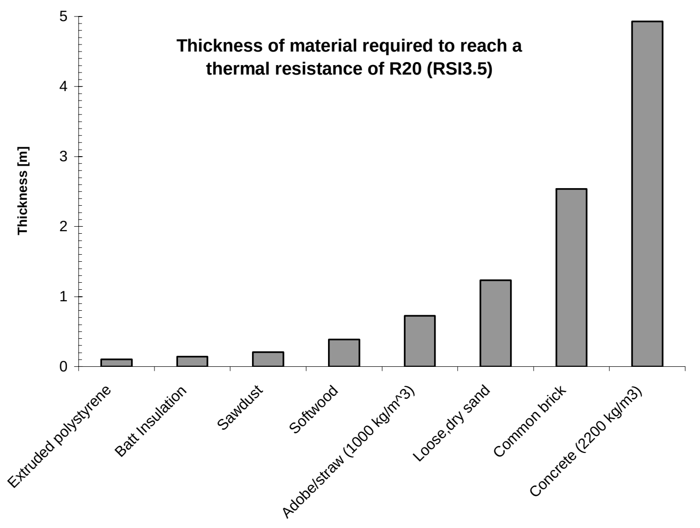


Fibers

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

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”



Assemblies

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

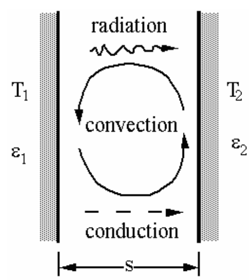
$$R_{tot} = R_1 + R_2 + R_3 \ldots$$

- The conductance of the assembly is then

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

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***



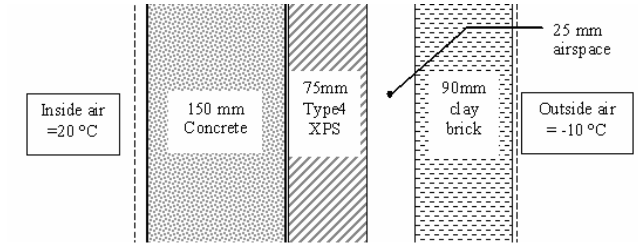
Air Spaces

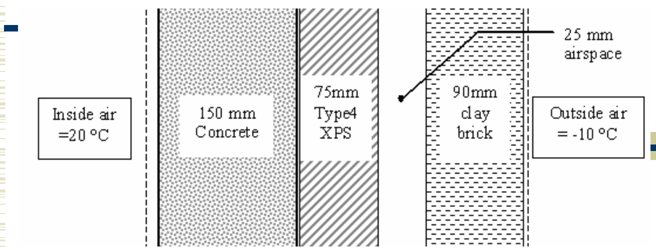
Situation (non reflective surfaces)	RSI Value	Conductance
Heat Flow Down (20-100 mm)	0.18	5.5
Heat Flow Across (20-100 mm)	0.17	5.9
Heat Flow Up (20-100 mm)	0.15	6.5

Surface Films

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

Example: Calculating the Conductance of an Assembly





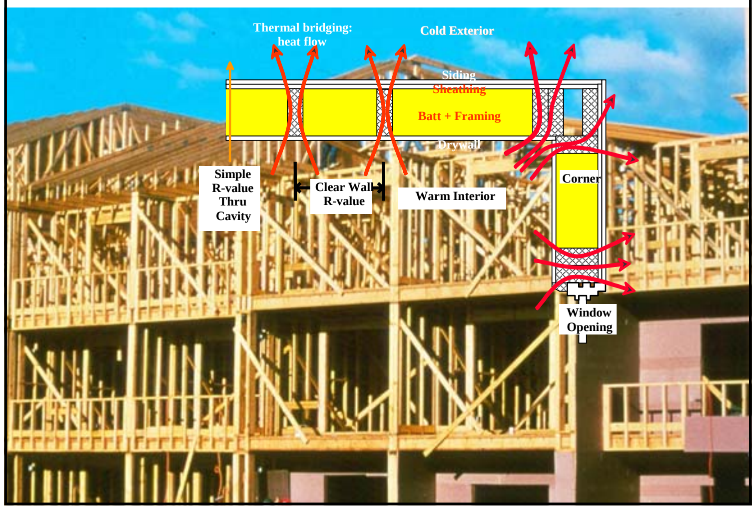
Layer Material	Conductivity	Thickness	Conductance	Resistance
Interior film [note 1]	N.A.	N.A.	8.3	0.120
Concrete	1.8	0.150	12	0.083
Type 4 XPS	0.029	0.075	0.39	2.56
Air space [note 2]	N.A.	25	N.A.	0.17
Brick	1.3	0.090	14.4	0.069
Exterior film [note 1]	N.A.	N.A.	34	0.029
		RSI total		**3.04**
		Overall Heat Transfer, U		**0.33**

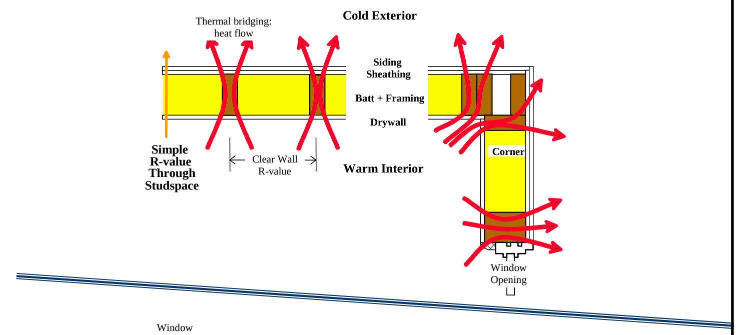
But there are Complications

- The actual thermal resistance of an assembly is affected by

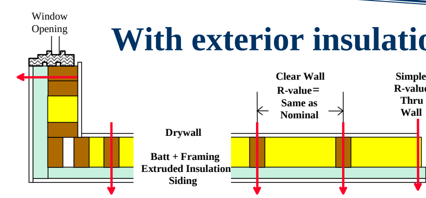
1. **Thermal Bridges**
2. **Thermal Mass**
3. **Air Leakage**

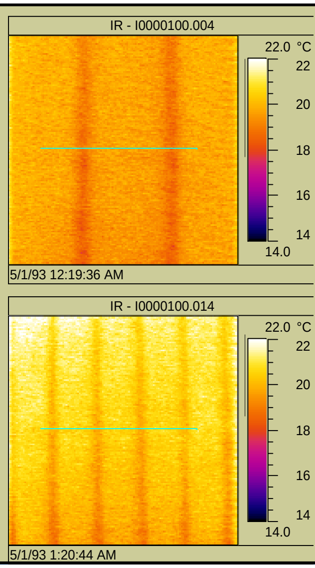
Thermal Bridging

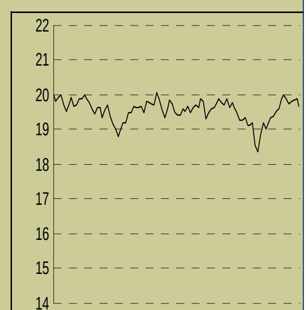




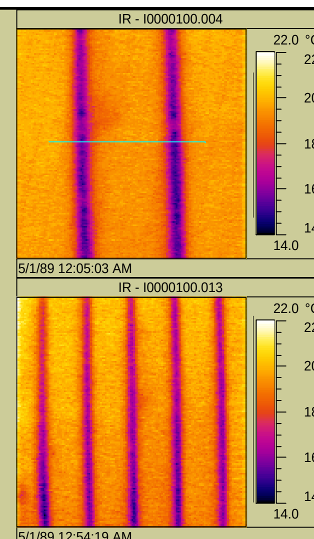
With exterior insulation

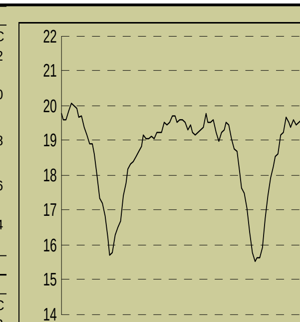




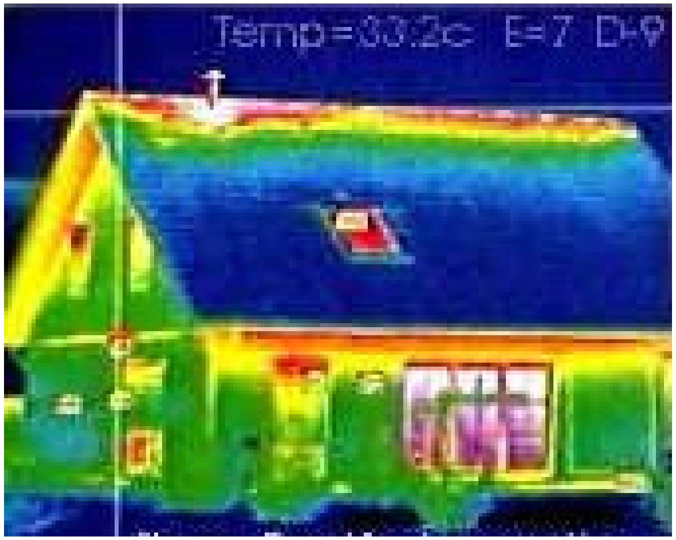


2x4 wood stud w/R12 batt





2x4 steel stud w/R12 batt



Thermal Mass

- Only comes into play when the heat transfer is not steady state
- Dampens the temperature changes experienced on the other side of the assembly

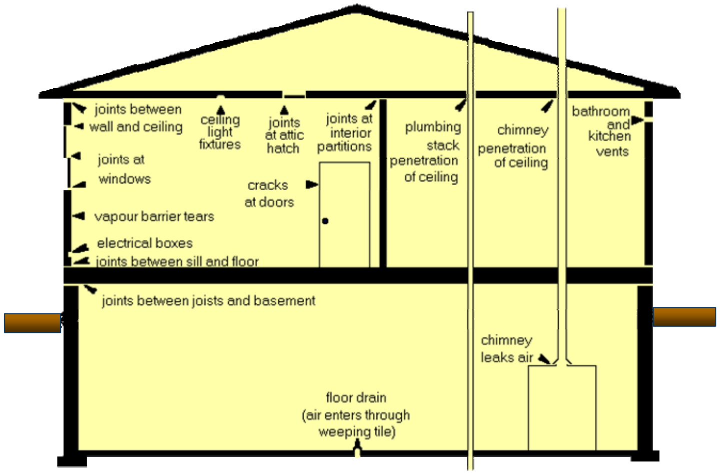
Air Leakage

- Air moving through the assembly allows heat to bypass the insulation
- Three types of air leakage to be concerned about:
  1. **Through Wall**
  2. **Convective Loops in Wall**
  3. **Wind Washing**

Thru Wall Airflow

- Air leakage accounts for 30 to 50% of a well-insulated house space conditioning
- Air leakage is a major moisture source
- Control, minimize leaks
- Air barrier system can be anywhere in wall
- Many materials stop airflow, most systems don't

- Build tight, ventilate right

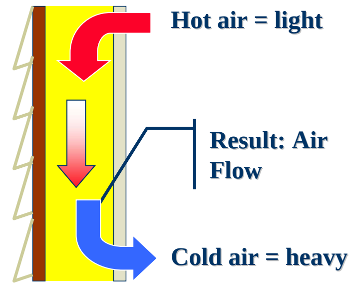


Typical Air Leakage Points

Convective Loops

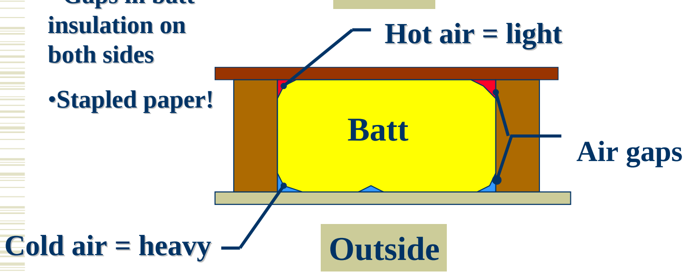
Cold Climate

Robs insulation capacity



Convective Loop in Wall (Internal Stack Effect)

- **Gaps in batt insulation on both sides**
- **Stapled paper!**

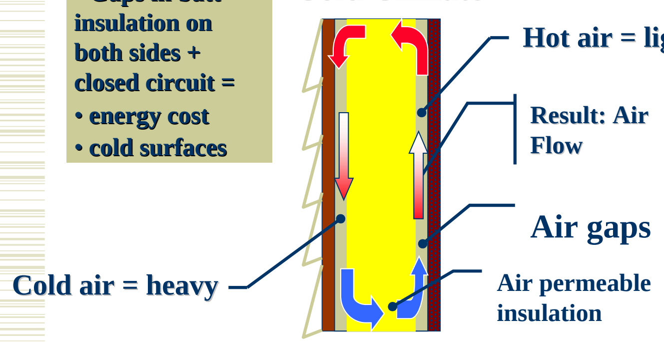


Common batt performance problem

Convective Loop in Wall (Internal Stack Effect)

- **Gaps in batt insulation on both sides + closed circuit =**
- **energy cost**
- **cold surfaces**

Cold Climate



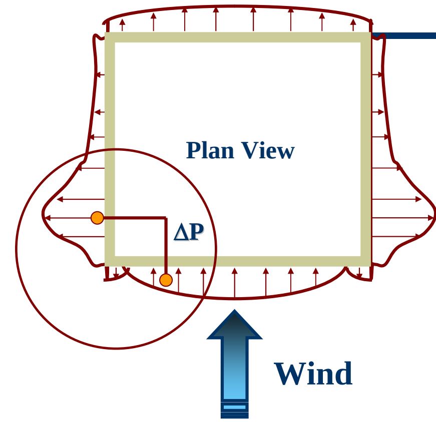
Convective Loops

- Convection varies directly with temperature difference
- Requires flow path through cracks/insulation

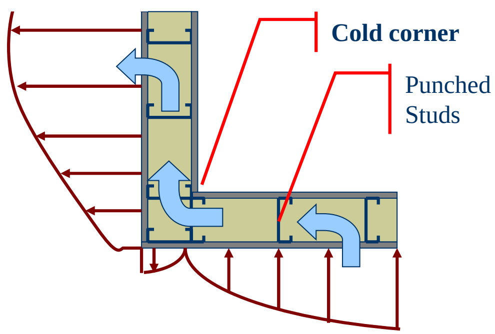
Solutions

- Minimize temperature difference by using layers of insulation
- Fill space completely
- Use low air permeance insulations

Wind Pressure Distribution



Lateral Airflows



Windwashing

- Need some airtightness outside studspace
- Sealed housewrap, attached building paper
  - prevent flapping and thus pumping
- Sheathing sealed with tape
  - both OSB and insulated sheathing
  - high density MI
- High density cavity insulation
  - some foams, maybe dense cellulose

So what is the real R-value ?

- Thermal Resistance (i.e. 1/conductance)
  - R-value
  - Thermal Bridging
- Airtightness
  - about 30 - 50% of energy loss
- Mass
  - smooths peaks and valleys
  - takes advantage of heat within (sun, equipment)
- Buildability / Inspectability
  - do you get what you spec/design?

Typically quoted R-values

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

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.

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.

Codes and R-values

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

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.

Typical R-values

Wall Description	$R_{imagine}$	R_{cc} (Center of cavity)	R_{cw} (Clear wall)	R_{ww} (Whole wall)
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

Example House

- Excel

Insulation Systems

- Fiberglass or rockwool batt
  - Blow in batt
- Cellulose
- foam in place
- insulated sheathings
- radiant barriers
- SIPS

Batt Insulation

- Low-density rockwool and glass fibre
- R3.2 to 3.8 per inch
- Very low vapour resistance
- very high air permeablity
- non-combustible

- Inexpensive
- Beware convective loops and wind washing

Cellulose

- R value of 3.2 to 3.7 depending on density
- Controls convection at over 3, maybe 4 pcf
- Can fill irregular cavity spaces
- Variations with installation method
- Settling can be a problem with low density
- Don’t blow too wet
- Provides moisture storage
- Controls rot/mold by leaching borate
- Is <u>not</u> part of an air barrier system!

Cellulose Install

Blow-in-batts

- Net or adhesive holds sprayed fiber in cavity
- Can use glass, rockwool, cellulose
- fills space and around obstructions
- avoids settling problems?
- Control convection

Spray Foam

- Primarily polyurethane foam
- open cell (CO_2 blown) Icynene
  - R4/inch
  - 16 perms for 3 inch
  - 1.6 lps/m^2 @ 75 Pa
- closed cell (HCFC/pentane blown)
  - R6-7/inch
  - 1 or 2 perms
  - <0.01 lps/m^2 @ 75 Pa

Spray Foam

- Open cell
  - neither air or vapour barrier
  - stops convection / wind washing
- Closed cell
  - air barrier and part vapour barrier
  - excellent air seal in difficult areas!
  - Beware: adhesion and movement/shrinkage cracks
- Both Expensive

Radiant barriers

- Often misunderstood
- Performance depends on temperature difference
- How reflective is the material? Is all dust and corrosion avoided?
- Must have an air space!!!

There MUST be an airspace for radiant products to work

Website

- University of Waterloo

  Building

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  Group

www.civil.uwaterloo.ca/beg