Applied Computer Modeling for Building Engineering

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Overview

- Why Modeling?
- Heat Flow
  - Therm / Frame
  - Heat 2D / Heat 3D
  - Case studies
- Heat & Moisture
  - WUFI-ORNL & Validation
  - Case studies
- Fire Energy and Lighting
- Summary

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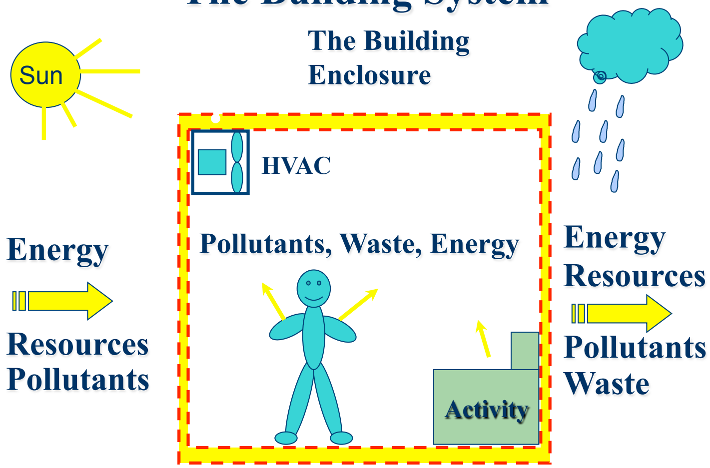
The Building System



Pollutants: Moisture, odour, + +

Modeling for fun and profit

- Predict and understand temperature and moisture condition in & on bldg enclosure
- Avoid design errors
- Understand problems
- Aid the design of repairs
- Development of new systems/products
- Develop understanding of performance (teach)

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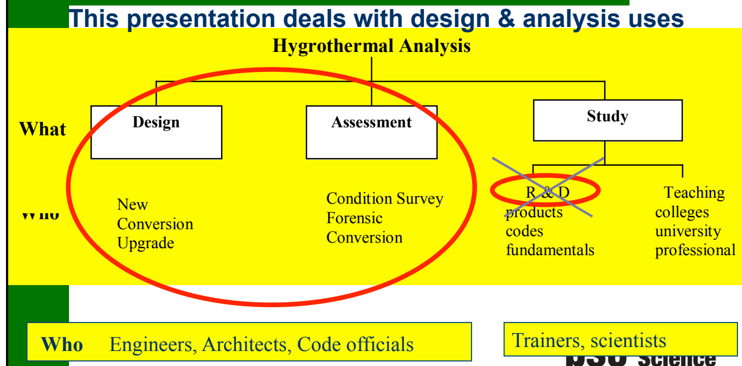
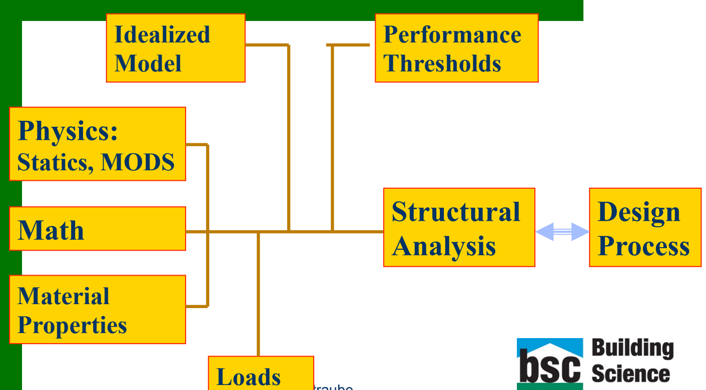
What are "Models"

- By definition, an approximation of reality
- Typically a model is designed for a particular purpose,
  - e.g. calculate energy
- As simple as
  - Q= U •ΔT → Q(t) = U •ΔT(t)
- As complex as full building dynamic simulation including occupant behaviour, plant, controls, etc.

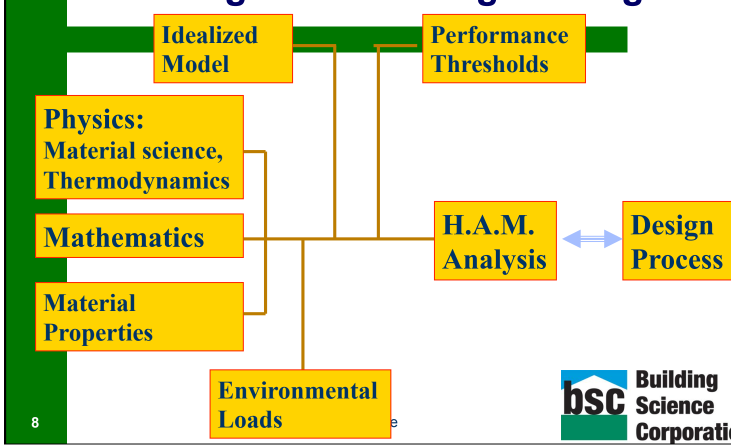
What and for Whom?



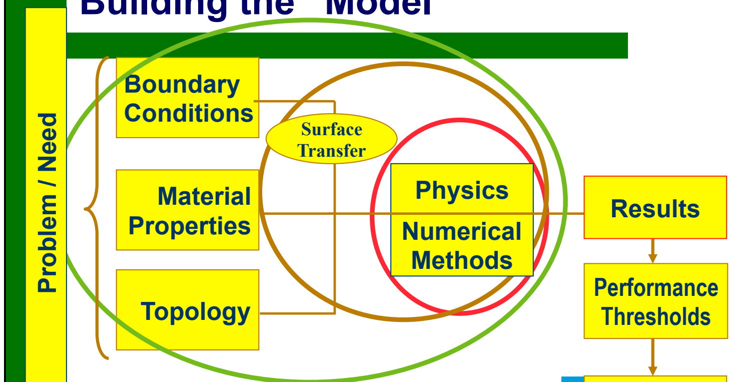
Structural Engineering



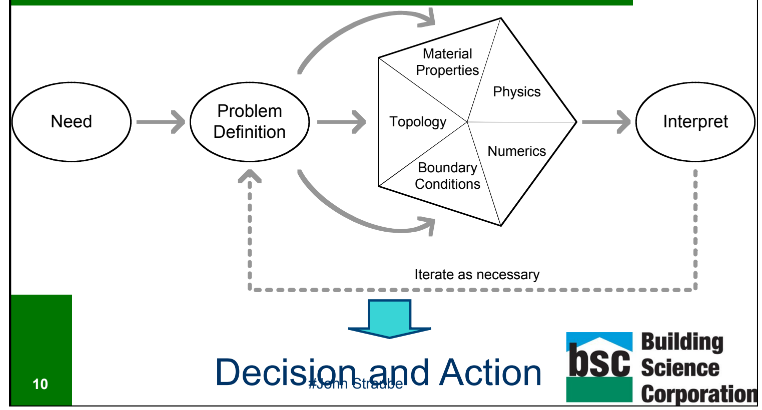
"Building Science" Engineering



Building the "Model"



The Process



Requirements

- Vary with Need, Time available, expertise
- Geometry (topology)
- Boundary Conditions (operating conditions)
- Material Properties
- Physics
- Performance Thresholds

What to Model

- Heat
  - Flow (Energy)
  - Temperatures
- Air
  - Energy
  - Contaminant transport
- Moisture
  - Durability, mold
- Light
- Fire

Heat Flow

- Steady-state or Dynamic
  - steady-state -- for average conditions or for lightweight construction
  - Dynamic -- to assess thermal mass, transient conditions
- One- Two- or Three-dimensional
- Free Tools
  - Use Therm or Frame
- Both 2-D steady-state

Building Science Basics

- Of THERM

Heat & Temperature

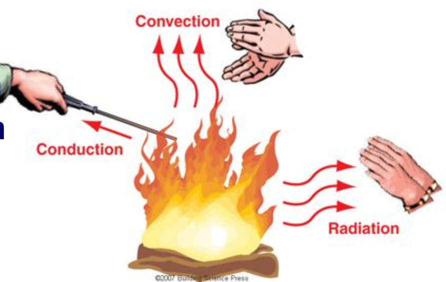
- Heat
  - A form of energy (like Light & Sound)
- Temperature
  - A measure of the amount of thermal energy
- Heat Flow
  - Movement of heat energy
- Heat Flux
  - The density of heat flow

Heat Flow

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

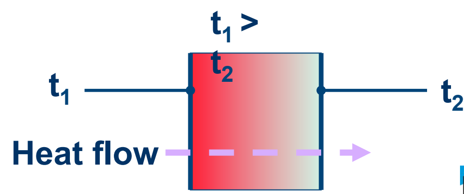
How to Control Heat Flow?

Modes of heat transfer:
- Radiation
- Convection
- Conduction



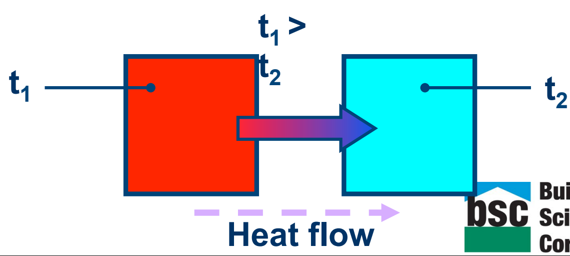
Conduction

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



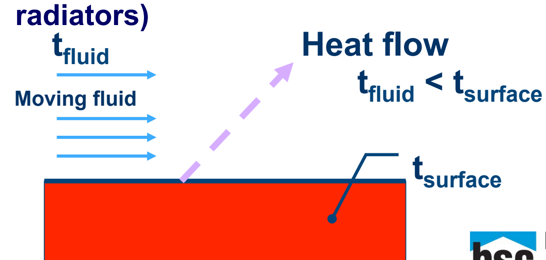
Convection

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



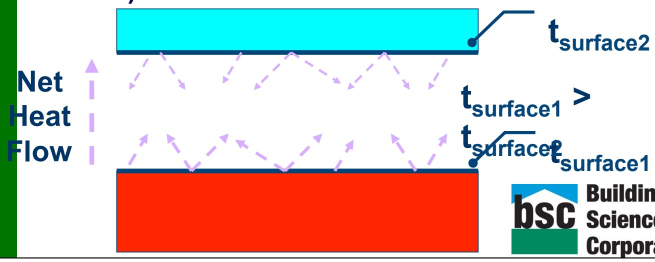
Convection

- 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

Thermal conductivity

- A material property, symbol k
  - Units: Btu / (hr ft F), Btu / (hr in F), W / (m K)
- Measurements include all 3 heat flow modes
  - Called "apparent conductivity"
- Conductivity varies with
  - density
  - Temperature
  - Moisture content
  - age

1 W/mK = 0.5778 Btu/hr ft F

Conductivity Data

Material	Density (kg/m3)	Conductivity Range (W/m K)	Conductance Range (W/m2 K)
Board / sheet products			
Plywood	400 - 600	0.08 - 0.11	
OSB	575 - 725	0.09 - 0.12	
Waferboard		0.1	
Hardboard		0.105	
Vegetable Fiberboard	270 - 300	0.045 - 0.07	
Particleboard	590	0.102	
Particleboard	1000	0.17	
Strawslab	260 - 350	0.085 - 0.11	
Corrugated Metal Deck			negligible
Finishes			
Ceramic Tiles		1	
Acoustic Tiles - fibreboard		0.065	
Acoustic Tiles - glassfibre		0.036	
Gypsum Board	800 - 900	0.16	
Sand Plaster / Lath		0.71	
Gypsum plaster / Lath		0.16 - 0.35	
Sand :Cement plaster	1570	0.53	
Gypsum plaster w/perlite	720	0.22	
Gypsum plaster w/sand	1680	0.8	

Conductance & Resistance

- Resistance & Conductance are layer properties
- Expresses how easily heat can flow through a *layer* of the material

C = 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

Calculating Heat Flow

$$Q = CA(T_1 - T_2) = CA(\Delta T) = CA(\Delta T)/R$$

- Where
  - Q = heat flow rate (W = J/s)
  - A = area that the heat is flowing through (m^2)
  - ΔT = temperature difference across layer (°C)
  - U = overall transmittance / conductance of the assembly (W/m^2K)

Calculation

- Given thermal conductivity
  - k = 0.029 W/mK
- What is the conductance of a 25 mm thick layer?
  - C = k / l = 0.029 / 0.025 = 1.16
- What is the RSI value
  - RSI = 1/C = 1/1.16 = 0.86

What is the R-value?

R-value

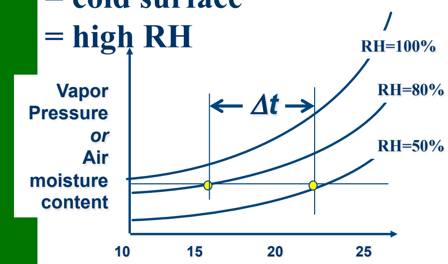
- R-value (imperial units)
  - °F / (ft^2 / Btu / hr)
- RSI (metric SI units)
  - °C / (m^2 / Watts)
- RSI = R / 5.67
  - Eg. R20 / 5.67 = RSI3.52
- R = RSI * 5.67
  - RSI2.1 * 5.67 = R12

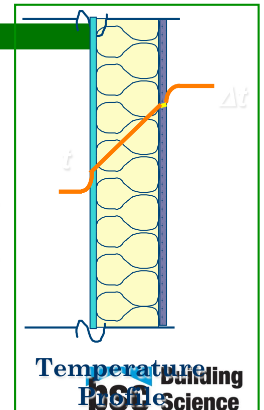
Thermal Bridging

- Why calculate?
  - Heat Loss calculations
  - Surface Condensation
    - dust marking
    - mould
    - windows
  - Interstitial Condensation
- 2-D steady state is easy
- 2-D dynamic may be needed, not much effort
- 3-D is quite time consuming, but feasible

Wall Temperatures and RH

Poor insulation
= cold surface
= high RH



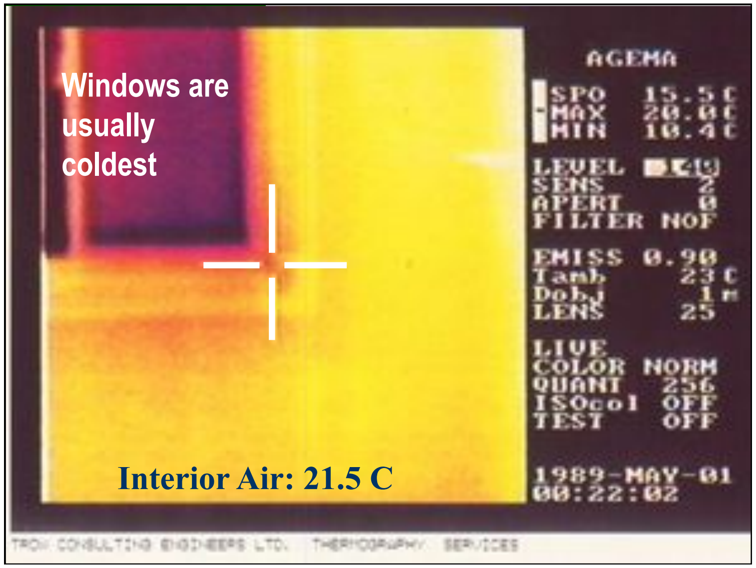


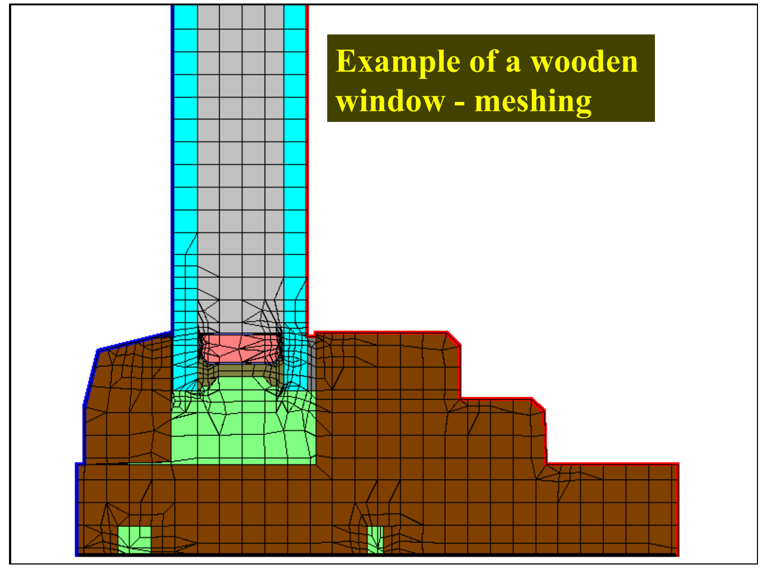
Interior Air at 72 F
Surface temperatures cannot be less than:

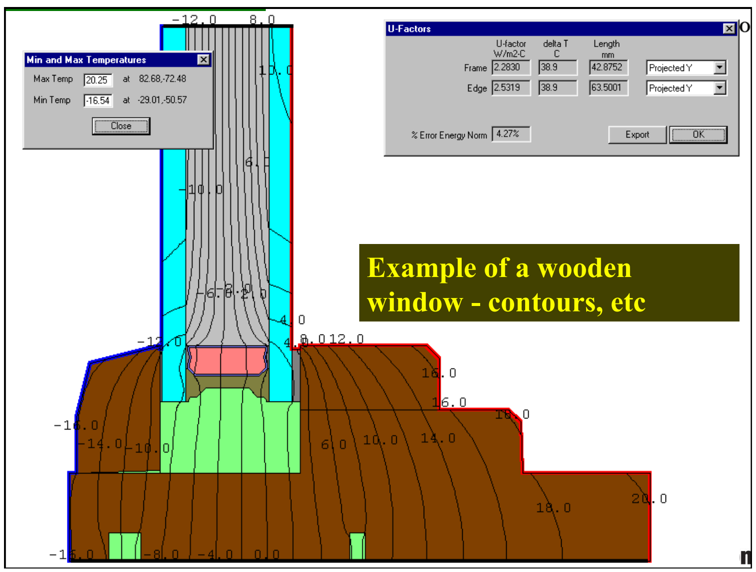
Interior RH	Condensation Temperature	Temperature @80%RH
20	28	33
40	46	52
50	52	57
60	57	63

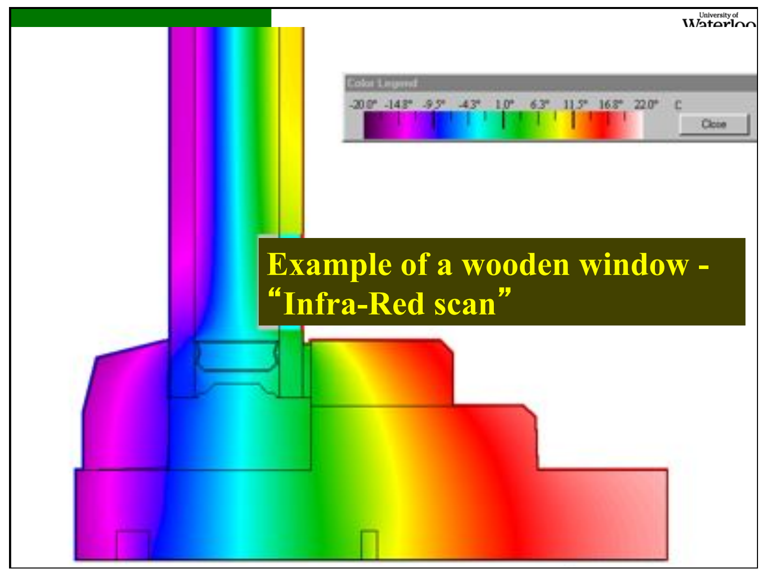
Two-D Steady-state

- Therm (windows.lbl.gov/software/therm)
  - Free, downloadable
  - Can use AutoCad templates
  - Primary intent -- window energy calculations
  - Can do much more


Windows are usually coldest
Interior Air: 21.5 C
AGEMA
SPO 15.5 C
MAX 20.0 C
MIN 10.4 C
EMISS 0.90
Tamb 23 C
LIVE
COLOR NORM
QUANT 256
1989-MAY-01
00:22:02

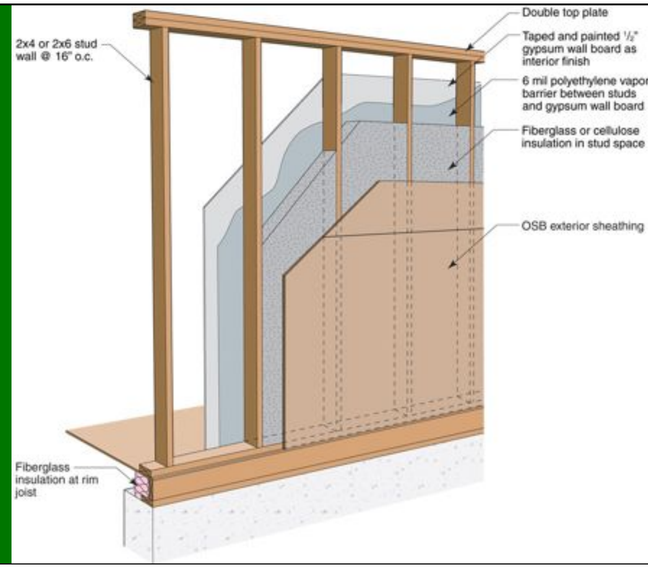

Example of a wooden window - meshing

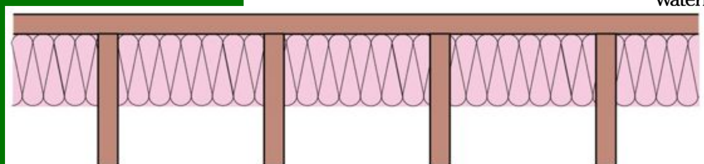

Min and Max Temperatures
U-Factors
Example of a wooden window - contours, etc


Color Legend
Example of a wooden window - "Infra-Red scan"

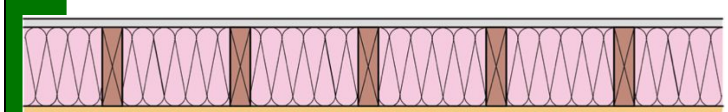
Example 2-D to 3D arrangement

- In many enclosure systems we can convert multiple 2D sections into a 3D result
- This has been demonstrated experimentally as being very accurate for wood framing

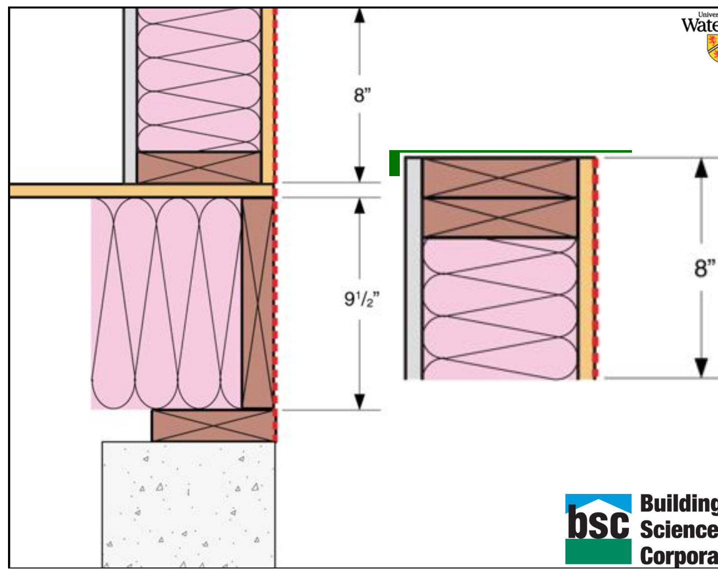


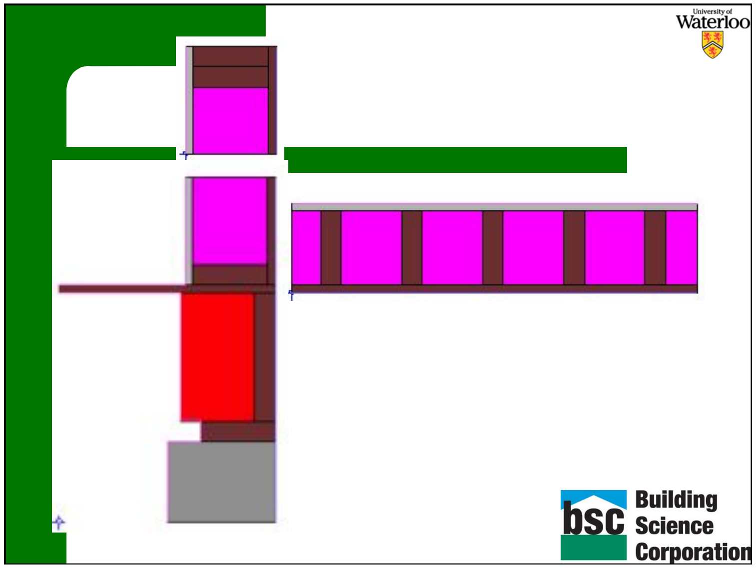


Plan View @ rim joist/ floor



Plan View @ wall

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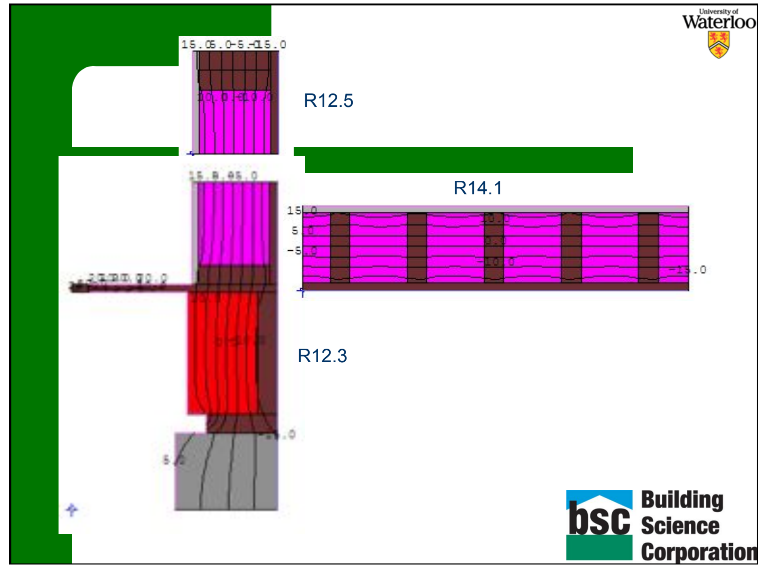
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R12.5
R14.1
R12.3
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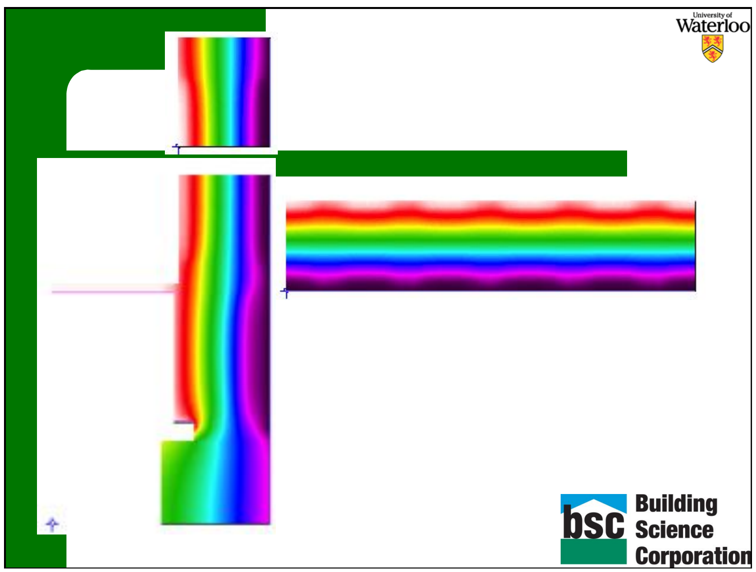
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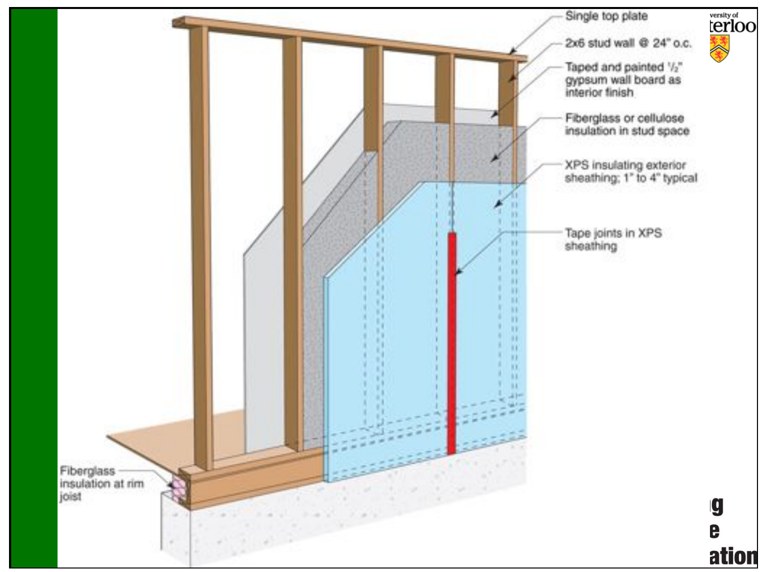
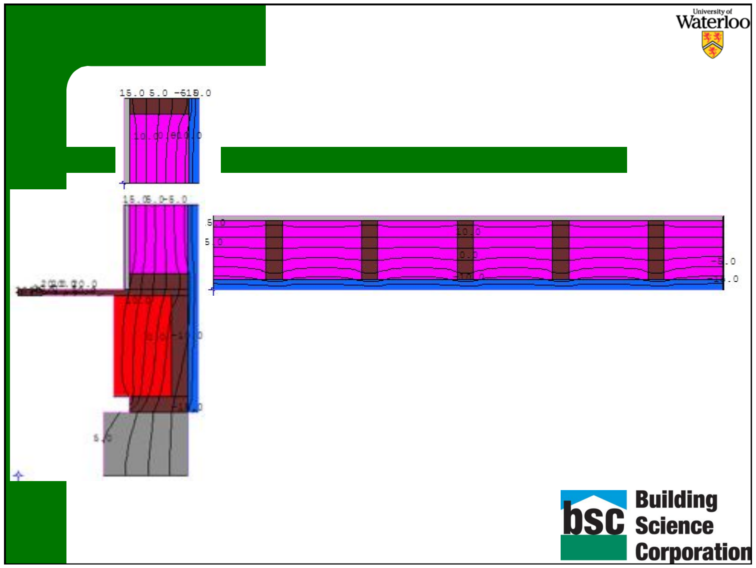
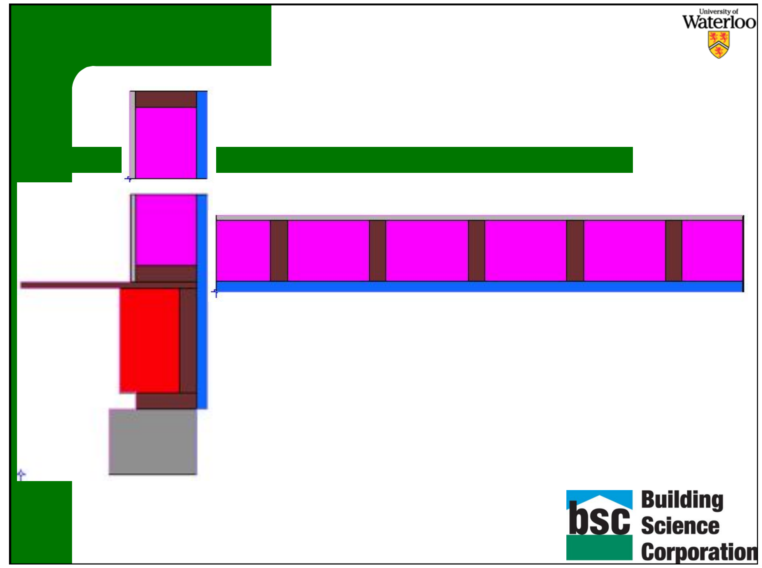
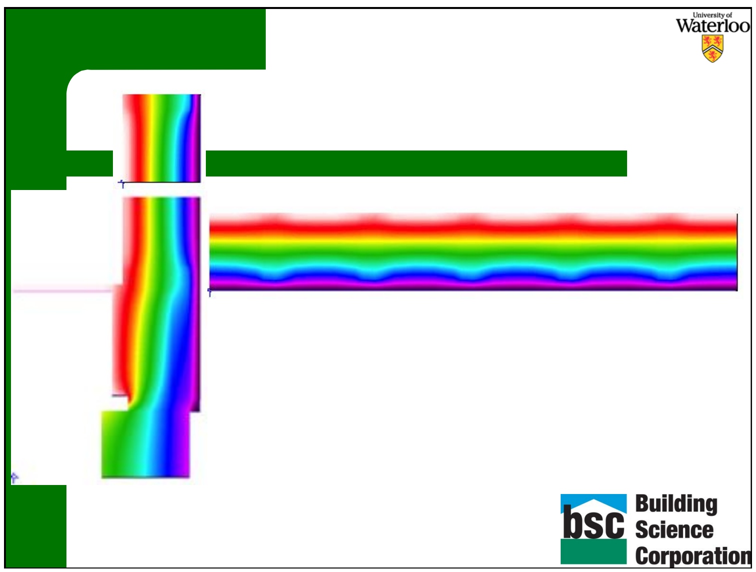
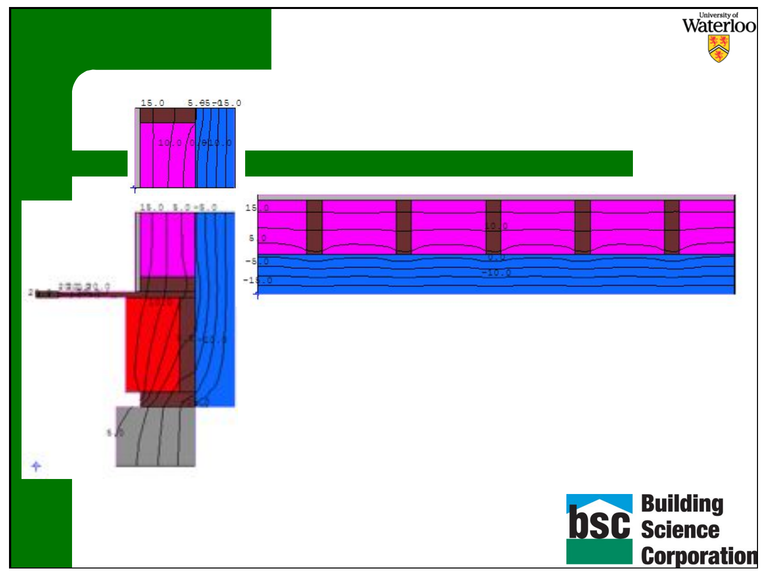
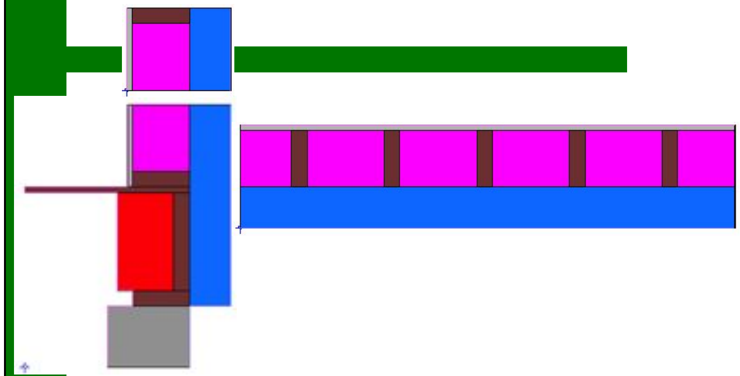

Single top plate
2x6 stud wall @ 24" o.c.
Taped and painted 1/2" gypsum wall board as interior finish
Fiberglass or cellulose insulation in stud space
XPS insulating exterior sheathing; 1" to 4" typical
Tape joints in XPS sheathing
Fiberglass insulation at rim joist

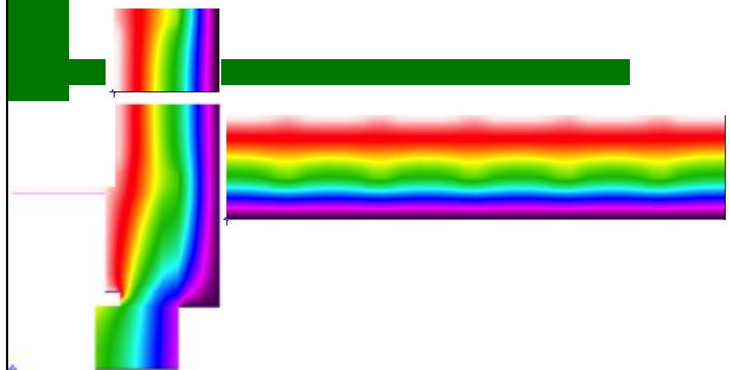












Many other walls

Case	Description	Whole Wall R-value	Rim Joist	Clear Wall R-value	Top Plate	Framing Factor
1a	2x6 OVE, 24"oc, R19FG + OSB	**15.2**	12.3	16.1	12.5	16%
1aii	2x6, 16"oc, R19FG + OSB (25%ff)	**13.7**	12.3	14.1	12.5	25%
1b	2x4 OVE, 24"oc, R13FG + OSB	**11.1**	9.8	11.5	9.8	16%
1bii	2x4, 16"oc, R13FG + OSB (25%ff)	**10.0**	9.8	10.1	9.8	25%
2a	2x6 OVE, 24"oc R19FG + 1" R5 XPS	**20.2**	18.5	20.6	20.3	16%
2b	2x6 OVE, 24"oc R19FG + 4" R20 XPS	**34.5**	29.0	35.6	35.4	16%
3	2x6 OVE, 24"oc, 2x3 R19+R8 FG	**21.5**	13.4	23.5	18.4	16%
4	Double stud wall 9.5" R34 cellulose	**30.1**	14.4	33.5	28.8	
5	Larsen Truss 12" R43 cellulose	**36.5**	18.6	40.5	34.4	
6a	SIPs (3.5" EPS)	**14.1**	12.3	14.5	10.6	
6b	SIPs (11.25" EPS)	**36.2**	14	41.6	28.2	
7a	ICF - 8" foam ICF (4" EPS)	**16.4**		16.4		
7b	ICF - 15" foam ICF (5" EPS)	**20.6**		20.6		
7c	ICF - 14" cement woodfiber ICF with Rockwool	**17.4**		17.4		
8a	2x6 OVE, 24" o.c., 5" 2 pcf R29 SPF, OSB	**19.1**	13.6	20.3	19.5	16%
8b	2x6 OVE, 24" o.c., 5.5" R21 0.5 pcf SPF, OSB	**16.5**	13.1	17.2	16.6	16%
9	2x6 OVE, 24"oc, 2" SPF and 3.5" fibrous fill	**17.5**	13.2	18.4	17.7	16%
10	Double stud with 2" 2.0 pcf foam, 10" FG	**32.4**	15.9	36.2	28.5	
11	modified Larsen Truss with ext. spray foam	**37.1**	18.8	40.6	41.9	16%
12	2x6 OVE, 24"oc, EIFS - 4" EPS	**30.1**	23.8	31.4	31.1	16%

Lets try some THERM

- 4" Brick,
- 8" block backup,
- 2" XPS insulation
- ½" drywall
- At 8" slab penetration

Example 1

- Create a drawing page 40” x40”
- Choose a snap grid of 0.5”
- Draw 15x7.5 CMU, 8” slab x 24, 15x7.5” CMU
- Choose materials, create as needed
- Add and change colors

Materials

- CMU
- Concrete
- Gypsum wall board

Table 5.1. Thermal conductivities of the bricks at two mean temperatures

Thickness	Density	T(mean)	Thermal Conductivity	Brick No. and Type
mm	$kg\ m^{-3}$	°C	$W\ m^{-1}\ K^{-1}$	
12.0	2294	10.0	0.789	1. White Concrete Brick
12.0	2294	22.5	0.792	""
12.4	1935	10.8	0.489	2. Red Matt Clay Brick
12.4	1935	24.1	0.500	""
12.3	1719	9.82	0.425	3. Buff Matt Clay Brick
12.3	1719	24.2	0.434	""
12.3	1821	9.82	0.509	4. Textured Coated Clay Brick
12.3	1821	23.4	0.522	""
12.2	2315	11.2	0.728	5. Concrete Brick
12.2	2315	24.0	0.737	""
12.2	1973	10.5	0.614	6. Calcium Silicate Brick
12.2	1973	23.6	0.623	""

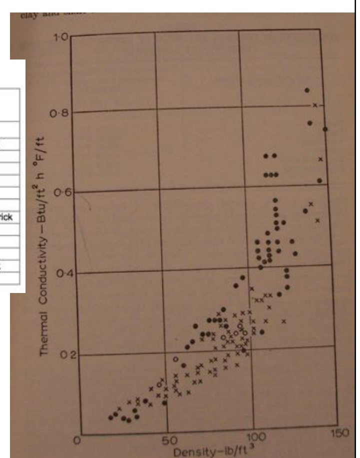


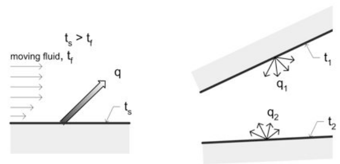
Fig. 9.1. Thermal Conductivity of Lightweight Aggregate Concrete of Various Types

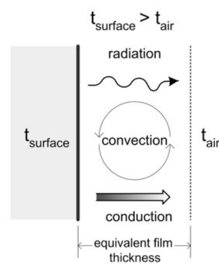
Boundary Conditions

- Practice making new ones
- Beware confusion re: convection re radiation at surfaces
- May wish to use radiation models
  - Careful understanding needed
- U-factor tags. What do you want to know?
- Temperature @ cursor option

Details

- Surface films
  - Radiation
  - Conduction
  - Convection
- Air cavities
- Radiation





Surface Films

Surface position	Flow direction	Surface emittances	
Still air (e.g., interior)		$\varepsilon = 0.90$	$\varepsilon = 0.05$
Horizontal (i.e., ceilings and floors)	Upward Downward	9.3 6.1	4.3 1.3
Vertical (i.e., walls)	Horizontal	8.3	3.4
Moving air (e.g., exterior)			
6.7 m/s (winter)	Any	34	34
3.4 m/s (summer)	Any	23	23
Average conditions	Any	17	16

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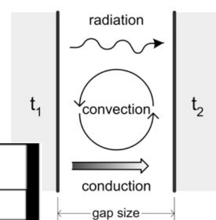
Airspace

Position of surface	Direction of flow	13 mm		20 mm		40 mm		90 mm	
		Emittance Factor F_E							
		0.00.05	0.0.90	0.00.05	0.0.90	0.00.05	0.0.900	0.00.05	0.0.90
Mean temp. 32 °C									
Horizontal	Up	2.78	7.69	2.56	7.69	2.38	5.26	2.13	7.14
	Down	2.44	7.14	1.72	6.67	1.06	5.88	1.45	5.56
Vertical	Horiz.	2.44	7.14	1.75	6.67	1.56	6.67	1.67	6.67
Mean temp -18°C									
Horiz.	Up	2.78	4.55	2.63	5.56	2.44	5.26	2.17	5.00
	Down	2.00	5.00	1.41	4.35	1.18	3.70	1.82	3.45
Vert.	Horiz.	2.00	5.00	1.59	4.55	1.69	4.55	1.69	4.55



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Some further case studies

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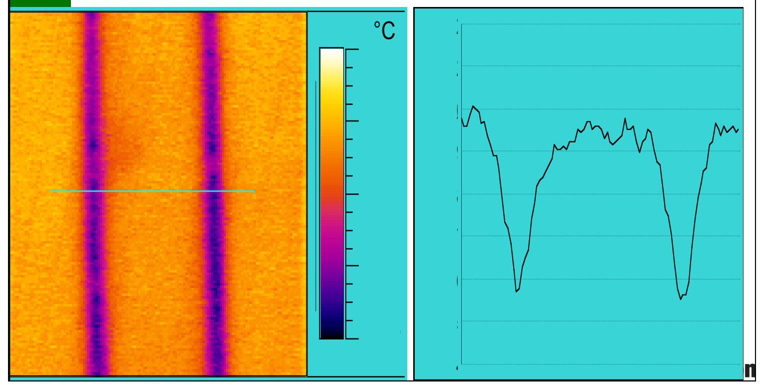
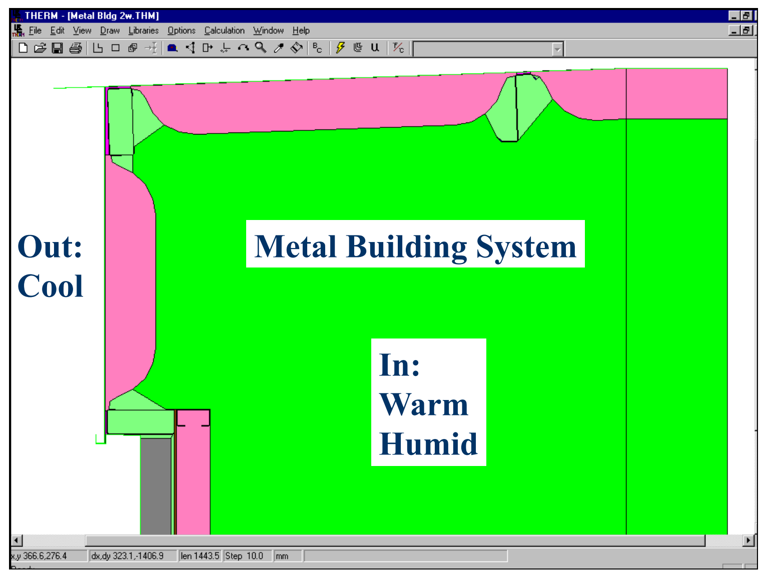
Steel Framing

- Metal Building Systems and Steel Studs
- Can be Thermal Bridges
  - Consume Energy
  - cause dust marking
  - Surface condensation
- How much/little insulation is needed?

Infra-Red Photos

From inside a building at 22 C



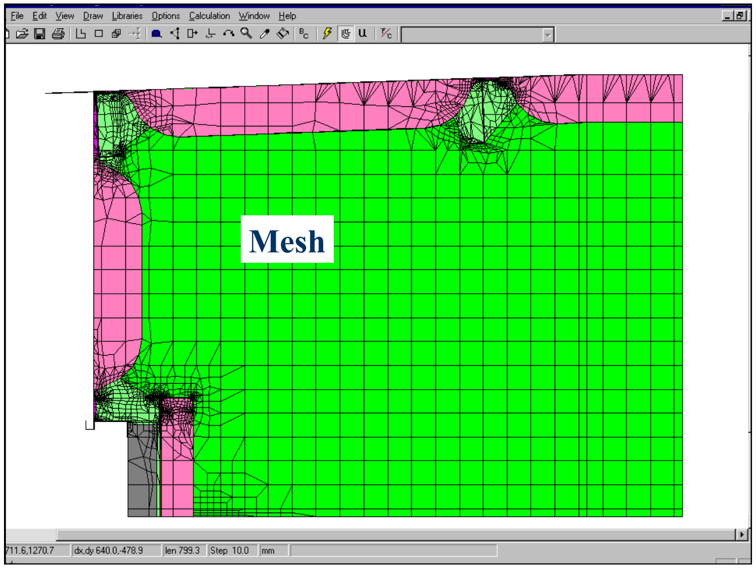


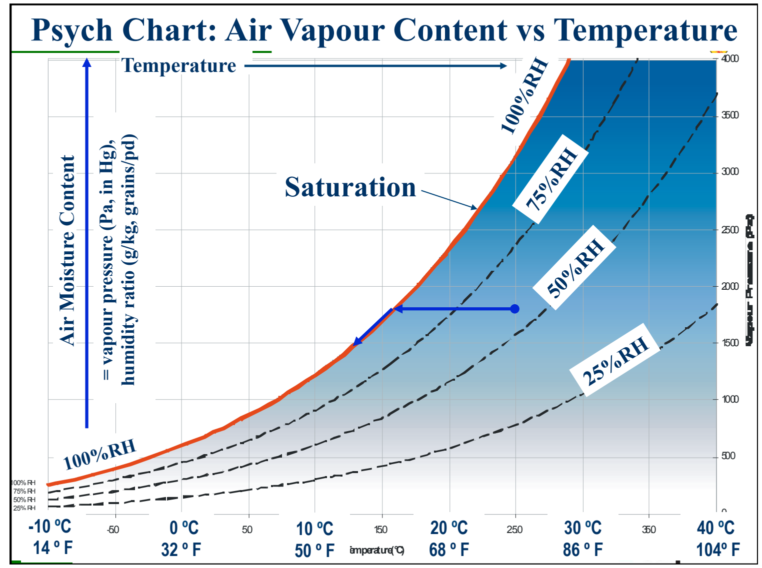
Mixing Models

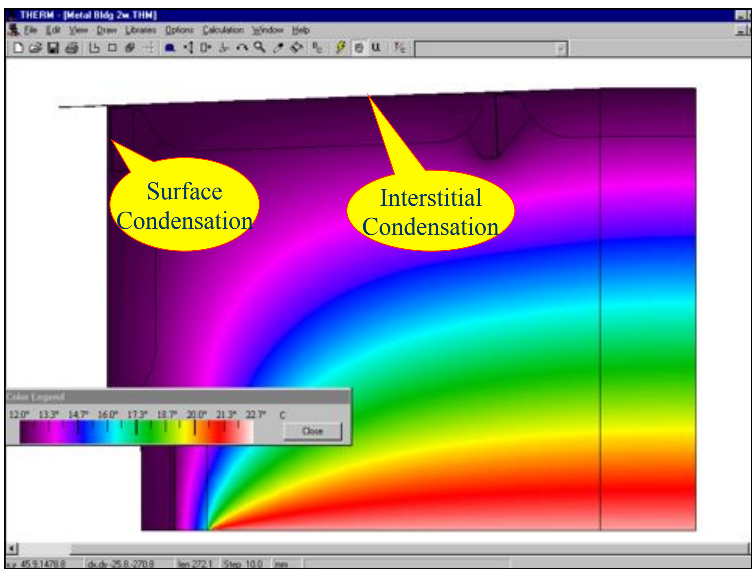
- One model or modeling approach
- e.g.Temperature flow, combined with dewpoint
- "suite of models"
  - range of complexity/accuracy
  - range of expertise required

Case Study Major manufacturing plant

- High interior humidity for film production

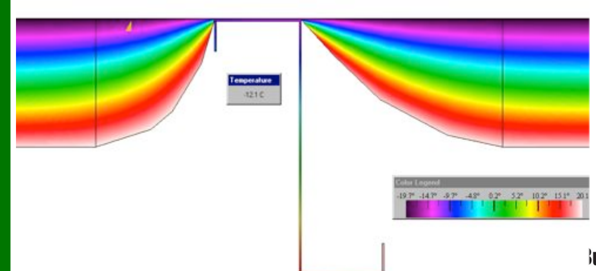






Case Study- Rec. Complex

- Metal building system
- Condensation and Dripping?



- Add ¾” insulation block
- Zero risk
- Now – other building details

WUFI

Moisture Modeling

- Reasons
  - Durability
  - Mold growth
  - Vapor barriers
  - Drying out
  - Leak tolerance
  - Cupping / curling

Moisture Models

- Must understand
  - boundary conditions
  - material properties
  - transport mechanism
  - deterioration/damage mechanism
  - construction realities
- Most models are presently 1-D
- Research models are 2-D/3-D

Moisture Models

- Spreadsheet
  - Static, approximate
- WUFI from IBP and ORNL
  - Very robust, good interface, powerful

Moisture Models

- Vapor diffusion easy to model
- "Hygric mass" often requires transient models
- Temperature and moisture are coupled!
- Challenges
  - Liquid transport is difficult
  - Moisture properties poorly known
  - Boundary conditions poorly known

Results

- Compare competing wall designs
- Conduct parametric studies
- How high MC? For how long?
- Interpretation is difficult, e.g.,
  - No gain year over year
  - Freeze-thaw cycles when over 90% saturation
  - Hours or days over 80% or 95% RH
  - Mold models
  - Annual plots
- Need material performance thresholds

Glaser Method

Element	R	ΔT	t °C	M	R_v	ΔP_v	P_v	P_{sat}	RH
			21.0				990	2474	40%
Inside Film	0.120	1.8		10000	0.000	2			
			19.2				988	2212	45%
Vapour retarder	0.000	0.0		60	0.017	344			
			19.2				643	2212	29%
Batt insulation	2.500	37.6		2000	0.001	10			
			-18.4				633	143	442%
Plywood	0.012	0.2		40	0.025	517			
			-18.6				117	141	83%
Outside Film	0.029	0.4		20000	0.000	1			
			-19.0				115	136	85%

Average Winter Conditions

Element	R	ΔT	t°C	M	Rv	ΔP	P	Psat	RH
			21.0				990	2474	40%
Inside Film	0.120	1.1		10000	0.000	3			
			19.9				987	2307	43%
Vapour retarder	0.000	0.0		60	0.017	506			
			19.9				481	2307	21%
batt	2.500	23.5		2000	0.001	15			
			-3.6				465	465	100%

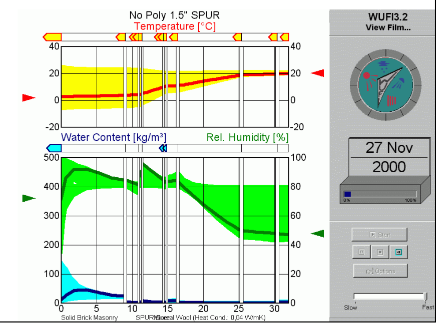
Flow To back of sheathing
Permeance: 57.9 Pressure: 524
Flow to: 30369 ng/m2 s = 0.11 g/m2/hr

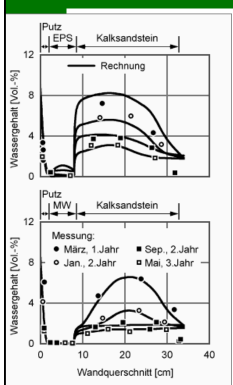
plywood	0.012	0.1		40	0.025	81			
			-3.7				385	462	83%
Outside Film	0.029	0.3		20000	0.000	1			
			-4.0				384	452	85%
Total Resistance	2.66	23.9			0	603			

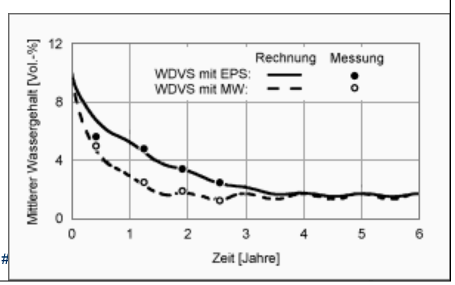
Flow Away from back of sheathing
Permeance: 40 Pressure: 81
Flow Away: 3243 ng/m2 s = 0.01 g/m2/hr
Net Accumulation 0.10 g/m2/hr

WUFI Pro /ORNL

- Dynamic hourly, liquid, adsorbed, diffusion storage
- Handles driving rain. Easy, fast, validated
- Intuitive interface







What does WUFI need?

- Thermal conductivity
  - Can do temperature dependent, phase change
- Liquid "wicking" from wet to dry
  - Liquid diffusivity
  - Usually based on simple water uptake tests
- Vapor diffusion from more to less
  - Vapor permeance test (usually E96)
  - Prefer at multiple RH levels
- Water storage function
  - isotherm

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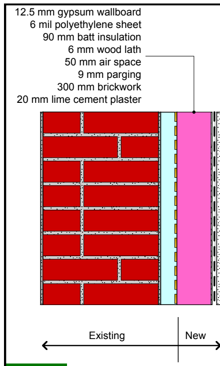
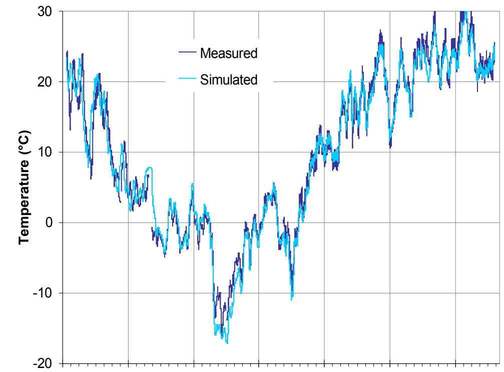
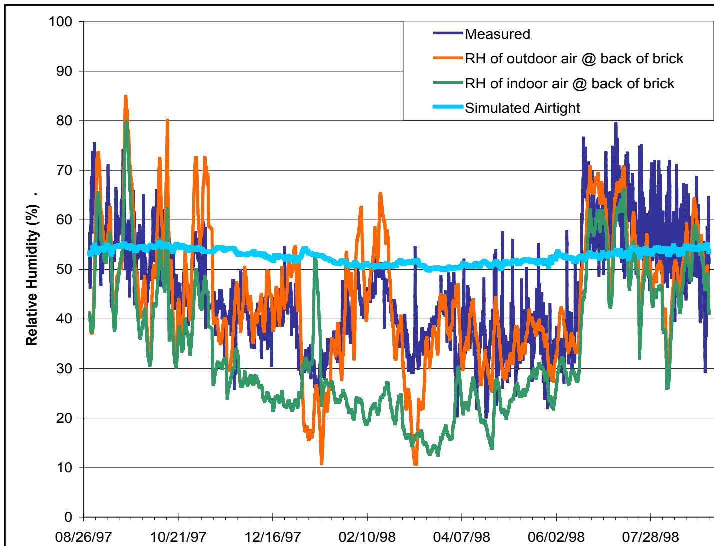
WUFI ORNL

- Free version
- Cant change material properties
- Cant change as many boundary conditions
- Water injection (leaks) and air injection (ventilation and air leaks)

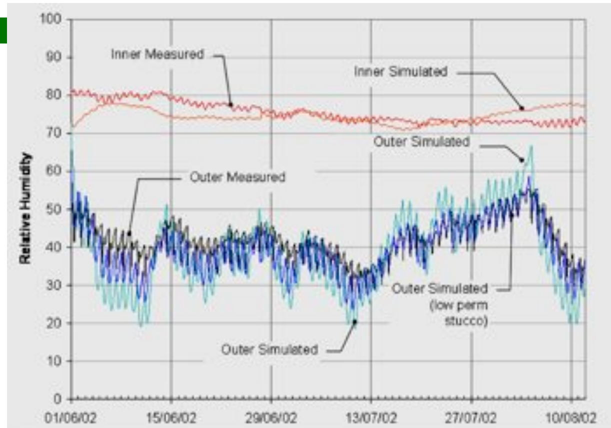


Prince Albert masonry retrofit: CMHC





California Strawbale



Lets try some WUFI

- 4” Brick,
- 8” block backup, (use white concrete brick)
- 2” EPS insulation
- ½” drywall w/ paint
- North-facing NYC, low-rise

- Do we need a vapor barrier?

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Notes

- Watch solar absoption at surfaces!
- Vapor control at inside, outside
- When do RH and T peak? Min?
- What interior humidity and temp?
- How many sides? Rain variations?
- How long should you run it?
- Can we analyze the data?
- Quick graph, monitors, export data

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Example2: wood stud wall

- Brick veneer, 1” airspace, Tyvek, OSB, R19 batt, drywall
- In NYC housing

- Interior RH, orientation, rain load
- Cladding switch to vinyl?
- Leaks?
- Analysis and interpretation

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Waterloo

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Case Study - Cuban Resort

- Canadian firm in hot humid climate

Questions:

- Do we need an exterior vapor barrier?
- Does wall meet the design specs?
  - U < 1, RSI >1 (R_{imp} > 5.6)

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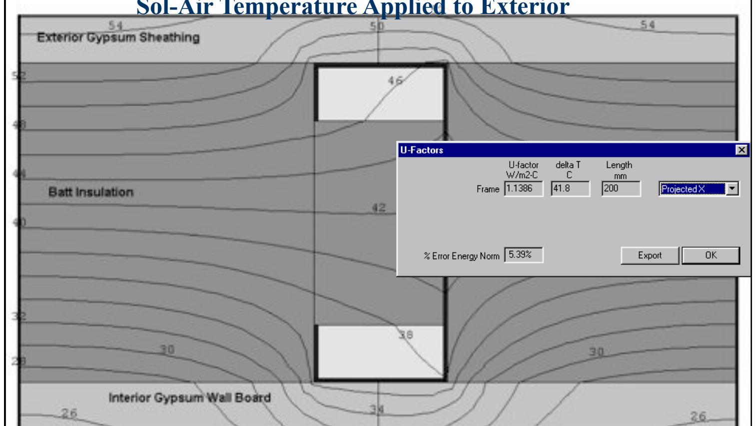
Sol-Air Temperature Applied to Exterior



Steel Stud and Gypsum

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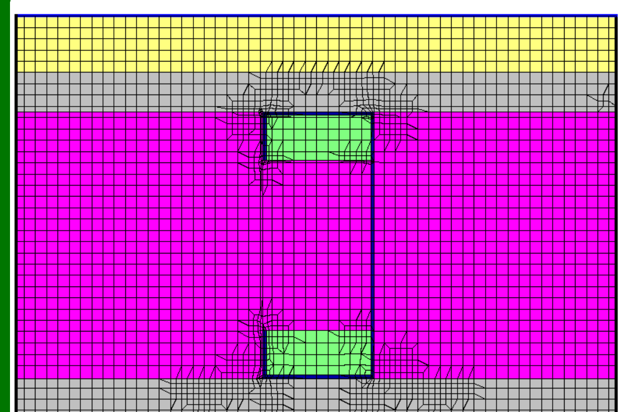
Solution -- use 19 mm exterior Insulation



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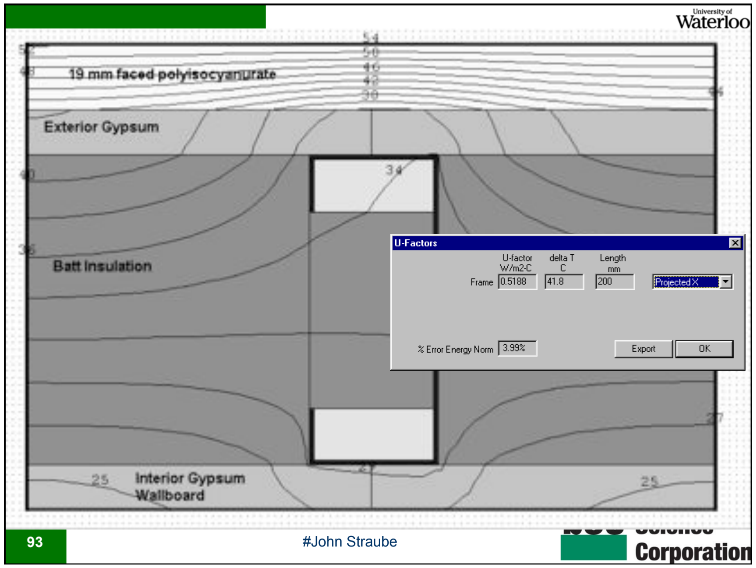

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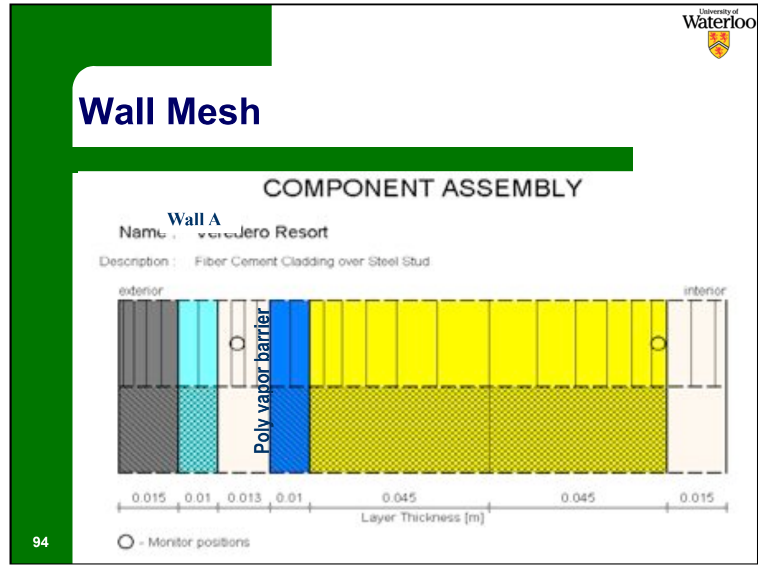
19 mm faced polyisocyanurate
Exterior Gypsum
Batt Insulation
Interior Gypsum Wallboard
U-Factors
U-factor W/m2-C
delta T C
Length mm
Frame 0.5188 41.8 200 Projected X
% Error Energy Norm 3.99%
Export
OK
93
#John Straube
Corporation



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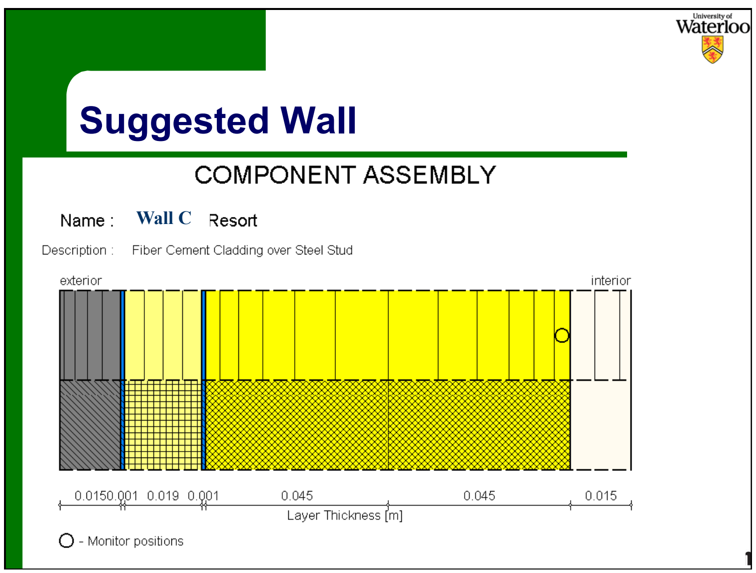
Wall Mesh
COMPONENT ASSEMBLY
Wall A
Description : Fiber Cement Cladding over Steel Stud
exterior
interior
Poly vapor barrier
0.015 0.01 0.013 0.01 0.045 0.045 0.015
Layer Thickness [m]
- Monitor positions
94



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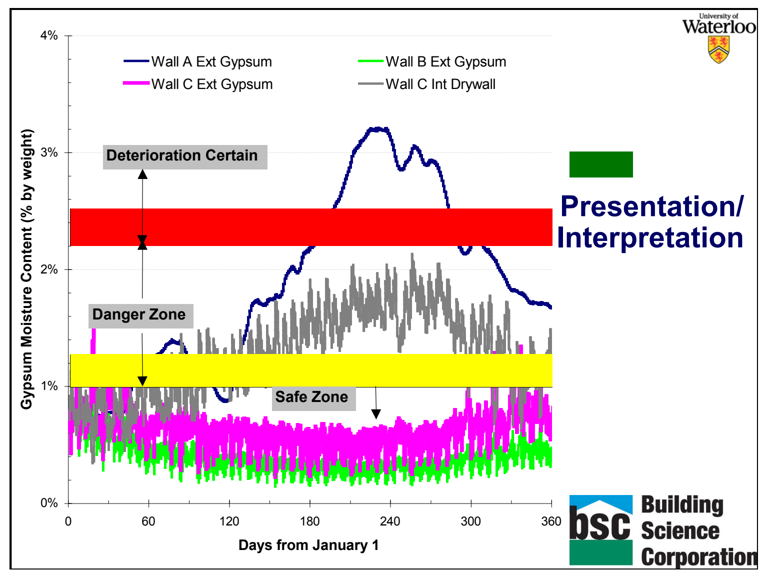
Suggested Wall
COMPONENT ASSEMBLY
Name : Wall C Resort
Description : Fiber Cement Cladding over Steel Stud
exterior
interior
0.015 0.001 0.019 0.001 0.045 0.045 0.015
Layer Thickness [m]
- Monitor positions



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Wall A Ext Gypsum
Wall B Ext Gypsum
Wall C Ext Gypsum
Wall C Int Drywall
Deterioration Certain
Danger Zone
Safe Zone
Gypsum Moisture Content (% by weight)
4%
3%
2%
1%
0%
0 60 120 180 240 300 360
Days from January 1
Presentation/ Interpretation
bsc Building Science Corporation

Conclusions

- Therm and WUFI are very useful
- Must be used to solve the right problems
- Can’t solve many practical problems
- Material properties and boundary conditions are very important to get right
- Need to check against experience and common sense.