CAE 463/524
Building Enclosure Design
Fall 2013

Lecture 5: September 18, 2013
Finish complex conduction in building enclosures

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Last time

- Correction's from previous week's lecture on surface energy balances
- Complex conduction in enclosures
  - Parallel path
  - Isothermal
  - ASHRAE Zone Method
  - Thermal bridges: applications

Today's objectives

- Finish complex conduction
  - THERM modeling
  - Slab and below-grade wall/floor heat transfer
  - Thermal mass

- Return HW 1 graded
- Assign HW 2
  - Using THERM
- Begin to assign campus project teams

Campus projects (project 1)

Objective: Take what you learn about heat, air, and moisture transport (and failures) in building enclosures and apply those fundamentals to critically assess the enclosure of a building on IIT's campus

- Will also recommend retrofits to increase performance
- In previous versions, all students used Crown Hall
  - We'll expand on that
- Use of thermal imaging and other tools
- "Real" field experience

Deliverables:

- Report of findings

  (I will give you an example)

Due date: November 6

Project 1: Assessment of IIT building enclosures

Tools available for your campus project

Temperature/RH data loggers

Heat flux meter

IR thermometer

IR camera

Solar radiation

Blower door (envelope leakage)

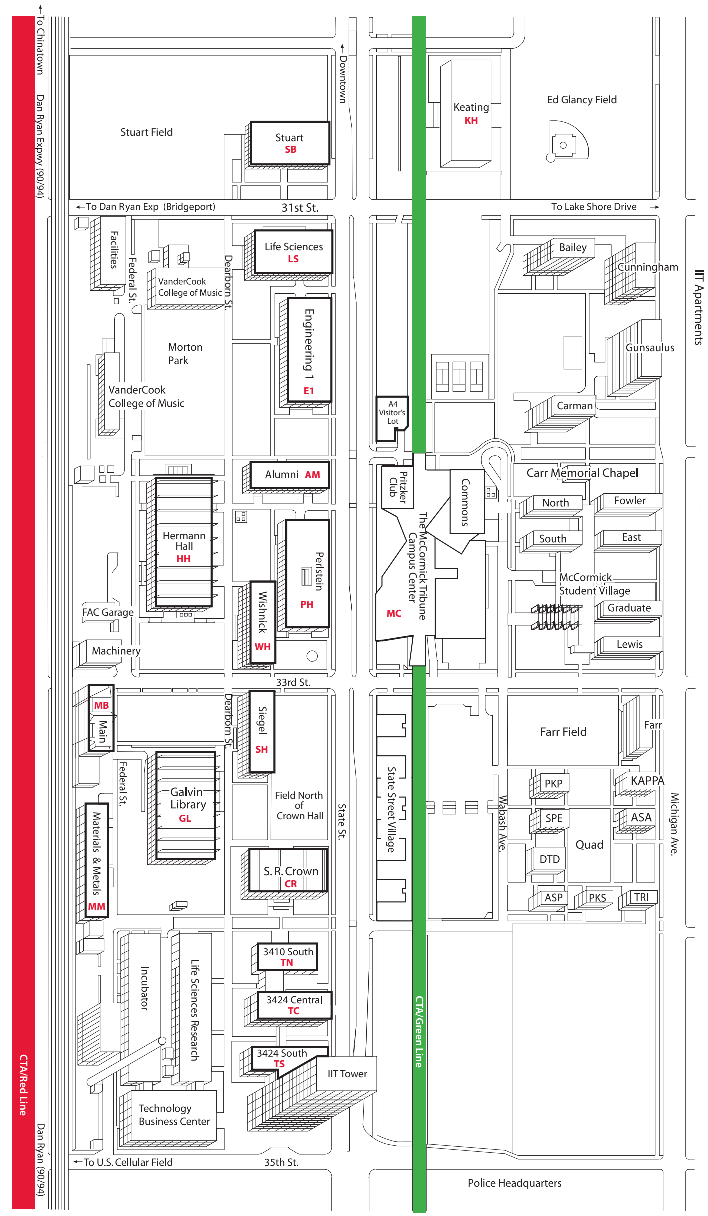
Teams for campus project (expectations on BB now)

- You will work in teams of 3 or 4
  - 13 students in this course; 2 are online students
  - 3 teams of 3 and 1 team of 4
- Online students will be paired with in-person students
  - I suggest sharing duties between on campus assessments and report writing if on-line students can't arrange for a campus visit
- Email me your groups and building choice ASAP
  - I will assign otherwise

IIT campus map

Buildings to choose from:

Building	Architect
1 - Siegel Hall	Mies, 1956
2 - Alumni Hall	Mies, 1945
3 - Crown Hall	Mies, 1950
4 - Hermann Hall	SOM, 1962
5 - Stuart Building	Goldsmith, 1971
6 - Engineering 1	Goldsmith, 1966
7 - Life Sciences	Goldsmith, 1966



Take-home exam

- I am planning to assign the take-home exam Wednesday October 16th

- Due date of Wednesday October 23rd

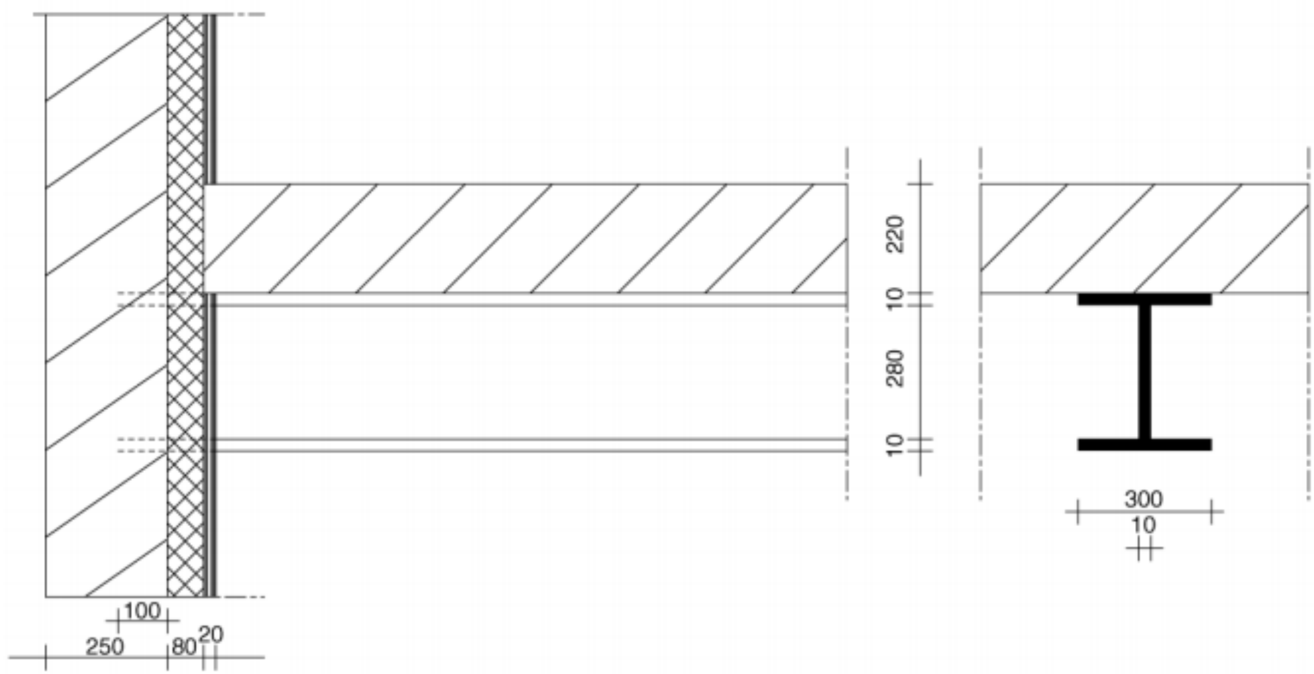
- Open notes, book, internet, etc.

COMPLEX CONDUCTION

Finishing up

Thermal analysis of these even more complex geometries

- How do we estimate U and R values for complex geometries and combinations of materials like this one?



- Simple 1-D calculations can have significant errors
  - Hard (or impossible) to capture all phenomena
- Need to model 2-D or 3-D heat transfer using computer simulations

2-D AND 3-D HEAT TRANSFER USING NUMERICAL SOLVERS

Numerical solutions

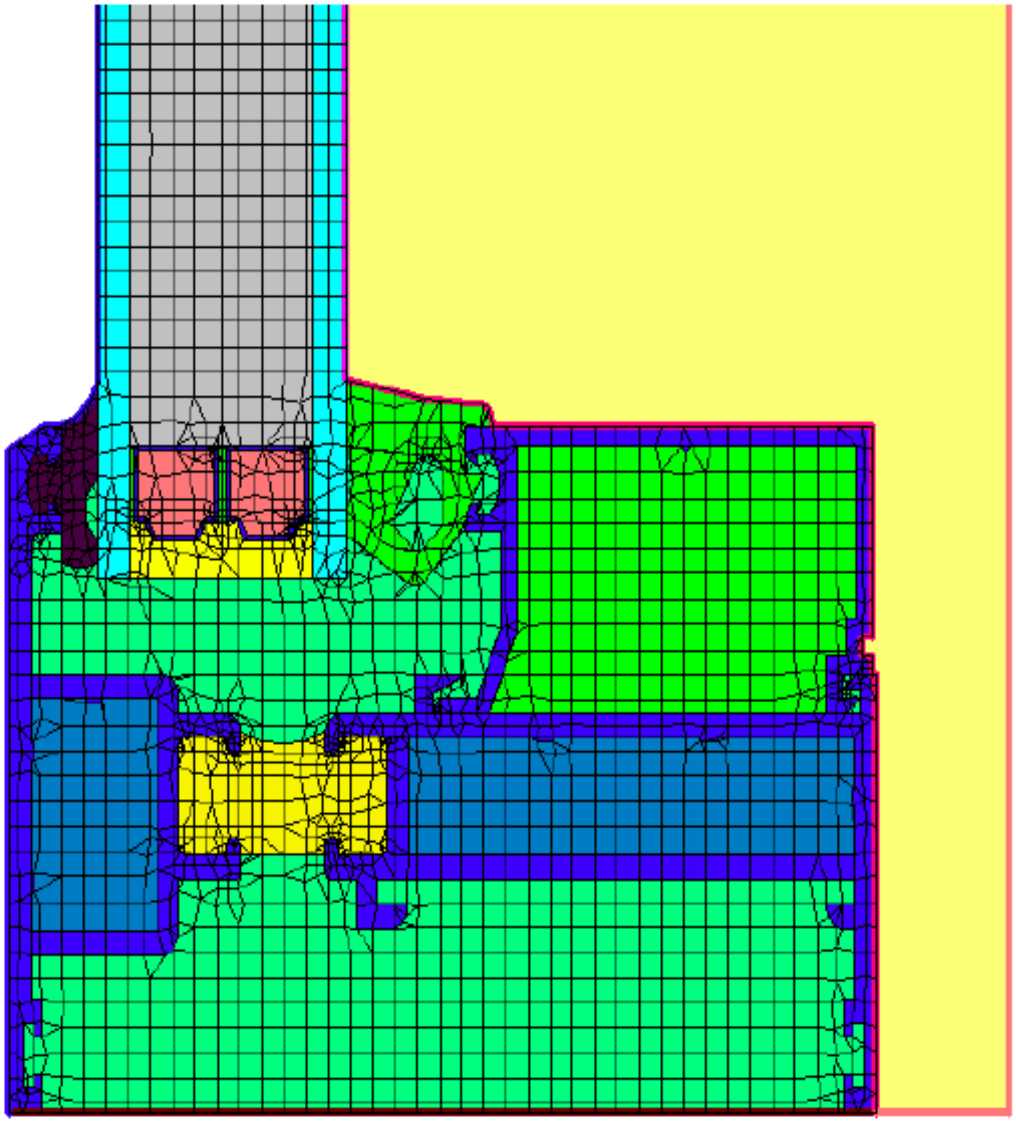
- In addition to our analytical solution methods, there is another way to solve these problems:
  - Numerical analysis using computers

- For assemblies with thermal bridges, it is probably a better solution to utilize finite-element or similar heat transfer software to estimate the U-value, R-value, and temperatures in and around the assembly

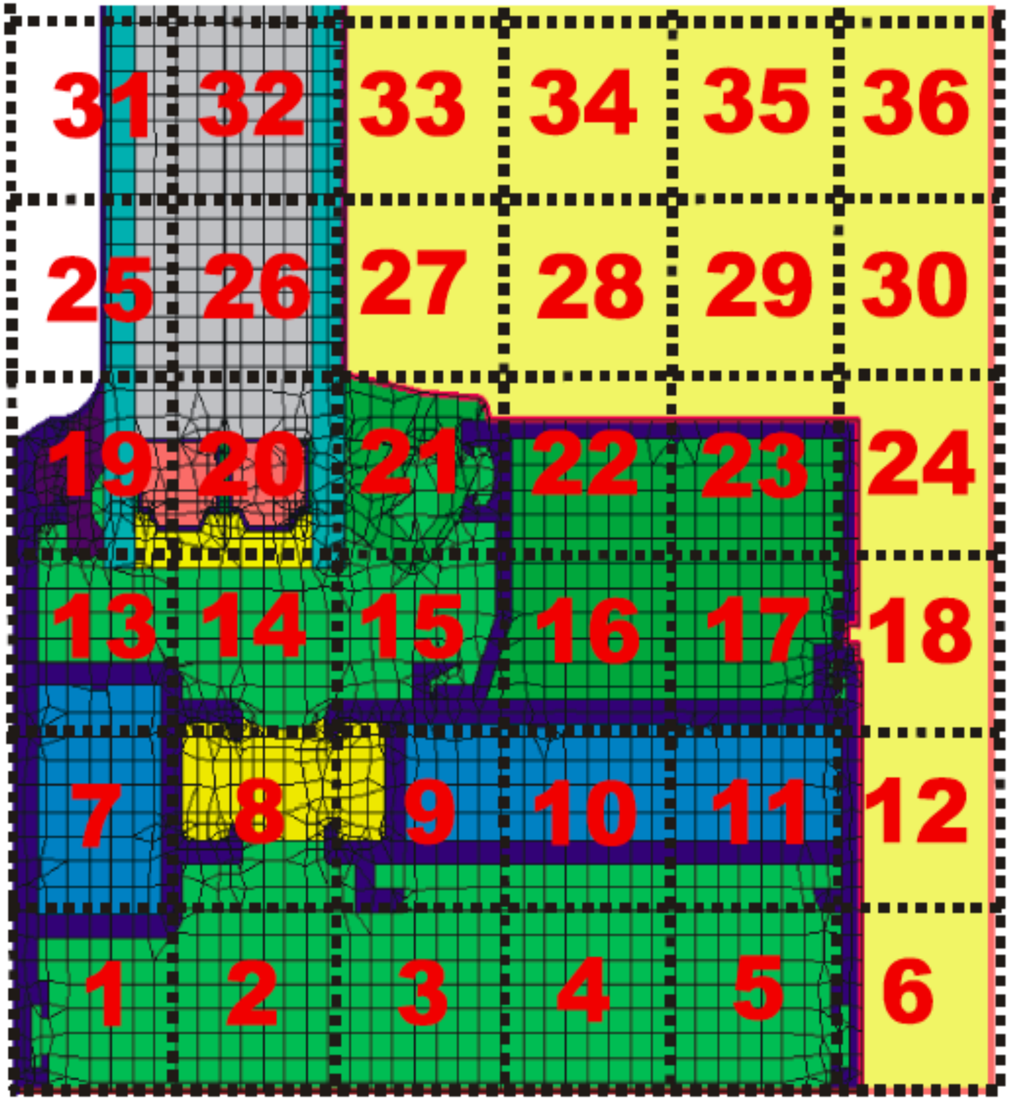
Basic idea

- Break assembly into a hundreds or thousands of homogenous elements
- Use the basic equations of heat transfer and write heat balances on each element to create a huge set of simultaneous equations
- Define boundary conditions to initiate the equation solving
- Solve the simultaneous equations numerically to find heat flow and temperatures throughout the entire system or assembly

Grid for numerical solver

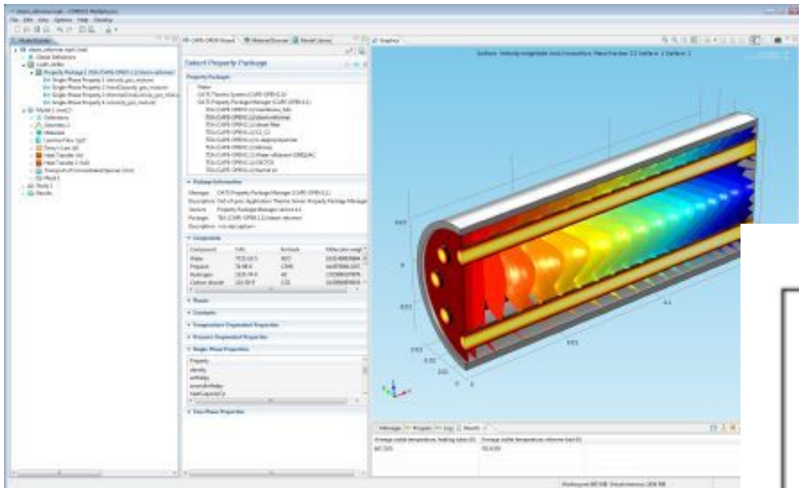


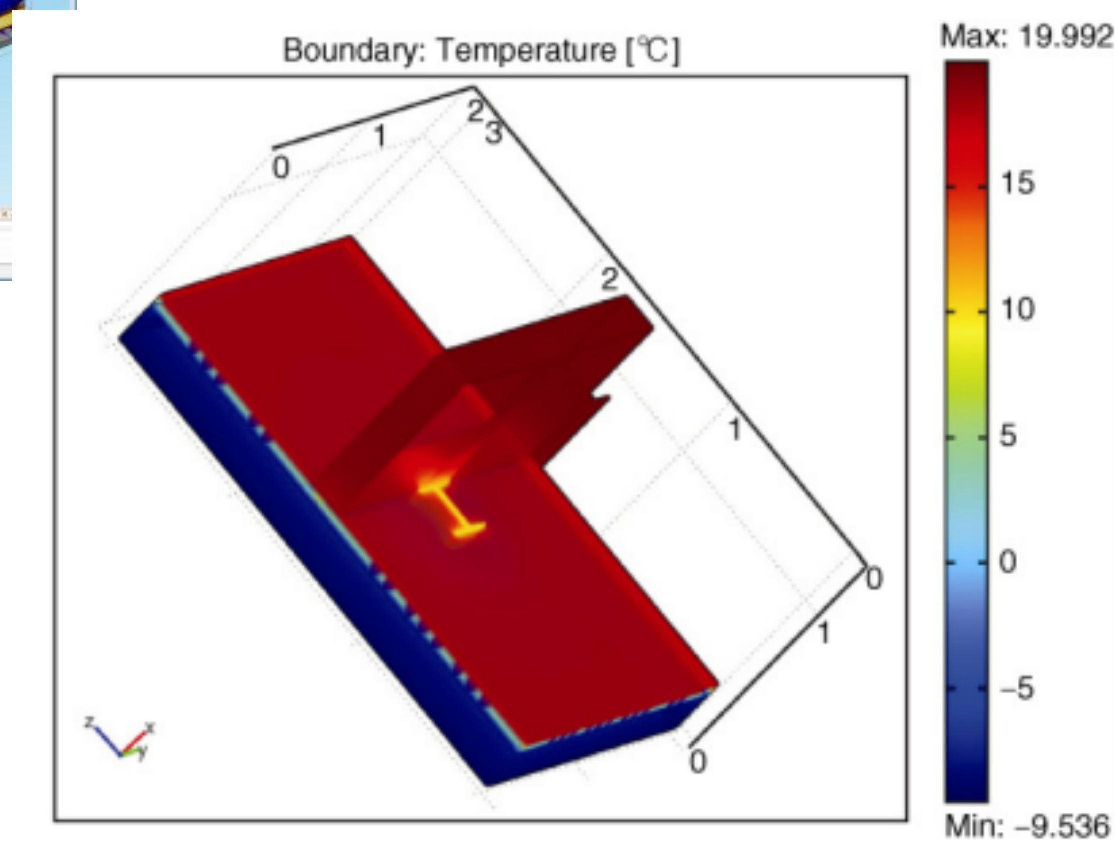
Grid for numerical solver



3-D solvers

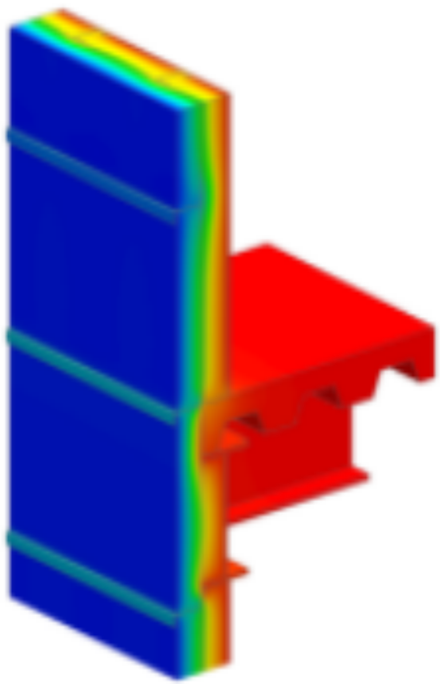
- COMSOL finite element solver

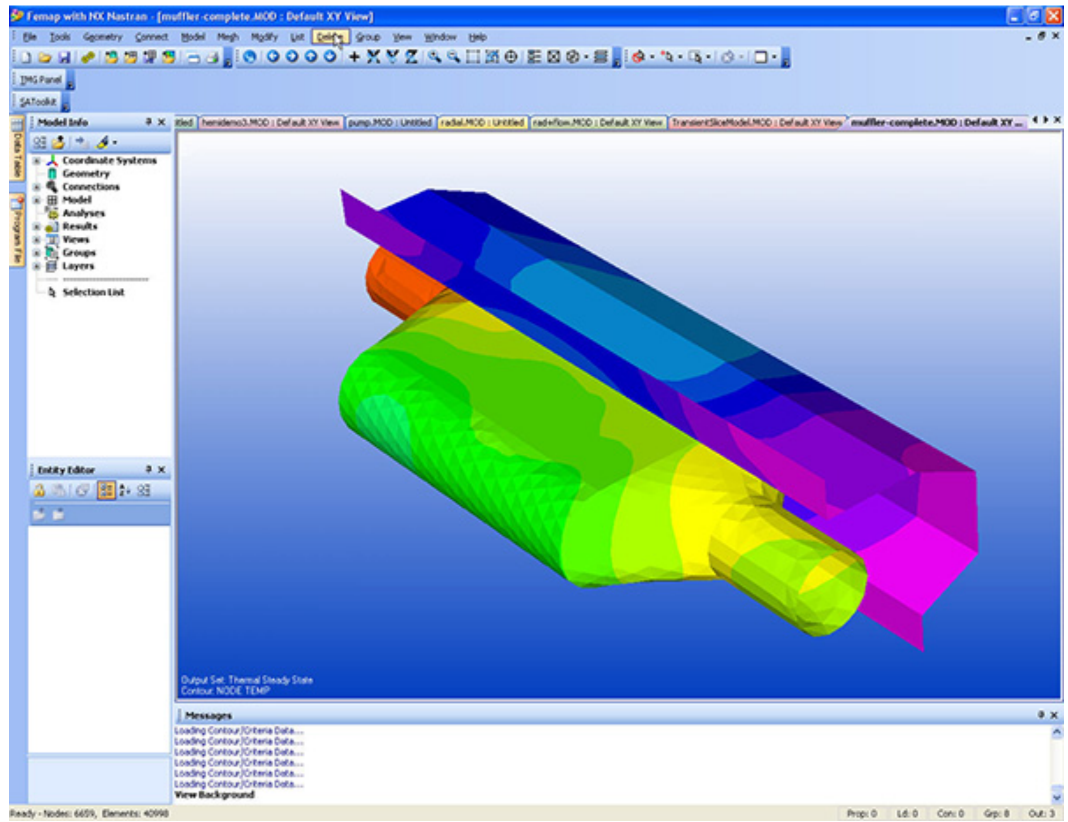




3-D solvers

- Femap finite element analysis





SIEMENS

THERM – popular 2-D solver

- A very popular 2-D heat transfer program used in the US – especially for window analysis - is called THERM
  - URL to download: http://windows.lbl.gov/software/therm/therm.html
  - Requires registration but is FREE
- THERM is used with WINDOW for designing windows
  - But can also be used as a stand alone program for any assembly
  - Very similar 2-D and 3-D programs often used in Europe are called heat2 and heat3
- You will use THERM on a HW
  - You can download from my website: http://built-envi.com/courses/cae-463524-building-enclosure-design-fall-2013/
  - Only runs on Windows ☹
  - I've requested it be installed in the AM 218 computer lab

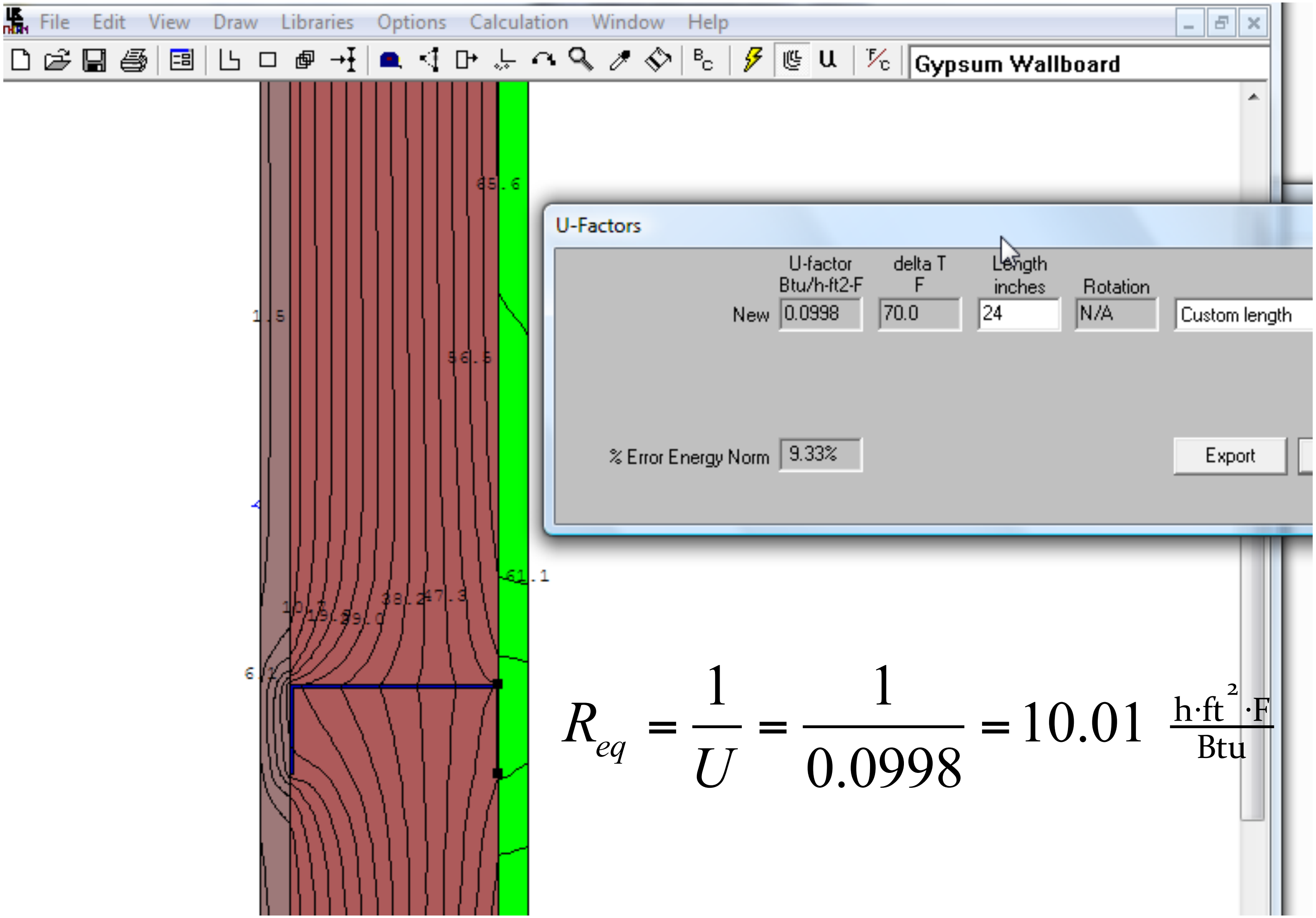
Using THERM

- In THERM you draw out an assembly
  - Assign materials
  - Assign boundary conditions
  - And let the program solve for the temperatures and heat flow throughout the assembly

- Drawing is somewhat cumbersome
  - Can also import CAD files
  - THERM Drawing Tips:
    http://windows.lbl.gov/software/**therm**/Docs/Chapter10.pdf

- The program then can analyze that output to calculate a U-value (or R-value) for the entire 2-D assembly
  - Also plots isotherms throughout the assembly

Example screenshot: THERM analysis of steel stud



$$R_{eq} = \frac{1}{U} = \frac{1}{0.0998} = 10.01 \ \frac{\mathrm{h \cdot ft^2 \cdot F}}{\mathrm{Btu}}$$

Governing equations for THERM

1-D Conduction

$$q_{cond} = -k\frac{dT}{dx} = -\frac{k}{L}dT$$

2-D Conduction

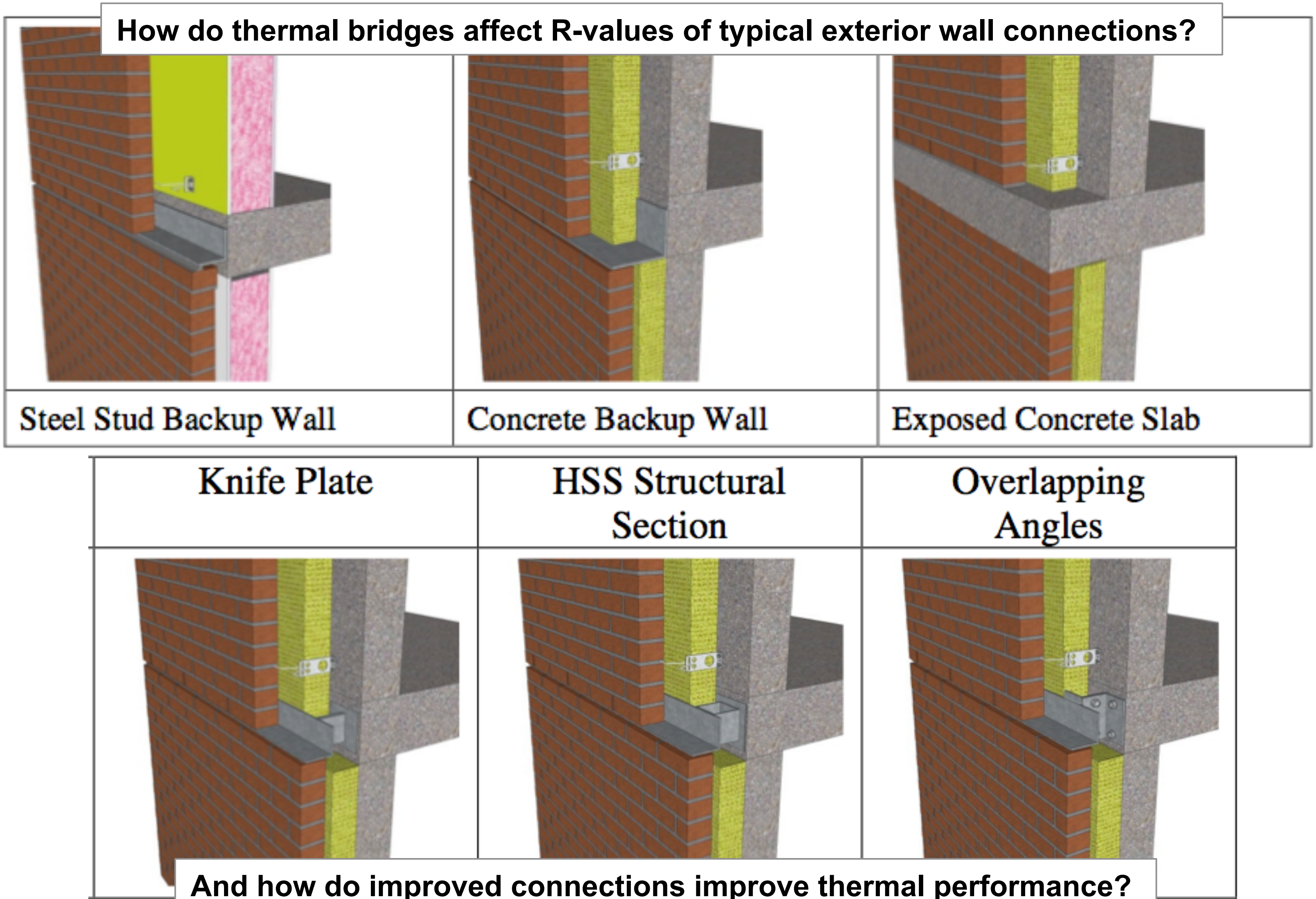
$$q_{cond} = -k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

- Energy balance at a surface of each discretized element is the same as previously, except the conduction term contains X and Y components

- Set boundary conditions on interior and exterior and the solver will compute temperature throughout assembly
  - Then it can calculate a U-value for the whole assembly

What you can do with THERM

How do thermal bridges affect R-values of typical exterior wall connections?

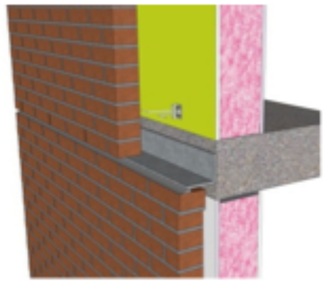
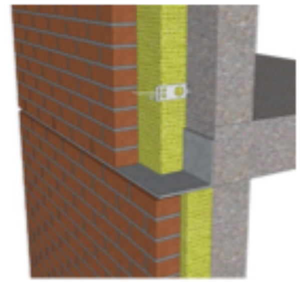
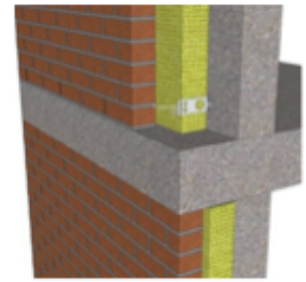
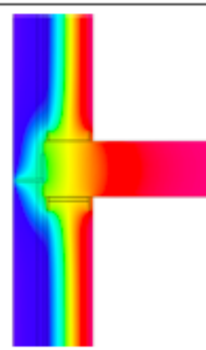
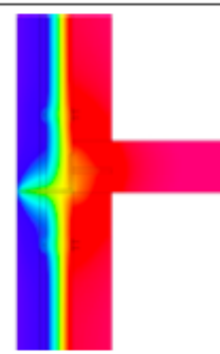
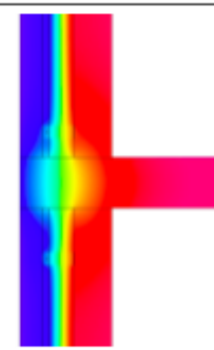


And how do improved connections improve thermal performance?

Finch et al. 2013, 12th Canadian Masonry Symposium

What you can do with THERM

Table 1: Summary of Nominal and Effective R-Values and U-Values for Baseline Masonry Shelf Angle Support Options Showing Impact of Thermal Bridging

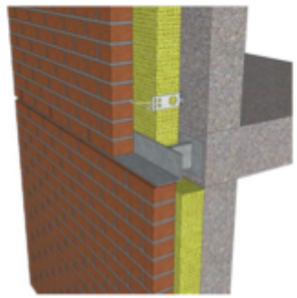
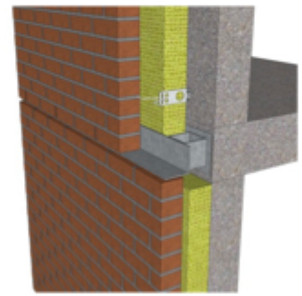
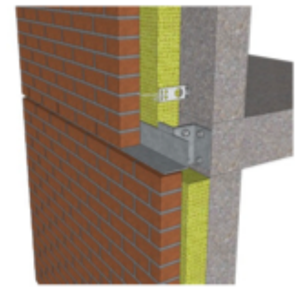
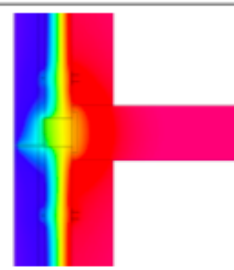
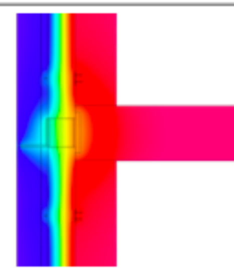
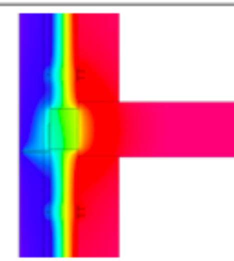
	Steel Stud Backup	Poured Concrete Backup	Exposed Slab Edge
			
			
Nominal Insulation R-Value/U-Value	R-20 (RSI 3.52) U-0.05 (USI 0.284)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)
Effective Assembly R-Value/U-Value	R-7.3 (RSI 1.29) U-0.137 (USI 0.777)	R-10.5 (RSI 1.84) U-0.096 (USI 0.543)	R-9 (RSI 1.58) U-0.112 (USI 0.634)
Effective Reduction	63.5%	37.5%	46.4%
Linear Transmission	-	ψ = 0.339 IP (0.586 SI)	ψ = 0.478 IP (0.827 SI)

Finch et al. 2013, 12th Canadian Masonry Symposium

Let's explore improving this connection

What you can do with THERM

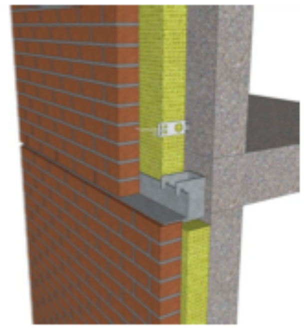
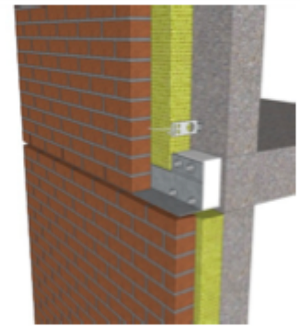
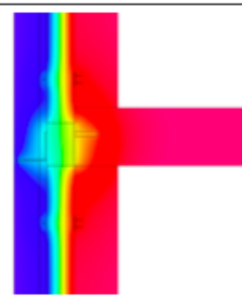
Table 2: Summary of Nominal and Effective R-Values and U-Values for Typical Stand-Off Modifications to the Baseline Masonry Shelf Angle Support Options Showing Impact of Thermal Bridging

	Knife Plate	HSS Structural Section	Overlapping Angles
			
			
	shelf angle: 4"x4"x1/4" outside of insulation. 4"x4"x3/4" stand-off knife plates welded to embed plates at 48" o.c.	shelf angle 4"x4"x1/4" outside insulation. 4"x4"x1/4" HSS tube welded to embed plates at 48" o.c.	shelf angle 4"x4"x1/4" outside insulation. 2-6"x4"x5/16" angles bolted to slab edge at 48" o.c.
Nominal Insulation R-Value/U-Value	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)
Effective Assembly R-Value/U-Value	R-14.8 (RSI 2.6) U-0.068 (USI 0.384)	R-14.8 (RSI 2.6) U-0.068 (USI 0.385)	R-15.0 (RSI 2.64) U-0.067 (USI 0.379)
Effective Reduction	16.4%	16.5%	15.3%
Linear Transmission	ψ = 0.096 IP (0.166 SI)	ψ = 0.097 IP (0.168 SI)	ψ = 0.089 IP (0.153 SI)

Finch et al. 2013, 12th Canadian Masonry Symposium

What you can do with THERM

Table 3: Summary of Nominal and Effective R-Values and U-values for Propriety Masonry Shelf Angle Support Options Showing Impact of Thermal Bridging

	Standoff Bracket	4-Bolt Cast-In
		
		
	shelf angle 4"x4"x1/4" outside insulation. Proprietary clip is ¼" thick steel, 4"x4"x1/4" 6 "lg C-section. Non-welded connection. .	Shelf angle 4"x4"x1/4" outside insulation. Pre-manufactured cast-in place thermal break connection with 4 stainless steel bolts attached to 7"x7"x 3/8" plate.
Nominal Insulation R-Value/U-Value	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)
Effective Assembly R-Value/U-Value	R-14.9 (RSI 2.62) U-0.067 (USI 0.381)	R-16.4 (RSI 2.9) U-0.061 (USI 0.345)
Effective Reduction	16.4%	7%
Linear Transmission	ψ = 0.091 IP (0.158 SI)	ψ = 0.037 IP (0.064 SI)

Finch et al. 2013, 12th Canadian Masonry Symposium

THERM demonstration

HW 2 assigned

- In HW 2 you will use THERM to analyze an enclosure assembly with a thermal bridge

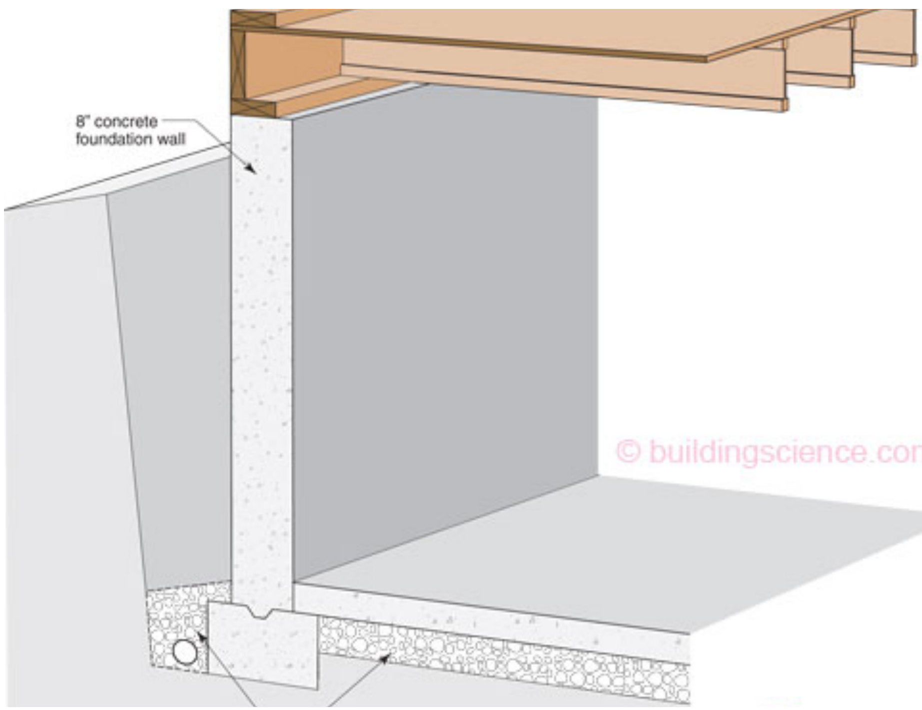
- Let me know ASAP if you have any computer issues

WRAPPING UP COMPLEX CONDUCTION

(1) Below-grade walls and floors
(2) On-grade heat transfer
(3) Combined assembly U-values
(4) Thermal storage in materials

Below-grade heat flow

- Where does heat flow?
  - Depends on surface and ground temperature distributions



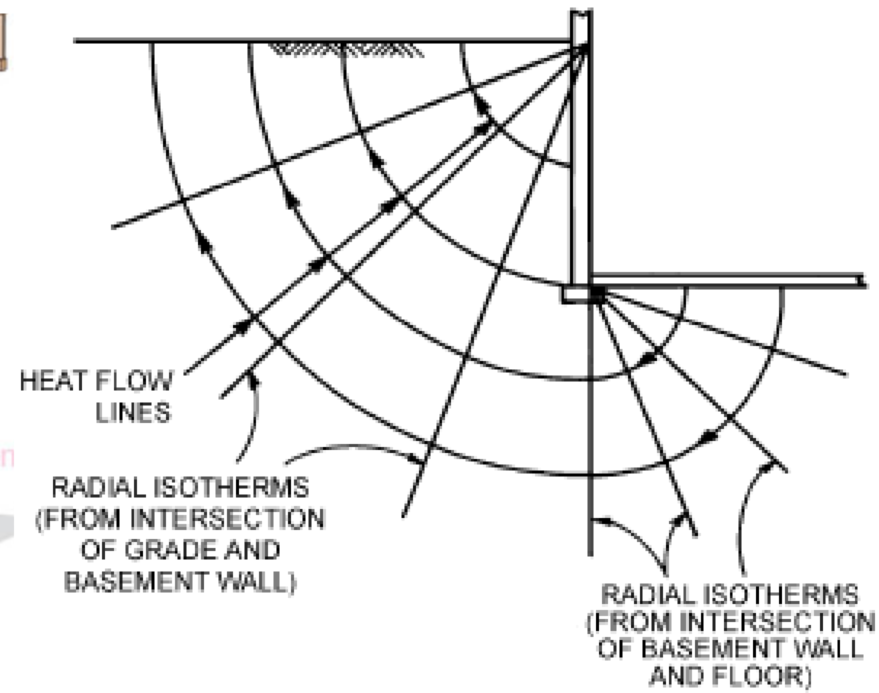


Fig. 4 Heat Flow from Basement

Mean ground temperatures

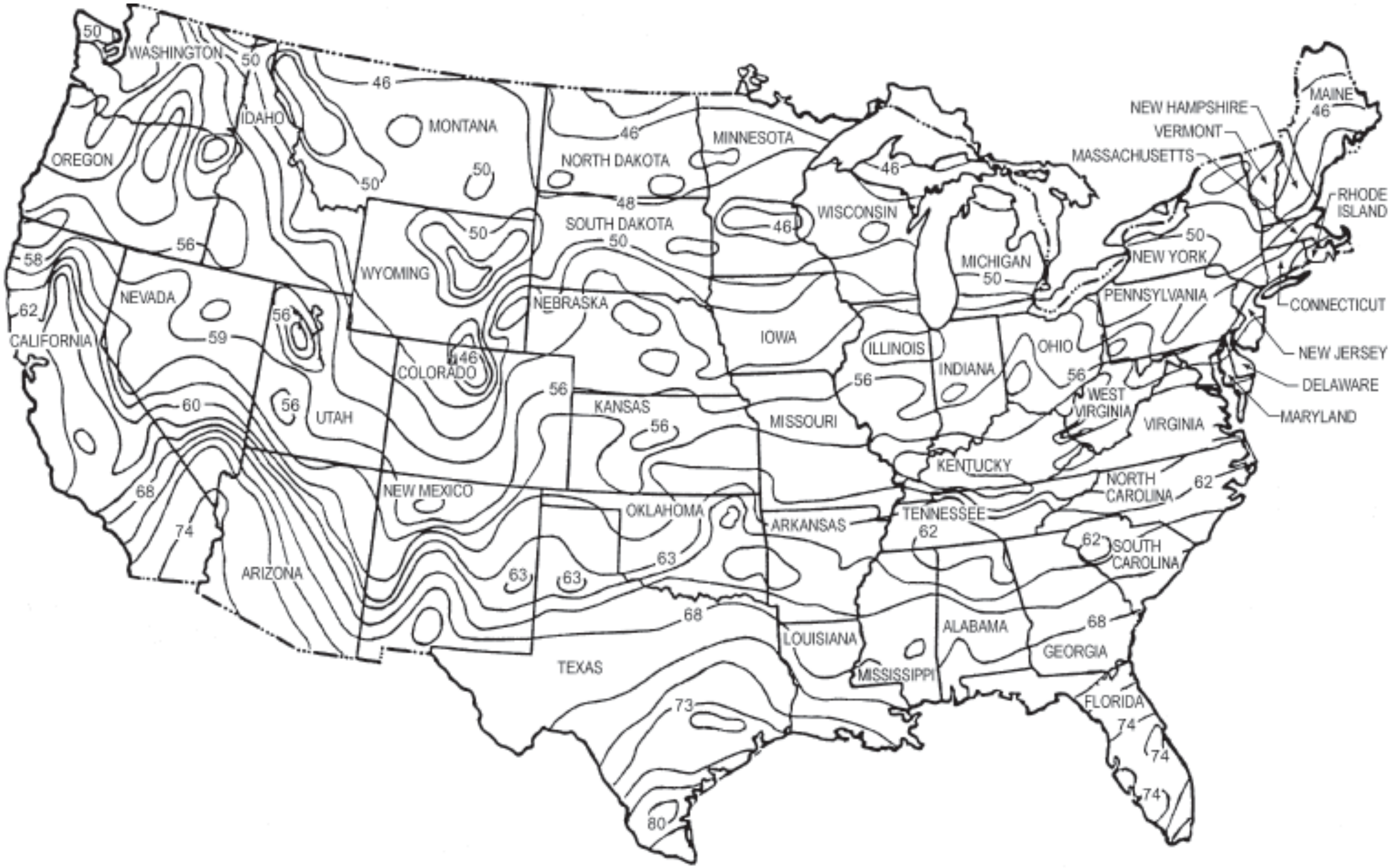
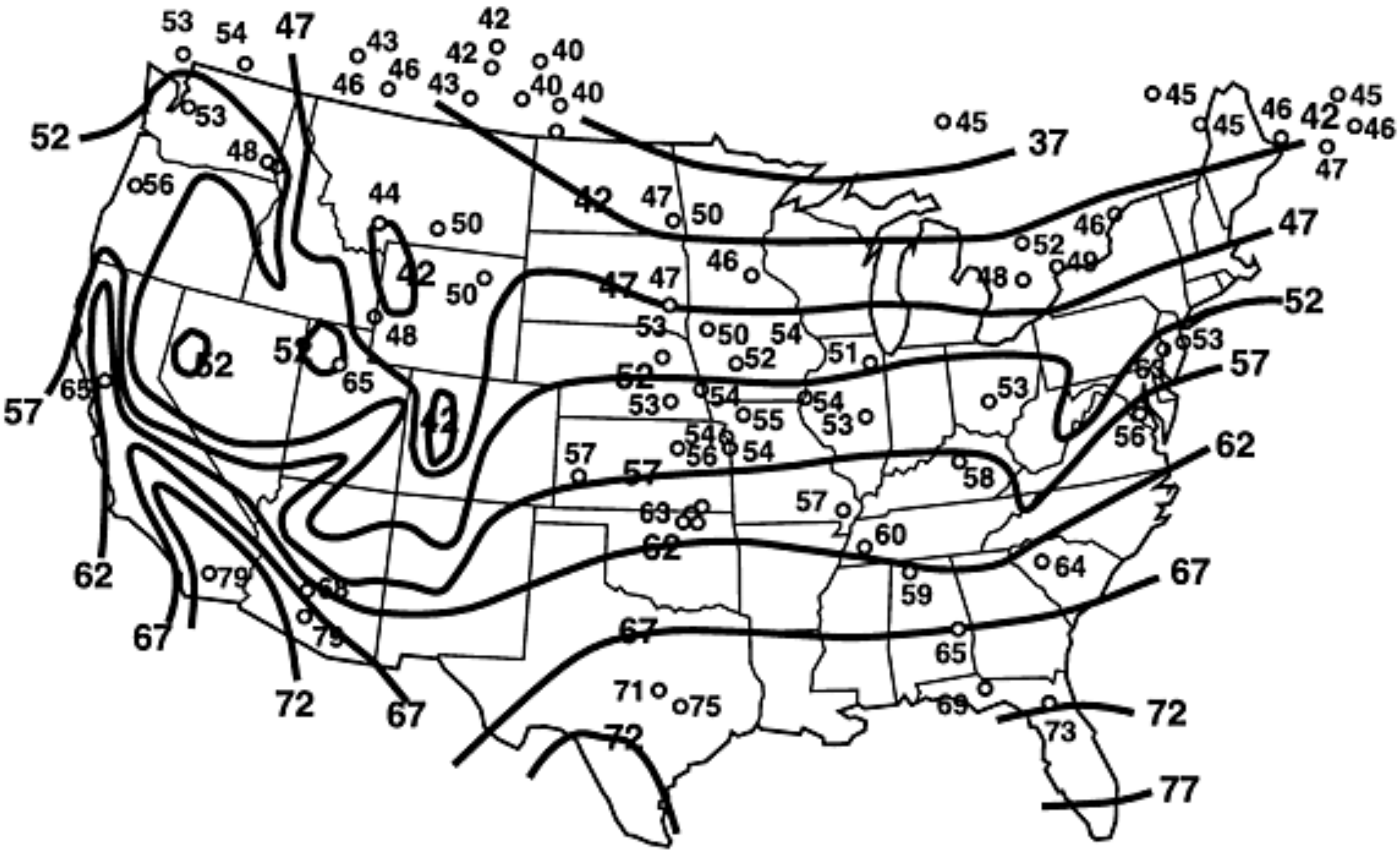


Fig. 17 Approximate Groundwater Temperatures (°F) in the Continental United States

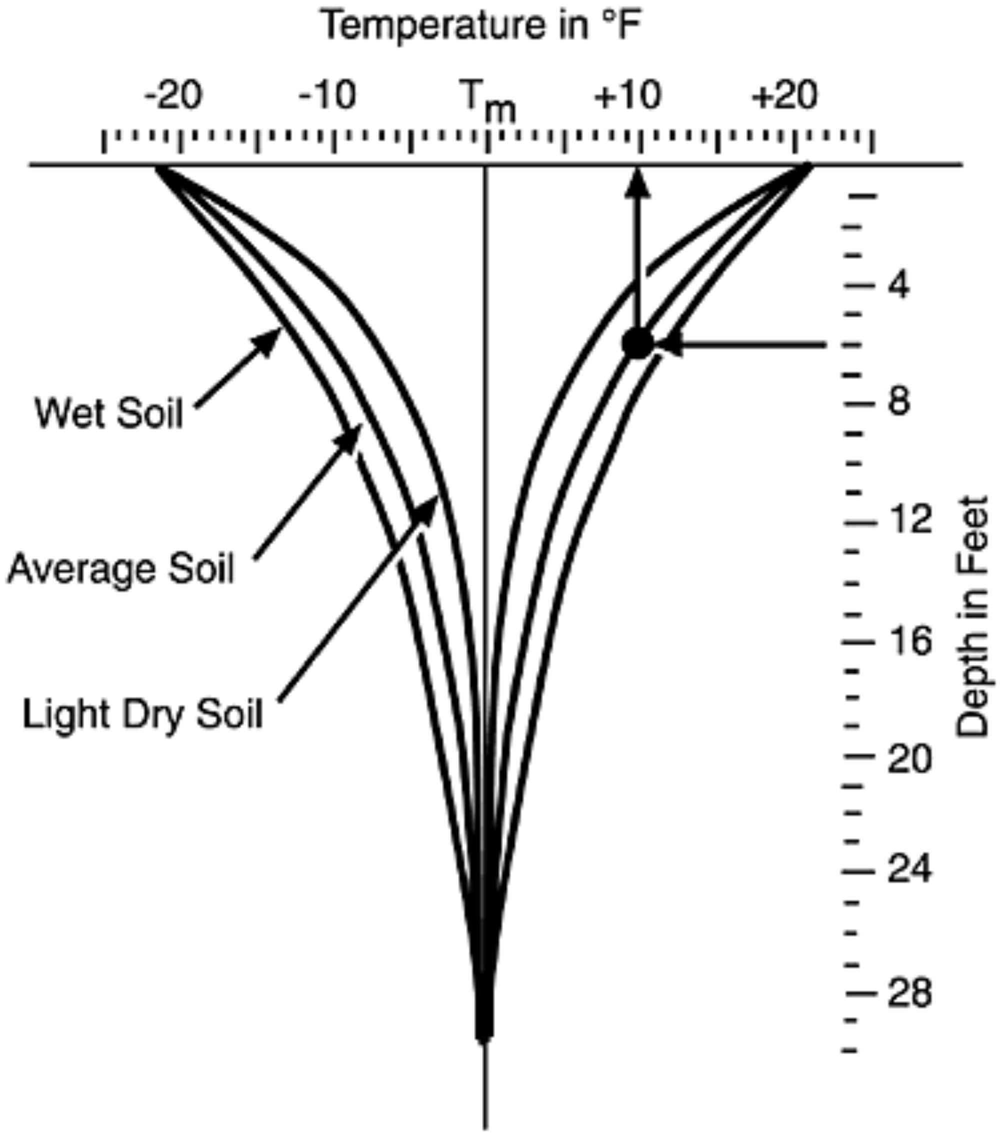
Source: 2011 HVAC Apps Chapter 34, Figure 17

Mean ground temperatures



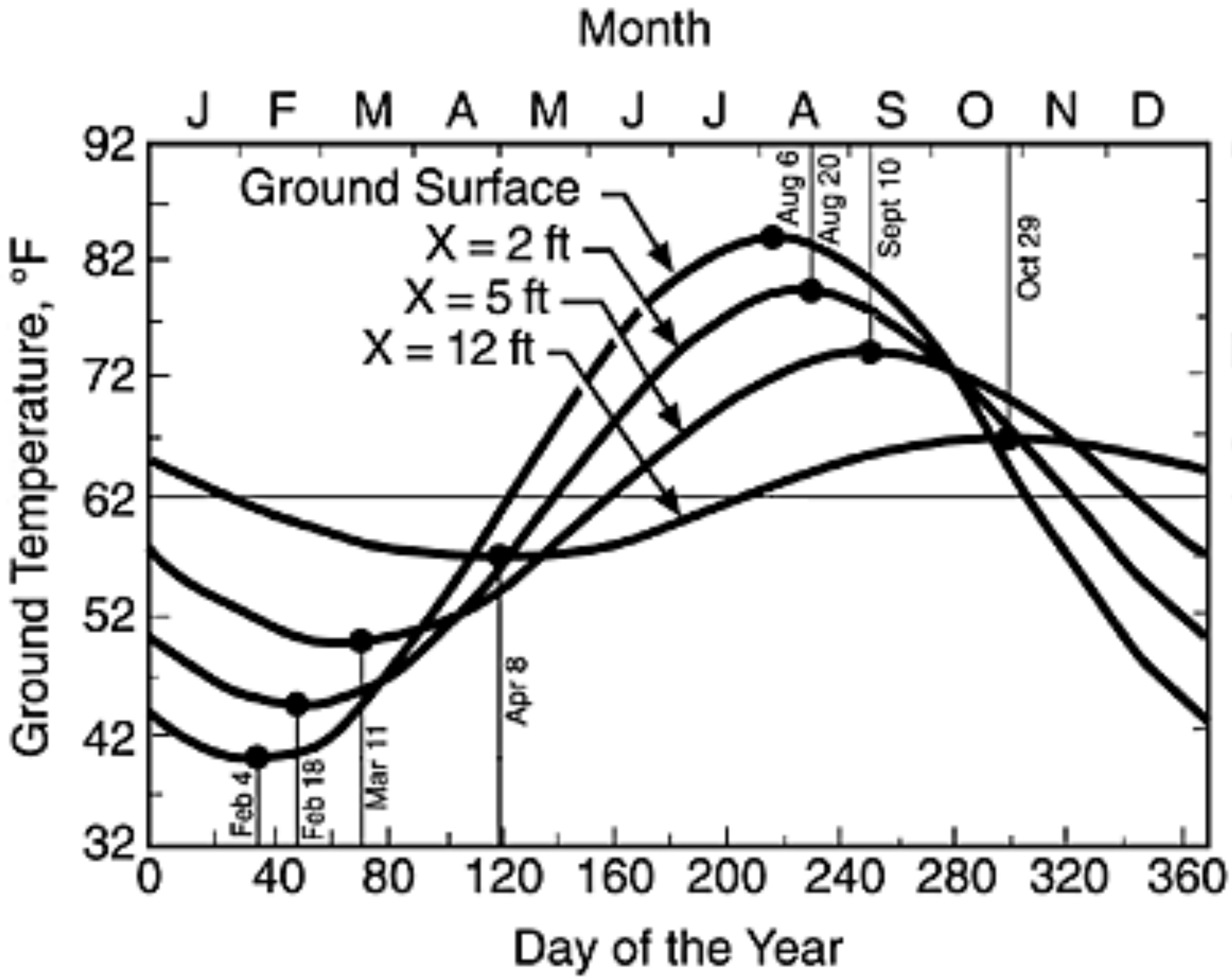
Source: http://www.geo4va.vt.edu/A1/A1.htm

Ground temperatures vary with depth and soil moisture



Source: http://www.geo4va.vt.edu/A1/A1.htm

Ground temperatures vary with season



Source: http://www.geo4va.vt.edu/A1/A1.htm

Design ground temperatures

- Design (worst-case) ground temperatures
  - Adjust mean ground temperature by a peak seasonal amplitude:

$$T_{gr} = T_{gm} - T_A$$

where

T_A = the ground temperature variation amplitude (right)

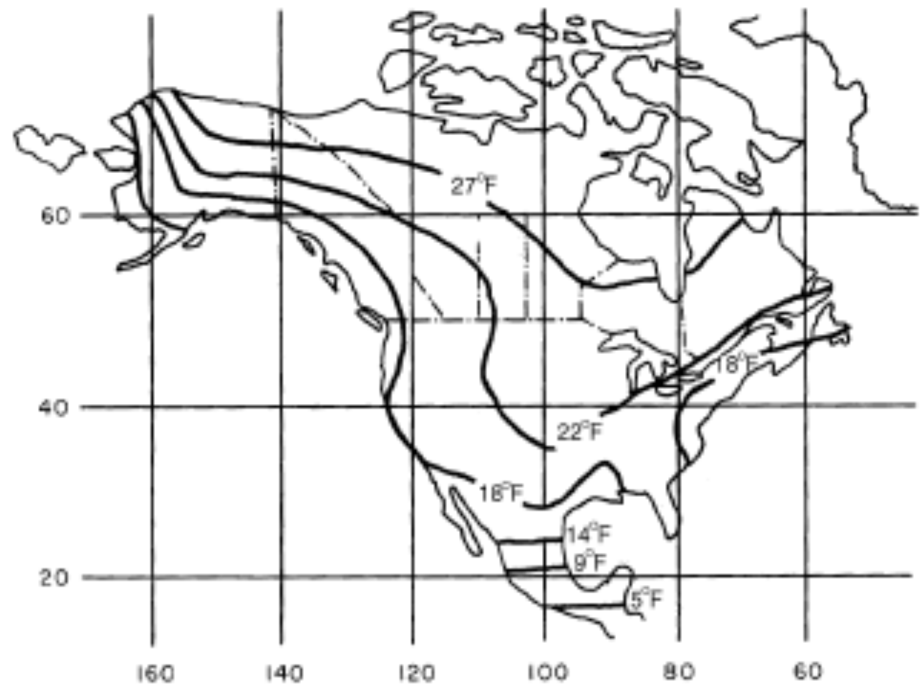
T_{gm} = mean ground temperature

*Note for Chicago:

$T_A \approx 22°F$ $T_{gm} \approx 54°F$

$T_{gr} \approx 54\text{-}22 = 32°F$

Alternatively, T_{gr} can be estimated as the mean air temperature in the coldest month



Ground Temp **Amplitude**, T_A

Source: 2005 ASHRAE Handbook Chapter, 29, Fig 2

Below-grade heat transfer

- Heat transfer through below-grade walls and floors
  - Conduction is truly 2-D
  - 1-D modeling is not appropriate
- Heat transfer through walls
  - Between inside and surrounding soil (not exterior air)
  - Depends on the wall area
    - Wall area depends upon perimeter but also height
- Heat transfer through the floor
  - Between inside and the soil below
  - Depends on the floor area
- ASHRAE HOF has some guidelines for transforming 2-D into 1-D

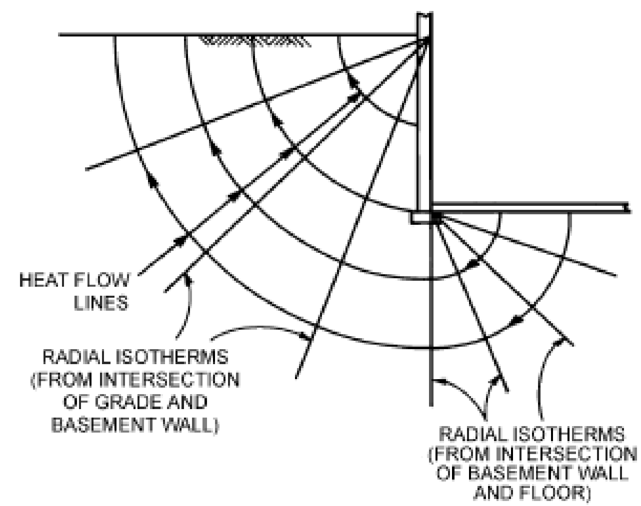


Fig. 4 Heat Flow from Basement

Below-grade heat transfer

$$Q = AU_{avg}(T_i - T_{gr}) \text{ [W]}$$

$$q = U_{avg}(T_i - T_{gr}) \text{ [W/m}^2\text{]}$$

where

A is the wall or floor area below grade [m^2] (analyze any wall portion above-grade in the normal way)

T_i is the below grade inside temp [K]

T_{gr} is the design ground surface temp [K]

U_{avg} is the average U factor for the below grade surface [W/(m^{2}K)] (see following slides)

Below grade depth parameters

z_1 = start of section to analyze

z_2 = end of section

z_f = bottom of floor

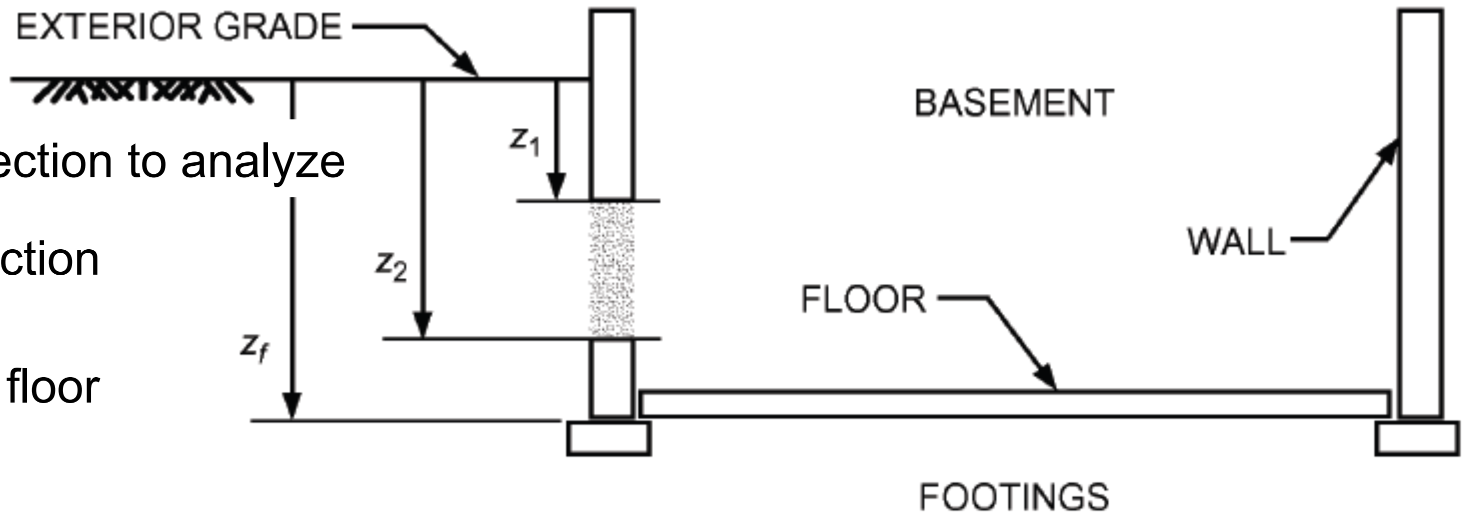


Fig. 14 Below-Grade Parameters

$U_{avg,bf}$ for below-grade floors

- For average below-grade floor value with a floor depth of height z_f from ground ("grade")

$$U_{avg,bf} = \frac{2k_{soil}}{\pi w_b} \times \left[\ln\left(\frac{w_b}{2} + \frac{z_f}{2} + \frac{k_{soil}R_{other}}{\pi}\right) - \ln\left(\frac{k_{soil}R_{other}}{\pi}\right)\right]$$

k_{soil} = soil thermal conductivity ≈ 1.4 W/mK
R_{other} = R value of floor + insulation + convection [m^{2}K/W]
w_b = shortest dimension of basement width [m]
z_f = floor depth below grade [m]

Pre-computed tables for $U_{avg,bf}$

Table 17 Average U-Factor for Basement Floors

z_f (depth of floor below grade), m	$U_{avg,bf}$, W/(m²·K) — w_b (shortest width of basement), m: 6	7	8	9
0.3	0.370	0.335	0.307	0.283
0.6	0.310	0.283	0.261	0.242
0.9	0.271	0.249	0.230	0.215
1.2	0.242	0.224	0.208	0.195
1.5	0.220	0.204	0.190	0.179
1.8	0.202	0.188	0.176	0.166
2.1	0.187	0.175	0.164	0.155

Soil conductivity is 1.4 W/(m·K); floor is uninsulated. For other soil conductivities and insulation, use Equation (38).

- Assuming un-insulated concrete floor

$U_{avg,bw}$ for below-grade walls

$$U_{avg,bw} = \frac{2k_{soil}}{\pi(z_1 - z_2)} \times \left[\ln\left(z_2 + \frac{2k_{soil}R_{other}}{\pi}\right) - \ln\left(z_1 + \frac{2k_{soil}R_{other}}{\pi}\right)\right]$$

- k_{soil} = soil thermal conductivity ≈ 1.4 W/mK
- R_{other} = R value of wall, insulation and inside surface resistance [m²K/W]
- z_1, z_2 = depths of top and bottom of wall segment under consideration [m]

Pre-computed tables for $U_{avg,bw}$

Table 16 Average U-Factor for Basement Walls with Uniform Insulation

Depth, m	$U_{avg,bw}$ from grade to depth, $W/(m^2 \cdot K)$ Uninsulated	R-0.88	R-1.76	R-2.64
0.3	2.468	0.769	0.458	0.326
0.6	1.898	0.689	0.427	0.310
0.9	1.571	0.628	0.401	0.296
1.2	1.353	0.579	0.379	0.283
1.5	1.195	0.539	0.360	0.272
1.8	1.075	0.505	0.343	0.262
2.1	0.980	0.476	0.328	0.252
2.4	0.902	0.450	0.315	0.244

Soil conductivity = 1.4 $W/(m \cdot K)$; insulation is over entire depth. For other soil conductivities and partial insulation, use Equation (37).

- Assuming concrete walls with uniform insulation

Below-grade example problem

Determine the heat flow, Q, through a basement enclosure

- Basement is 60 ft x 25 ft
- Walls are 5 ft below grade
  - Covered with R-4 (IP) insulation
  - Walls and floor are 6" concrete

Other information:

- k_{soil} = 0.8 Btu/(h ft^2 °F)
- R_{wall} = 4.0 (insul.) + 0.68 (convection) + 0.60 (6" concrete) = 5.28 (IP)
- R_{floor} = 0.61 (convection) + 0.6 (6" concrete) = 1.21 (IP)
- z_1 = 0, z_2 = 5 ft, z_f = 5 ft, w_b = 25 ft
- $A_{wall,bg}$ = 2*(5*25) + 2*(5*60) = 850 ft^2
- $A_{floor,bg}$ = 25*60 = 1500 ft^2
- Assume T_{in} = 65°F and T_{gr} = 40°F

Below-grade example problem

$$U_{avg,bw} = \frac{2(0.8)}{\pi(5-0)}\left[\ln\left(5+\frac{2(0.8)5.28}{\pi}\right)-\ln\left(0+\frac{2(0.8)5.28}{\pi}\right)\right] = 0.11 \ \frac{\text{Btu}}{\text{hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}}$$

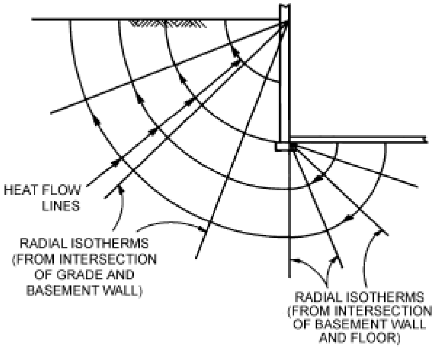


Fig. 4 Heat Flow from Basement

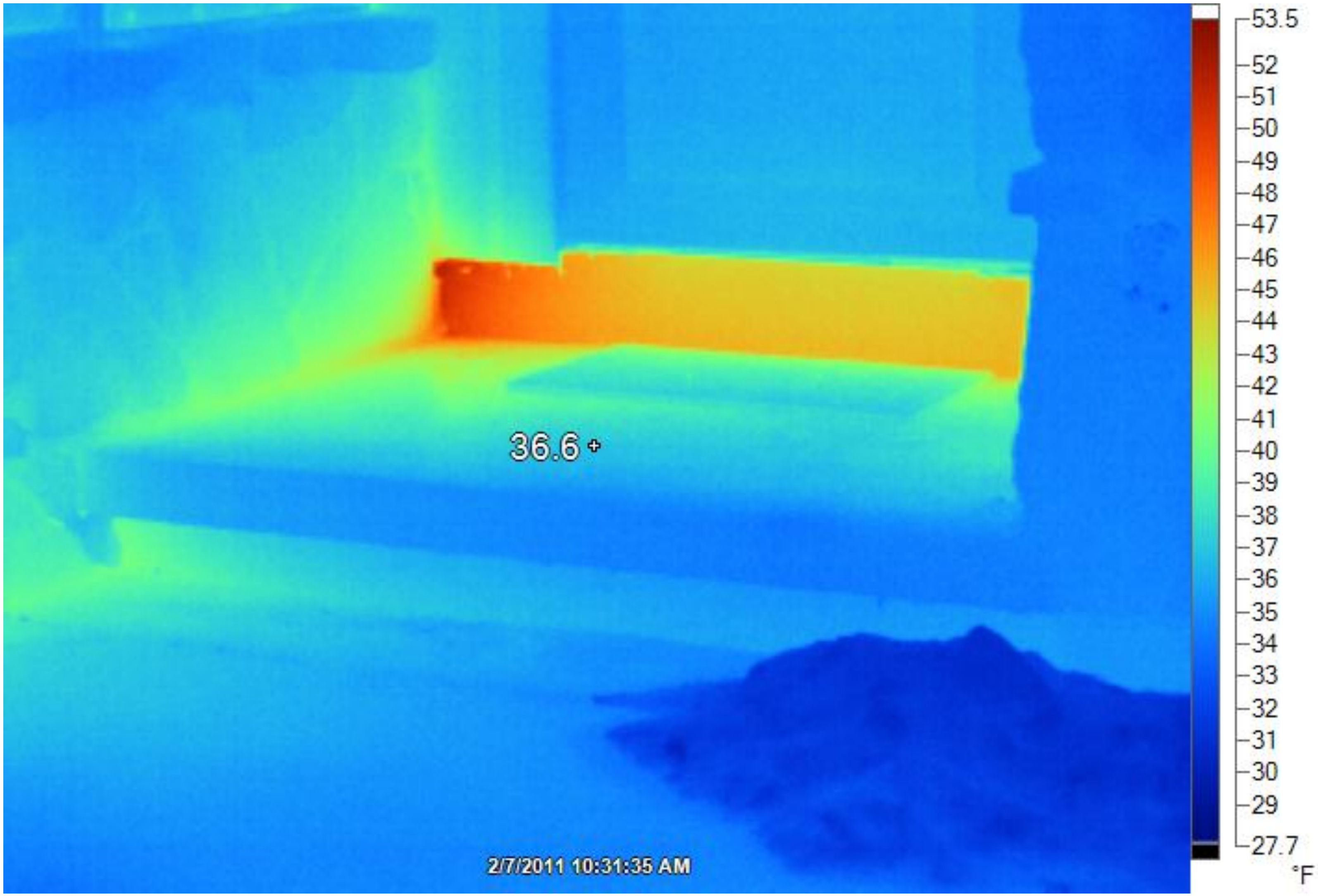
On-grade heat transfer

On-grade heat transfer

- Heat transfer for slab-on-grade floors
  - Concrete slabs can be heated or unheated
  - In either case:
    - Ground is often at a lower temperature than indoor air
      - Soil and concrete are fairly conductive
    - Perimeter can be exposed directly to outdoor air

  - It turns out that the perimeter is often most important for both energy and comfort
    - Need to insulate the perimeter

Slab-on-grade floors



Slab-on-grade floors

- Heat transfer through slab-on-grade floors
  - Function of perimeter of slab (not area)

$$Q = pF_p\left(T_i - T_o\right)$$

where T_i and T_o are the inside and outside temps [K]

p is the perimeter of the exposed floor surface [m]

F_p is the heat loss coefficient per unit length of perimeter [W/mK]

Design considerations

- To reduce heat transfer through slab on grade floors, we obviously need to:
  - Reduce the perimeter length, and/or
  - Decrease the heat loss coefficient, F_p
- Decreasing F_p is as simple as adding insulation to the foundation exterior
  - Typically no need to exceed $R = 8$ (IP)

Figure 3. Insulated Form Board Field Installation

Heat loss coefficient: F_p

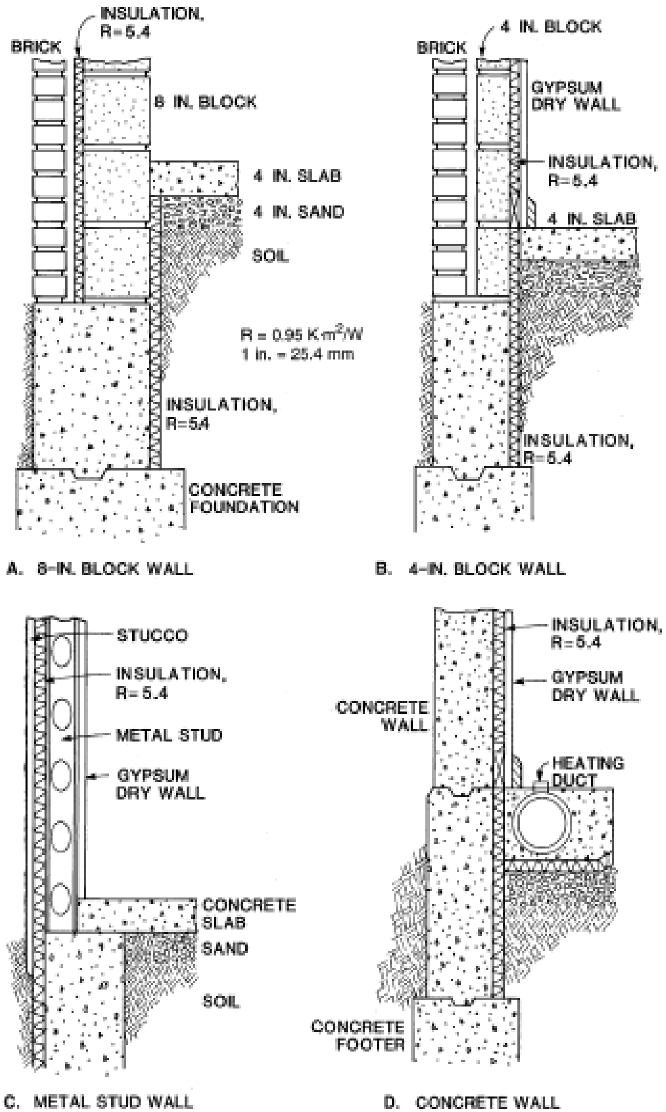


Fig. 8 Slab-on-Grade Foundation Insulation

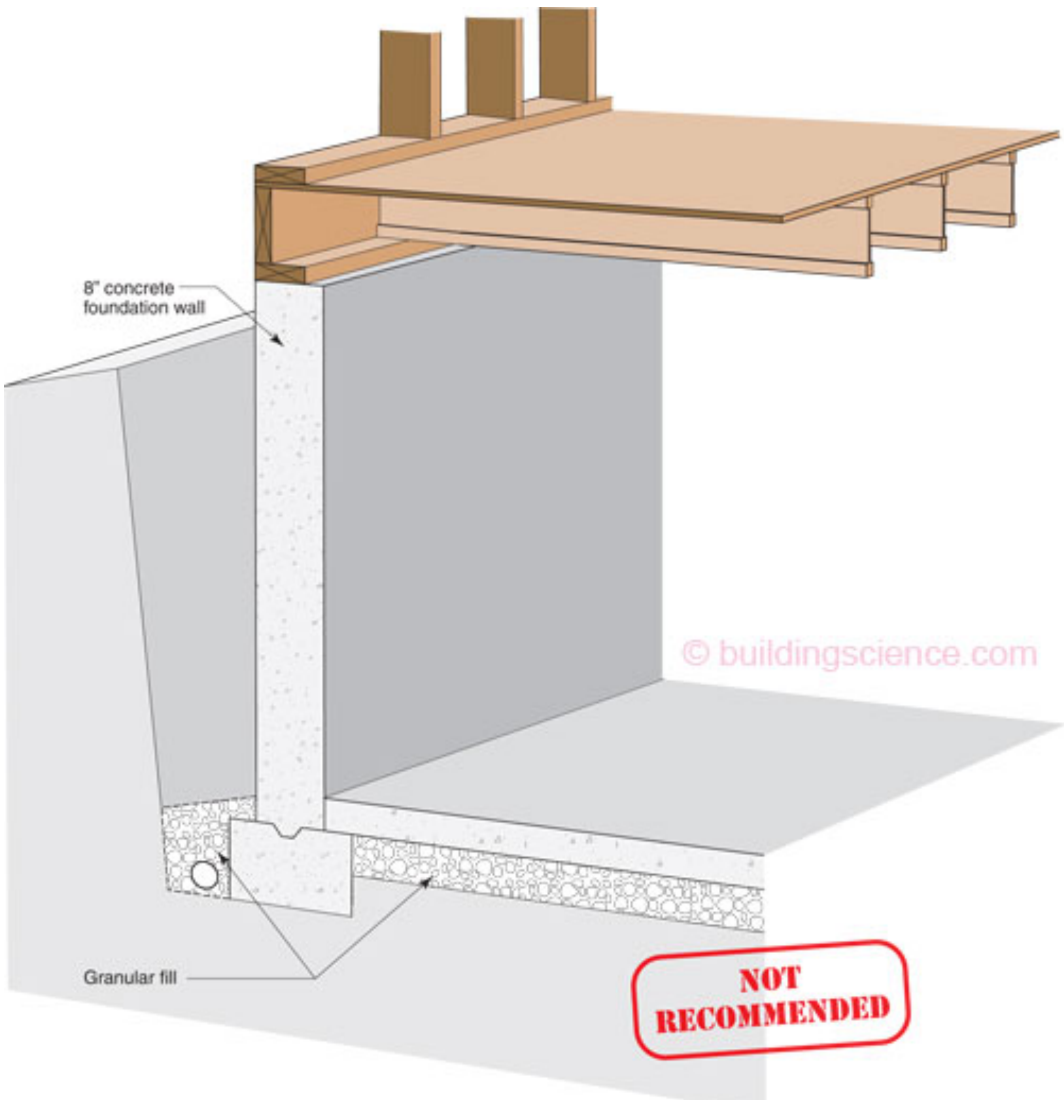
Table 18 Heat Loss Coefficient F_p of Slab Floor Construction

Construction	Insulation	F_p, W/(m·K)
200 mm block wall, brick facing	Uninsulated	1.17
	R-0.95 (m^2·K)/W from edge to footer	0.86
4 in. block wall, brick facing	Uninsulated	1.45
	R-0.95 (m^2·K)/W from edge to footer	0.85
Metal stud wall, stucco	Uninsulated	2.07
	R-0.95 (m^2·K)/W from edge to footer	0.92
Poured concrete wall with duct near perimeter*	Uninsulated	3.67
	R-0.95 (m^2·K)/W from edge to footer	1.24

*Weighted average temperature of the heating duct was assumed at 43°C during heating season (outdoor air temperature less than 18°C).

Slab-on-grade and below-grade enclosures

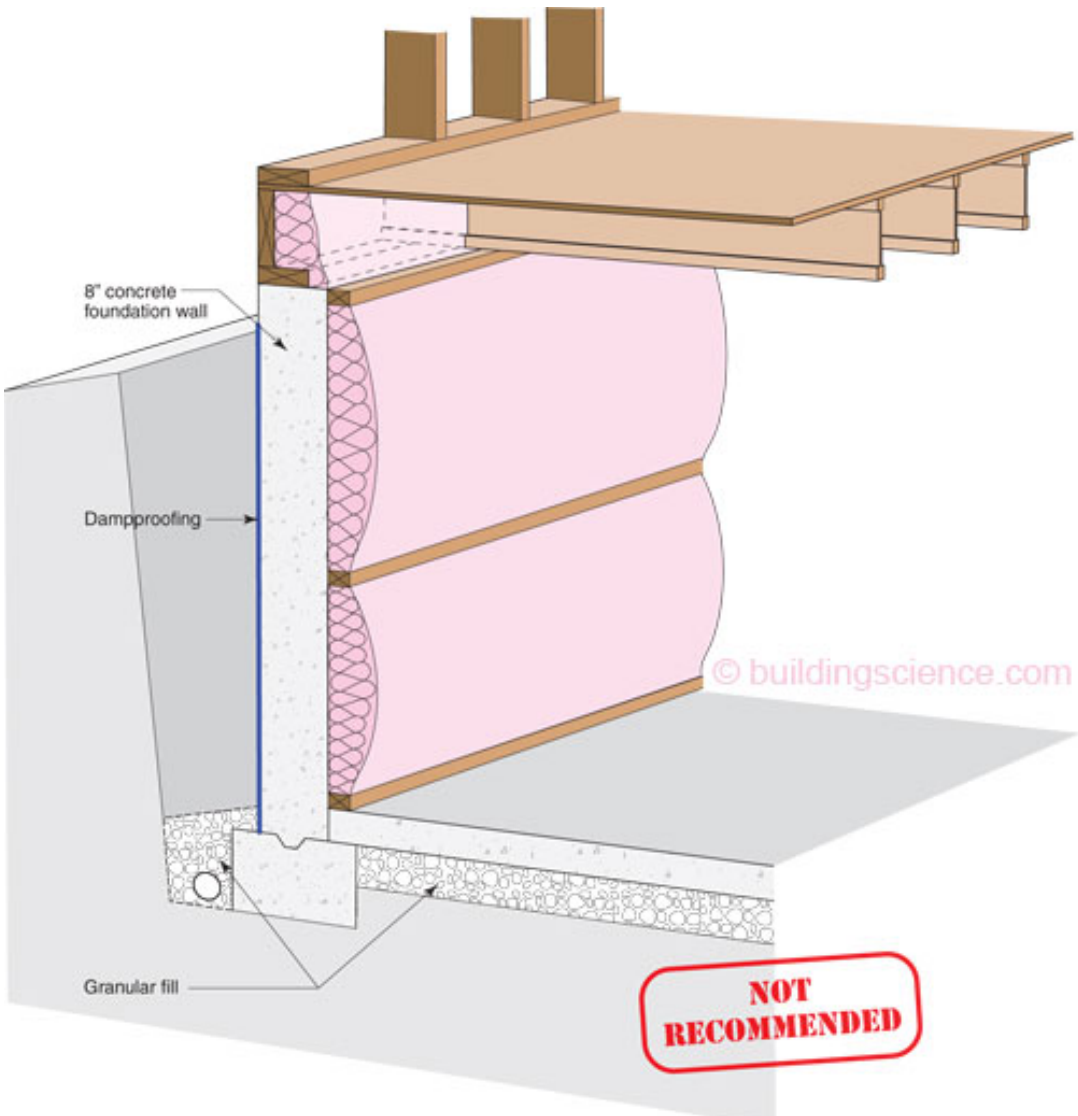
Uninsulated concrete foundation wall and slab



- No thermal control
- Not even allowed by code if basement is conditioned
- No moisture control
- Water vapor diffusion and capillary action are near-constant moisture sources

Slab-on-grade and below-grade enclosures

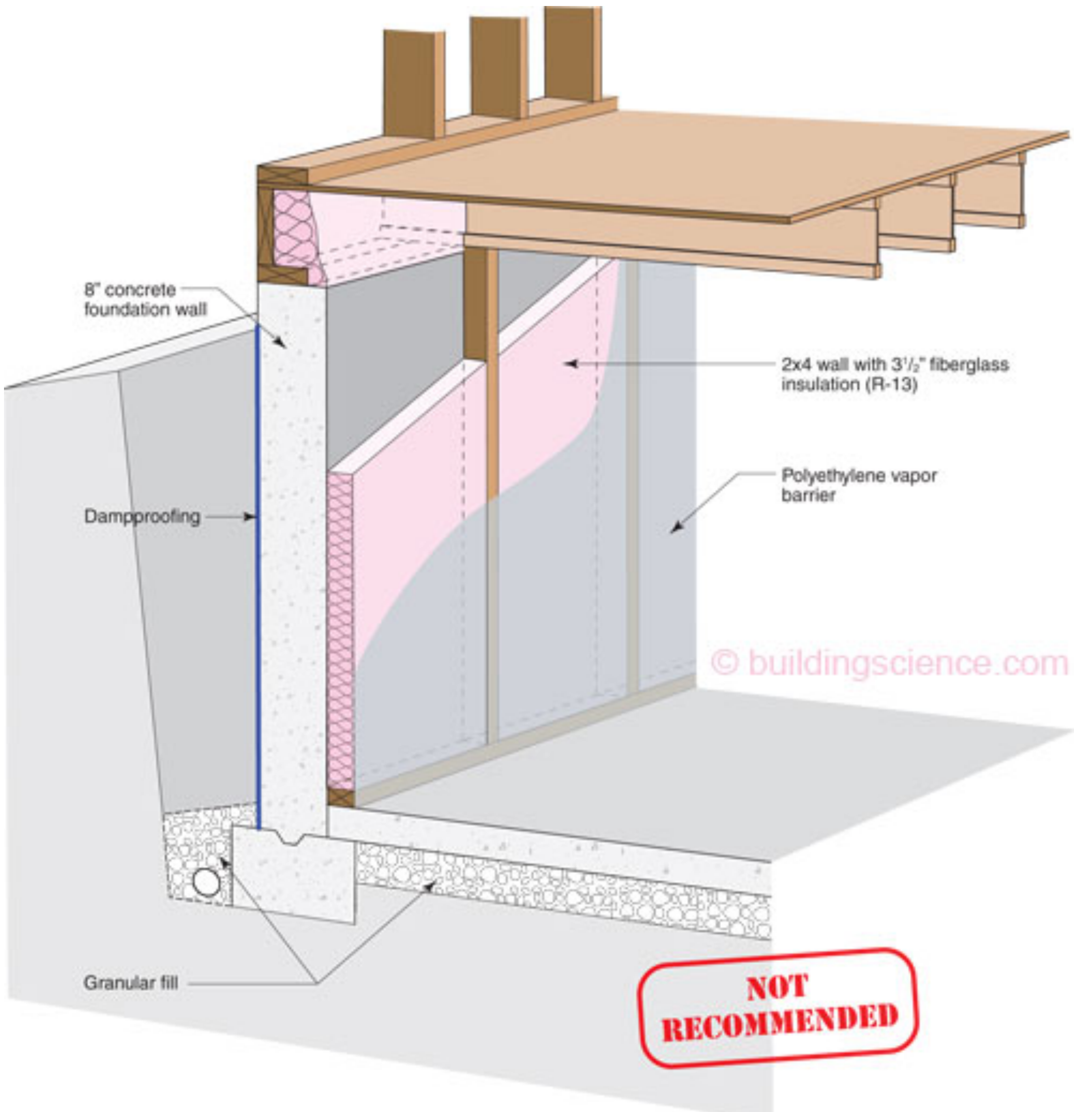
Code minimum R-10 (IP) continuous insulation in a framed wall



- Slab not insulated
- Better thermal control
- Inexpensive
- Sometimes wall insulation batt is covered with vapor barrier
- Moisture issues (batt is air and vapor permeable)
- High RH at concrete wall most of the year

Slab-on-grade and below-grade enclosures

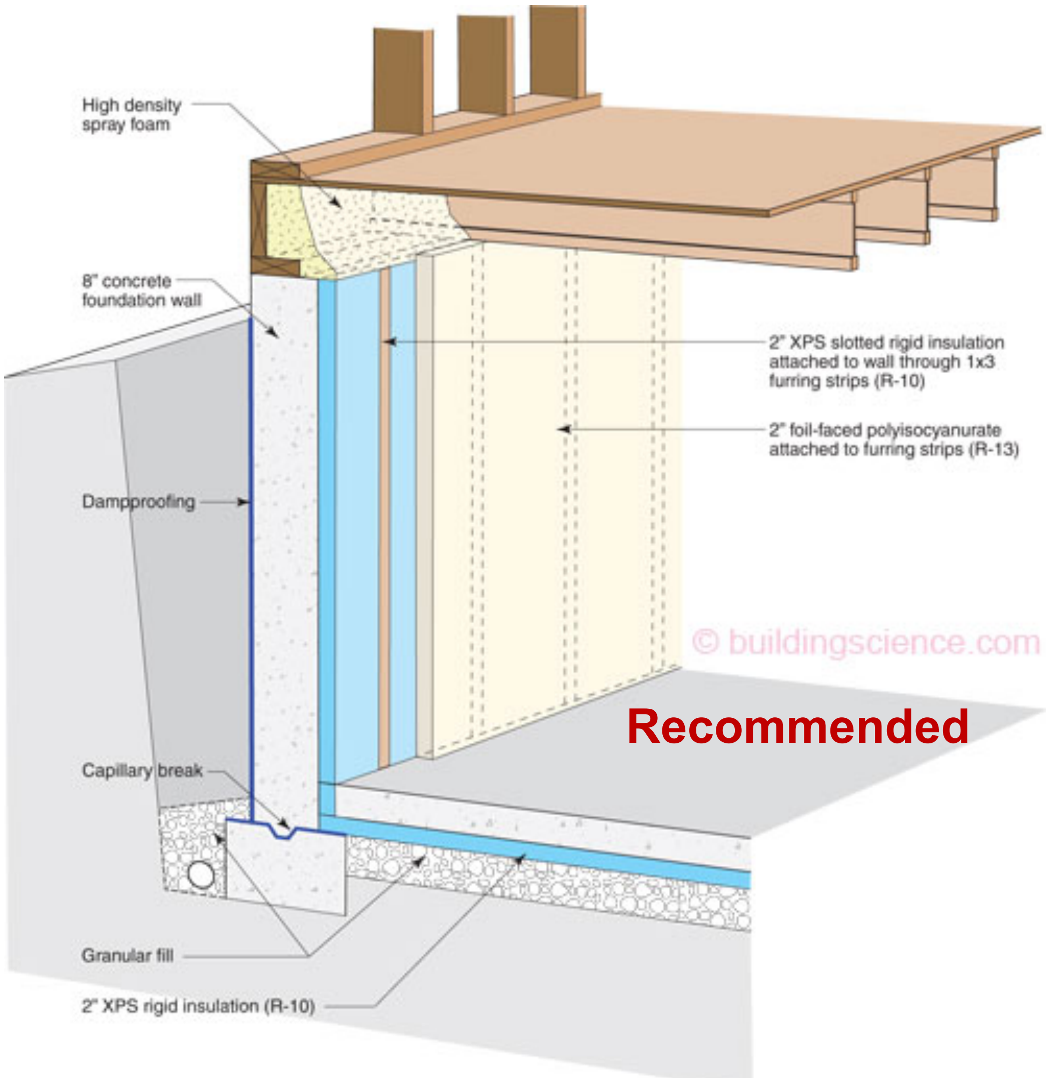
R-13 (IP) insulation in a 2x4 framed wall

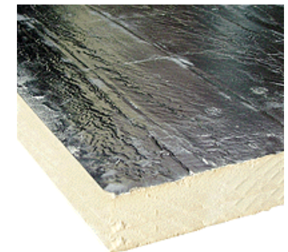


- Similar to last construction
- Moisture issues
- High RH at concrete wall most of the year
- Particularly a problem if there is any air leakage

Slab-on-grade and below-grade enclosures

2” XPS rigid insulation + 2” foil-face polyisocyanurate foam board

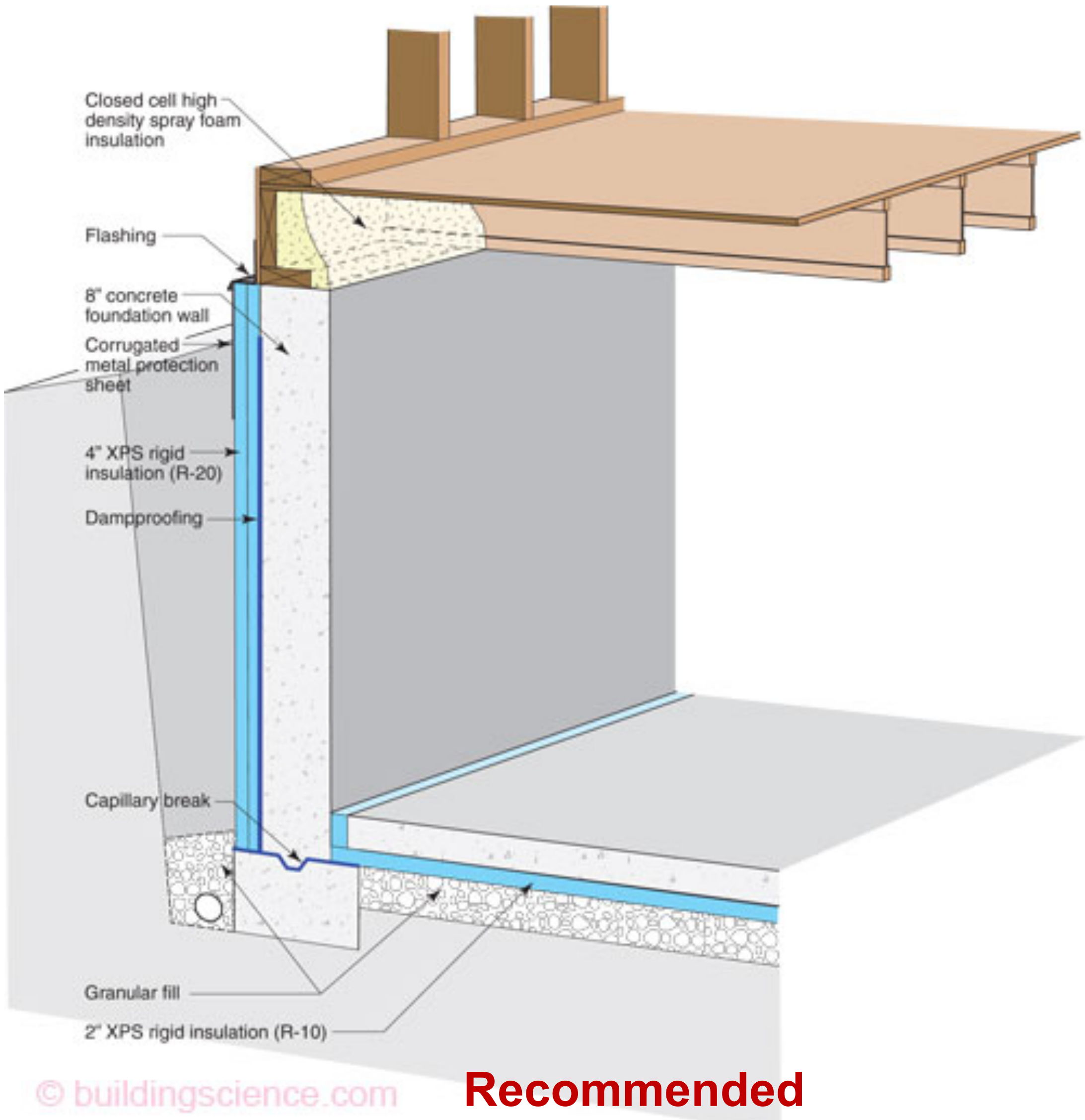




- Very good thermal control (R-23 walls)
- Water vapor diffusion is prevented
- Capillary action is prevented by the thermal/capillary break at the edge of the slab and top of footing

Slab-on-grade and below-grade enclosures

Rigid XPS exterior insulation



Recommended

- Very good thermal control (R-20 walls)
- Exterior insulation can be joined with first floor insulation
- Excellent resistance to vapor diffusion
- Capillary action is a potential problem (through the footing)
    - Need a break
- Exposed concrete provides moisture buffer after it dries
- May be hard to construct

Using THERM for finding U_{avg}

- You can use THERM to model 2-D heat transfer but be careful …
  - Must create new convection boundary conditions for interior convection to/ from floor
  - Must model a large area of soil around the foundation as a solid with adiabatic boundary conditions
  - Must model outside soil/air interface with new exterior convection

- Basement floor is a 3-D problem and so it cannot be easily modeled in THERM

Combining elements in an actual enclosure

- So far we have been exploring single assemblies
  - Just roofs or just walls without windows and doors
  - If you design a building without windows and doors, something probably went wrong!
- Concept of **combined thermal transmittance**: U_o
  - U_o is the combined thermal transmittance of the respective areas of a gross exterior wall, roof, or floor
    - It is basically an area-weighted average U-value

$$U_o = (U_{wall}A_{wall} + U_{window}A_{window} + U_{door}A_{door})/A_o$$

where

U_o = average thermal transmittance of gross wall area
A_o = gross area of exterior walls
U_{wall} = thermal transmittance of all elements of opaque wall area
A_{wall} = opaque wall area
U_{window} = thermal transmittance of window area (including frame)
A_{window} = window area (including frame)
U_{door} = thermal transmittance of door area
A_{door} = door area (including frame)

Combined thermal transmittance example

- Calculate U_o for a 10 m x 2.4 m wall with two double-glazed windows with wood/vinyl frames and one solid core door
  - One window is 1.5 x 0.86 m; the other window is 0.9 x 0.76 m
    - Let's say we looked up window U-value in a table
    - U_{window} = 2.90 W/m²K
  - The door is 0.86 x 2 m
    - Let's say we also looked up its U-value in a table
    - U_{door} = 1.42 W/m²K
  - The wall has a U value of U_{wall} = 0.404 W/m²K

$$A_{window} = (1.500 \times 0.860) + (0.900 \times 0.760) = 1.97 \text{ m}^2$$

$$A_{door} = (0.860 \times 2.000) = 1.72 \text{ m}^2$$

$$A_{wall} = (10 \times 2.4) - (1.97 + 1.72) = 20.31 \text{ m}^2$$

Therefore, the combined thermal transmittance for the wall is

$$U_o = \frac{(0.404 \times 20.31) + (2.90 \times 1.97) + (1.42 \times 1.72)}{10 \times 2.4}$$

$$= 0.68 \text{ W/(m}^2 \cdot \text{K)}$$

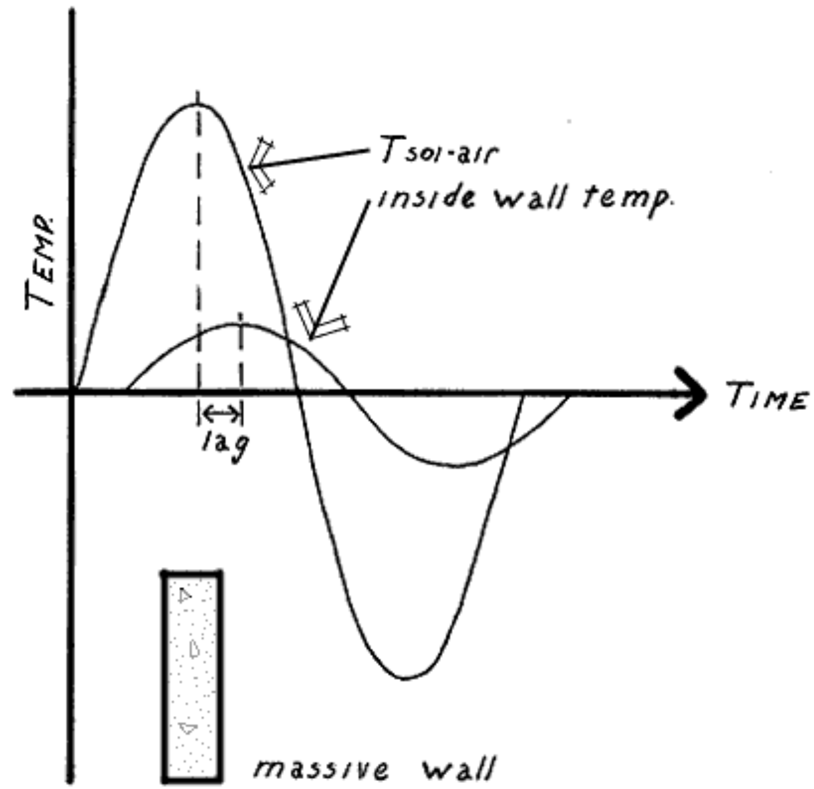
THERMAL MASS

Heat storage and release

Thermal mass

- Thermal mass refers to materials that have the capacity to store thermal energy for extended periods of time

- Thermal mass can be used effectively to absorb daytime heat gains
  - Reduces peak cooling load
  - Releases heat during the night (can reduce heat load)



Historical use of thermal mass

- Thermal mass is **NOT** a new idea
- The use of thermal mass in construction dates to the beginning of history
  - Stone caves are great examples of ancient thermal mass buildings
  - Mud-brick houses have been used for thousands of years by numerous civilizations in hot climates
    - Helps buffer harsh exterior conditions

Types of thermal mass

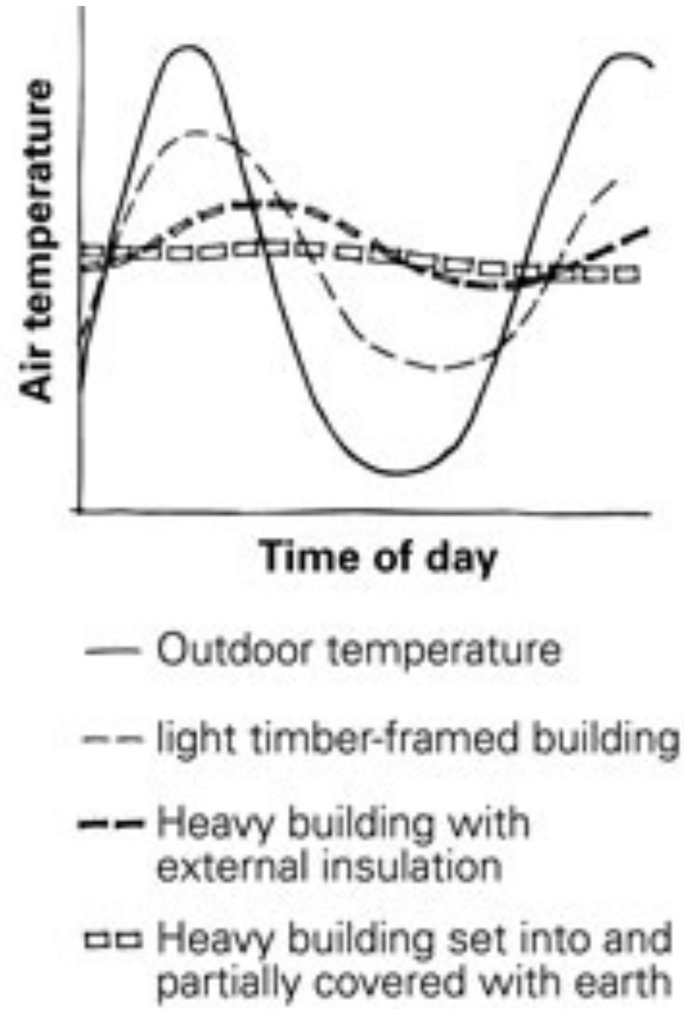
- Traditionally, materials with high thermal mass have also had a high mass themselves:
  - Water, earth, stone, brick, cement, concrete, thick tiles
  - All these materials have high densities and high specific heat capacities

- More recently, phase change materials are being used:
  - Solid-liquid salts, paraffin wax, crystalline hydrocarbons
  - These are materials that melt at room temperature and can store/release large amounts of latent heat with much lower mass than traditional materials
  - More on these later

Thermal mass: Why do we care?

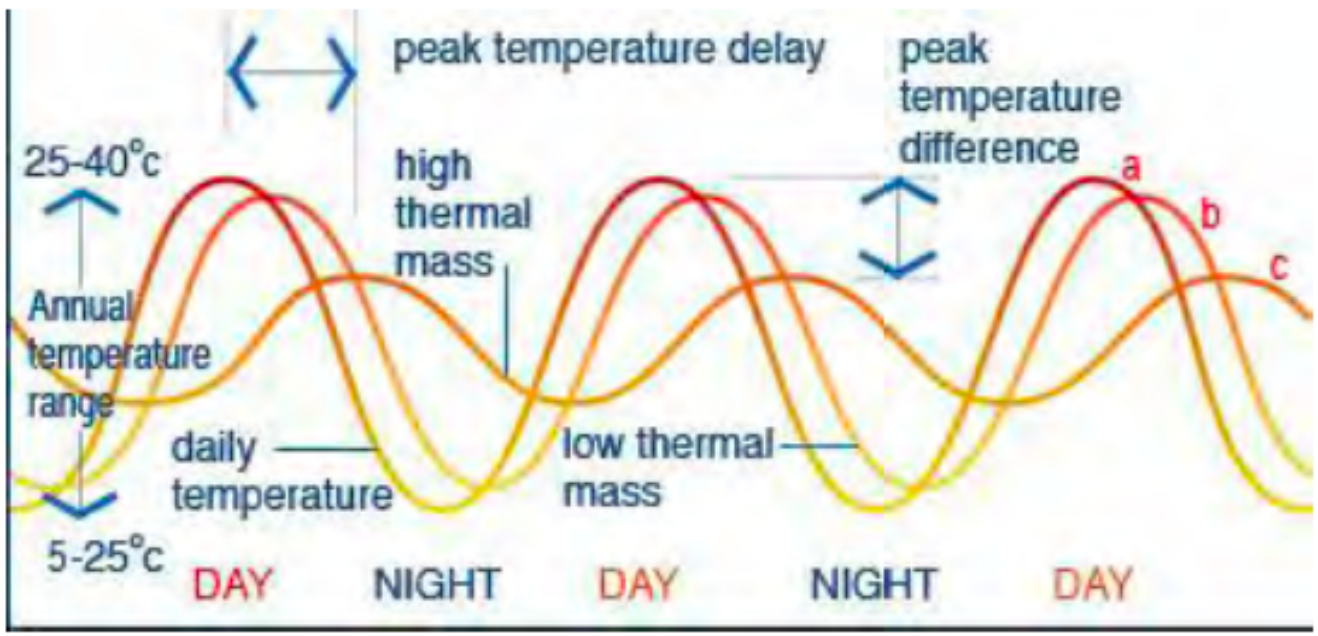
- A high thermal mass will be slow to heat up
  - But also slow to cool down
  - Can store large amounts of heat

- The result is that exterior temperatures can fluctuate greatly
  - But the interior temperature will fluctuate less



Thermal mass

- All materials/constructions have some thermal mass
  - But constructions with a high thermal mass have large effects on the dynamic energy transfer in a building
  - Thermal mass can be both useful and detrimental to maintaining thermal comfort with changing heating and cooling loads



What thermal mass is not

- Thermal mass is not the same as thermal insulation/thermal resistance
  - In fact, most materials with high thermal resistance have low thermal mass

- Some material in a construction needs to have a high heat capacity for the construction to have a high thermal mass

Heat Capacity, HC

- The heat capacity (HC) of a material is the product of the density of the material, the specific heat capacity, and the material thickness
  - HC = $\rho L C_p$ [J/m^{2}K]
  - HC is a measure of the ability of a material to store energy per unit area
  - L = length [m]
  - ρ = density [kg/m^3]
  - C_p = specific heat capacity [J/kgK]
  - You sometimes also see HC*A = ρLAC_p [J/K]

- Heat capacity is important to thermal mass, but needs to be compared with thermal conductivity to get the whole story

Thermal Diffusivity, α

- Thermal diffusivity, α, is the measure of how fast heat can travel through an object
- α is proportional to conductivity but inversely proportional to density and specific heat:

$$\alpha = \frac{k}{\rho C_p} \quad [\mathrm{m}^2/\mathrm{s}]$$

- The lower the α, the better the material is as a thermal mass (low conductivity relative to storage ability)
  - The time lag between peak internal and external temperature is related to the diffusivity of the walls
  - Steel has a high ρC_p but also a high k so it is not as good a thermal mass as concrete or masonry

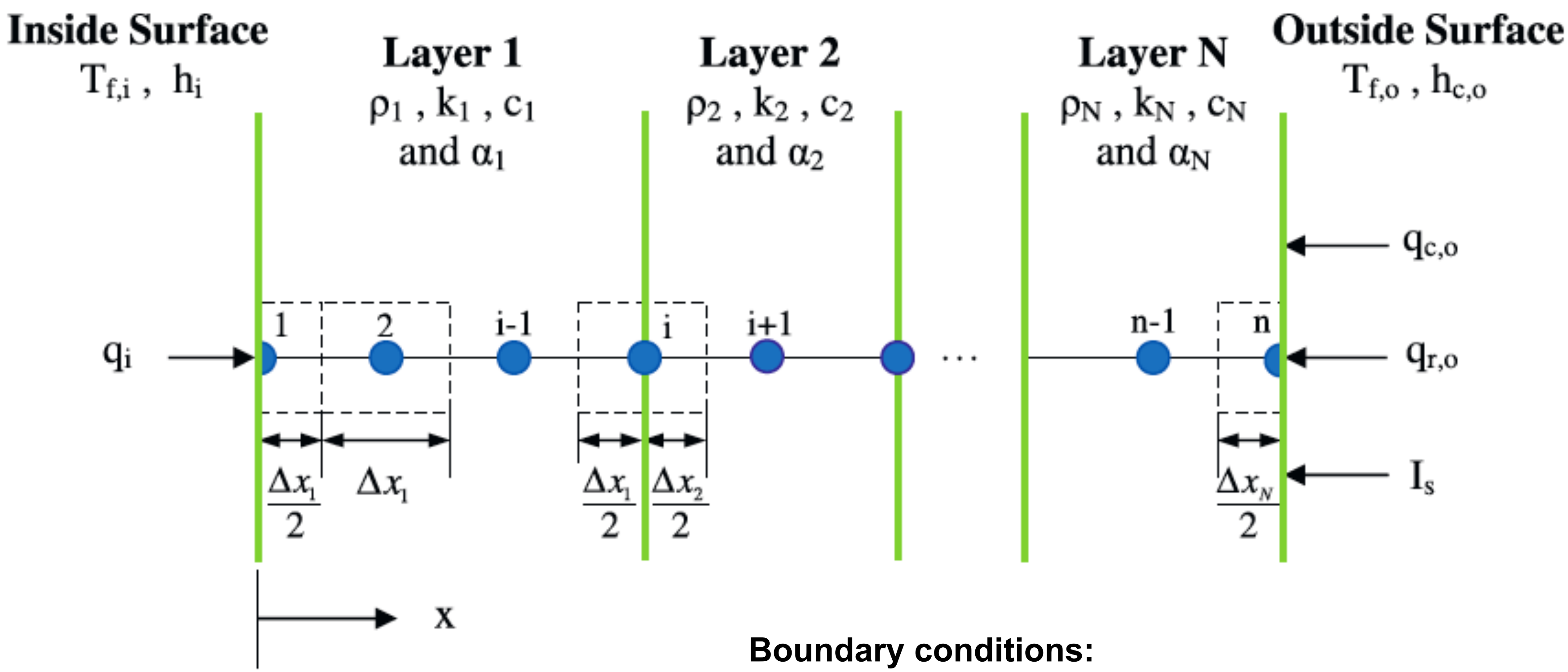
Thermal properties

- All three material properties can be found in ASHRAE HOF chapter on thermal transmission data (Ch. 25 in 2005 HOF)
  - Thermal conductivity, density, and specific heat

Description	Density, kg/m³	Conductivity[b] (*k*), W/(m·K)	Conductance (*C*), W/(m²·K)	Resistance[c] (*R*) 1/*k*, (m·K)/W	Resistance[c] (*R*) For Thickness Listed (1/*C*), (m²·K)/W	Specific Heat, kJ/(kg·K)
Gypsum partition tile						
75 by 300 by 760 mm, solid	—	—	4.50	—	0.222	0.79
75 by 300 by 760 mm, 4 cells	—	—	4.20	—	0.238	—
100 by 300 by 760 mm, 3 cells	—	—	3.40	—	0.294	—
Concretes[o]						
Sand and gravel or stone aggregate concretes (concretes with more than 50% quartz or quartzite sand have conductivities in the higher end of the range)	2400	1.4-2.9	—	0.69-0.35	—	—
	2240	1.3-2.6	—	0.77-0.39	—	0.8-1.0
	2080	1.0-1.9	—	0.99-053	—	—
Limestone concretes	2240	1.60	—	0.62	—	—
	1920	1.14	—	0.88	—	—
	1600	0.79	—	1.26	—	—

Modeling thermal mass

- Conduction and thermal mass together can be modeled using discrete nodes in 1-dimension:



Governing equation:

$$\boxed{\frac{\partial^2 T_j}{\partial x^2} = \frac{1}{\alpha_j}\frac{\partial T_j}{\partial t}}$$

$$\alpha = \frac{k}{\rho C_p} \quad [\mathrm{m}^2/\mathrm{s}]$$

$$t = \text{time [s]}$$

Boundary conditions:

$$-k_1 \left.\frac{\partial T}{\partial x}\right|_{x=0} = h_i(T_{f,i} - T_{x=0}) \qquad T_j(x,0) = T_0$$

$$-k_N \left.\frac{\partial T}{\partial x}\right|_{x=L} = h_{c,o}(T_{x=L} - T_{f,o}) - \alpha I_s - q_{r,o}$$

Modeling thermal mass

- Conduction and thermal mass together can be modeled using a lumped capacitance approach in 1-dimension:

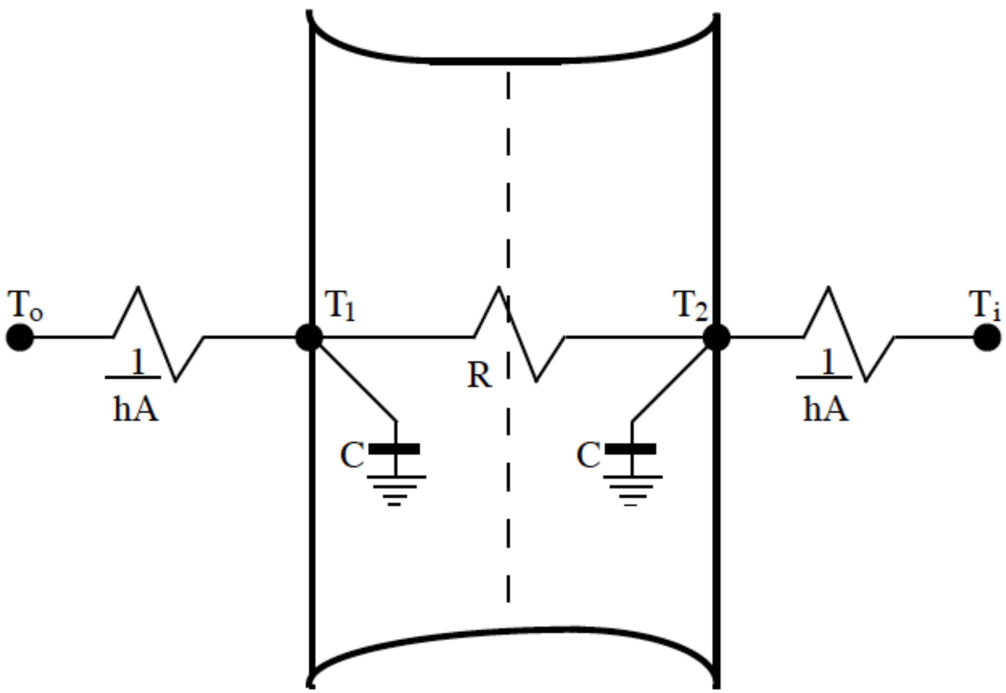


Figure 9. Two Node State Space Example.

$$C\frac{dT_1}{dt} = hA\left(T_o - T_1\right) + \frac{T_2 - T_1}{R}$$

$$C\frac{dT_2}{dt} = hA\left(T_i - T_2\right) + \frac{T_1 - T_2}{R}$$

where:

$$R = \frac{\ell}{kA},$$

$$C = \frac{\rho c_p \ell A}{2}$$

Lumped capacitance model

- Wall example: Exterior surface balance at T_1 changes

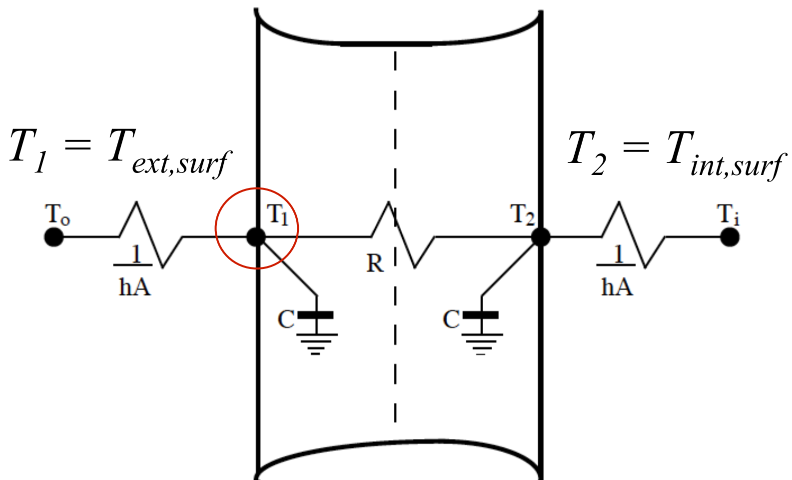


Figure 9. Two Node State Space Example.

From:

$$q_{sw,solar} + q_{lw,surface-sky} + q_{lw,surface-air} + q_{lw,surface-ground} + q_{convection} - q_{conduction} = 0$$

To:

$$q_{sw,solar} + q_{lw,surface-sky} + q_{lw,surface-air} + q_{lw,surface-ground} + q_{convection} - q_{conduction} = \rho C_p \frac{L}{2}\frac{dT}{dt}$$

Lumped capacitance model

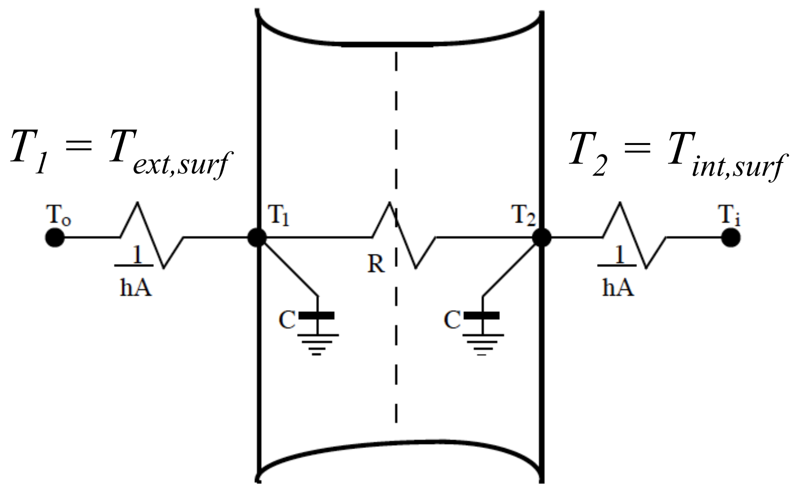


Figure 9. Two Node State Space Example.

Steady state surface energy balance…

$$\alpha I_{solar} + \varepsilon_1 \sigma F_{sky}(T_{sky}^4 - T_1^4) + \varepsilon_1 \sigma F_{air}(T_{air}^4 - T_1^4) + \varepsilon_1 \sigma F_{ground}(T_{ground}^4 - T_1^4) + h_{conv}(T_{air} - T_1) - U(T_1 - T_2) = 0$$

…becomes a time-varying surface energy balance:

$$\alpha I_{solar} + \varepsilon_1 \sigma F_{sky}(T_{sky}^4 - T_1^4) + \varepsilon_1 \sigma F_{air}(T_{air}^4 - T_1^4) + \varepsilon_1 \sigma F_{ground}(T_{ground}^4 - T_1^4) + h_{conv}(T_{air} - T_1) - U(T_1 - T_2) = \frac{\rho C_p}{\Delta t}\frac{L}{2}(T_1^n - T_1^{n-1})$$

Time lags and decrement factors

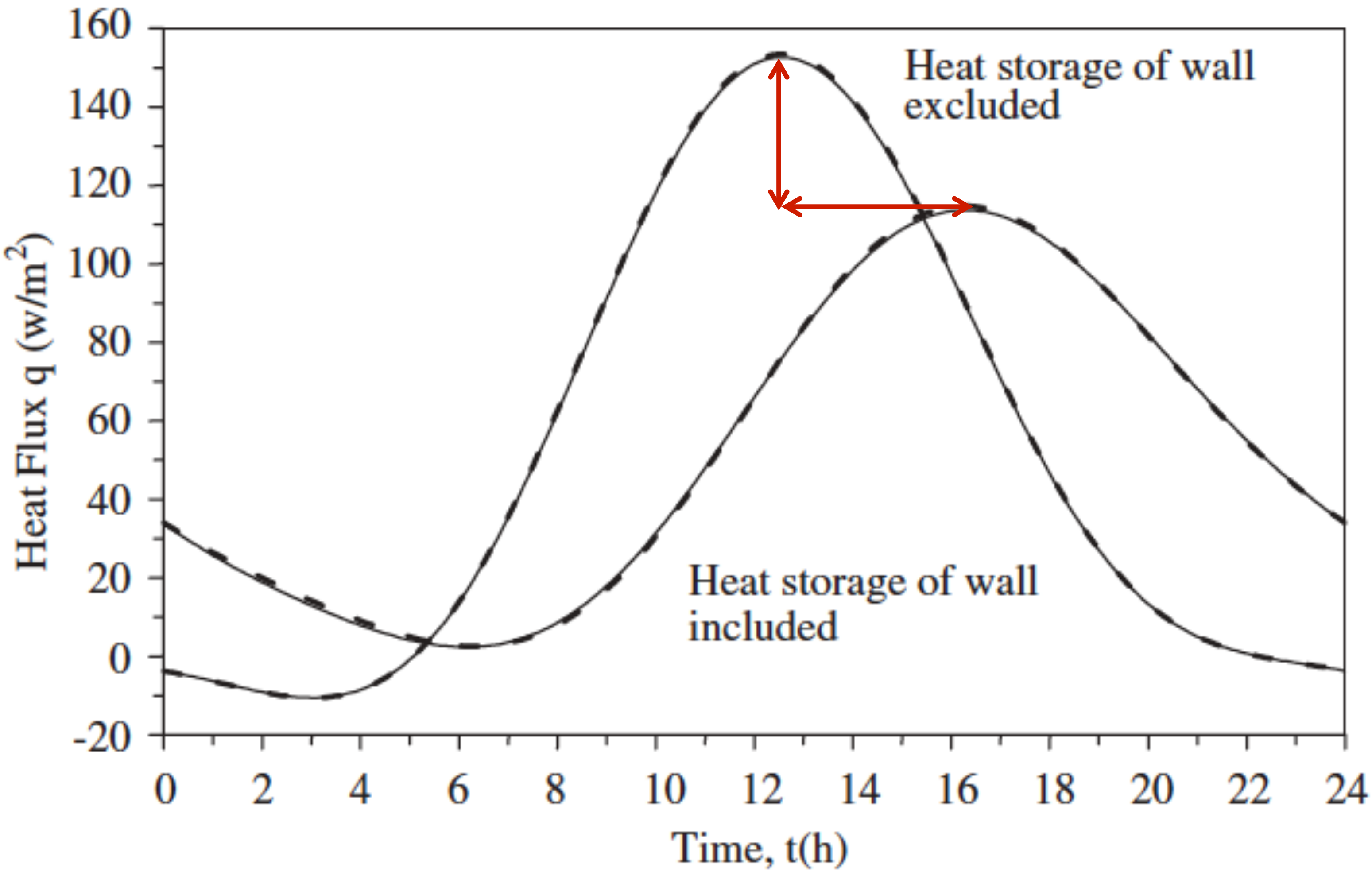
- These models (and measurements) can also be used to describe time lags and decrement factors

- Time lag describes:
  - For a given peak exterior surface temperature at a certain time for a material *without* thermal mass
  - How much later (in time) does the peak interior surface temperature actually occur because of thermal lag effects?

- Decrement factor describes:
  - How much lower is the peak temperature swing (amplitude) with an enclosure with high thermal mass relative to no thermal mass
    - e.g., How squished is the peak temperature profile?

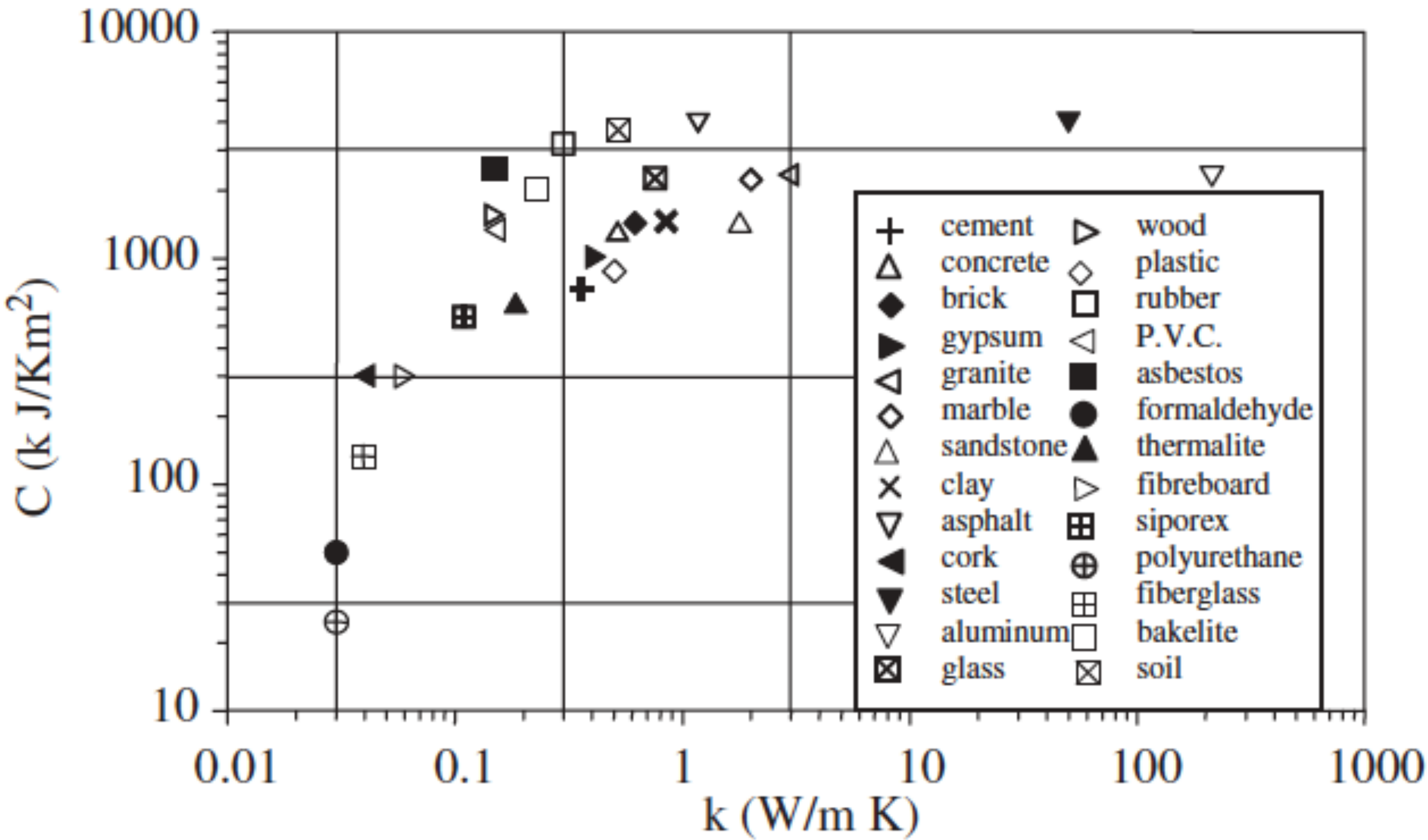
Thermal mass impacts

Decrement factors (ϕ) and time lags (f)



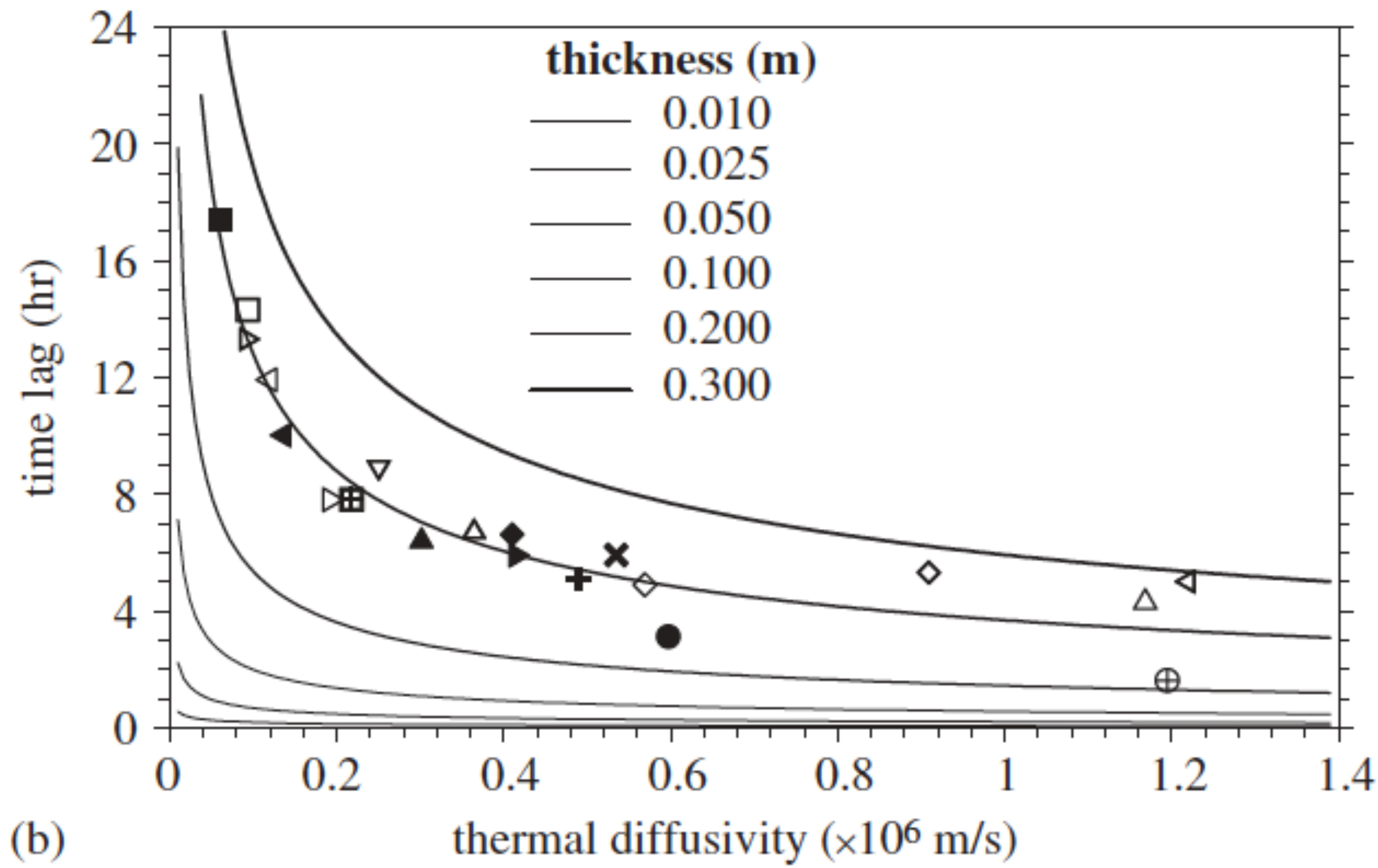
Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Material properties for thermal mass



Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Modeled time lag of several materials with varying thickness



Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Computed time lags and decrement factors for materials

Table 1

Thickness	$L = 0.001\,m$		$L = 0.010\,m$		$L = 0.025\,m$		$L = 0.050\,m$		$L = 0.100\,m$		$L = 0.200\,m$		$L = 0.300\,m$		$L = 1.000\,m$	
Building material	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f	ϕ (h)	f
Cement layer	0.01	0.730	0.09	0.647	0.26	0.544	0.69	0.426	1.89	0.284	5.12	0.128	8.23	0.054	>24	≈0
Concrete block	0.01	0.733	0.16	0.672	0.44	0.588	1.14	0.477	2.88	0.312	6.81	0.118	10.31	0.043	>24	≈0
Brick block	0.01	0.735	0.17	0.683	0.46	0.609	1.15	0.506	2.83	0.343	6.65	0.137	9.86	0.053	>24	≈0
Gypsum plastering	0.01	0.732	0.12	0.660	0.28	0.564	0.89	0.450	2.34	0.299	5.93	0.123	9.27	0.048	>24	≈0
Granite (red) block	0.02	0.739	0.24	0.726	0.59	0.701	1.28	0.646	2.62	0.515	5.01	0.288	6.95	0.166	>24	≈0
Marble (white) block	0.02	0.739	0.22	0.721	0.56	0.689	1.25	0.626	2.66	0.487	5.31	0.255	7.56	0.136	>24	≈0
Sandstone block	0.02	0.737	0.16	0.720	0.40	0.688	0.92	0.633	2.03	0.519	4.47	0.306	6.45	0.176	21.77	≈0
Clay layer	0.02	0.736	0.17	0.698	0.45	0.639	1.10	0.551	2.61	0.396	5.98	0.178	8.84	0.078	>24	≈0
Soil layer	0.03	0.732	0.40	0.669	1.31	0.569	2.93	0.409	6.12	0.184	12.08	0.036	18.65	0.001	>24	≈0
Asphalt layer	0.04	0.738	0.41	0.706	1.03	0.647	2.31	0.526	4.62	0.309	8.82	0.100	12.00	0.034	>24	≈0
Steel slab	0.04	0.741	0.38	0.736	0.89	0.719	1.79	0.658	3.05	0.516	4.41	0.313	5.09	0.227	8.95	0.031
Aluminum slab	0.02	0.741	0.23	0.739	0.55	0.733	1.13	0.708	2.09	0.631	3.43	0.459	4.14	0.352	5.86	0.113
Cork board	0.00	0.656	0.08	0.323	0.32	0.174	1.10	0.097	3.66	0.044	10.02	0.008	15.77	0.001	>24	≈0
Wood board	0.02	0.717	0.24	0.559	0.79	0.403	2.27	0.259	5.89	0.103	13.31	0.014	20.28	0.000	>24	≈0
Glass block	0.02	0.735	0.39	0.692	0.73	0.624	1.64	0.517	3.77	0.329	7.74	0.116	11.65	0.041	>24	≈0
Plastic board	0.01	0.733	0.10	0.671	0.27	0.587	0.73	0.482	1.90	0.339	4.94	0.162	7.84	0.073	>24	≈0
Bakelite board	0.01	0.724	0.34	0.603	0.96	0.466	2.32	0.315	5.76	0.136	12.53	0.022	19.49	0.001	>24	≈0
Rubber board	0.03	0.728	0.39	0.629	1.17	0.501	3.01	0.331	6.76	0.127	14.34	0.017	21.82	0.000	>24	≈0
PVC board	0.01	0.717	0.20	0.559	0.65	0.406	1.90	0.265	5.11	0.116	11.92	0.019	18.01	0.002	>24	≈0
Asbestos layer	0.03	0.716	0.37	0.557	1.23	0.396	3.39	0.230	7.97	0.069	17.41	0.004	>24	0.000	>24	≈0
Formaldehyde board	0.00	0.632	0.01	0.271	0.06	0.139	0.23	0.077	0.84	0.040	3.19	0.018	5.96	0.008	>24	≈0
Fiberglass	0.00	0.656	0.01	0.322	0.10	0.174	0.52	0.099	1.71	0.051	5.70	0.018	9.92	0.006	>24	≈0
Thermalite board	0.01	0.721	0.09	0.582	0.28	0.439	0.81	0.309	2.36	0.181	6.52	0.064	10.43	0.021	>24	≈0
Fiberboard layer	0.00	0.682	0.06	0.379	0.24	0.234	0.80	0.138	2.66	0.069	7.86	0.019	12.54	0.005	>24	≈0
Siporex board	0.01	0.710	0.09	0.517	0.26	0.355	0.92	0.231	2.81	0.123	7.81	0.035	12.31	0.009	>24	≈0
Polyurethane board	0.00	0.632	0.01	0.271	0.03	0.139	0.12	0.077	0.42	0.040	1.63	0.020	3.36	0.120	17.31	≈0

Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Why are these important?

- Time lag
  - Doesn't impact energy use directly
    - But impacts time of energy use
  - Can shift peak loads
  - Meaningful for peak loads on aggregate basis
    - Also for energy markets with dynamic pricing

- Decrement factor
  - Directly impacts energy use
    - Dampens rate of conduction through enclosure
  - Can allow for smaller HVAC equipment
    - Lower upfront costs
    - Important in design phase

Thermal time constant (*TTC*)

- The thermal time constant is defined as the sum of the product of the heat capacity of a layer i and the cumulative thermal resistance up to layer i

$$TTC = \sum_i \rho_i C_{pi} L_i R_{o \to i, cumulative}$$

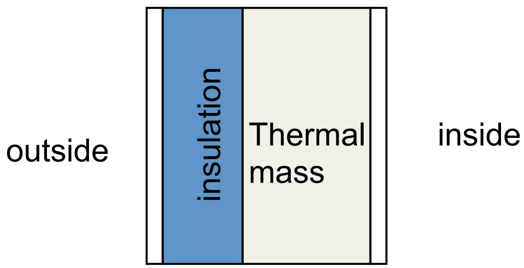
Units of time [sec]

- *TTC* is a measure of time it takes heat to propagate through the wall and is a kind of "effective" thermal insulating capability
  - The higher the TTC, the lower the overall heat transfer through the structure

Example TTC calculation

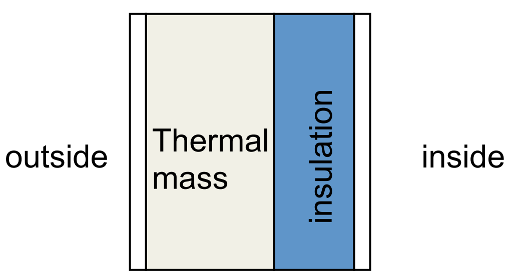
$$\sum_i \rho_i C_{pi} L_i R_{o \to i,cumulative}$$

Wall 1: exterior insulation



TTC = 43.8

Wall 2: interior insulation



TTC = 7.8

TABLE 3-8. CALCULATION OF THE THERMAL TIME CONSTANT OF 2 WALLS (METRIC)

Wall #1

LAYER	THICK l_i(m)	DENSITY ρ_i(Kg/m³)	RESIST. r_i	CUMULAT. RESIST.	HC ρ*c	QR_i Hr
Ext. surface						0.03
Ext. plaster	0.02	1800	0.025	0.0425	414	0.35
Polystyrene	0.025	30	0.71	0.41	12	0.12
Concrete	0.10	2200	0.06	0.795	506	40.2
Int. plaster	0.01	1600	0.014	0.832	368	3.1
Wall's TTC						43.8

Wall #2

LAYER	THICK l_i(m)	DENSITY ρ_i(Kg/m³)	RESIST. r_i	CUMULAT. RESIST.	HC ρ*c	QR_i Hr
Ext. surface						0.03
Ext. plaster	0.02	1800	0.025	0.0425	414	0.35
Concrete	0.10	2200	0.06	0.085	506	4.3
Polystyrene	0.025	30	0.71	0.47	12	0.14
Int. plaster	0.01	1600	0.014	0.832	368	3.1
Wall's TTC						7.8

TTC example

- The Thermal Time Constant (TTC) of the concrete wall with exterior insulation is nearly 5x larger than the concrete wall with interior insulation
  - This means the wall with exterior insulation will be a better thermal mass

- The assembly with the interior insulation has the large thermal mass directly exposed to the large temperature swings of the outdoors
  - By placing the insulation between the exterior air and the thermal mass, it takes longer to "charge" and "discharge" the thermal mass with heat
  - **To take advantage of thermal mass, the mass should be in contact with the indoor environment**

Next time

- Moisture flows in enclosures
- Moisture problems and prevention