

# CAE 463/524

## Building Enclosure Design

Spring 2016

---

**Week 14: April 12, 2016**

Thermal mass modeling

Finish energy simulation and enclosure design

Built  
Environment  
Research

@ IIT



*Advancing energy, environmental, and  
sustainability research within the built environment*

[www.built-envi.com](http://www.built-envi.com)

Twitter: [@built\\_envi](https://twitter.com/built_envi)

**Dr. Brent Stephens, Ph.D.**

Civil, Architectural and Environmental Engineering

Illinois Institute of Technology

[brent@iit.edu](mailto:brent@iit.edu)

# Scheduling

---

- Take home exam graded and returned today
- HW #4 was assigned last week
  - eQUEST modeling of energy impacts of enclosures on a commercial building
- Next week: Codes and standards in enclosure design
- Two weeks: Guest lecture, Bruce Kaskel, WJE
- May 3: Final report due at 11:59 PM
  - PDF format uploaded to BB

# Final project topic selection

---

## Name

Blat Tatay, Andrea  
Curioni, Dina P.  
Jarma, David A.  
Jordan, Taylor L.  
Kane, Benjamin M.  
Lim, Keonho  
Mitchell, Alexander R.  
Panczak, Bianca J.  
Rice, Lindsey E.  
Townley, Nina V.  
Ashayeri Jahan Khanemloo, Mehdi  
Babaei Sonbolabadi, Kamal  
Cueto, Patrick Kevin M.  
Del Pino Torres, Julia Del Rosario  
Faramarzi, Afshin  
Foss, Stephen M.  
Qiu, Luanzhizi  
Sharghi, Ali  
Sudhakaran, Naveen  
Zhang, Xu  
Castro, Jose L.  
Dipietro, Salvatore D.  
Lee, JiWan

## Final project topic

Double skin facades  
Green roofs  
Double skin façade  
BIPV  
Double skin impact on energy  
  
Natural building materials  
Smart glass  
Water penetration strategies  
BIPV  
PCM  
VIP  
  
Green roofs  
Aerogels  
Smart glazing  
Green roofs  
Open joint ventilated facade  
VIP  
Green walls or cool roofs?  
Cool roofs  
ETFE or historic masonry  
EIFS

# Last time

---

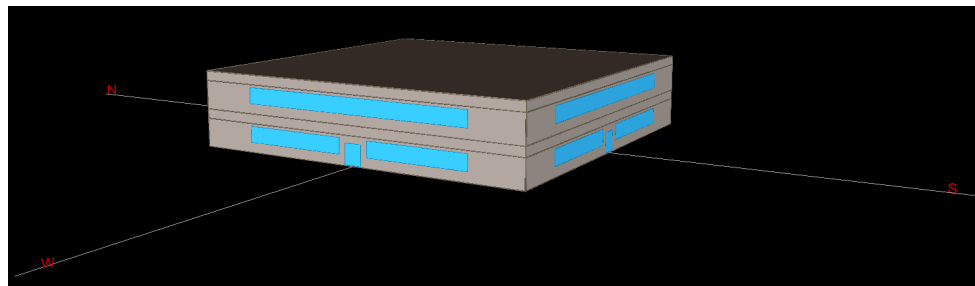
- Introduced energy simulation in building enclosure design
  - Introduced system of equations
  - Introduced eQUEST
- In HW4 you had to make changes to the enclosure and explore impacts on annual electricity, natural gas, and overall energy costs



# HW #4 eQUEST modeling

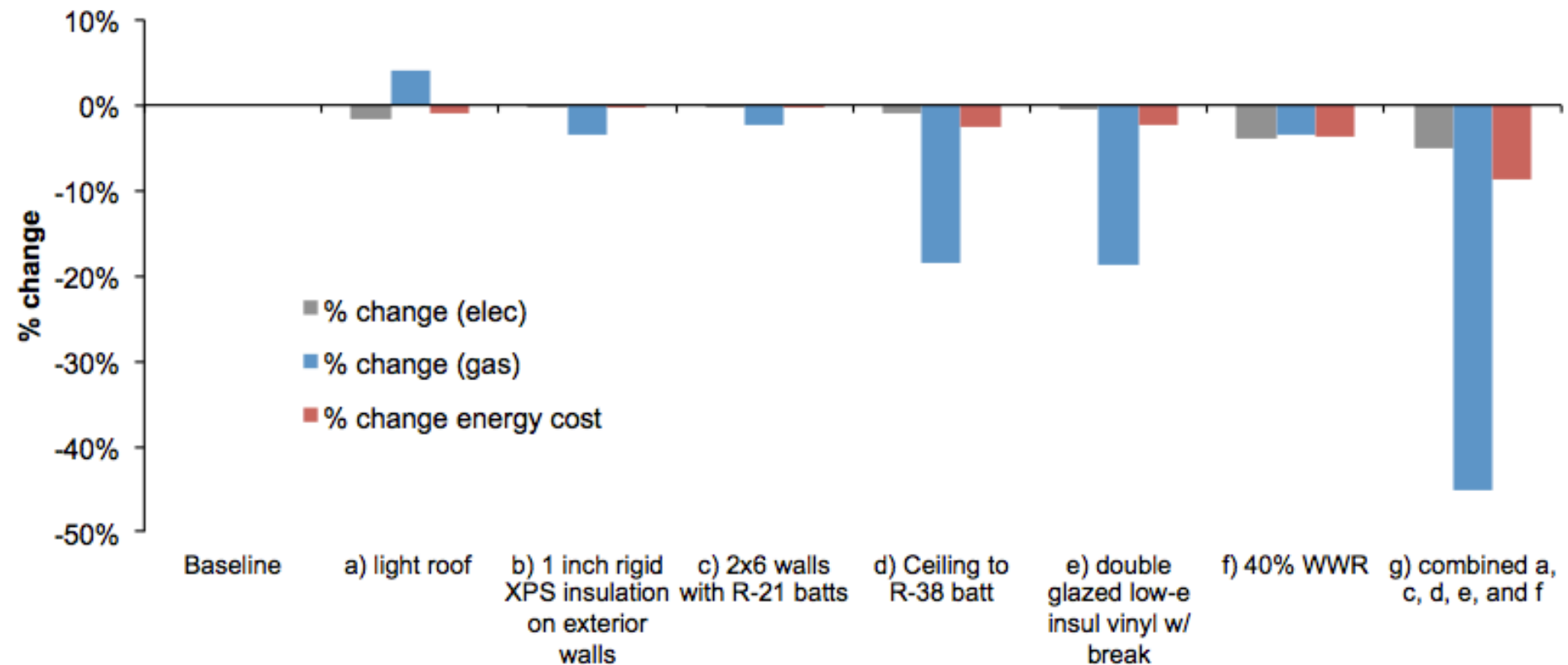
---

- eQUEST modeling of a commercial building
- 2 story office building in Madison, WI
  - 20,000 sq ft (square shape)
  - Baseline: dark uninsulated roof, metal frame with R-11 batts, concrete floors, 53% WWR with double pane clear windows  $\frac{1}{4}$  thick  $\frac{1}{4}$  air gap with no thermal breaks
  - Individual changes: light roof, 1 in R-7 rigid polyiso insulation on exterior walls, R-21 walls with R-4 rigid insulation, R-38 roof insulation with radiant barrier, improved windows to double low-e argon filled  $\frac{1}{2}$ " gap with insulated spacers, and decreased WWR to 40%



# HW #4 eQUEST modeling solutions

- Baseline results ~190,000 kWh electric and 445 MMBTU gas
  - About \$27,300 in total energy costs annually



# This time

---

- Notes of roofing materials (missing input from last lecture)
  - “Built up roofing?”
- Thermal mass and thermal mass modeling
- Finish energy simulation in building enclosure design
  - BEopt for residential energy simulation
    - And as a utility for enclosure design
    - Assign HW 5

# **ROOFING APPLICATIONS**

# Roofing

---

- The roof often receives the most severe physical and chemical degradation of any building component
  - Extreme temperature swings
  - Extreme UV exposure
  - High wind and rain exposure
- Good roofing is hard to design
  - Roofing the subject of nearly 65% of the lawsuits against architects and builders<sup>1</sup>
  - Low-slope roofing has the shortest lifespan of any component – typically 12-15 years<sup>1</sup>



<sup>1</sup>Mehta, *Building Construction*, Pearson, 2008

# Two main types of roofs

---

- Sloped (steep) roofs
  - Used primarily on smaller buildings
- Low-slope roofs
  - Used primarily on larger buildings



# Principal elements of a roof assembly

---

- Substrate – provides support for roofing
  - Framing
  - Decking
  - Insulation and/or concrete fill
- Roofing
  - Barrier formed to protect substrate from elements
  - Continuous membrane or overlapping units for water protection

# Low-slope roofs

---

- Advantages

- Can cover large horizontal surfaces
- Simpler geometry, often less expensive
- Roof can have other functions
  - Patio, decks, parking, etc.



- Disadvantages

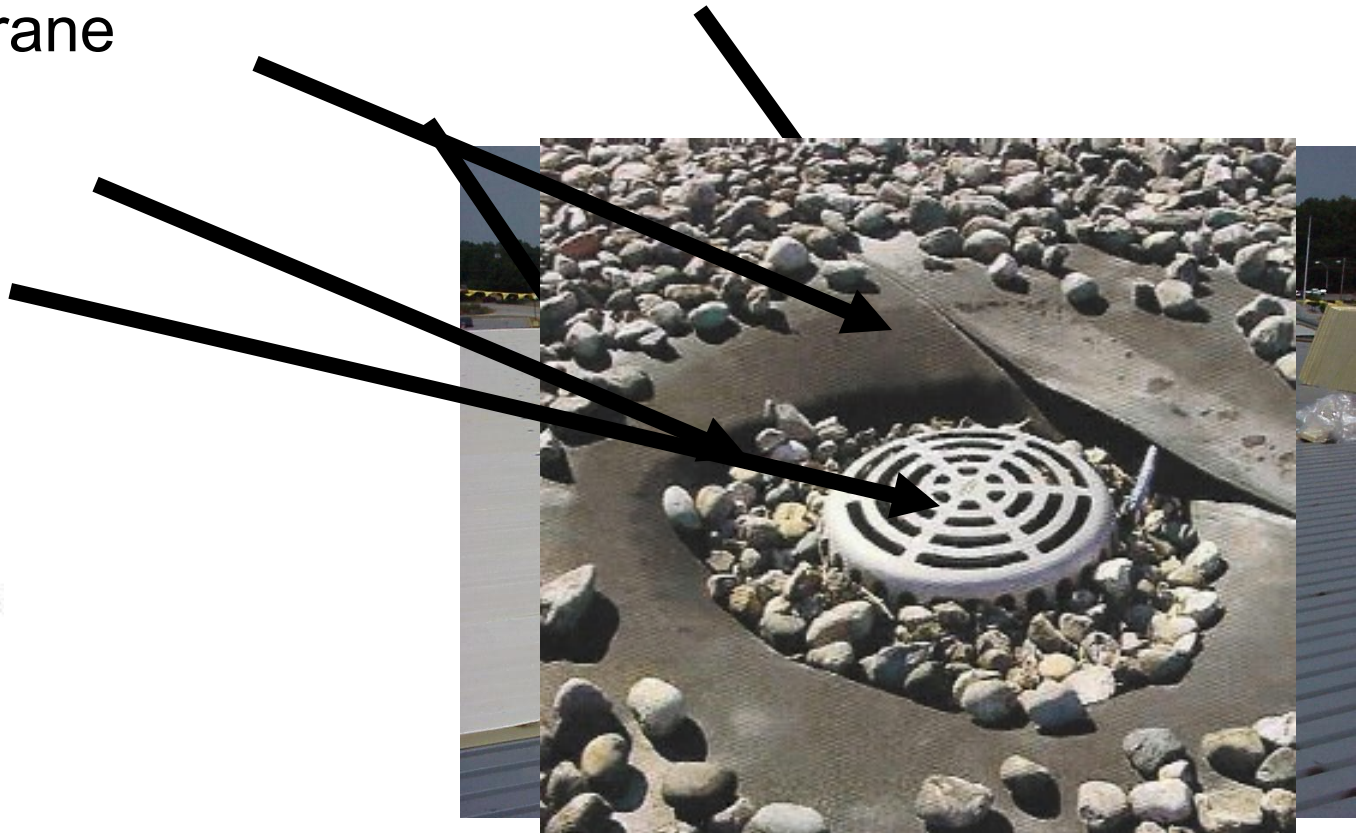
- Water drains slowly
- Slight structural movements can tear the membrane
- Water vapor pressure can blister and rupture the membrane
- Increased structural load from wind and accumulation



# Low-slope roof components

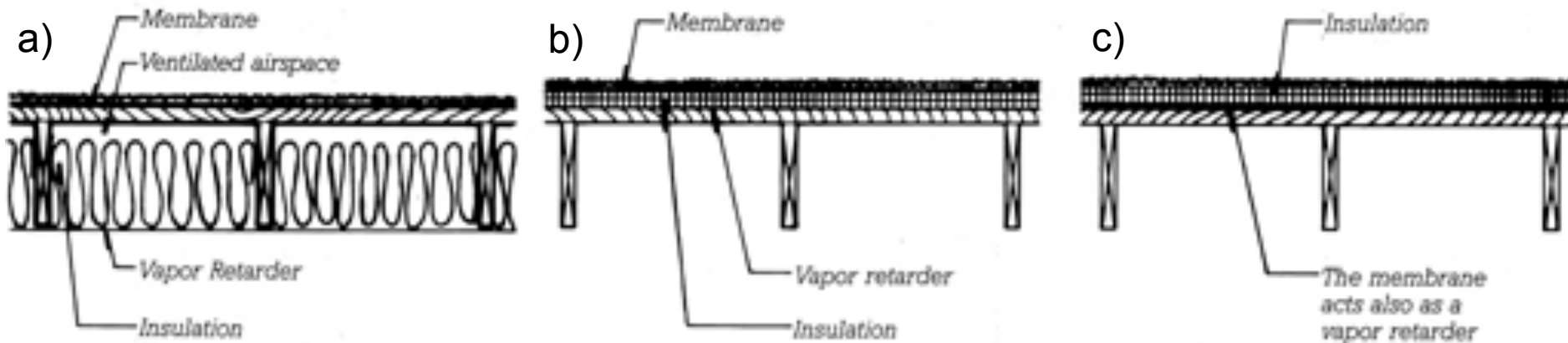
---

- Structural support: Deck on frame
- Thermal insulation
- Roof membrane
- Roof ballast
- Drainage
- Flashing



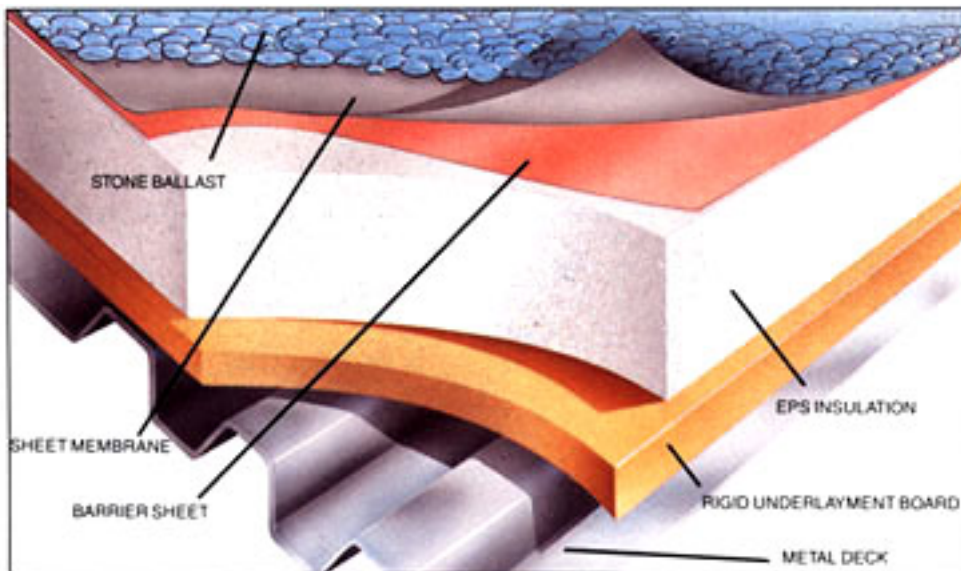
# Roof thermal insulation

- Insulation is typically required to meet code
- Location and placement:
  - a) Below the deck: thermal bridging is a problem
  - b) Between the deck and membrane: membrane is exposed
  - c) Above the membrane: helps protect membrane
- Rigid insulation attachment
  - Adhered or mechanically attached



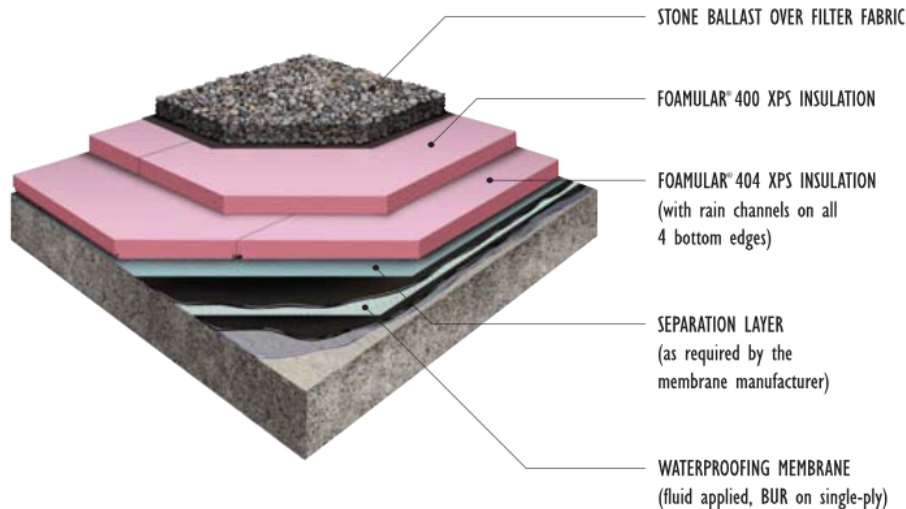
# Roof thermal insulation

- Over-deck insulation is usually EPS, XPS, polyiso, or rigid fiberglass
  - These are the only insulation materials that can handle the wind/snow/roofing loads and still provide high insulating capabilities
  - High R values of EPS and polyiso gives good insulating capabilities with only a few inches of insulation

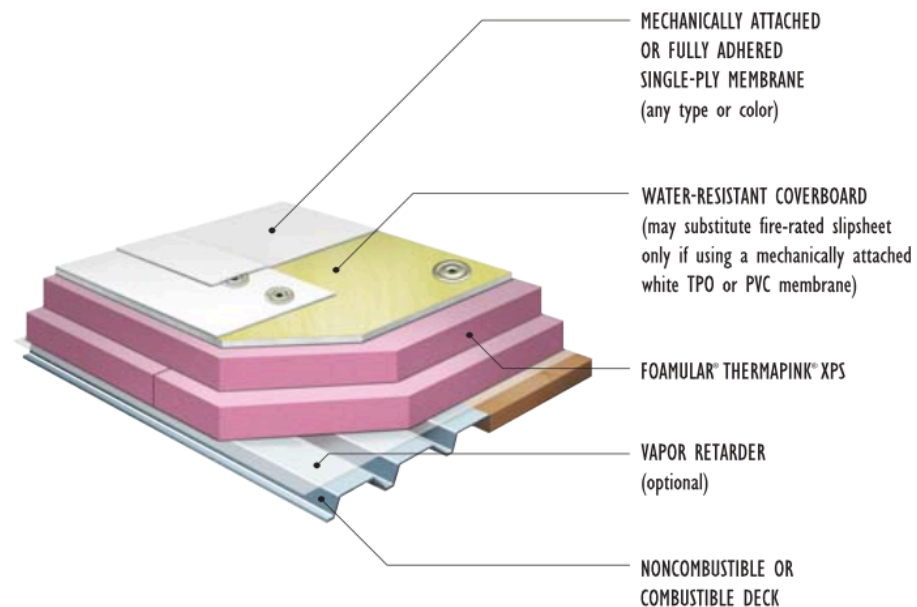


# Roof thermal insulation: Over or under membrane?

- It depends... pay attention to manufacturer recommendations



**“Protected membrane roof”  
or  
“Inverted membrane roof”**

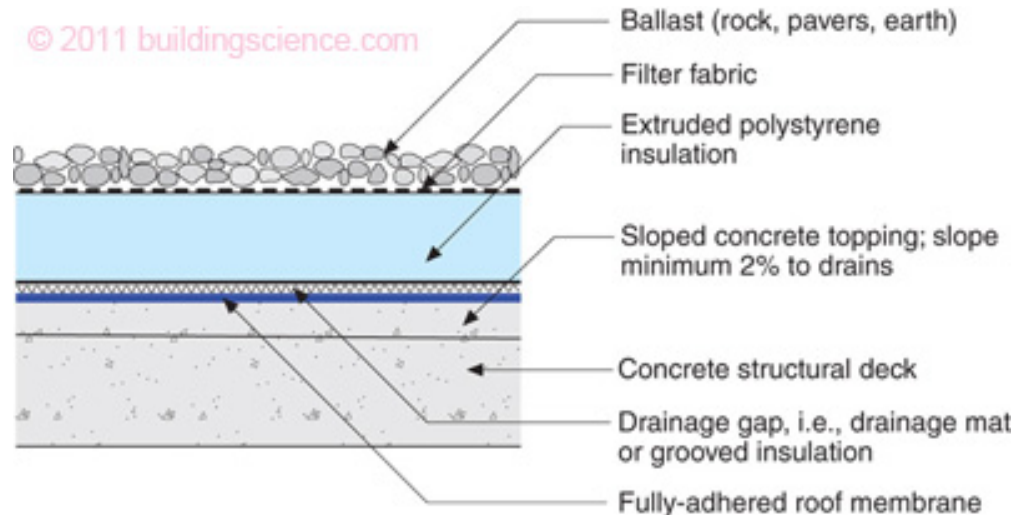
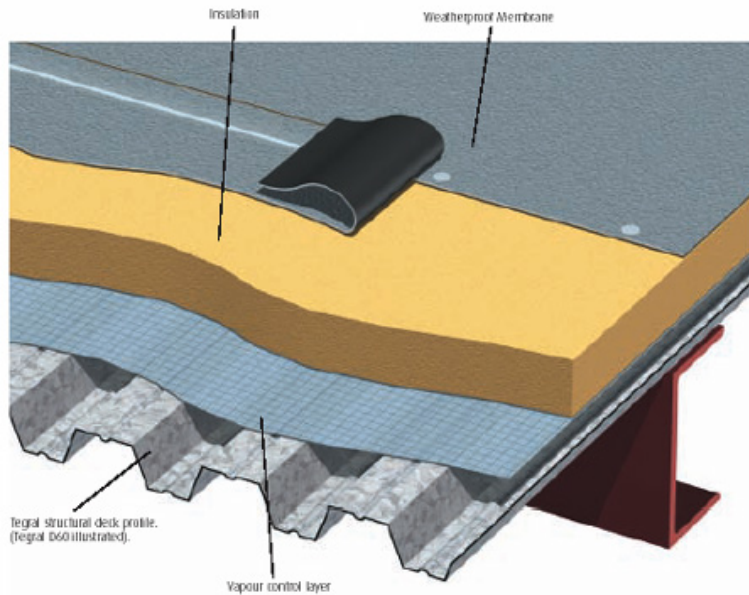


**Typical membrane installation**



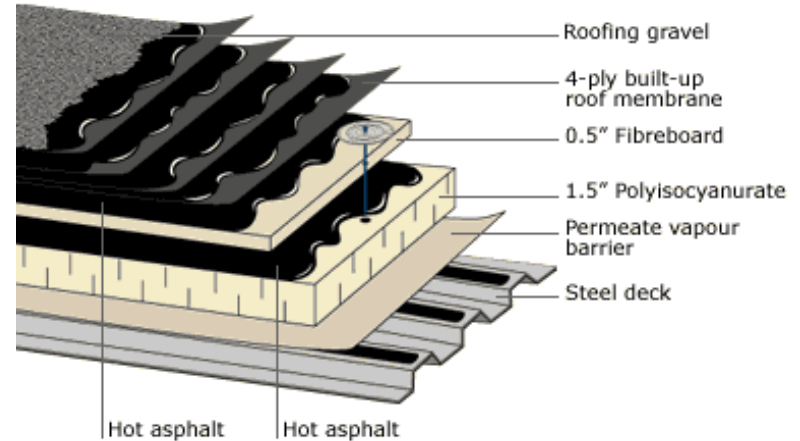
# Roof membranes

- Membrane roofing systems are used to prevent leaks and move water off of roofs
- Three main categories:
  - Built-up roof membrane
  - Single-ply roof membrane
  - Fluid-applied roof membrane

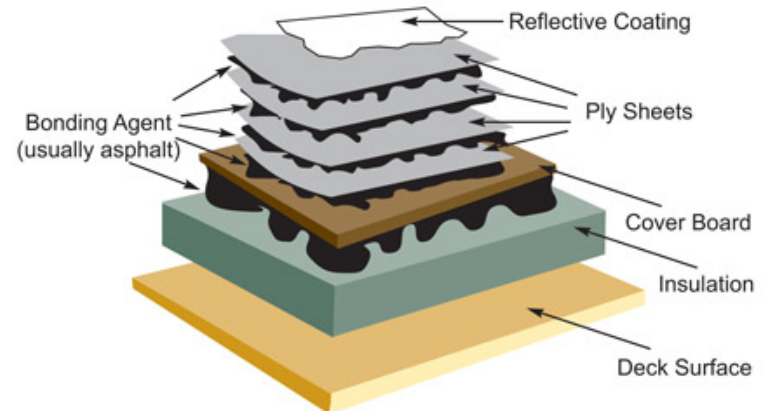


# Built-up roof membranes

- Standard built-up roof membrane
  - 3-5 layers of felts + bitumen (asphalt)
  - Bitumen provides waterproofing
    - Semi-solid crude oil product
  - Felt provides the structural support needed
    - Because bitumen will soften (and can even melt) at high temperatures



- Modified bitumen sheets
  - Bitumen has polymers added to improve the UV protection and make it more cold resistant
  - Felt or fiberglass sheets are embedded with modified bitumen
    - 2 to 3 layers of the sheets are installed with more modified bitumen between



# Built-up roof membranes

---

- Multiple plies of asphalt-impregnated felt bedded in bitumen (hot asphalt or coal tar)
- Forms a “laminated” membrane typically 2-4 plies thick
- Stinks during install!



# Advantages and disadvantages of BUR

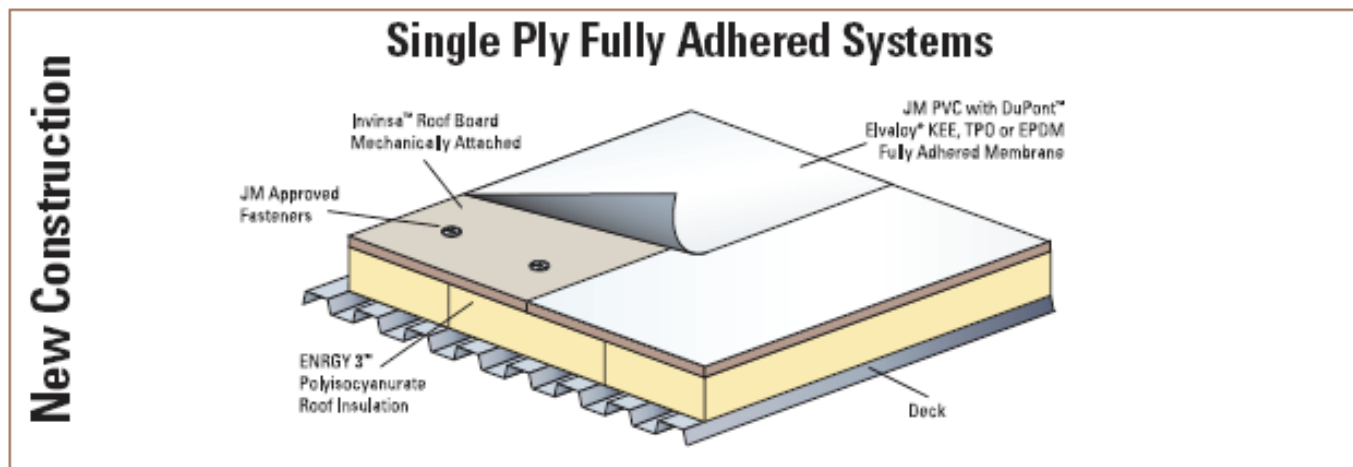
---

- Advantages
  - Can be easily repaired/patched in case of leaks
  - Can last longer than a single ply membrane roof
  - High tensile strength limits movement and reduces chances for fracturing
  - If structure does move, BUR can move with it
- Disadvantages
  - Not seamless, more locations for possible leaks
  - Higher cost (more materials, time and labor)
  - Less sustainable (uses much more raw materials and energy to install)
  - Fumes during installation



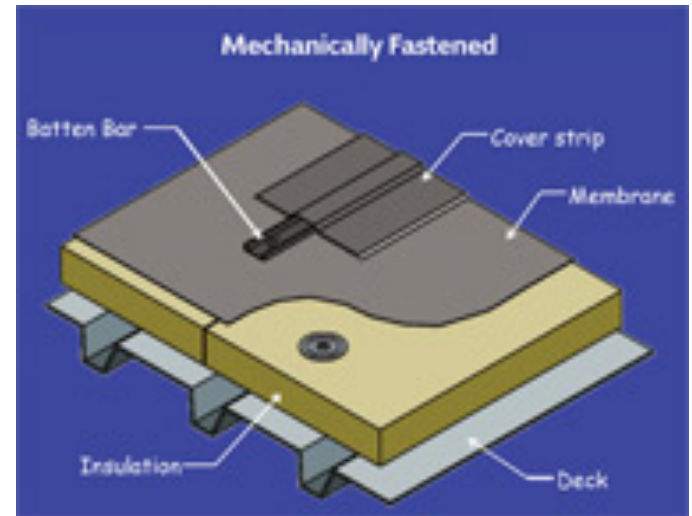
# Single-ply roof membrane

- Sheet materials that are applied to the roof in a single layer
- Attached to the roof:
  - Adhesives
  - Ballast weight
  - Concealed fasteners



# Single-ply materials

- Thermosetting
  - Compounded rubber polymer
  - Cannot be softened
  - Must be joined by adhesives or pressure sensitive tapes
  - EPDM
    - Ethylene propylene diene monomer
      - Most widely used
    - Also Neoprene, CPE, etc.
- Thermoplastics
  - May be softened and joined by heat or solvent welding
  - Polyvinyl Chloride (PVC) – widely used, polymer-modified bitumens, PVC alloys, etc.



# EPDM

---

- EPDM (ethylene propylene diene monomer) is a thermosetting polymer (a synthetic rubber) that does not soften once it has cured
  - This material can stretch, but cannot be heat welded
  - It must be adhered or taped
- EPDM can stretch 300-500% of its original length before tearing
- Typical thicknesses are 45 to 60 mm
- EPDM has poor inherent fire resistance
- EPDM is black and must be covered for high solar reflectivity (low absorptivity)

# 12 ft. wide EPDM membrane

---





# PVC and TPO

---

- PVC (polyvinyl chloride) is a soft and pliable form of the common plastic
  - PVC is very flexible, but is far less stretchable than EPDM
  - PVC membranes can be heat fused
- TPO (thermoplastic polyolefin) is also a thermoplastic
  - TPO is more flexible and stretchable than PVC but less than EPDM
  - TPO does not lose its flexibility over time like PVC
- These are easily used for cool roofing materials

# Hand-held welding tool for PVC

---

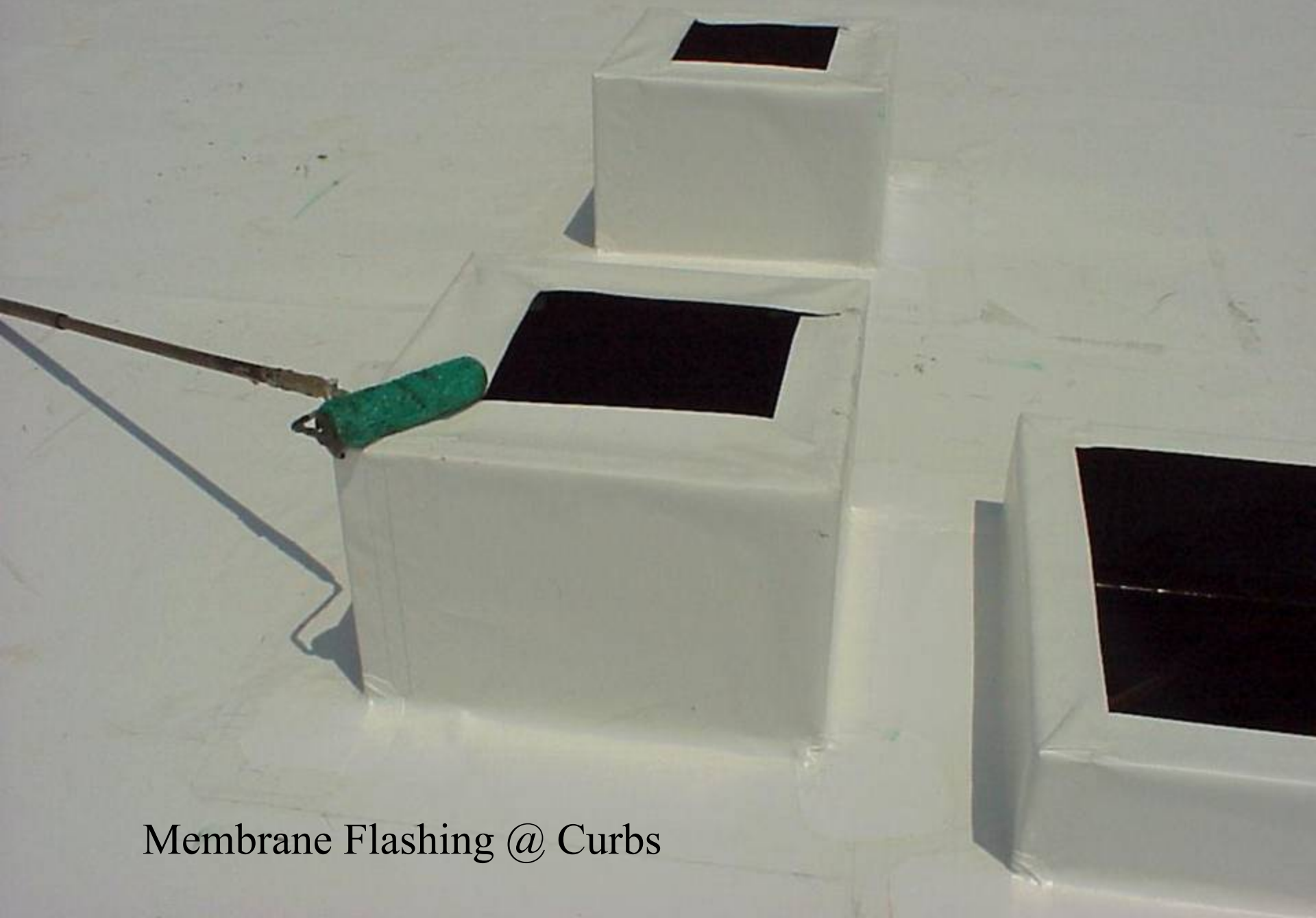


# Applying PVC or TPO

---

- Self-propelled hot air welding machine for PVC or TPO





Membrane Flashing @ Curbs



# Fluid-applied membranes

---

- Fluids applied with a roller or spray gun and cure to form a rubbery membrane

Main Use: Complex shapes that are difficult to roof by conventional means such as domes and shells

Fluid applied membranes can also be installed fairly quickly so when speed is more important than cost, consider these



# Advantages and disadvantages of membranes

---

- Advantages
  - Lower cost
  - No seams (if properly installed)
  - Lighter weight
  - Can expand/contract much better than BUR
- Disadvantages
  - Any small puncture can cause leaks
  - Harder to repair small leaks
  - Must be completely (or near completely) replaced when repairs/modifications are made
  - Shorter lifetime than BUR

# Ballast and traffic decks

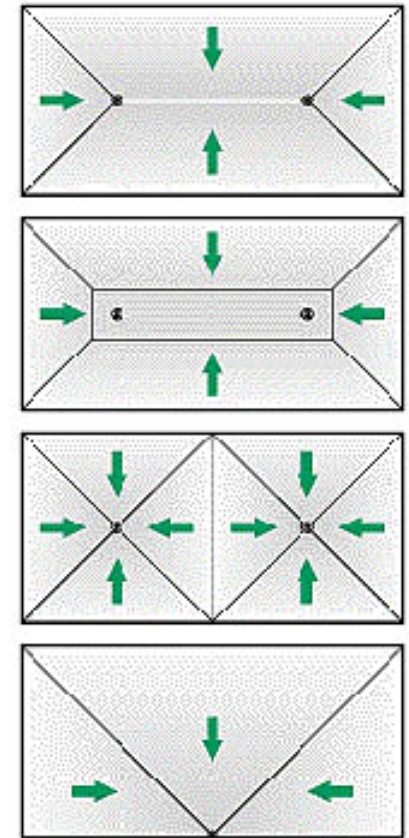
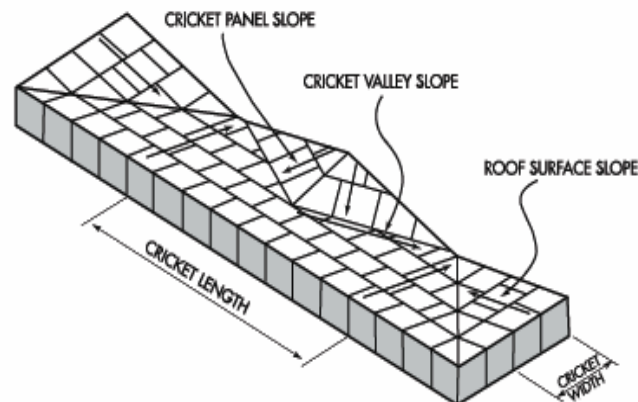
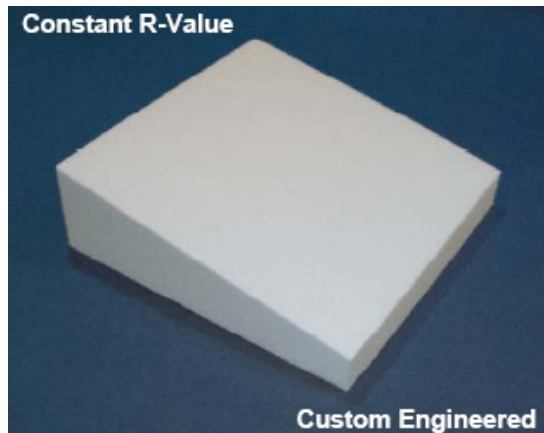
---

- Ballast material
  - Stone aggregate
  - Precast concrete blocks or Pavers
- Purpose:
  - Hold down membrane
  - Protect membrane from ultraviolet light
  - Protect membrane from physical wear
- Traffic decks – installed over membranes for walks, terraces, drives, etc.



# Tapered insulation

- To promote proper drainage roof should have a  $\frac{1}{4}$ " slope for every 12"
- This can be achieved through the use of tapered roof insulation



Typical Drainage Pattern

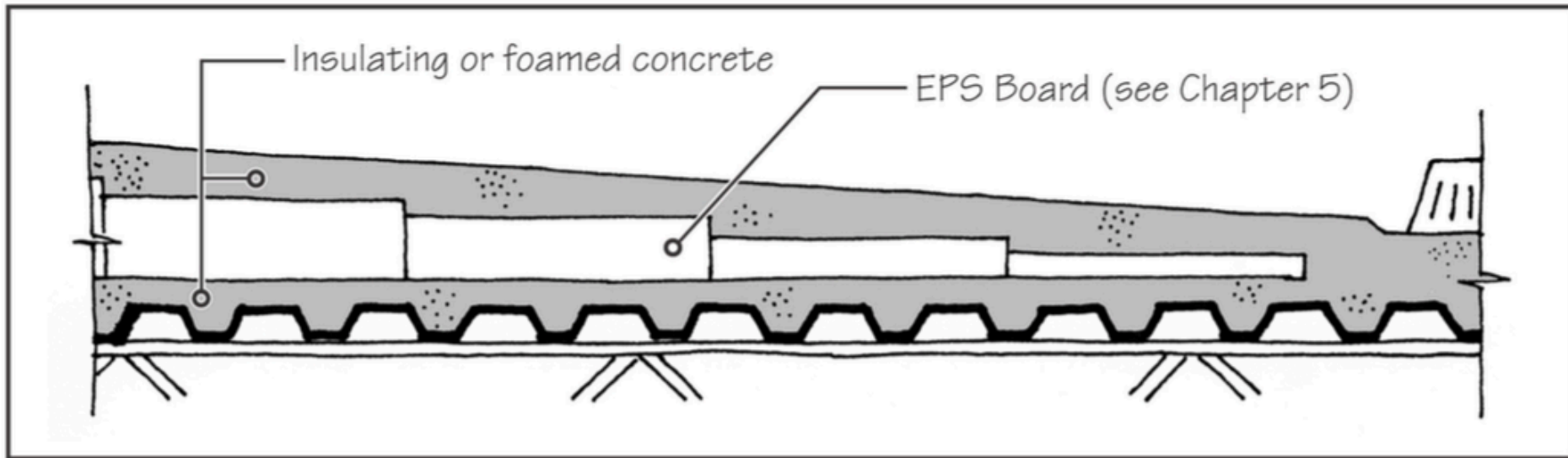
# Insulating and foamed concrete

---

- **Insulating concrete** is a very lightweight concrete made with perlite or vermiculite as a high insulating granular additive
  - $0.8 < R \text{ per inch} < 1.2$  (normal concrete is about  $R=0.2$  per inch)
- **Foamed concrete** (also called cellular or aerated concrete) has a foaming concentrate that creates tiny air bubbles within the concrete
  - Increases thermal resistance
  - $0.5 < R \text{ per inch} < 2$
- Both of these are popular for use on roofs where the strength requirements are lower than for floors or walls

# Embedded insulation

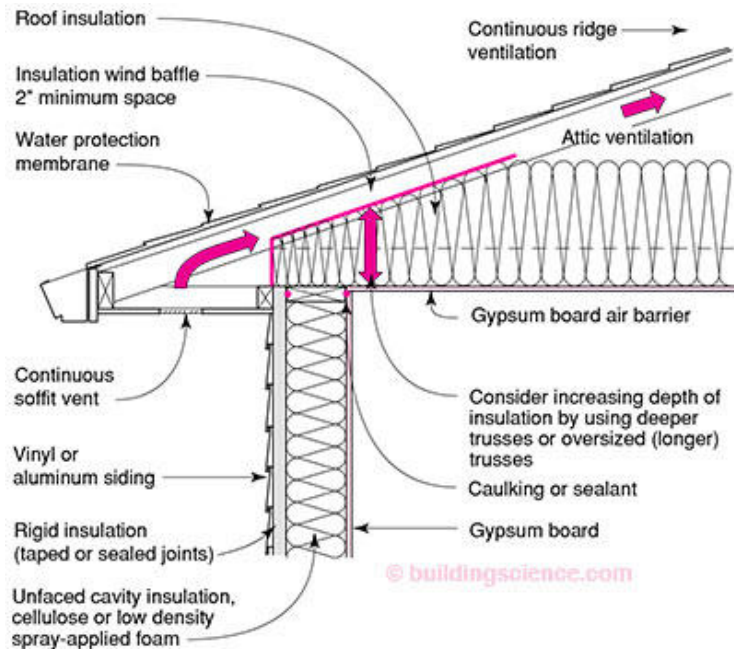
- EPS or polyiso insulation can be embedded within the concrete itself
- This is commonly done with foamed or insulating concrete



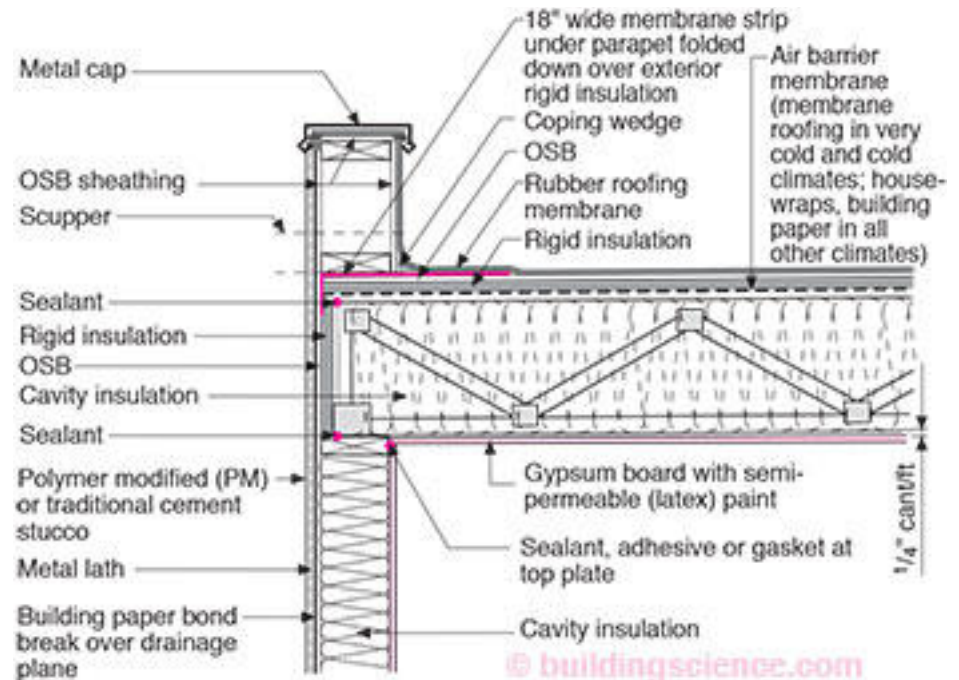


# For more information on roofing design

- <http://buildingscience.com/documents/reports/rr-0404-roof-design/view>



**Vented roof assembly**



**Unvented flat roof w/ thermal control**

- [https://www.wbdg.org/design/env\\_roofing.php](https://www.wbdg.org/design/env_roofing.php)

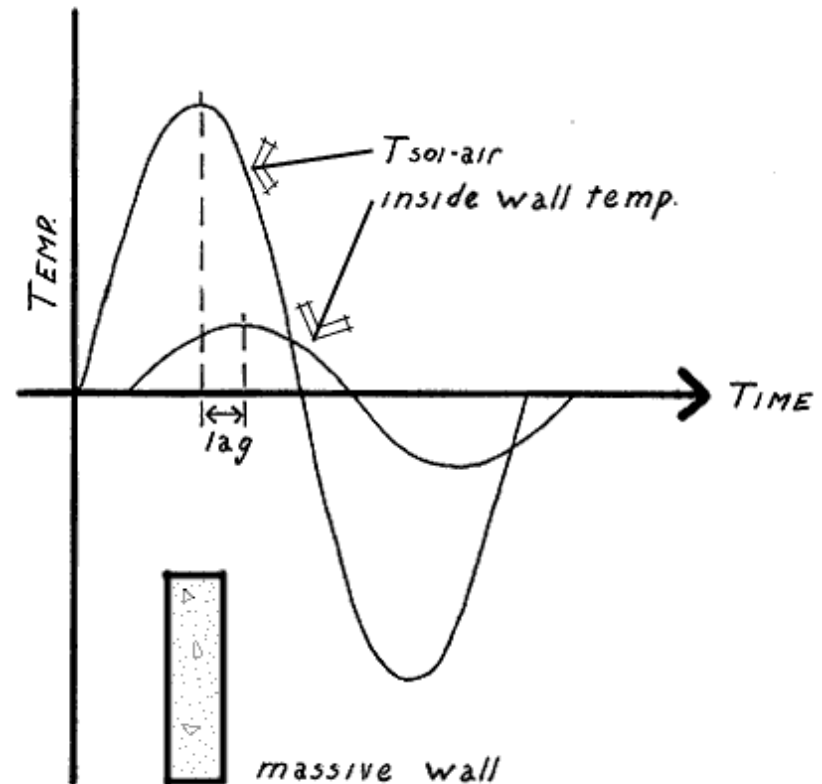
# **THERMAL MASS**

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 absorb daytime heat gains
- Reduces peak cooling load
- Releases heat during the night (can reduce heat load or can extend cooling 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



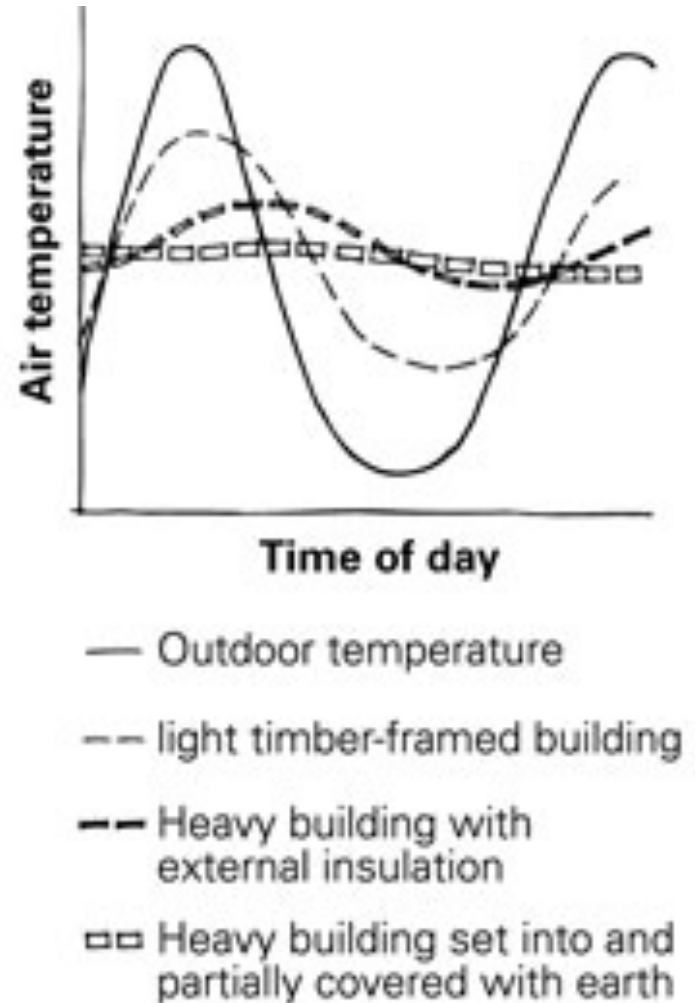
# Types of thermal mass

---

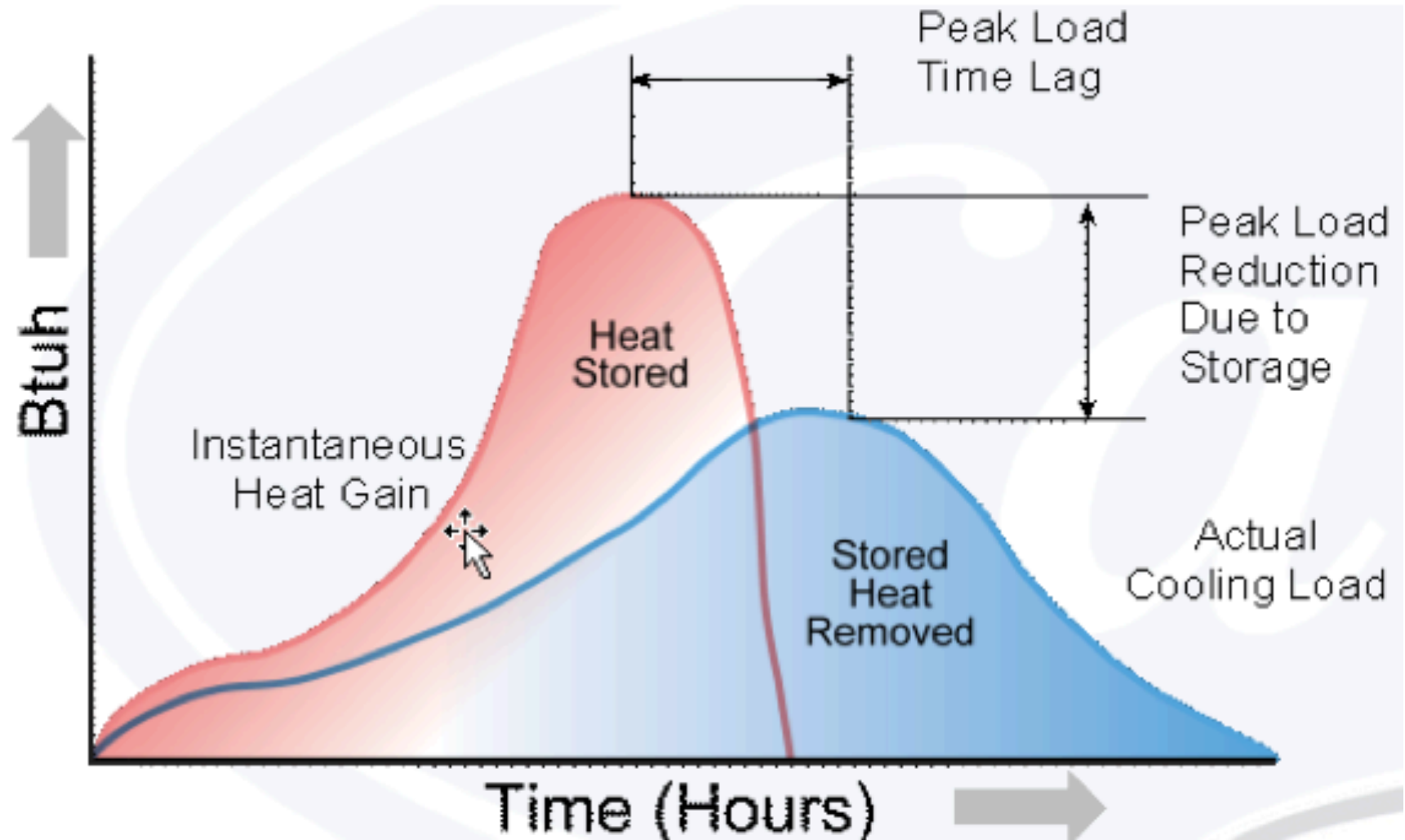
- Traditionally, materials with high **thermal mass** have also had a high mass themselves:
  - Water, earth, stone, brick, cement, concrete, thick tiles
  - All these materials have high **densities** and high **specific heat capacities**
- More recently, phase change materials are being used:
  - Solid-liquid 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

# Thermal mass: Why do we care?

- 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
- 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



# Cooling load calculations and thermal mass



# 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<sup>2</sup>K]
  - HC is a measure of the ability of a material to store energy per unit area
  - $L$  = length [m]
  - $\rho$  = density [kg/m<sup>3</sup>]
  - $C_p$  = specific heat capacity [J/kgK]
  - You sometimes also see  $HC \cdot A = \rho L A C_p$  or  $\rho V C_p$  [J/K]
- Heat capacity is important to thermal mass, but needs to be compared with **thermal conductivity** to get the whole story



# Thermal Diffusivity, $\alpha$

---

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

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

- The lower the  $\alpha$ , 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  $\rho C_p$  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
  - Thermal conductivity, density, and specific heat

Description	Density, kg/m <sup>3</sup>	Conductivity <sup>b</sup> ( <i>k</i> ), W/(m·K)	Conductance ( <i>C</i> ), W/(m <sup>2</sup> ·K)	Resistance <sup>c</sup> ( <i>R</i> )		Specific Heat, kJ/(kg·K)
				1/ <i>k</i> , (m·K)/W	For Thickness Listed (1/ <i>C</i> ), (m <sup>2</sup> ·K)/W	
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	—
<i>Concretes</i> <sup>o</sup>						
Sand and gravel or stone aggregate concretes (concretes	2400	1.4-2.9	—	0.69-0.35	—	—
with more than 50% quartz or quartzite sand have	2240	1.3-2.6	—	0.77-0.39	—	0.8-1.0
conductivities in the higher end of the range) .....	2080	1.0-1.9	—	0.99-0.53	—	—
Limestone concretes .....	2240	1.60	—	0.62	—	—
	1920	1.14	—	0.88	—	—
	1600	0.79	—	1.26	—	—

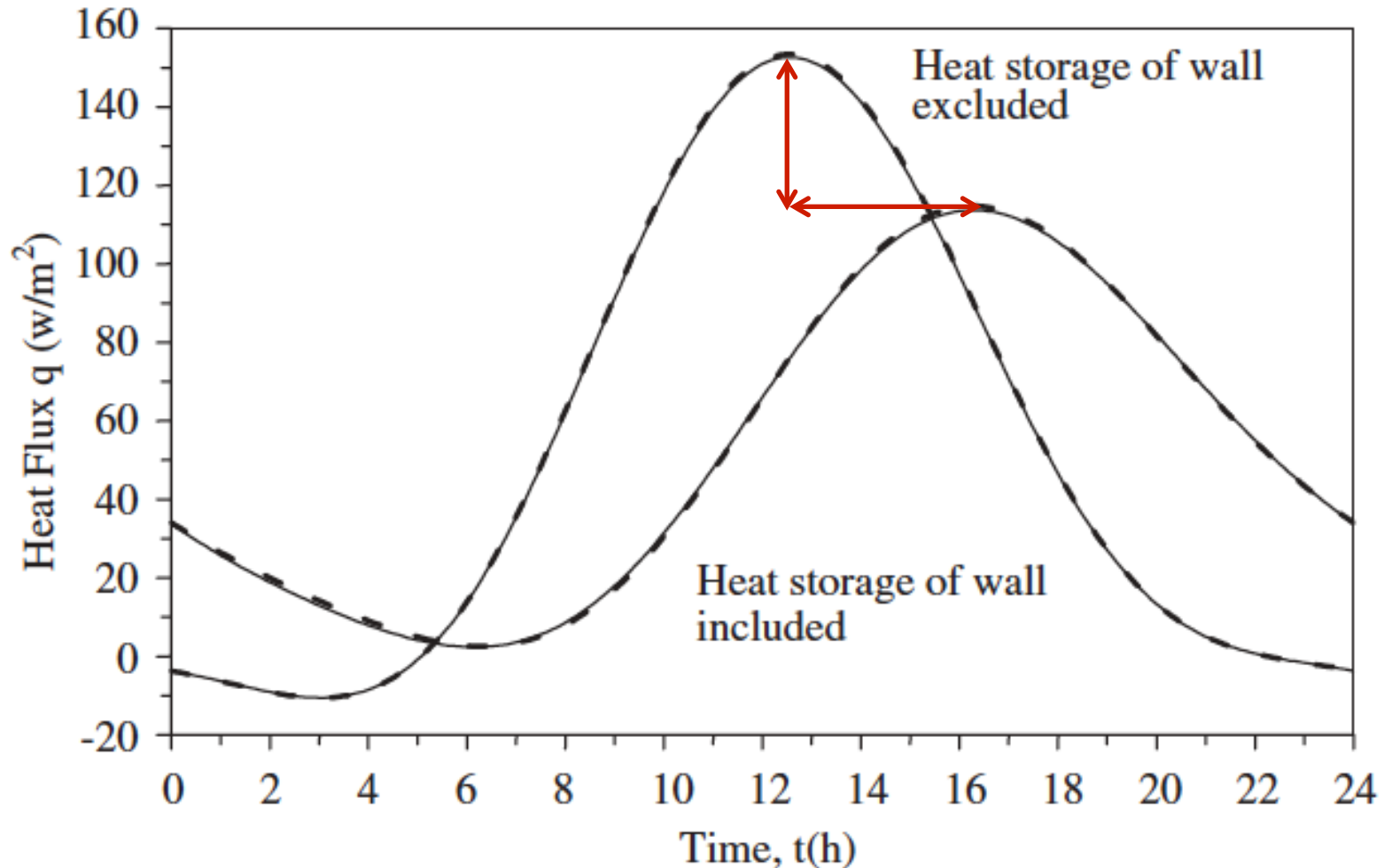
# Time lags and decrement factors

---

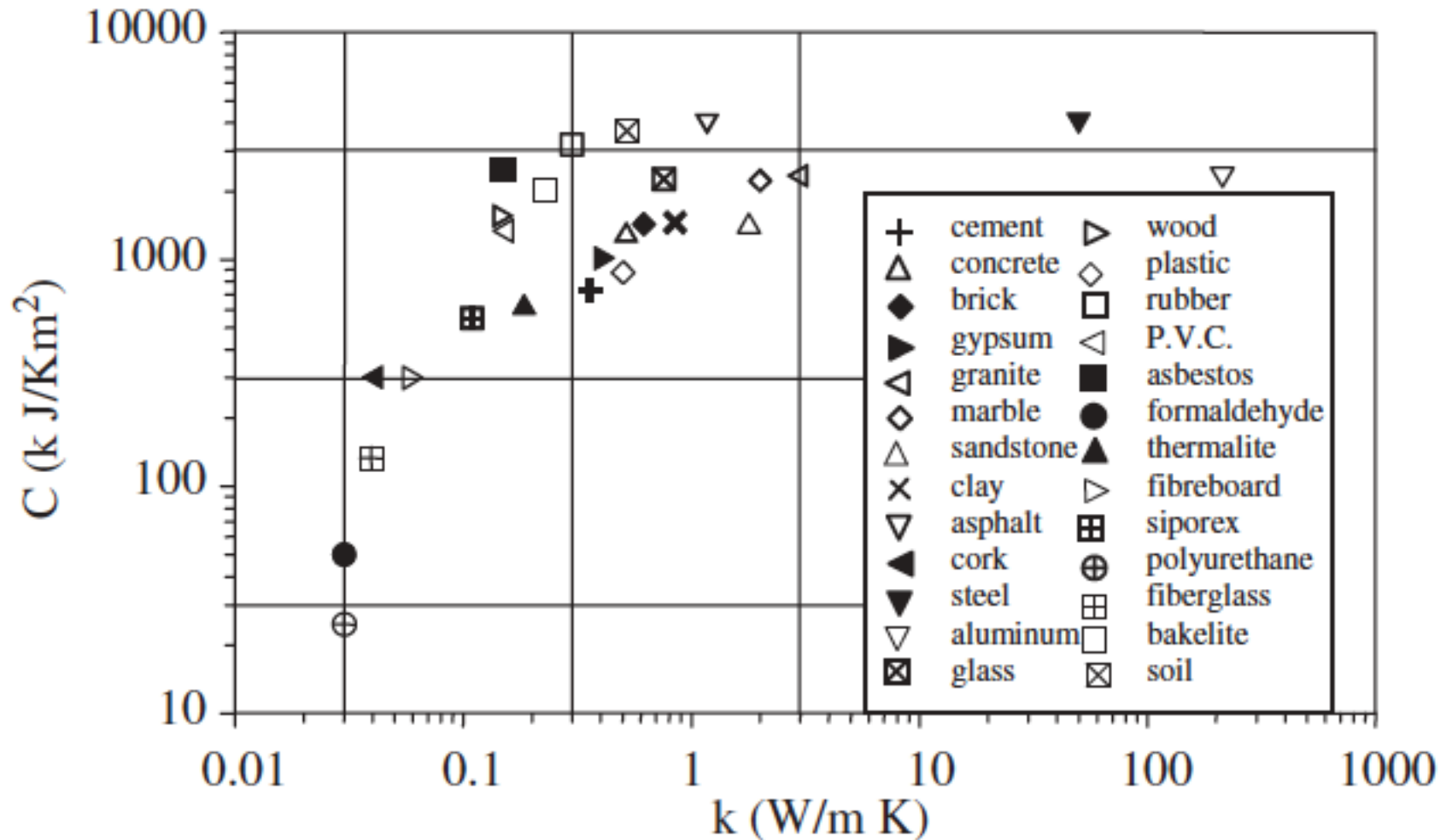
- These models (and measurements) can also be used to describe **time lags** and **decrement factors**
- Time lag describes:
  - For a given peak exterior surface temperature at a certain time for a material *without* thermal mass
  - How much later (in **time**) does the peak interior surface temperature 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

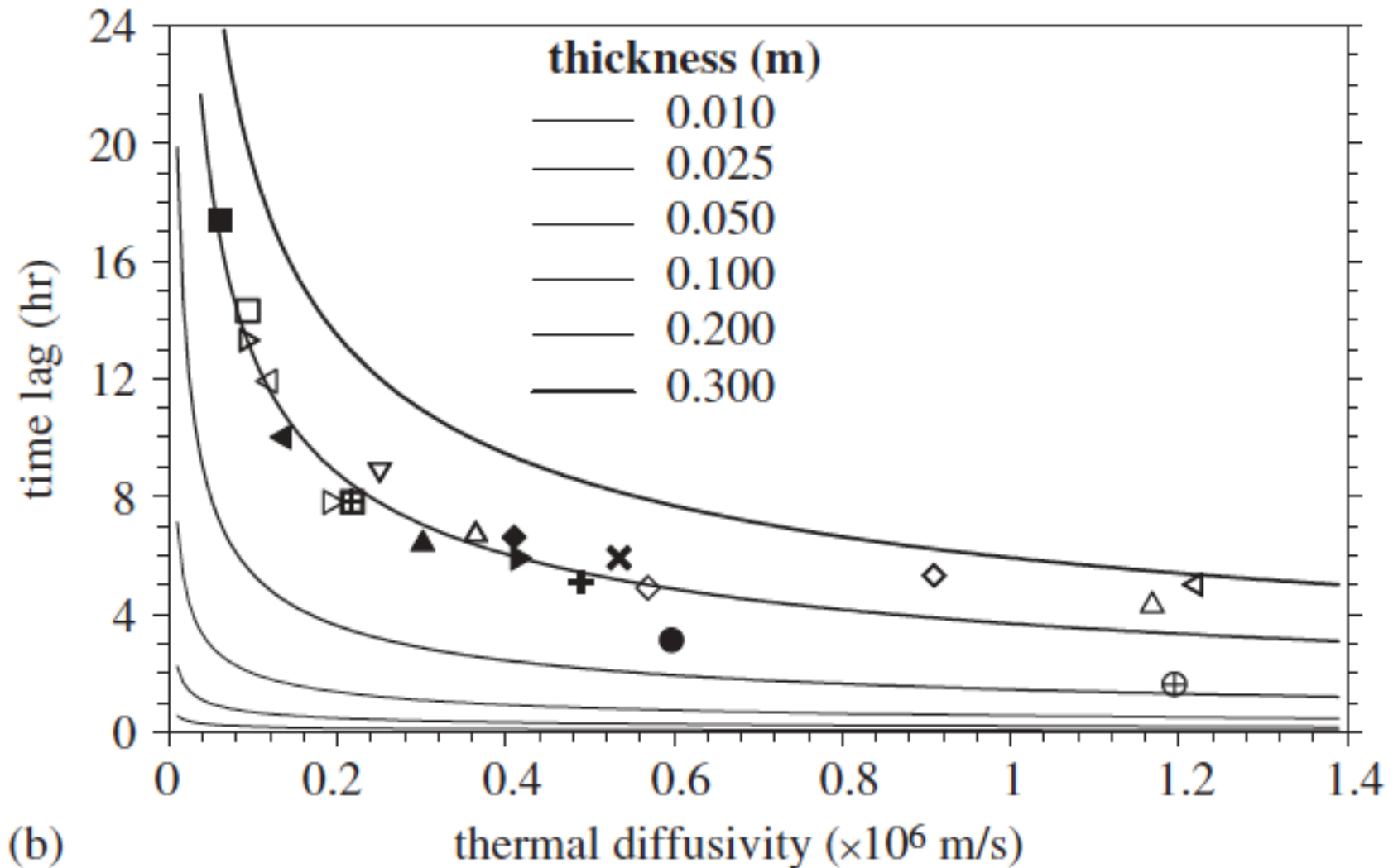
## Decrement factors ( $\phi$ ) and time lags ( $f$ )



# Material properties for thermal mass



## Modeled time lag of several materials with varying thickness



# 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  $i$

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

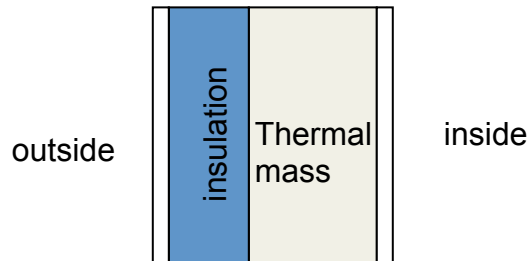
Units of time [sec]

- $TTC$  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: insulation placement

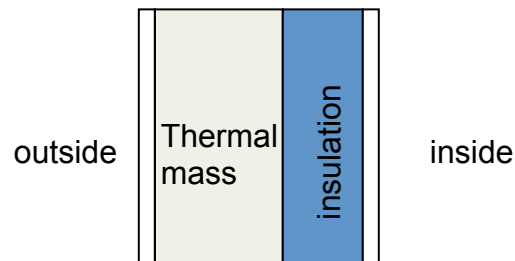
$$\sum_i \rho_i C_{pi} L_i R_{o \rightarrow i, cumulative}$$

## 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 $\rho_i$ (Kg/m <sup>3</sup> )	RESIST. $r_i$	CUMULAT. RESIST.	HC $\rho^*c$	QR <sub>i</sub> 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 $\rho_i$ (Kg/m <sup>3</sup> )	RESIST. $r_i$	CUMULAT. RESIST.	HC $\rho^*c$	QR <sub>i</sub> 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**

# **THERMAL MASS MODELING FOR ENERGY SIMULATIONS**

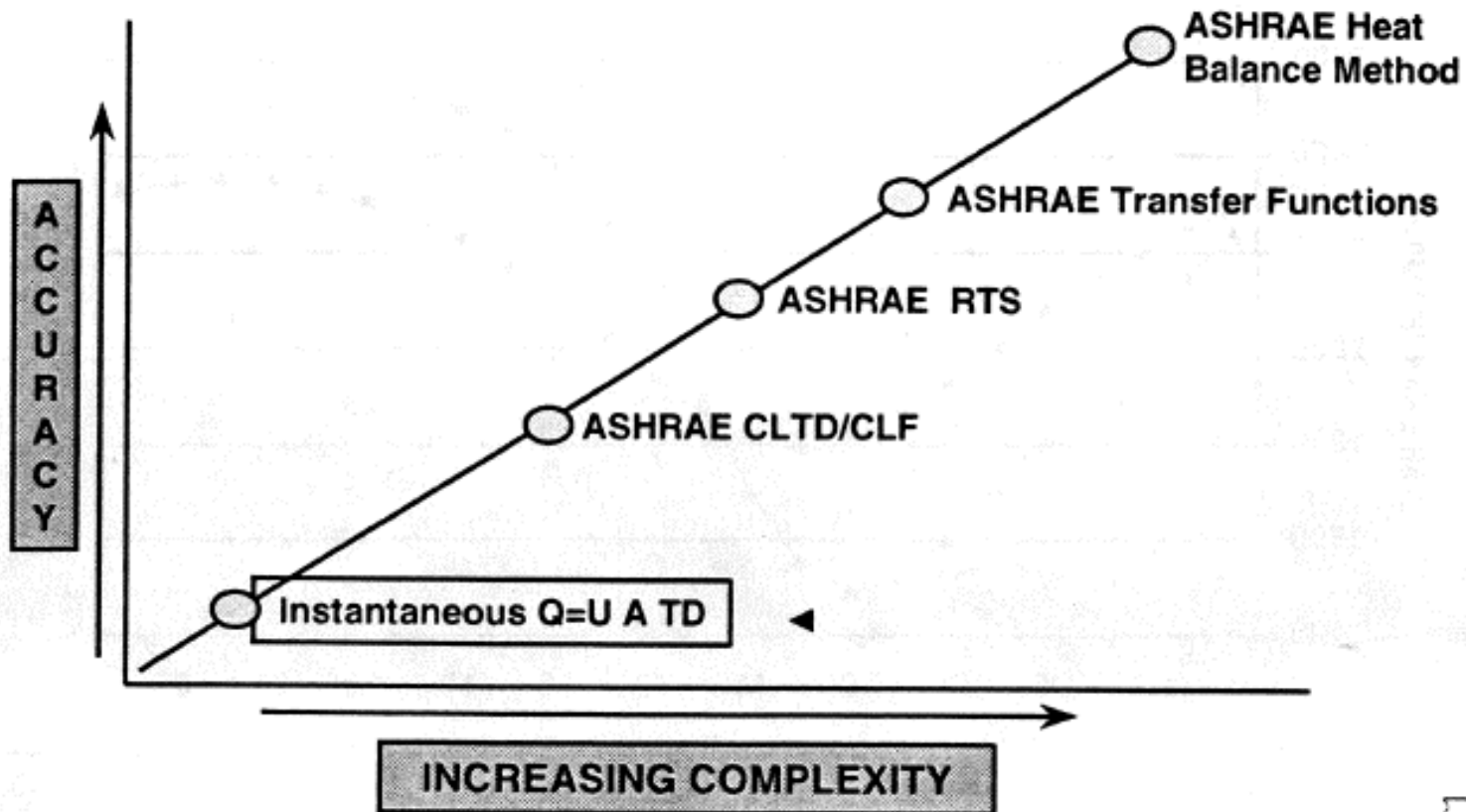
# How do we model thermal mass?

---

- Thermal mass can have a large impact on time-varying energy use and thus needs to be accounted for in energy simulation programs
- There are several ways to model thermal mass, with varying degrees of complexity and accuracy
- We briefly talked about some of these in CAE 331/513 Building Science (lectures on cooling load calculations)

# Cooling load calculation methods vary in how they treat thermal mass

## Load Estimating Methods



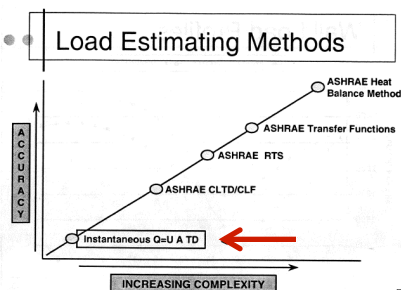


# Instantaneous UA(dT) method

- The methods used for heat load calculations:

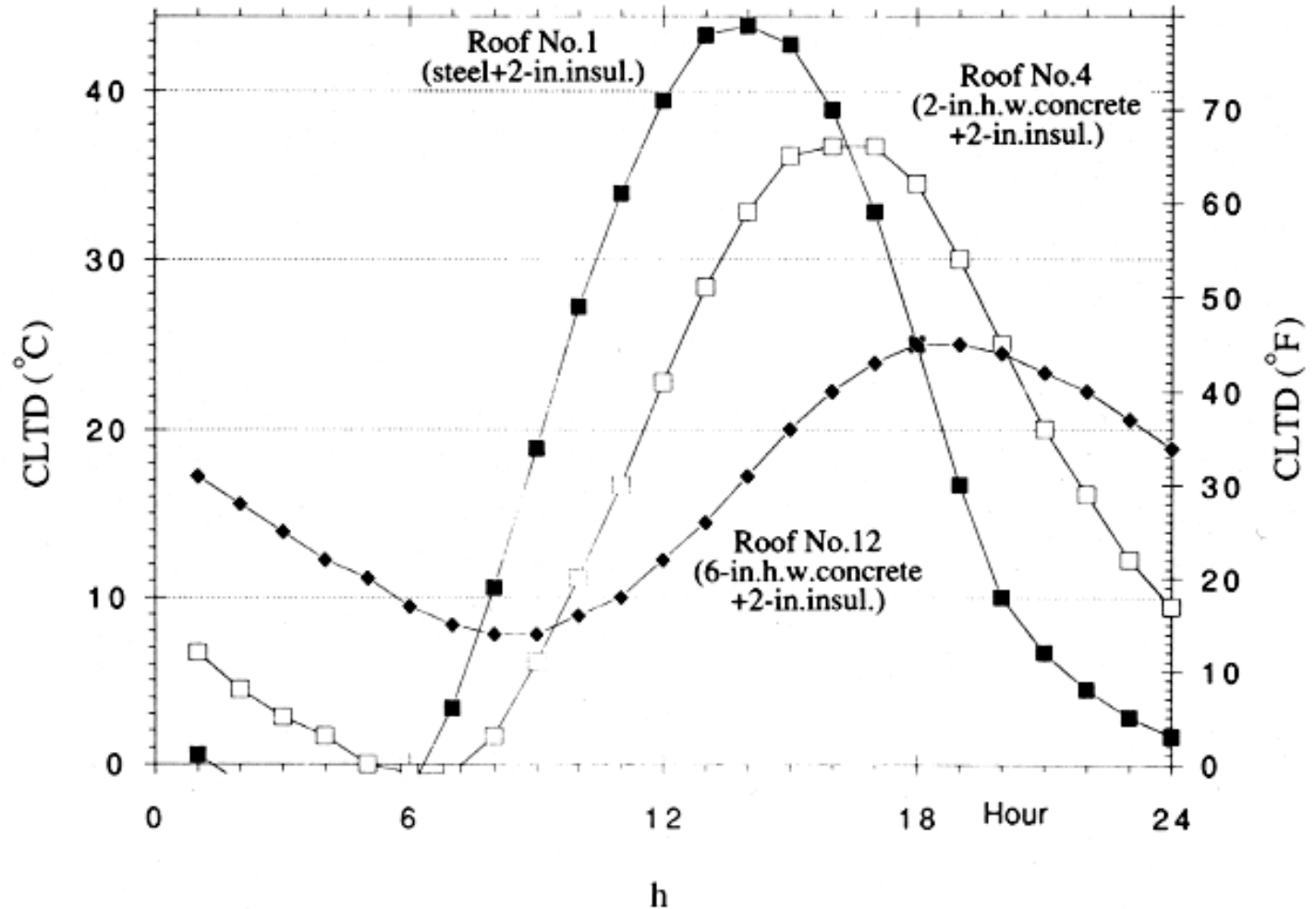
$$Q = UA\Delta T \quad \text{or} \quad Q = K_{total}\Delta T$$

- Don't include any thermal mass
  - Simplest and least accurate

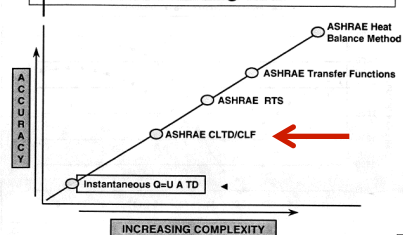


# CLTD method

$$Q_{cooling,conduction} = UA(CLTD_t)$$



## Load Estimating Methods



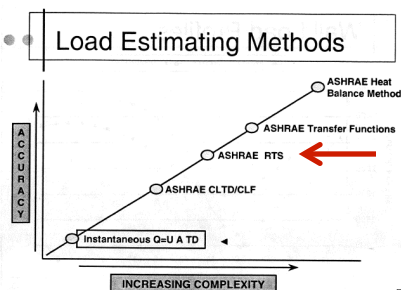
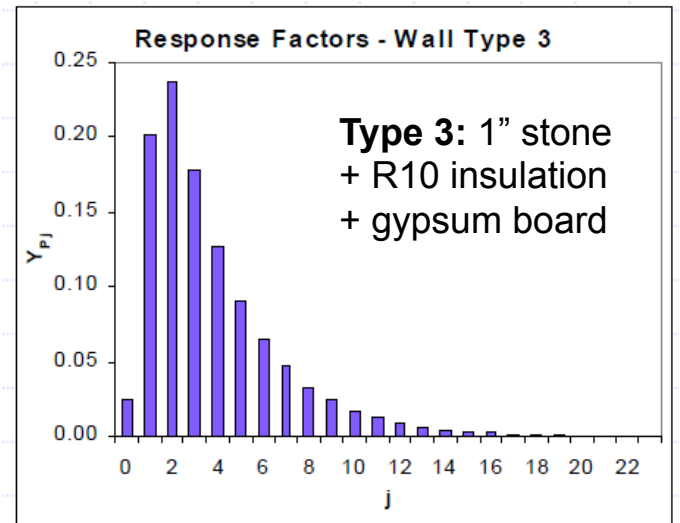
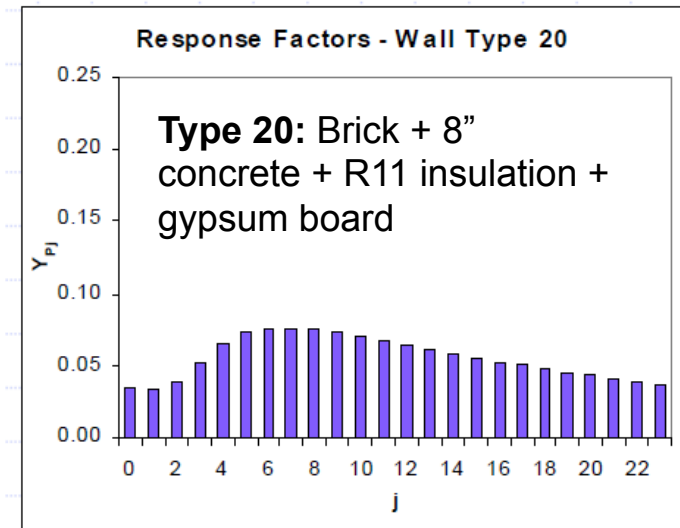
# Radiant time series (RTS) method

$$q(n) = C_0 U(T_e(n) - T_i(n)) + C_1 U(T_e(n-1) - T_i(n-1)) + \dots + C_{23} U(T_e(n-23) - T_i(n-23))$$

where  $T_e = T_{sol-air}$

$Y_{pn} = C_n U$  is the periodic response factor (PRF) in [W/m<sup>2</sup>K]

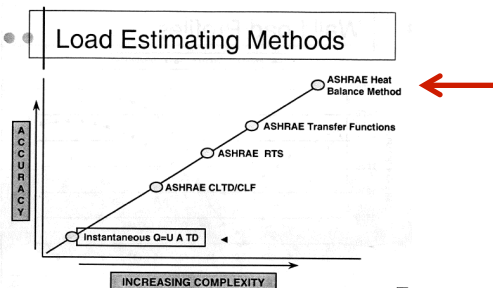
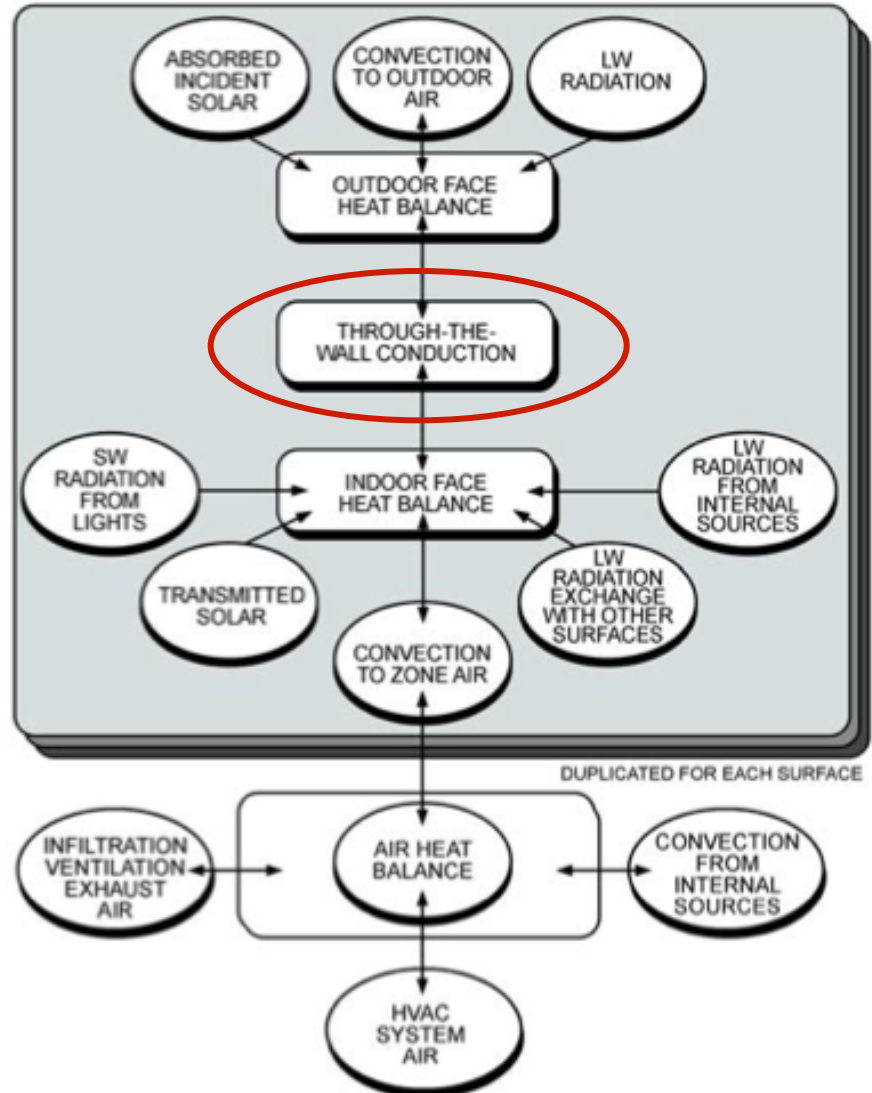
$$q_{conduction,in,8am} = Y_{p0}(T_{e,8am} - T_{rc}) + Y_{p1}(T_{e,7am} - T_{rc}) + Y_{p2}(T_{e,6am} - T_{rc}) + Y_{p3}(T_{e,5am} - T_{rc}) + Y_{p4}(T_{e,4am} - T_{rc}) + Y_{p5}(T_{e,3am} - T_{rc}) + \dots + Y_{p22}(T_{e,11am} - T_{rc}) + Y_{p23}(T_{e,10am} - T_{rc}) + Y_{p24}(T_{e,9am} - T_{rc})$$



# Heat balance method (HBM)

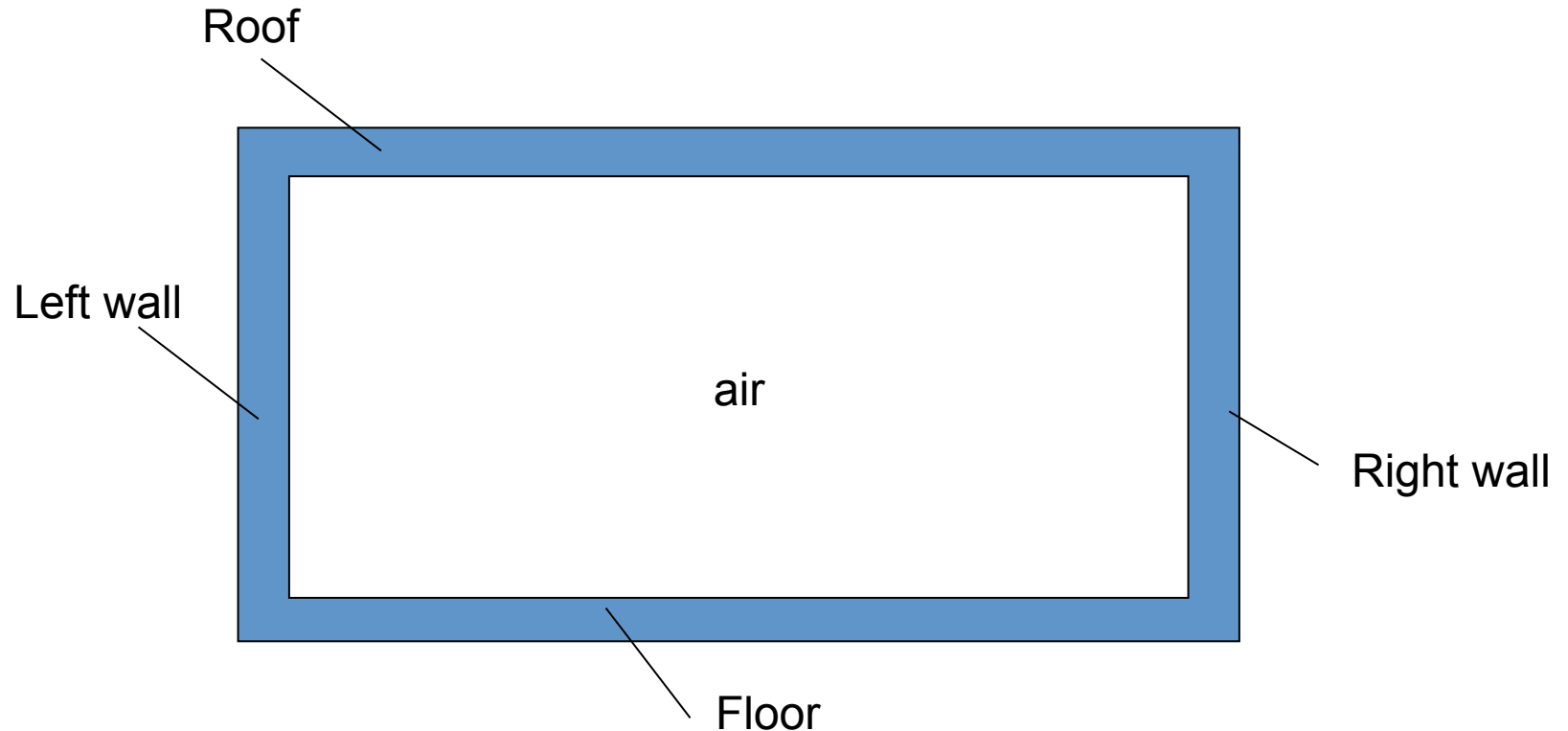
The same as our energy balance method introduced last time

- Most complex and most accurate method
- Within this method, there are various ways of treating thermal mass



# Simplest 'box' model

---



Elements are connected by:

- 1) Convection – air node
- 2) Radiation – surface nodes

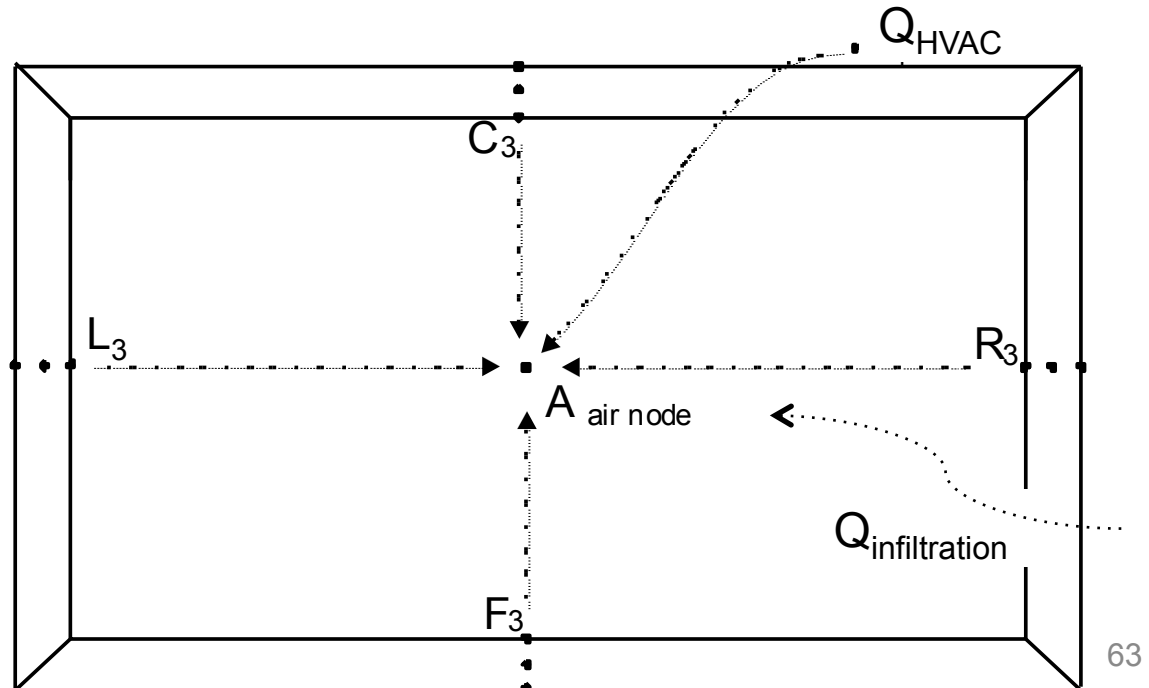
# Unsteady energy balance for air node

- To get the impact on indoor air temperature (and close the system of equations)
  - Write an energy balance on the indoor air node
  - Air impacted directly only by convection (bulk and surface)

$$(V_{room} \rho_{air} c_{p,air}) \frac{dT_{air,in}}{dt} = \sum_{i=1}^n h_i A_i (T_{i,surf} - T_{air,in}) + \dot{m} c_p (T_{out} - T_{air,in}) + Q_{HVAC}$$

## In plain English:

The change in indoor air temperature is equal to the sum of convection from each interior surface plus outdoor air delivery (by infiltration or dedicated outdoor air supply), plus the bulk convective heat transfer delivered by the HVAC system



# Unsteady energy balance for air node

---

- Discretizing for time  $t$  versus time  $t - \delta t$ :

$$C_z \frac{T_z^t - T_z^{t-\delta t}}{dt} + T_z^t \left( \sum_{i=1}^{N_{surfaces}} h_i A_i + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p + \dot{m}_{inf} C_p + \dot{m}_{sys} C_p \right) =$$

$$\sum_{i=1}^{N_{sl}} \dot{Q}_i^t + \dot{m}_{sys} C_p T_{supply}^t + \left( \sum_{i=1}^{N_{surfaces}} h_i A_i T_{si} + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p T_{zi} + \dot{m}_{inf} C_p T_{\infty} \right)^{t-\delta t}$$



# Bringing all modes (and **nodes**) together

- For an example room like this, you would setup a system of equations where the temperature at each node (either a surface or within a material) is unknown
  - 12 material nodes + 1 indoor air node

Heat Xfer @ external surfaces:  
Radiation and convection

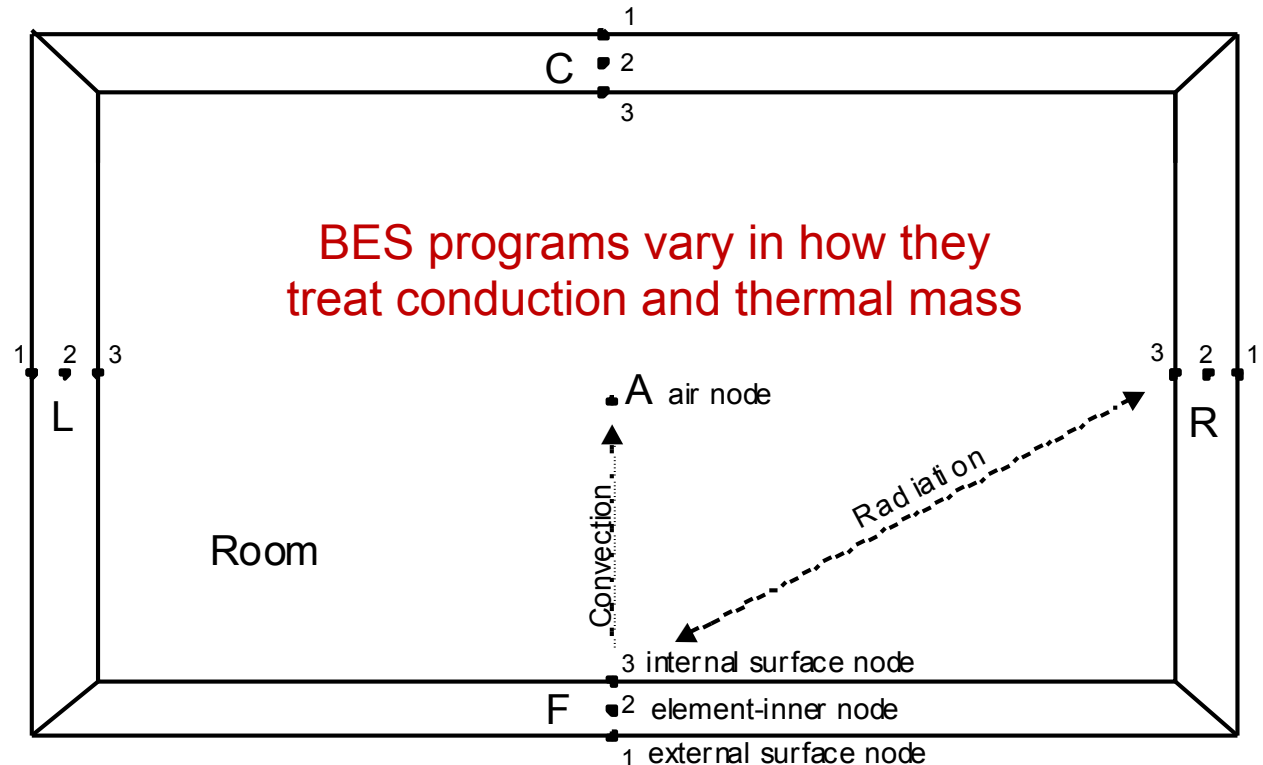
At surface nodes:

$$\sum q = 0$$

At nodes inside materials:

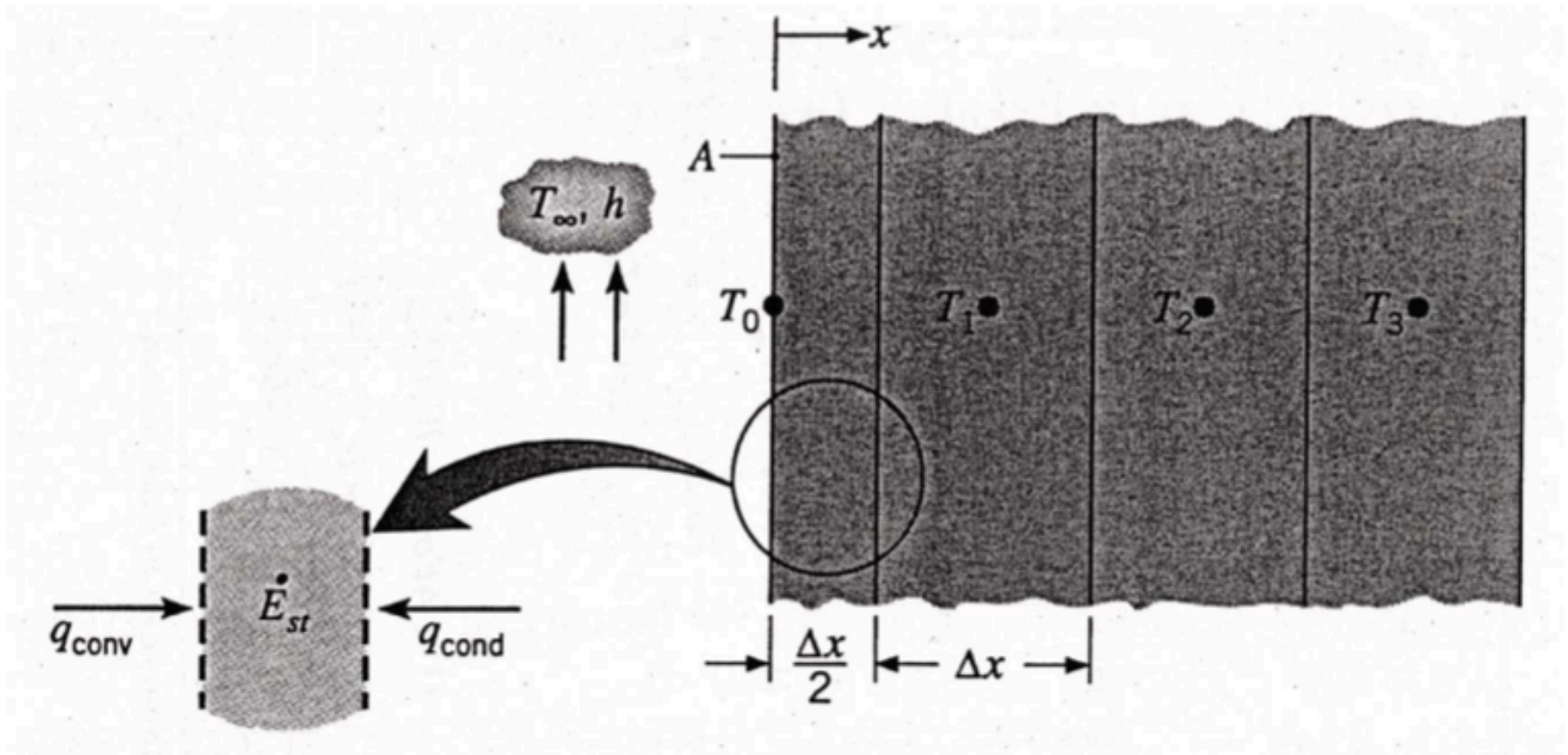
$$mc_p \frac{dT}{dt} = \sum q_{at\ boundaries}$$

Based on density  
and heat capacity  
of material



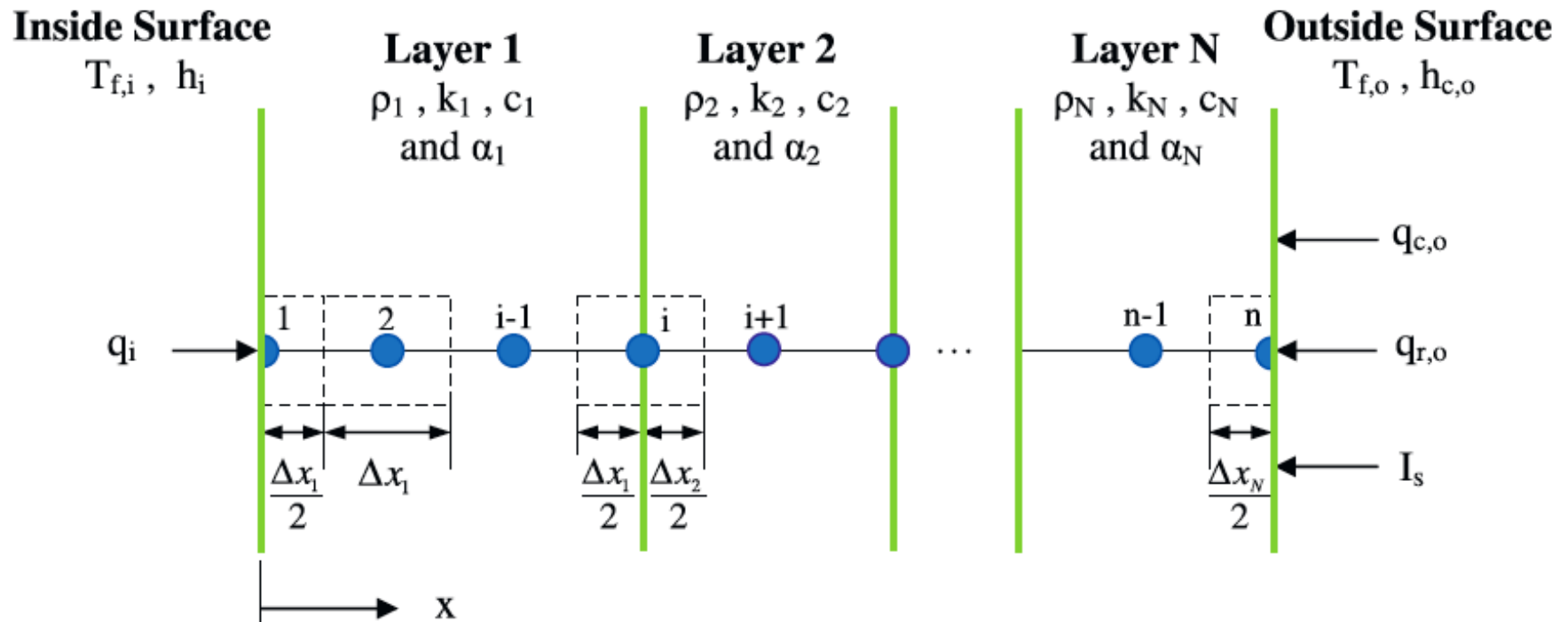
# Modeling thermal mass: Transient (unsteady) conduction

- Divide material assembly into multiple nodes



# Modeling thermal mass: Unsteady conduction

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



Governing equation:

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

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

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

Boundary conditions:

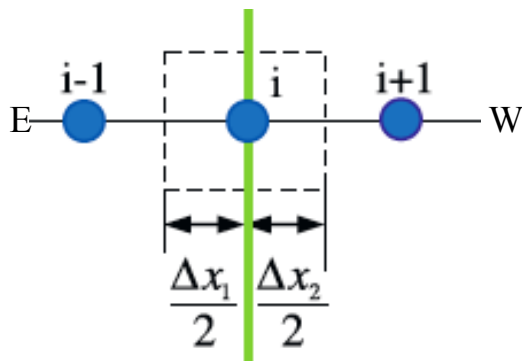
$$-k_1 \left. \frac{\partial T}{\partial x} \right|_{x=0} = h_i (T_{f,i} - T_{x=0}) \quad T_j(x, 0) = T_0$$

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

# Modeling thermal mass: Unsteady conduction

- Conduction finite difference solution (**implicit**)

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \frac{1}{2} \left[ \left( k_w \frac{(T_{i+1}^{j+1} - T_i^{j+1})}{\Delta x} + k_E \frac{(T_{i-1}^{j+1} - T_i^{j+1})}{\Delta x} \right) + \left( k_w \frac{(T_{i+1}^j - T_i^j)}{\Delta x} + k_E \frac{(T_{i-1}^j - T_i^j)}{\Delta x} \right) \right] \quad (36)$$



Where:

$T$  = node temperature

Subscripts:

$i$  = node being modeled

$i+1$  = adjacent node to interior of construction

$i-1$  = adjacent node to exterior of construction

$j+1$  = new time step

$j$  = previous time step

$\Delta t$  = calculation time step

$\Delta x$  = finite difference layer thickness (always less than construction layer thickness)

$C_p$  = specific heat of material

$k_w$  = thermal conductivity for interface between  $i$  node and  $i+1$  node

$k_E$  = thermal conductivity for interface between  $i$  node and  $i-1$  node

$\rho$  = density of material

**Selecting grid size:**

$$\left( Fo = \alpha \Delta t / \Delta x^2 \right) < 0.5$$

Implicit = temperatures are evaluated at time  $j+1$  as a function of temperatures at time  $j$

# Modeling thermal mass: Unsteady conduction

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

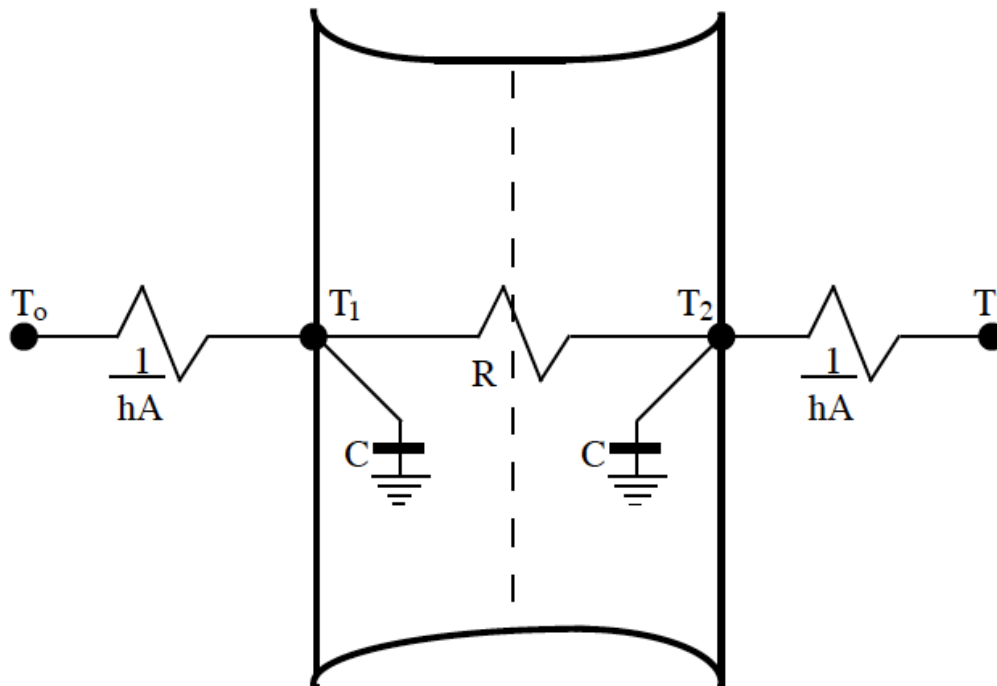


Figure 9. Two Node State Space Example.

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

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

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

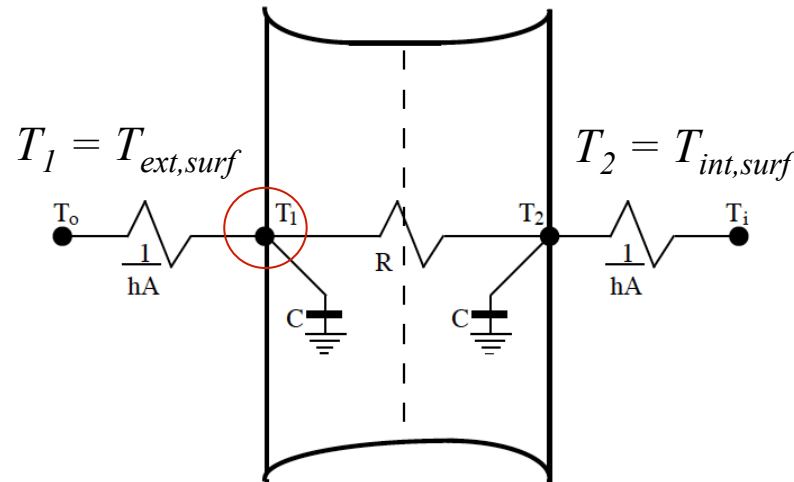


Figure 9. Two Node State Space Example.

$$q_{sw,solar}$$

$$+q_{lw,surface-sky}$$

**From:**

$$+q_{lw,surface-ground}$$

$$+q_{convection}$$

$$-q_{conduction} = 0$$

$$q_{sw,solar}$$

$$+q_{lw,surface-sky}$$

**To:**

$$+q_{lw,surface-ground}$$

$$+q_{convection}$$

$$-q_{conduction} = \rho C_p \frac{L}{2} \frac{dT}{dt}$$

# Lumped capacitance model for conduction

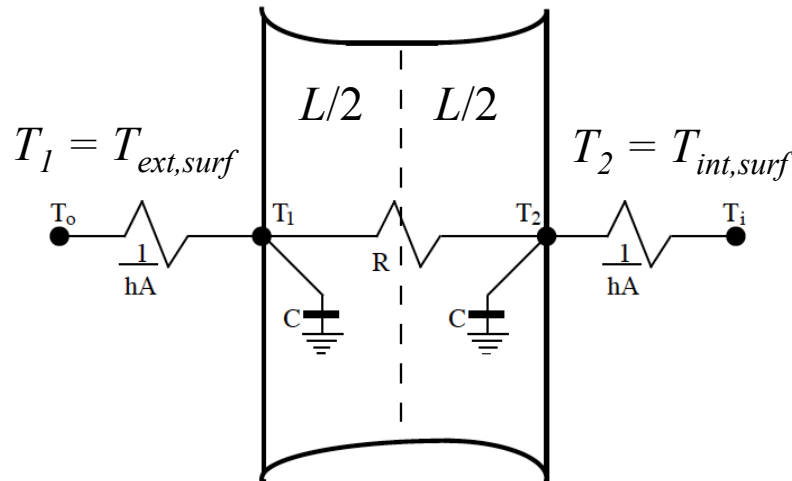


Figure 9. Two Node State Space Example.

**Steady state surface energy balance...**

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

**...becomes a **time-varying** surface energy balance:**

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



# Dynamic thermal mass: Example in a Hot Box

---

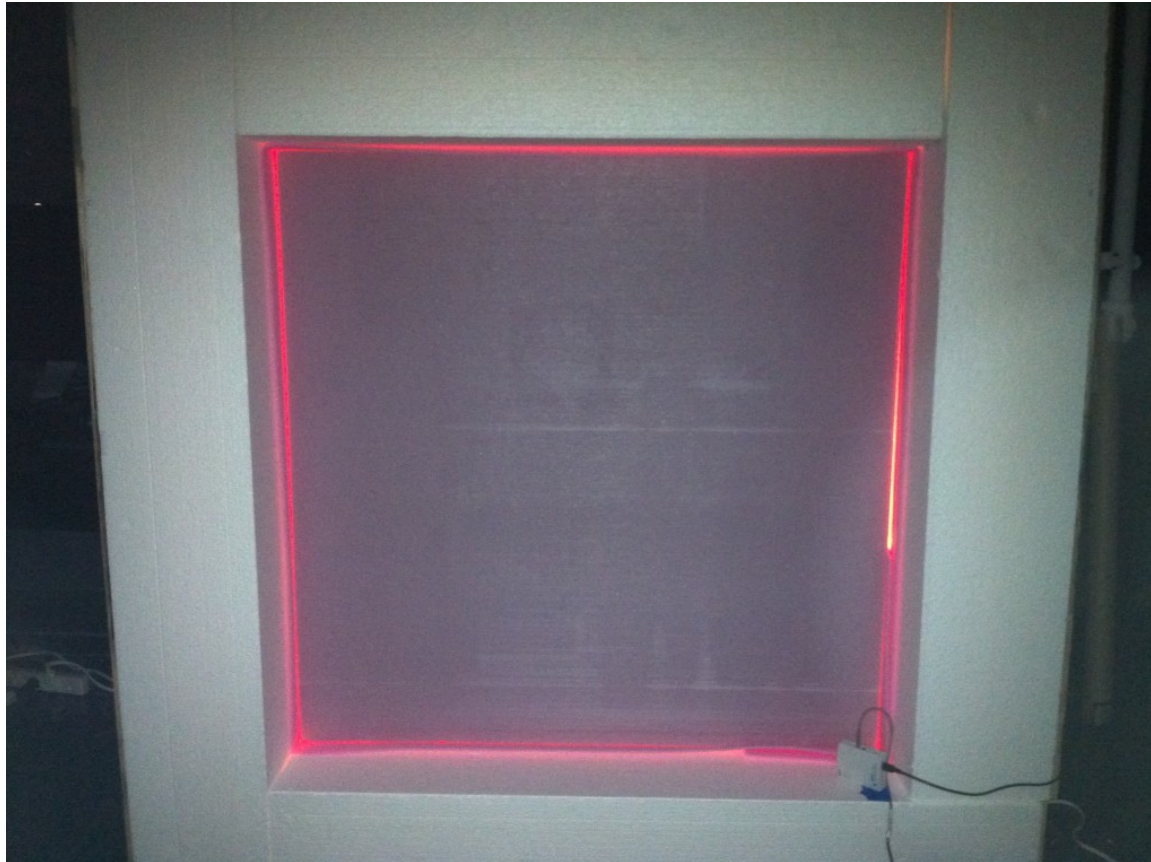
- Three 25 W bulbs inside a 1 m<sup>3</sup> insulated box with 8 inches of EPS insulation on all sides
- Known R-5 insulation installed as the sample



# Dynamic thermal mass: Example in a Hot Box

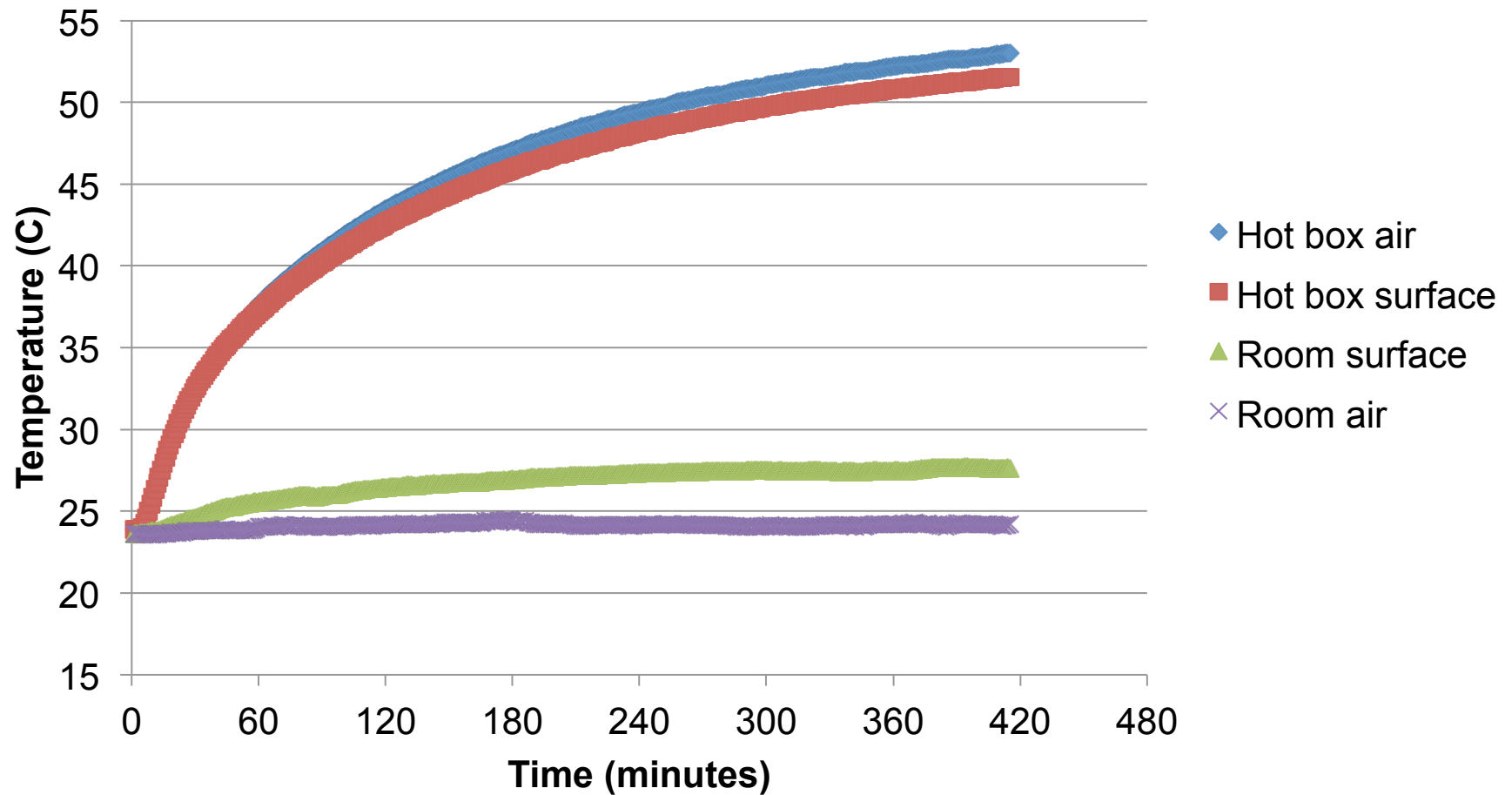
---

- Three 25 W bulbs inside a 1 m<sup>3</sup> insulated box with 8 inches of EPS insulation on all sides
- Known R-5 insulation installed as the sample



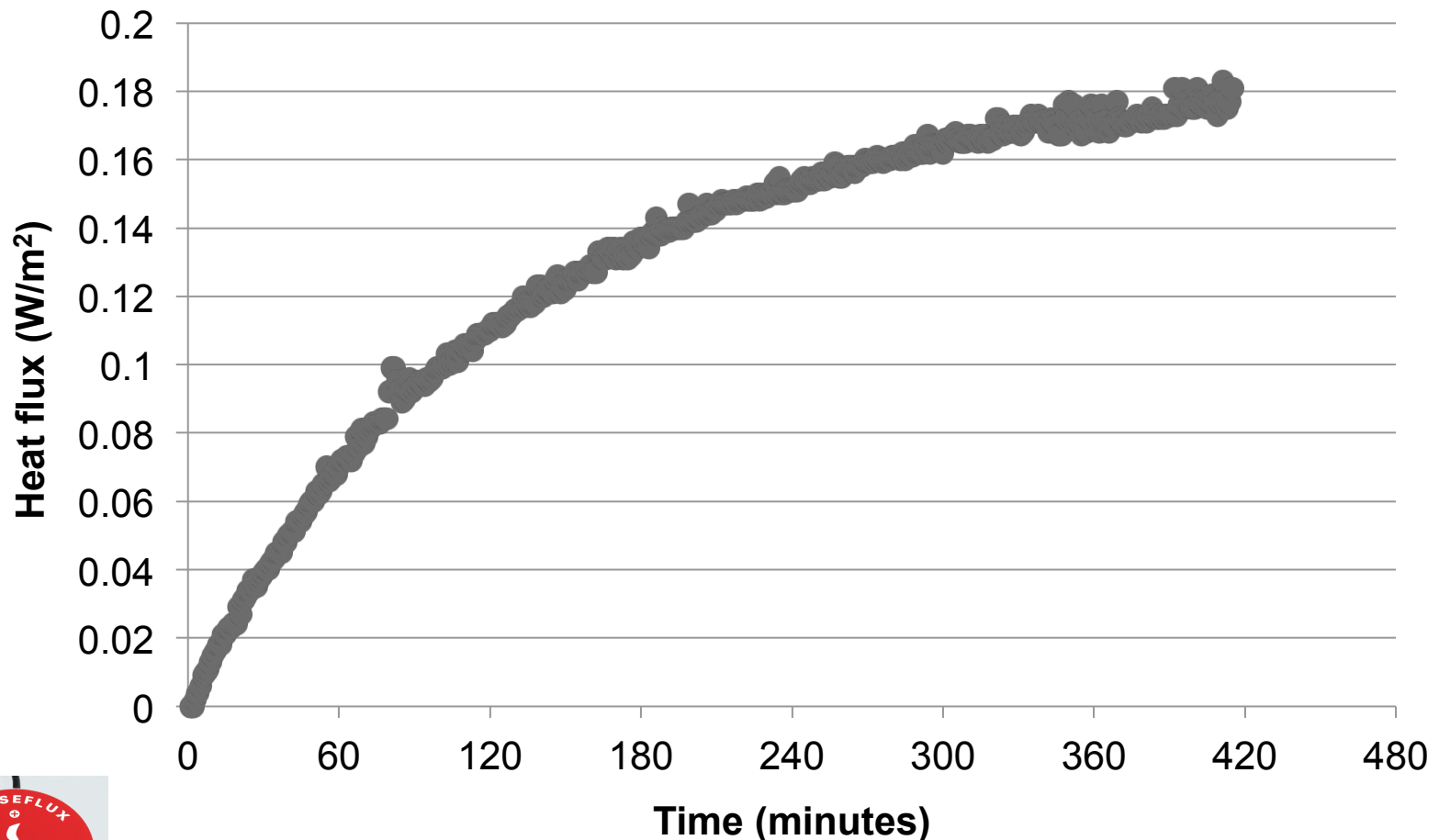
# Dynamic thermal mass: Example in a Hot Box

## Measured temperatures



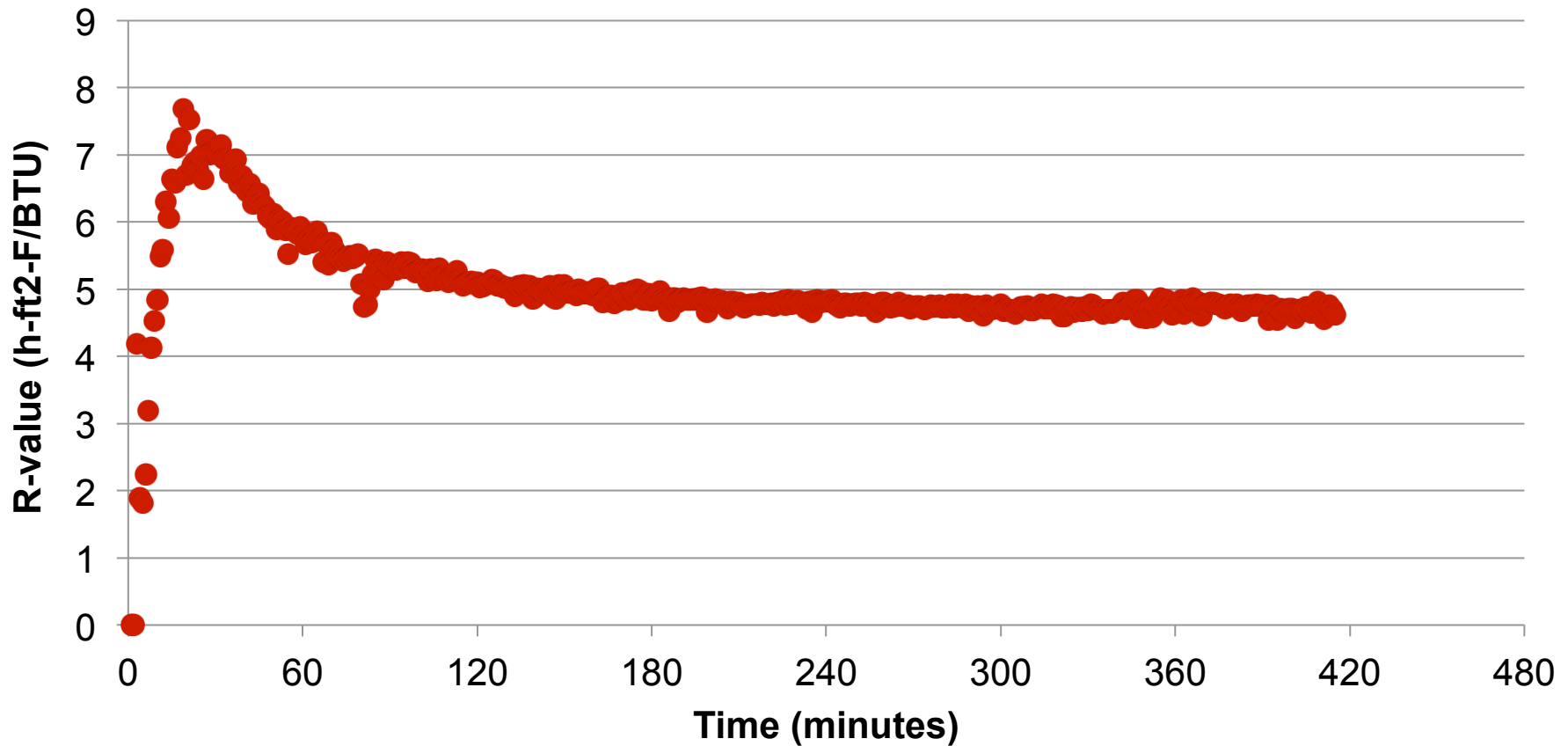
# Dynamic thermal mass: Example in a Hot Box

## Measured heat flux through the R-5 sample



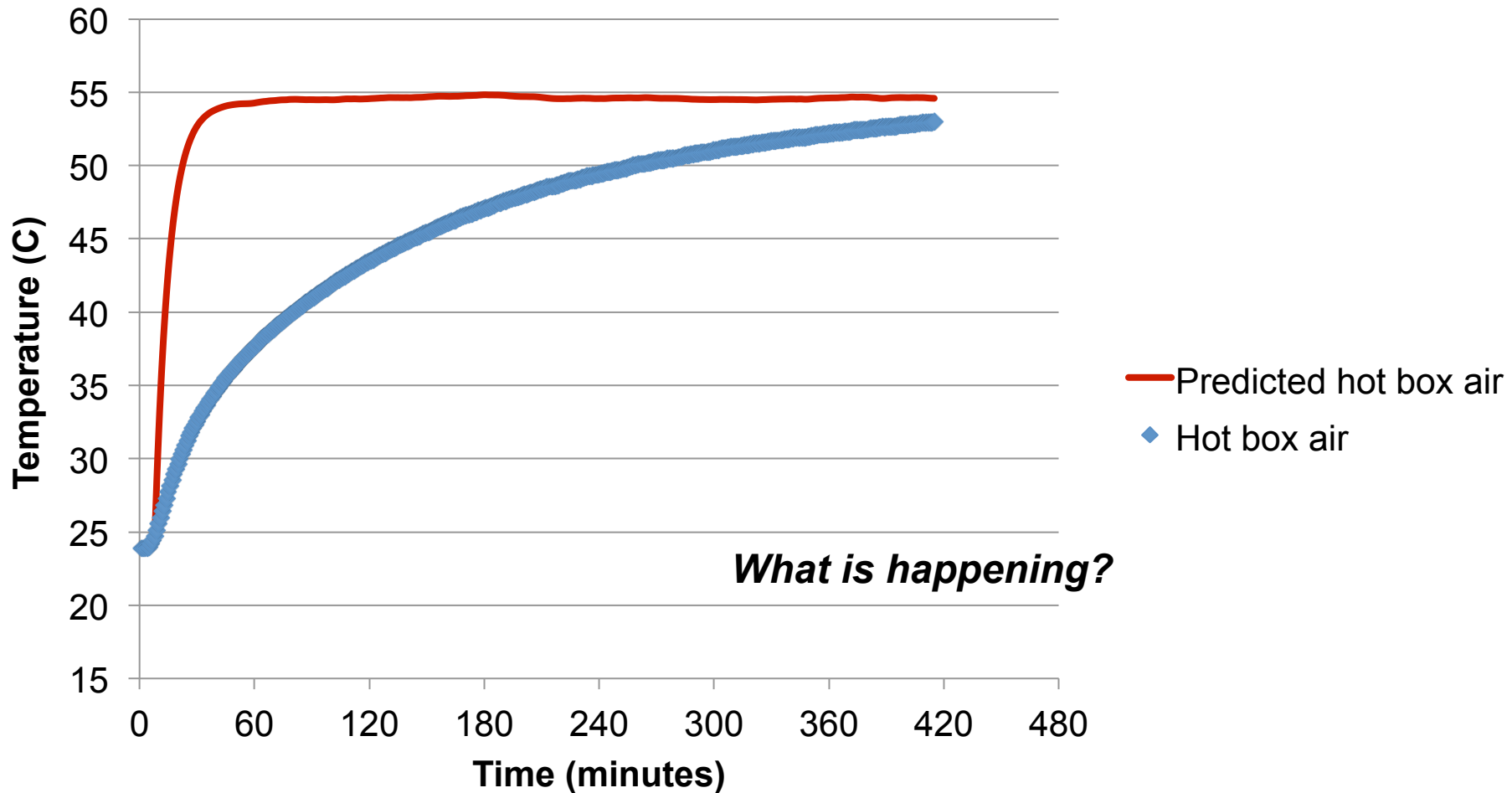
# Dynamic thermal mass: Example in a Hot Box

Calculated R-value from flux and surface temperatures



# Dynamic thermal mass: Example in a Hot Box

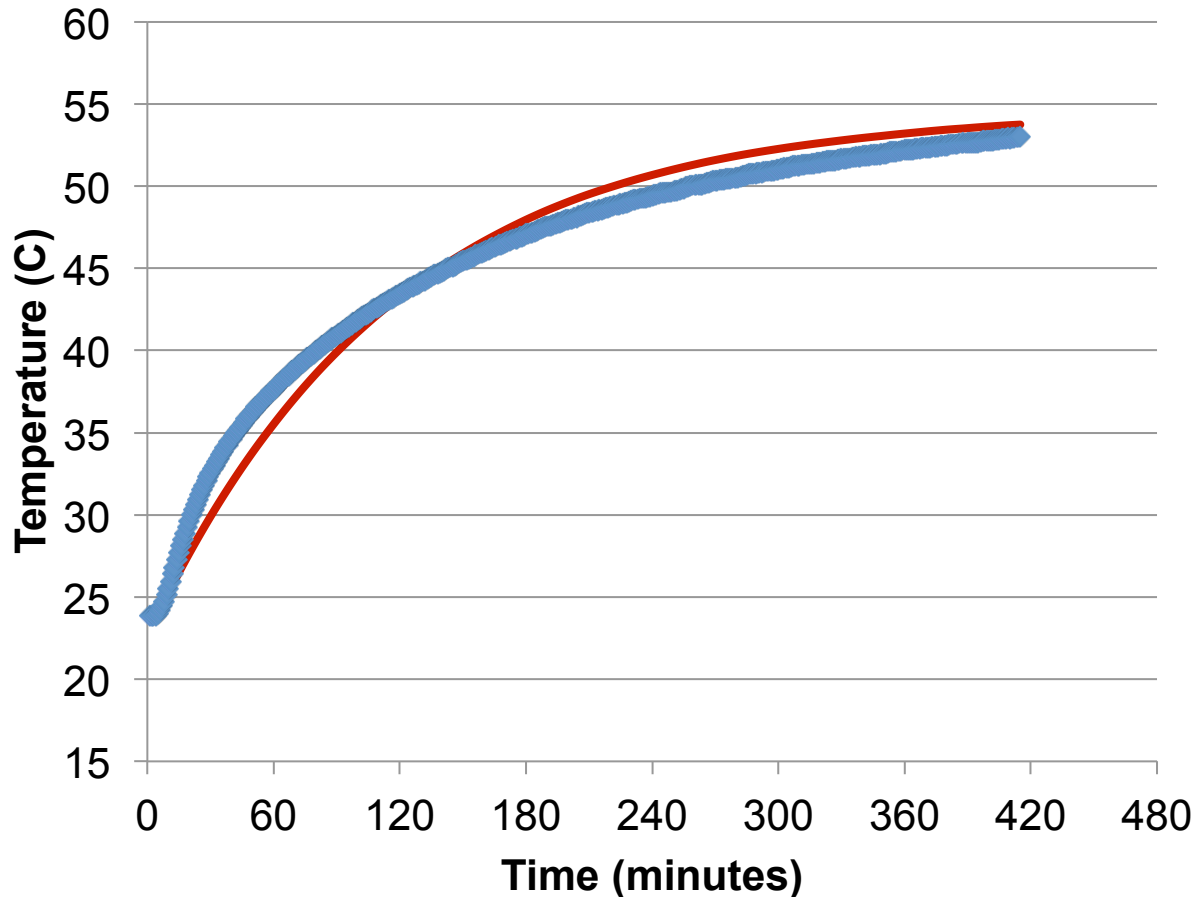
Predicted hot box air temperatures (**ignoring heat capacity of insulation**)



$$(V_{box} \rho_{air} c_{p,air}) \frac{dT_{air,in}}{dt} = \sum_{i=1}^n h_i A_i (T_{i,surf} - T_{air,in}) + \dot{m} c_p (T_{out} - T_{air,in})$$

# Dynamic thermal mass: Example in a Hot Box

Predicted hot box air temperatures (adding heat capacity of insulation)



**Assuming:**

Density = 13 kg/m<sup>3</sup>

C<sub>p</sub> = 1200 J/kgK

V = 1 m<sup>3</sup>

— Predicted hot box air

◆ Hot box air

Accounting for heat capacity allows for more accurate estimation of when the peak occurs (about 8 hours later)

Adding this term: 
$$\frac{(V\rho C_p)_{insulation}}{\Delta t}(T_1^n - T_1^{n-1})$$



Finishing building energy modeling...

# BEOPT AND ENERGYPLUS

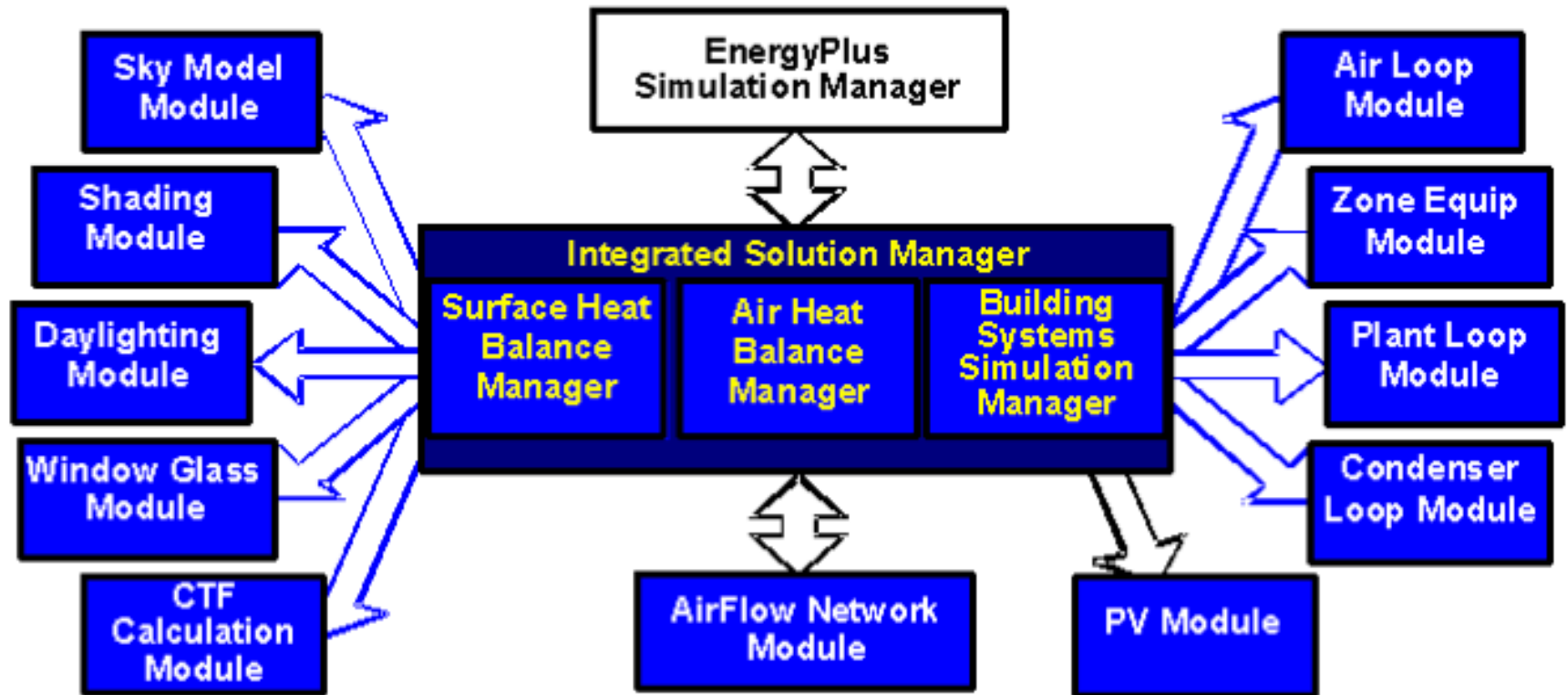


# EnergyPlus

---

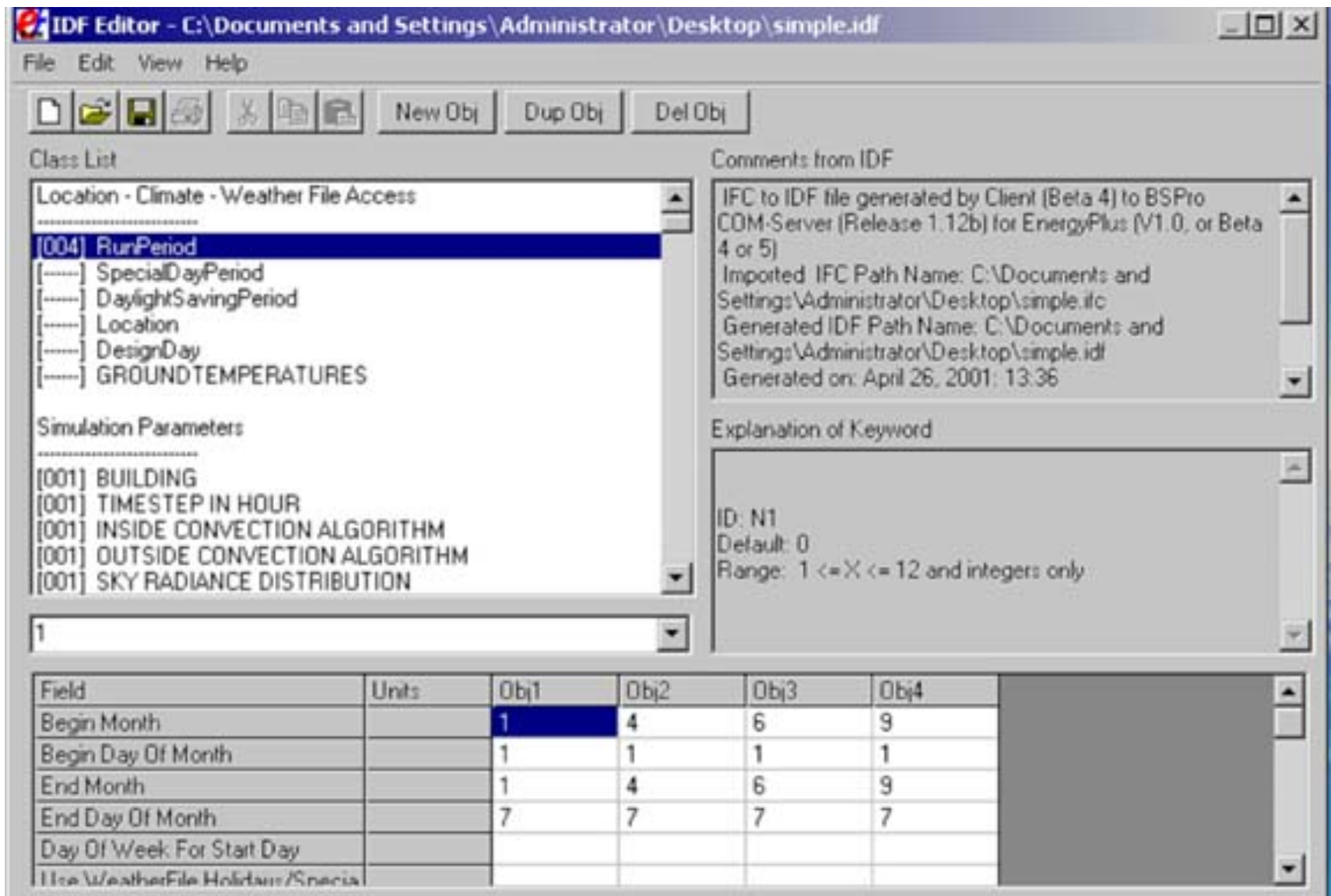
- EnergyPlus is an extremely powerful building energy simulation tool
  - Uses hourly or sub-hourly time steps
  - Models nearly all physical phenomena well
    - Including transient heat conduction (thermal mass)
  - Combined heat and mass (air) transfer modeling
  - Excellent system models
  - Thermal comfort modeling
  - Modular for future extensions
- [http://apps1.eere.energy.gov/buildings/energyplus/energyplus\\_about.cfm](http://apps1.eere.energy.gov/buildings/energyplus/energyplus_about.cfm)
- Runs on Windows, Mac, and Linux

# EnergyPlus program organization



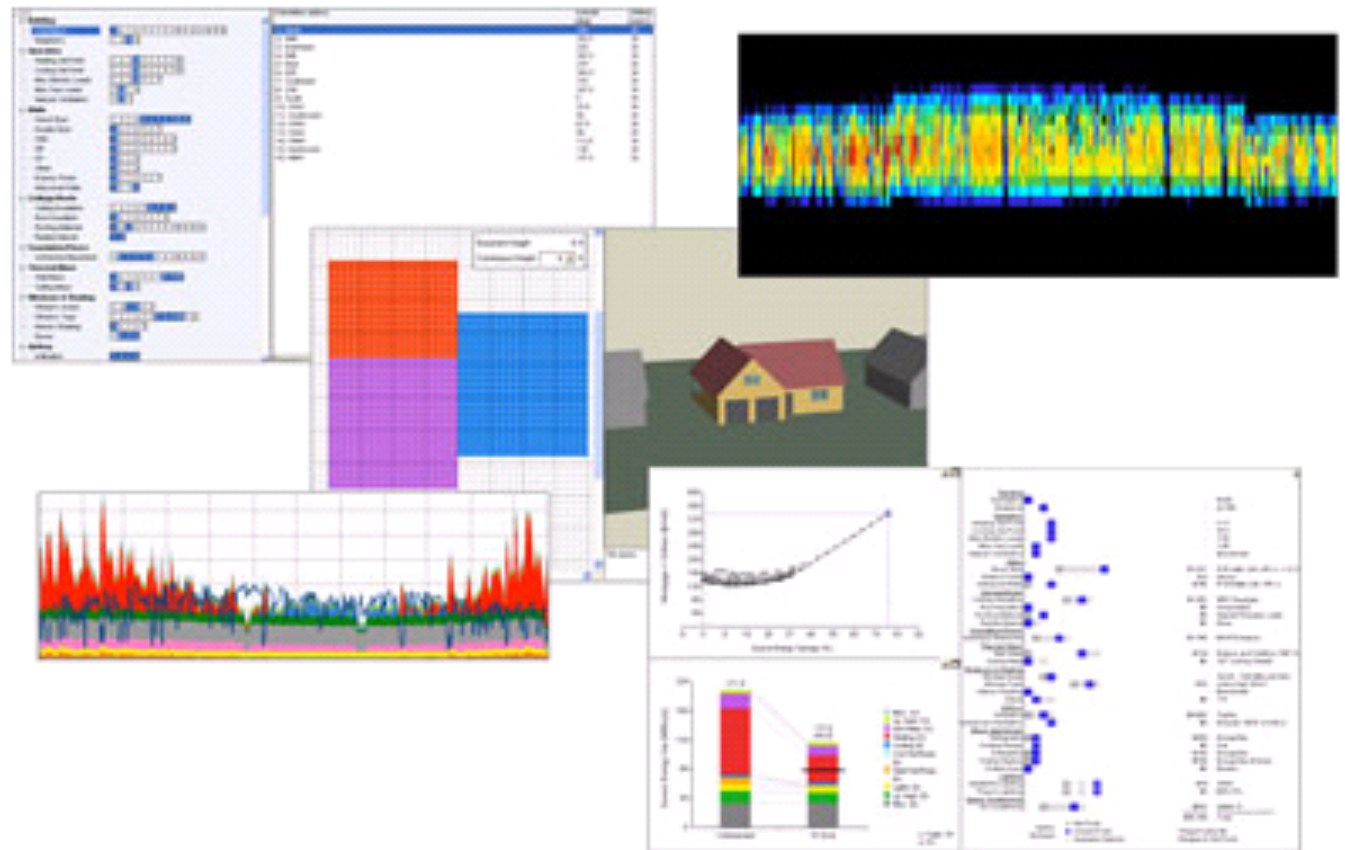
One **huge** limitation: it does not have a graphical user interface (GUI)

# EnergyPlus only has a text based input file editor



# We need front-end GUIs for EnergyPlus

- *OpenStudio*
- DesignBuilder
- EFEN
- AECOsim
- Hevacomp
- N++
- gEnergy
- *Simergy*
- *Sefaira*
- *BEopt*



# BEopt

---

- BEopt (Building Energy Optimization) combines a user-friendly GUI for building model geometry and specifying enclosure details, systems, etc. with both parametric analysis and an optimization engine for identifying cost-optimal efficiency packages
  - Includes annual energy costs/savings, construction costs, and material/equipment costs
  - <https://beopt.nrel.gov>
- Strictly limited to residential buildings
- Only runs on Windows
- Uses either EnergyPlus or DOE-2.2 as the simulation engine
  - eQUEST uses DOE-2.2
  - We will use EnergyPlus (more robust)

# BEopt: Start with building geometry

Levels: **Fnd** 1st 2nd 3rd 4th Roof

Beds 3 Baths 2 Total Finished 772 sqft

Wall Height 8 ft

**Spaces**


- ☒ Living
- ☒ Garage
- ☐ Erase

**Attached Walls**

- ☐ Left-Facing
- ☐ Right-Facing
- ☐ Back-Facing

Scale: 1 cell = 1 ft



Front



No errors.

# BEopt: Then pick basic characteristics

**Building**

EPW Location USA\_GA\_Atlanta-Hartsfield-Jackson.  

Terrain Suburban

**Economics**

Project Analysis Period

30 years

Inflation Rate

3.0 %

Discount Rate (Real)

3.0 %

Material Cost Multiplier

1.00

Labor Cost Multiplier

1.00

**Mortgage**

Down Payment

0.0 %

Mortgage Interest Rate

7.0 %

Mortgage Period

30 years

Marginal Income Tax Rate, Federal


28.0 %


Marginal Income Tax Rate, State

0.0 %

**Incentives**

Tax Credits & Rebates

Whole-House Efficiency 

PV 

**Electricity** Natural Gas Oil Propane

**Utility Rates**

☒ User Specified

Marginal

0.0800

\$/kWh

☐ State Average

Fixed

8.00

\$/month

☐ National Average

Average

0.0870

\$/kWh

☐ OpenEI Utility Rate

Fuel Escalation (Real)

0.00 %/year

**Energy Factors**

Source/Site Ratio

3.365

Carbon Factor

1.670 lb/kWh

**Net-Metered Annual Excess Sellback Rate**

☒ Retail Electricity Cost

0.08000 \$/kWh

☐ User Specified

86



# BEopt: Then pick basic characteristics

My Design

Orientation

Neighbors

Operation

Heating Set Point

Cooling Set Point

Misc Electric Loads

Misc Gas Loads

Misc Hot Water Loads

Natural Ventilation

Interior Shading

Walls

Wood Stud

Double Wood Stud

CMU

SIP

ICF

Other

Wall Sheathing

Exterior Finish

Interzonal Walls

Ceilings/Roofs

Unfinished Attic

Roof Material

Radiant Barrier

Foundation/Floors

Slab

Carpet

Thermal Mass

Exterior Wall Mass

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

1 2 3 4

1 2 3 4 5 6 7 8 9 10

1 2 3 4 5 6 7 8 9 10

1 2 3 4 5 6 7 8

1 2 3 4

1 2 3 4

1 2 3 4

1 2 3 4 5 6

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

1 2 3 4 5 6 7

1 2 3 4 5 6

1 2 3 4 5 6 7 8 9

1 2 3 4

1 2 3 4

1 2 3 4 5 6 7 8 9 10 11 12

1 2 3 4 5 6 7 8 9 10 11

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23

1 2 3 4 5 6 7 8 9 10 11 12 13

1 2

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

1 2 3 4 5 6

1 2 3 4 5

Option

R-Assembly  
[h-ft^2-R/Btu]

Framing Factor  
[frac]

Cost  
[\$/ft^2 Exterior Wall]

1) None

2) Uninsulated, 2x4, 16 in o.c.

3) Uninsulated, 2x6, 24 in o.c.

4) R-7 Fiberglass Batt, Gr-3, 2x4, 16 in o.c.

5) R-7 Fiberglass Batt, Gr-2, 2x4, 16 in o.c.

6) R-7 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.

7) R-11 Fiberglass Batt, Gr-3, 2x4, 16 in o.c.

8) R-11 Fiberglass Batt, Gr-2, 2x4, 16 in o.c.

9) R-11 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.

10) R-13 Fiberglass Batt, Gr-3, 2x4, 16 in o.c.

11) R-13 Fiberglass Batt, Gr-2, 2x4, 16 in o.c.

12) R-13 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.

13) R-15 Fiberglass Batt, Gr-3, 2x4, 16 in o.c.

14) R-15 Fiberglass Batt, Gr-2, 2x4, 16 in o.c.

15) R-15 Fiberglass Batt, Gr-1, 2x4, 16 in o.c.

16) R-19 Fiberglass Batt, Gr-3, 2x6, 24 in o.c.

17) R-19 Fiberglass Batt, Gr-2, 2x6, 24 in o.c.

18) R-19 Fiberglass Batt, Gr-1, 2x6, 24 in o.c.

19) R-21 Fiberglass Batt, Gr-3, 2x6, 24 in o.c.

20) R-21 Fiberglass Batt, Gr-2, 2x6, 24 in o.c.

21) R-21 Fiberglass Batt, Gr-1, 2x6, 24 in o.c.

22) R-13 Cellulose, Gr-3, 2x4, 16 in o.c.

23) R-13 Cellulose, Gr-2, 2x4, 16 in o.c.

24) R-13 Cellulose, Gr-1, 2x4, 16 in o.c.

25) R-19 Cellulose, Gr-3, 2x6, 24 in o.c.

3.6

3.7

8.3

8.7

8.9

9.6

10.1

10.5

10.3

10.9

11.4

10.9

11.7

12.2

13.4

14.6

15.5

14.6

16.1

17.2

10.3

10.9

11.4

14.0

0.25

0.22

0.25

0.25

0.25

0.25

0.25

0.25

0.25

0.25

0.25

0.25

0.25

0.25

0.22

0.22

0.22

0.22

0.22

0.22

0.25

0.25

0.25

0.22

\$1.84

\$1.76

\$2.41

\$2.43

\$2.46

\$2.49

\$2.51

\$2.54

\$2.53

\$2.55

\$2.58

\$2.57

\$2.59

\$2.62

\$2.58

\$2.60

\$2.62

\$2.61

\$2.64

\$2.66

\$2.55

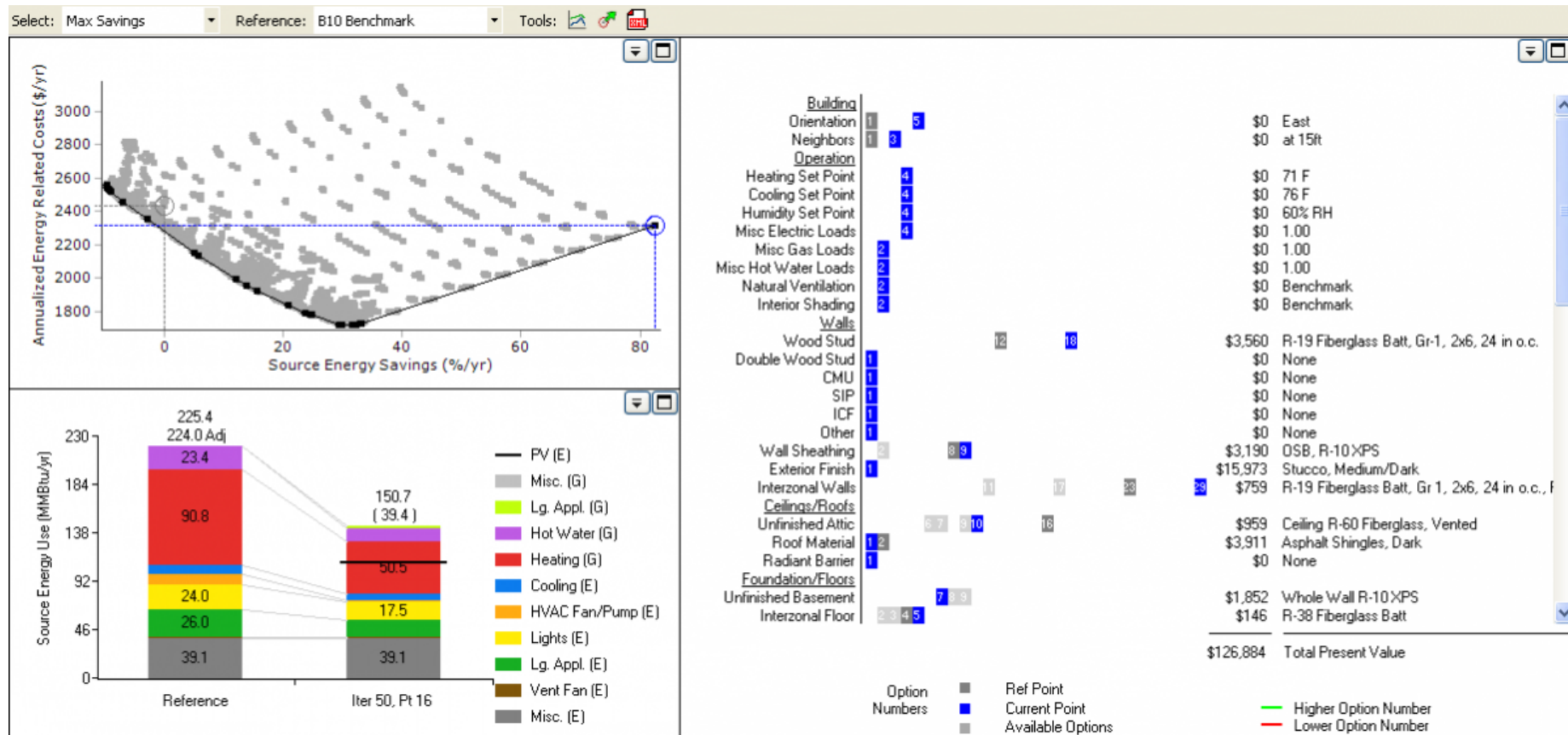
\$2.57

\$2.60

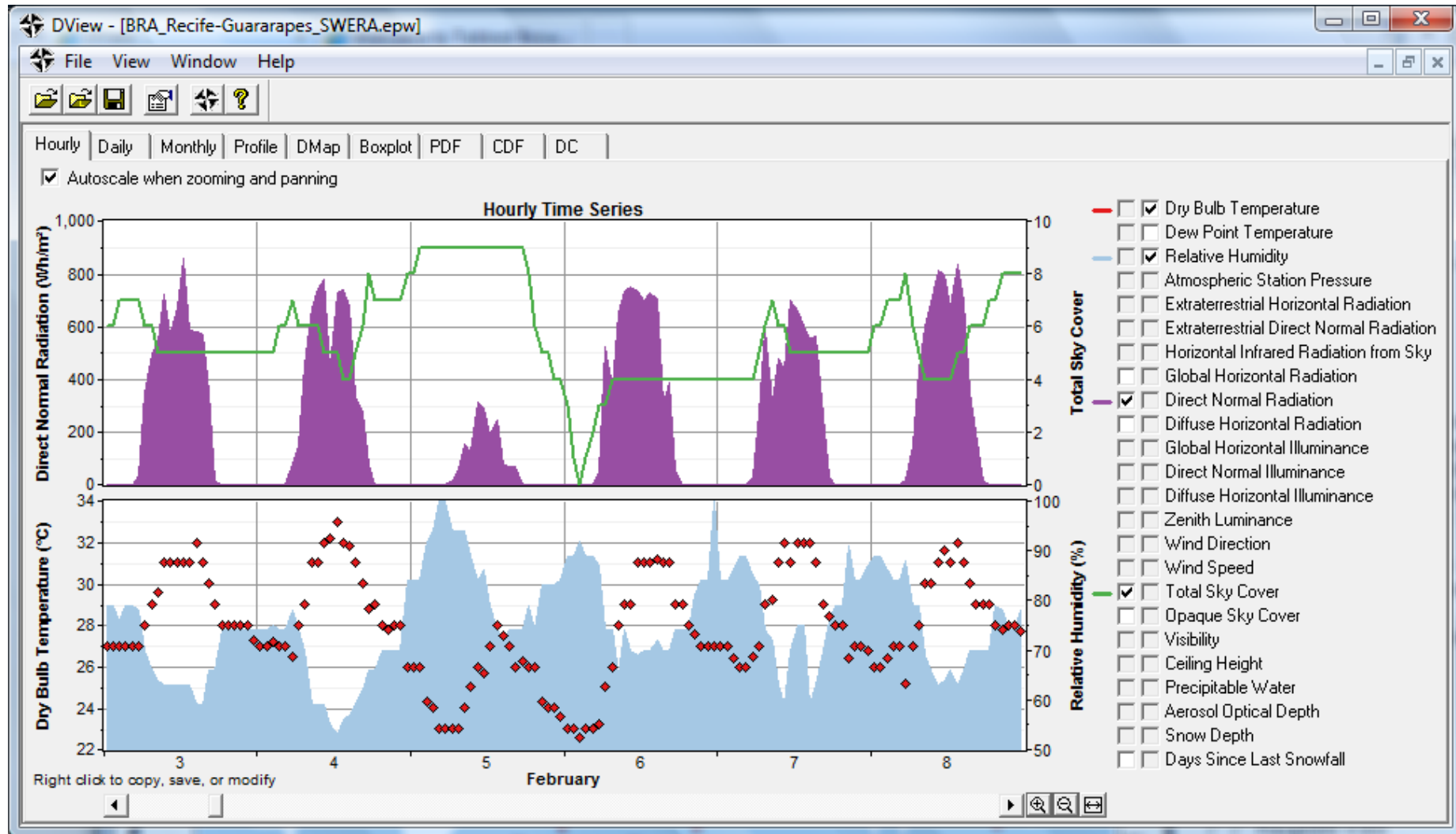
\$2.64

Standard wood stud framed walls with cavity insulation. When batt insulation must be compressed to fit within the cavity (e.g. R19 in a 5.5' 2x6 cavity), R-values reflect this effect.

# BEopt: Simulate and compare results



# BEopt: Can also download DView for detailed results



# BEopt + EnergyPlus demonstration

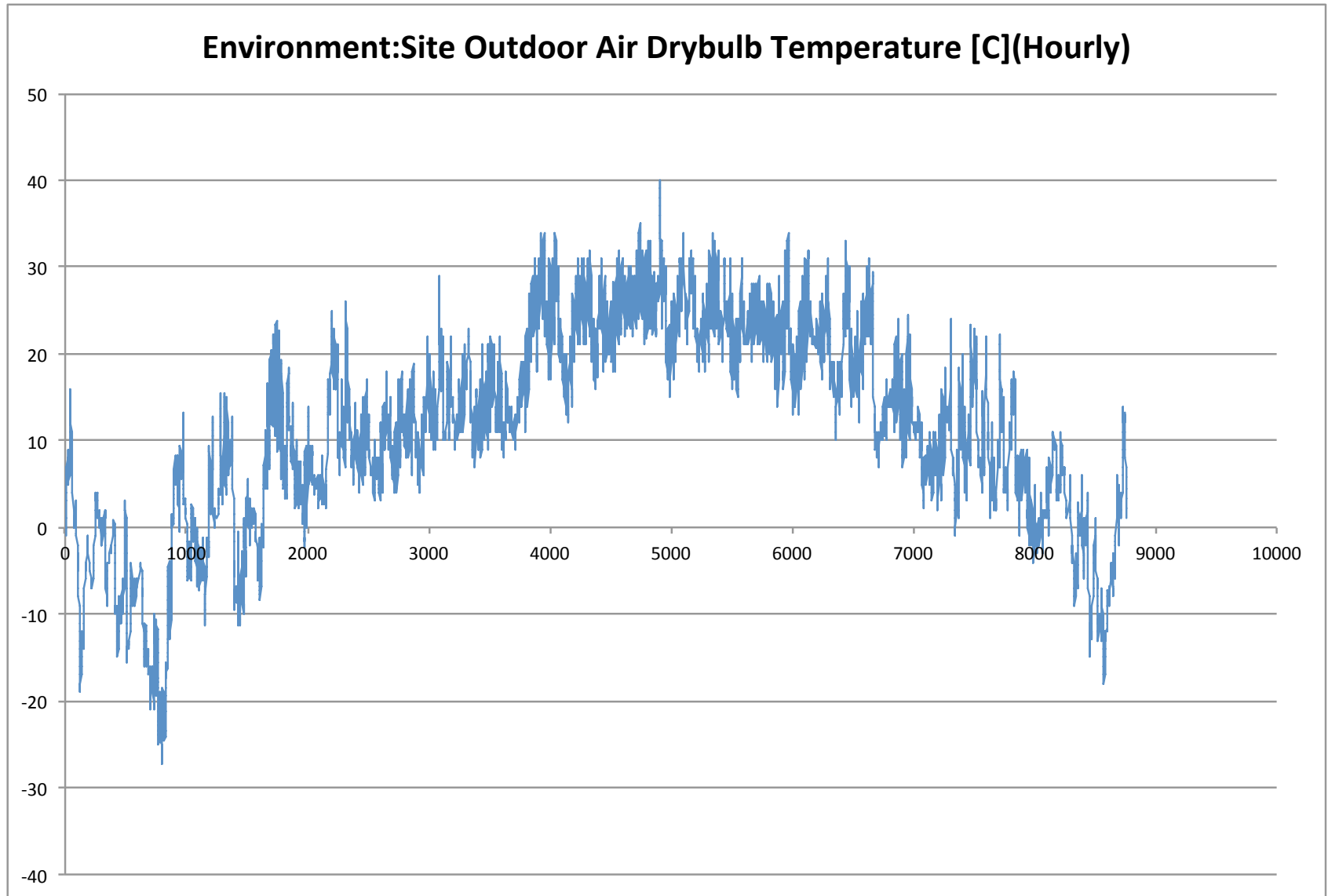
---

- HW 5
  - Similar to HW 4
  - Explores enclosure trade-offs with a single-family home using BEopt and EnergyPlus
- Assigned today
  - Due next week

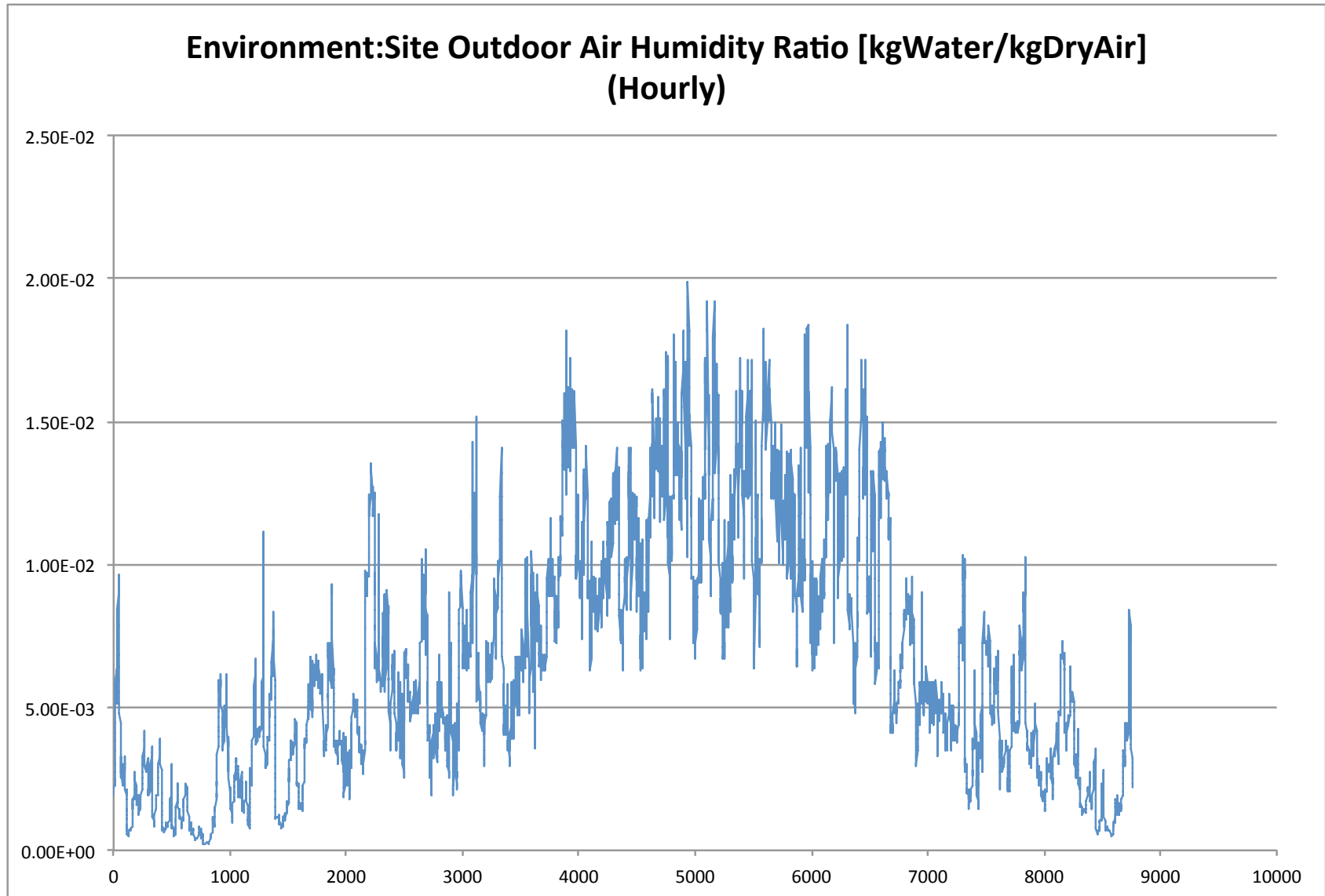
# **EXAMPLE WHOLE BUILDING ENERGY SIMULATION**

Hourly inputs and results

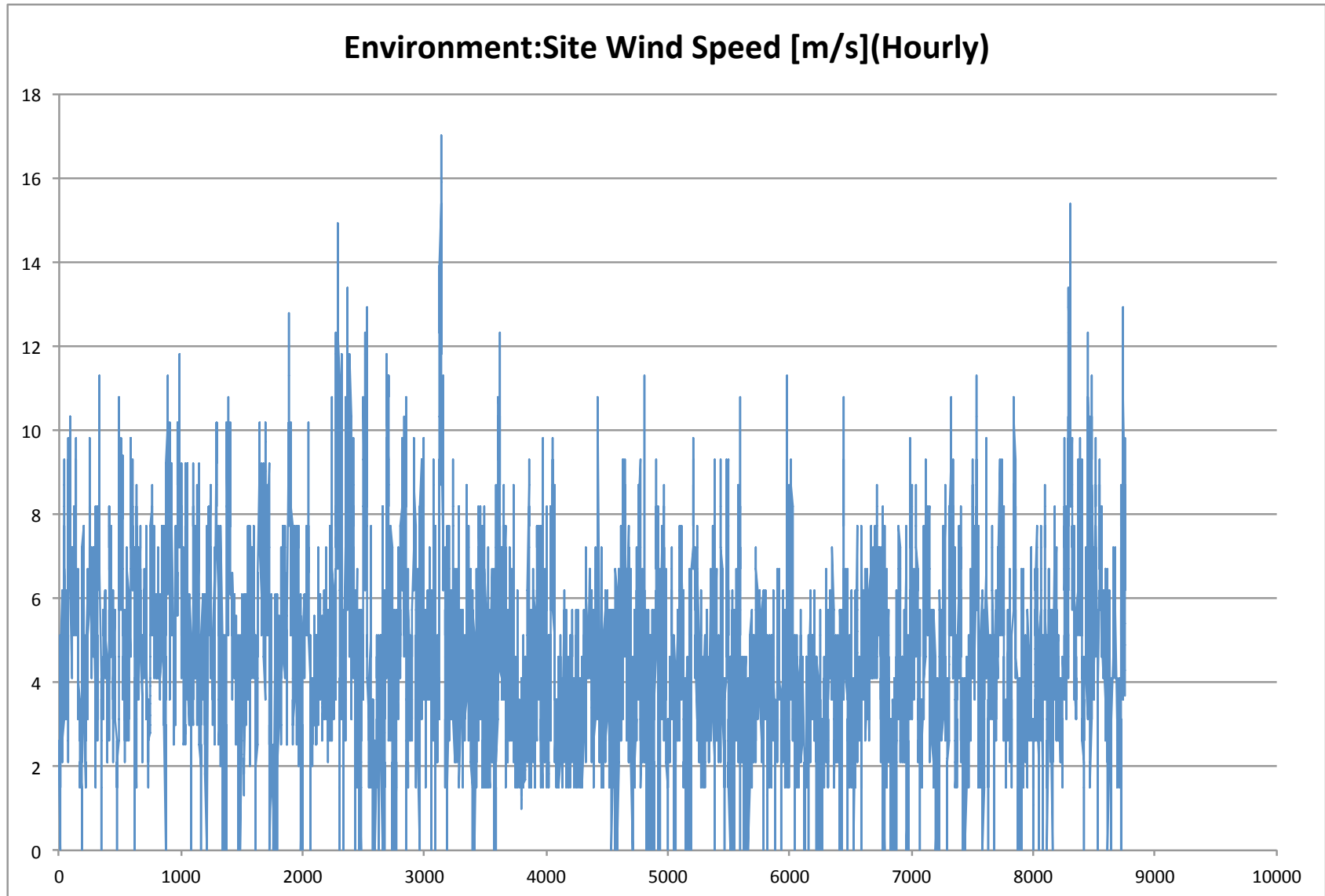
# Annual energy simulation: Example home in Chicago



# Annual energy simulation: Example home in Chicago

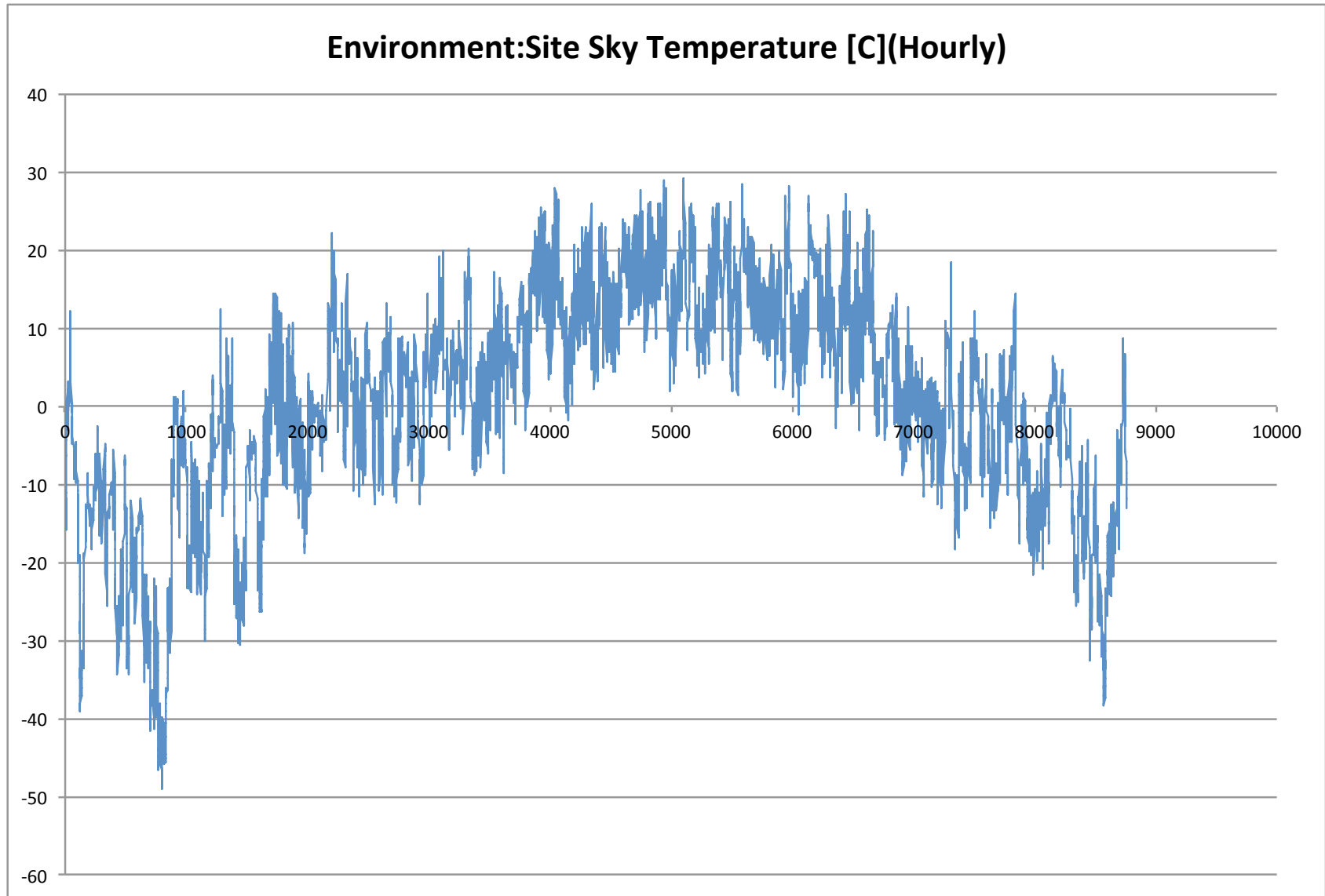


# Annual energy simulation: Example home in Chicago

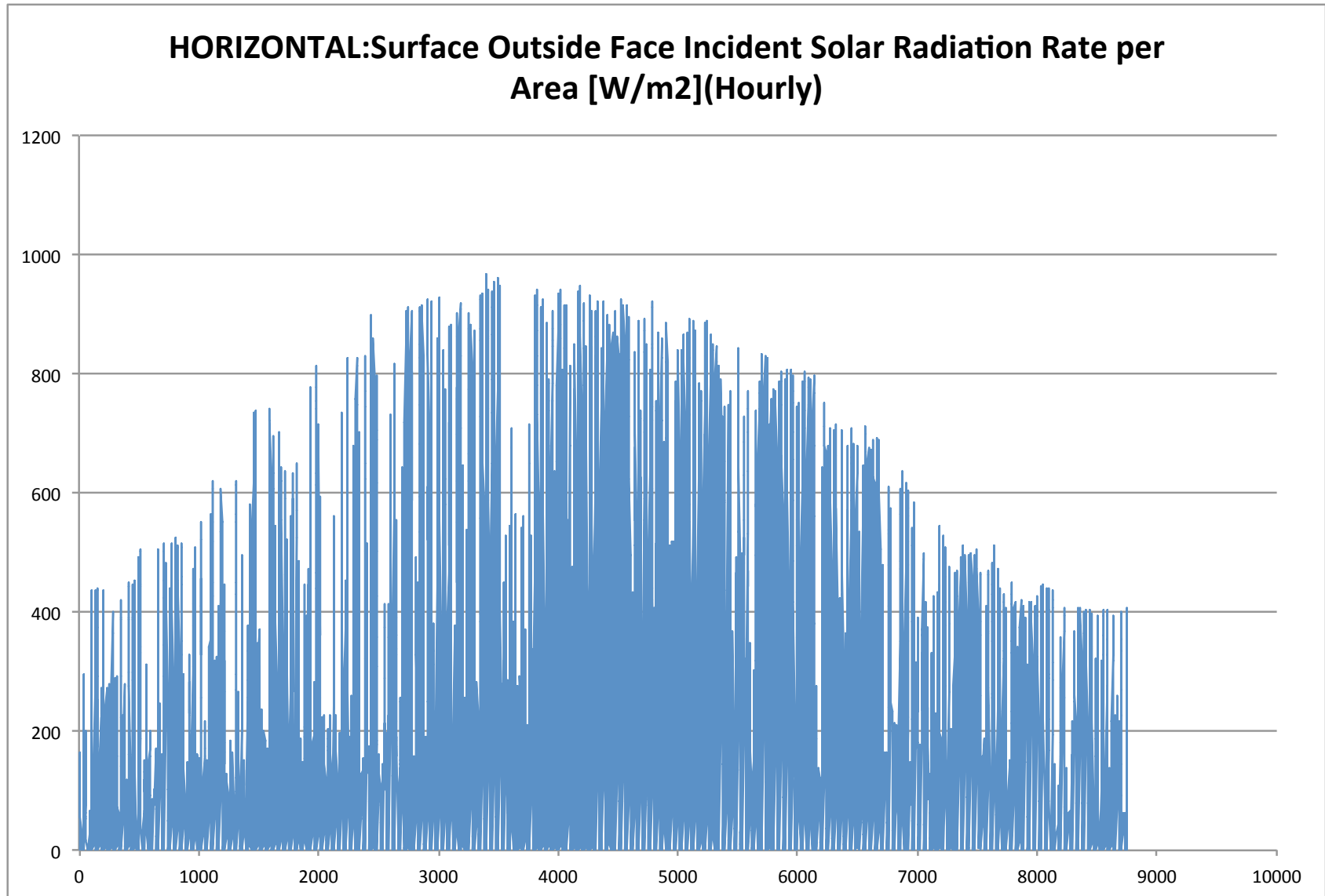




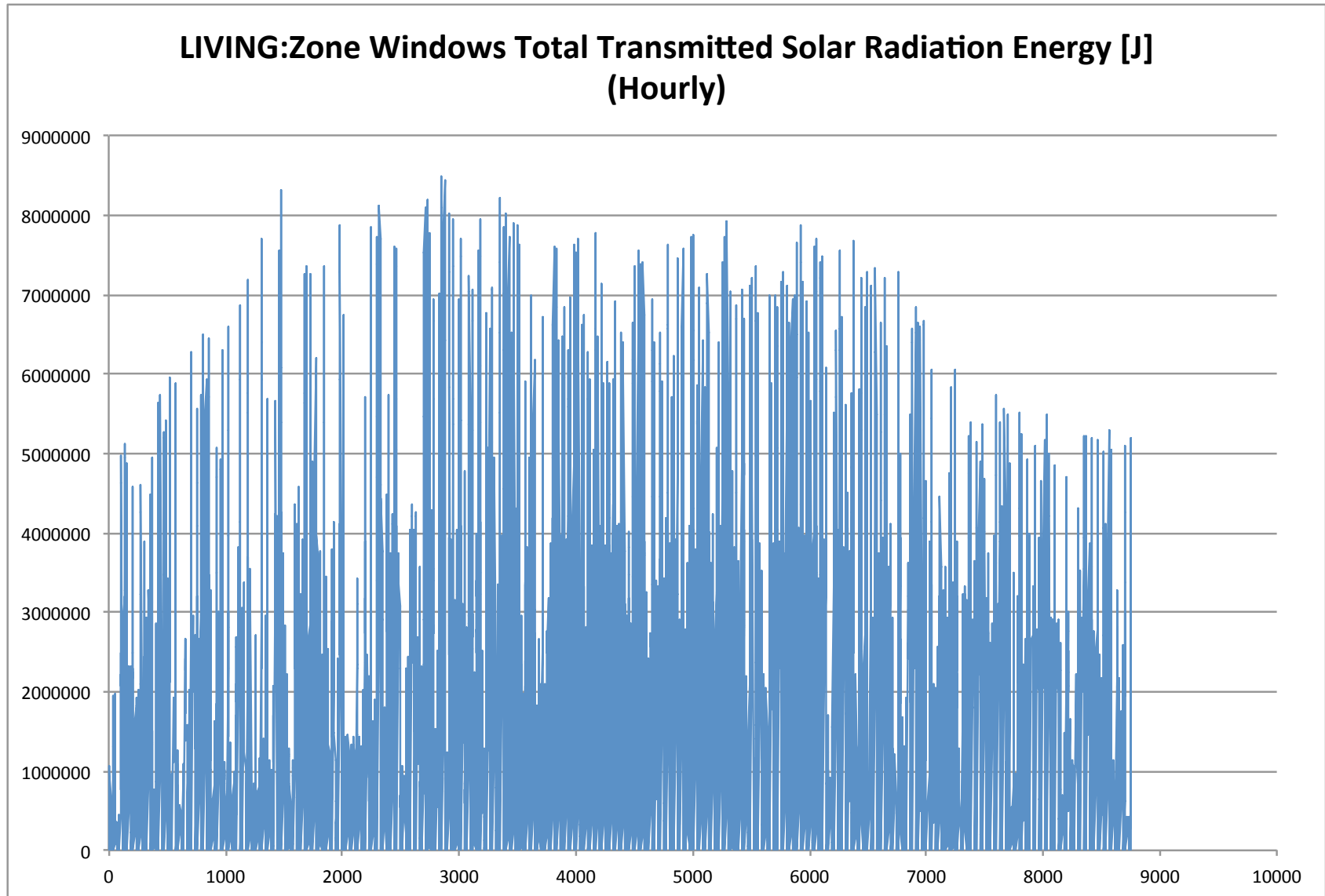
# Annual energy simulation: Example home in Chicago



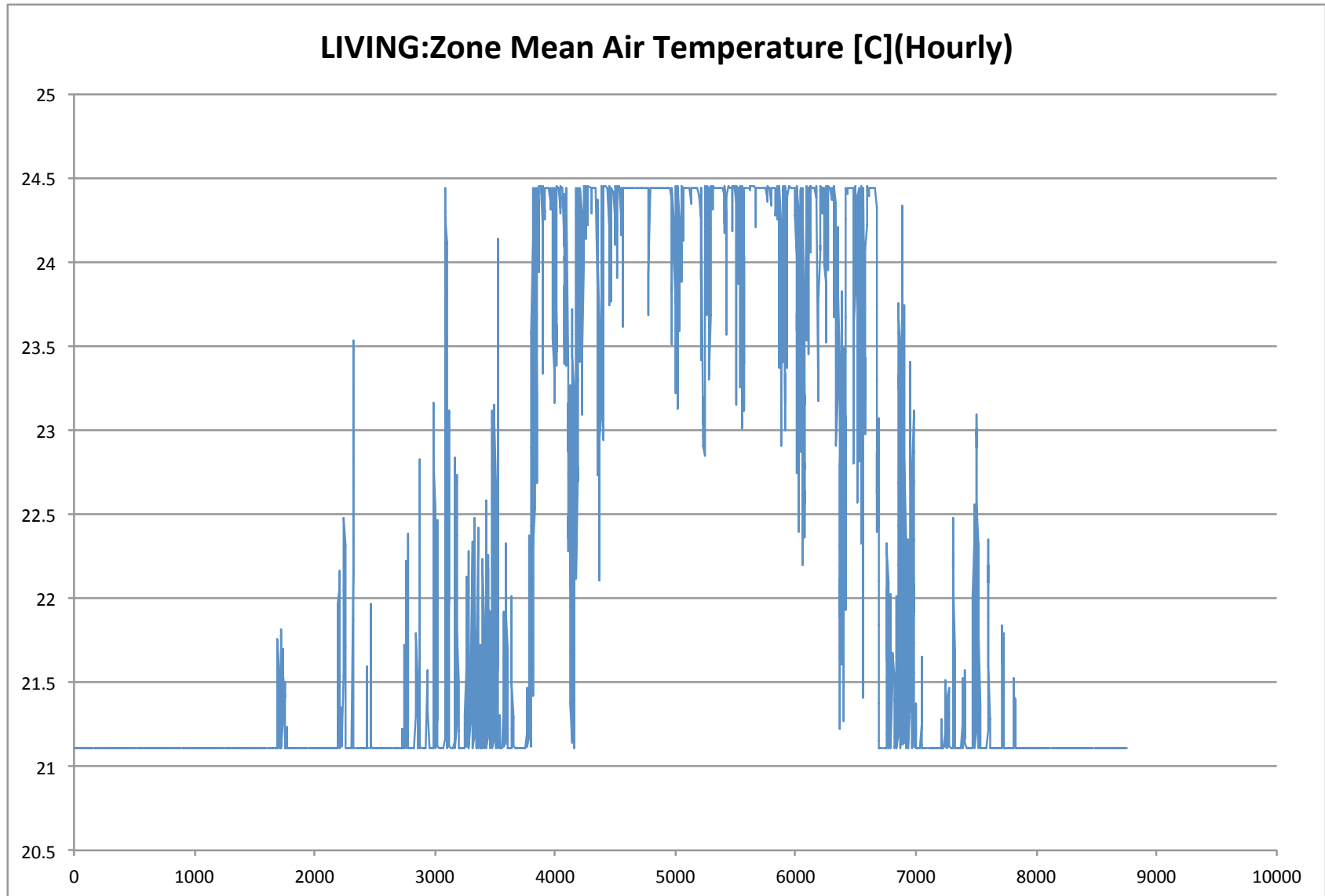
# Annual energy simulation: Example home in Chicago



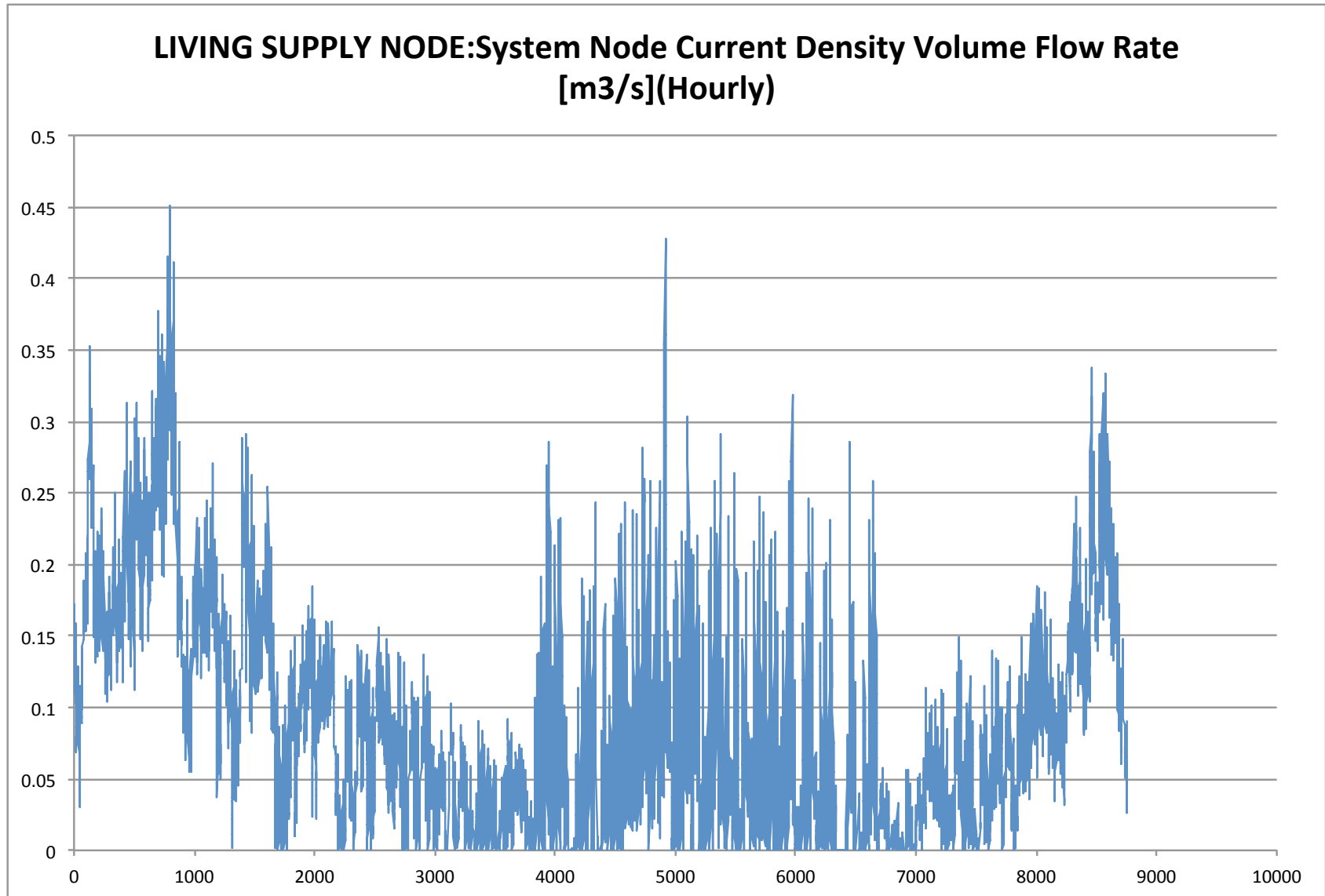
# Annual energy simulation: Example home in Chicago



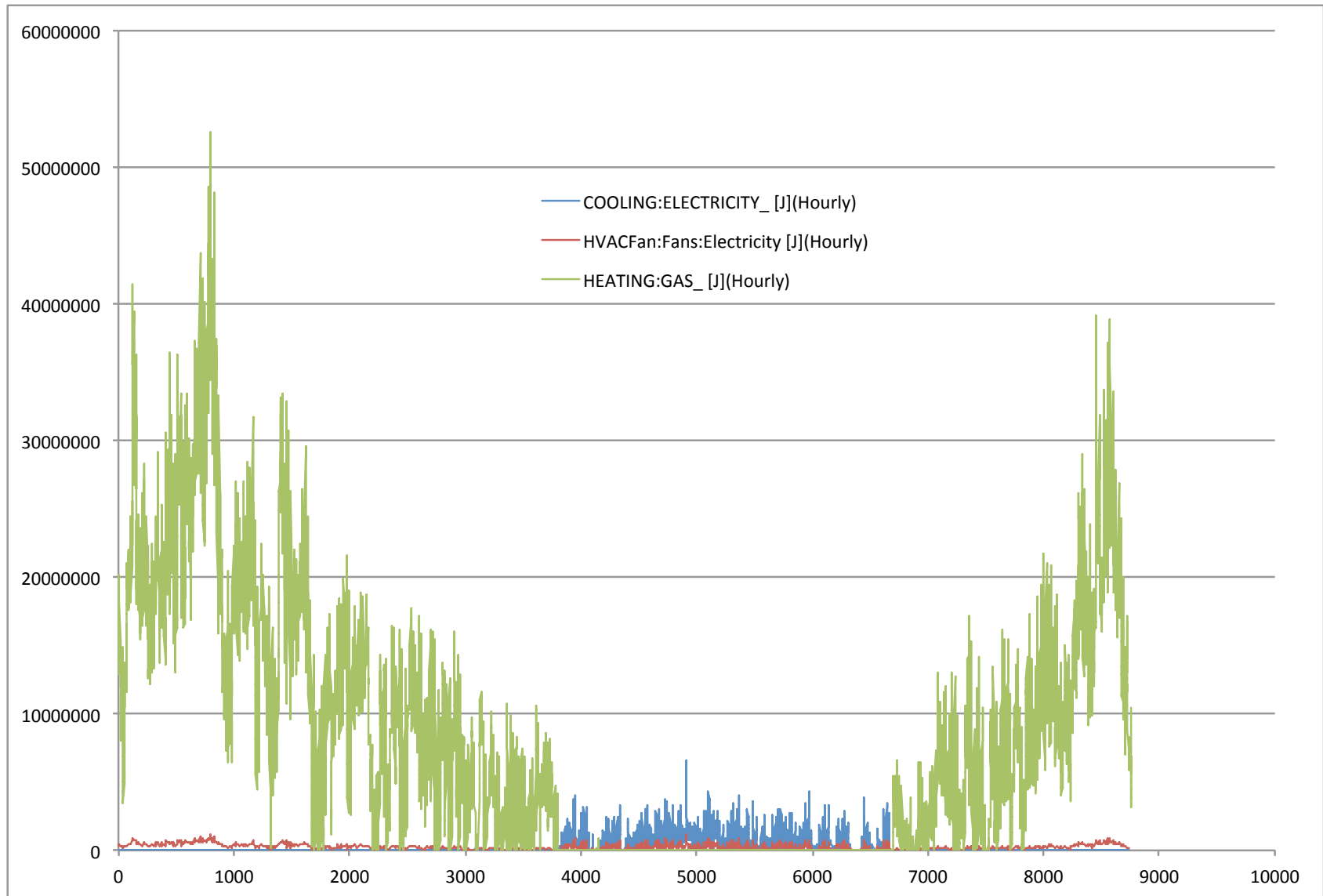
# Annual energy simulation: Example home in Chicago



# Annual energy simulation: Example home in Chicago



# Annual energy simulation: Example home in Chicago



# Annual energy simulation: Example home in Chicago

---

• Annual summary	<b>Electric</b>	<b>Gas</b>
Total J	29270600548	90956293121
Total kWh	8131	
Total MMBTU		86.2
\$/unit	\$0.10	\$8.00
<b>Annual energy cost</b>	<b>\$813</b>	<b>\$690</b>

~\$1500 in annual energy costs in this home

- Once we've established a baseline, we can make design and system changes to predict the impacts on energy, costs, and environmental pollution

# Cost analysis during design

---

- Were any of those enclosure design changes worth it financially?
- For any energy efficiency improvement, you expect lower energy bills
  - But that improvement also had an upfront (capital) cost
- Payback periods
  - How long will it take for energy savings to cover the initial cost?
  - Several methods to calculate
    - Simple payback
    - Cash flow analysis
    - Net present value
    - Internal rate of return
    - Return on investment



# Cost analysis during design

---

- Simple payback
  - Say you are considering a \$5,000 improvement
  - Your energy simulations predict \$350 per year in savings on energy bills
    - Assuming rates stay constant
  - The simple payback period is:  $Payback = \frac{\$5000}{\$350 / year} = 14.3 \text{ years}$
  - After ~14 years, you will have covered your upfront costs
- Rate of return on investment
  - Inverse of payback period

$$ROI = \frac{1}{14.3 \text{ years}} = 7\%$$

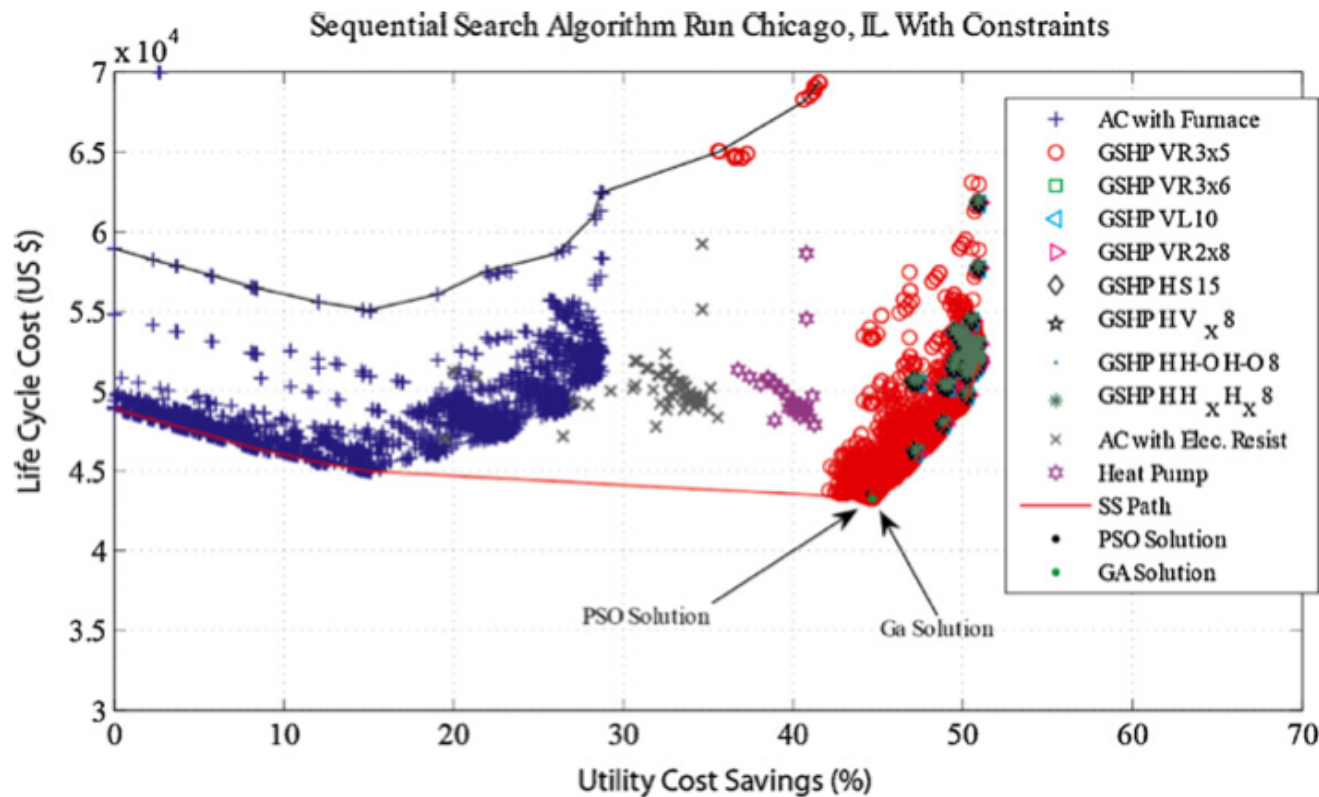
# Cost analysis during design

---

- Cash flow analysis and net present value methods
  - If you take out a loan to pay for efficiency improvements, you need to factor in the interest rate on that loan/mortgage
    - Will likely extend the payback period to cover principal + interest
- Other considerations:
  - Inflation
    - Somewhat predictable
  - Changes in energy costs
    - More variable
    - Most assume energy costs will rise at a constant rate
    - Not always the case (e.g., natural gas prices today)
    - If energy costs rise above predicted, payback period shortens
      - Vice versa for falling energy costs
- Overall: who pays capital costs and who pays for energy costs?

# Life cycle cost in design

- New methods of energy simulation are taking advantage of optimization algorithms to find least cost, most effective solutions for energy efficiency
- EnergyPlus and DOE2 engines both now integrate with BEopt



**Fig. 6.** LCC as a function of utility cost reduction for Chicago, IL.