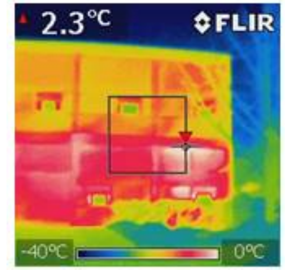
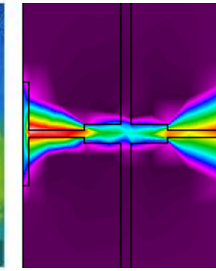
CAE 331/513
Building Science
Fall 2014





Week 11: November 4, 2014
Heating and cooling loads

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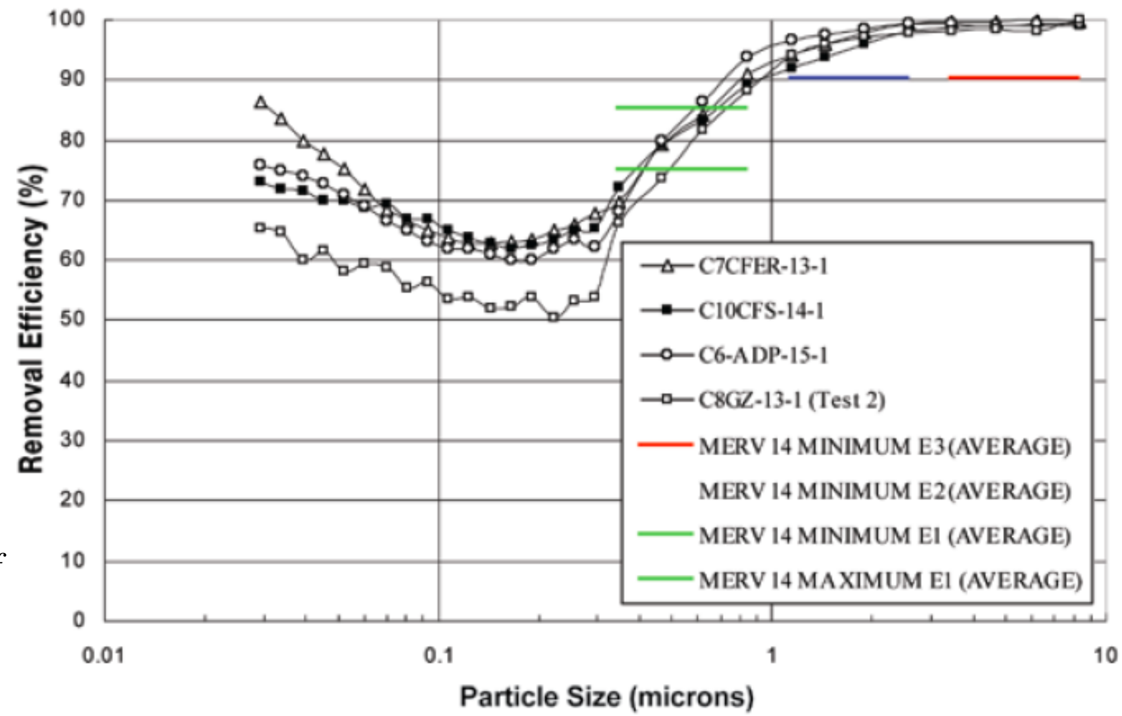
Scheduling updates

Week	Date	Lecture Topics	Reading	Assignment Due
1	Aug 26	Introduction to building science	Kreider Ch. 1	
	Aug 28	Pre-requisite review and energy concepts		
2	Sep 2	Heat transfer in buildings	Kreider Ch. 2	
	Sep 4	Heat transfer in buildings		HW1
3	Sep 9	Heat transfer in buildings	Kreider Ch. 6	
	Sep 11	*No class – away at a conference*		
4	Sep 16	Finish heat transfer in buildings	Kreider Ch. 6	
	Sep 18	Human thermal comfort	Kreider Ch. 4	
5	Sep 23	Psychrometrics (chart)	Kreider Ch. 4	
	Sep 25	Psychrometrics (equations)		HW2 (revised)
6	Sep 30	Psychrometrics (processes)		
	Oct 2	HVAC systems (introduction)	Kreider Ch. 9-10	HW3
7	Oct 7	*Class cancelled*		
	Oct 9	Exam review		
8	Oct 14	**Exam 1**		
	Oct 16	*Guest lecture: Tommy Zakrzewski, Buro Happold*		
9	Oct 21	HVAC systems (mechanical properties)		
	Oct 23	Ventilation and indoor air quality	Kreider Ch. 3/5	
10	Oct 28	Ventilation and indoor air quality		
	Oct 30	Finish indoor air quality (filtration) Heating loads	Kreider Ch. 7	
11	Nov 4	Cooling loads	Kreider Ch. 8	HW4
	Nov 6	Cooling loads		
12	Nov 11	Energy estimation	Kreider Ch. 14	HW5
	Nov 13	Energy efficiency and sustainable buildings		
13	Nov 18	**Exam 2**		
	Nov 20	Building performance diagnostics		
14	Nov 25	Electrical, lighting, and acoustics		HW6
	Nov 27	*No class – Thanksgiving Day*		
15	Dec 2	*No class – Review panel in DC*		
	Dec 4	*No class – Review panel in DC*		
15-16	TBD	We will schedule a final exam review sometime between Friday Dec 5 and Tuesday Dec 9		
Final	Dec 11	**Final exam (comprehensive): 2-4 pm**		

Last time

- Particle filtration
  - CADR
  - Removal efficiency
  - MERV

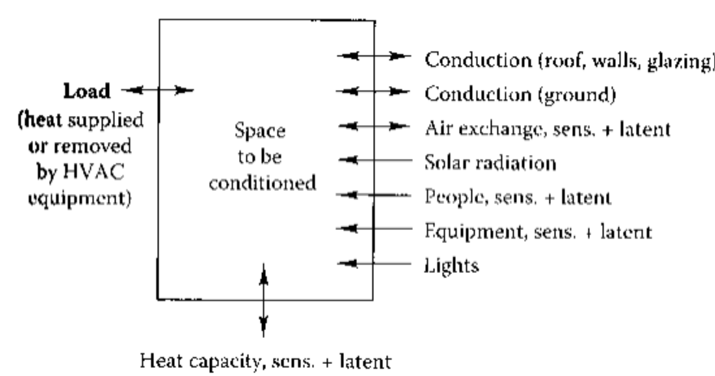
$$C = \frac{PC_{out} + \frac{E}{\lambda V}}{1 + \frac{CADR}{\lambda V}} \quad CADR = \eta \dot{V}_f$$



- Heating and cooling load calculations
  - Design conditions, losses/gains

$$Q_{h,\max} = K_{total}(T_{in} - T_{out}) - Q_{gain}$$

$$K_{total} = (UA)_{cond} + \rho C_p \dot{V}$$

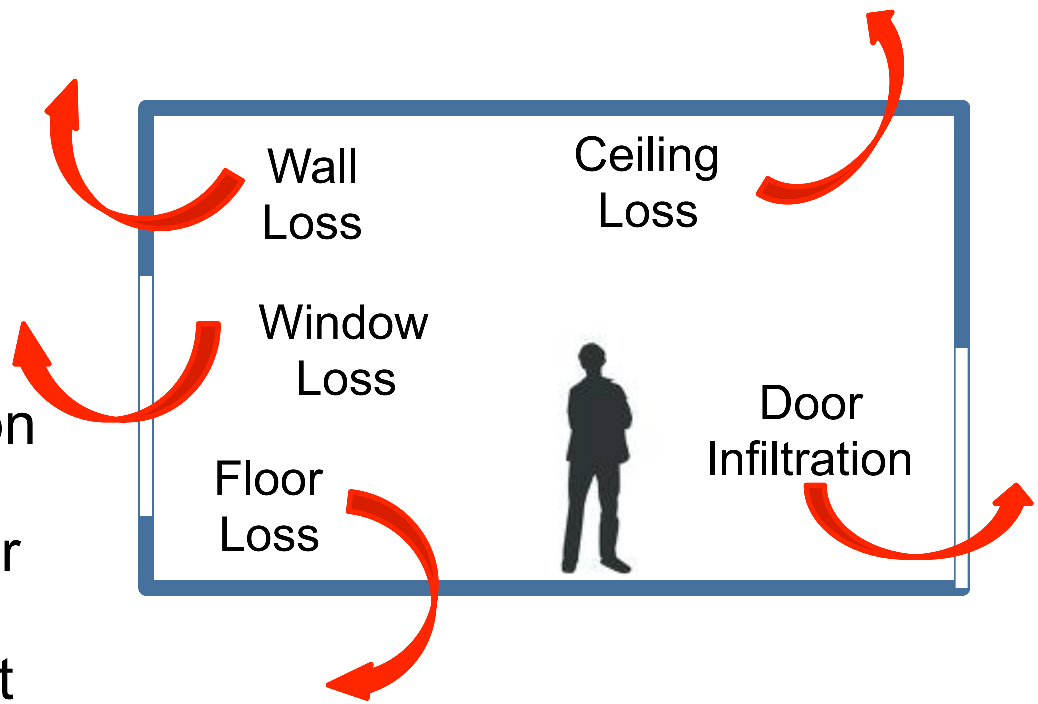


Heating load calculations

The peak heating load is simple and relies only on:

Overall envelope transmission and **infiltration**

- Transmission load (enclosure losses) is the heat lost to the outside through the building enclosure
  - Roof, wall, floor, window
- Infiltration load (or ventilation load) is the heat required to warm up the cold outside air that leaks into the building through cracks or is brought in via ventilation



Heating load calculations

$$Q_{h,\max} = K_{total}(T_{in} - T_{out}) - Q_{gain}$$

Example:

- Find the design heat load for a 12 m x 12 m x 2.5 m (39.4 ft x 39.4 ft x 8.2 ft) building with an insulated (R-4.2 m^2K/W) flat roof and R-2.5 m^2K/W walls
  - Double glazed windows (U = 3 W/m^2K) cover 20% of the walls
  - The air exchange rate is 0.5 per hour
  - Ignore floor heat transfer
  - Design conditions of -10°C (14°F) out and 22°C (71.6°F) in
  - Internal gains = 1 kW (3.4 kBTU/hr)

Selecting equipment

- Once you know your design heating load, you can select equipment

$$Q_{h,\max} = 5.5\ \mathrm{kW} = 18.7\ \mathrm{kBTU/hr}$$

XB80 >

80 percent efficient furnace with AFUE
Four-speed blower motor
Single-stage heating furnace

Add to Compare

Cost:	$$$$$
AFUE (Heating Efficiency):	80
Energy Star:	No
Convertible:	Yes

XC95m >

Up to 97.3% AFUE
Communicating capability
Fully modulating heat

Add to Compare

Cost:	$$$$$
AFUE (Heating Efficiency):	Up to 97.3% AFUE
Energy Star:	Yes
Convertible:	Yes

Selecting equipment

- Once you know your design heating load, you can select equipment

$$Q_{h,\max} = 5.5 \text{ kW} = 18.7 \text{ kBTU/hr}$$

MODEL	HEIGHT (IN.)	WIDTH (IN.)	DEPTH (IN.)	NOMINAL CAPACITY OUTPUT (BTUH)
TUE1A040A9241A	40	14.5	28	31,000
TUE1A060A9241A	40	14.5	28	47,000
TUE1A060A9361A	40	14.5	28	47,000
TUE1B060A9361A	40	17.5	28	47,000
TUE1B080A9361A	40	17.5	28	63,000

COOLING LOADS

Cooling loads

- Cooling load calculations are more complicated than heating load calculations
- Peak cooling loads will be during the day when solar radiation is present
  - People and equipment can also be highly variable
- Radiation varies during the day and building **thermal mass** affects radiative heating and cooling
  - Calculations must be ***dynamic*** to account for ***storage***

$$Q_{sensible} = Q_{cond} + Q_{air} + Q_{floor} - Q_{gains} \pm Q_{storage}$$

Remember:
Q is positive (+) when there is a heating load (cold outside)
Q is negative (-) when there is a cooling load (hot outside)

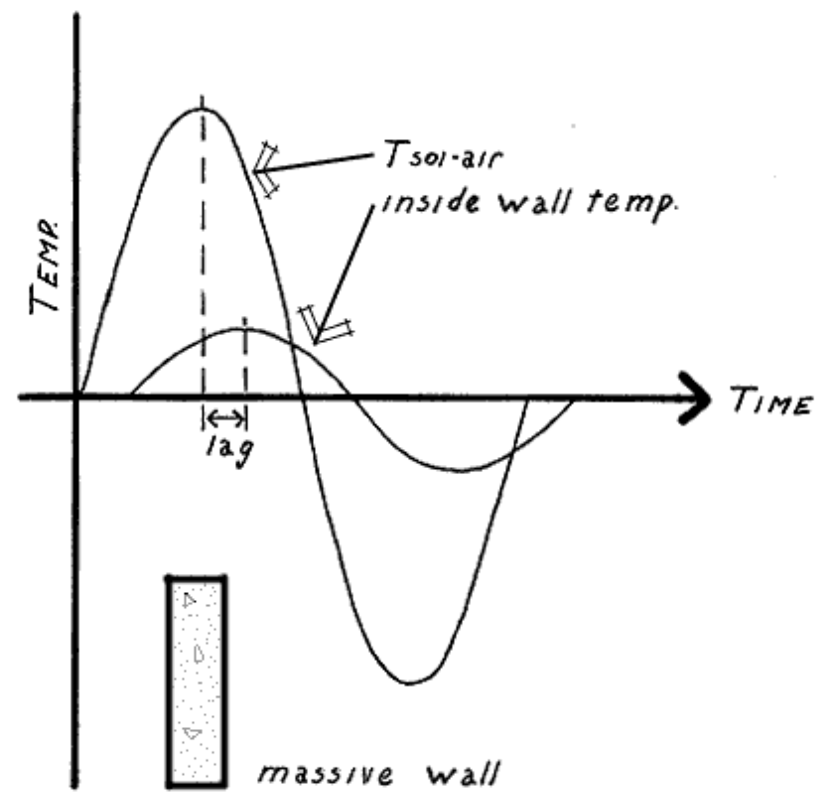
Dynamic response for cooling loads

- Cooling load calculations differ because gains from **radiation** do not directly heat up the air in the space
  - Only **convection** from interior surfaces contributes to an immediate temperature rise in the air space
- Radiation through windows and from interior surfaces will be absorbed by other interior surfaces, and then those surfaces will eventually transfer that heat energy to the air by convection
  - But the addition of heat doesn't occur immediately
- Because radiative heating is not direct, **heat storage** through **thermal mass** can create a thermal lag and this can have a large effect on cooling loads

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)



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

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 = $\rho L A C_p$ 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, 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:

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

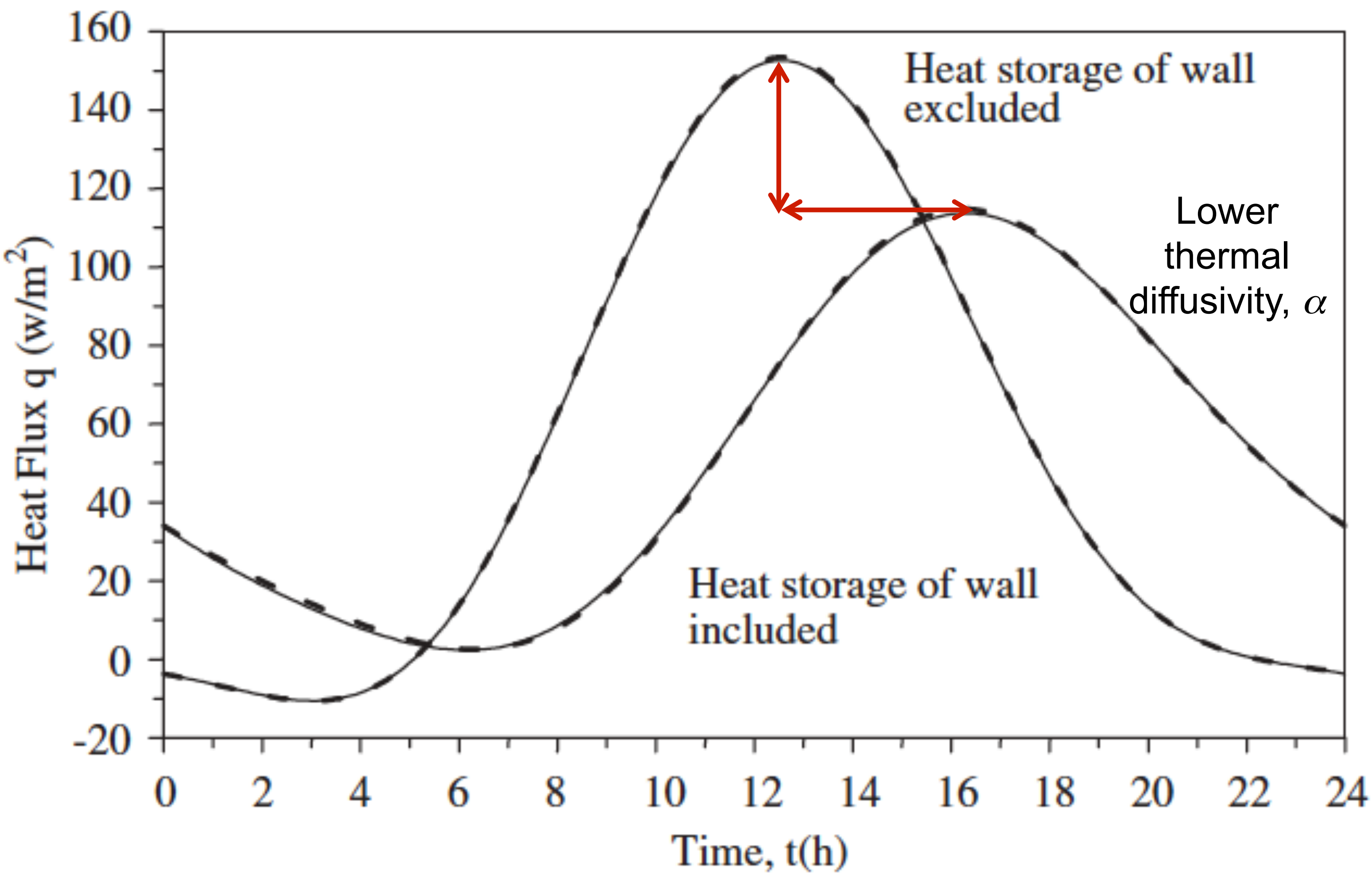
- The lower the α, the better the material is as a thermal mass (low conductivity relative to storage ability)
  - The time lag between peak internal and external temperature is related to the diffusivity of the walls
  - Steel has a high ρC_p but also a high k so it is not as good a thermal mass as 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	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	—	0.99-053	—	—
Limestone concretes	2240	1.60	—	0.62	—	—
	1920	1.14	—	0.88	—	—
	1600	0.79	—	1.26	—	—

Accounting for thermal mass impacts



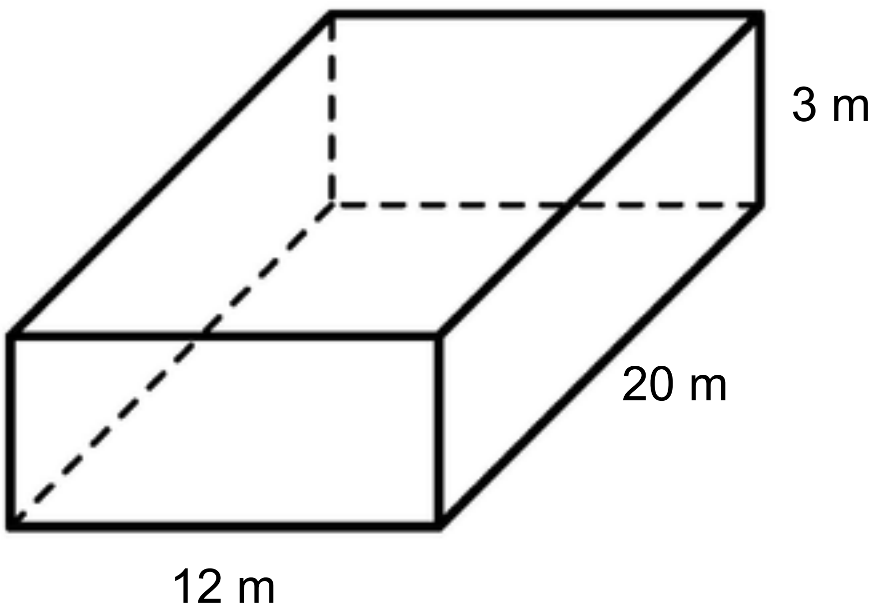
Asan, H. 2006. Numerical computation of time lags an decrement factors for different building materials. *Building and Environment* 41:615-620.

Dealing with thermal mass in cooling load calculations

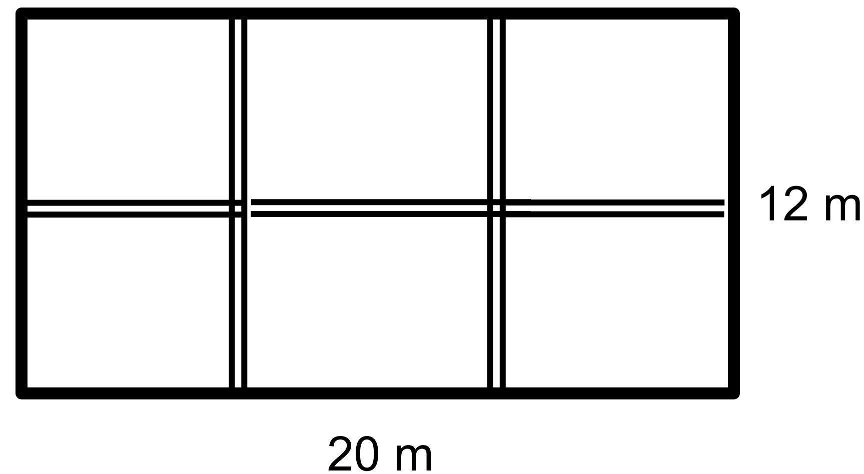
- How important is it to consider thermal mass in cooling load calculations?

Dealing with thermal mass in cooling load calculations

- Imagine a house with interior drywall partitions, exterior drywall, a concrete floor, and no internal gains:



Assume there are 6 rooms



- 0.5 inches thick gypsum drywall in the roof and walls
- 4 inches of concrete in the floor
- Area of interior + exterior drywall =
  (20m)(3m)(4 sides) + (12m)(3m)(6 sides) = 456 m^2

Dealing with thermal mass in cooling load calculations

- If you account for the heat capacity of all the materials:

Location	Material	Area, A (m^2)	Thickness, L (m)	V=AL (m^3)	Cp (kJ/kgK)	ρ (kg/m^3)	ρCp (kJ/m^3K)	HC=ρCpV (kJ/K)
Roof	Drywall	240	0.013	3.1	1.2	800	960	2995
Walls	Drywall	456	0.013	5.9	1.2	800	960	5691
Concrete	Floor	240	0.102	24.4	0.92	2000	1840	44867
Indoor	Air	240	3	720	1	1.15	1.15	828
							Total HC	**54381**

- Suppose during a summer afternoon the mean temperature of this mass increases just 1°C during a 5 hour period:

$$\frac{\Delta T}{\Delta t} = \frac{1\ \mathrm{K}}{5\ \mathrm{hours}} = 0.2\ \frac{\mathrm{K}}{\mathrm{hr}}$$

Dealing with thermal mass in cooling load calculations

- The amount of thermal energy stored in materials would be:

$$Q_{storage} = V\rho C_p \frac{\Delta T}{\Delta t} = (54381\frac{\text{kJ}}{\text{K}})(0.2\ \frac{\text{K}}{\text{hr}})(\frac{1\text{hr}}{3600\text{s}}) \approx 3\ \text{kW}$$

- At summer design conditions of T_{in} = 22°C and T_{out} = 36°C and assuming K_{tot} = 250 W/K

$$Q_{sensible} = K_{tot}(T_{in} - T_{out}) + Q_{storage}$$

$$Q_{sensible} = (250\frac{\text{W}}{\text{K}})(22 - 36°\text{C}) + 3000\ \text{W}$$

$$Q_{sensible} = 500\ \text{W}$$

Dealing with thermal mass is necessary for other types of loads as well

- Need to account for heat capacity of building materials and the fraction of radiative versus convective heat given off by systems and equipment

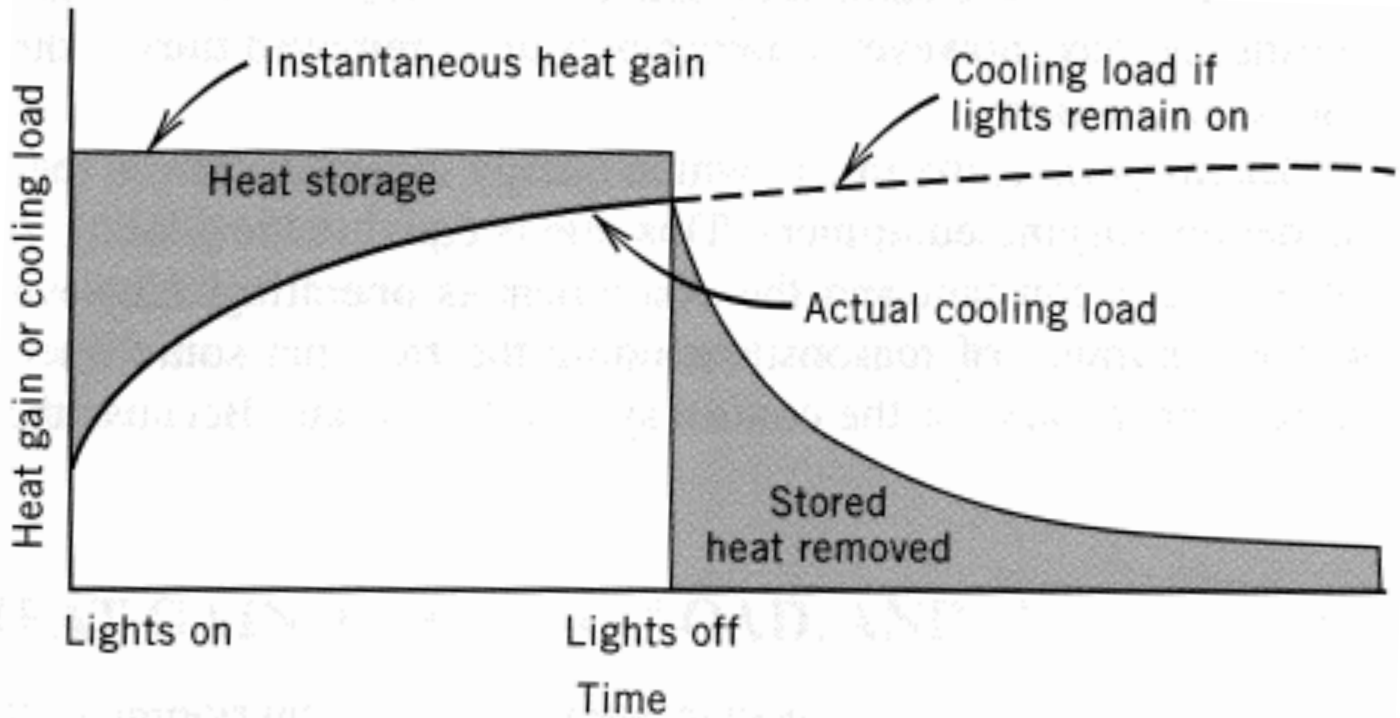


Figure 8-3 Actual cooling load from fluorescent lights.

Dynamic thermal mass: Example in a Hot Box

- Three 25 W bulbs inside a 1 m^3 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

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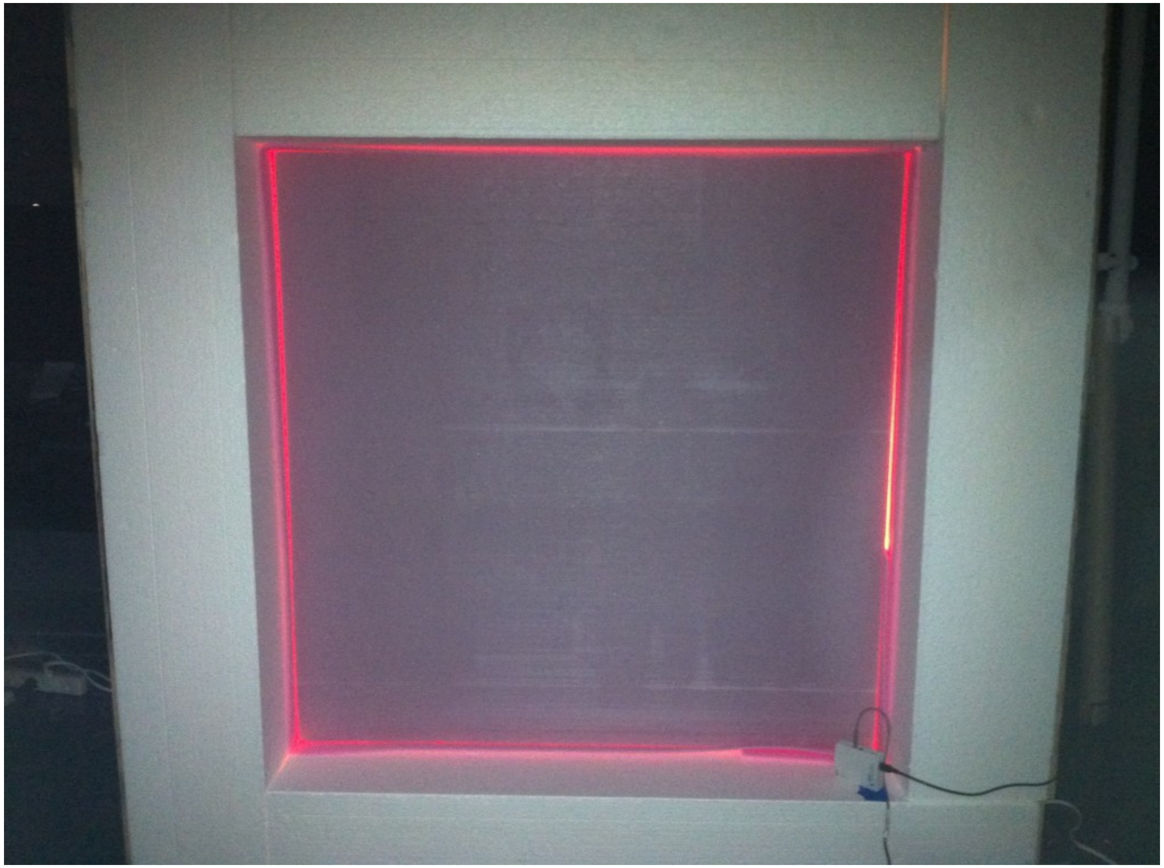
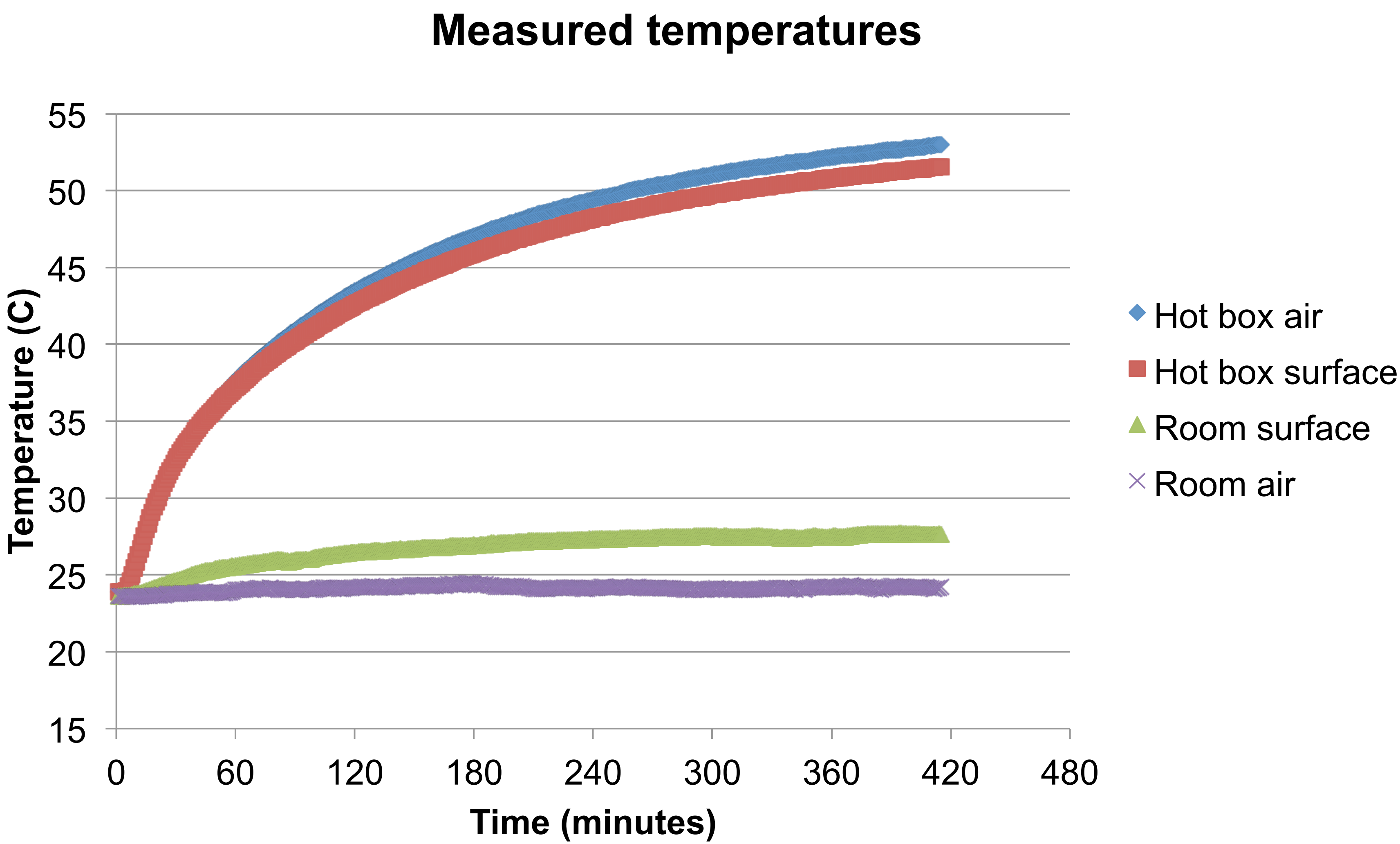
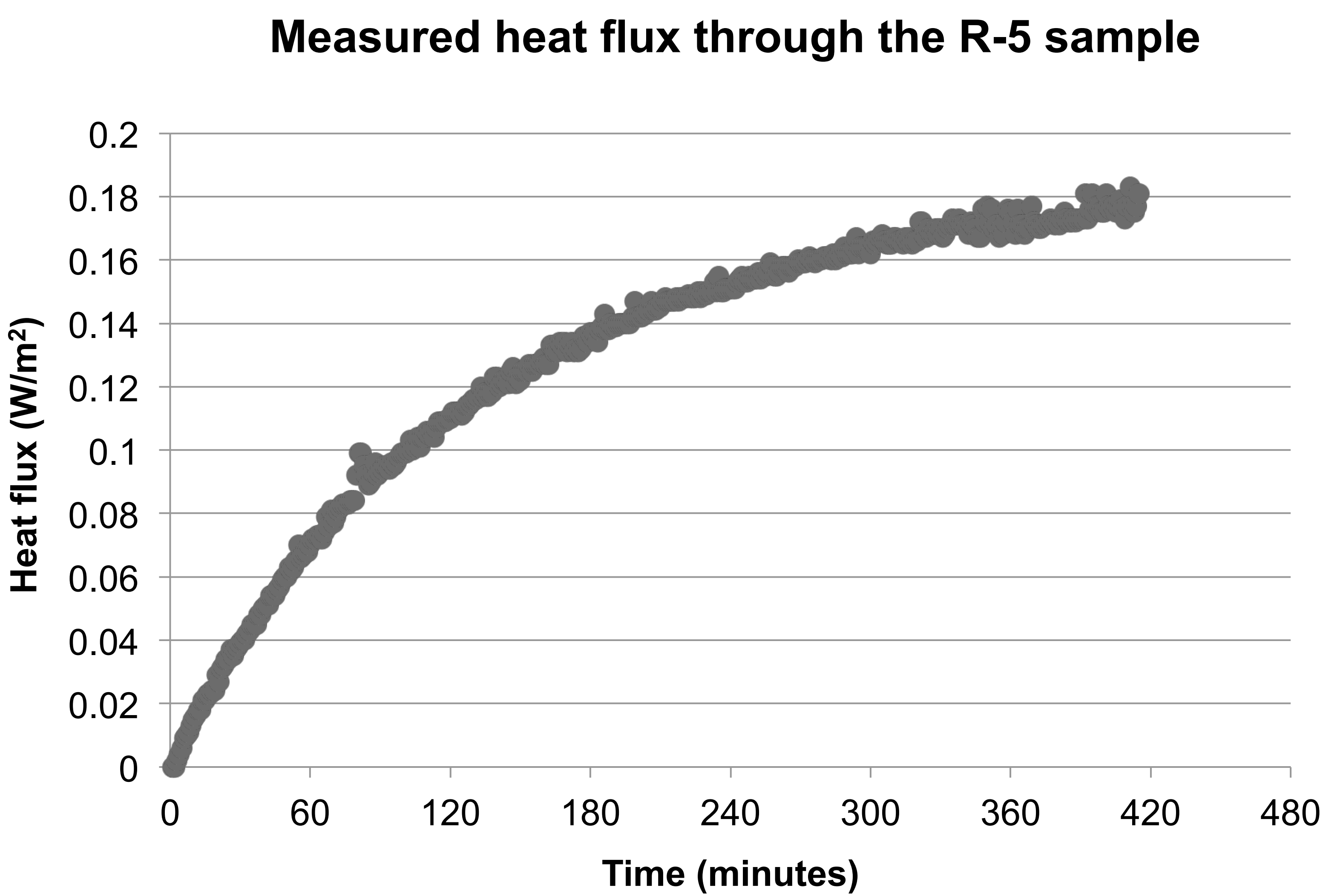


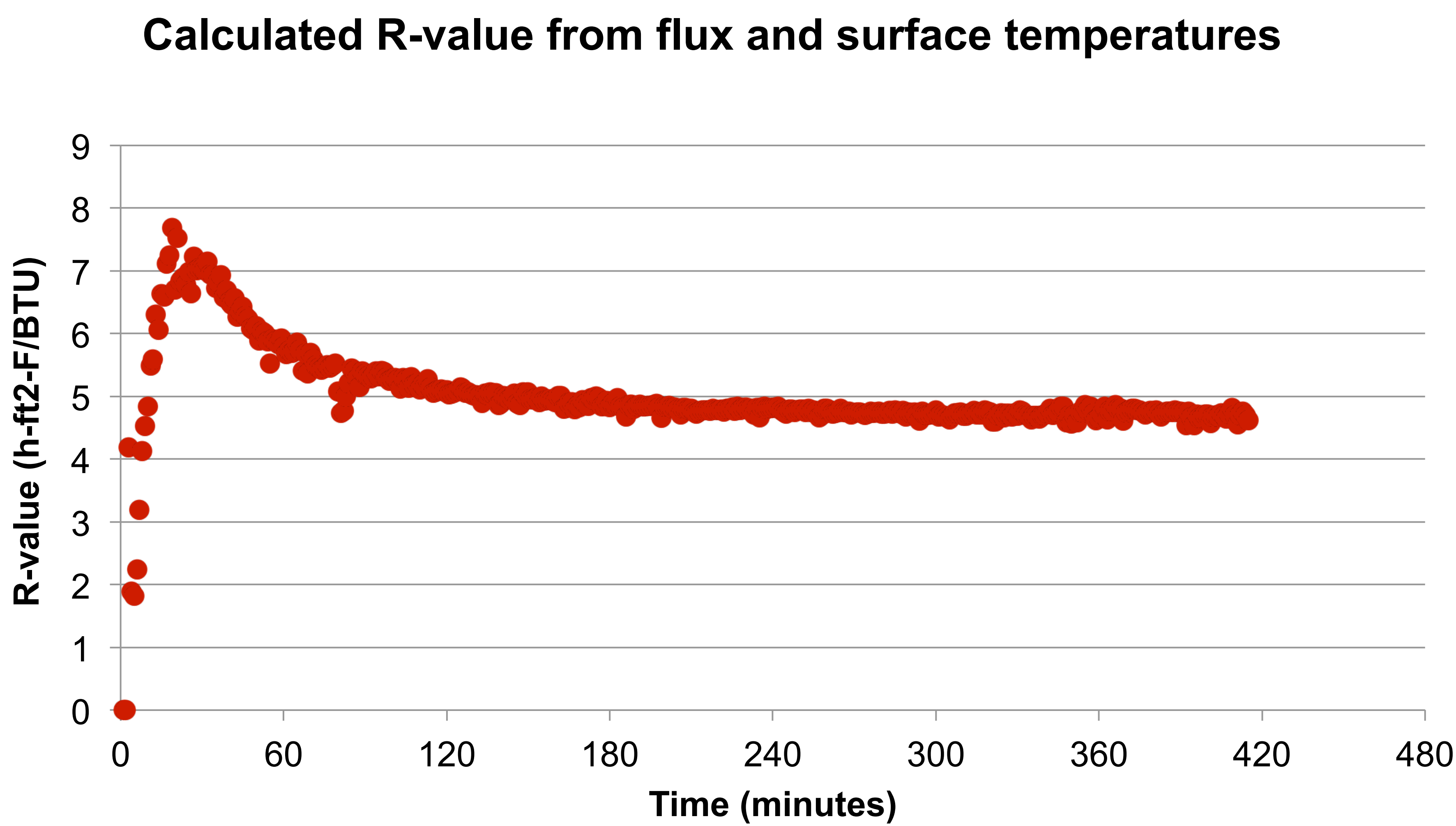
Dynamic thermal mass: Example in a Hot Box



Dynamic thermal mass: Example in a Hot Box

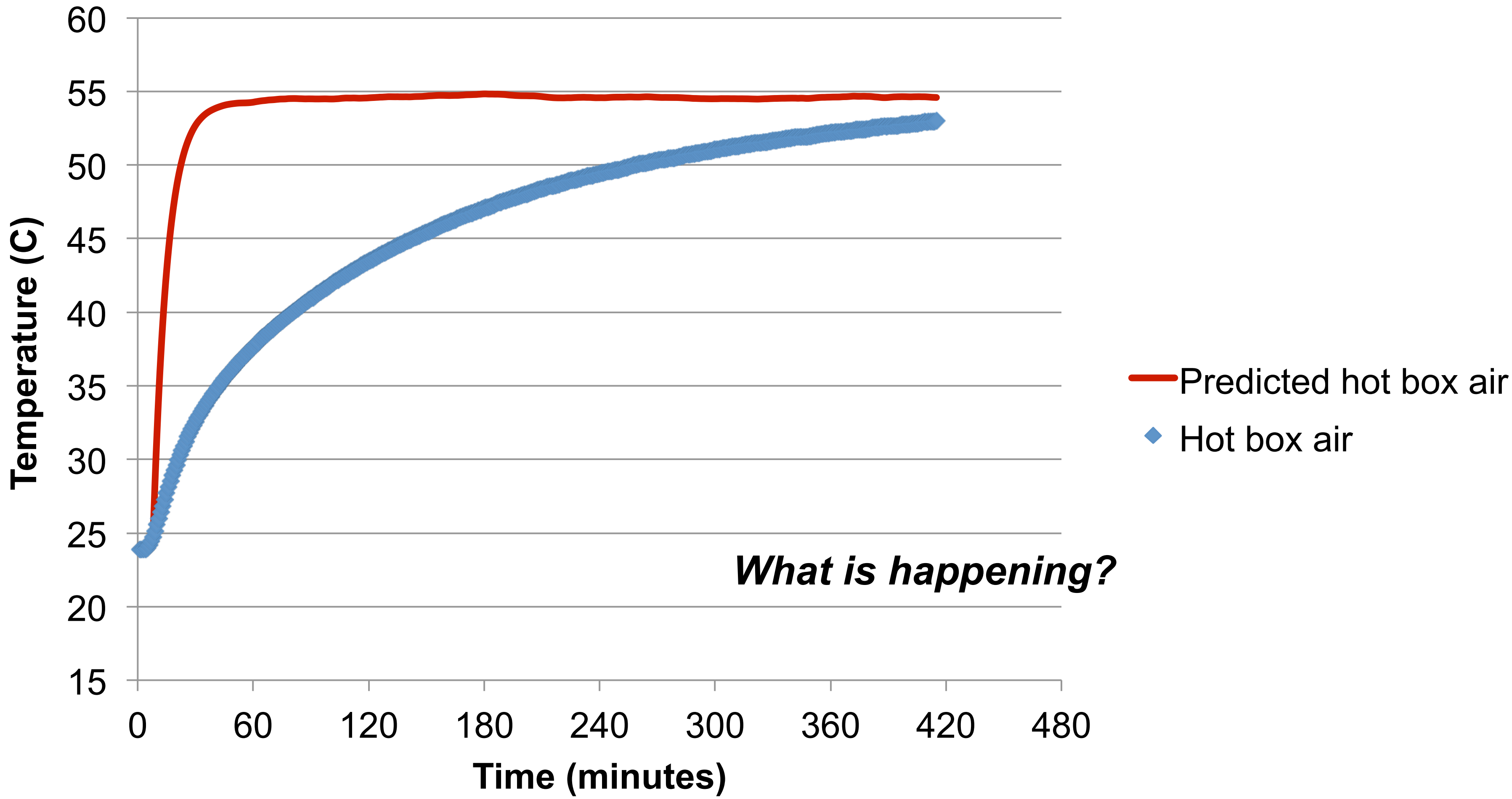


Dynamic thermal mass: Example in a Hot Box



Dynamic thermal mass: Example in a Hot Box

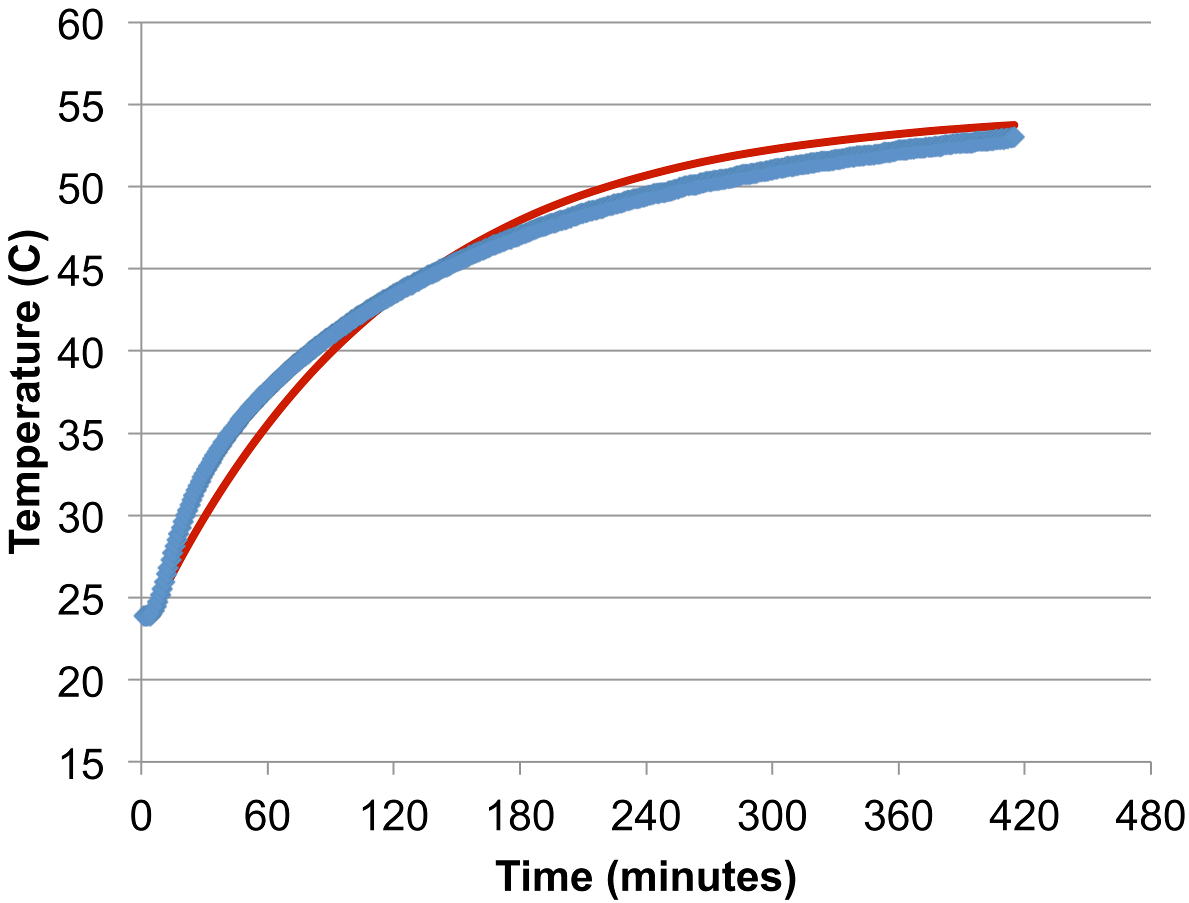
Predicted hot box air temperatures (ignoring heat capacity of insulation)



What is happening?

Dynamic thermal mass: Example in a Hot Box

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



Assuming:
Density = 13 kg/m^3
C_p = 1200 J/kgK
V = 1 m^3

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

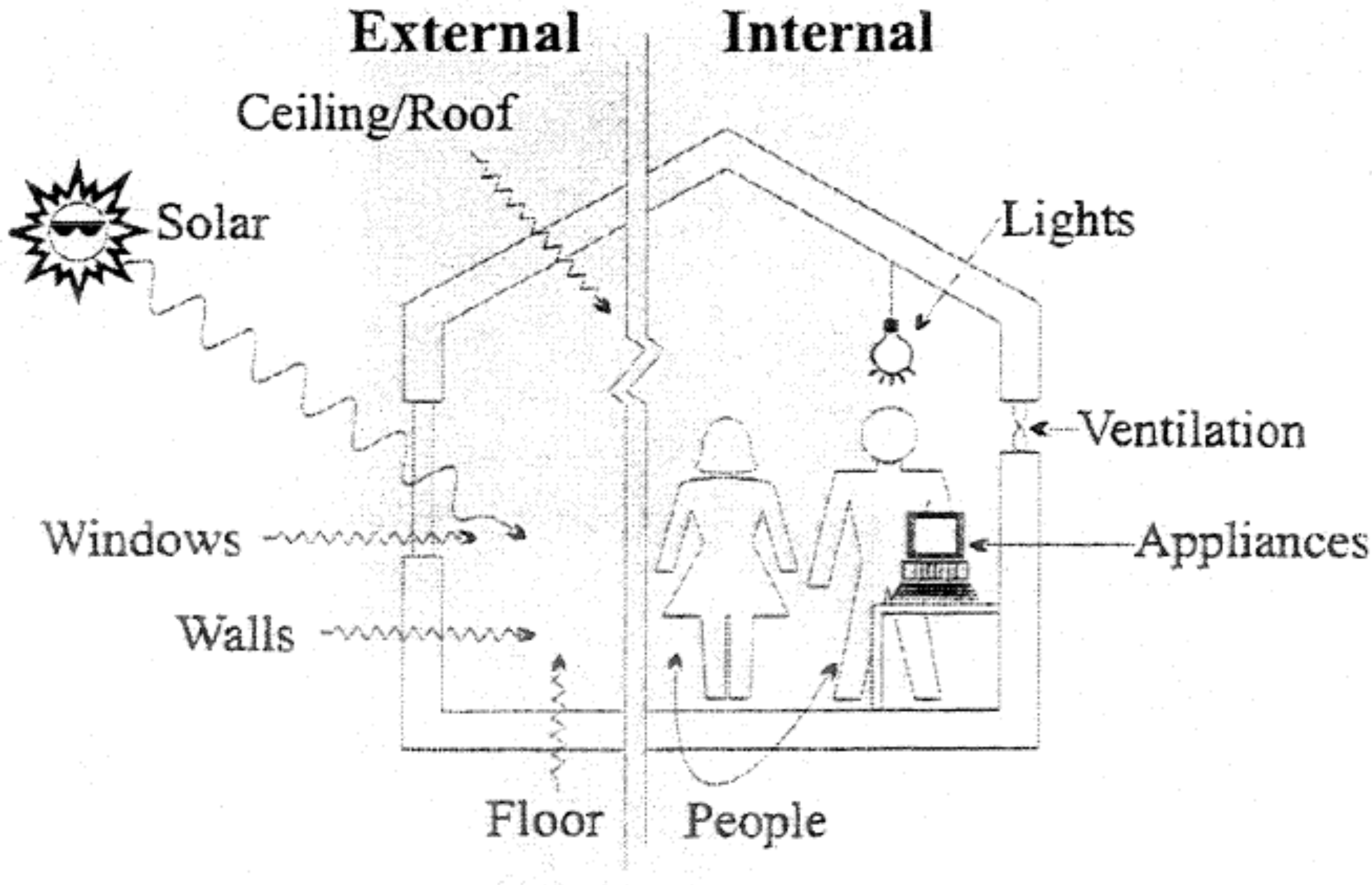
COOLING LOAD CALCULATION METHODS

Cooling load calculation methods

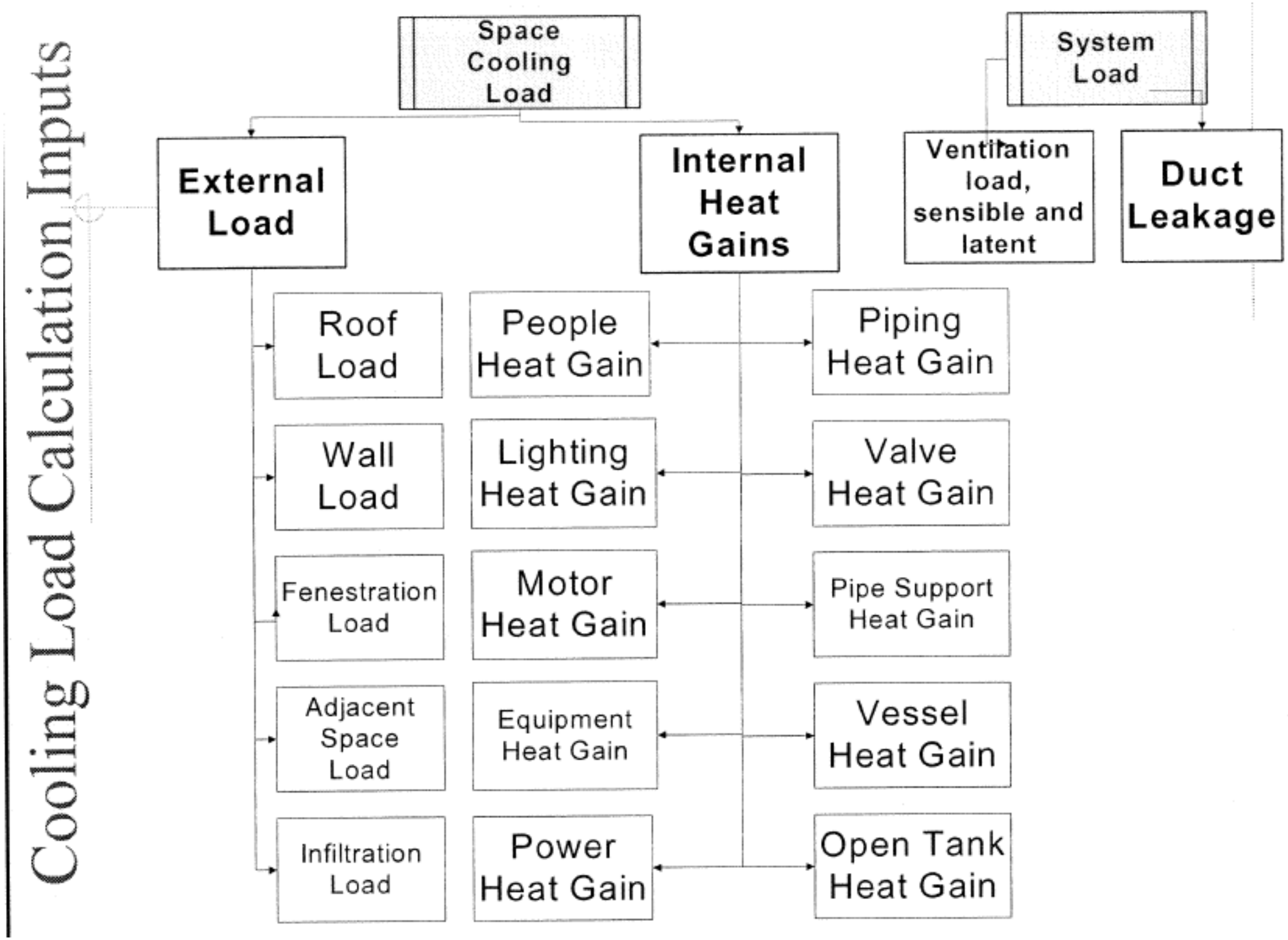
- Dynamic response and thermal mass makes cooling load calculations much more complex than heating load calculations

- There are many methods of estimating peak cooling loads
  - They vary in complexity, accuracy, computational time, and requirements for detailed inputs
  - Almost all methods require a computer program to solve

Internal and external inputs for cooling load calculations



Inputs for all cooling load calculations

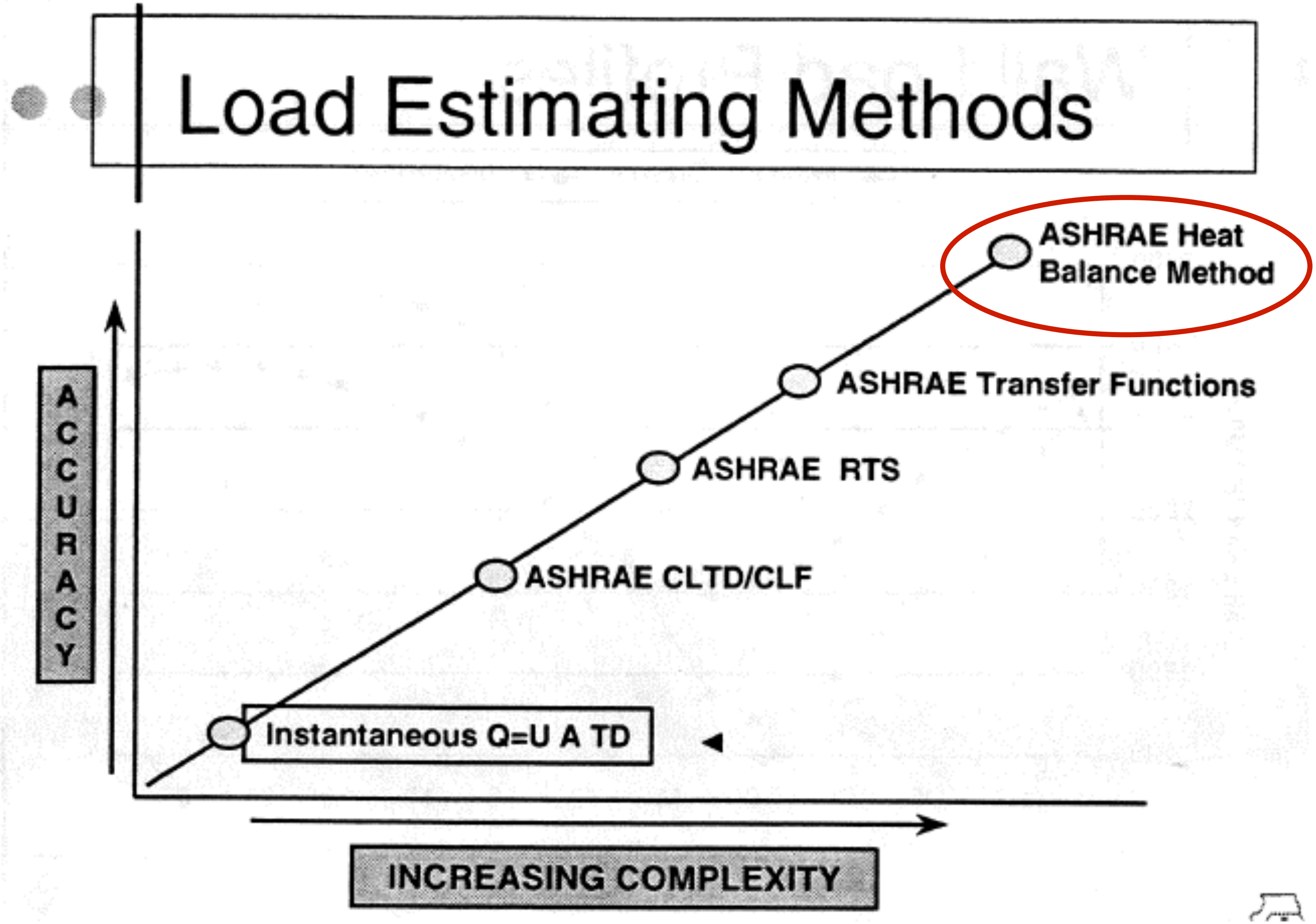


There are several cooling load calculation methods

- Transfer Function
- Total Equivalent Temperature Difference (TETD)
- Cooling Load Temperature Difference / Cooling Load Factor (CLTD/CLF)
- Heat Balance Method (HBM)
- Radiant Time-Series Method (RTSM)

- They all rely on spreadsheets and/or computer programs

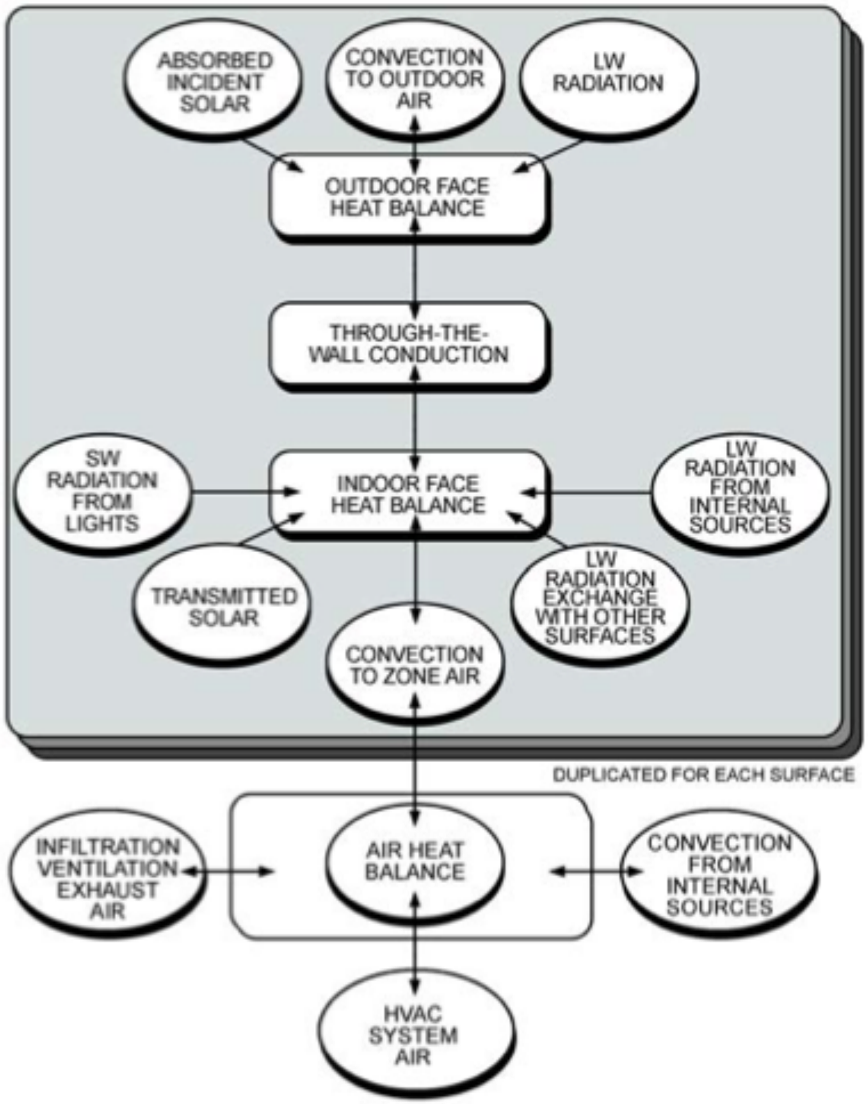
Accuracy of methods



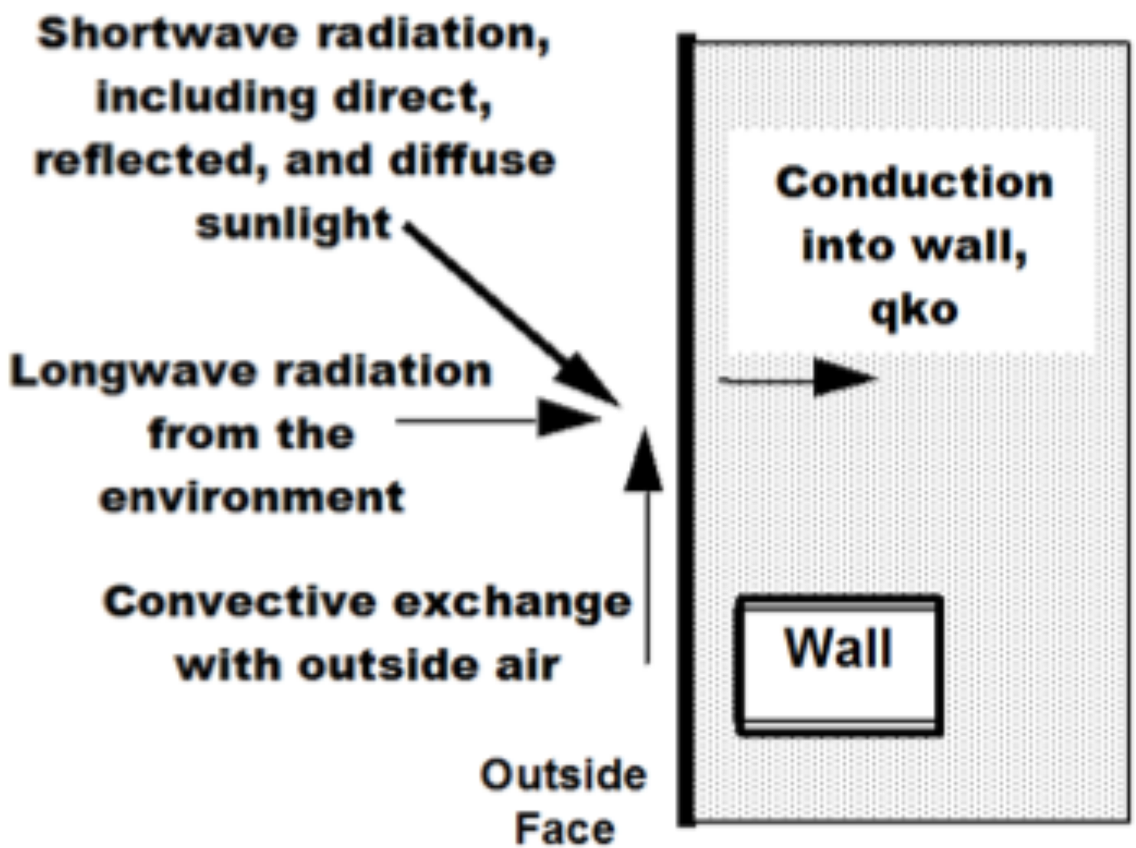
Heat balance method (HBM)

- HBM is based on the law of conservation of energy
  - A set of energy balance equations for an enclosed space is solved simultaneously for unknown surface and air temperatures
- Consists of three important energy balance equations:
  - Outside surfaces heat balance
  - Inside surfaces heat balance
  - Indoor air heat balance
    - The energy balance is based on the fundamental heat transfer equations we already know
- Calculations are initiated by hourly outdoor weather data
  - Design day meteorological data (or full year)
- It is more fundamentally linked than other approaches
  - Makes fewer assumptions than the other methods
    - But is more complex to solve
  - Provides basis for modern energy simulation programs

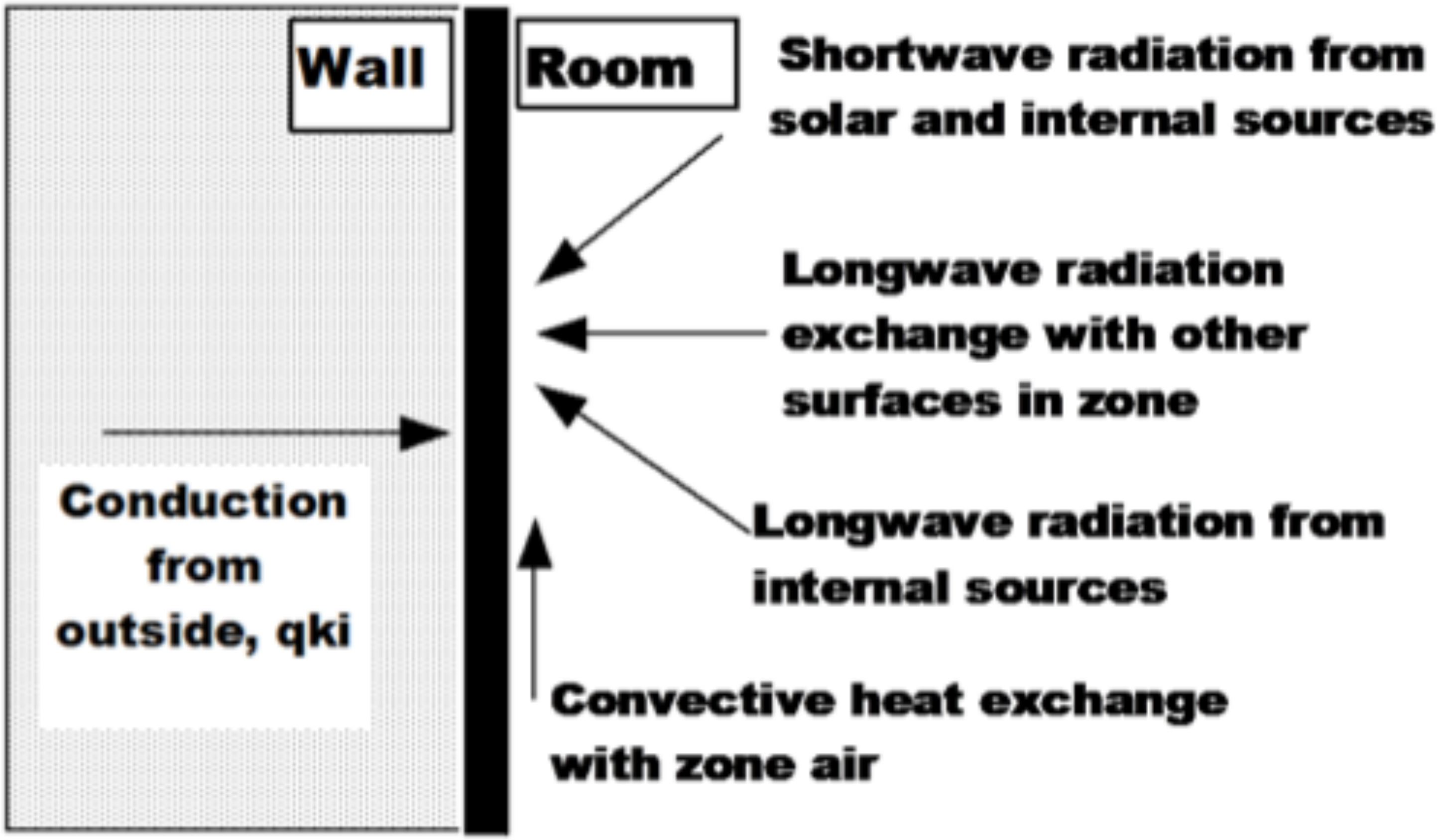
Heat balance method (HBM)



Heat balance method (HBM): Outside surface heat balance

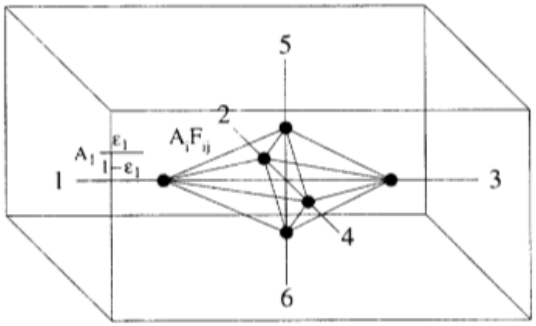


Heat balance method (HBM): Inside surface heat balance



Heat balance method (HBM): Indoor air heat balance

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



where:

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$ = sum of the convective internal loads

$\sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right)$ = convective heat transfer from the zone surfaces

$\dot{m}_{\inf} C_p \left(T_\infty - T_z\right)$ = heat transfer due to infiltration of outside air

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p \left(T_{zi} - T_z\right)$ = heat transfer due to interzone air mixing

$\dot{Q}_{sys}$ = air systems output

$C_z \frac{dT_z}{dt}$ = energy stored in zone air

$C_z = \rho_{air} C_p$

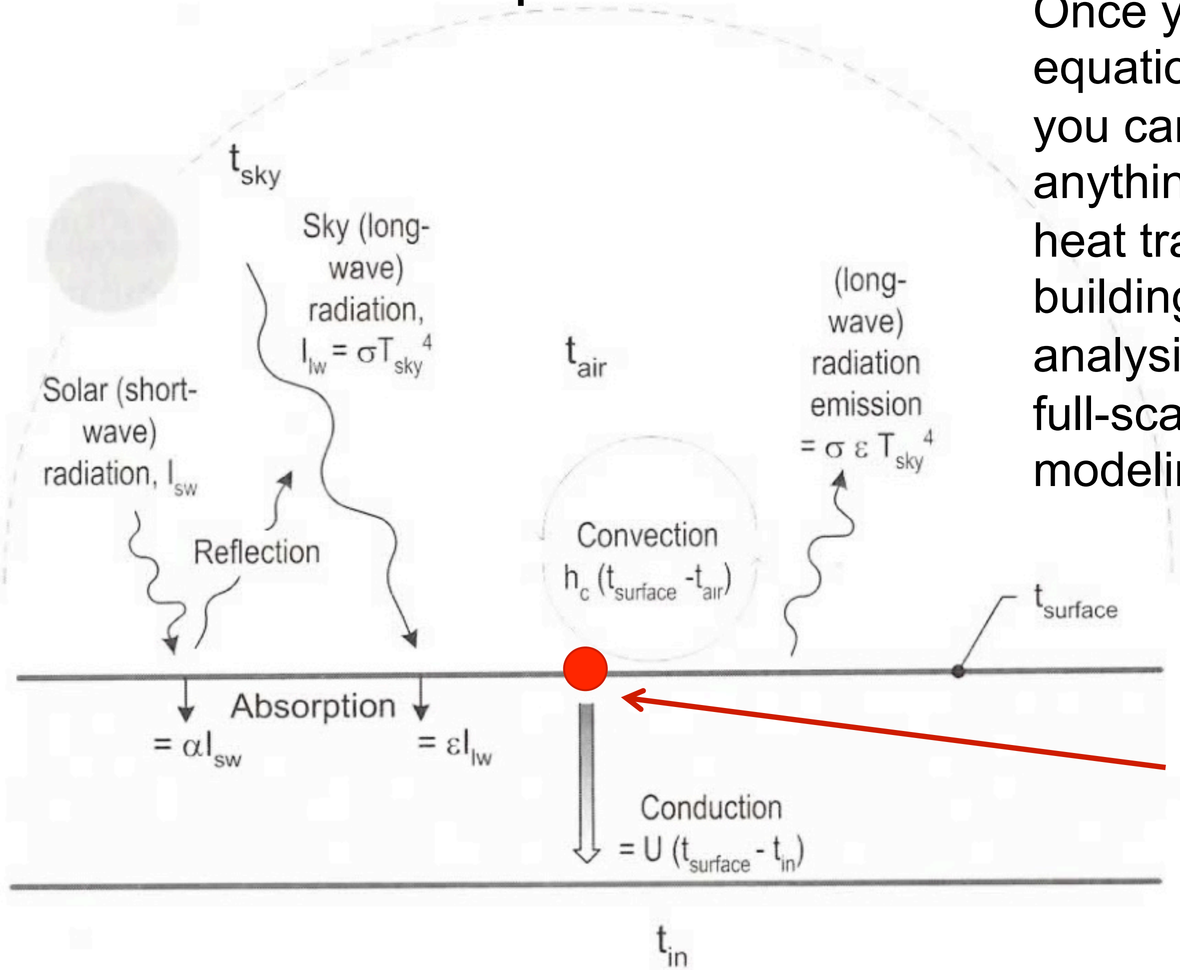
ρ_{air} = zone air density

C_p = zone air specific heat

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

HBM: Surface energy balance

- Exterior surface example: roof



Once you have this equation described, you can do just about anything regarding heat transfer in building enclosure analysis, leading into full-scale energy modeling

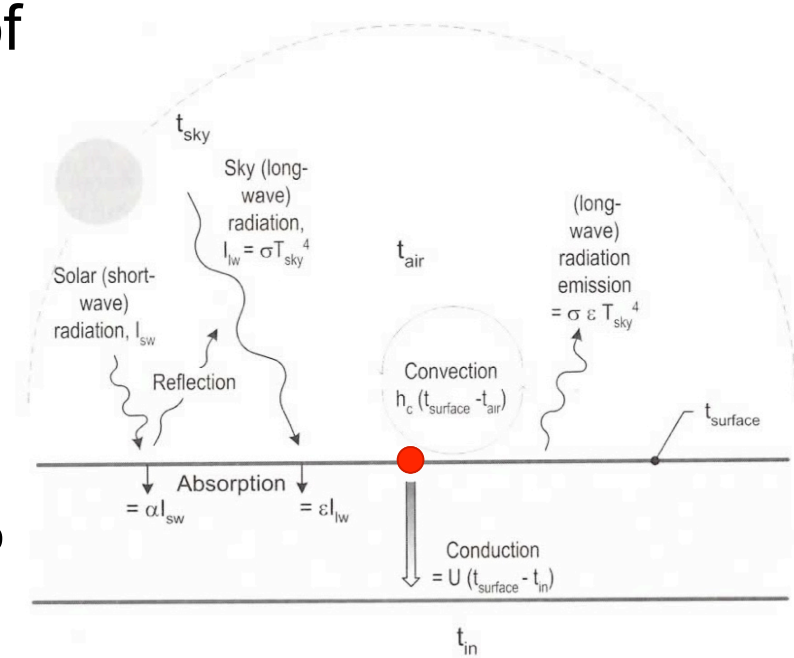
Steady-state energy balance at this exterior surface:
What enters must also leave (no storage)

$$q_{solar} + q_{longwaveradiation} + q_{convection} - q_{conduction} = 0$$

HBM: Surface energy balance

- Exterior surface example: roof

$$\boxed{\sum q = 0}$$



We can use this equation to estimate indoor and outdoor surface temperatures

At steady state, net energy balance is zero

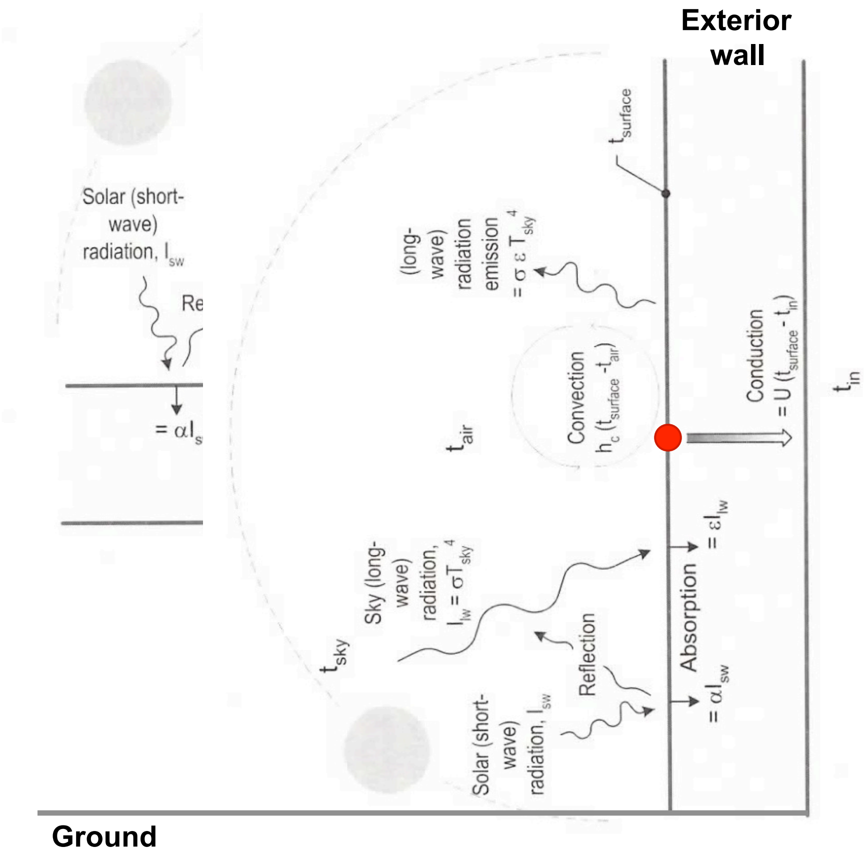
- Because of T^4 term, often requires iteration

Solar gain	αI_{solar}	$q_{sw,solar}$
Surface-sky radiation	$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surf}^4)$	$+q_{lw,surface-sky}$
Convection on external wall	$+h_{conv}(T_{air} - T_{surface})$	$+q_{convection}$
Conduction through wall	$-U(T_{surface} - T_{surface,interior}) = 0$	$-q_{conduction} = 0$

HBM: Surface energy balance

- Similarly, for a vertical surface:

$$q_{solar} + q_{lwr} + q_{conv} - q_{cond} = 0$$



$$\alpha I_{solar}$$
$$+\varepsilon_{surface}\sigma F_{sky}(T_{sky}^4 - T_{surface,ext}^4)$$
$$+\varepsilon_{surface}\sigma F_{ground}(T_{ground}^4 - T_{surface,ext}^4)$$
$$+h_{conv}(T_{air} - T_{surface,ext})$$
$$-U(T_{surface,ext} - T_{surface,int}) = 0$$

HBM: Combining surface energy balances

- 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

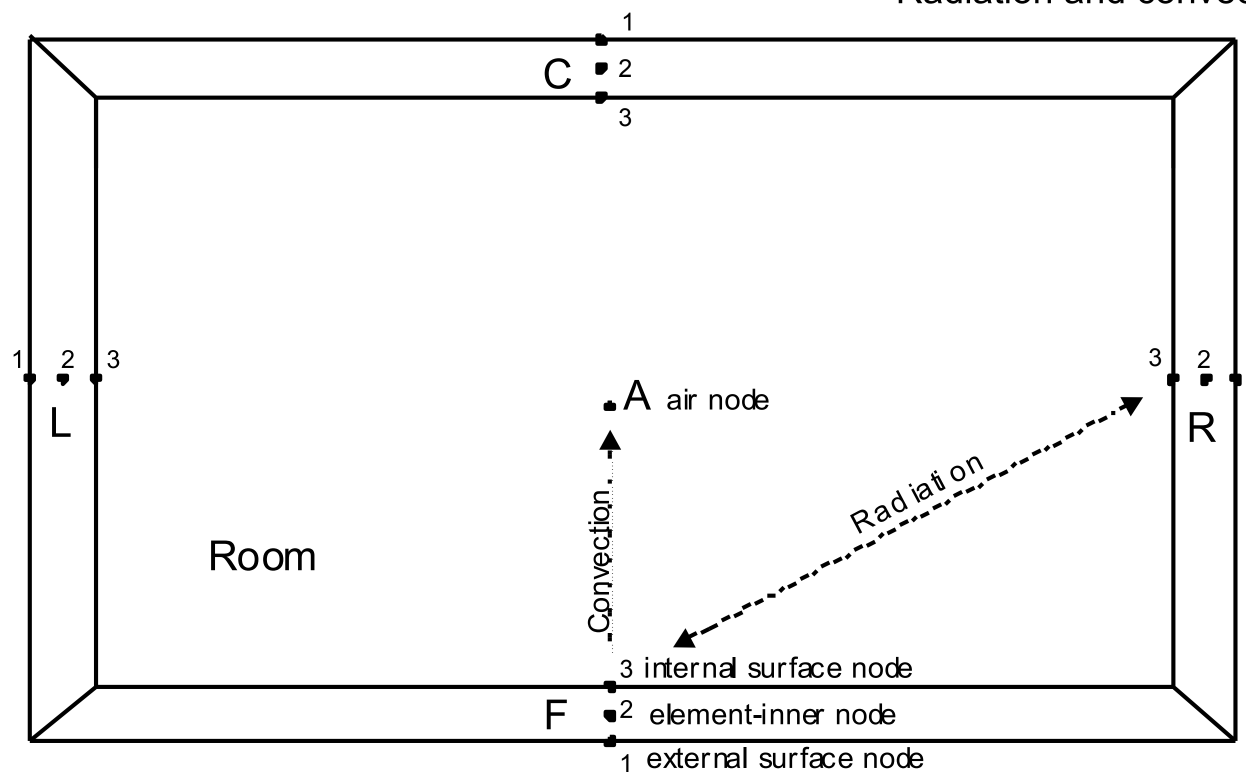
At surface nodes:

$$\sum q = 0$$

At nodes inside materials:

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

Based on density and heat capacity of material…



Modeling thermal mass: Unsteady conduction

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

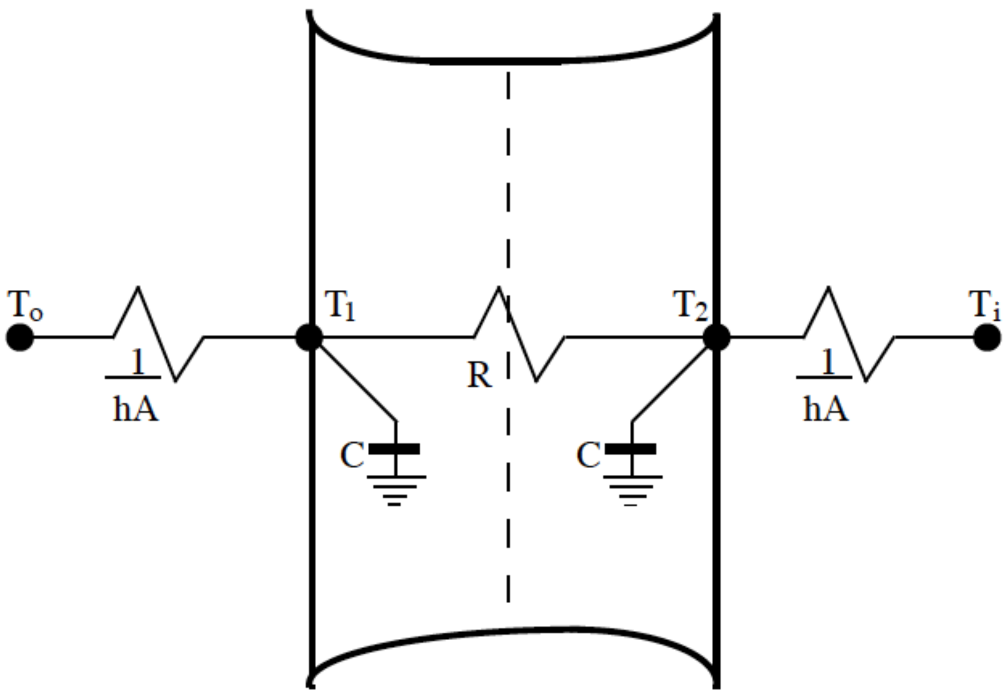


Figure 9. Two Node State Space Example.

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

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

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

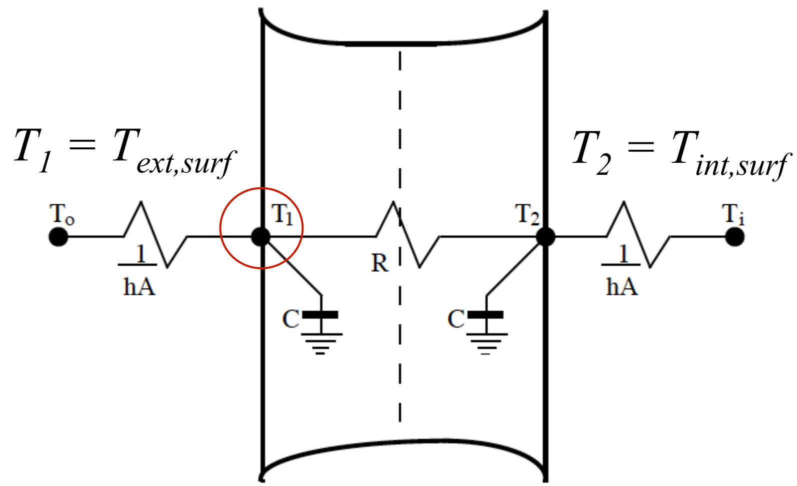


Figure 9. Two Node State Space Example.

From:

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

To:

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

Lumped capacitance model

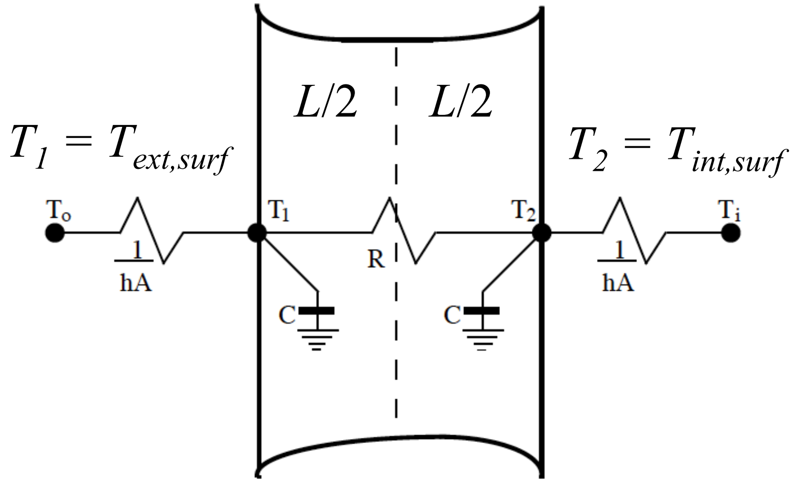


Figure 9. Two Node State Space Example.

Steady state surface energy balance…

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

…becomes a time-varying surface energy balance:

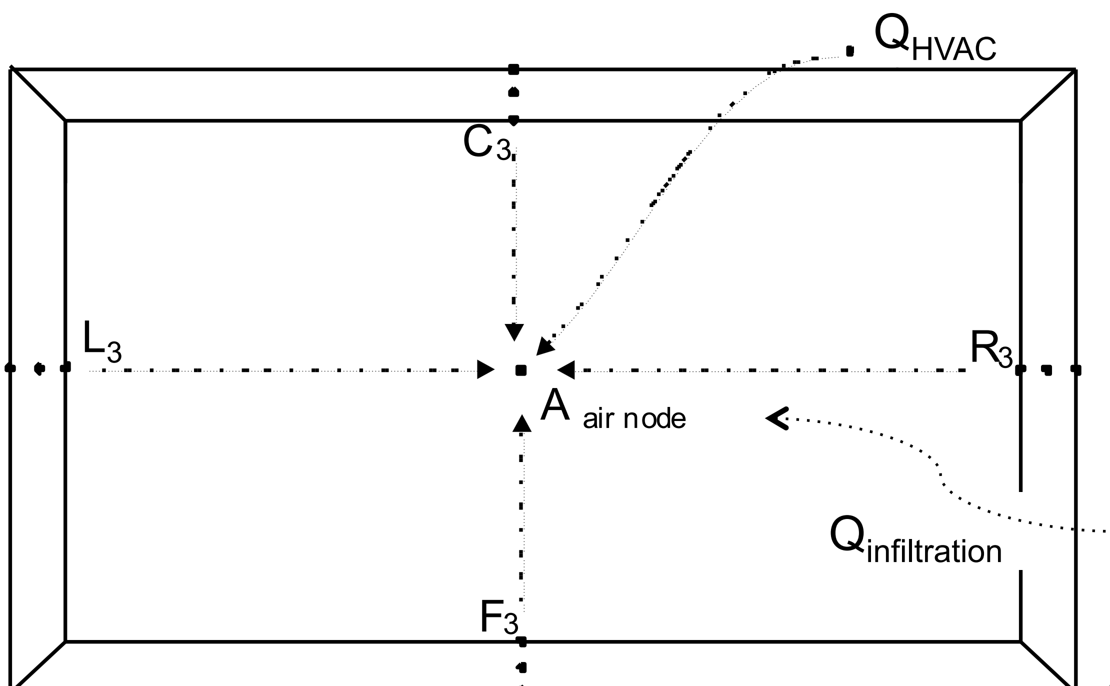
$$\alpha I_{solar} + \varepsilon_1 \sigma F_{sky}(T_{sky}^4 - T_1^4) + \varepsilon_1 \sigma F_{ground}(T_{ground}^4 - T_1^4) + h_{conv}(T_{air} - T_1) - U(T_1 - T_2) = \frac{\rho C_p}{\Delta t}\frac{L}{2}(T_1^n - T_1^{n-1})$$

HBM: Air energy balance

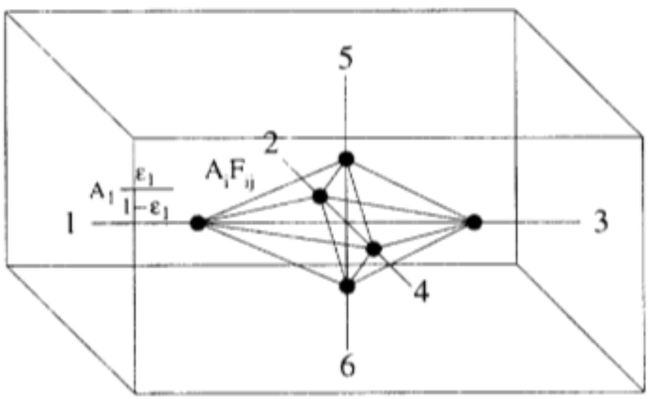
- To get the impact on indoor air temperature (and close the system of equations)
  - Write an energy balance on the indoor air node
  - Air impacted directly only by convection (bulk and/or surface)

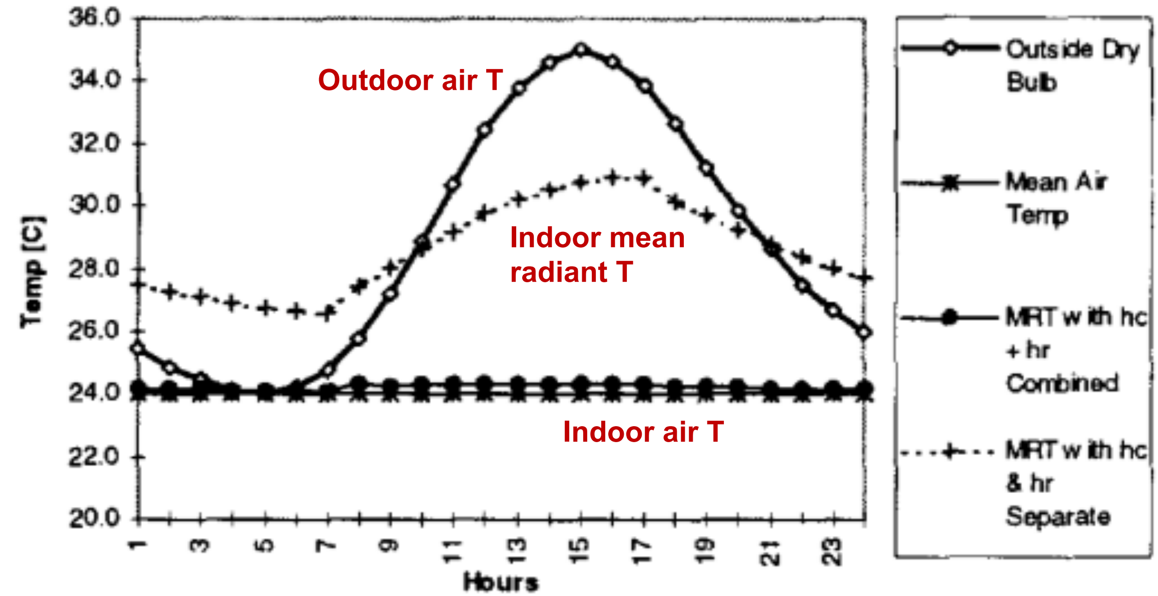
$$(V_{room}\rho_{air}c_{p,air})\frac{dT_{air,in}}{dt} = \sum_{i=1}^{n} h_i A_i \left(T_{i,surf} - T_{air,in}\right) + \dot{m}c_p\left(T_{out} - T_{air,in}\right) + Q_{HVAC}$$

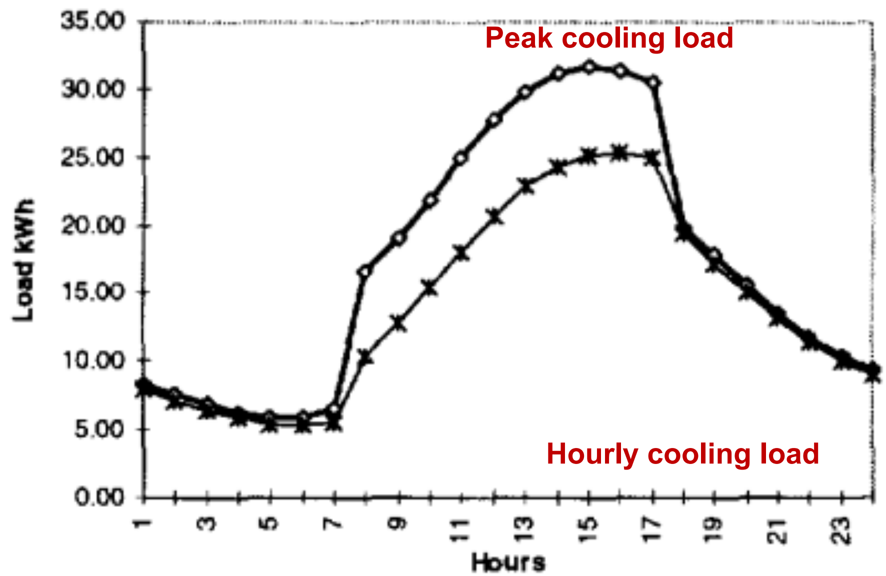
In plain English:
The change in indoor air temperature is equal to the sum of convection from each interior surface plus outdoor air delivery (by infiltration or dedicated outdoor air supply), plus the bulk convective heat transfer delivered by the HVAC system



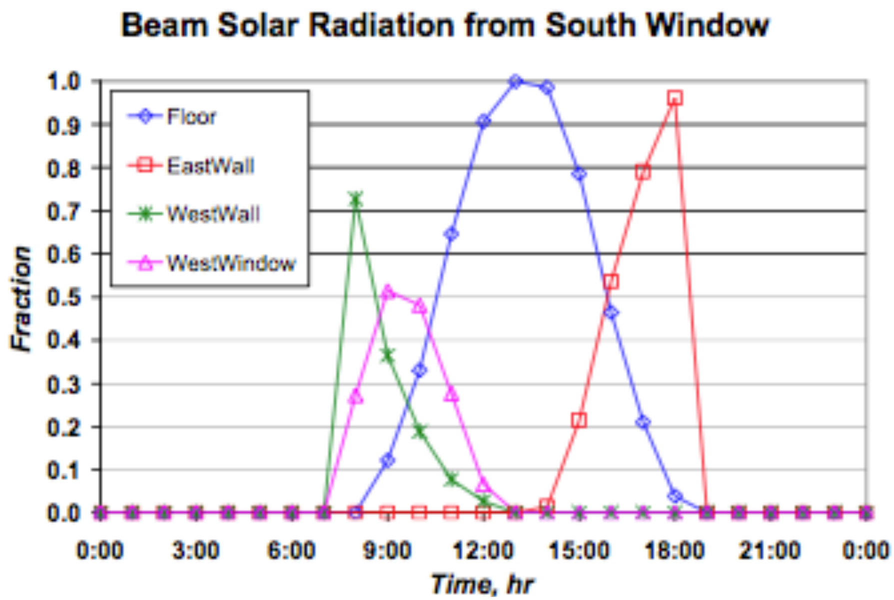
Using HBM to calculate peak loads

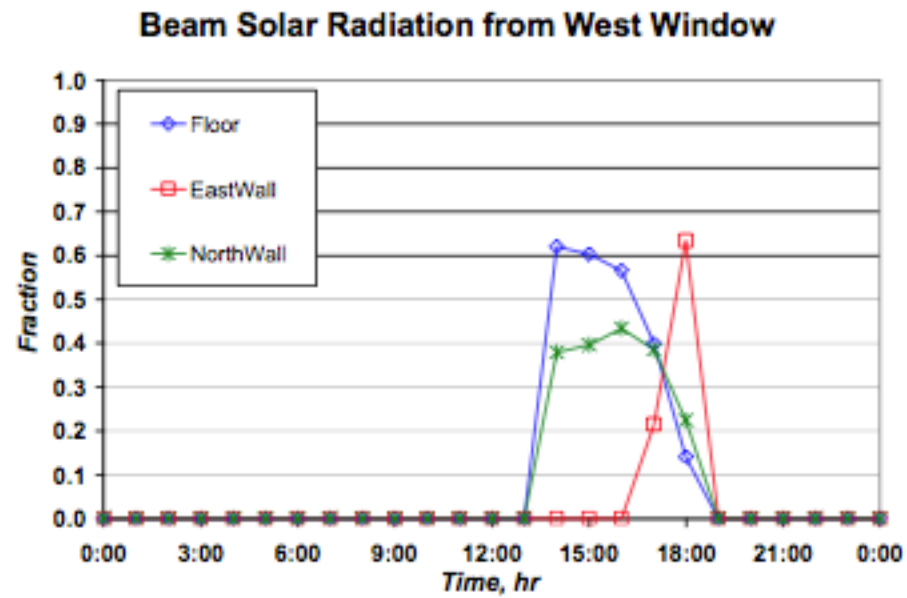


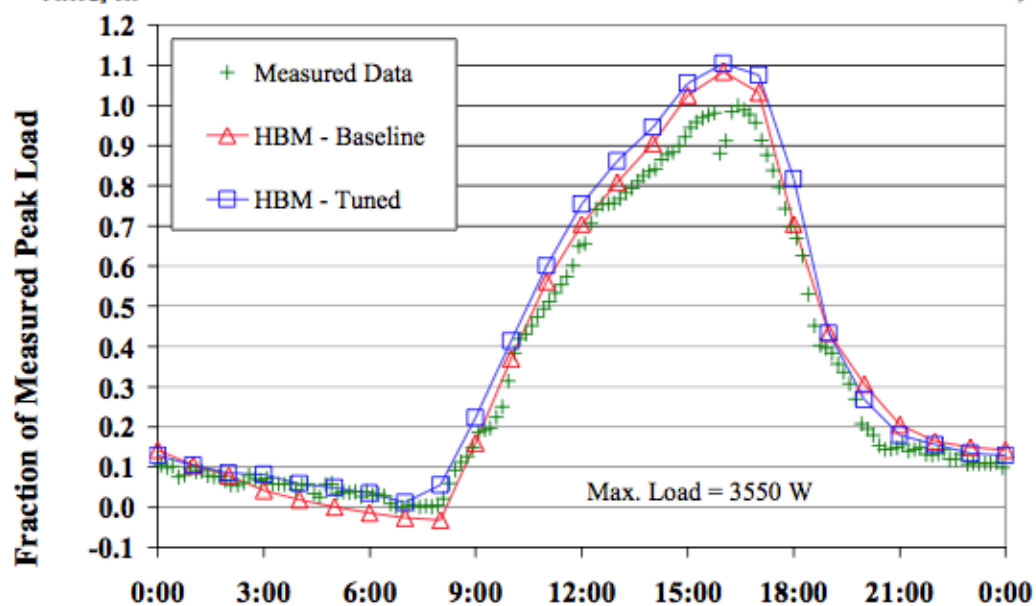




Using HBM to calculate peak loads







HW 5

- HW 5 assigned today
- Due Tuesday November 11