

Load Estimation (II)



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Contents



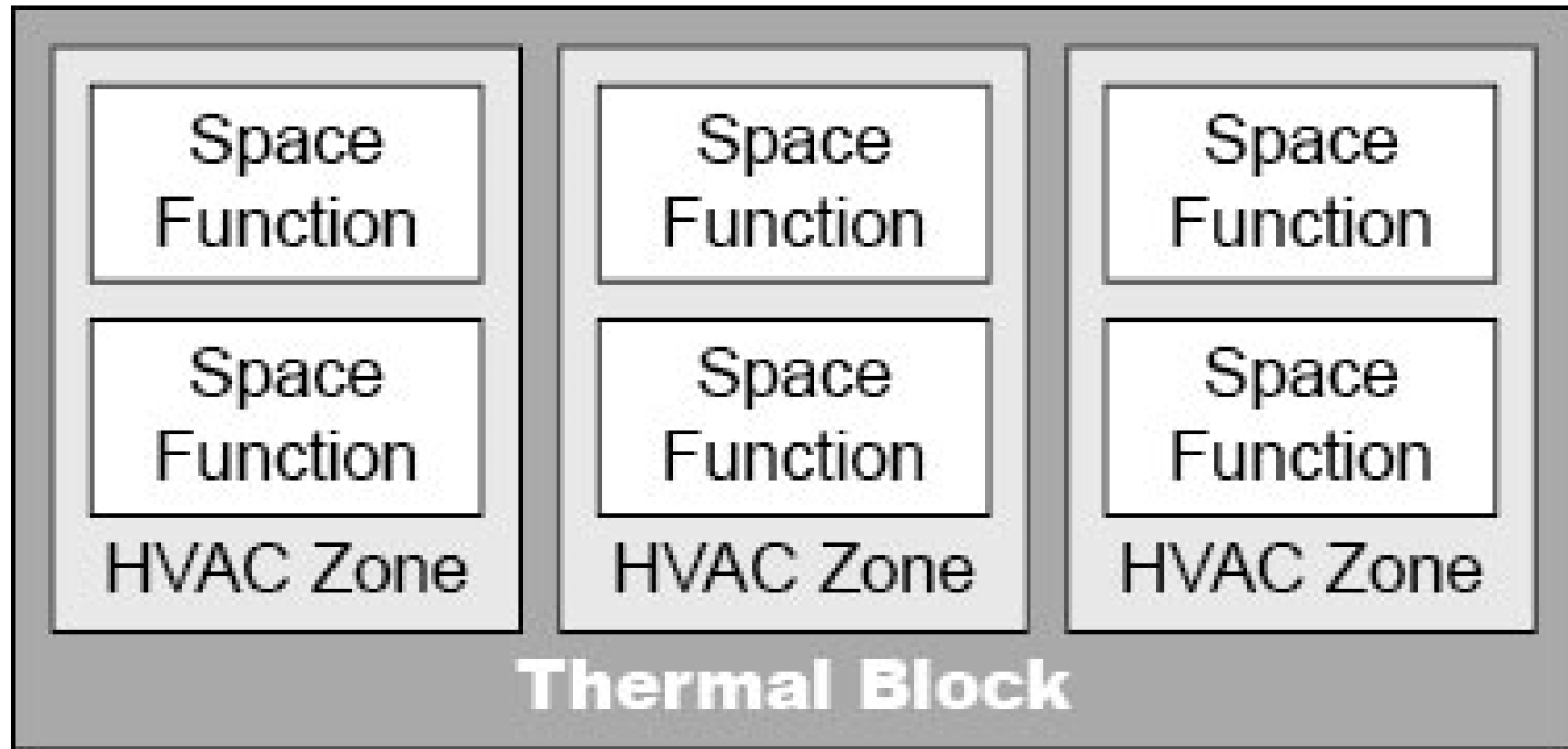
- Cooling Load Principles
- Cooling Load Profiles
- HVAC System Sizing
- Calculation Methodology
- Heating Load
- Software Applications



Cooling Load Principles

- Terminology:
 - Space – a volume w/o a partition, or a partitioned room, or group of rooms
 - Room – an enclosed space (a single load)
 - Zone – a space, or several rooms, or units of space having some sort of coincident loads or similar operating characteristics
 - Thermal zones
 - Tenant zoning (actual usage)

Hierarchy of space functions, HVAC zones and thermal blocks



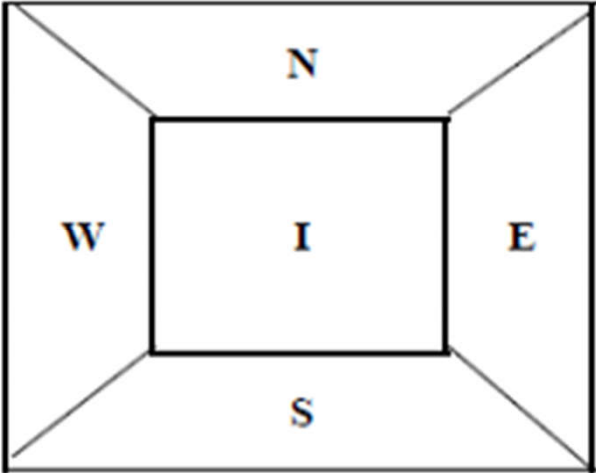
Thermal Block is a space or collection of spaces within a building having sufficiently similar space conditioning requirements so that those conditions could be maintained with a single thermal control device.

HVAC Zone is a physical space within the building that has its own thermostat and zonal system for maintaining thermal comfort.

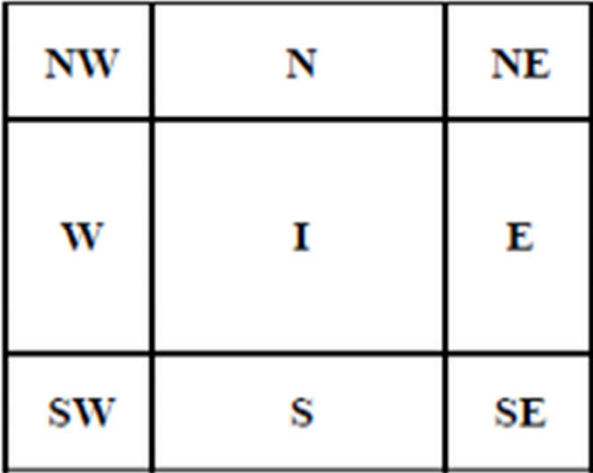
Space Function is a sub-component of a thermal zone that has specific baseline lighting requirements and for which there are associated defaults for outside air ventilation, occupancy, receptacle loads, and hot water consumption.

HVAC zoning considerations

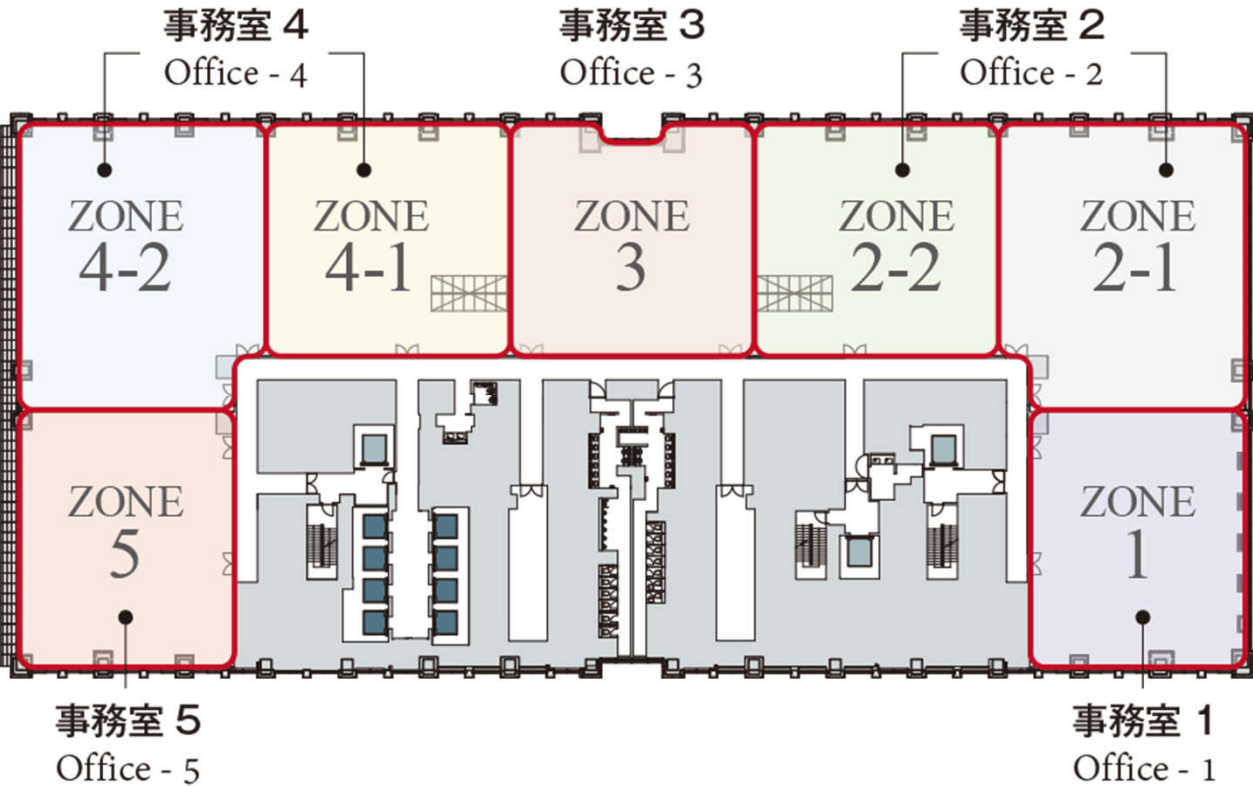
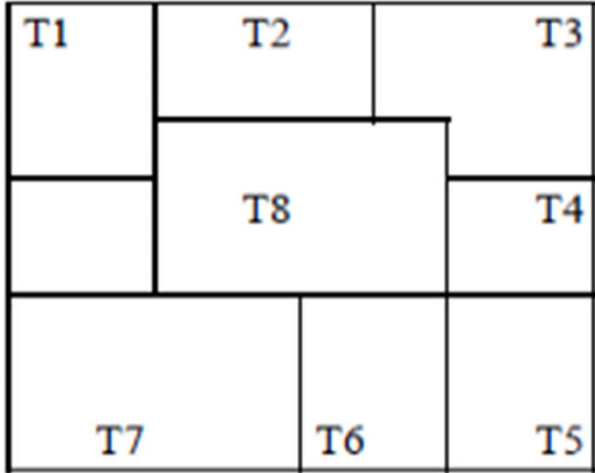
Thermal zones (5 zones)



Thermal zones (9 zones)

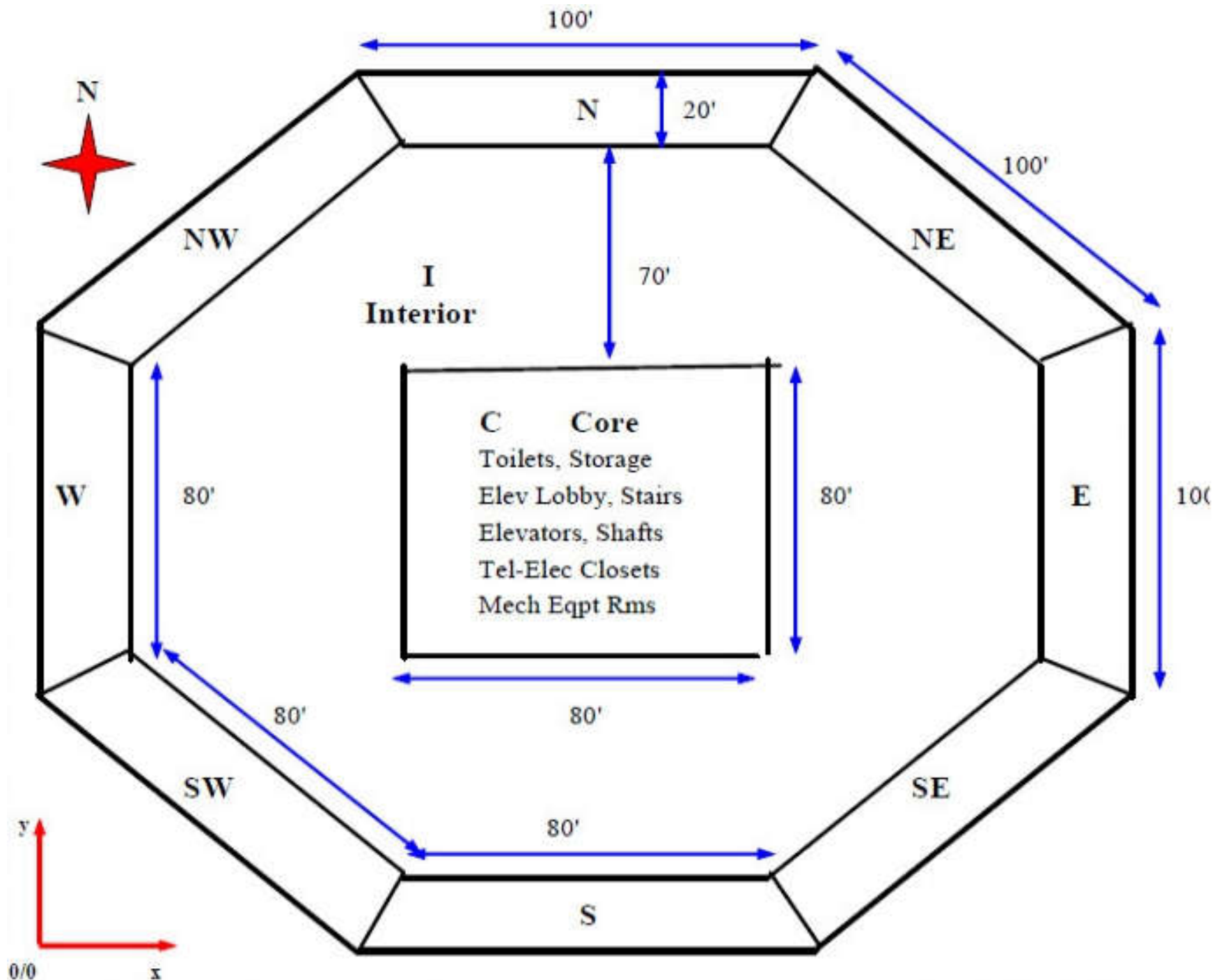


Tenant zoning



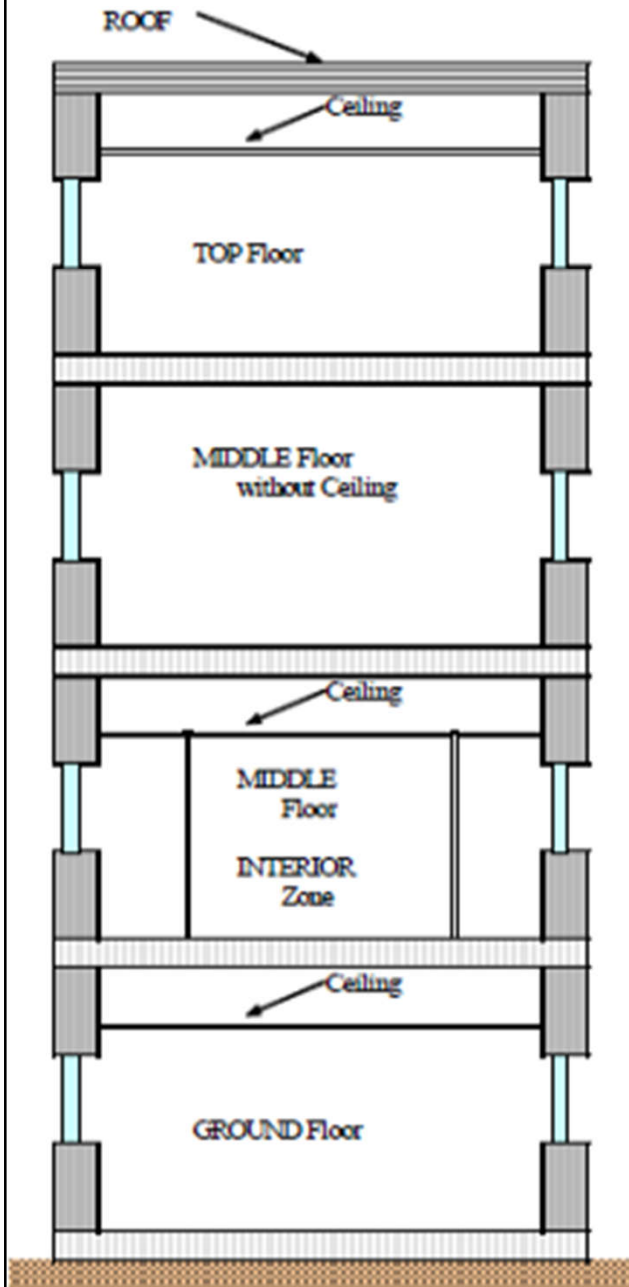
(Image Source: <http://energy-models.com/comfort>; https://office.mec.co.jp/en/otemachi_park/facility.html)

Examples of HVAC thermal zones in a building



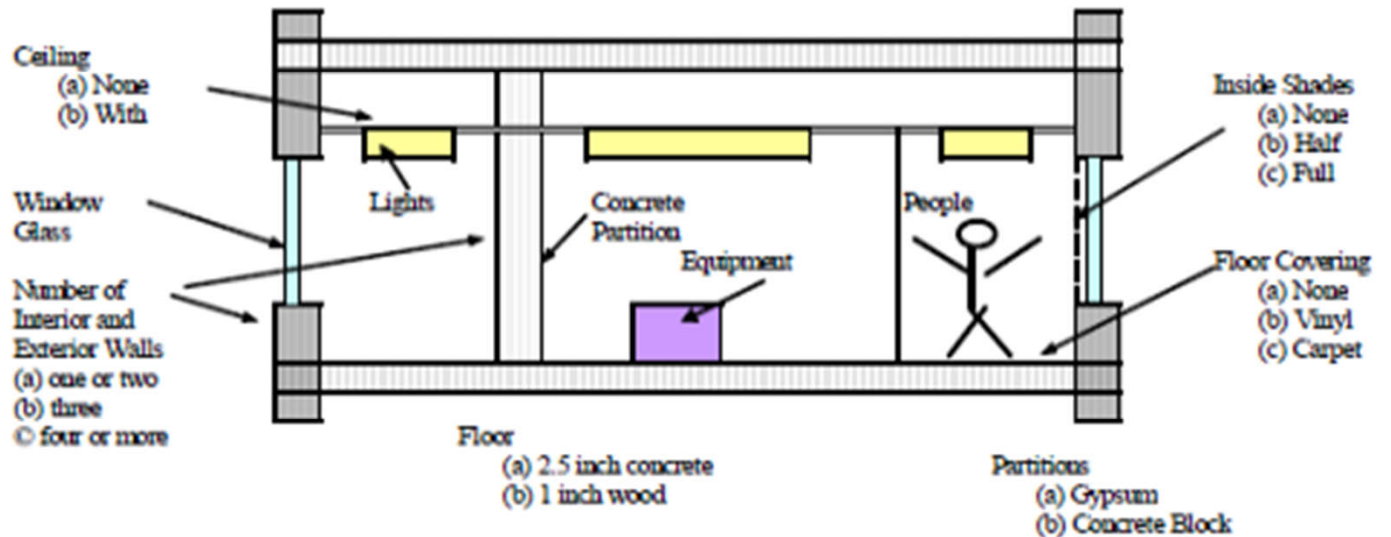
HVAC zoning in multi-story and single-story buildings

MULTI-STORY BUILDING

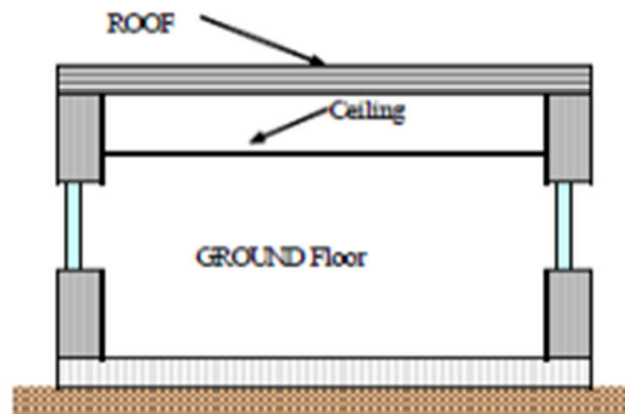


BUILDING FLOOR TYPES

- (1) Single Story (ground floor and roof)
- (2) Top Floor (multi-story with roof)
- (3) Middle Floor (multi-story without ground & roof)
- (4) Ground Floor (multi story)
- (5) Interior Zones
- (6) Exterior Zones



SINGLE-STORY BUILDING



PLAN VIEW OF BUILDING (ZONES)





Cooling Load Principles

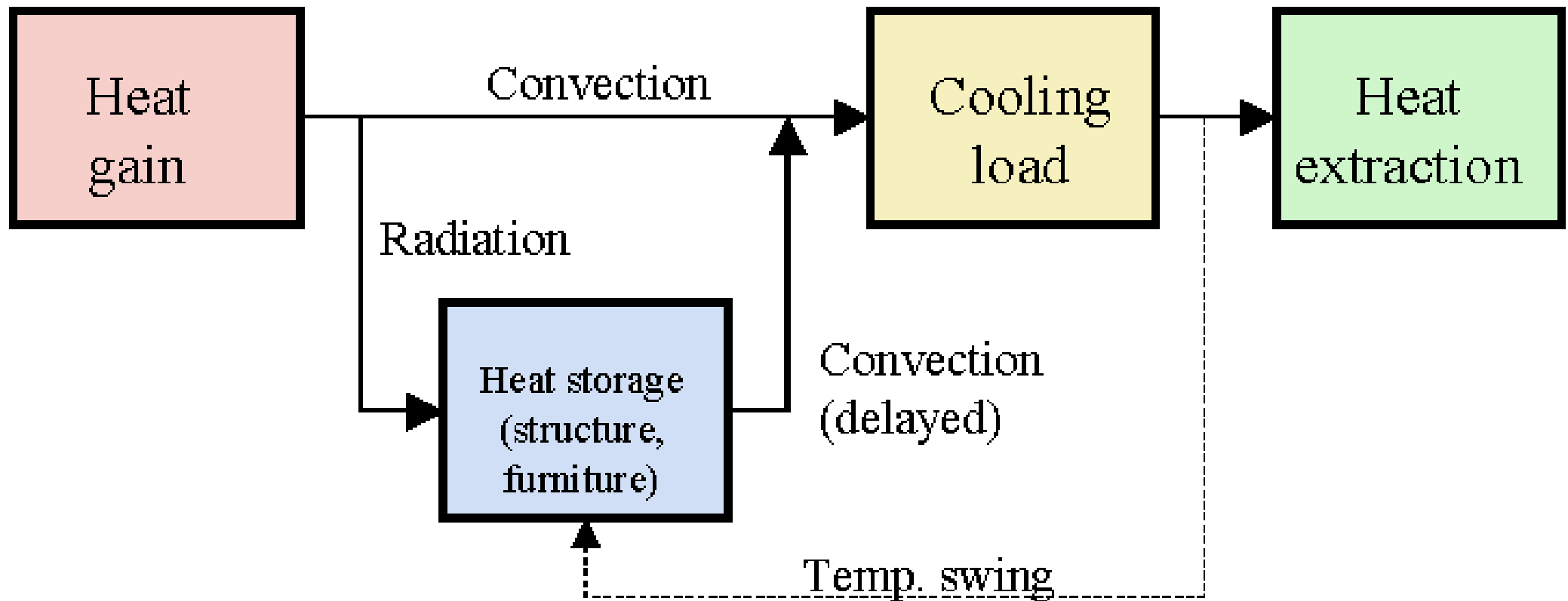
- Issues to consider for HVAC zoning
 - Single-story building:
 - Ceiling type (with or without suspended ceiling)
 - Floor type & ground slab contact
 - Multi-story building:
 - Floor level & room location
 - Top floor, middle floor, first/ground floor
 - Rooms with external envelope, interior rooms
 - Ceiling type (with or without suspended ceiling)
 - Floor type & ground slab contact
 - Control of indoor conditions, tenant zones



Cooling Load Principles

- Definitions
 - Space heat gain: instantaneous rate of heat gain that enters into or is generated within a space
 - Space cooling load: the rate at which heat must be removed from the space to maintain a constant space air temperature
 - Space heat extraction rate: the actual rate of heat removal when the space air temp. may swing
 - Cooling coil load: the rate at which energy is removed at a cooling coil serving the space

Conversion of heat gain into cooling load & heat extraction



Can you explain the process of cooling load conversion?



Cooling Load Principles

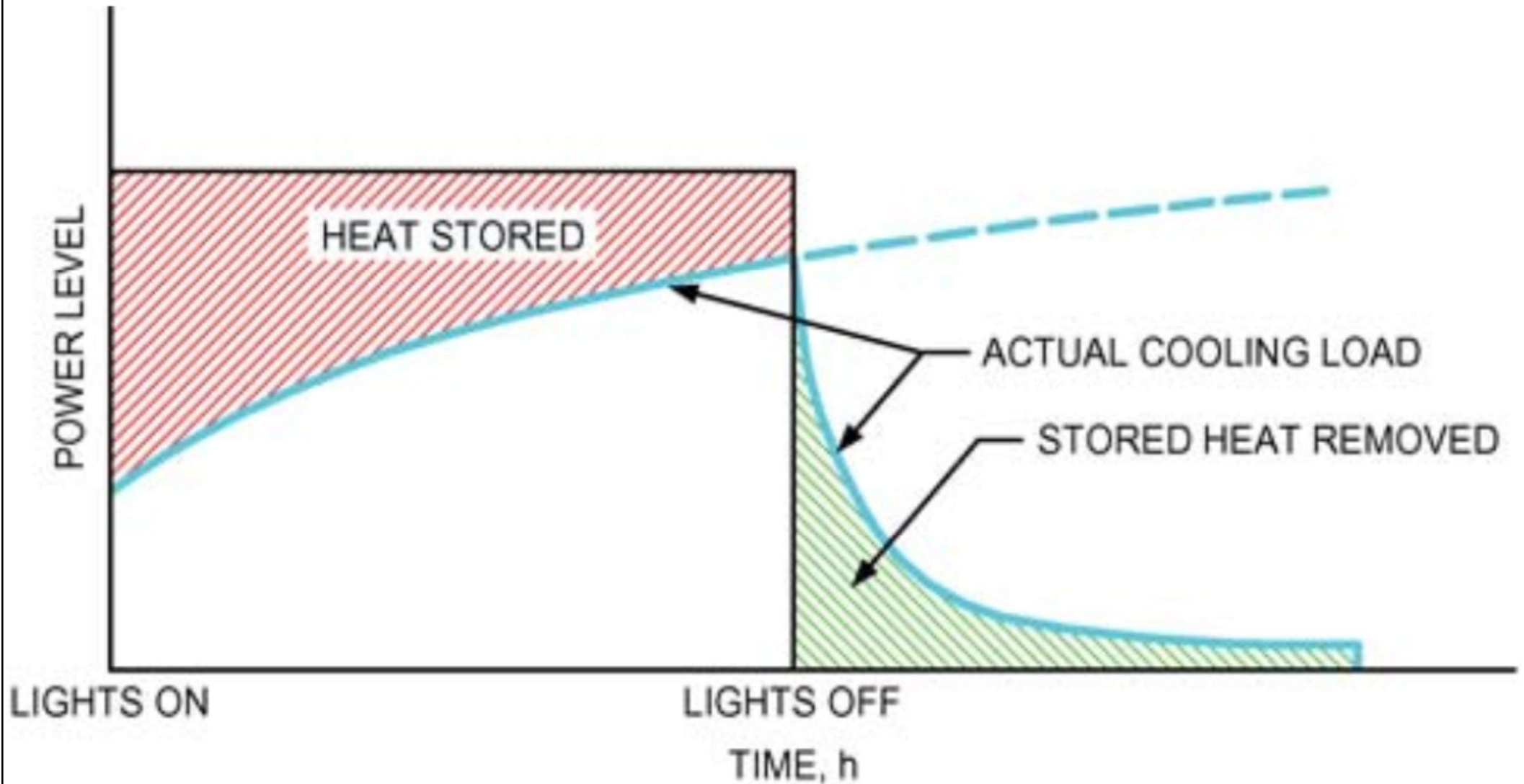
- Heat gains, heat extraction rate, and cooling loads values are often not equal due to thermal inertia effects
 - Heat is stored in the mass of the building and furnishings delaying the time at which it can become a heat gain and be extracted by the cooling equipment to maintain the desired indoor conditions
 - Another reason is inability of the cooling system to keep dry bulb temperature & humidity constant



Cooling Load Principles

- Instantaneous heat gain vs space cooling loads
 - They are NOT the same
- Effect of heat storage
 - Night shutdown period
 - HVAC is switched off. What happens to the space?
 - Cool-down or warm-up period
 - When HVAC system begins to operate
 - Need to cool or warm the building fabric
 - Conditioning period
 - Space air temperature within the limits

Thermal storage effect in cooling load from lights



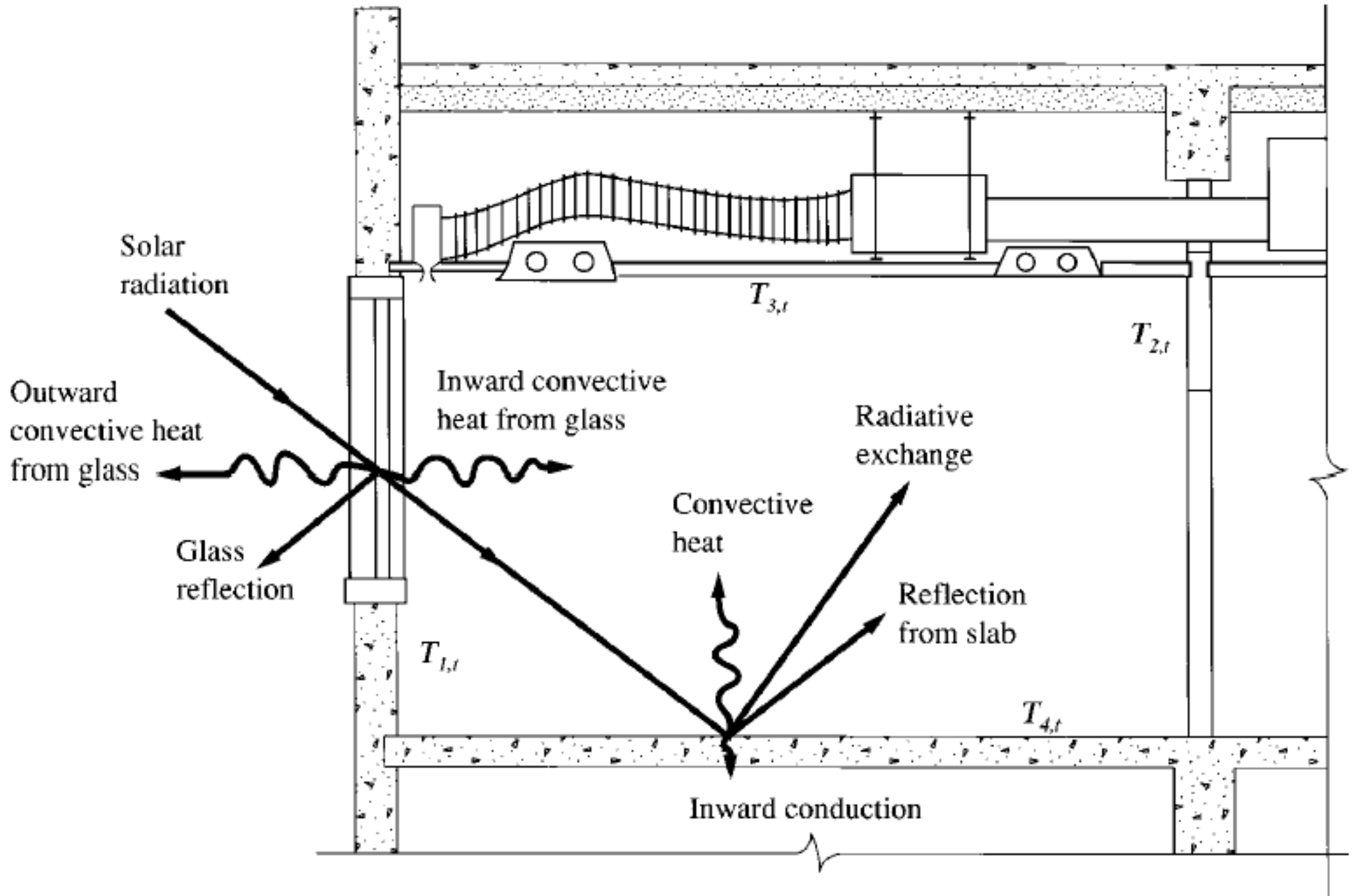
Can you explain the thermal storage effect and its impact on the cooling load?



Cooling Load Principles

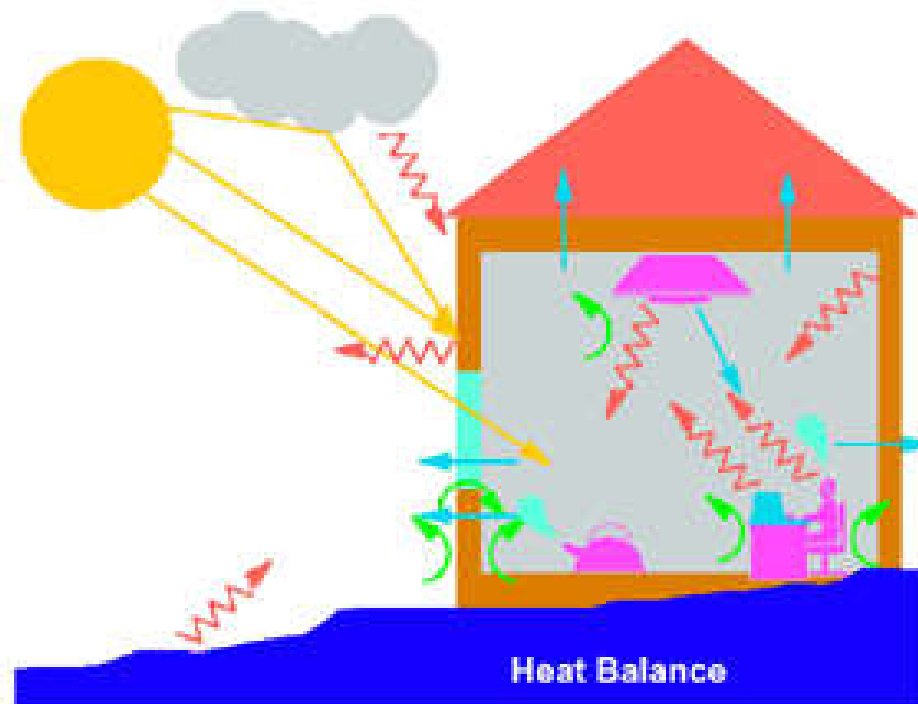
- Space load and equipment load
 - Space heat gain (sensible, latent, total)
 - Space cooling / heating load [*at building*]
 - Space heat extraction rate
 - Cooling / heating coil load [*at air-side system*]
 - Refrigeration load [*at the chiller plant*]
- Instantaneous heat gain
 - Convective heat
 - Radiative heat (heat absorption)

Convective and radiative heat in a conditioned space

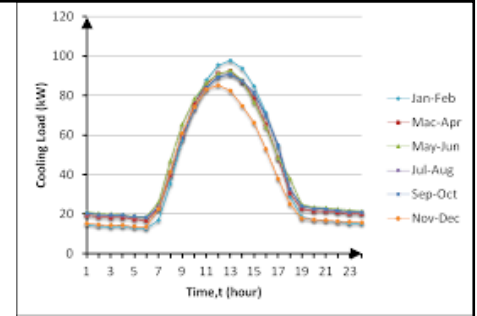


Convective and radiative components for sensible heat gains

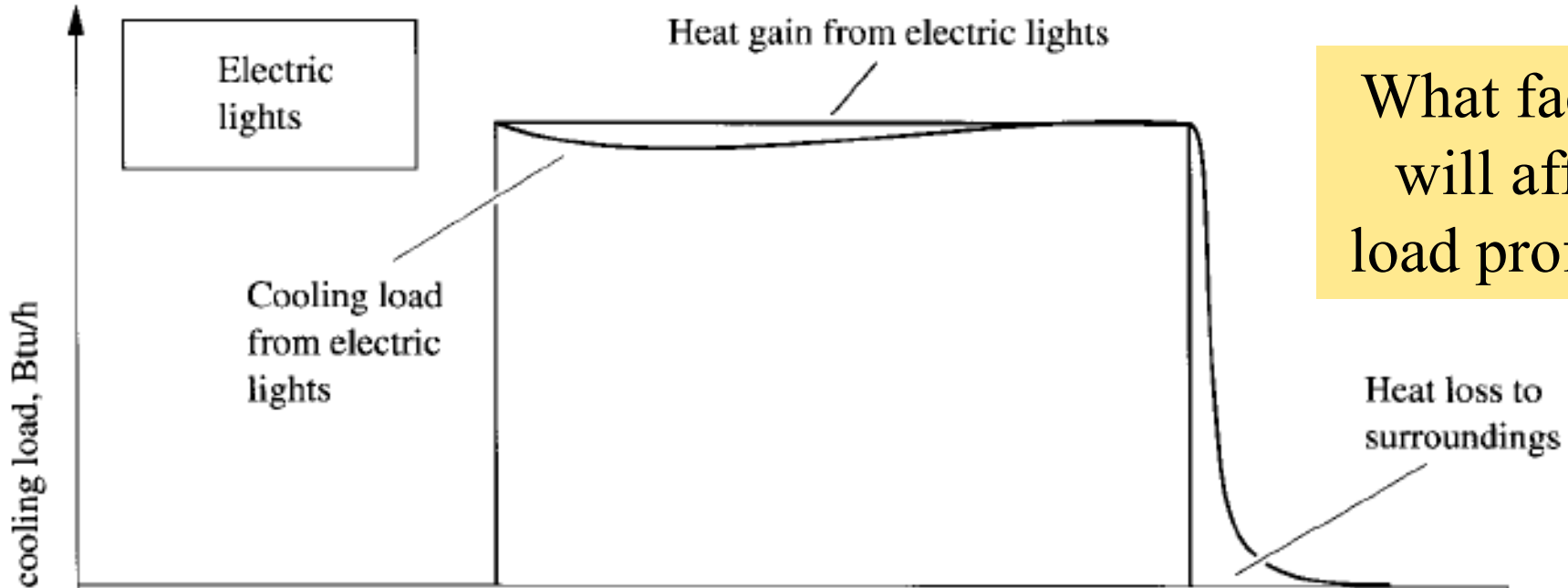
Sensible heat gains	Convective (%)	Radiative (%)
Solar radiation with internal shading	42	58
Fluorescent lights	50	50
Occupants	67	33
External wall, inner surface	40	60



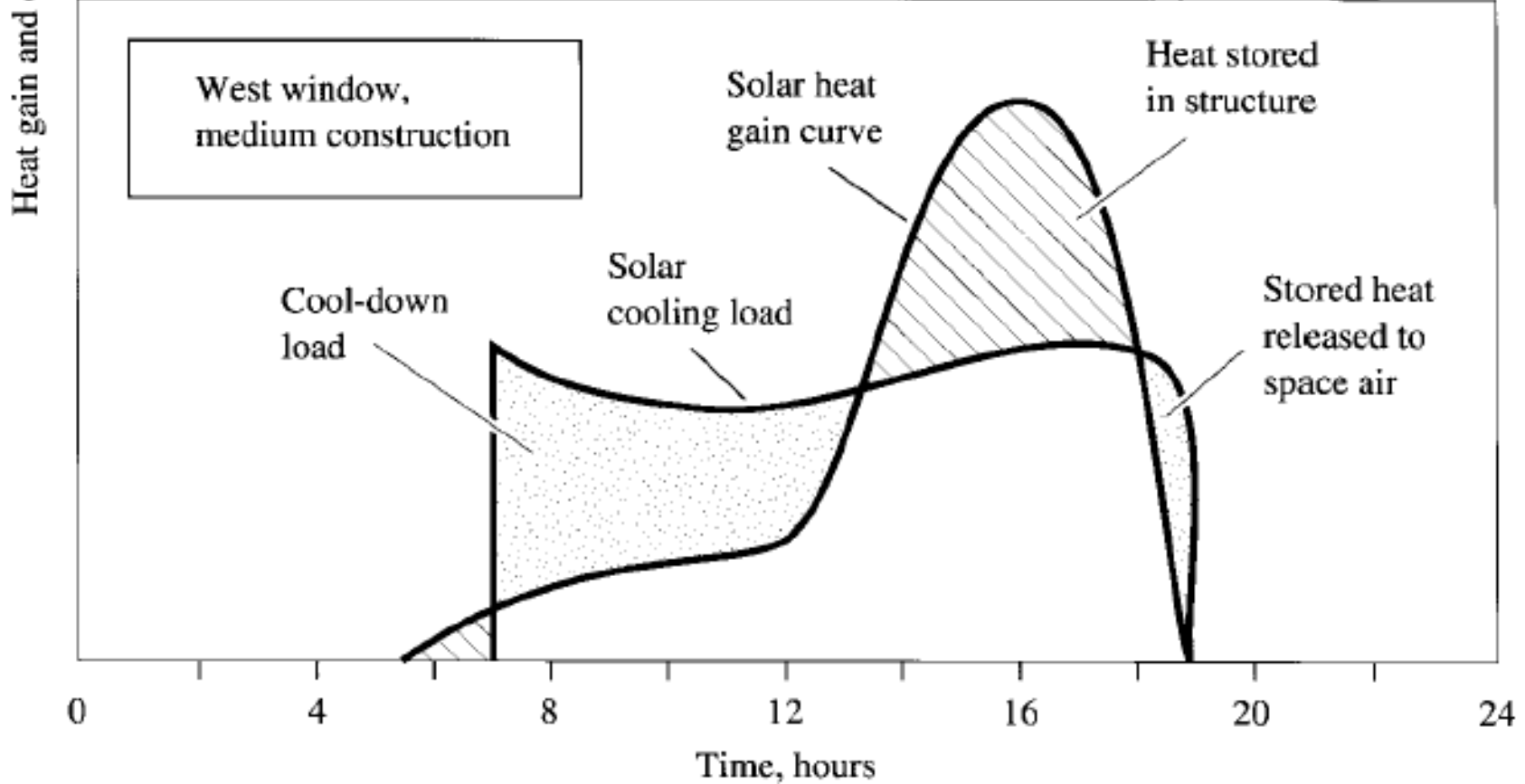
Cooling Load Profiles



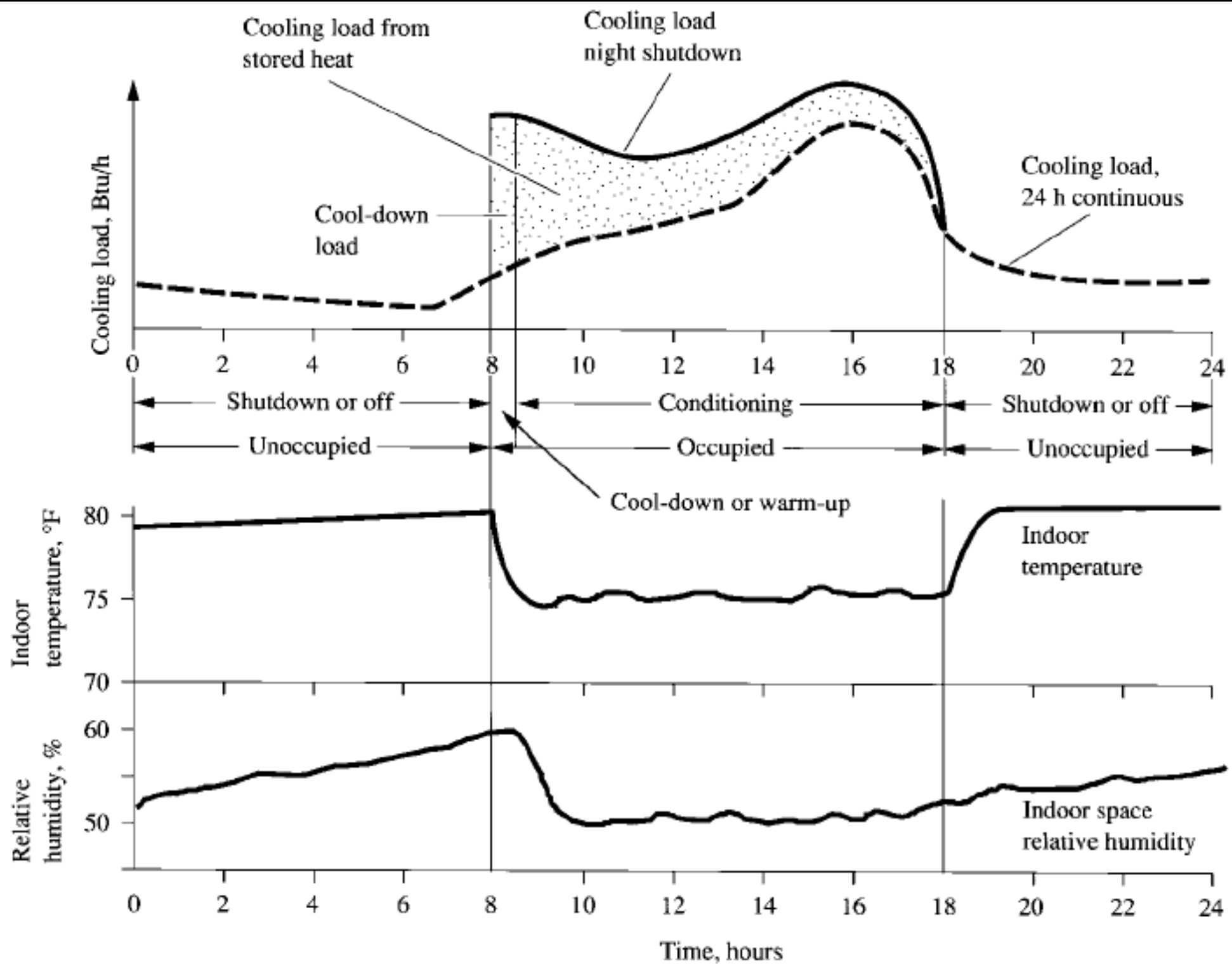
- Cooling load profiles
 - Shows the variation of space cooling load
 - Such as 24-hr cycle
 - Useful for building operation & energy analysis
- Peak load and block load
 - Peak load = max. cooling load
 - For air systems, the supply volume flow rate required is calculated based on the zone peak load
 - Block load = sum of zone loads at a specific time
 - For sizing HVAC zonal equipment & plant



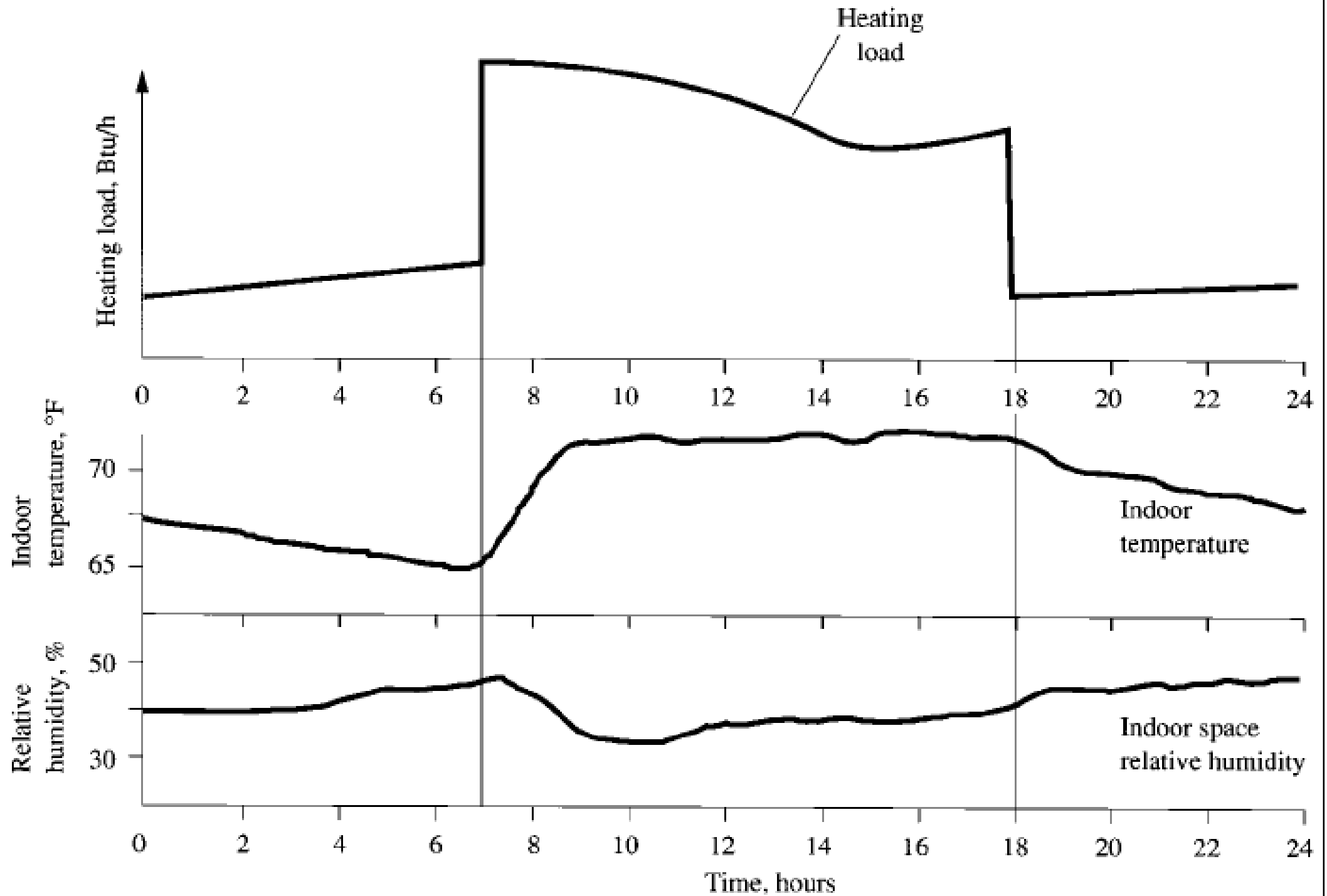
What factors will affect load profiles?



(Source: Wang, S. K., 2001. *Handbook of Air Conditioning and Refrigeration*, 2nd ed.)

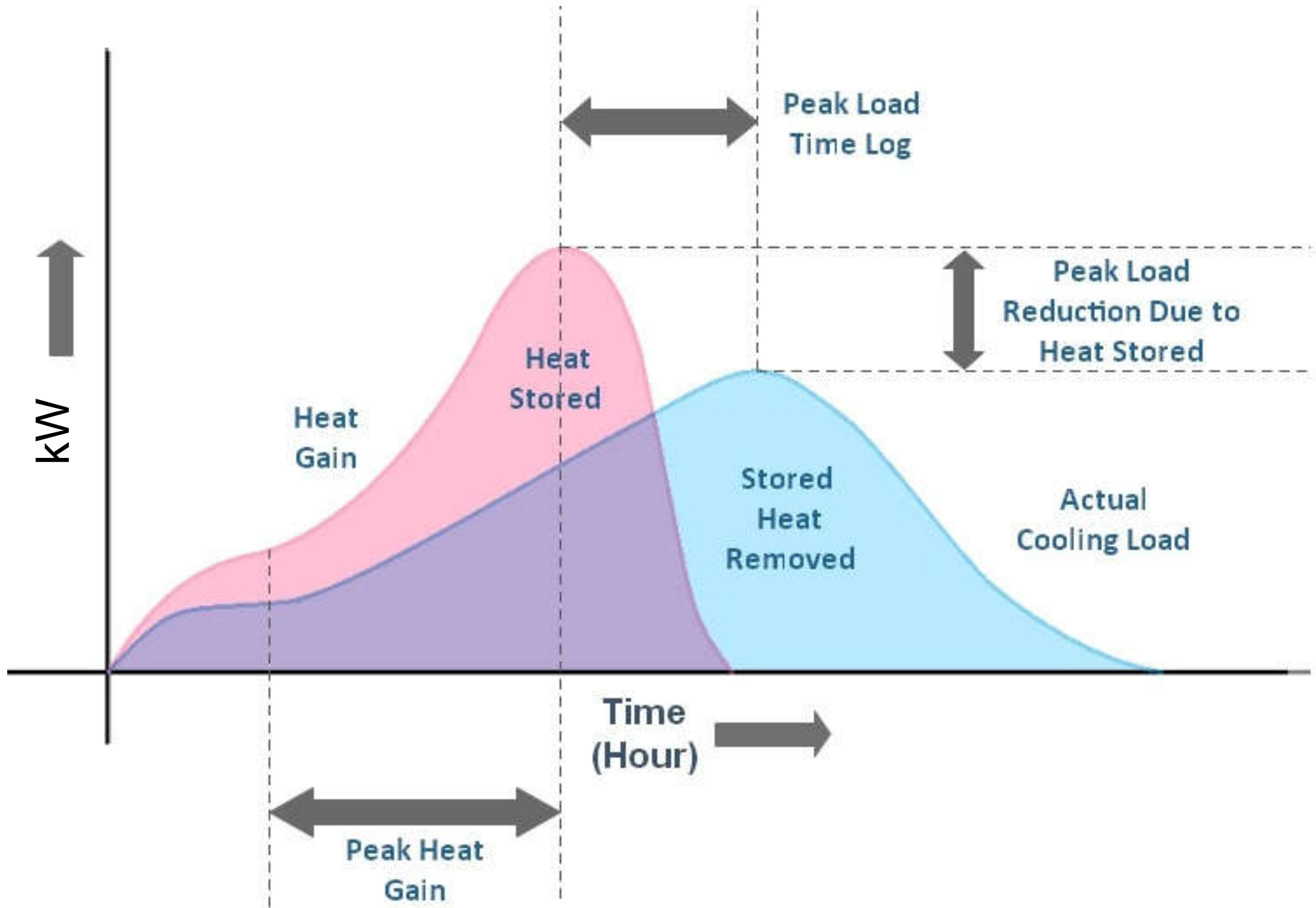


(Source: Wang, S. K., 2001. *Handbook of Air Conditioning and Refrigeration*, 2nd ed.)

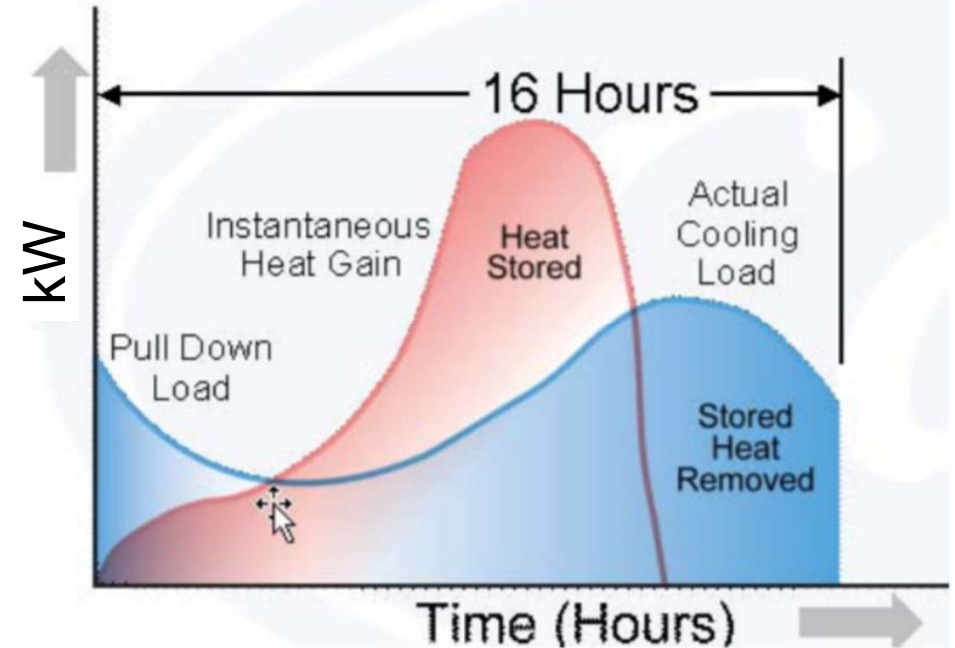
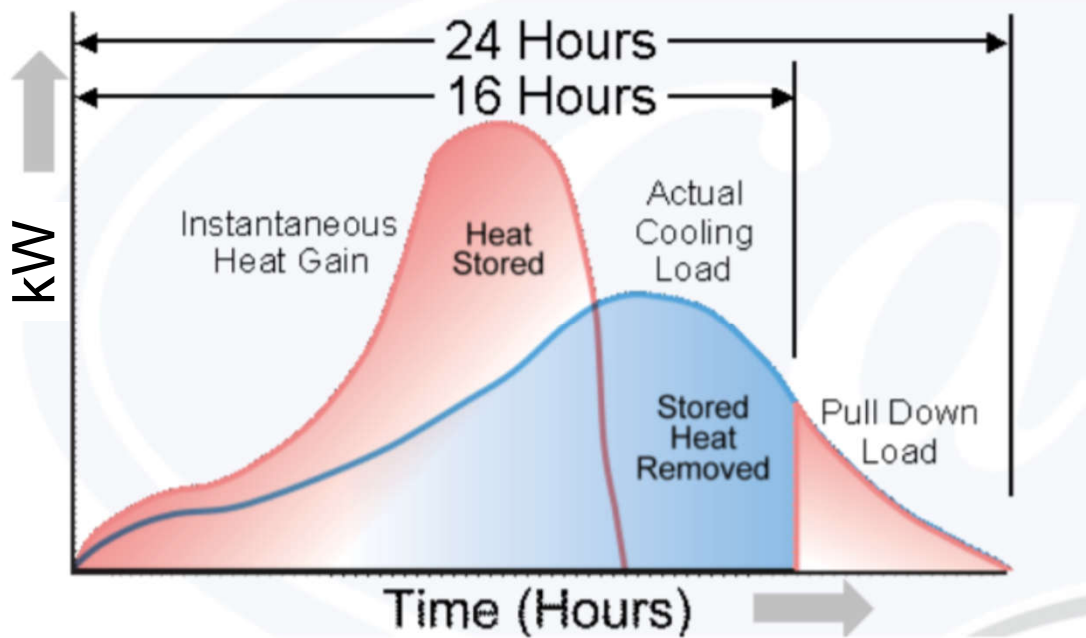
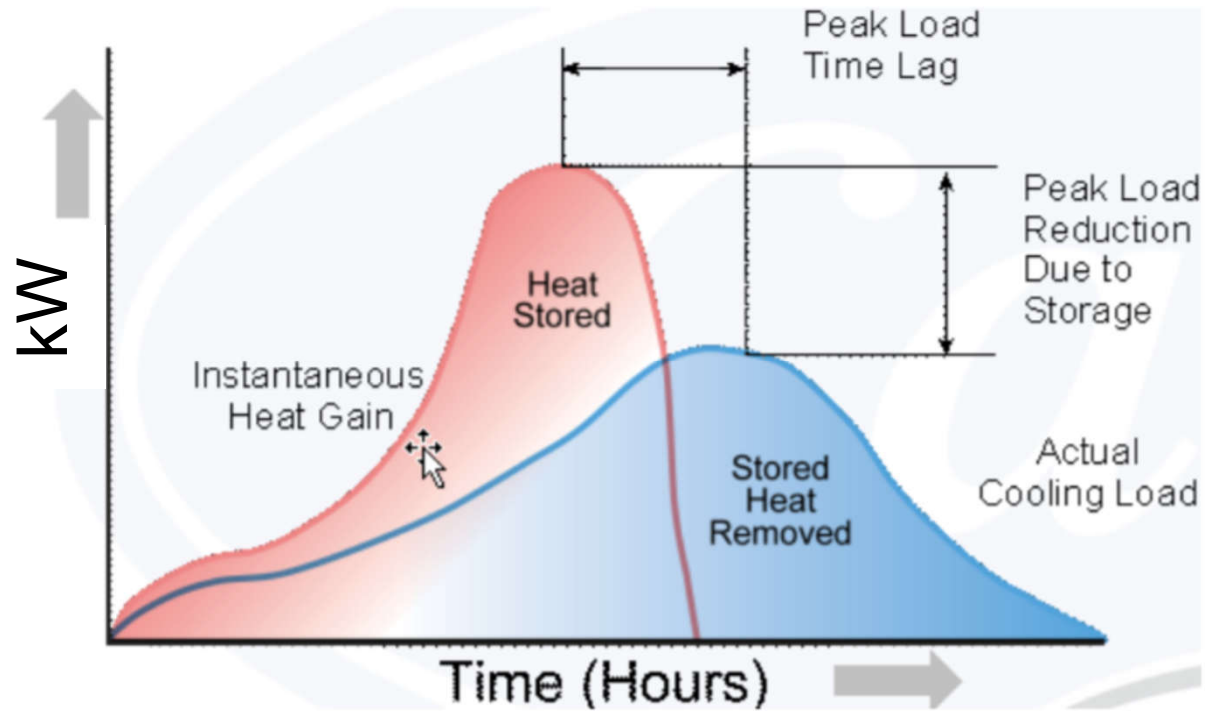


(Source: Wang, S. K., 2001. *Handbook of Air Conditioning and Refrigeration*, 2nd ed.)

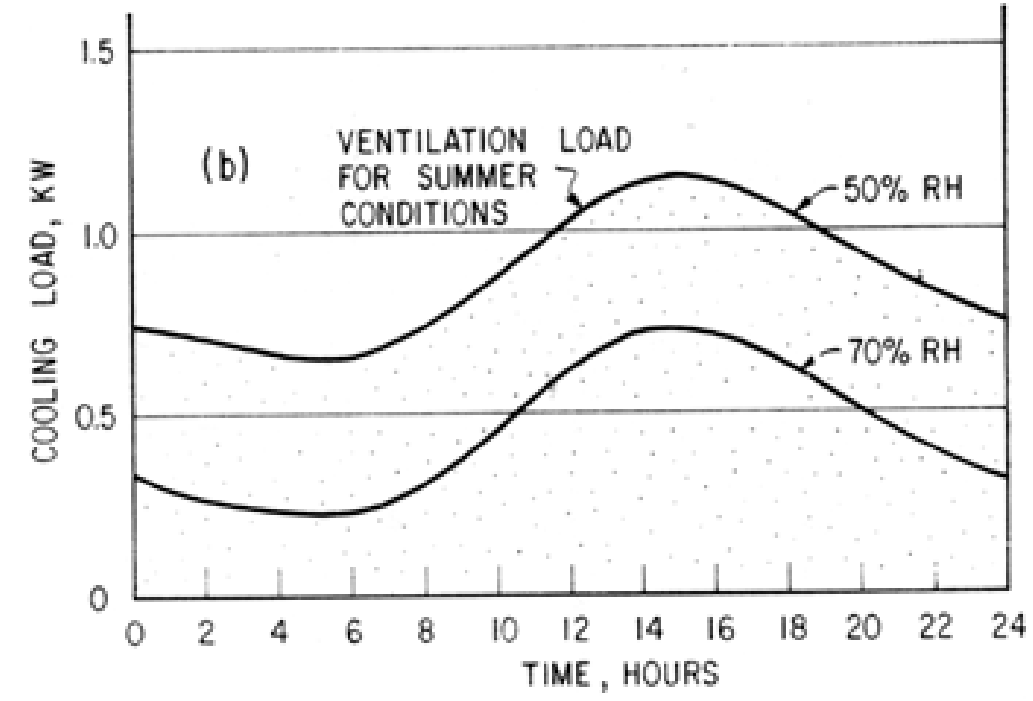
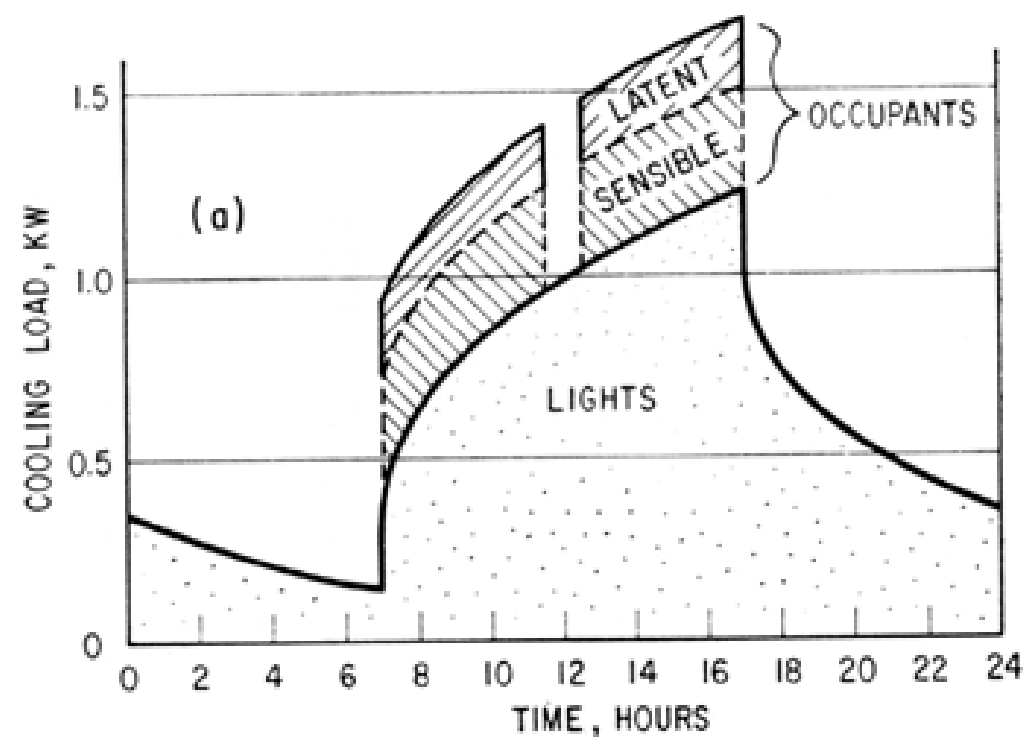
Peak load time lag due to thermal storage



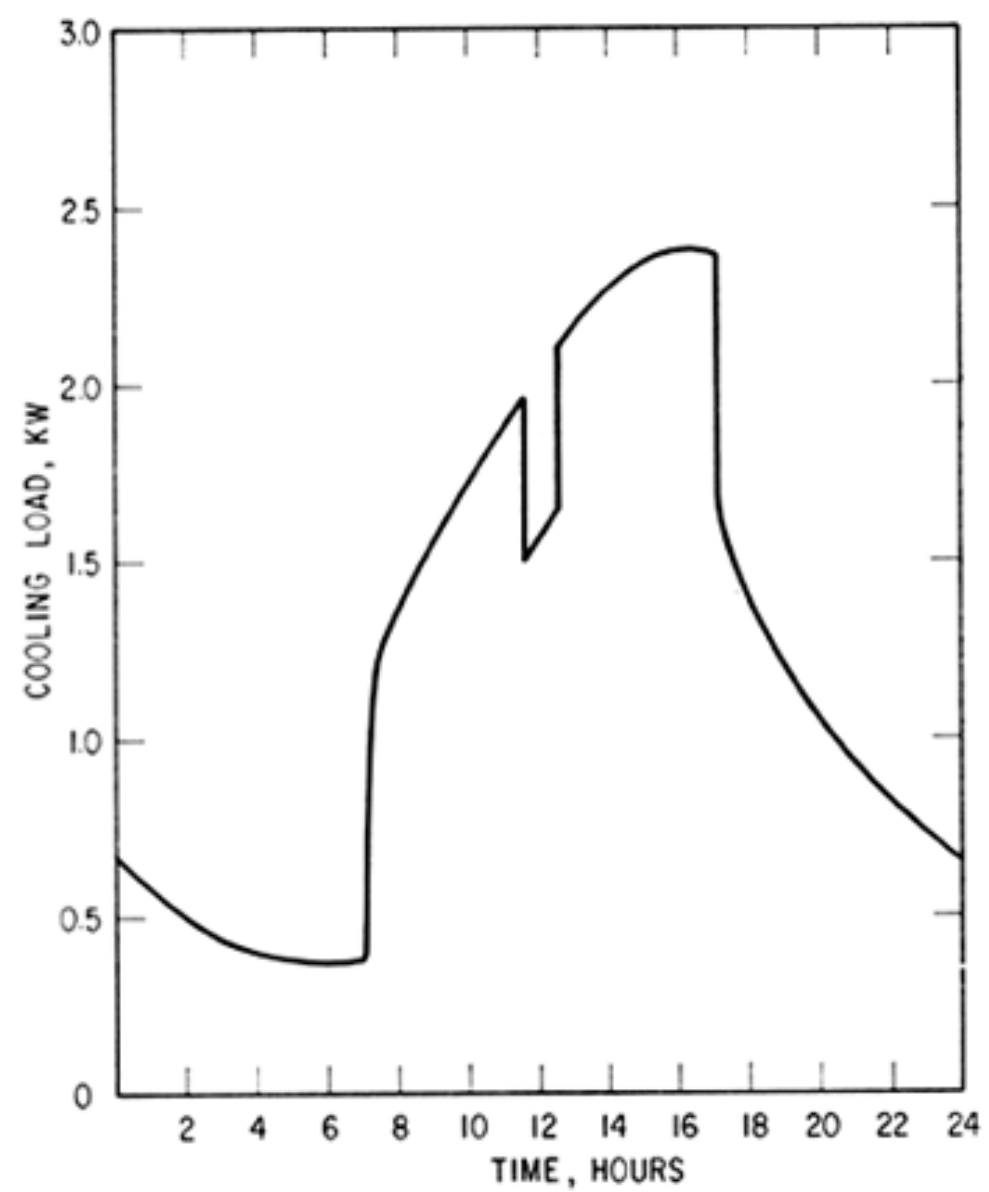
Effects of conditioning period on actual cooling load



Cooling load profiles



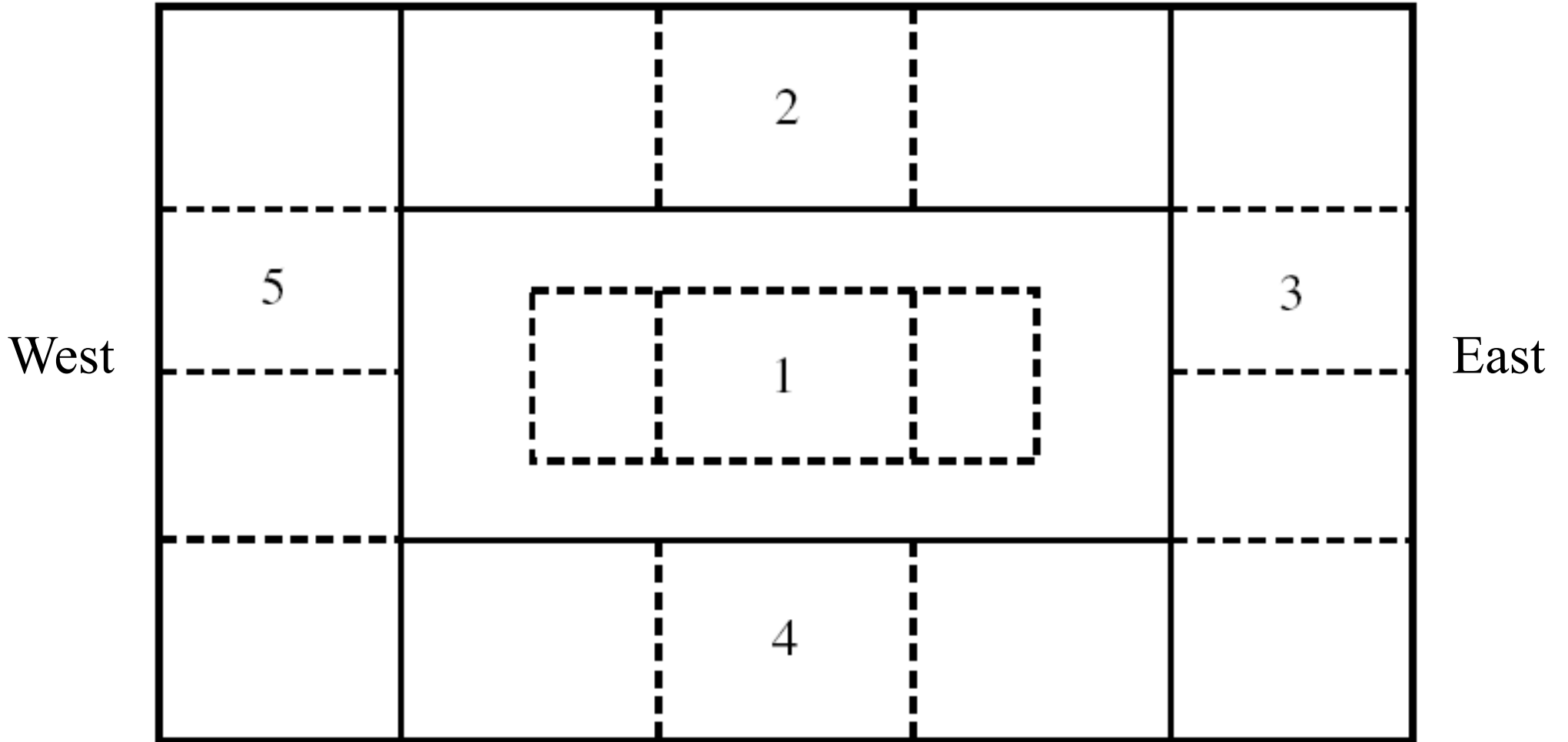
Total cooling load



(Source: D.G. Stephenson, 1968)

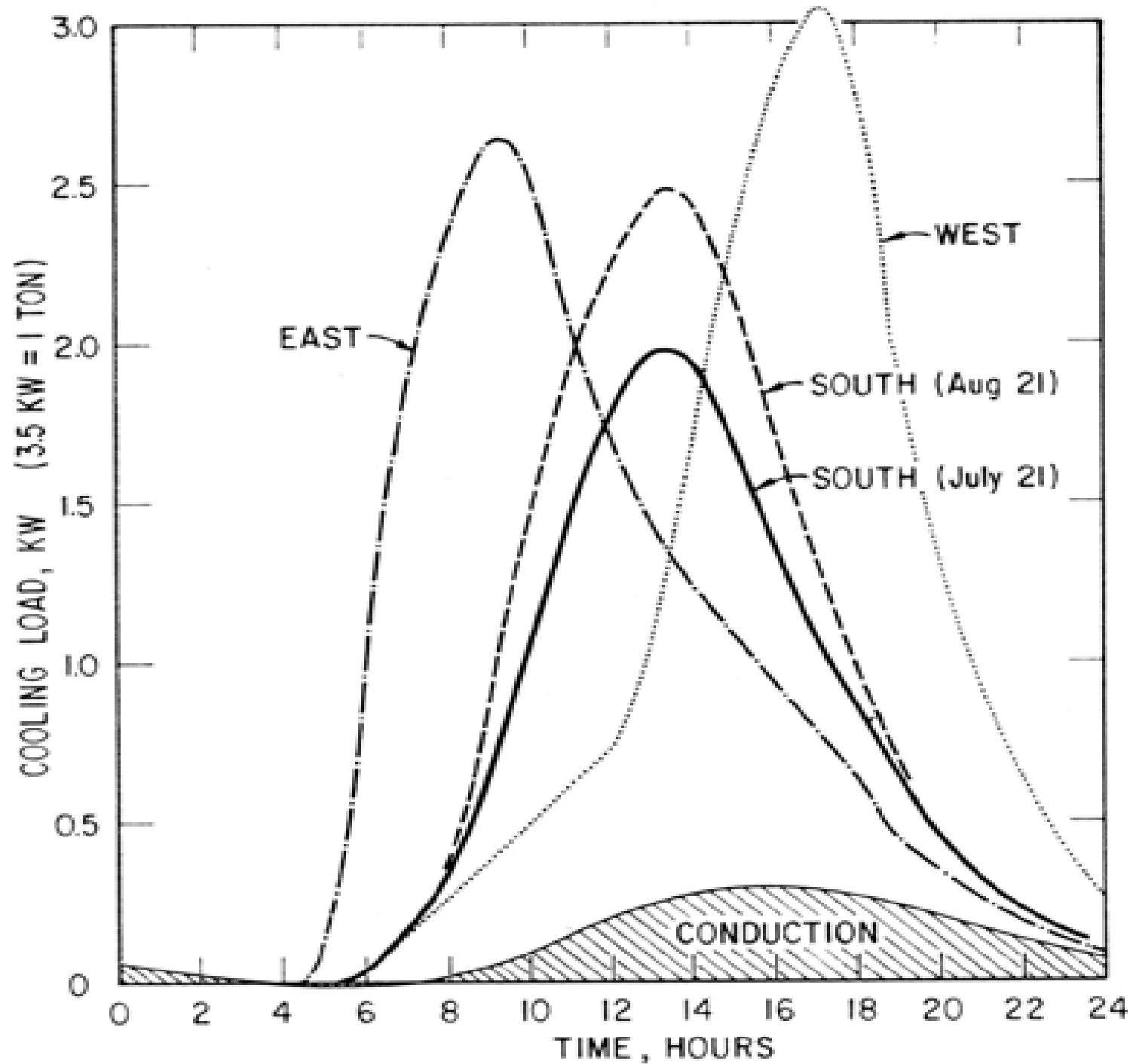
Block load and thermal zoning

North



South

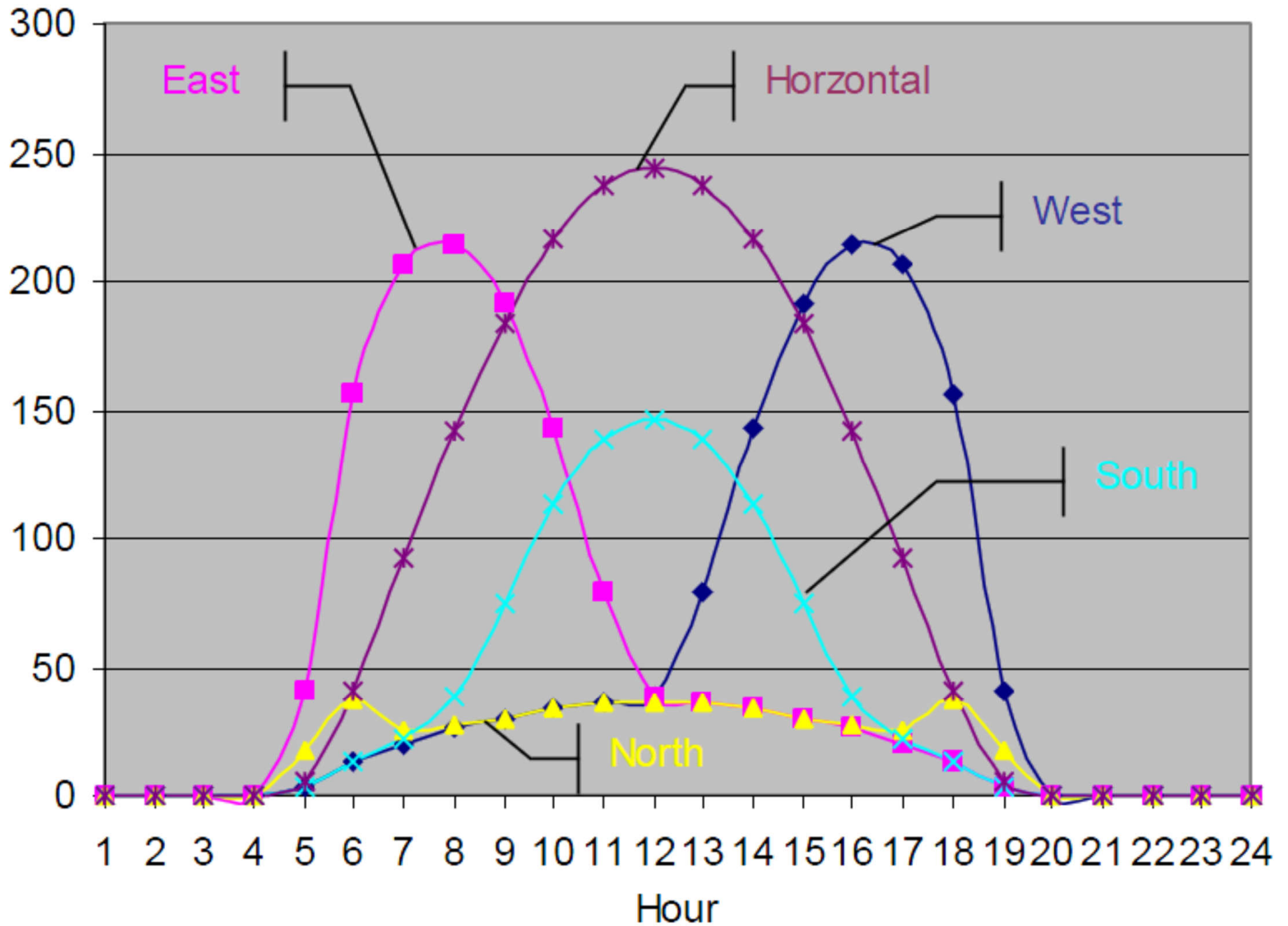
Cooling loads due to windows at different orientations



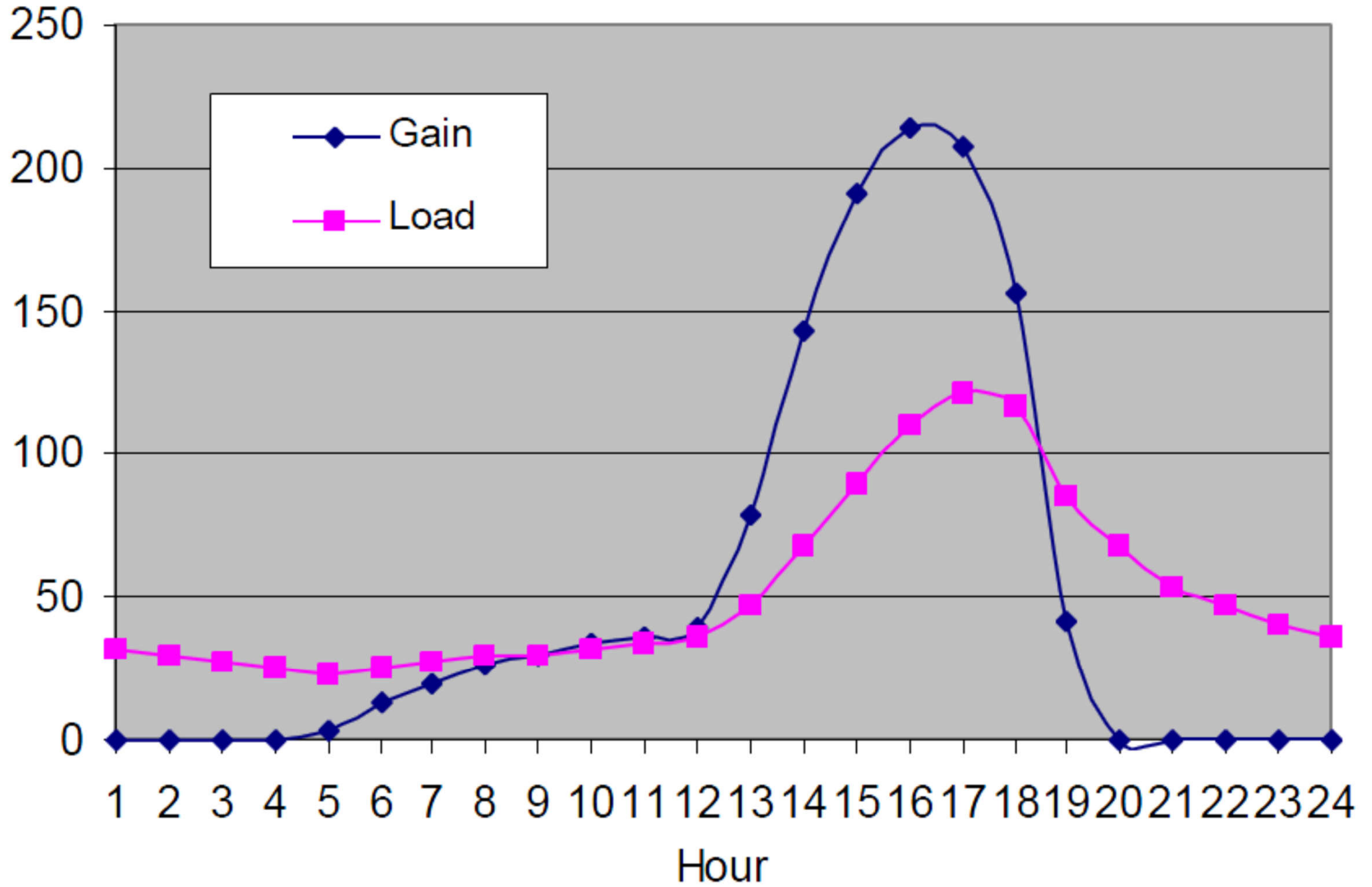
Do you know why the profiles and peak cooling loads like these?

(Source: D.G. Stephenson, 1968)

Profiles of solar heat gain (July) (for latitude 48 deg N)



Solar cooling load vs. heat gain (July, west) (latitude 48 deg N)



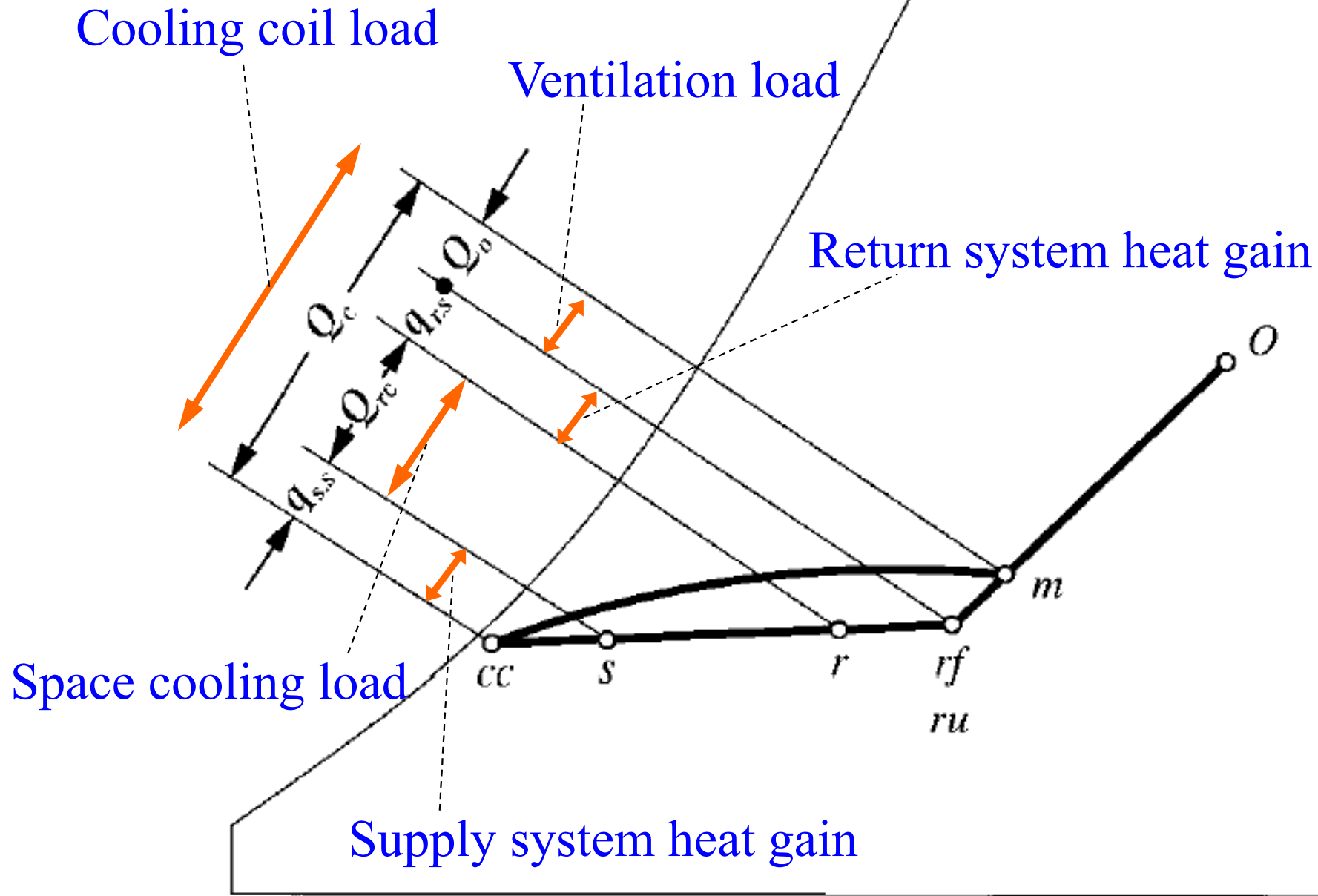
(Source: Keith E. Elder)



HVAC System Sizing

- Cooling coil load consists of:
 - Space cooling load (sensible & latent)
 - Supply system heat gain (fan + air duct)
 - Return system heat gain (plenum + fan + air duct)
 - Load due to outdoor ventilation rates (or ventilation load)
- Do you know how to construct a summer air conditioning cycle on a psychrometric chart?
 - See also lecture notes on Psychrometrics

Typical summer air conditioning cycle

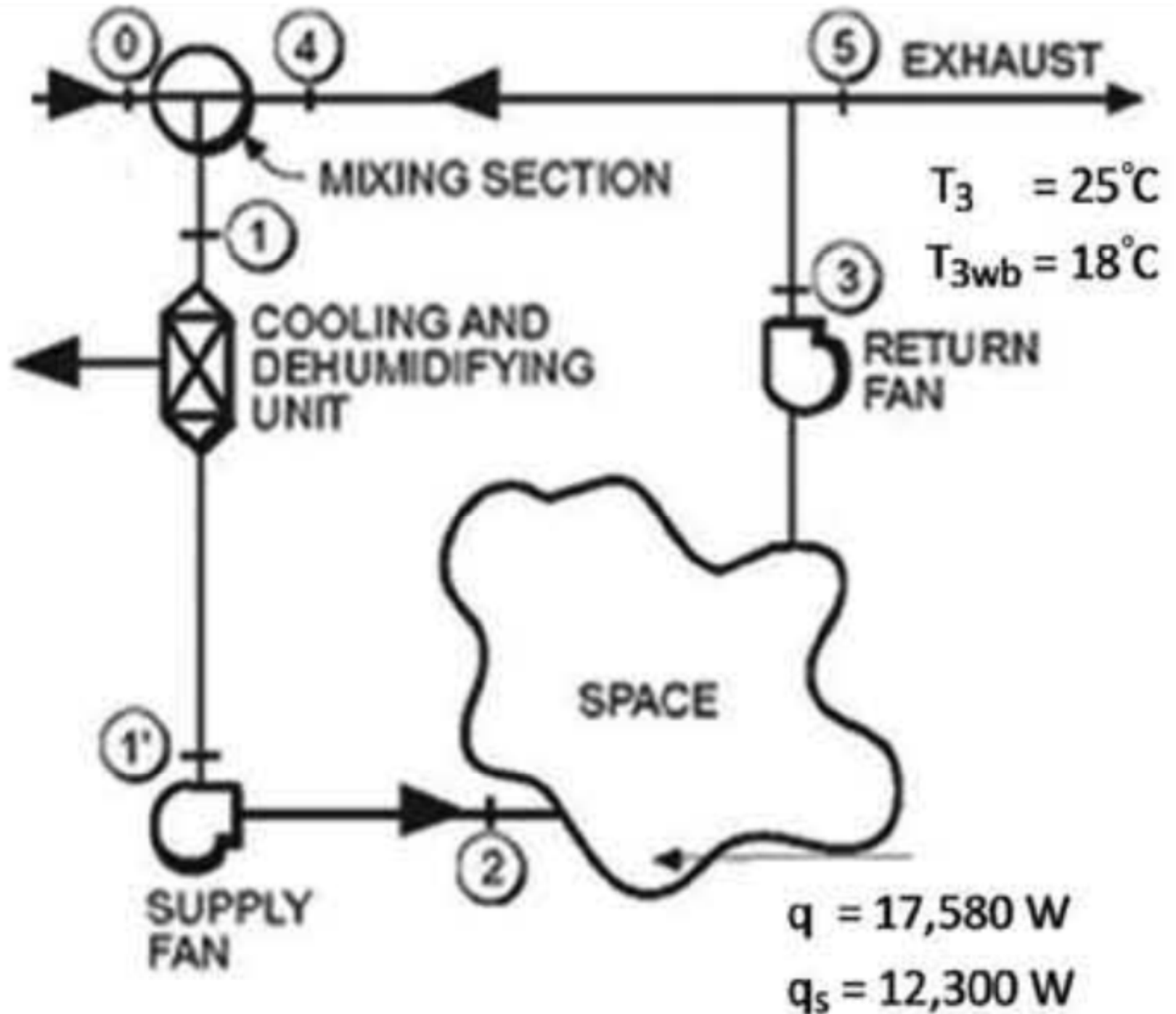


An example of cooling & dehumidification system

$t_o = 32^\circ\text{C}$

$\phi_o = 55\%$

ODA = 250 L/s





HVAC System Sizing

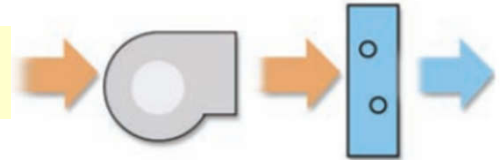
- System heat gain (fan + air duct)
- Three types of heat generation:
 - Fan motor heat gain = power input to motor \times (1 – motor efficiency)
 - Fan blade heat gain = power input to fan \times (1 – fan efficiency)
 - Duct friction heat gain = power input to fan \times fan efficiency
- Fan locations: blow-through, draw-through

HVAC System Sizing



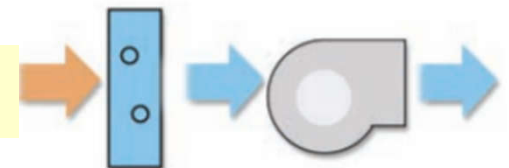
- Components of fan heat

Blow-through



- If the fan is located upstream and blows air through the cooling coil, the fan heat causes an increase in the temperature of the air entering the coil
- If the fan is located downstream and draws air through the cooling coil, the fan heat causes an increase in the temperature of the air supplied to the space

Draw-through





HVAC System Sizing

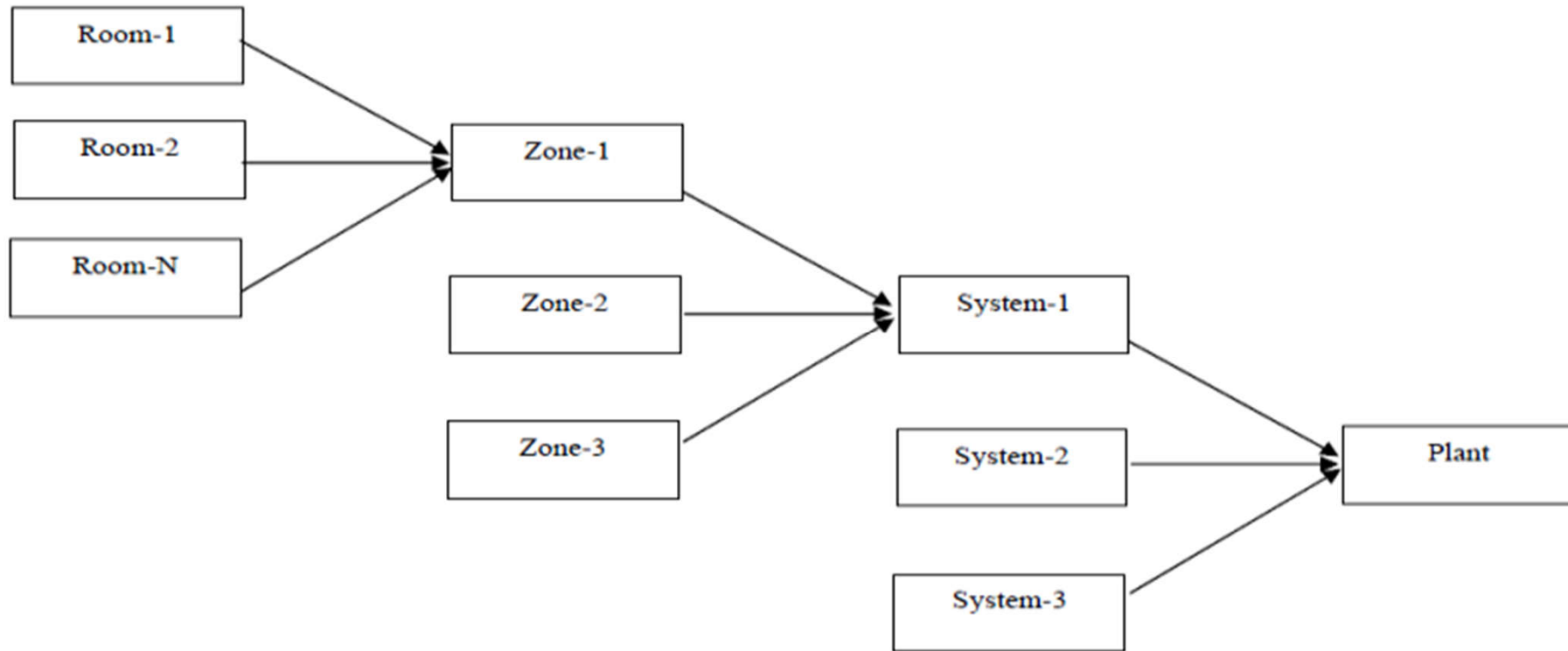
- Space cooling load $\text{Supply airflow (L/s)} = \frac{\text{Sensible load (kW)}}{1.2 \times \Delta t}$
 - To determine supply air flow rate & size of air system, ducts, terminals, diffusers
 - It is a component of cooling coil load
 - Infiltration heat gain is an instant. cooling load
- Cooling coil load
 - To determine the size of cooling coil & refrigeration system
 - Remember, ventilation load is a coil load



HVAC System Sizing

- Hierarchy of cooling load & energy calculations
 - Room: Calculate the peak cooling loads (a) sensible (b) latent
 - Zone: Simultaneous peak of rooms + zone loads (terminal fans, recirculation air, etc.)
 - System: Simultaneous peak of zones + system loads (outdoor air, fans, ductwork)
 - Plant: Simultaneous peak of systems

Hierarchy of cooling load & energy calculations



Room:	(a) Sensible: exterior (roofs, walls, windows, infiltration), interior (people, equipment, lights) (b) Latent: (infiltration, people, equipment)
Zone:	Used to control conditions in several rooms based on control (e.g. thermostat) in one of the rooms
System:	(a) Sensible: (outdoor air, fans, recirculate air, ductwork, equipment etc.) (b) Latent: (outdoor air, recirculate air)
Plant:	(a) Sensible Cooling (Chillers, Cooling Towers, Pumps, etc.) (b) Heating (Boilers, Heat Exchangers, Pumps, etc.)

Components of room heat gains & cooling load

	SHG	LHG	COMMENTS
External	<input checked="" type="checkbox"/>		
Walls	<input checked="" type="checkbox"/>		Radiation,, conduction, heat transfer, using CLTD's, Sol-air, temperature, time lags.
Roofs	<input checked="" type="checkbox"/>		
Windows (glass on wall)	<input checked="" type="checkbox"/>		
Skylight (glass on roof)	<input checked="" type="checkbox"/>		Solar radiation and conduction using SCL, zones.
Partitions	<input checked="" type="checkbox"/>		
Floors	<input checked="" type="checkbox"/>		Heat transfer by conduction
Ceilings	<input checked="" type="checkbox"/>		
Infiltration	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Latent and sensible heat transfer with mass transfer.
Internal	<input checked="" type="checkbox"/>		
▪ People	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Sensible heat gain using CLF
▪ Lights	<input checked="" type="checkbox"/>		
▪ Equipment	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	Latent heat gain is instantaneous
Total Room	SHG	LHG	Use to determine supply air quantity and condition.



HVAC System Sizing

- Review of load calculation results
 - Compare against rules-of-thumb (or check figures)
 - Vary across climates and space-functions
 - Add safety factors (oversizing margins)
 - Influenced by distribution losses, regional construction quality, space operation and start-up capacity
 - Select & size the HVAC system types
 - Air-side systems, diffusers, air ducts, central plant capacities, heating equipment, etc.

Review of load calculation results against rules-of-thumb

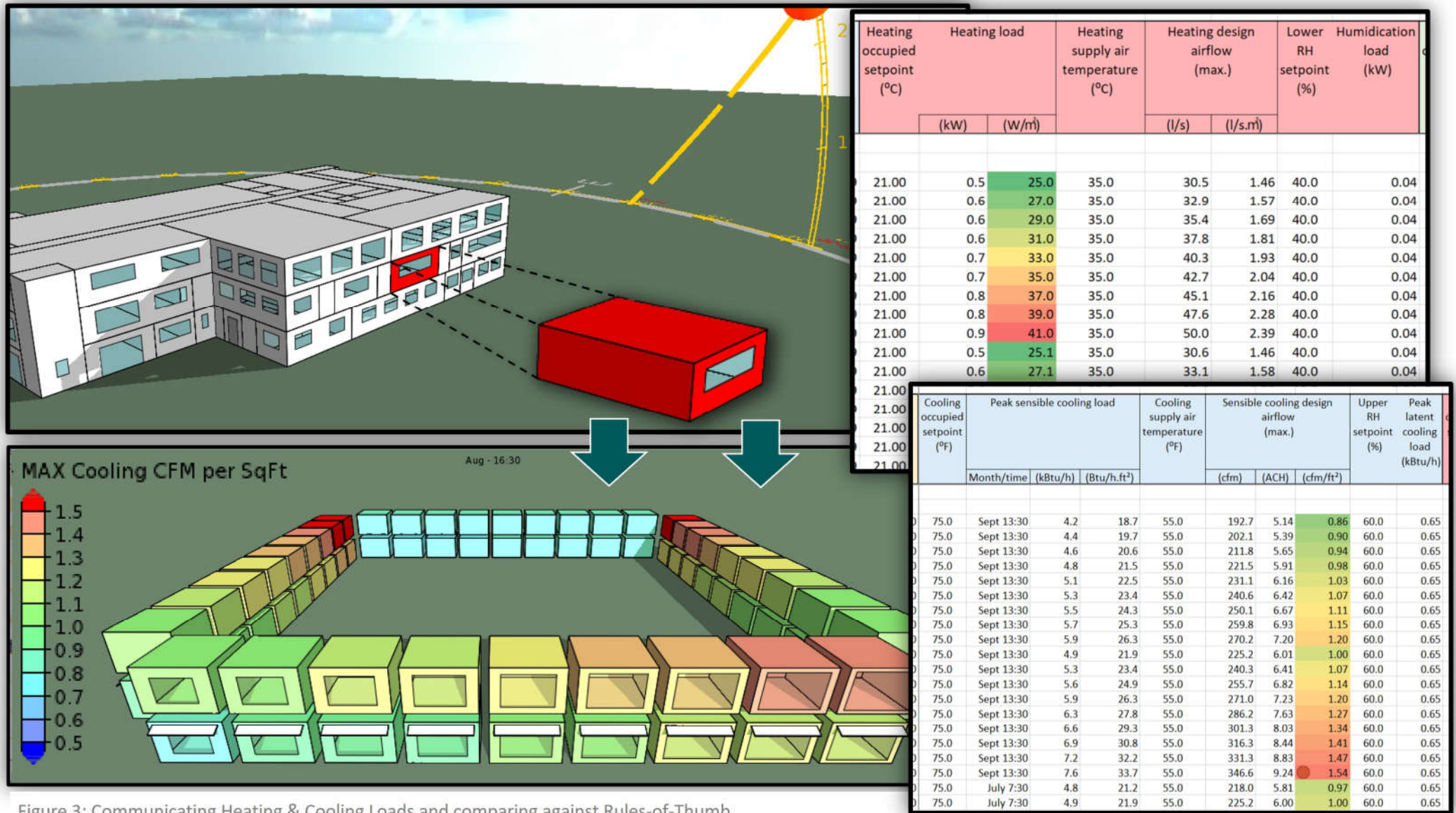


Figure 3: Communicating Heating & Cooling Loads and comparing against Rules-of-Thumb



HVAC System Sizing

- Moisture transfer & latent heat
 - Two paths:
 - Moisture migrates in building envelope
 - Air leakage (infiltration or exfiltration)
 - If slight RH variation is acceptable, then storage effect of moisture can be ignored
 - Latent heat gain = latent cooling load (instantaneously)
- What happens if both temp. & RH need to be controlled accurately?

Calculation Methodology



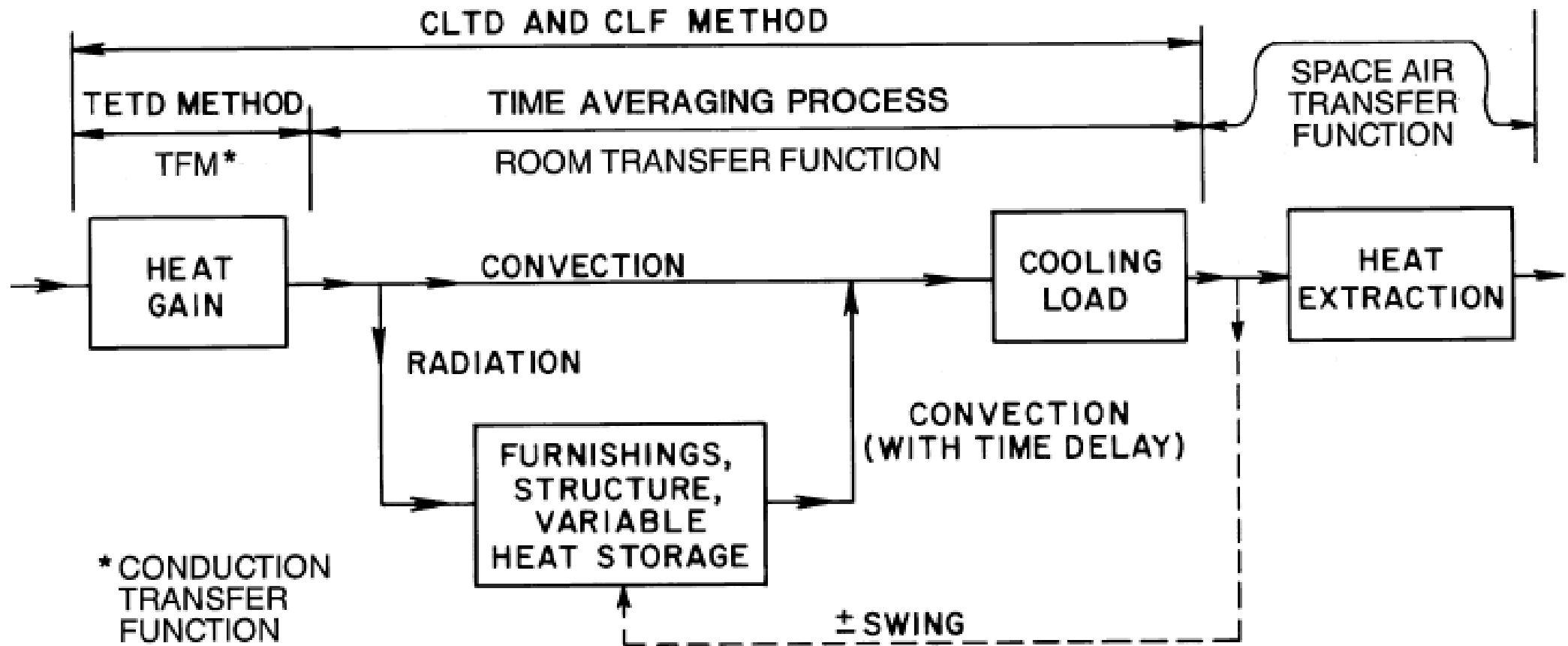
- Common cooling load calculation methods*:
 - Transfer function method (TFM)
 - Cooling load temperature difference/cooling load factor (CLTD/CLF) method
 - Total equivalent temp. differential/time averaging (TETD/TA) method
- Other existing methods:
 - Finite difference method (FDM)
 - CIBSE method (based on admittance)

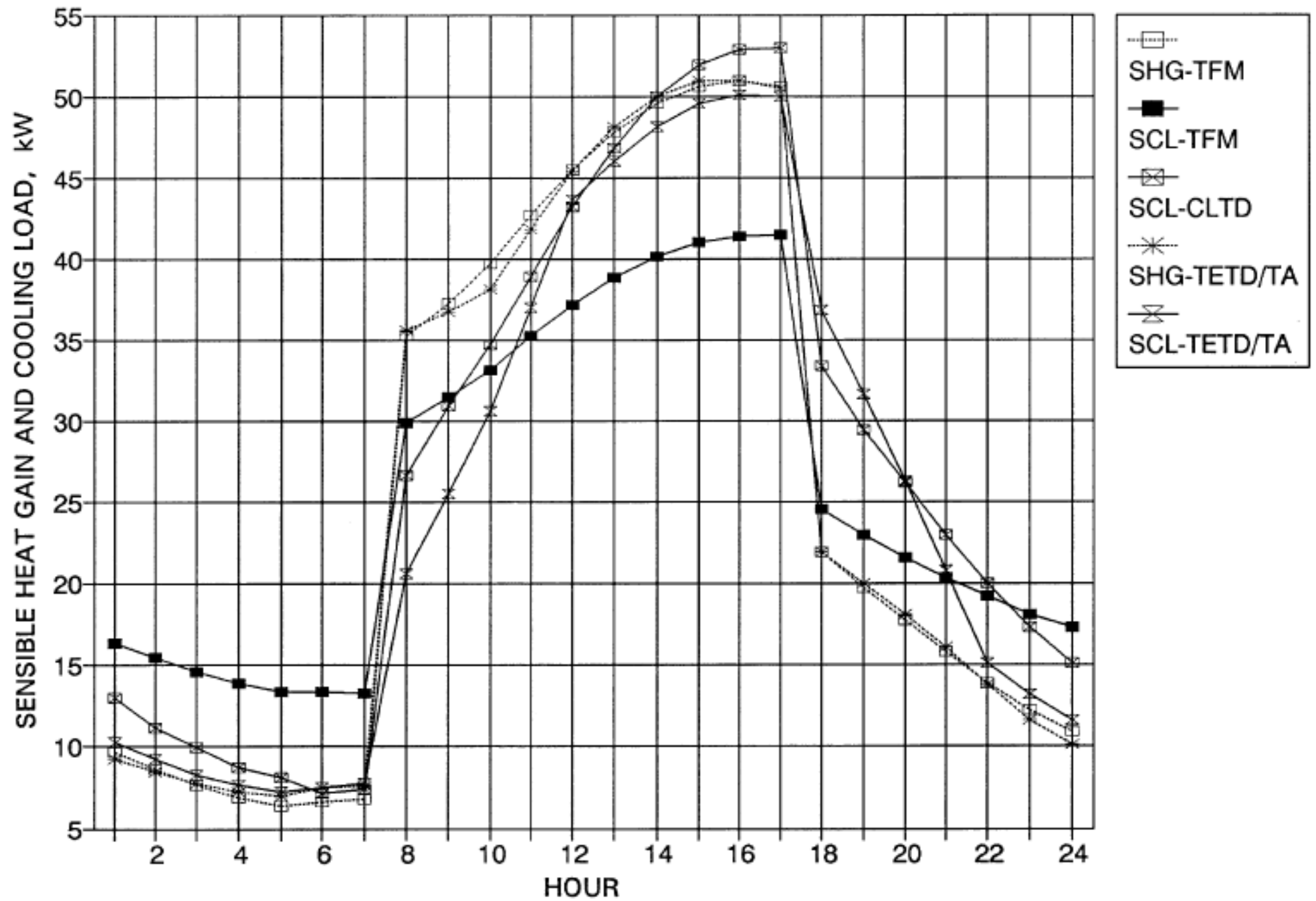
Calculation Methodology



- Transfer Function Method (TFM)
 - Laplace transform and z-transform of time series
- CLTD/CLF method
 - A one-step simplification of TFM
- TETD/TA method
 - Heat gains calculated from Fourier series solution of 1-dimensional transient heat conduction
 - Average heat gains to current and successive hours according to thermal mass & experience

Basic concepts of TFM, CLTD/CLF and TETD/TA methods





**Fig. 5 TFM versus CLTD/SCF/CLF Versus TETD/TA
Methods of Calculating Sensible Heat Gain and Cooling Load**

Calculation Methodology



- Sol-air temperature (t_e)
 - A fictitious outdoor air temperature that gives the rate of heat entering the outer surface of walls and roofs due to the combined effect of incident solar radiation, radiative heat exchange with the sky vault and surroundings, and convective heat exchange with the outdoor air

$$t_e = t_o + \frac{\alpha E_t}{h_o} - \frac{\varepsilon \Delta R}{h_o}$$

Outdoor air temp

Surface absorptance

Surface emittance

Heat balance at a sunlit surface, heat flux is equal to:

$$\frac{q}{A} = \alpha E_t + h_o(t_o - t_s) - \epsilon \Delta R$$

where

α = absorptance of surface for solar radiation

E_t = total solar radiation incident on surface, W/m²

h_o = coefficient of heat transfer by long-wave radiation and convection at outer surface, W/(m²·K)

t_o = outdoor air temperature, °C

t_s = surface temperature, °C

ϵ = hemispherical emittance of surface

ΔR = difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by blackbody at outdoor air temperature, W/m²

Assume the heat flux can be expressed in terms of sol-air temp. (t_e)

$$\frac{q}{A} = h_o(t_e - t_s)$$

Thus, sol-air temperature is given by: $t_e = t_o + \frac{\alpha E_t}{h_o} - \frac{\epsilon \Delta R}{h_o}$

Calculation Methodology



- Other methods:
 - Heat balance (HB) method
 - The rigorous approach (mainly for research use)
 - Requires solving of partial differential equations and often involves iteration
 - Radiant time series (RTS) method
 - A simplified method derived from HB procedure
 - Finite difference/element method (FDM or FEM)
 - Solve transient simultaneous heat & moisture transfer

Calculation Methodology



- Heat Balance (HB) Method
 - Use heat balance equations to calculate:
 - Surface-by-surface conductive, convective & radiative heat balance for each room surface
 - Convective heat balance for the room air
 - Calculation process
 - Find the inside surface temperatures of building structures due to heat balance
 - Calculate the sum of heat transfer from these surfaces and from internal loads

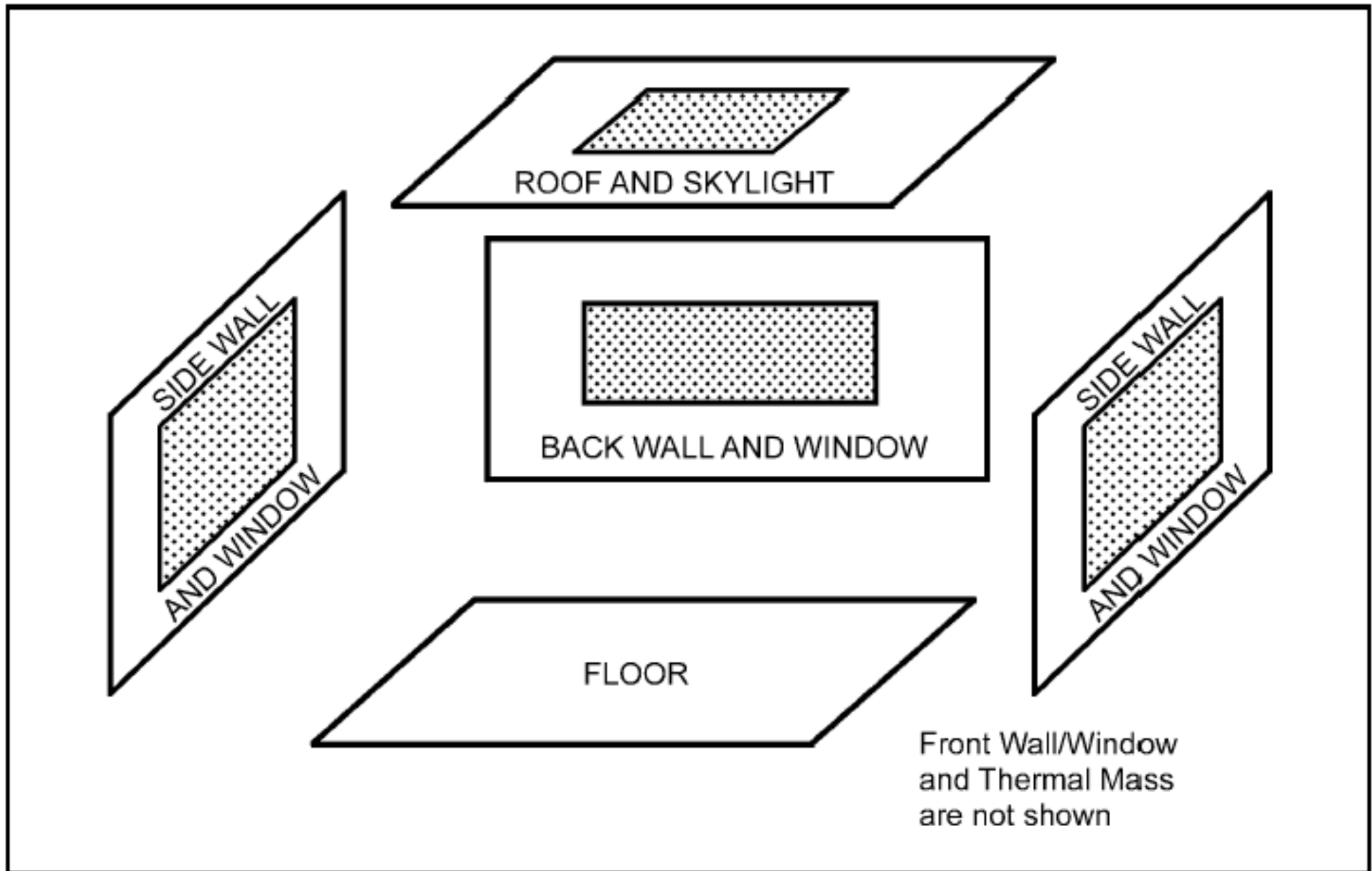
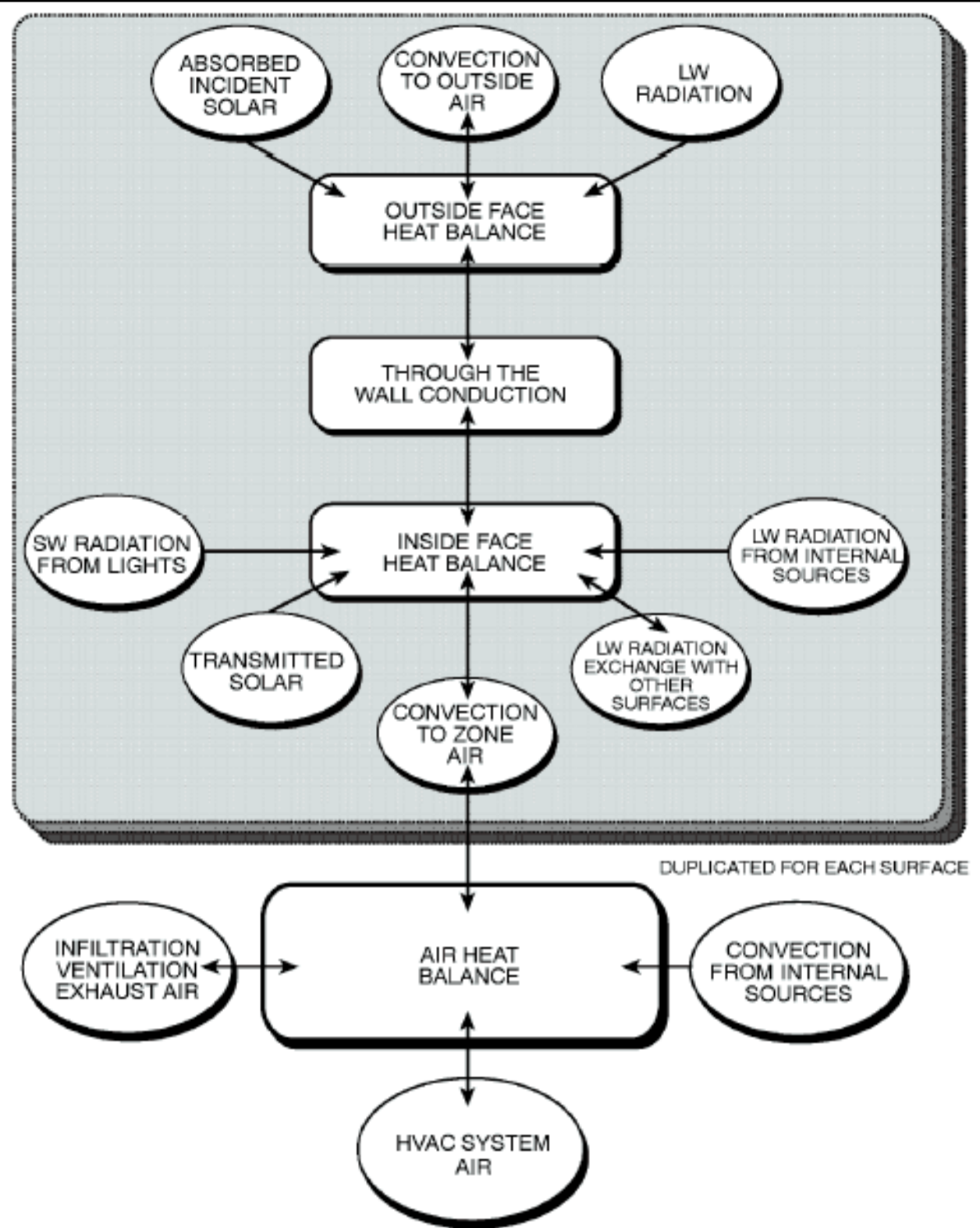


Fig. 7 Schematic View of General Heat Balance Zone

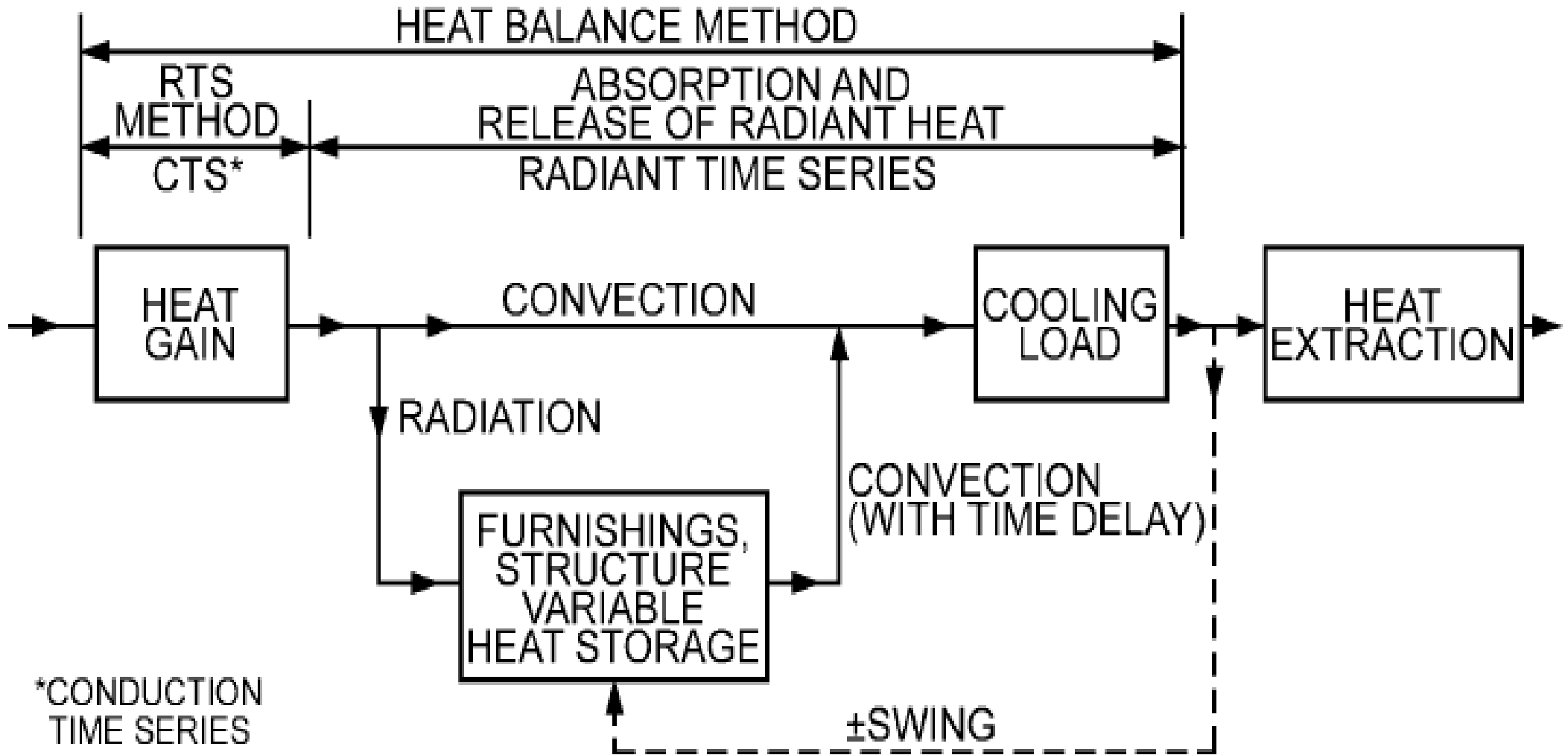
(Source: ASHRAE Handbook Fundamentals 2005)

Four heat balance processes in a zone:

1. Outside face heat balance
2. Wall conduction process
3. Inside face heat balance
4. Air heat balance



Basic concepts of heat balance and radiant time series methods

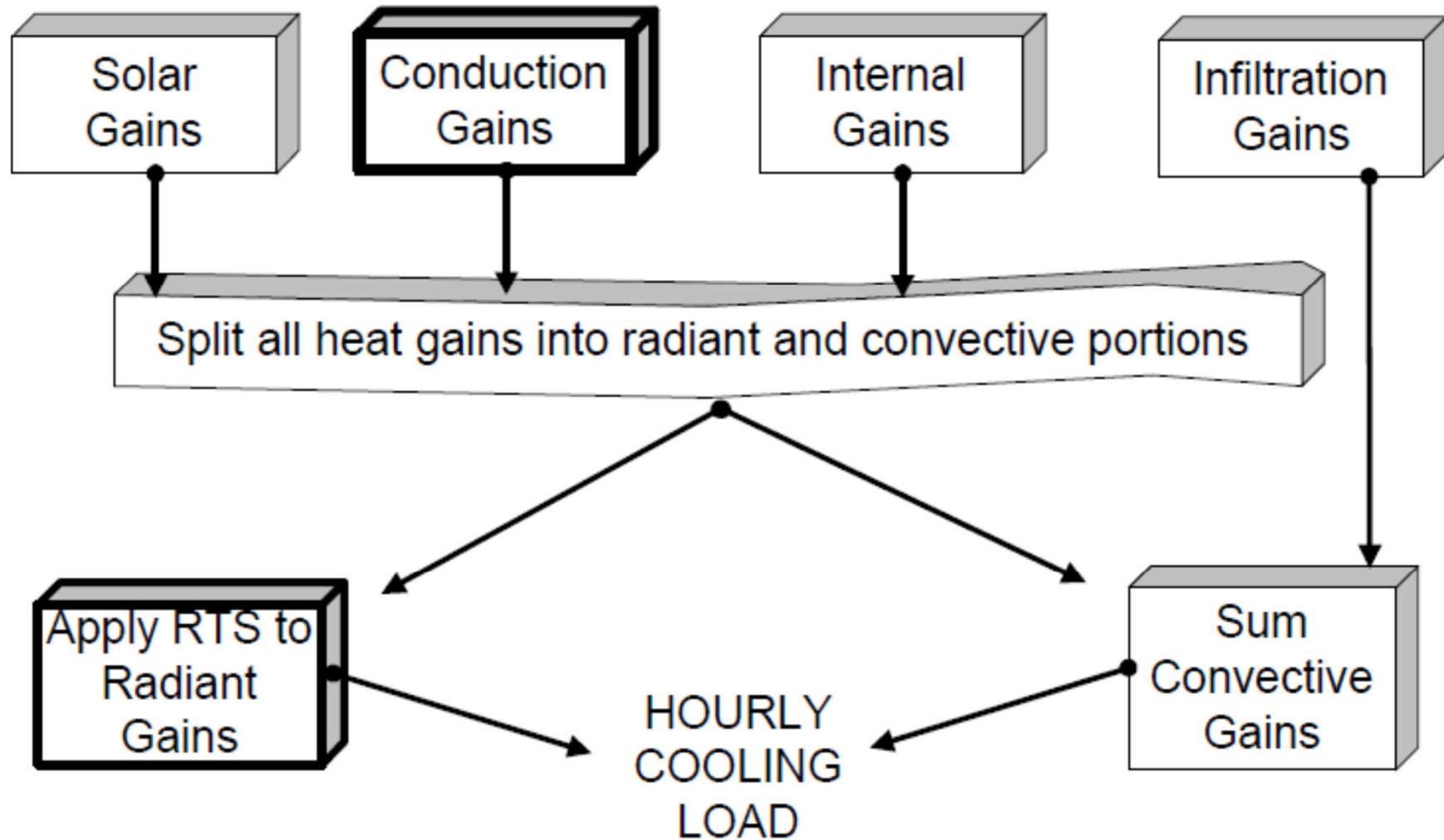


Calculation Methodology



- Radiant time series (RTS) method
 - A simplified method directly related to and derived from the HB calculation procedure
 - Does not require iterative calculations
 - Can quantify each component contribution to the total cooling load
 - Suitable for peak design load calculations, but not for annual energy simulations

Main ideas of radiant time series (RTS) method



The current heat transfer to/from the interior is equal to:

- part of the current convective heat transfer to the outside of the enclosure
- current solar heat gain through fenestration
- part of the earlier convective and radiative heat transfer to the outside of the enclosure (radiative portion of each heat gain by applying a radiant time series)

Split of heat gains into radiative and convective portions

Heat Gain	% radiative	% convective
Wall, window conduction	63	37
Roof conduction	84	16
People	70	30
Lighting	67	33
Equipment	20	80
Transmitted solar heat gain	100	0
Absorbed solar heat gain	63	37
Infiltration	0	100

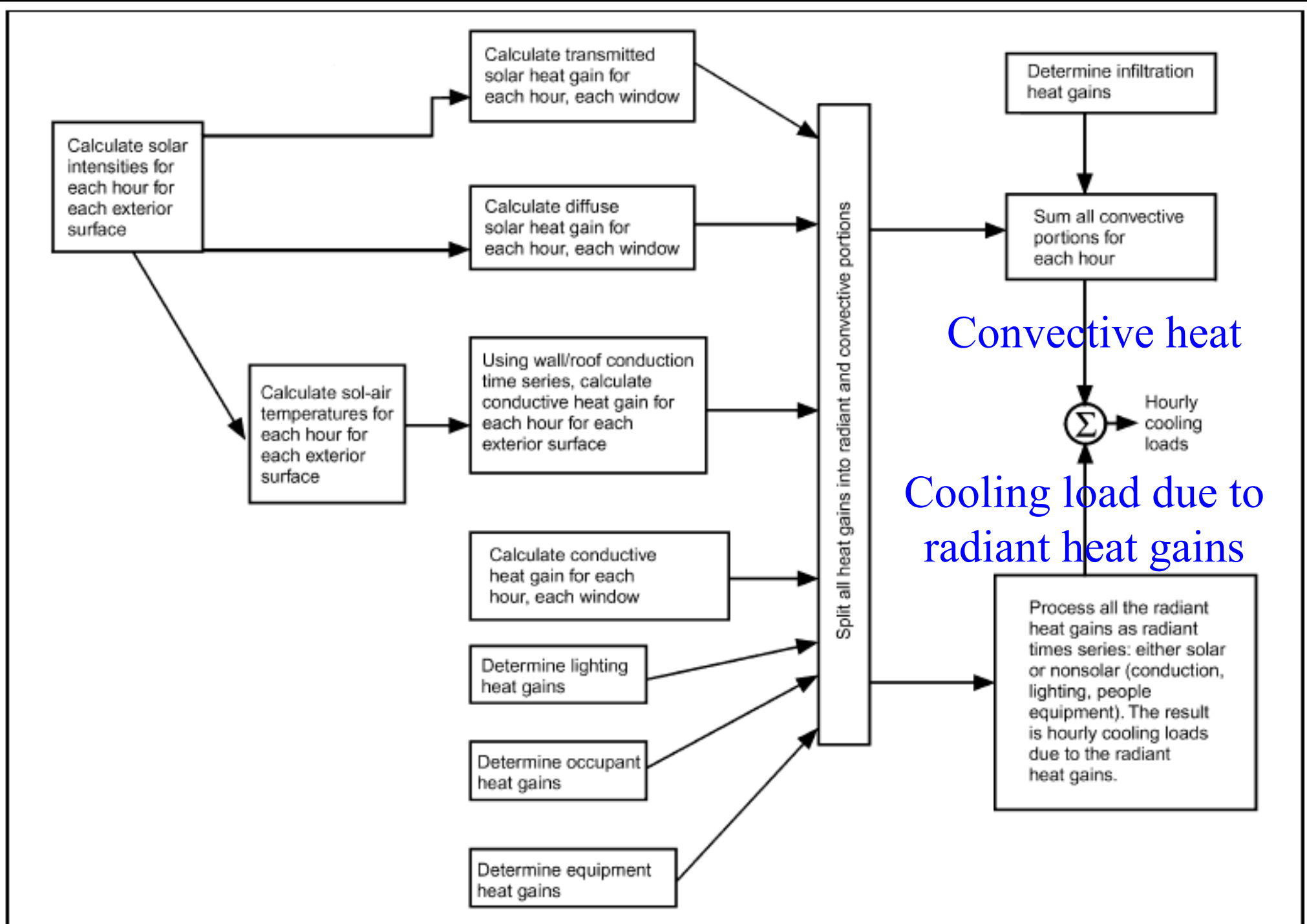


Fig. 8 Overview of Radiant Time Series Method

(Source: ASHRAE Handbook Fundamentals 2005)

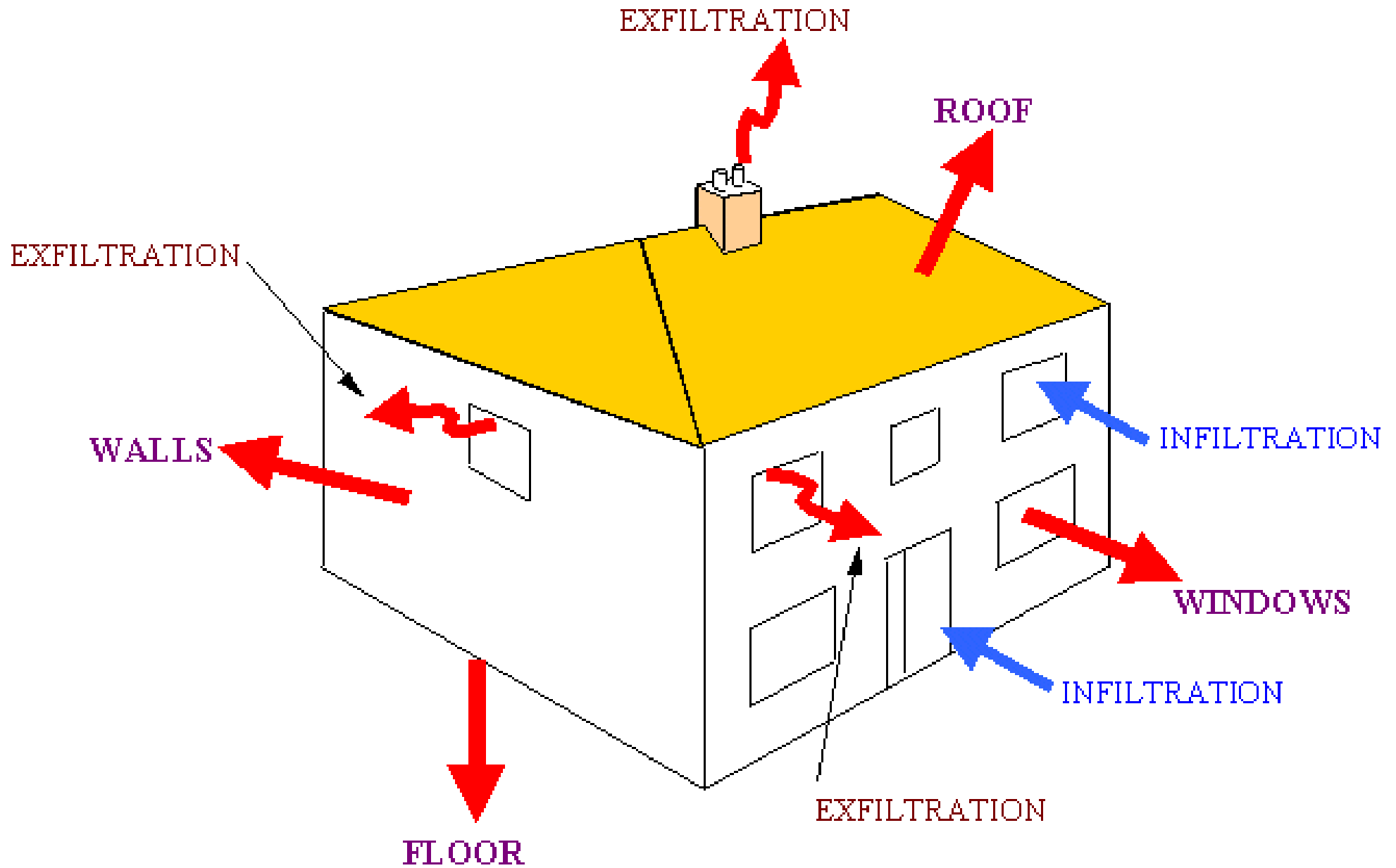
Heating Load



- Design heating load

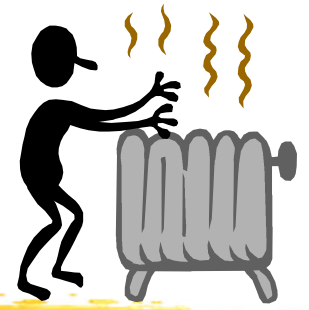
- Max. heat energy required to maintain winter indoor design temp.
 - Usually occurs before sunrise on the coldest days
 - Include transmission losses & infiltration/ventilation
- Assumptions:
 - All heating losses are instantaneous heating loads
 - Credit for solar & internal heat gains is not included
 - Latent heat often not considered (unless w/ humidifier)
 - Thermal storage effect of building structure is ignored

Heat losses for heating load calculation



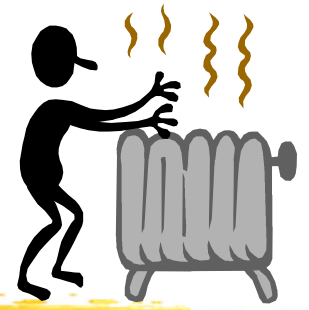
HEAT LOSS FROM A HOUSE

Heating Load



- A simplified approach to evaluate worst-case conditions based on
 - Design interior and exterior conditions
 - Including infiltration and/or ventilation
 - No solar effect (at night or on cloudy winter days)
 - Before the presence of people, light, and appliances has an offsetting effect
- Also, a warm-up/safety allowance of 20-25% is fairly common

Heating Load



- Estimate the maximum probable heat loss based on three kinds of heat losses:
 - (1) Heat transmitted through walls, ceiling, floor, glass, or other surfaces
 - (2) Heat required to warm outdoor air entering the space
 - (3) The heat needed to warm or thaw significant quantities of materials brought into the space
- The actual heat loss problem is transient

Table 12 Summary of Loads, Equations, and References for Calculating Design Heating Loads

Heating Load	Equation	Reference, Table, Description
Roofs, ceilings, walls, glass	$q = U A \Delta t$	<p>Chapter 24, Tables 1, 2, and 4</p> <p>Temperature difference between inside and outside design dry bulbs, Chapter 26. For temperatures in unheated spaces, see Equation (2); for attic temperatures, see Equation (3).</p> <p>Area calculated from plans</p>
Walls below grade	$q = U A \Delta t$	<p>See Table 14.</p> <p>Use Figure 6 to assist in determining Δt.</p>
Floors		
Above grade	$q = U A \Delta t$	For crawl space temperatures, see Equation (4).
On grade	$q = F_2 P \Delta t$	<p>See Table 16.</p> <p>See Equation (6).</p> <p>Perimeter of slab</p>
Below grade	$q = U A \Delta t$	<p>Use Figure 6 to assist in determining Δt.</p> <p>See Table 15.</p>
Infiltration and ventilation air		
Sensible	$q_s = 0.018 Q \Delta t$	Volume of outdoor air entering building. See Chapter 25 for estimating methods for infiltration.
Latent	$q_t = 80.7 Q \Delta W$	Humidity ratio difference, if humidification is to be added

Software Applications



- Advantages:
 - Time saving for tedious calculations & iterations
 - Calculating the block load for a multiple-space system easily & determine time of peak
 - Recalculate loads quickly when changes occur to the building design through the design process
 - Easier to perform trade-off or what-if analyses
 - Provide the basis for future energy calculations & analyses

Software Applications



- Examples of load calculation software:
 - Carmel Loadsoft 6.0 [AV 697.00028553 L79]*
 - Commercial and industrial HVAC load calculation software based on ASHRAE 2001 Fundamentals radiant time series (RTS) method
 - Carmel Residential 5.0 [AV 697.00028553 R43]*
 - Residential and light commercial HVAC load calculation software based on ASHRAE 2001 Fundamentals residential algorithms

Software Applications



- Examples of load calculation software: (cont'd)
 - Elite Software: CHVAC and RHVAC [AV 697 E43]* <http://www.elitesoft.com/>
 - CHVAC - Commercial HVAC Loads
 - RHVAC - Residential HVAC Loads
 - HVAC Load Explorer
 - <https://hvac.okstate.edu/hvac-load-explorer;>
<https://hvac.okstate.edu/hvac-load-explorer-0>
 - User's Guide
 - <http://www.philadelphia.edu.jo/academics/sammourah/uploads/HvacLoadExplorer.pdf>

Software Applications



- Examples of load/energy calculation software:
 - TRACE 700 (commercial program from Trane)
 - TRACE = Trane Air Conditioning Economics
 - <https://www.trane.com/commercial/north-america/us/en/products-systems/design-and-analysis-tools/trace-700.html>
 - Most widely used by engineers in USA
 - Will be phased out by the end of 2022 and replaced by the new TRACE 3D Plus platform
 - https://tranecds.custhelp.com/app/answers/detail/a_id/700/~/trace-700-phase-out-dates

Software Applications

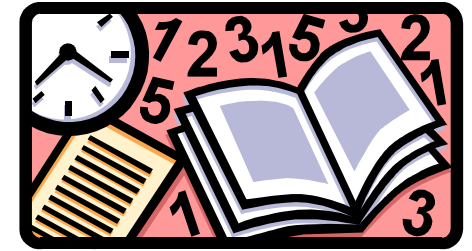


- Examples of load/energy calculation software:
 - Carrier E20-II HAP (hourly analysis program)
 - <https://www.carrier.com/commercial/en/us/software/hvac-system-design/hourly-analysis-program/>
 - A popular load software in HK
 - IES Virtual Environment (VE)
 - <https://www.iesve.com/software/loads>
 - HVAC loads sizing using the ASHRAE Heat Balance Method

Further Reading



- Hashim H. M., Sokolova E., Derevianko O. & Solovev D. B., 2018. Cooling load calculations, *IOP Conference Series: Materials Science and Engineering*, 463, 032030.
<https://iopscience.iop.org/article/10.1088/1757-899X/463/3/032030/pdf>
- Wang, S. K., 2001. *Handbook of Air Conditioning and Refrigeration*, 2nd ed., Chapter 6 Load Calculations, McGraw-Hill, New York. [[697.93 W24 h](#)][[eBook via Knovel](#)]
 - <https://gmpua.com/CleanRoom/HVAC/Cooling/Handbook%20of%20Air%20Conditioning%20and%20Refrigeration.pdf>



References

- ASHRAE, 2017. *ASHRAE Handbook Fundamentals 2017*, Chps. 14-18, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA. [[ASHRAE Catalog: 697 A82 T4](#)]
- Mao C., Baltazar J. C. & Haberl J. S., 2019. Comparison of ASHRAE peak cooling load calculation methods, *Science and Technology for the Built Environment*, 25 (2) 189-208.
- Spitler, J. D., 2014. *Load Calculation Applications Manual*, 2nd ed., SI ed., American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA. [[HKU ebook](#)]