

# CAE 331/513

## Building Science

Fall 2013

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### Lecture 10: November 11, 2013

Finish cooling loads

HVAC systems

Energy estimation methods

Built  
Environment  
Research

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# Scheduling

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- HW 5 graded and returned
  - Any questions on HW 4 (IAQ) or HW 5 (heating loads)?
- One more HW assigned today, due next week
- Final exam: Monday December 2, 5-7 PM
  - Will cover all course topics
  - Fewer problems than mid-term
- Grad students
  - Final projects and presentations due November 25<sup>th</sup>
  - Blog posts
    - 1 next week, November 18: Any topic
    - 1 the final week, November 25: Summarize your research paper

# Last time

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- Cooling load calculation methods
  - CLTD/CLF
  - Transfer functions
  - RTS

# Today's objectives

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- Finish RTS cooling load example (ASHRAE HOF)
- Heat balance methods
- HVAC systems and equipment
- Energy estimation methods

# Another RTSM example

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- ASHRAE Handbook of Fundamentals RTS example
  - Single room example, Chapter 30 in 2005 HOF

# Software tools for load calcs

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- These are not done by hand, sometimes by spreadsheet
  - Many use ACCA Manual J
- Most use computer programs
- Big list of programs:
  - [http://apps1.eere.energy.gov/buildings/tools\\_directory/subjects.cfm/pagename=subjects/pagename\\_menu=whole\\_building\\_analysis/pagename\\_submenu=load\\_calculation](http://apps1.eere.energy.gov/buildings/tools_directory/subjects.cfm/pagename=subjects/pagename_menu=whole_building_analysis/pagename_submenu=load_calculation)

# Last cooling load method: Heat balance method

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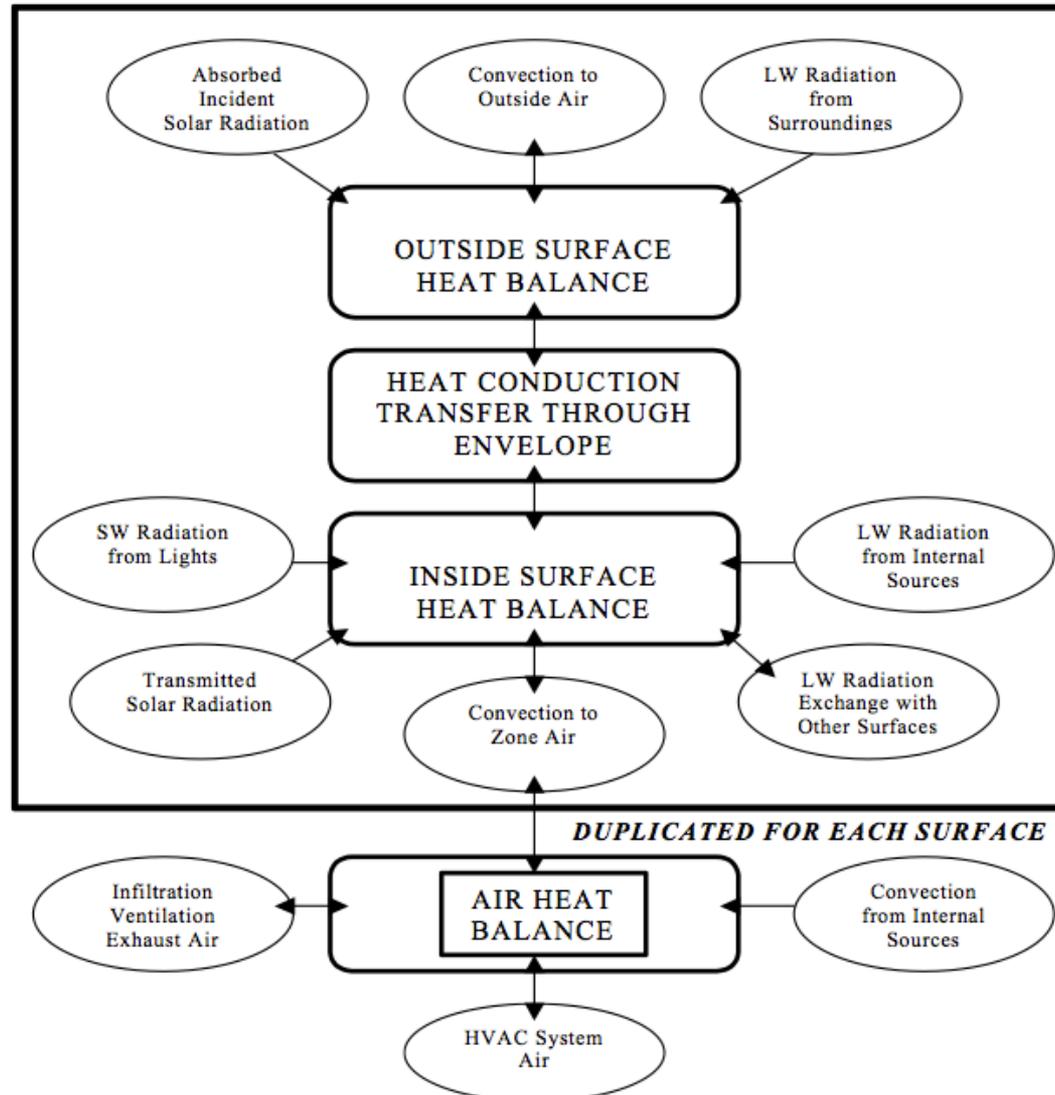
- Relies on a combination of surface and air energy balances
- More detailed than RTS
  - Actually used to generate the standardized profiles in RTS method
- Requires a computer program
  - More time consuming than other methods
- Foundation of modern energy simulation programs
  - We cover this topic in 463/524 Building Enclosure Design
  - Will eventually have a dedicated energy simulation course also

# Heat balance method (HBM)

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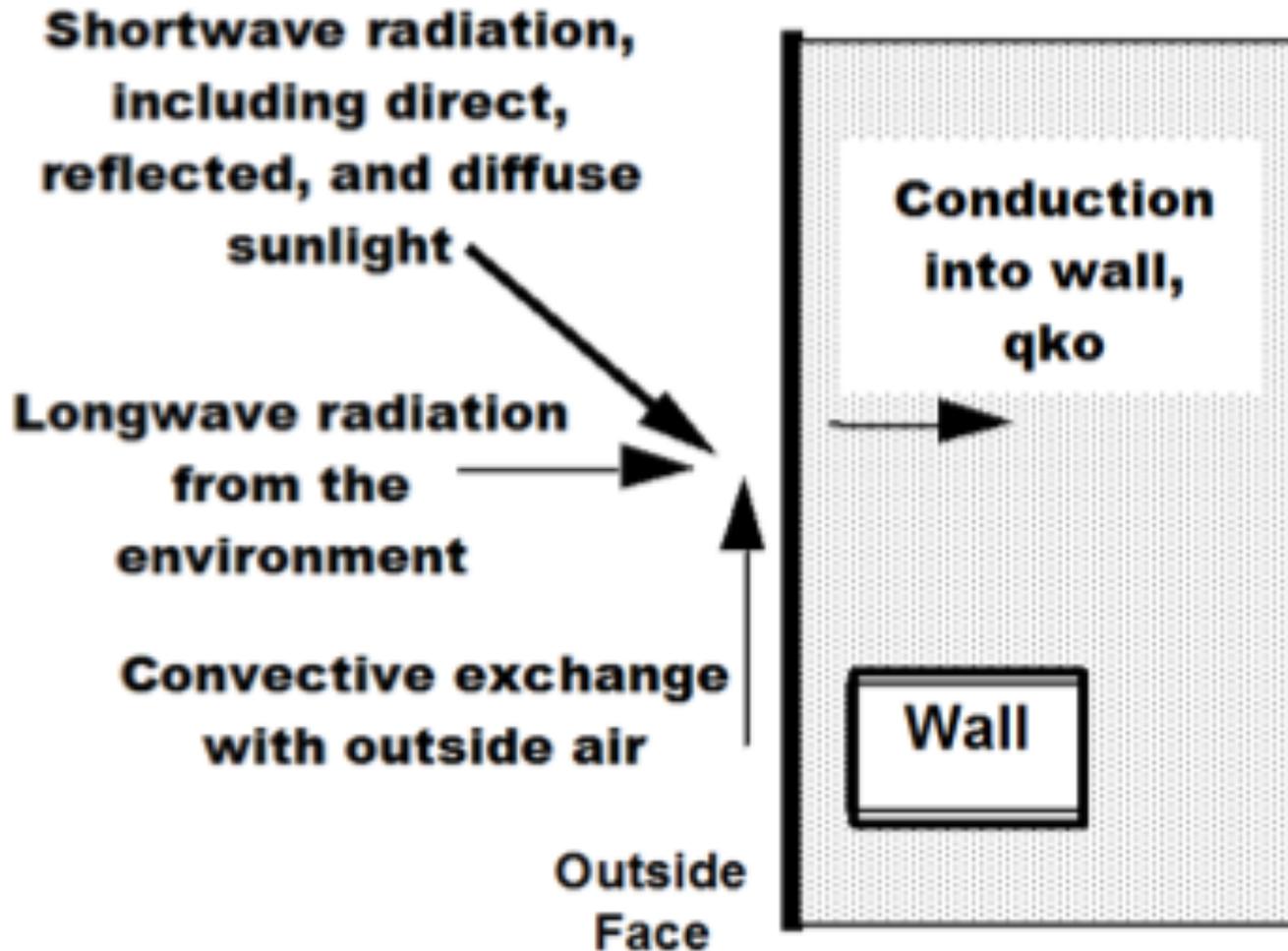
- HBM is based on the law of conservation of energy
- A set of energy balance equations for an enclosed space is solved simultaneously for unknown surface and air temperatures
- Many fewer assumptions; more fundamental
- Consists of three important energy balance equations:
  - Outside surface heat balance
  - Inside surface heat balance
  - Air heat balance
- Initiated by hourly outdoor climate conditions
  - Design day meteorological data (or full year)

# Heat balance method (HBM)

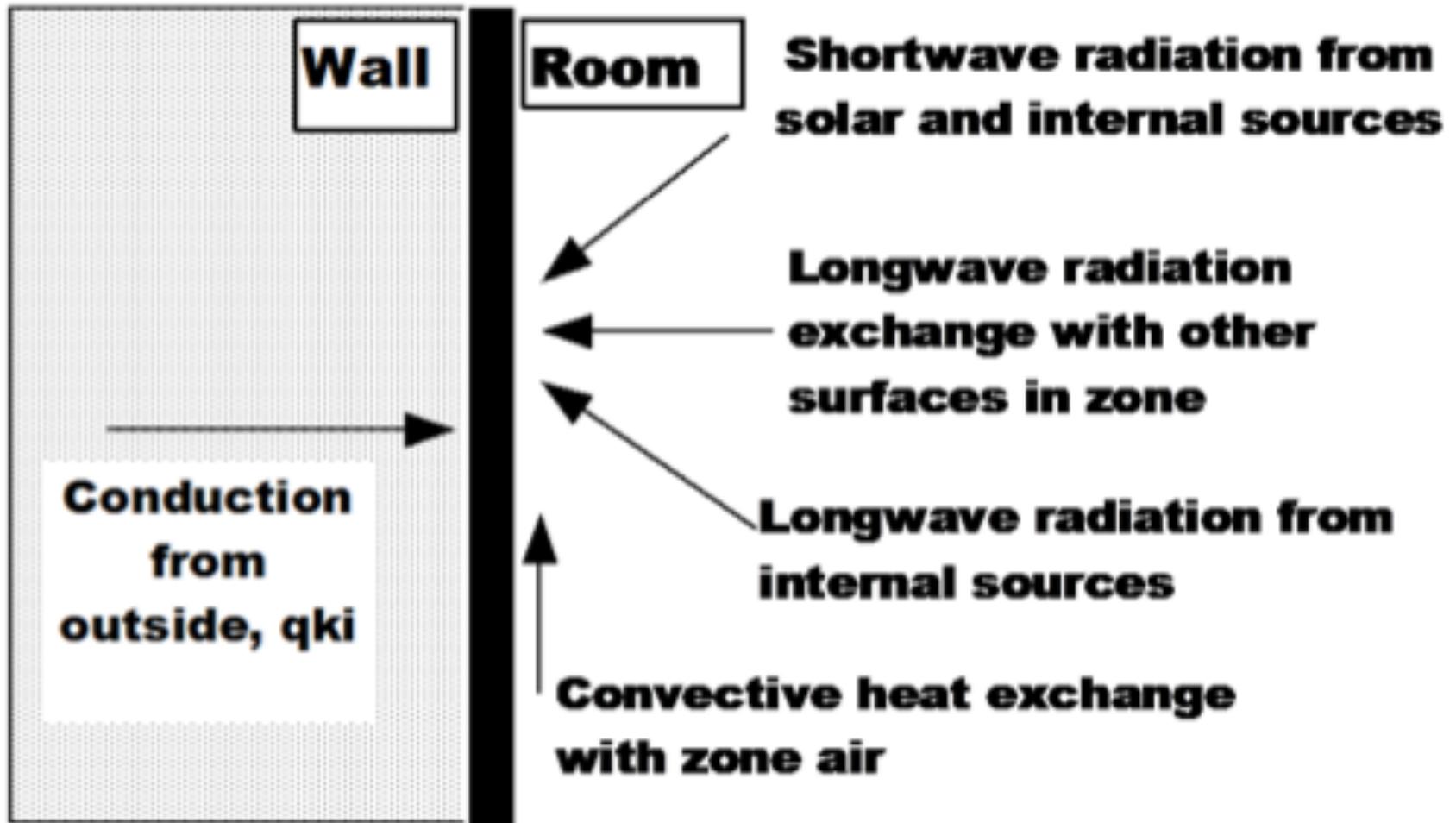


# Heat balance method (HBM): Outside heat balance

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# Heat balance method (HBM): Inside heat balance



# Heat balance method (HBM): Indoor air heat balance

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

where:

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

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

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

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

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

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

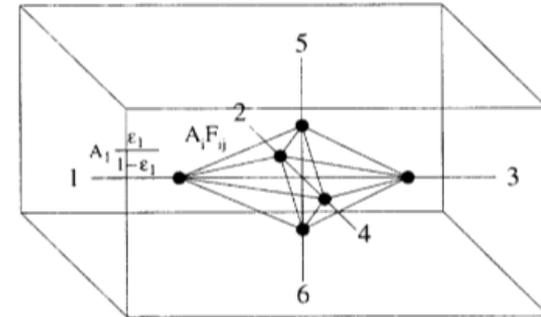
$$C_z = \rho_{air} C_p C_T$$

$\rho_{air}$  = zone air density

$C_p$  = zone air specific heat

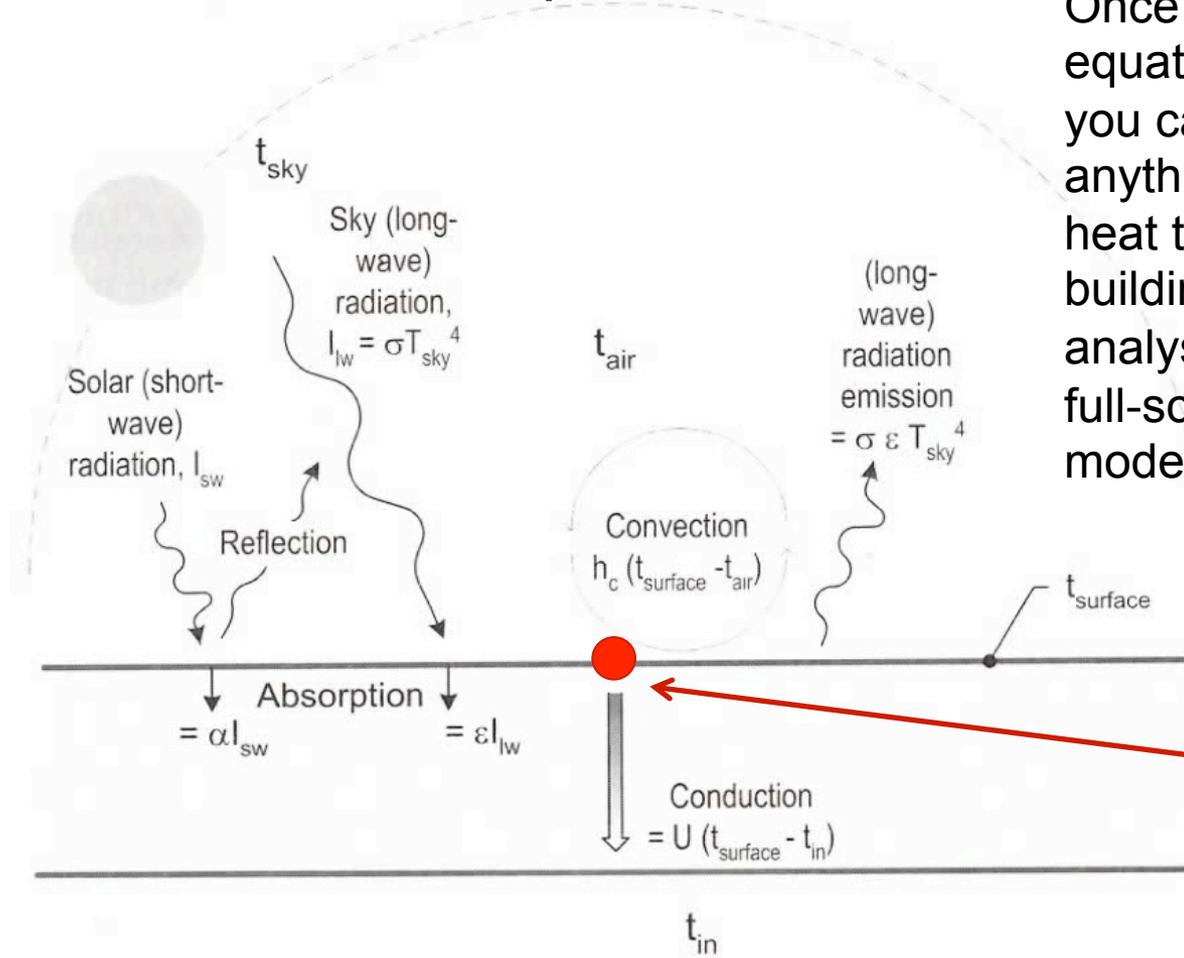
$C_T$  = sensible heat capacity multiplier (Detailed description is provided below)

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



# 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

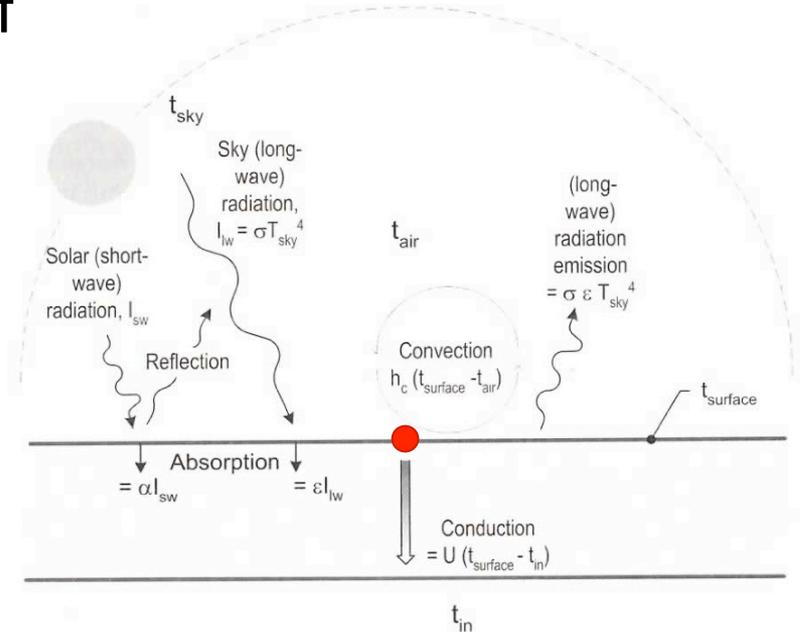
- Exterior surface example: roof

$$\sum q = 0$$

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

$$\alpha I_{solar}$$

$$q_{sw,solar}$$

Surface-sky radiation

$$+\epsilon_{surface} \sigma F_{sky} (T_{sky}^4 - T_{surf}^4)$$

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

Surface-air radiation

$$+\epsilon_{surface} \sigma F_{air} (T_{air}^4 - T_{surface}^4)$$

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

Convection on external wall

$$+h_{conv} (T_{air} - T_{surface})$$

$$+q_{convection}$$

Conduction through wall

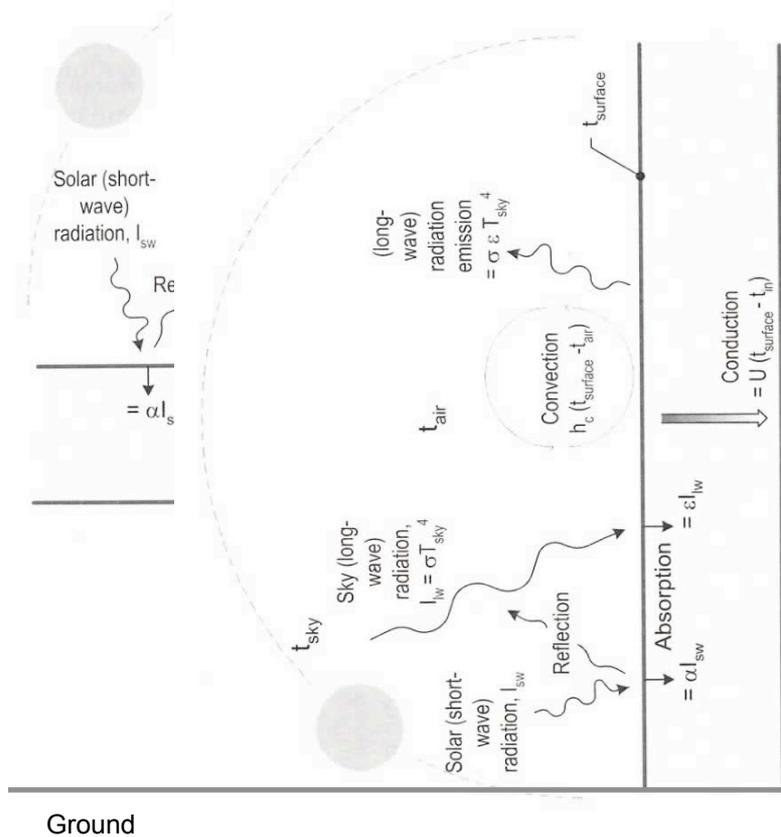
$$-U(T_{surface} - T_{surface,interior}) = 0$$

$$-q_{conduction} = 0$$

# HBM: Surface energy balance

- Similarly, for a vertical surface:

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



$$\alpha I_{solar}$$

$$+\epsilon_{surface} \sigma F_{sky} (T_{sky}^4 - T_{surface,ext}^4)$$

$$+\epsilon_{surface} \sigma F_{air} (T_{air}^4 - T_{surface,ext}^4)$$

$$+\epsilon_{surface} \sigma F_{ground} (T_{ground}^4 - T_{surface,ext}^4)$$

$$+h_{conv} (T_{air} - T_{surface,ext})$$

$$-U(T_{surface,ext} - T_{surface,int}) = 0$$

# 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

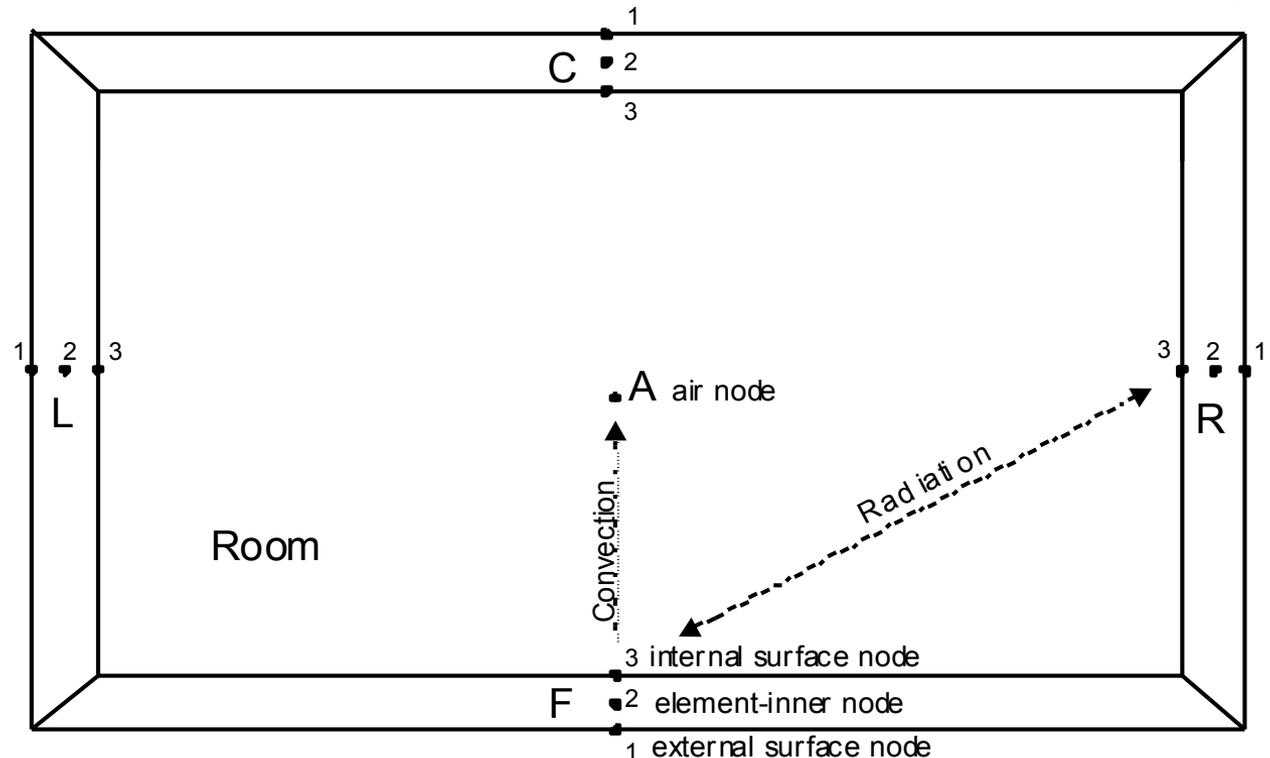
At surface nodes:

$$\sum q = 0$$

At nodes inside materials:

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

Based on density and heat capacity of material...



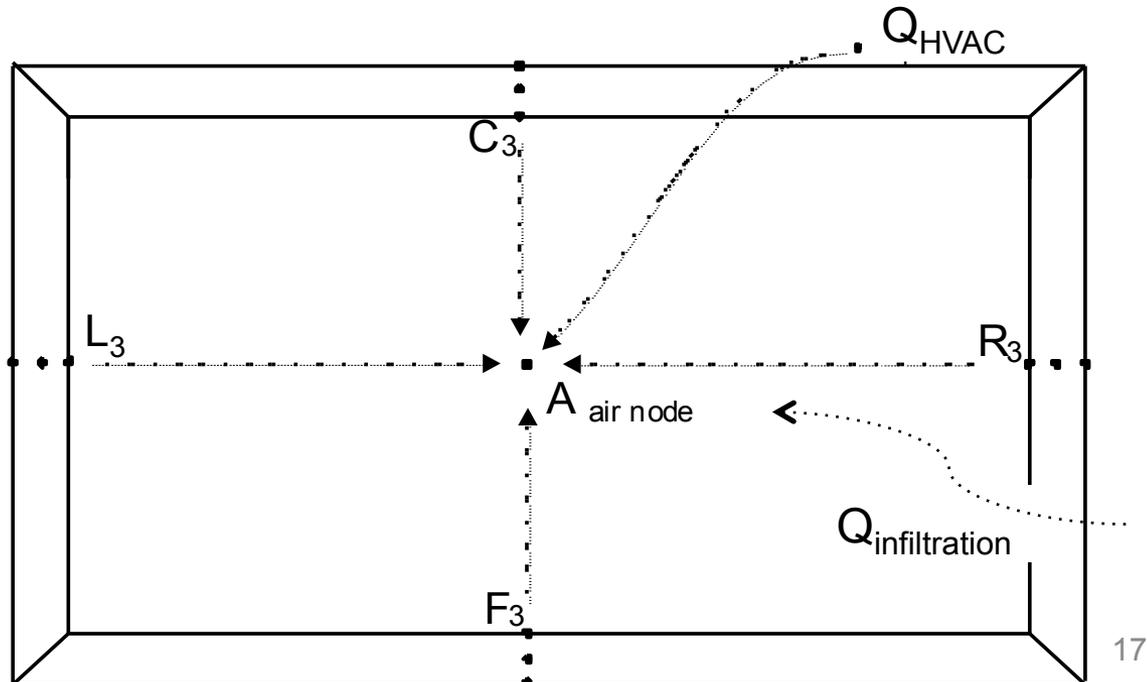
# HBM: Air energy balance

- 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)

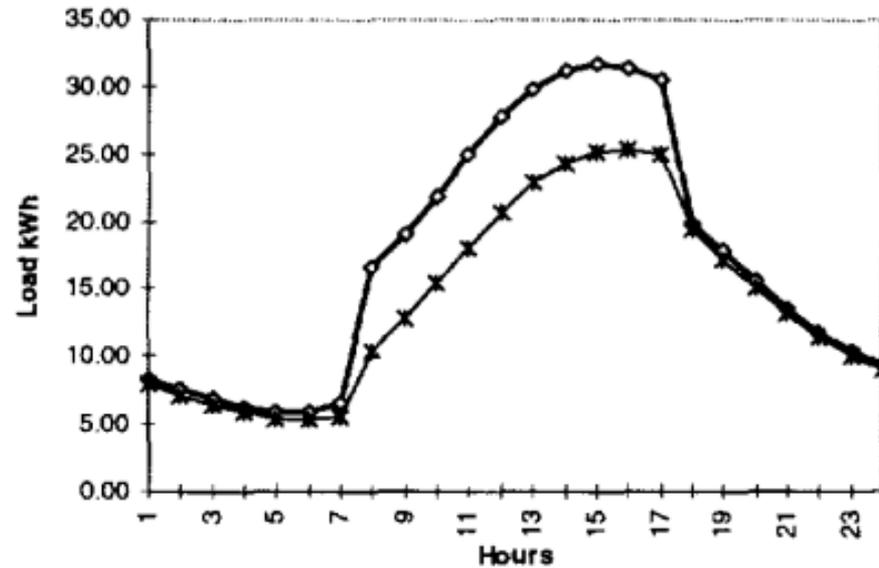
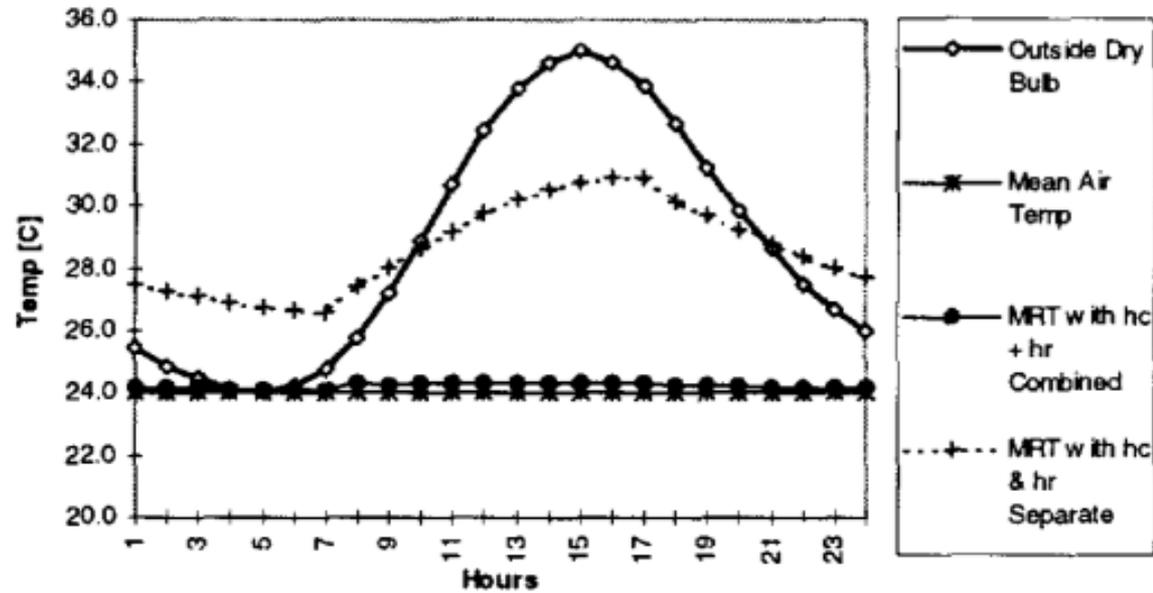
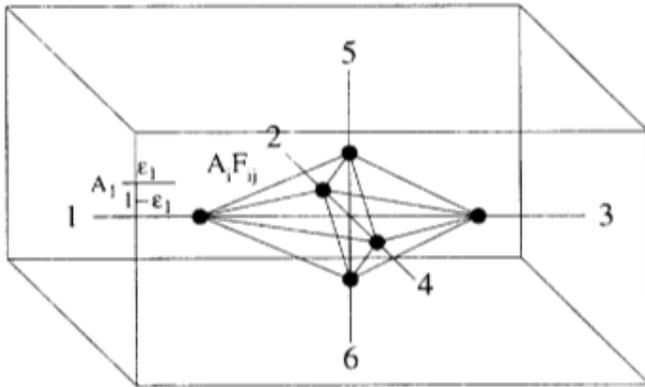
$$(V_{room} \rho_{air} c_{p,air}) \frac{dT_{air,in}}{dt} = \sum_{i=1}^n h_i A_i (T_{i,surf} - T_{air,in}) + \dot{m} c_p (T_{out} - T_{air,in}) + Q_{HVAC}$$

## 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

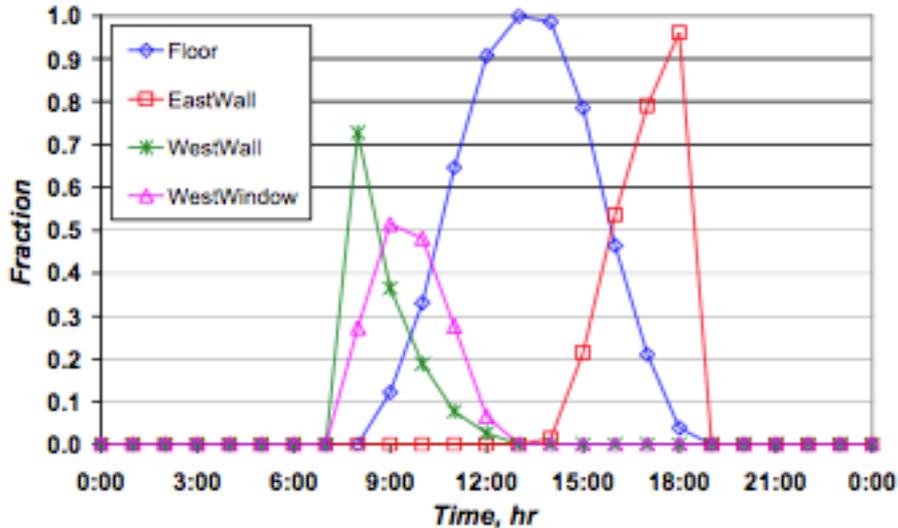


# Using HBM to calculate peak loads

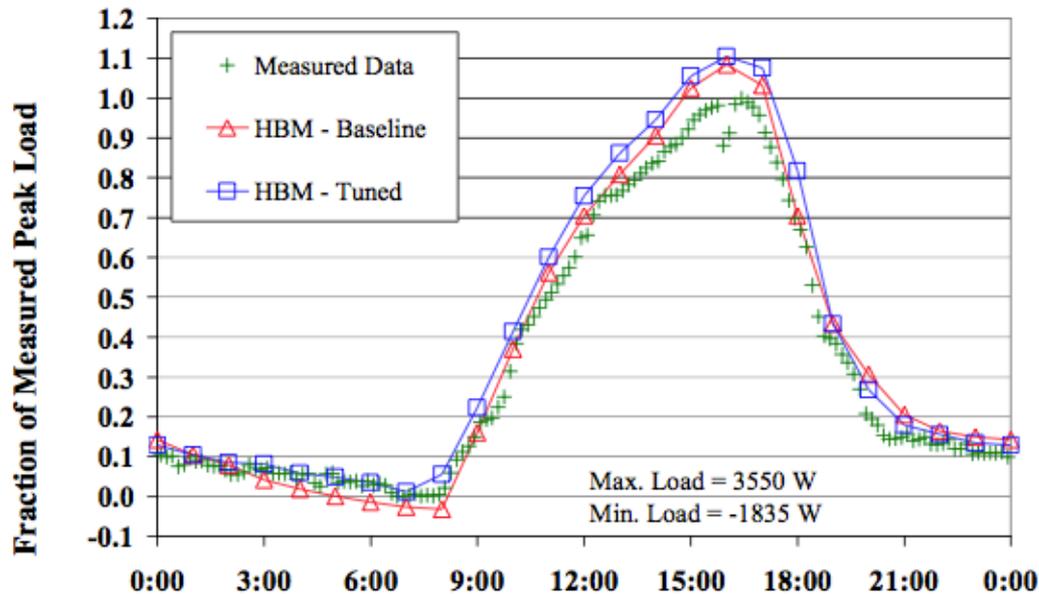
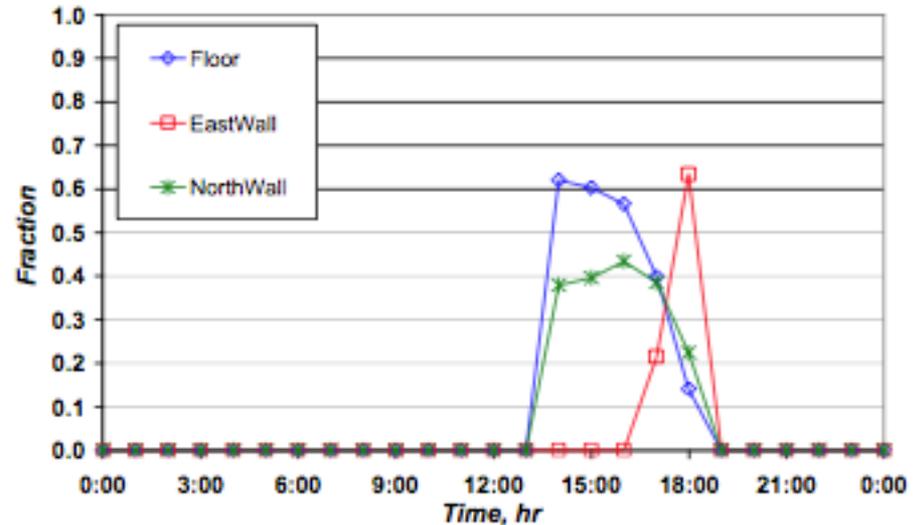


# Using HBM to calculate peak loads

### Beam Solar Radiation from South Window



### Beam Solar Radiation from West Window



# Energy simulation basics

## Energy2D

Interactive Heat Transfer Simulations for Everyone



# **HVAC SYSTEMS**

What do they look like?

# HVAC systems

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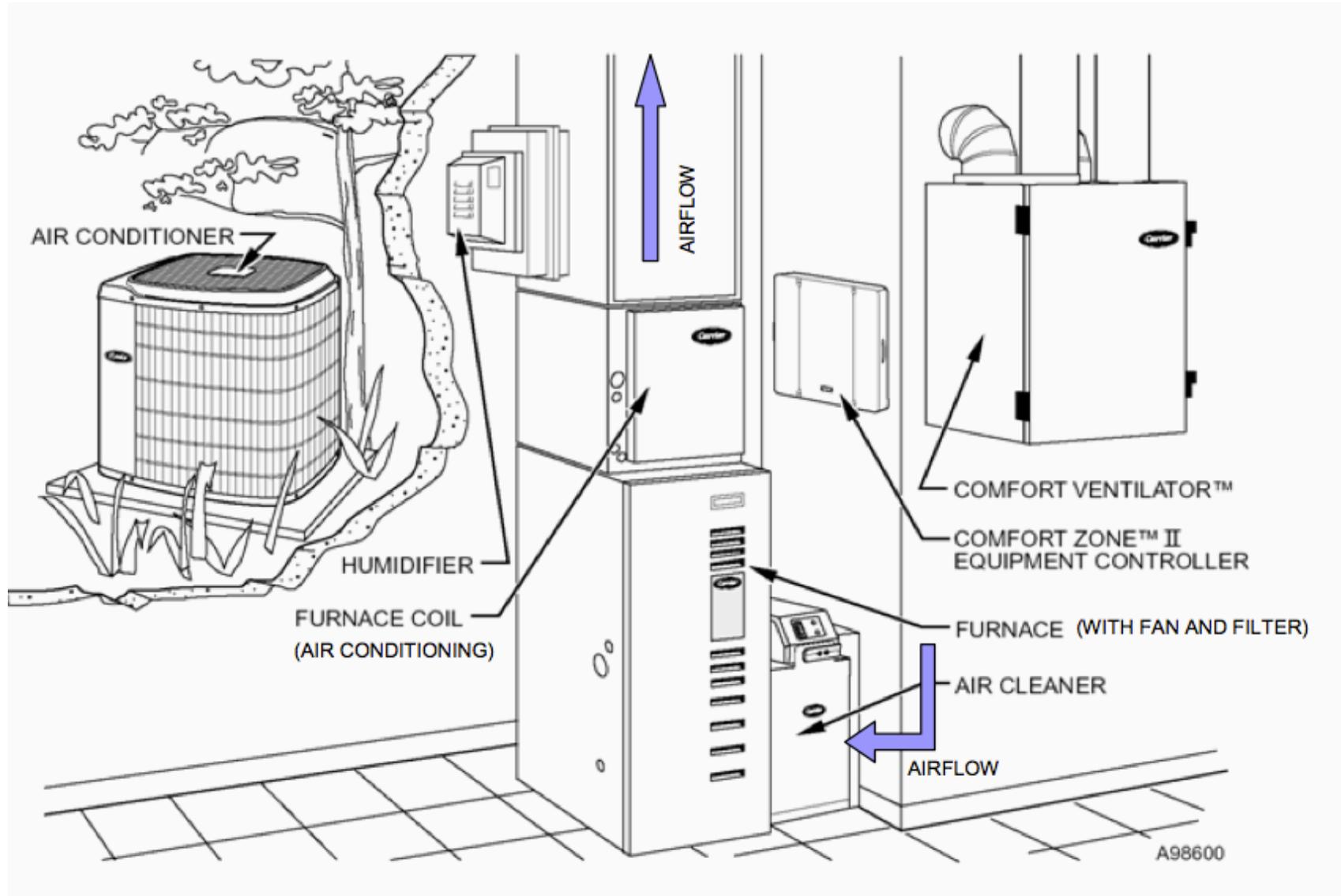
- Once we know our peak heating and cooling loads, we will need to select equipment
  - HVAC = Heating, Ventilating, and Air-Conditioning
- Primary systems
  - Vapor compression systems (i.e., chillers and condenser units)
    - Electrically driven
    - Thermally driven
  - Cooling towers
- Secondary systems
  - Distribution systems (air and water)

# HVAC system design options

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- We can rely on **central** HVAC systems
  - One system per building
  - May control all zones similarly or different zones differently
    - Depends on system type
- Or we can rely on **distributed** HVAC systems for every zone
  - Motels, strip malls, apartment buildings
- Need to figure out what medium we will use for heat transfer
  - Air, steam, water?
- Need to determine what capacity and efficiency we want

# Typical **central** residential system



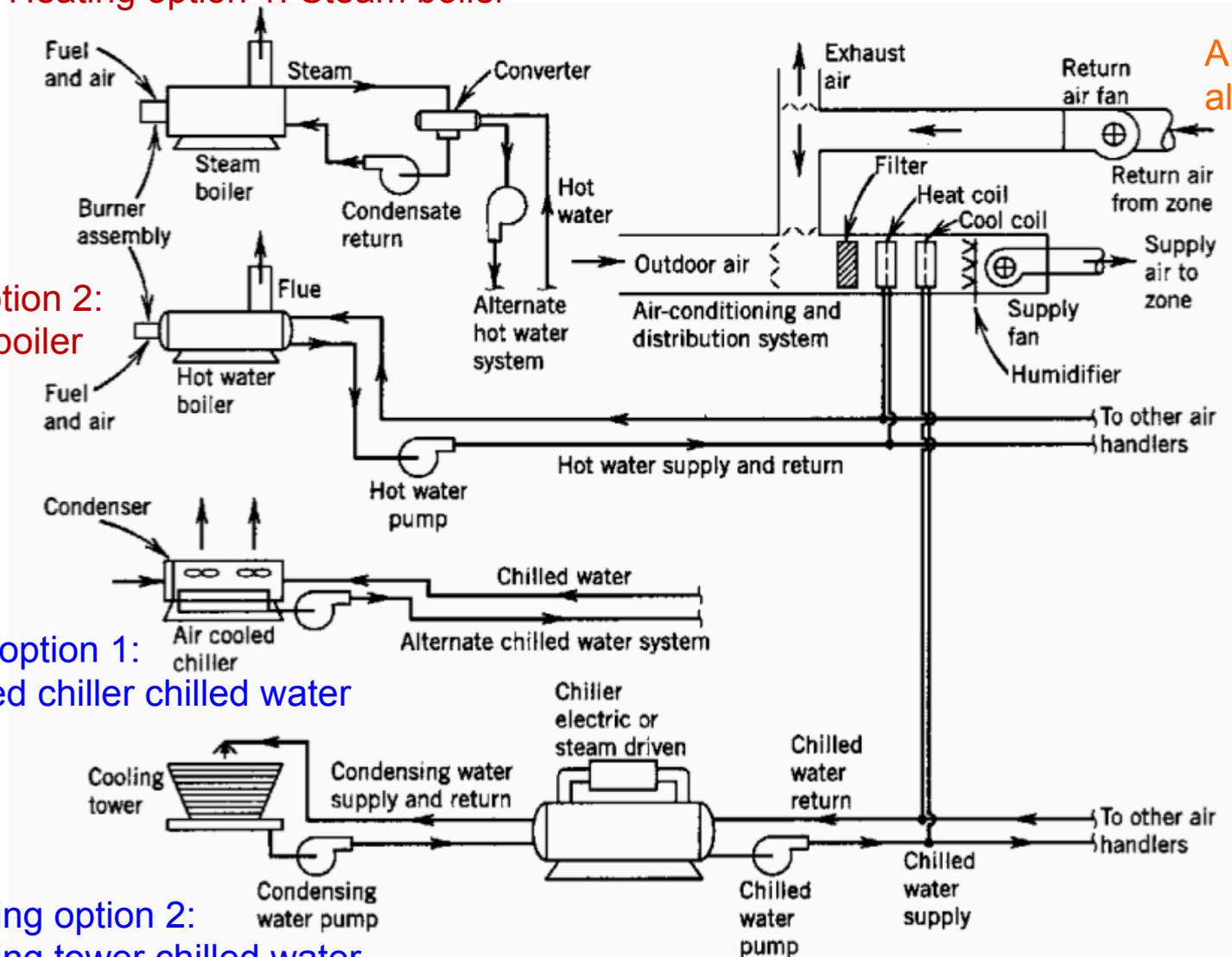
# Typical large commercial systems: **Central**

Heating option 1: Steam boiler

Heating option 2:  
Hot water boiler

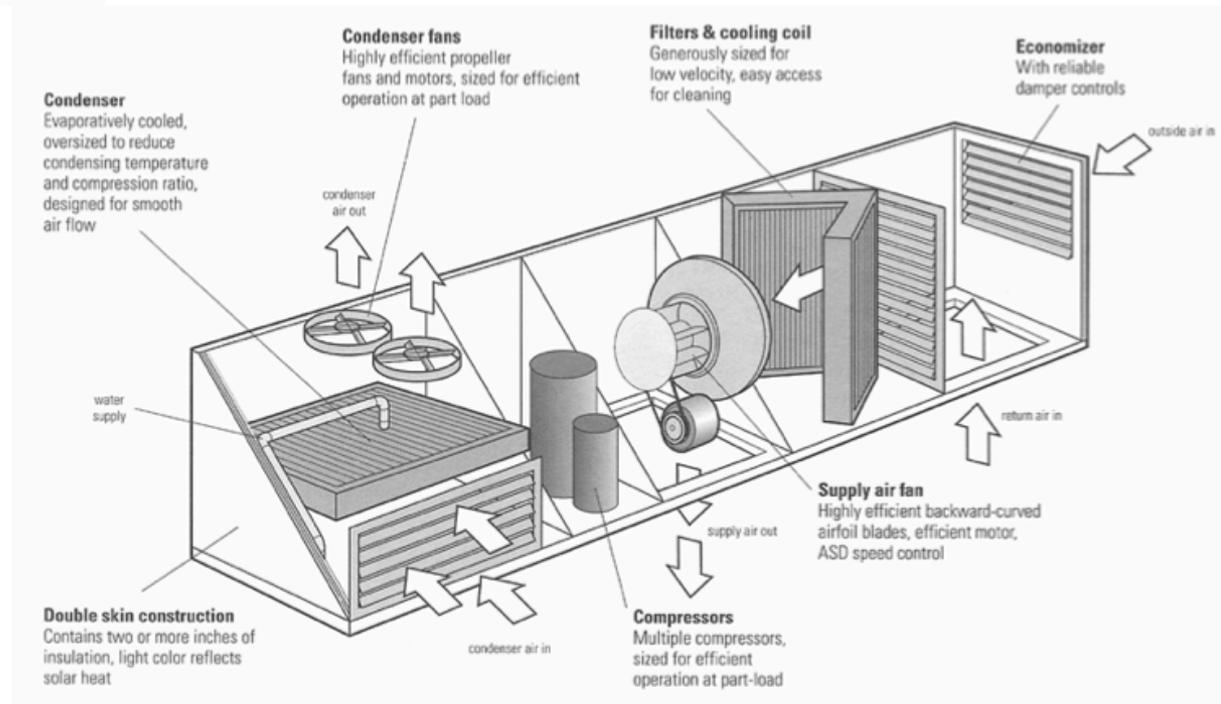
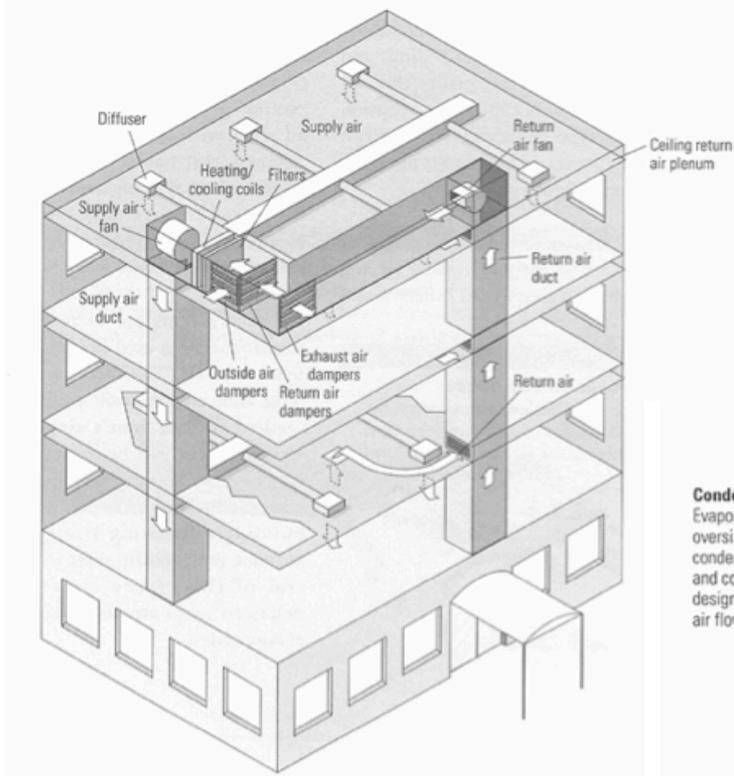
Cooling option 1:  
Air cooled chiller chilled water

Cooling option 2:  
Cooling tower chilled water



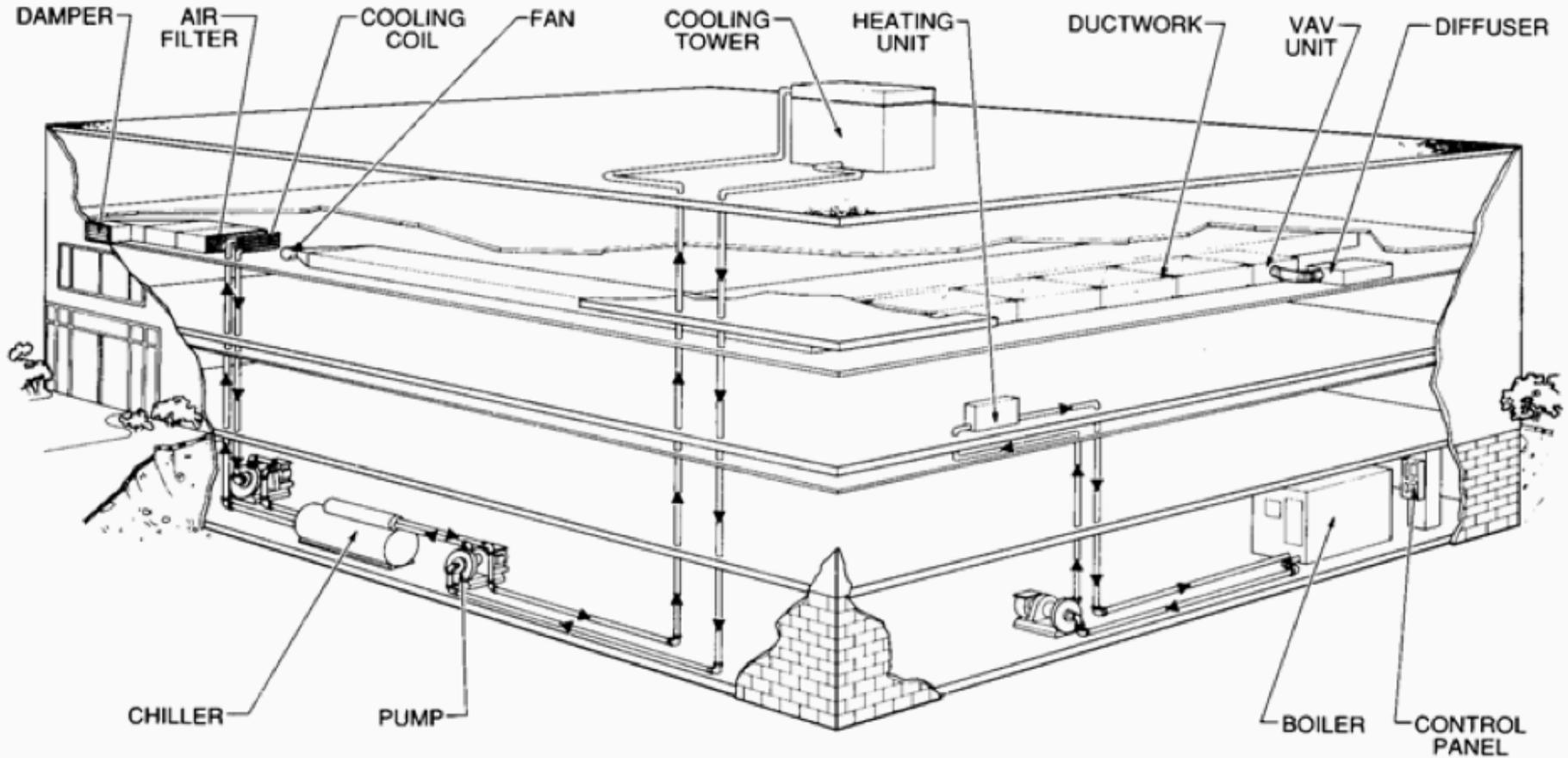
AHU serves all rooms

# Typical large commercial systems: **Central**

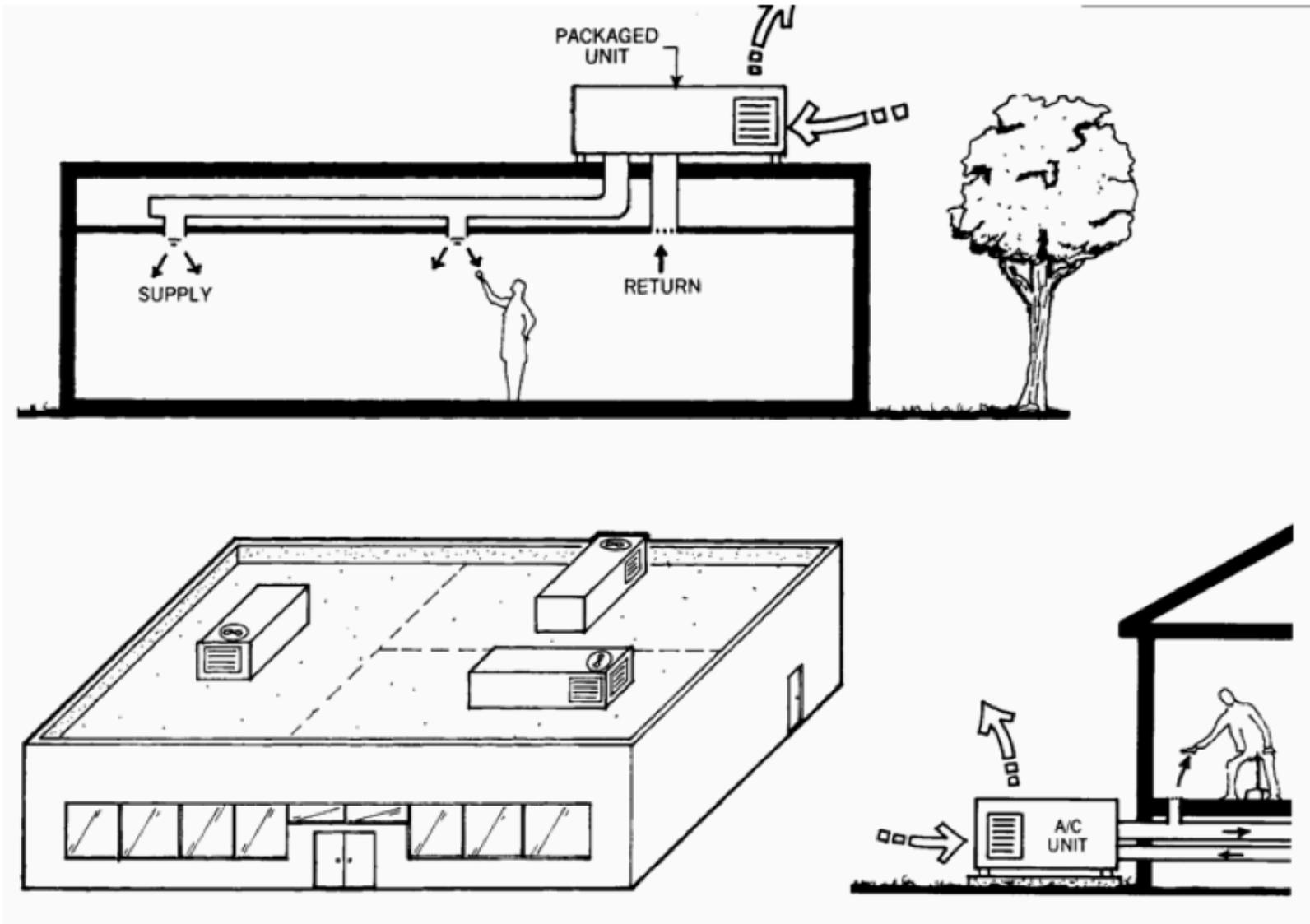


**Packaged central system**

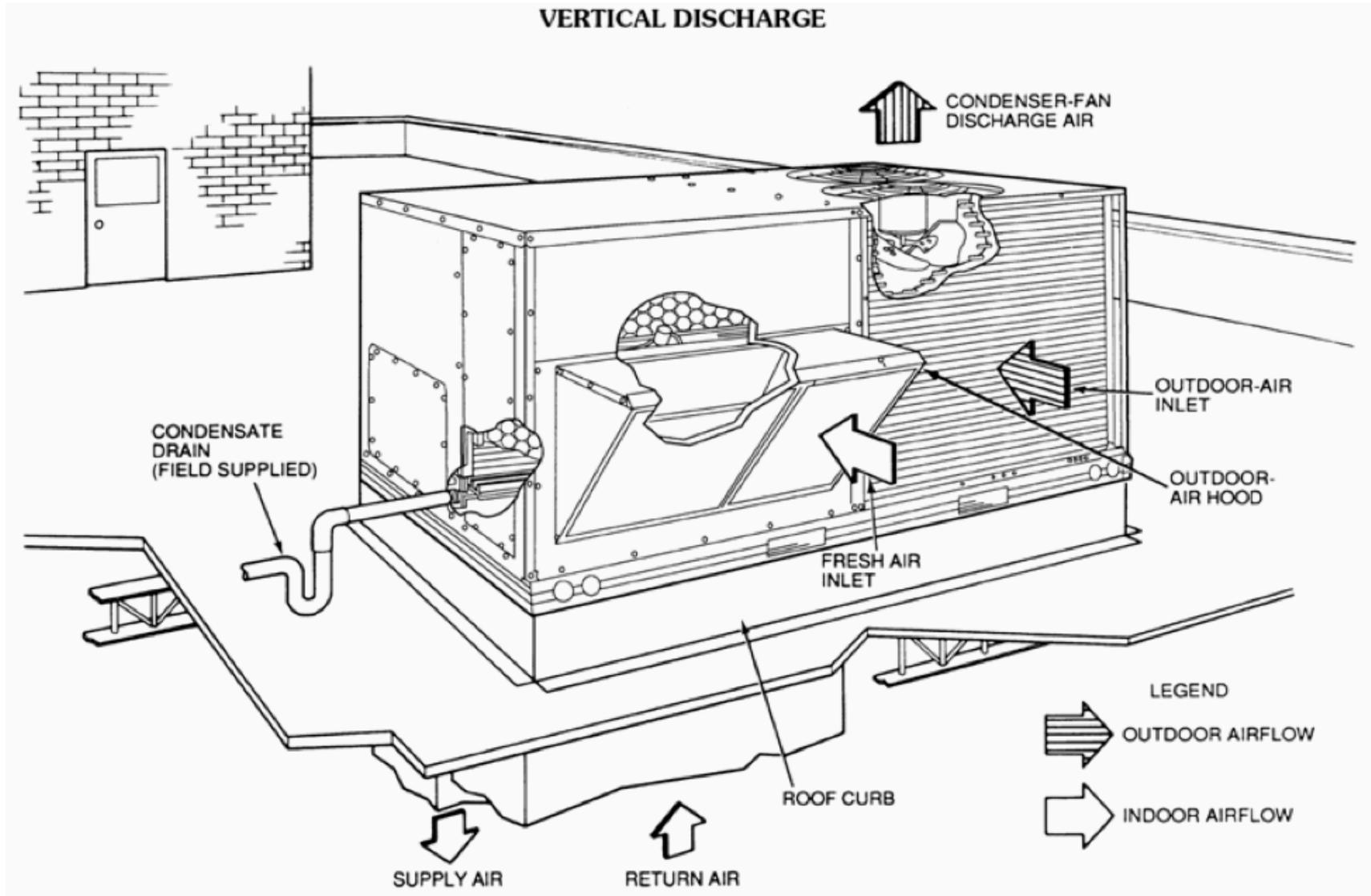
# Typical large commercial systems: **Central**



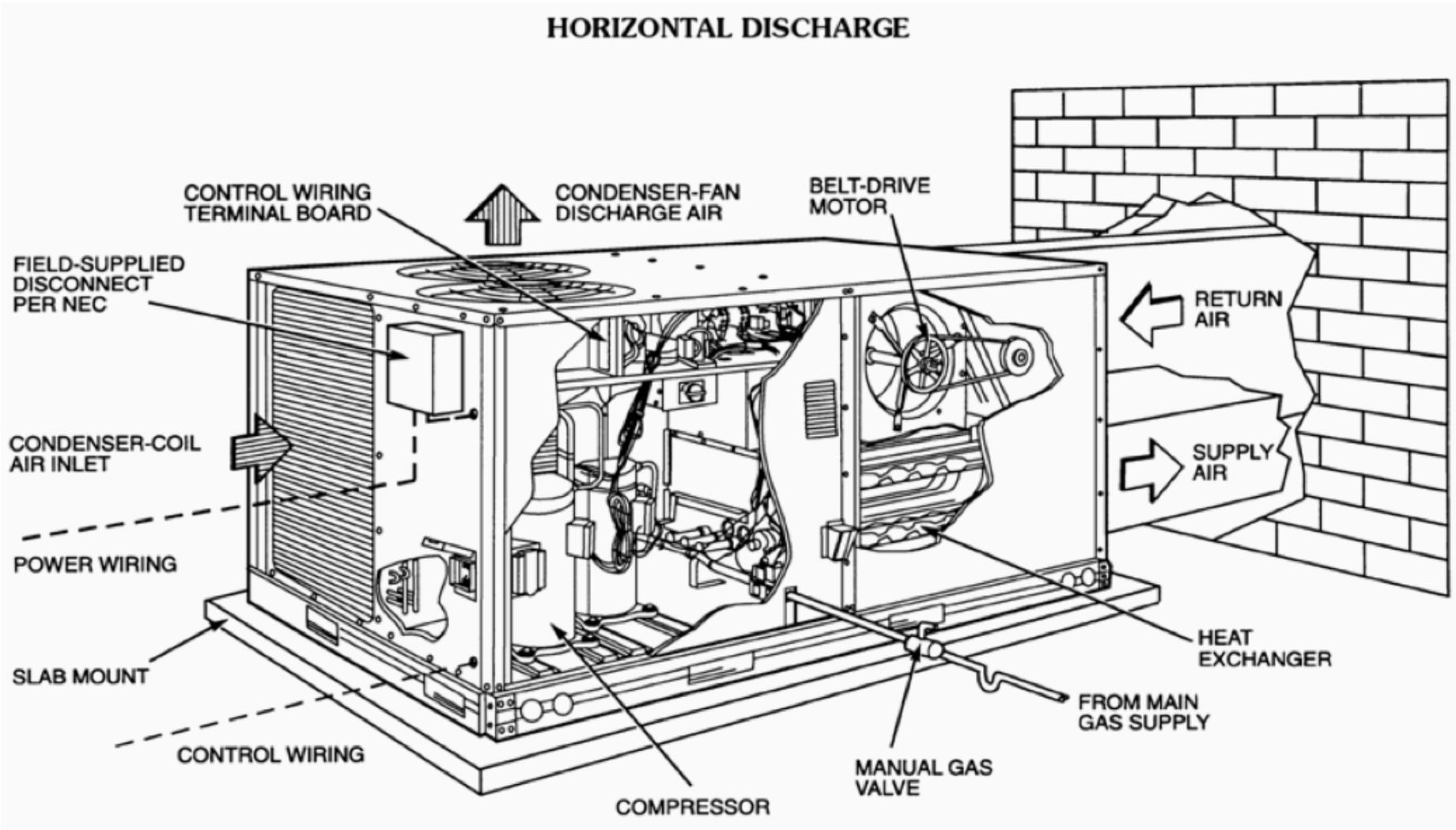
# Typical small commercial systems: **Distributed**



# Packaged roof top units (RTU)



# Slab installation



# Central vs. distributed systems

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## Central

- Large equipment has higher quality, efficiency, and durability
- Maintenance is concentrated
- Noise is removed from zone
- Diversity allows lower installed capacity
- Can use thermal storage

## Distributed

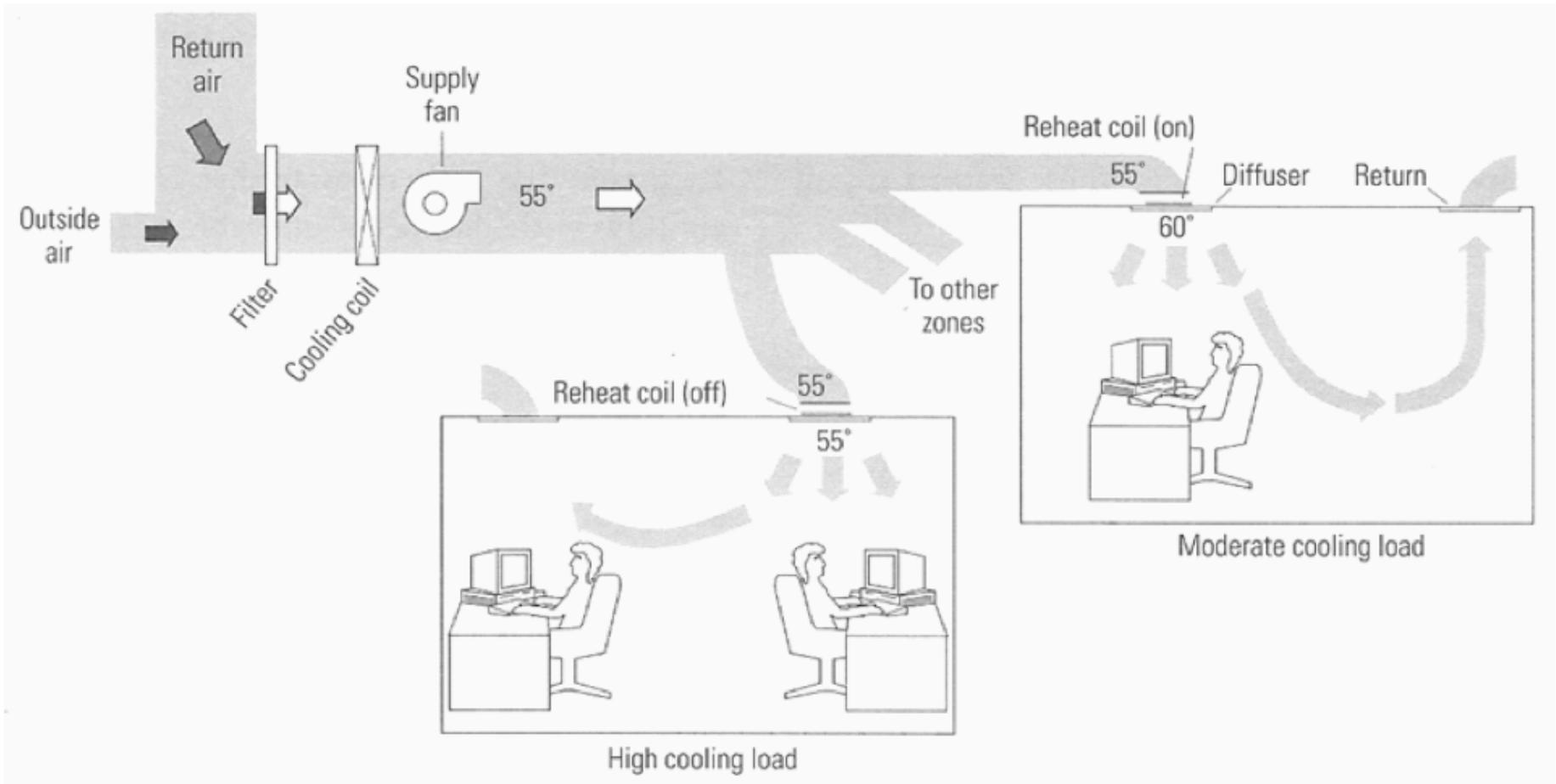
- Easy to provide zoning
- Direct control by occupants
- Easier independent scheduling for energy savings
- Generally lower capital costs and shorter lead time for equipment
- Don't need dedicated maintenance staff
- Can often install on roof (saves room in the building)

# All air air handling systems

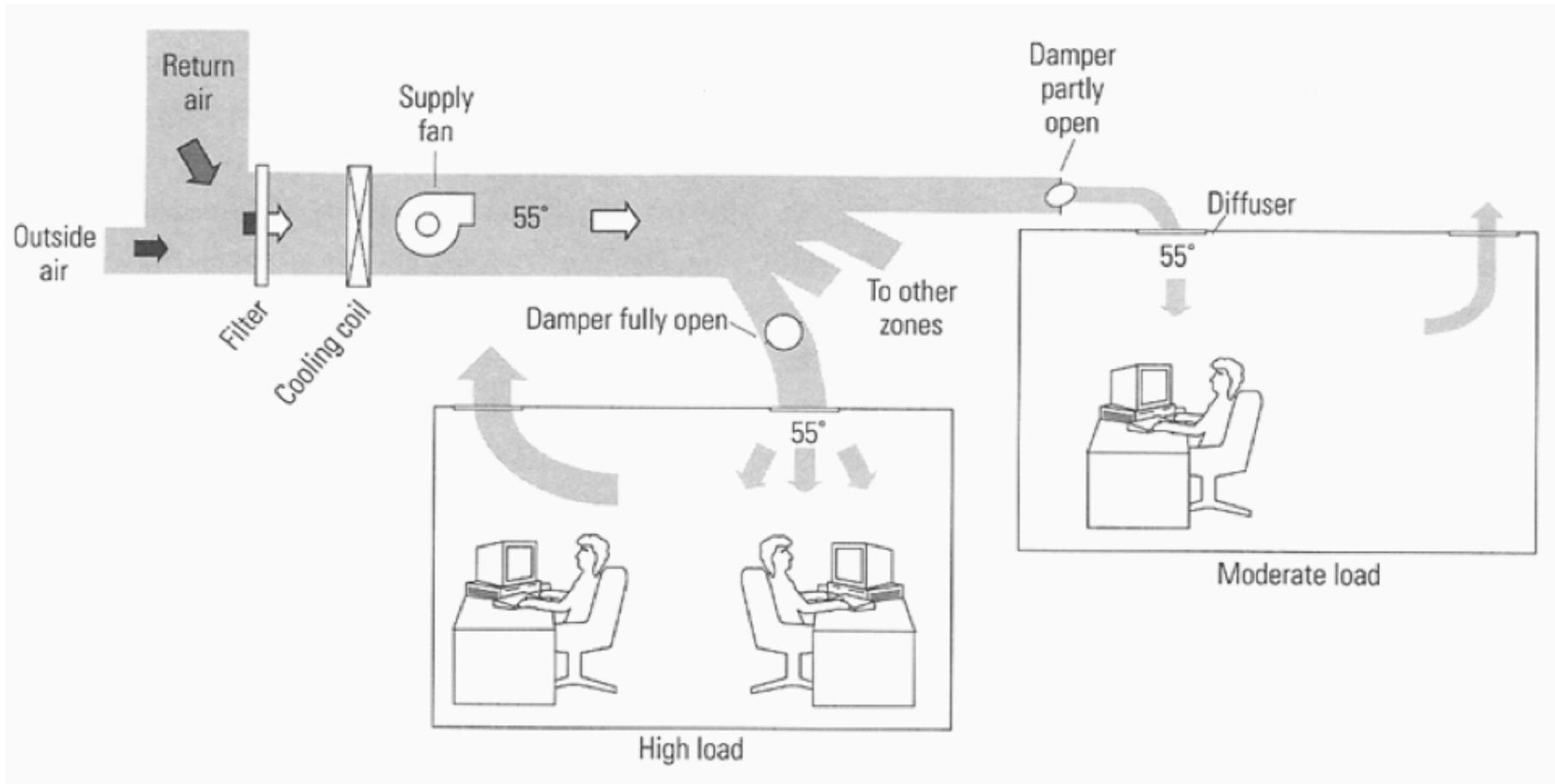
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- Constant air volume (CAV)
  - Constant zone airflow rates
  - Meets varying loads by varying supply air temperature
- Variable air volume (VAV)
  - Constant zone supply air temperature
  - Meets varying loads by varying supply airflow rates
- Dual duct (DD)
  - Mix hot and cold air at each zone
  - Use constant or variable supply airflow rate
- Multizone (MZ)
  - Mix hot and cold air for each zone at the air handler

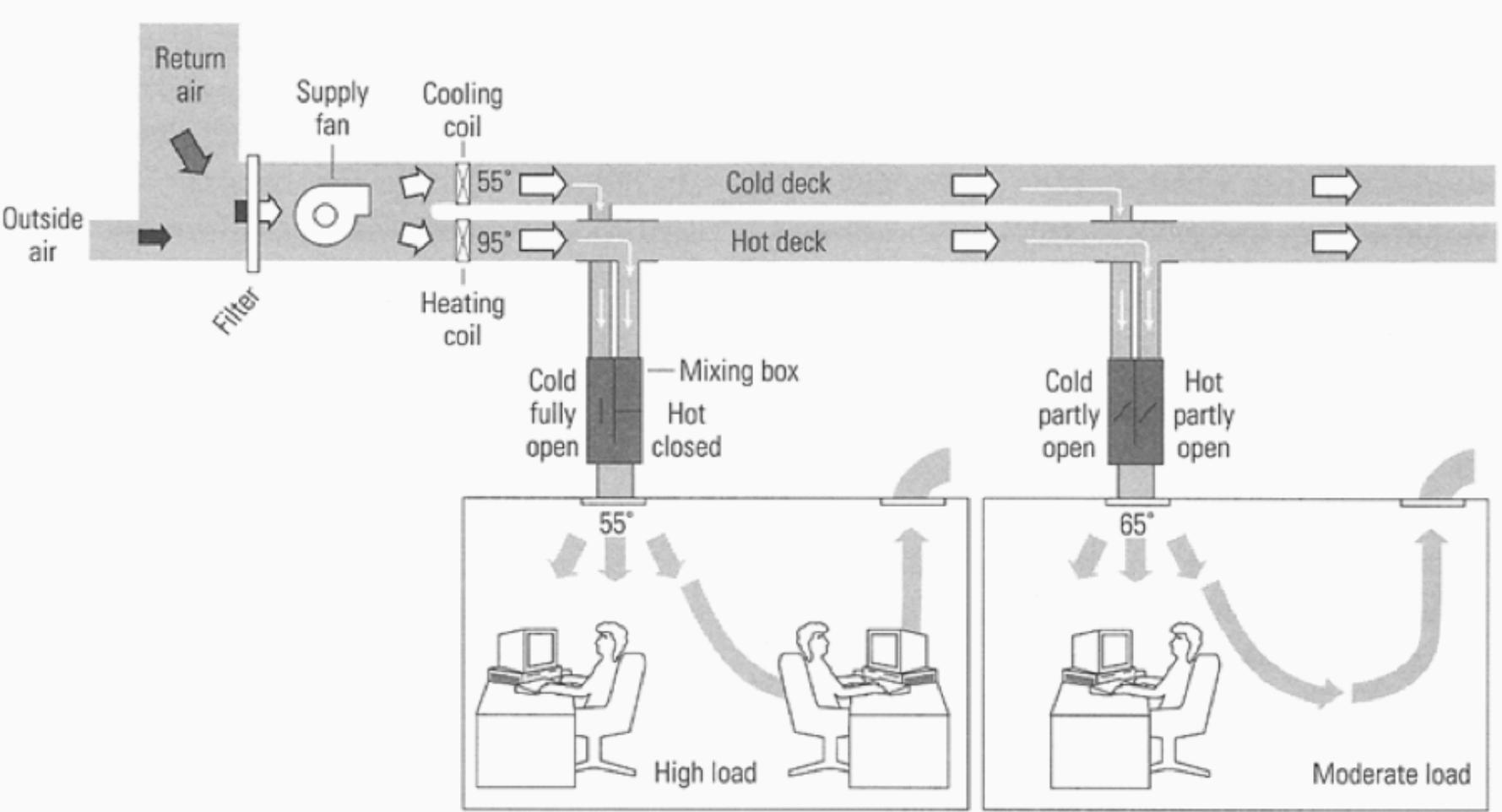
# Typical CAV



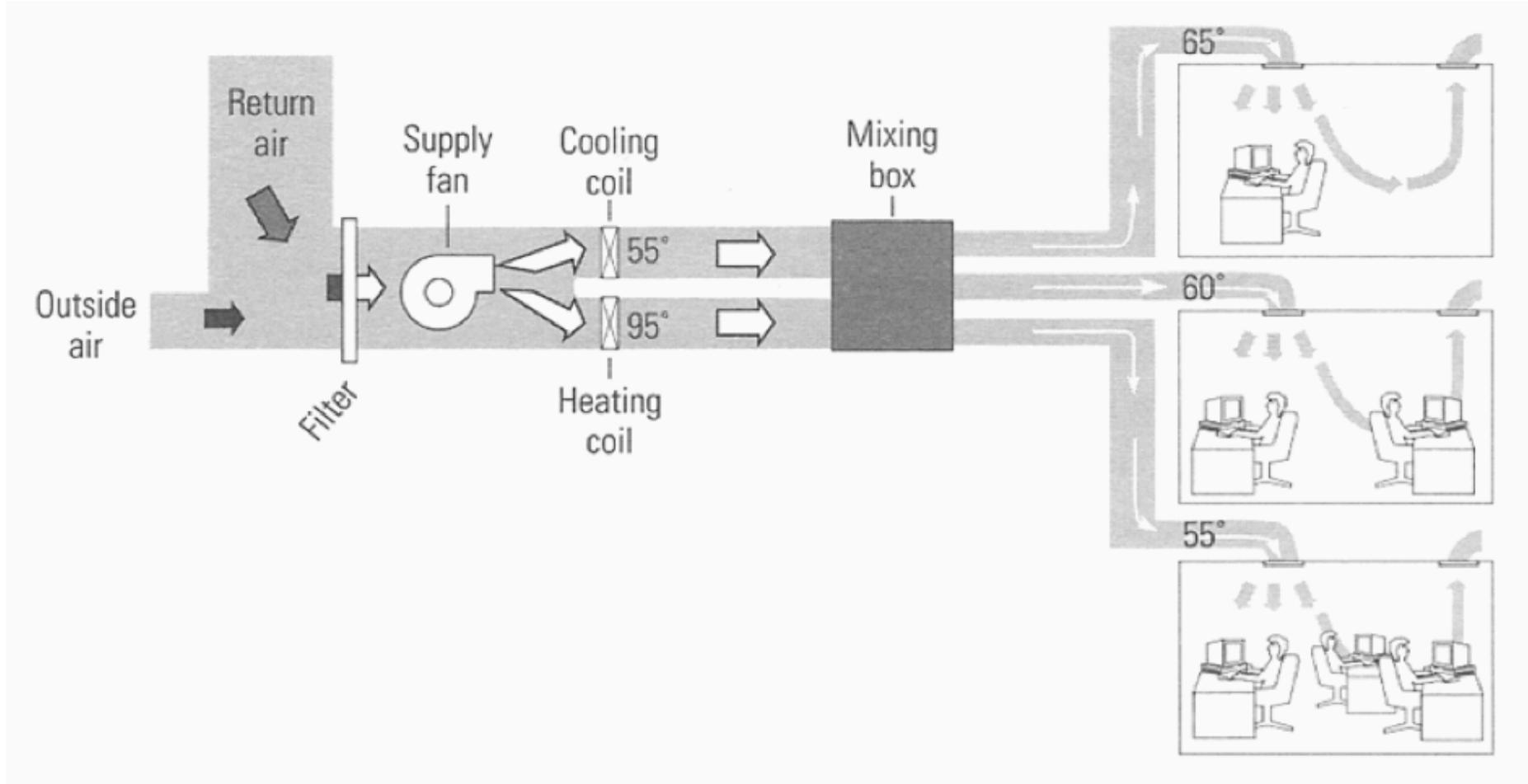
# Typical VAV



# Typical DD



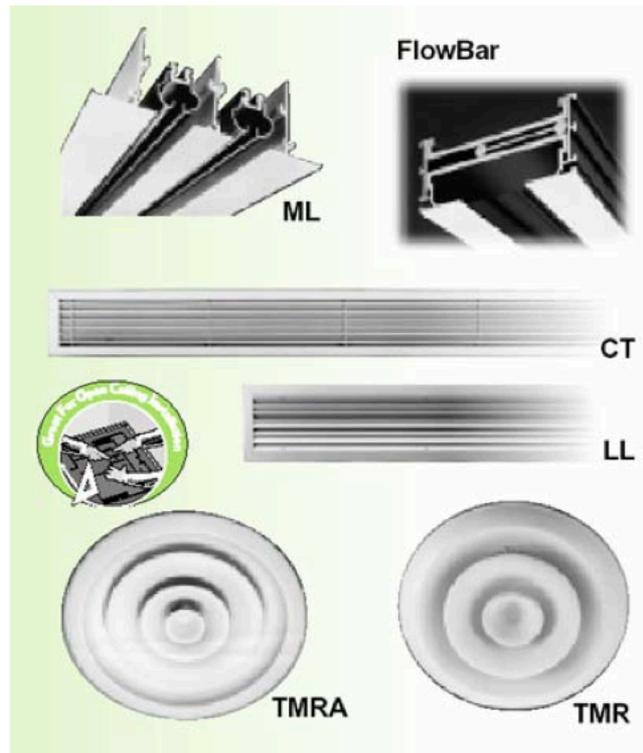
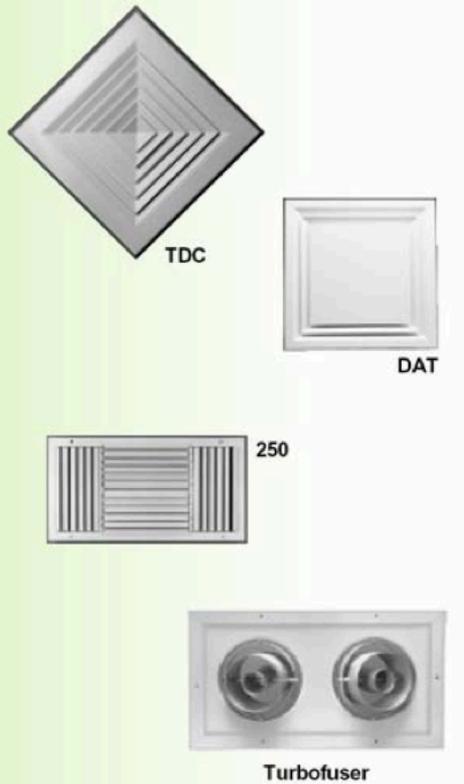
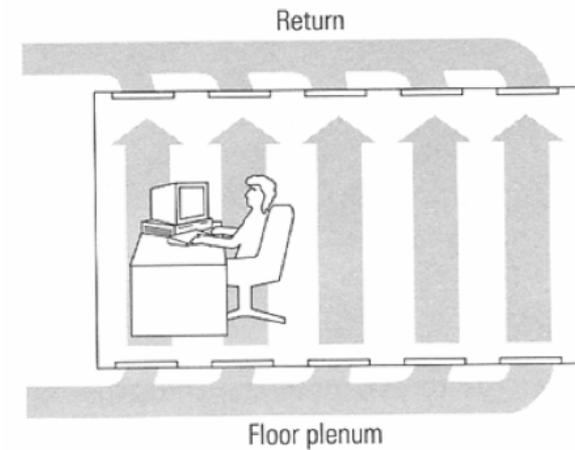
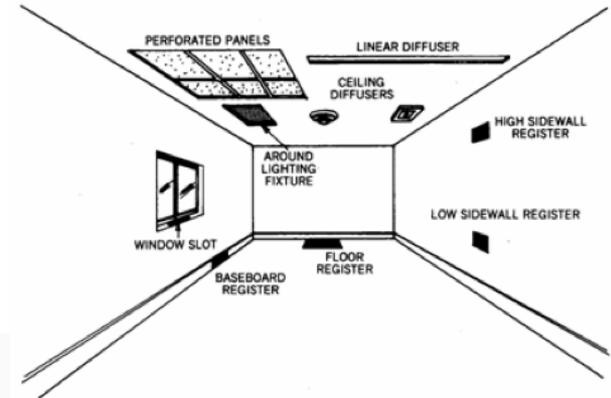
# Typical MZ



# Air supply and diffusers

- Mixed versus displacement ventilation

- Diffuser selection



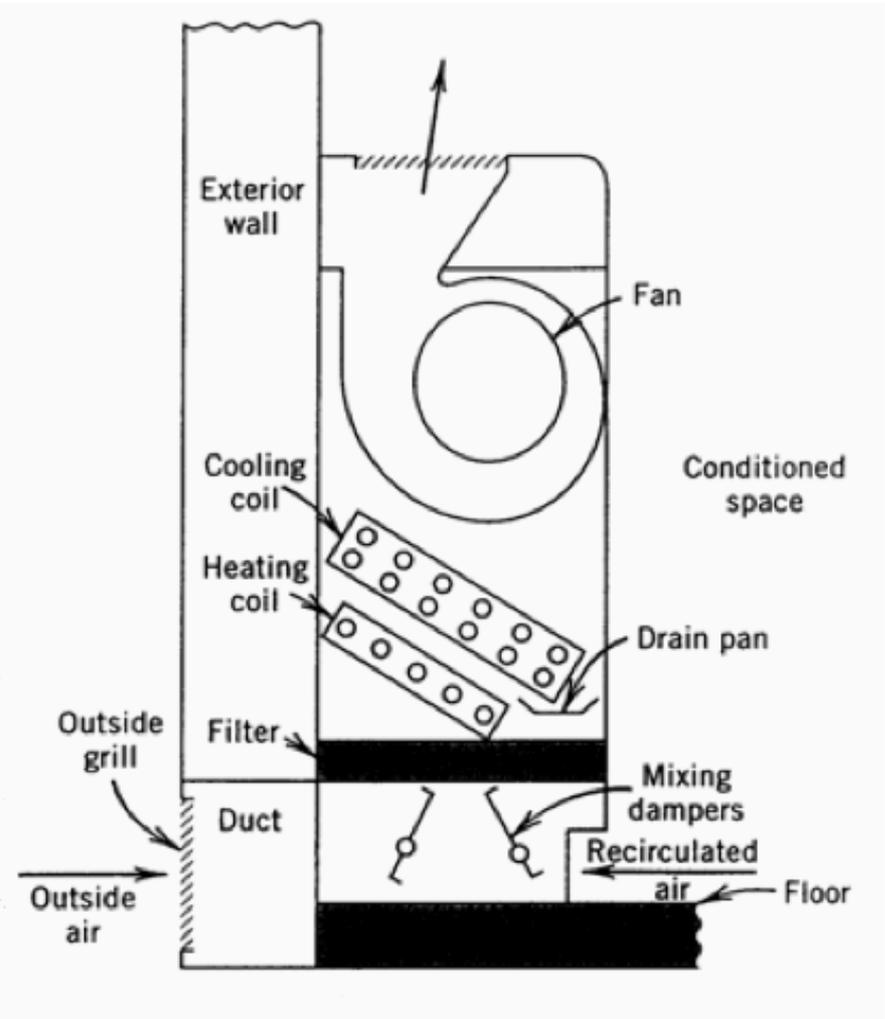
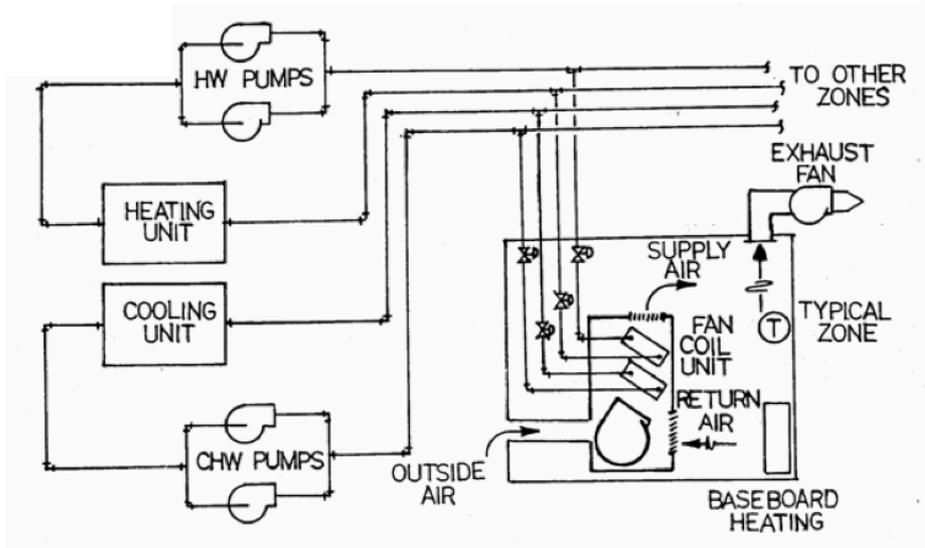
# Air-water systems

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- Many commercial buildings use a combination of conditioned air and zone water coils
- Ventilation requires air movement
- But zone heating and cooling loads can be met with fan coils

# Fan coils

- One or two coils
- Thermostat controls water flow
- Ventilation is met with conditioned or unconditioned outdoor air



# **HVAC SYSTEMS**

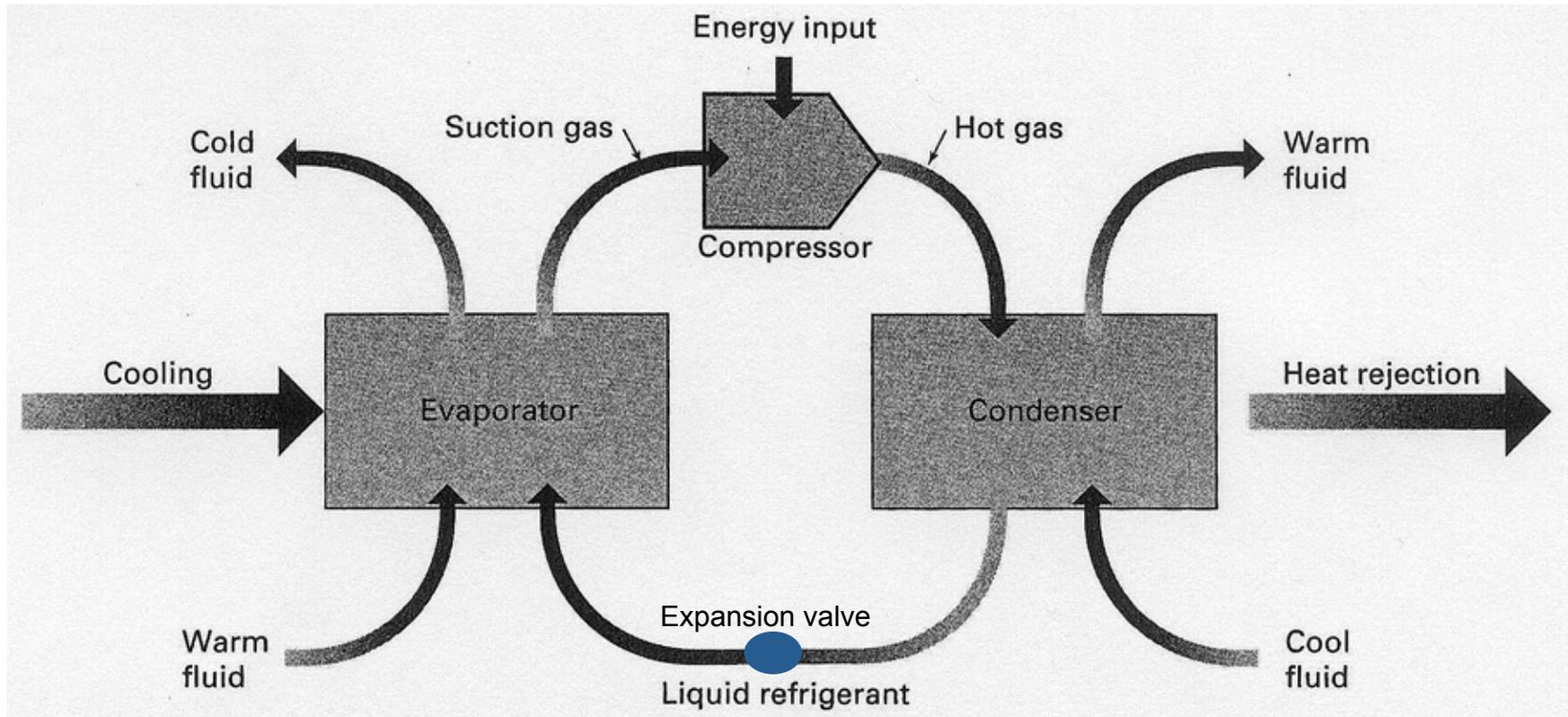
How do they actually work?

# Typical central residential systems

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- How a furnace works
  - <https://www.youtube.com/watch?v=VbSO23tnpuE>
- How your AC works
  - [https://www.youtube.com/watch?v=\\_IFUIA1PZ8U](https://www.youtube.com/watch?v=_IFUIA1PZ8U)
- Other parts of heating and cooling systems
  - <https://www.youtube.com/watch?v=y972RuNhYvE>
- “Learn HVAC” for commercial systems
  - <https://www.youtube.com/watch?v=fjZidB4N5Vc>

# Vapor compression cycle: AC units



Indoor 75°F

Outdoor 105°F

# Thermodynamics for HVAC

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- Enthalpy,  $h$  [J/kg, Btu/lb]

- Temperature change,  $\Delta T$

$$\Delta h = C_p \Delta T \quad \text{– only for the same phase (e.g. air or water)}$$

- What if we have change of the phase?
  - Evaporation or condensation

- Entropy,  $s$  [J/kgK, Btu/lb°F]

$$\Delta h = T \Delta s \quad \text{for evaporation or condensation}$$

# Vapor compression cycle: AC units

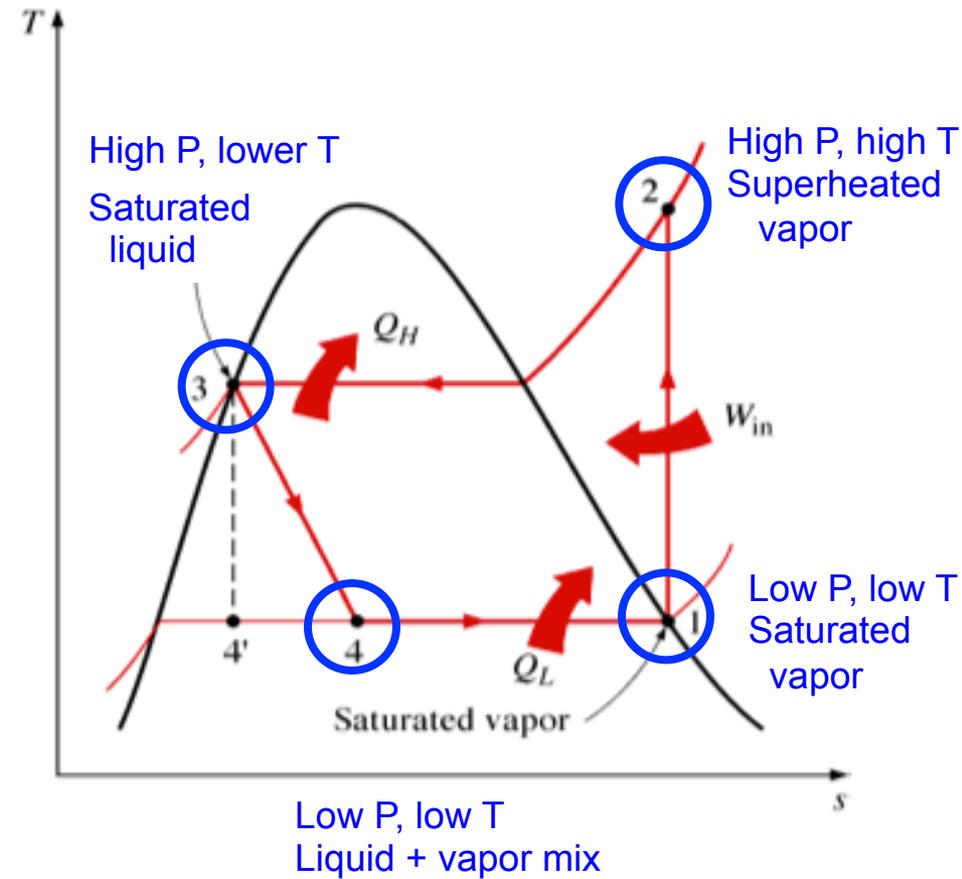
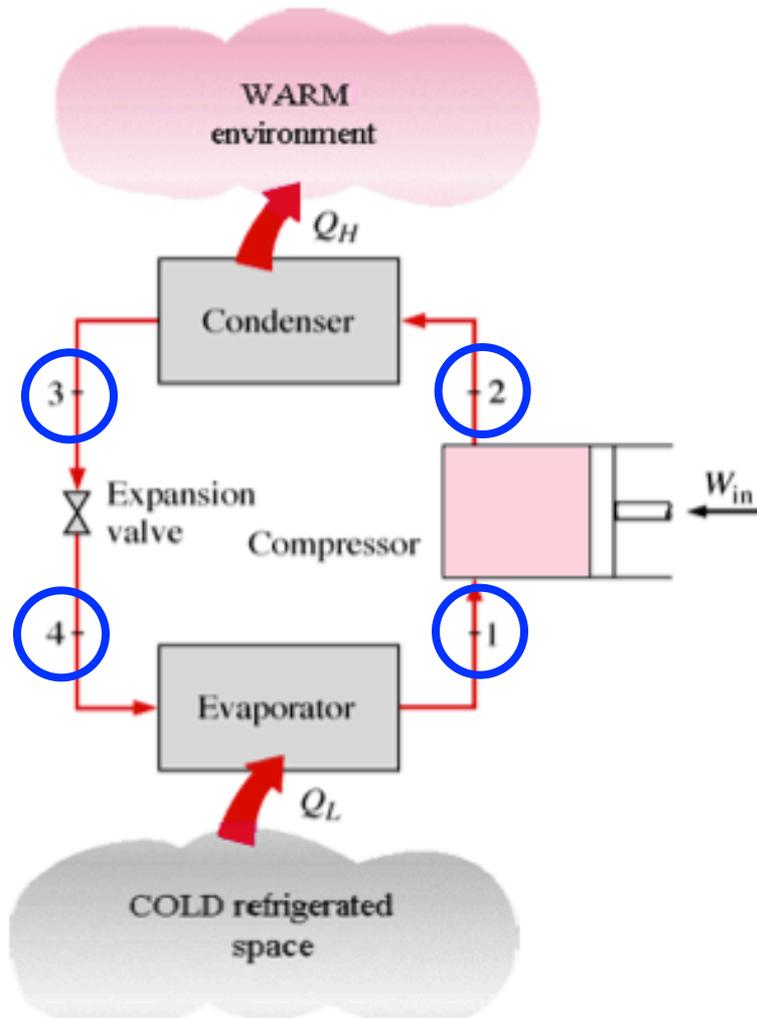


Figure 4-1: Ideal vapor compression cycle (Çengel and Turner 2001, 377)

## Question: What is the COP?

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- A. Congressional Observer Publications
- B. California Offset Printers
- C. Coefficient of Performance ←
- D. Slang for a policeman

$$COP = \frac{\text{Provided cooling energy [W]}}{\text{Used electric energy [W]}} = \eta$$

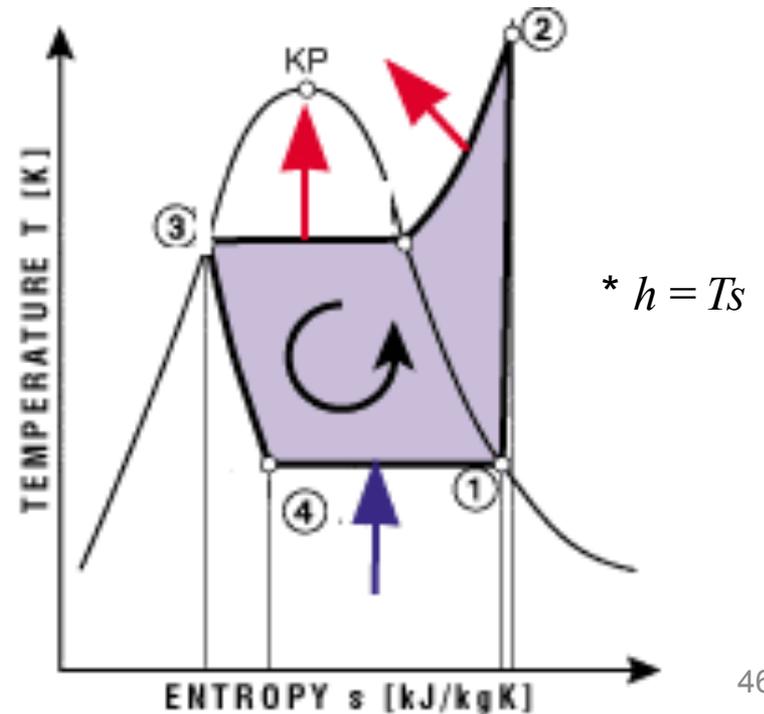
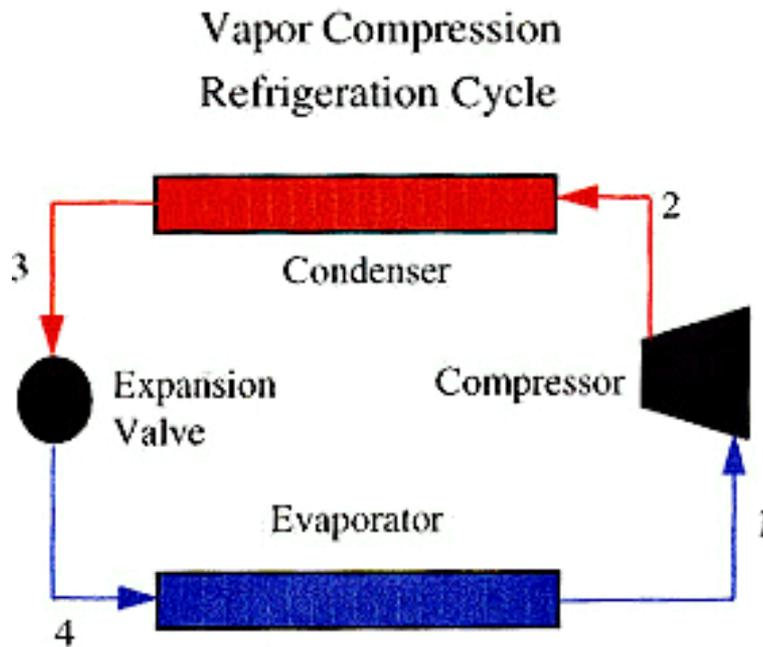
Equivalent to the efficiency of an air-conditioning unit

# What is the efficiency of a typical residential AC unit?

- A. 10%
- B. 50%
- C. 80%
- D. 100%
- E. 300% ←

For an ideal refrigeration cycle:

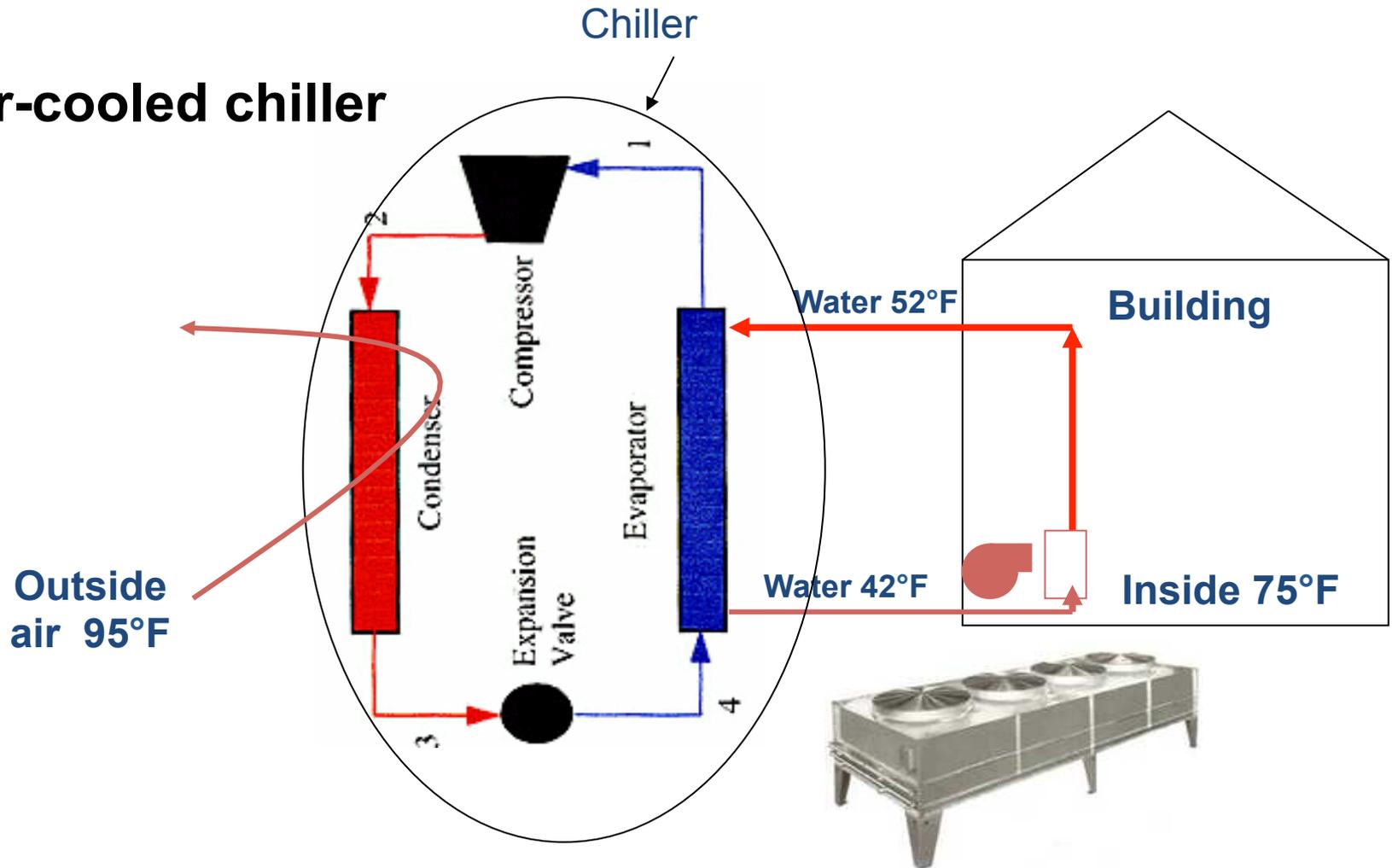
$$COP = \frac{Q_{cool}}{W_{elec}} = \frac{h_1 - h_4}{h_2 - h_1}$$



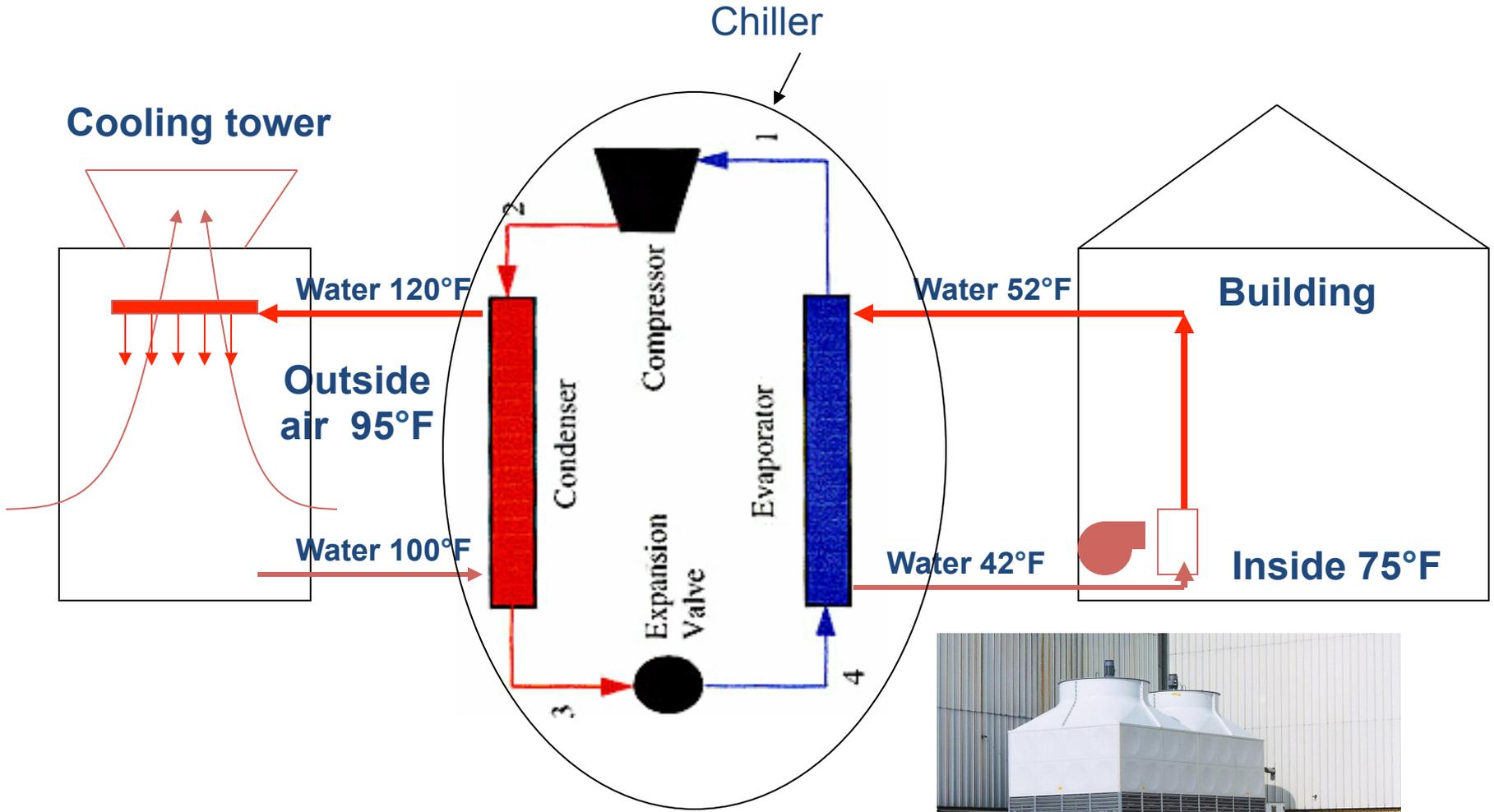
# Chillers

- Chillers use vapor compression or absorber system to produce chilled water for cooling spaces

## Air-cooled chiller

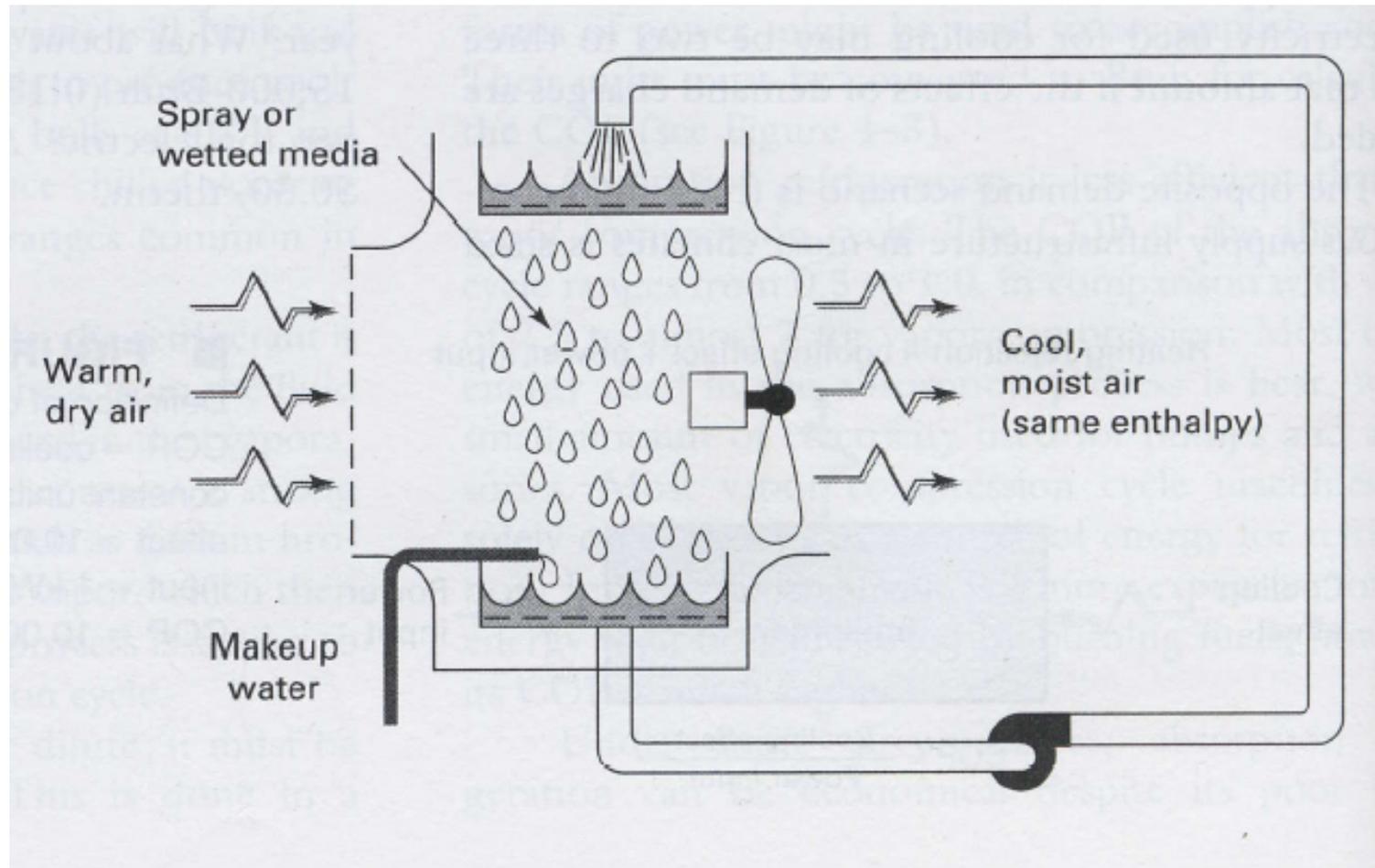


# Water cooled chiller

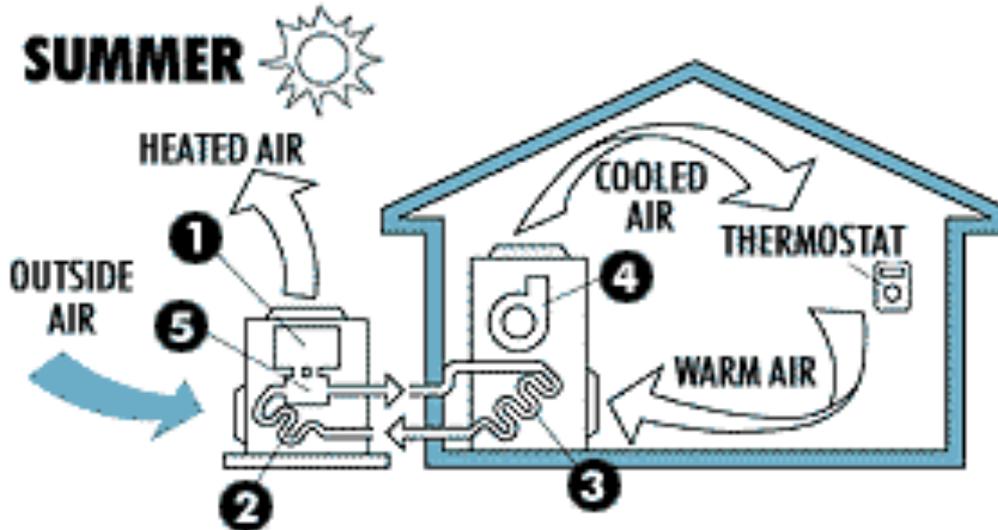
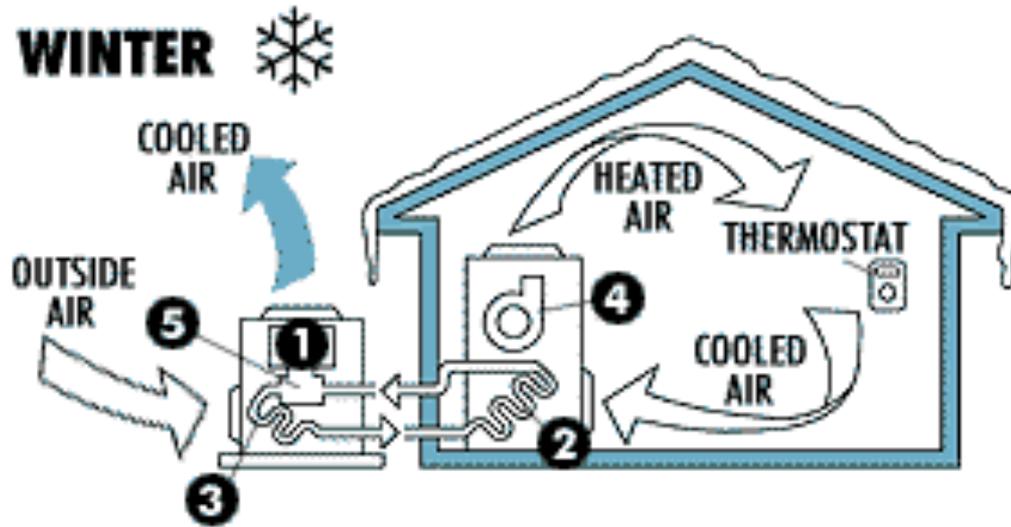


# Evaporative cooling

- Wet media/water spray – direct
  - Raise absolute humidity, lowers temperature of conditioned air



# Heat pumps



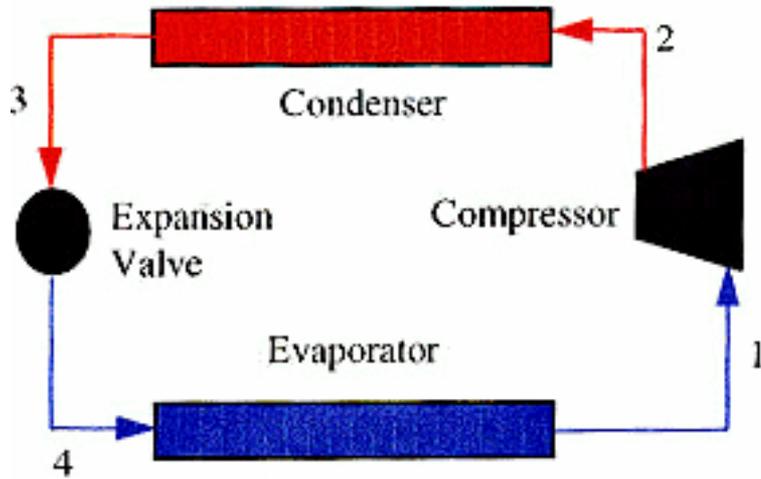
- 1) Compressor
- 2) Condenser
- 3) Evaporator
- 4) Air handler
- 5) Reversing valve and expansion valve

*Air-conditioner run in reverse*

# Heat pumps

## Cooling

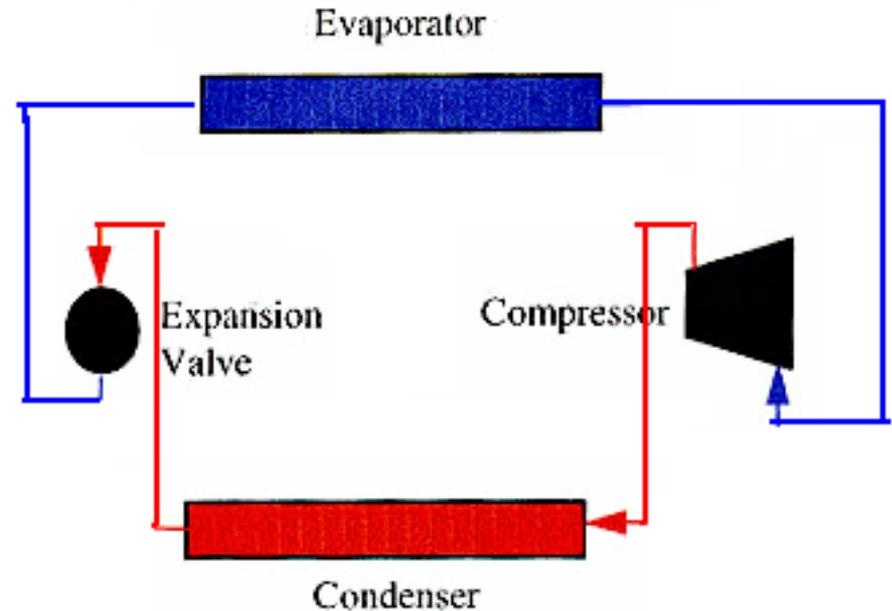
Outside 95°F



Inside 75°F

## Heating

Outside 55°F



Inside 75°F

*Air-conditioner run in reverse*

# What do we need to know about cooling systems?

## Equipment selection example

Need 1.2 tons  
Of water cooling  
1 ton = 12000 Btu/hr  
1.2 tons = 14,400 Btu/hr



Capacity is 1.35 ton  
only for:

115 F air condenser temp  
50 F of water temperature

<b>SPECIFICATIONS</b>	<b>IK-</b>	<b>.25A</b>	<b>.33A</b>	<b>.5A</b>	<b>.75A</b>	<b>1A</b>	<b>1.5A</b>	<b>2A</b>	<b>2W</b>	<b>3W</b>	<b>3A</b>	<b>4A</b>
<b>COMPRESSOR</b>	Capacity <sup>2</sup>	.25	.32	.41	.70	.98	1.35	2	2	3	3	4
	HP each	.25	.33	.50	.75	1	1.5	2	2	3	3	4
	Type <sup>3</sup>	H	H	H	H	H	H	H	H	H	H	H

**Notes:** 1. Full load amps must be used for sizing disconnects and supply wiring. 2. Tons of capacity at 12,000 BTU/ton @ 50°F LWT @ 105°F condensing temperature for water-cooled units and 115°F for air-cooled units. Capacities may be +/- 5% as reserved by the compressor manufacturer. Capacity multipliers are 50°F - 1.00; 40°F - .80; 30°F - .60; 20°F - .40. The minimum recommended operating temperature when no glycol is used is 48°F. 3. H - hermetic compressor used on this model. 4. Consult factory for 50hz operation. 5. Approximate unit weight crated for shipment.

# Capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates

Table 4. Example Manufacturer EPT (Subset of Data Displayed)

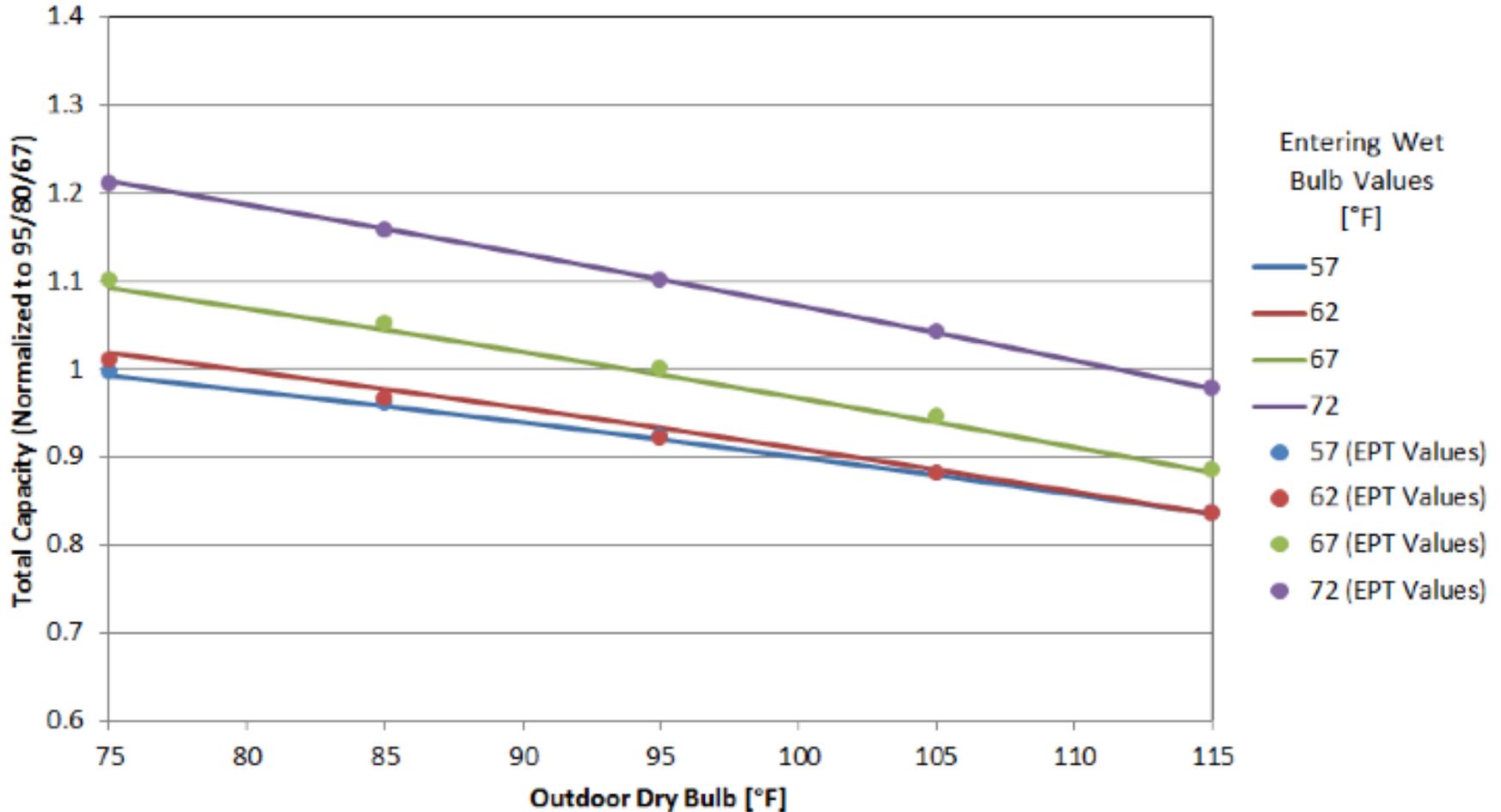
Evaporator Air		Condenser Air °F (°C)								
		75 (23.9)			95 (35)			105 (40.6)		
cfm	EWB °F (°C)	Capacity kBtu/h		Total Sys kW <sup>3</sup>	Capacity kBtu/h		Total Sys kW <sup>3</sup>	Capacity kBtu/h		Total Sys kW <sup>3</sup>
		Total <sup>1</sup>	Sens <sup>1,2</sup>		Total <sup>1</sup>	Sens <sup>2</sup>		Total <sup>1</sup>	Sens <sup>2</sup>	
875	72 (22)	34.32	17.27	1.96	31.24	16.13	2.44	29.59	15.54	2.71
	67 (19)	31.45	21.21	1.96	28.59	20.05	2.43	27.04	19.44	2.71
	63 (17)	29.35	20.58	1.96	26.66	19.40	2.43	25.19	18.78	2.70
	62 (17)	28.82	25.13	1.95	26.24	23.94	2.43	24.86	23.29	2.70
	57 (14)	28.00	28.00	1.95	25.89	25.89	2.43	24.74	24.74	2.70
1000	72 (22)	34.88	18.05	2.01	31.66	16.90	2.48	29.96	16.30	2.76
	67 (19)	31.98	22.49	2.01	29.00	21.31	2.48	27.40	20.68	2.75
	63 (17)	29.88	21.78	2.00	27.07	20.58	2.48	25.55	19.95	2.75
	62 (17)	29.44	26.90	2.00	26.81	26.81	2.48	25.62	25.62	2.75
	57 (14)	29.10	29.10	2.00	26.85	26.85	2.48	25.62	25.62	2.75
1125	72 (22)	35.27	18.78	2.06	17.61	17.61	2.53	30.22	17.07	2.81
	67 (19)	32.36	23.68	2.05	22.50	22.50	2.53	27.66	21.88	2.80
	63 (17)	30.25	22.90	2.05	21.70	21.70	2.52	25.82	21.07	2.80
	62 (17)	30.02	28.49	2.05	27.62	27.62	2.52	26.32	26.32	2.80
	57 (14)	29.99	29.99	2.05	27.62	27.62	2.52	26.32	26.32	2.80

<sup>1</sup> Total and sensible capacities are net capacities. Blower motor heat has been subtracted.

<sup>2</sup> Sensible capacities shown are based on 80°F (27°C) entering air at the indoor coil. For sensible capacities at other than 80°F (27°C), deduct 835 Btu/h (245 W) per 1000 cfm (480 L/S) of indoor coil air for each degree below 80°F (27°C), or add 835 Btu/h (245 W) per 1000 cfm (480 L/s) of indoor coil air per degree above 80°F (27°C).

<sup>3</sup> System kilowatt is the total of indoor and outdoor unit kilowatts.

# Capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates



# EER and SEER

---

- EER = energy efficiency ratio
  - Same as COP but in weird mixed units: (Btu/hr)/W
  - Example from previous page:

$$COP = \frac{8.5 \text{ [kW]}}{2.48 \text{ [kW]}} = 3.43$$

$$EER = \frac{29.0 \text{ [kBtu/hr]}}{2.48 \text{ [kW]}} = 11.7$$

$$EER = COP \times 3.41$$

- SEER = seasonal energy efficiency ratio, units: [Btu/Wh]
  - Cooling output during a typical cooling season divided by the total electric energy input during the same period
  - Represents expected performance over a range of conditions

$$EER \approx -0.02 \times SEER^2 + 1.12 \times SEER$$

# EER and SEER

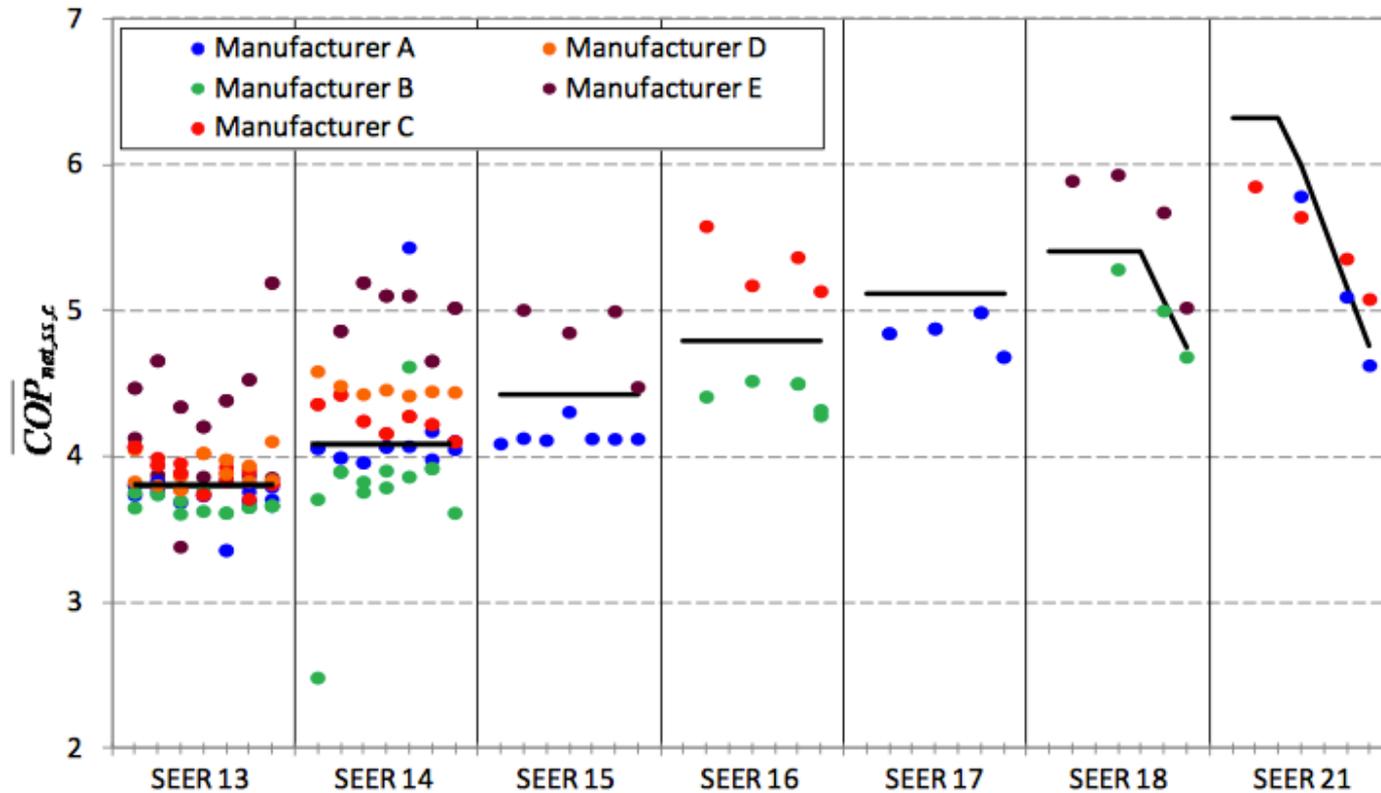


Figure 10. Simulation results for the AC library (shown in solid black lines) compared to individual AC units (individual capacities of 1.5, 2, 3, 4, and 5 tons shown in ascending order within SEER values)

- AC units must be 14 SEER (or 12.2 EER) beginning on January 1, 2015 if installed in southeastern region of the US

# **FLUID FLOWS**

For distribution systems

# Fluid flows in buildings

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- We use liquids and gases to deliver heating or cooling energy in building mechanical systems
  - Water, refrigerants, and air
- We often need to understand fluid motion, pressure losses, and pressure rises by pumps and fans in order to size systems
- We can use the Bernoulli equation to describe fluid flows in HVAC systems

$$p_1 + \frac{1}{2} \rho_1 v_1^2 + \rho_1 g h_1 = p_2 + \frac{1}{2} \rho_2 v_2^2 + \rho_2 g h_2 + K \frac{v^2}{2}$$

Static pressure      Velocity pressure      Pressure head      Friction

# Pressure losses

- We often need to find the pressure drop in pipes and ducts
- Most flows in HVAC systems are turbulent



$$\Delta p_{friction} = f \left( \frac{L}{D_h} \right) \left( \frac{1}{2} \rho v^2 \right)$$

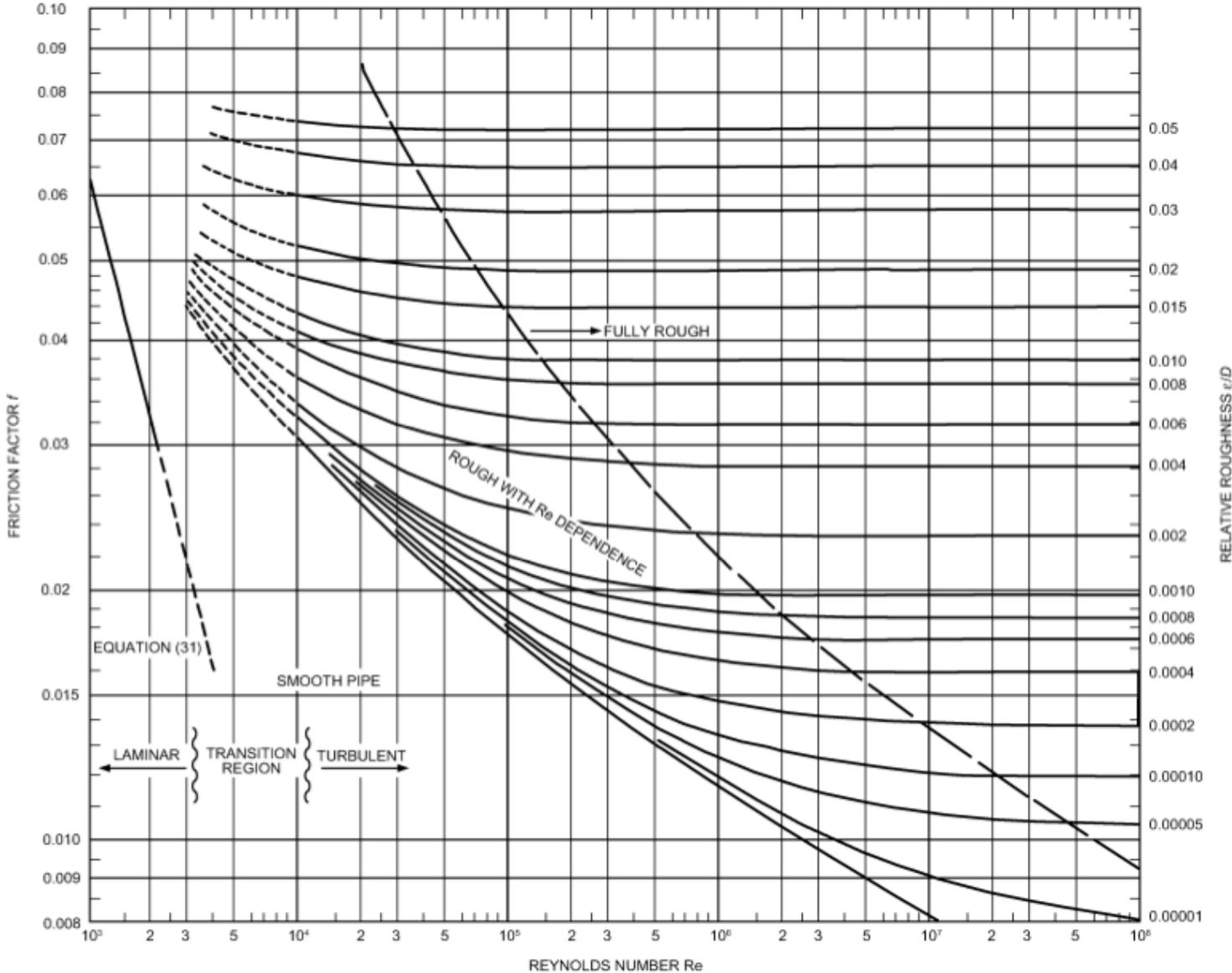
$$D_h = \frac{4A}{P} = \text{hydraulic diameter}$$

$$K = f \left( \frac{L}{D_h} \right) \quad \text{In a straight pipe}$$

$$K = f \left( \frac{L}{D_h} + \sum_{fittings} K_f \right) \quad \text{In a straight pipe with fittings}$$



# Friction factor



# Reynolds number

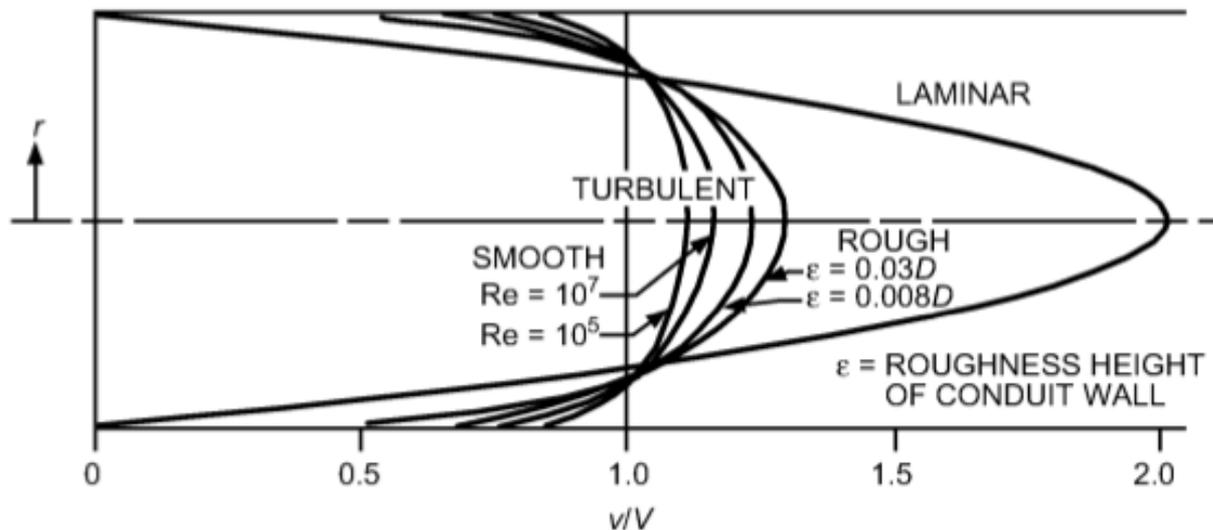
- Reynolds number relates inertial forces to viscous forces:

$$Re = \frac{VL}{\nu}$$

- Kinematic viscosity

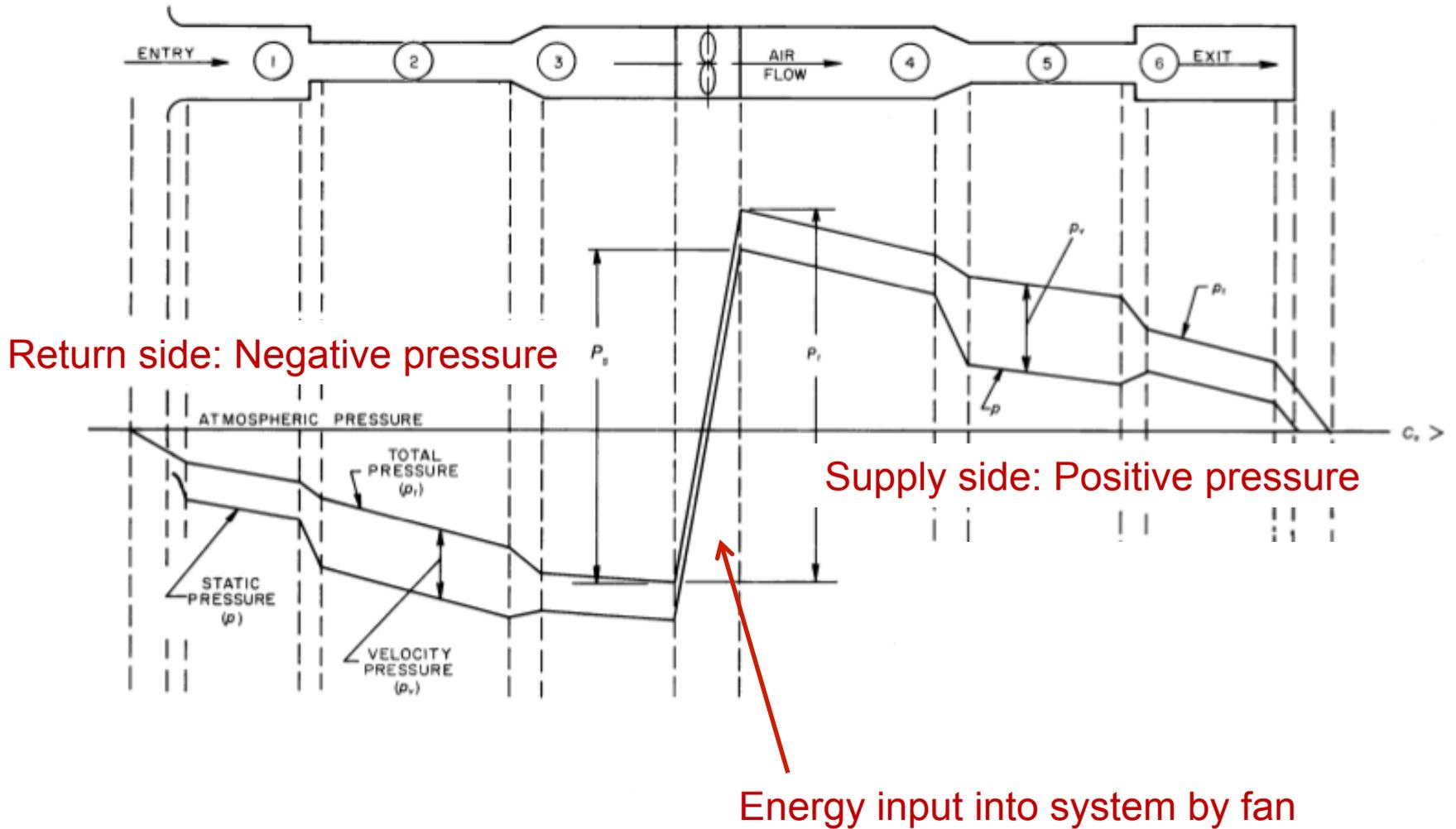
$$\nu = \frac{\mu}{\rho} = 1.5 \times 10^{-5} \frac{\text{m}^2}{\text{s}} \quad (\text{for air at } T=25^\circ\text{C})$$

$L = D_h$  in a pipe or duct



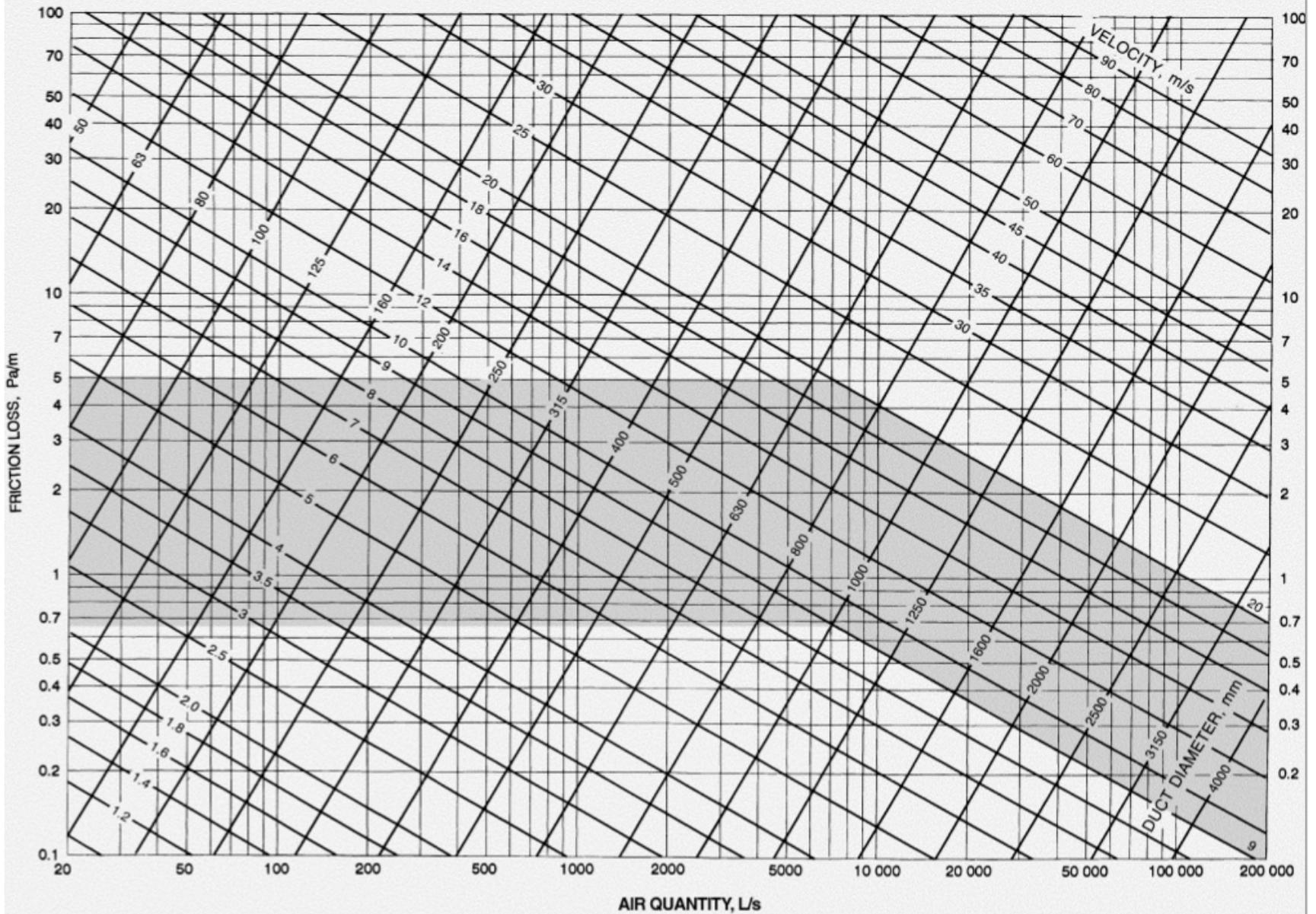
**Fig. 4 Velocity Profiles of Flow in Pipes**

# Pressure losses and rises



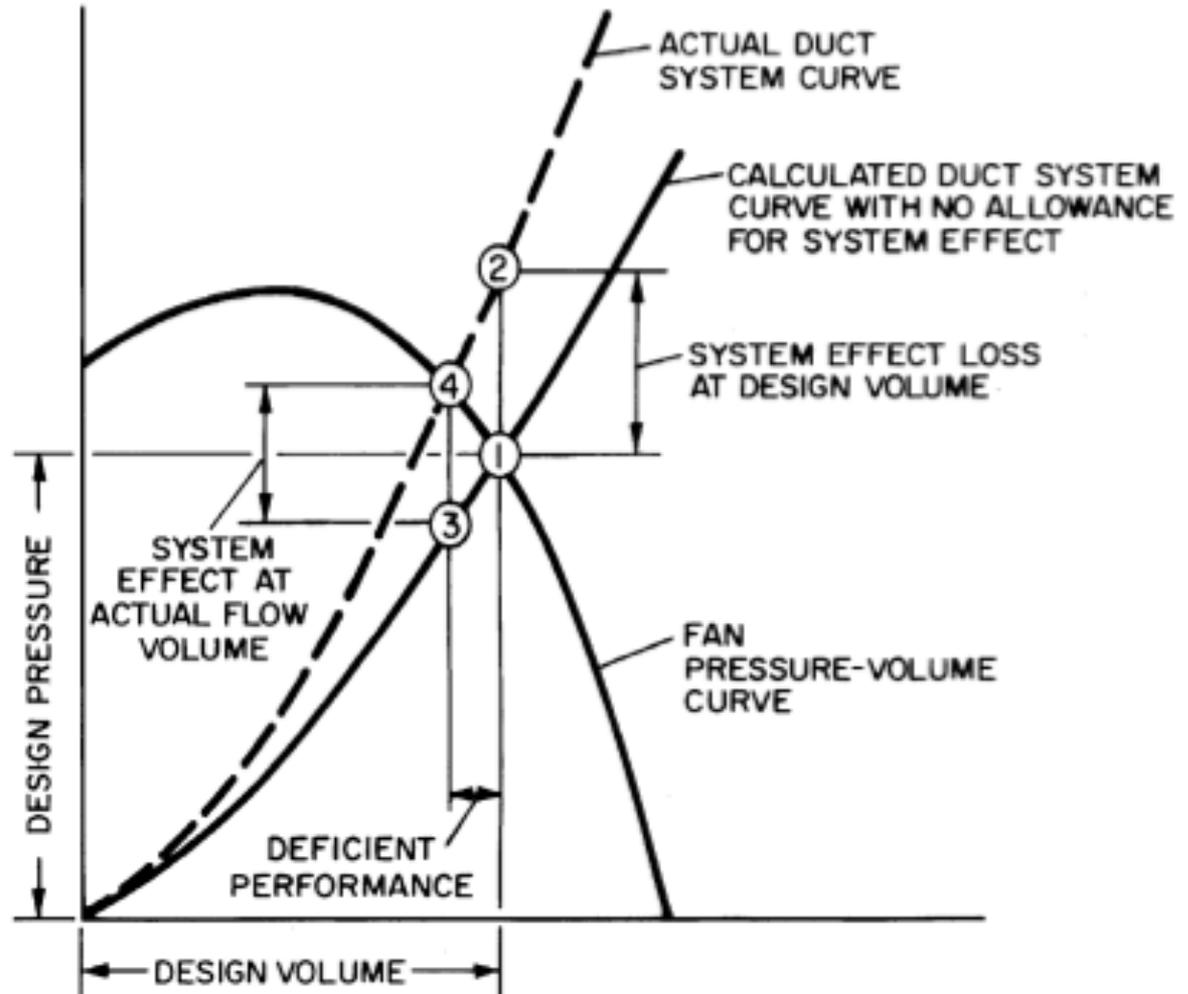
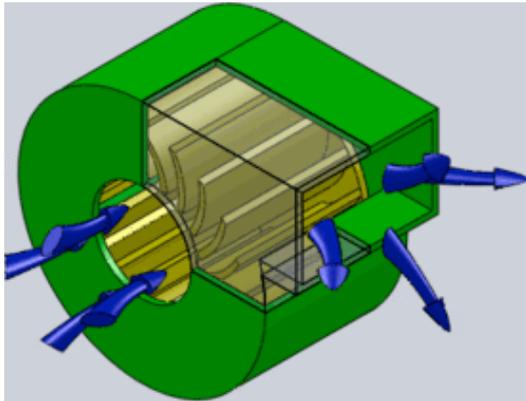


# Duct friction charts

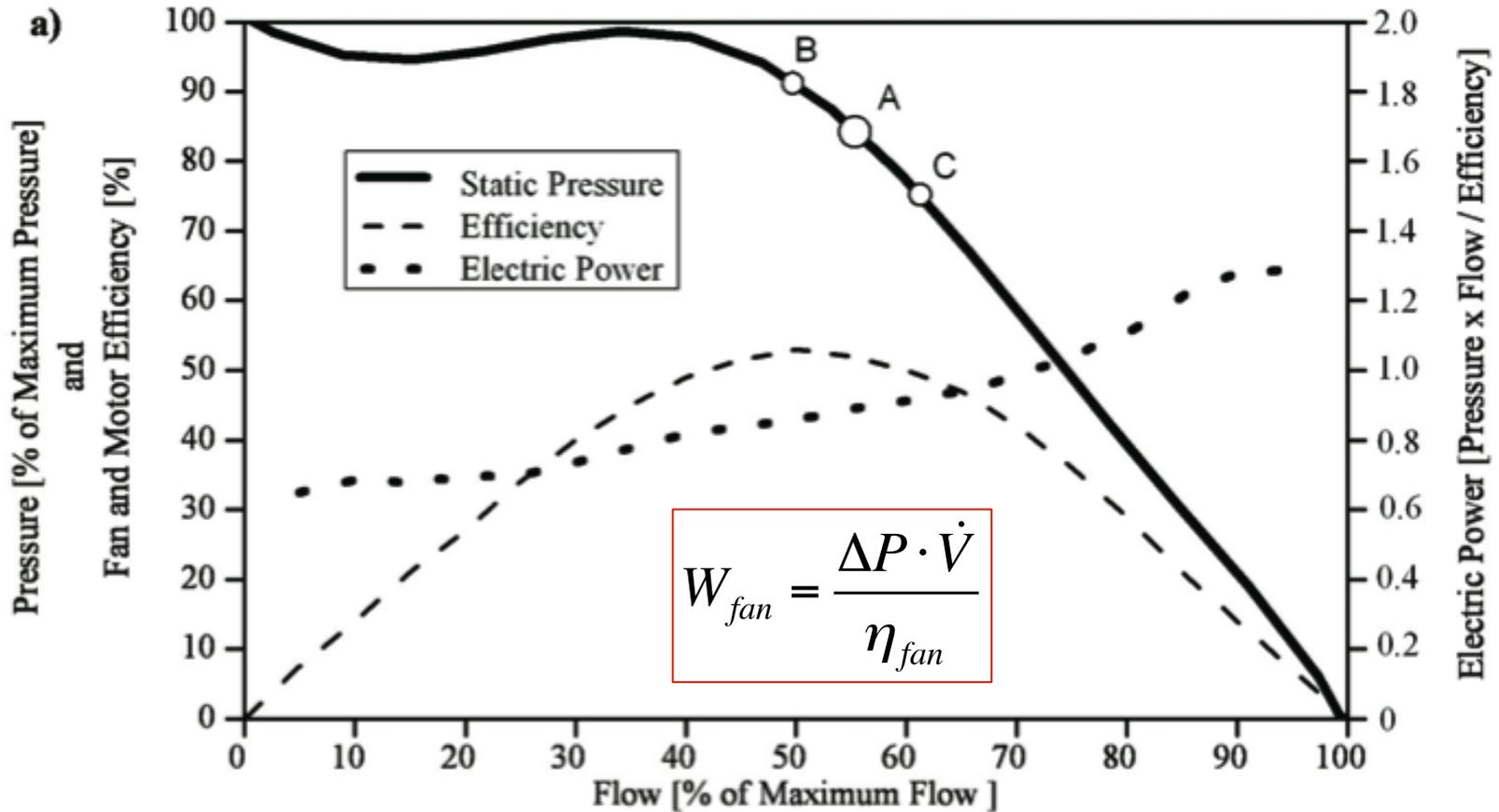


# Fan and system pressures

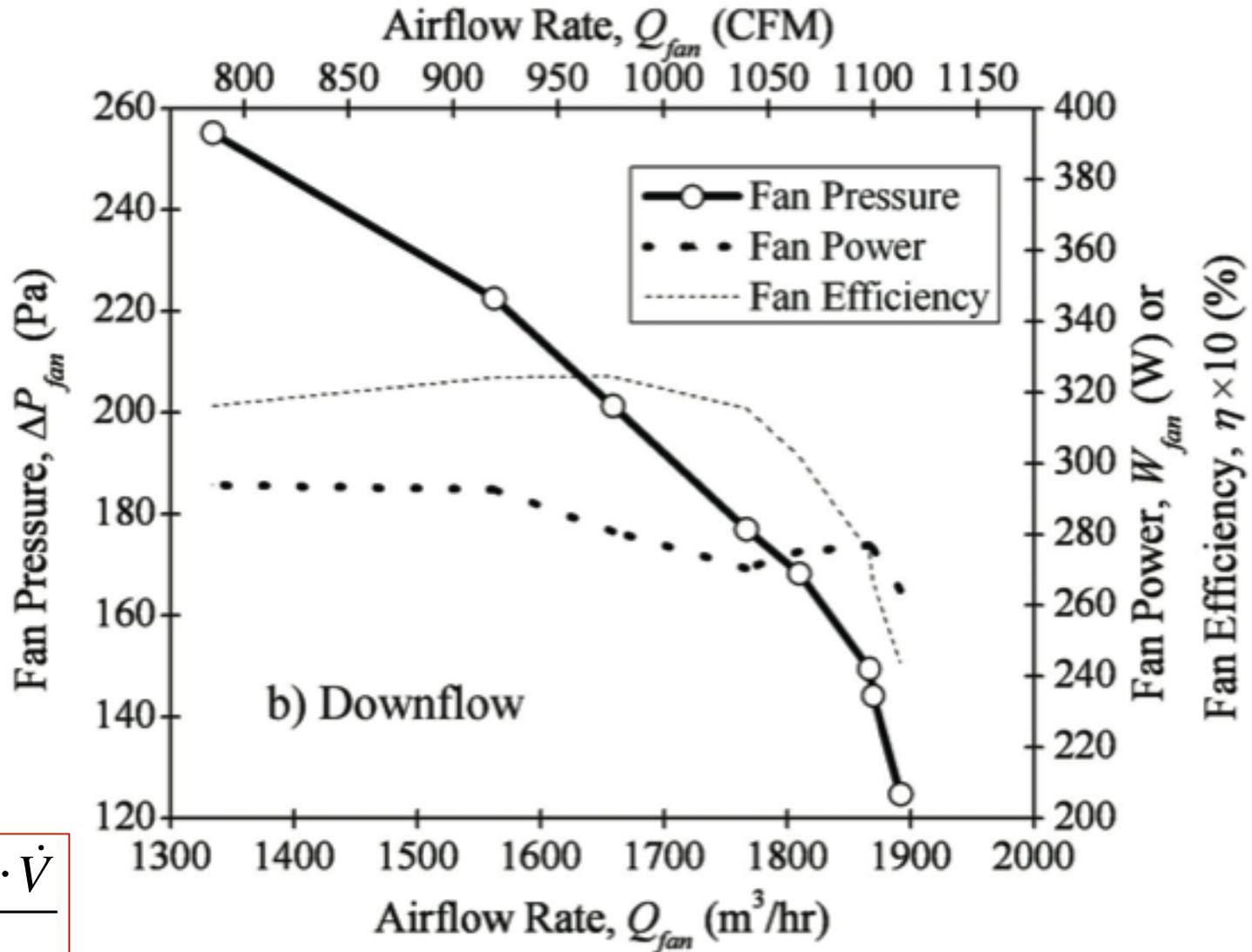
- Fan curves
- System curves



# Fan and system curves: Ideal



# Fan and system curves: Real



$$W_{fan} = \frac{\Delta P \cdot \dot{V}}{\eta_{fan}}$$

# **ENERGY ESTIMATION METHODS**

Annual heating and cooling energy requirements

# Simple energy estimation methods

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- Two methods:
  - Degree-day methods (simplest)
    - Constant equipment efficiency
  - Bin methods
    - Accounts for varying efficiencies or indoor conditions

# Degree-day method

---

- The simplest method of estimating energy use is the Degree-Day Method (DDM)
- The DDM makes uses the concept of the degree-day (DD) to estimate energy used for heating or cooling
- The method is better for estimating heating requirements than cooling requirements since solar gain is essentially ignored
- Works best where the efficiency of the HVAC equipment is constant

# DDM

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- The basic idea is that the energy use of a building is directly related to the temperature difference between outdoor and indoor air
- Heating equipment is assumed to run when the outdoor temperature drops below the “balance temperature”
  - The **balance temperature** is the outdoor air temperature at which the internal heat gains balance the heat loss to the outside
  - This is less than the interior temperature set point
- Cooling equipment is assumed to run when the outdoor temperature is above the balance temperature
  - The balance temperature might not be the same for heating and cooling because the interior temperature, interior heat gain, and building heat loss usually differ in summer and winter

# Heating degree days and cooling degree days

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- In many codes, standards, references and literature, you will see references to Heating Degree Days (HDD) or Cooling Degree Days (CDD)
  - In particular, the main energy code, ASHRAE 90.1 makes reference to HDD and CDD throughout
- HDD and CDD are design-days used to estimate the energy demand for heating and cooling using the DDM

# Calculating HDD and CDD

---

- A degree-day is the sum of the difference between the average outside temperature and a base temperature (often 65°F or 18°C) for a fixed time frame
  - Add up the product of time and temperature difference **below** the reference for heating (and the product of time and temperature difference **above** for cooling)
  - The most accurate estimates use minute-by-minute weather data

$$HDD_{REF} = \sum_i \frac{(T_{base} - T_{out})}{24 \text{ h}} \text{ when } T_{out} < T_{REF}$$

$$CDD_{REF} = \sum_i \frac{(T_{out} - T_{base})}{24 \text{ h}} \text{ when } T_{out} > T_{REF}$$

- Units: “degree-days” = °F-days or °C-days
- We can convert between HDD in °F to HDD in °C by multiplying by 5/9

# Selecting a base temperature

---

- $HDD_{65F}$  and  $CDD_{50F}$  are common HDD/CDD levels that are used regularly in industry, so you might use those regardless of your true base temperature
- If your building has a different base temperature, then you should immediately know that your estimates using DDM will not be accurate
- The best base temperature is the balance point temperature where internal gains balance the heat loss to outside

# Finding the balance point temperature

---

- We find the balance point temperature by setting the heat gain/loss of the building to zero and solving for the outside temperature

$$Q_h \approx \left[ (UA)_{total} + \dot{V}_{inf} \rho C_p \right] (T_{in} - T_{out})$$

at  $T_{out} = T_{bal}$ ,  $Q_h + Q_{int} = 0$ , so

$$T_{bal} = T_{in} - \frac{Q_{int}}{(UA)_{total} + \dot{V}_{inf} \rho C_p}$$

# Understanding balance point temperatures

---

$$T_{bal} = T_{in} - \frac{Q_{int}}{(UA)_{total} + \dot{V}_{inf} \rho C_p}$$

- As the insulation increases,  $T_{bal}$  drops
- As infiltration decreases,  $T_{bal}$  drops
- As internal gains increase,  $T_{bal}$  drops
- As a result, most modern buildings have a  $T_{bal}$  well below 65°F (usually closer to 55°F)

# Balance point example

---

- A 10000 ft<sup>3</sup> building has an overall UA of 250 Btu/hr, an infiltration rate of 0.7 ACH, and an internal gain of 5 kBtu/hr
- What is its balance point temperature?

## Balance point example

---

- A 10000 ft<sup>3</sup> building has an overall UA of 250 Btu/hr, an infiltration rate of 0.7 ACH, and an internal gain of 5 kBtu/hr
- What is its balance point temperature?

$$\dot{V}_{\text{inf}} = (ACH)V = (0.7)10000 = 7000 \frac{\text{ft}^3}{\text{hr}}$$

$$\text{Assume } \rho \approx 0.075 \frac{\text{lb}}{\text{ft}^3}, C_p \approx 0.24 \frac{\text{Btu}}{\text{lb}^\circ\text{F}}, T_{in} = 68^\circ\text{F}:$$

$$T_{bal} = 68 - \frac{5000}{250 + 7000(0.075)(.24)} = 68 - 13.3 = 54.7^\circ\text{F}$$

# Online CDD/HDD calculators

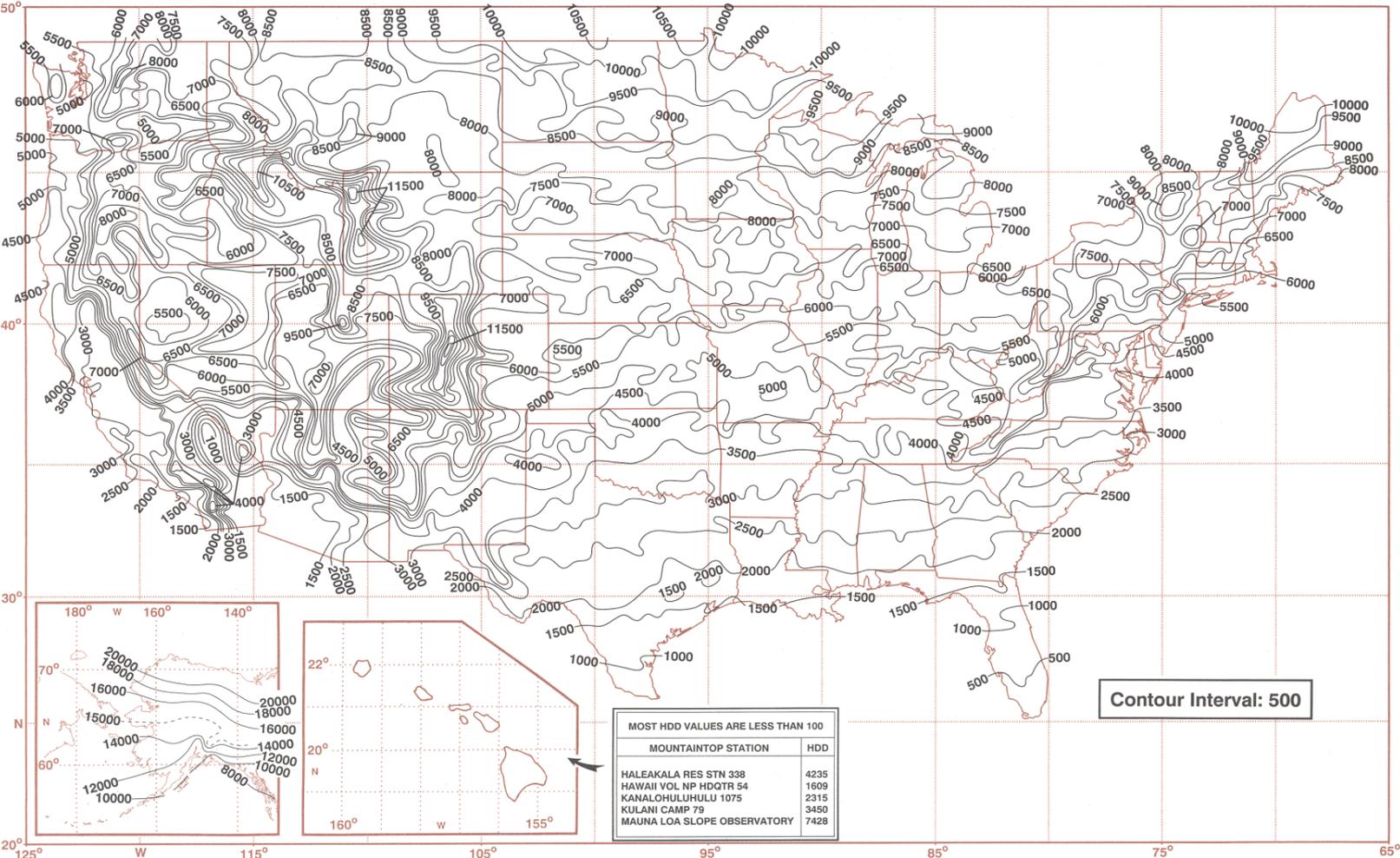
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- There are a number of online calculators that use TMY (typical meteorological year) data
  - <http://www.degreedays.net/>
  - [http://www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/cdus/degree\\_days/](http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/degree_days/)
  - <http://pnwpest.org/cgi-bin/usmapmaker.pl>

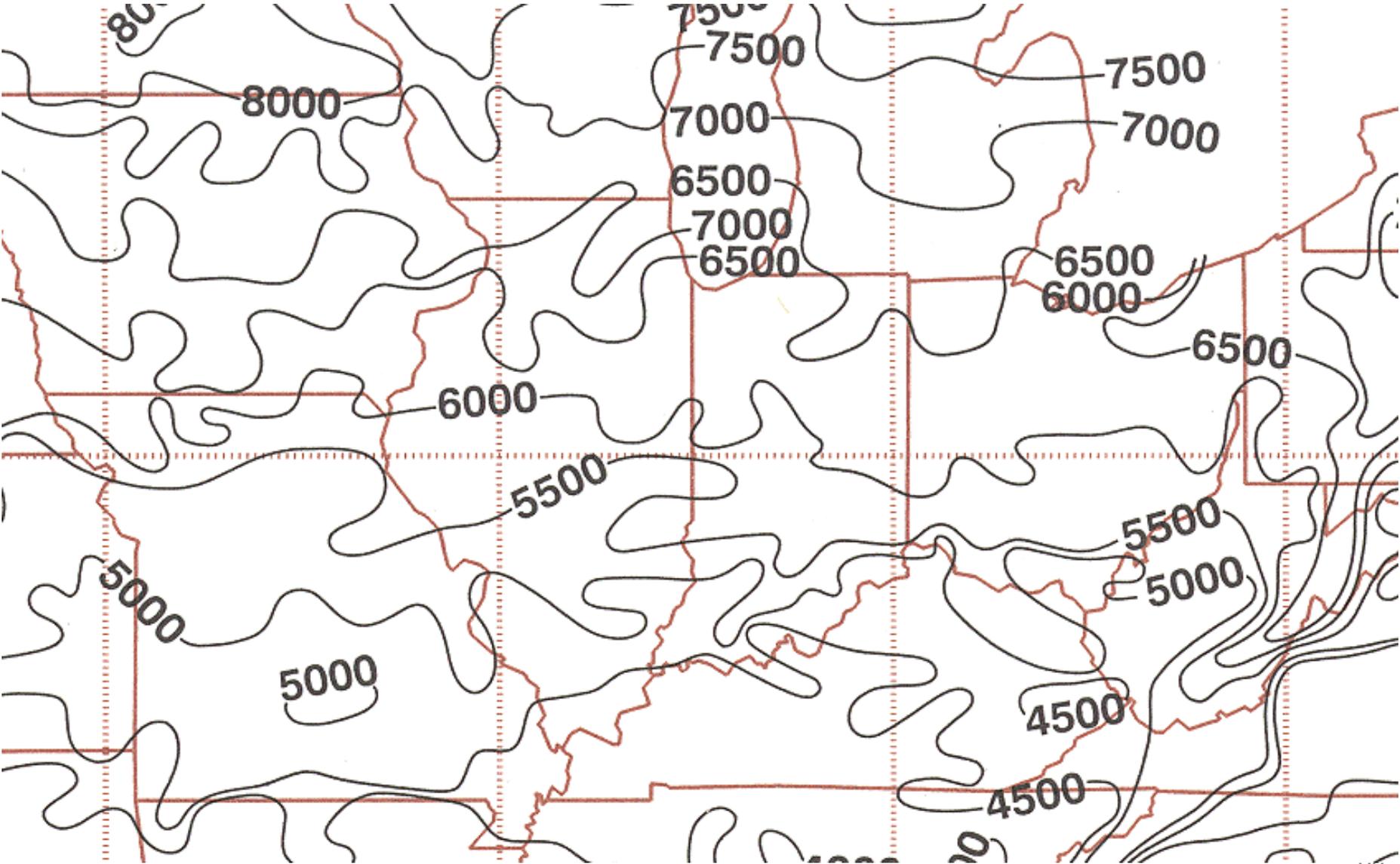
# HDD<sub>65F</sub> maps

## ANNUAL HEATING DEGREE DAYS

BASED ON NORMAL PERIOD 1961-1990



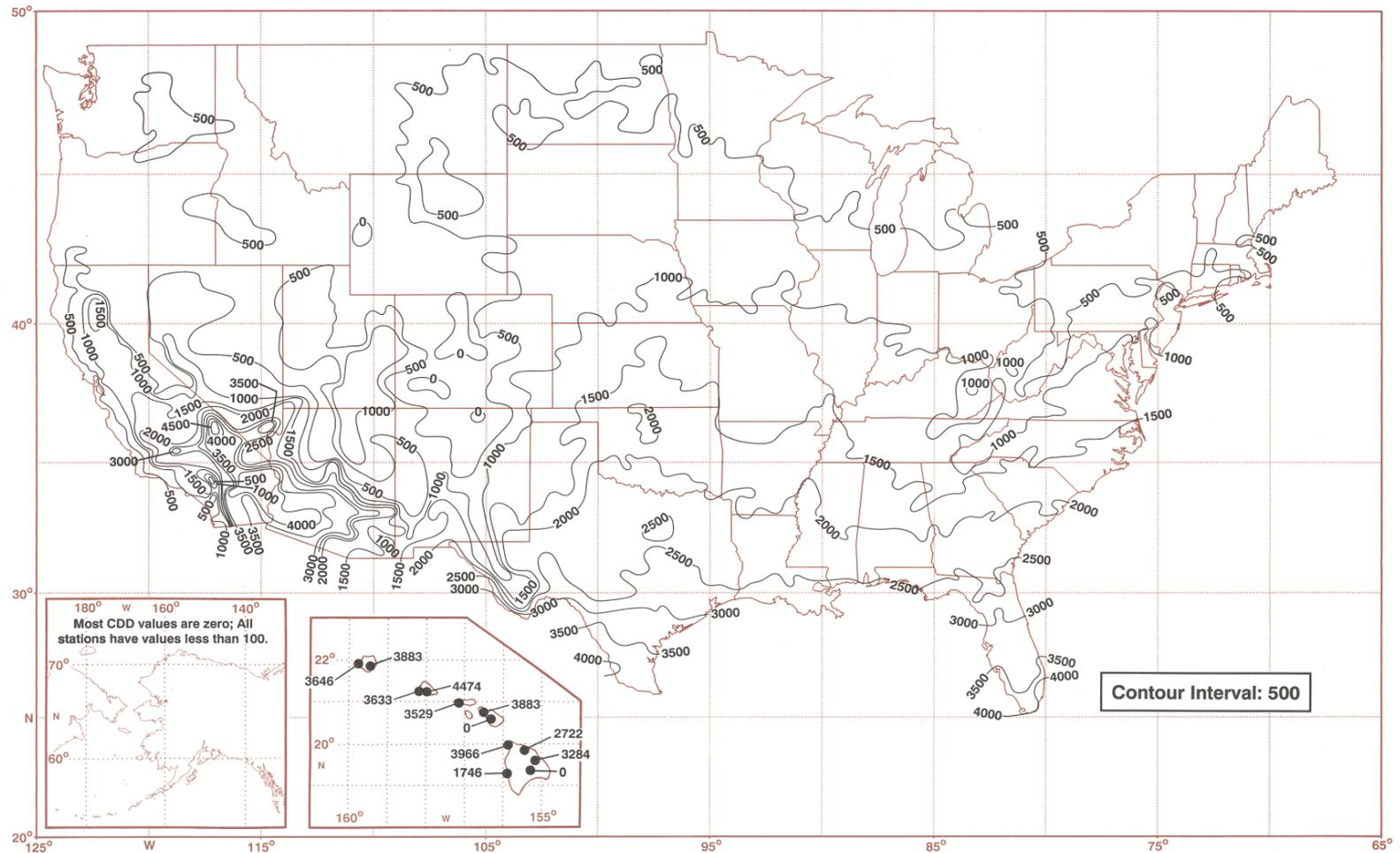
# HDD<sub>65F</sub> maps



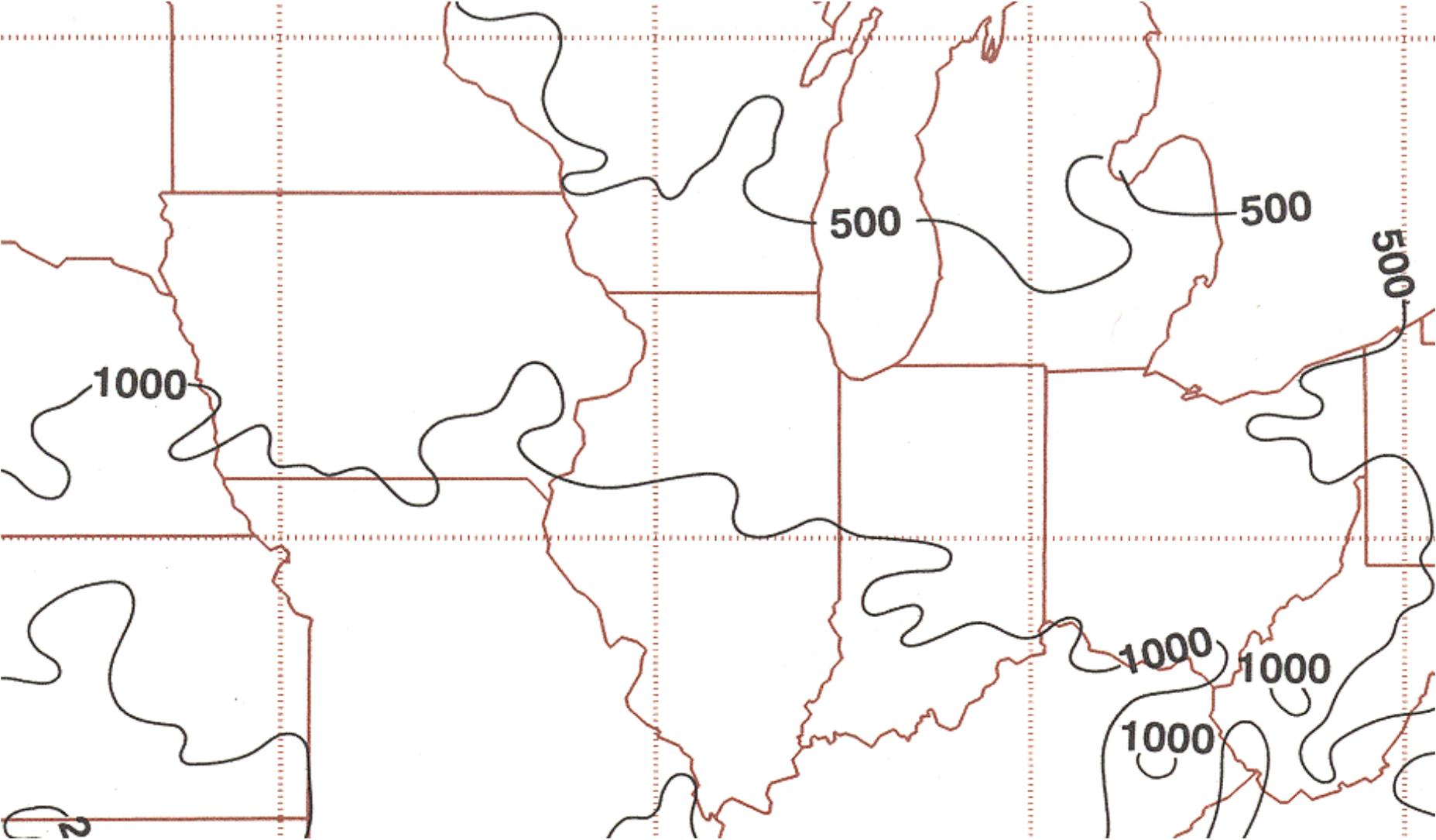
# CDD<sub>65F</sub> maps

## ANNUAL COOLING DEGREE DAYS

BASED ON NORMAL PERIOD 1961-1990



# CDD<sub>65F</sub> maps



# Chicago Area HDD/CDD (Fahrenheit)

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- HDD65 = 6280 and CDD65 = 1115
- HDD60 = 5080 and CDD60 = 1740
- HDD55 = 4220 and CDD55 = 2500
- HDD50 = 3080 and CDD50 = 3400
- HDD45 = 2280 and CDD45 = 4420
  
- All units are in °F-days

# Estimating energy use with HDD

---

- Now that we know how to get HDD, we can calculate the heating energy,  $E$ , required to keep the building heated
- Using hourly values:

$$E_{heating} = \frac{(UA)_{total}}{\eta} \int [T_{bal} - T_{out}(t)] dt \quad \text{when } T_{out} < T_{bal}$$

Where  $\eta$  = heating system efficiency (-)

- Using HDD:

$$E_{heating} = \frac{(UA)_{total}}{\eta} HDD$$

\*Convert HDD to degree-seconds

# Estimating energy use with HDD

---

- Example problem 8.1
- Find the annual heating bill for a house in New York under the following conditions:
  - $UA_{\text{total}} = 205 \text{ W/K}$
  - Heat gain = 569 W
  - $T_{\text{in}} = 21.1 \text{ degrees C}$
  - Heating system is 75% efficient
  - Fuel prices is \$8/GJ
  - HDD = 2800 K-days
- Find balance temperature
- Estimate energy requirements
- Estimate costs

# Estimating cooling energy use

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- Estimates for cooling energy are not as accurate but we can still use them

$$E_{cooling} = \frac{(UA)_{total}}{COP} \int [T_{bal} - T_{out}(t)] dt \quad \text{when } T_{out} > T_{bal}$$

$$E_{cooling} = \frac{(UA)_{total}}{COP} CDD$$

\*Make sure time units align

# Bin method

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- The Bin Method is another variation of the degree-day method where we break down the year into temperature ranges or “bins” and compute the energy use in each of the bins
  - 5 degree temperature ranges are usually used
- In this method, we can easily account for:
  - Varying loads
  - Varying heating/cooling systems
  - Varying system efficiencies
    - This is especially important for air-conditioner units and heat pumps where the efficiency depends greatly on the temperature at which it is working

# Bin method

- We need to find the number of hours ( $N_{bin}$ ) that the outdoor temperature ( $t_o$ ) is in a temperature bin

$$Q_{bin} = N_{bin} \frac{K_{tot}}{\eta_h} [t_{bal} - t_o]^+$$

**Table 7 Sample Annual Bin Data**

Site	Bin																				
	39/ 41	36/ 38	33/ 35	30/ 32	27/ 29	24/ 26	21/ 23	18/ 20	15/ 17	12/ 14	9/ 11	6/ 8	3/ 5	0/ 2	-3/ -1	-6/ -4	-9/ -7	-12/ -10	-15/ -13	-18/ -16	-21/ -19
Chicago, IL			74	176	431	512	960	660	591	780	510	770	686	1671	380	304	125	66	49	11	4
Dallas/Ft. Worth, TX	4	170	322	511	922	1100	1077	750	803	870	581	728	418	464	37	3					
Denver, CO			81	217	406	390	570	726	712	902	809	783	750	1467	446	216	106	85	52	44	8
Los Angeles, CA	4	10	9	16	56	194	1016	1874	2280	2208	843	227	23								
Miami, FL			14	648	2147	2581	1852	734	390	202	100	76	14	2							
Nashville, TN		4	82	366	717	756	1291	831	693	801	670	858	639	793	141	89	29				
Seattle, WA				10	88	139	330	497	898	1653	1392	1844	1127	715	40	26	1				

# Bin method

**Table 8 Calculation of Annual Heating Energy Consumption for Example 4**

Climate			House	Heat Pump							Supplemental		
A	B	C	D	E	F	G	H	I	J	K	L	M	N
Temp. Bin, °C	Temp. Diff., $t_{bal} - t_{bin}$	Weather Data Bin, h	Heat Loss Rate, kW	Heat Pump Integrated Heating Capacity, kW	Cycling Capacity Adjustment Factor <sup>a</sup>	Adjusted Heat Pump Capacity, kW <sup>b</sup>	Rated Electric Input, kW	Operating Time Fraction <sup>c</sup>	Heat Pump Supplied Heating, kWh <sup>d</sup>	Seasonal Heat Pump Electric Consumption, kWh <sup>e</sup>	Space Load, kWh <sup>f</sup>	Supplemental Heating Required, kWh <sup>g</sup>	Total Electric Energy Consumption, kWh <sup>h</sup>
16	1.8	693	0.70	12.80	0.764	9.78	3.74	0.072	488	187	485	—	187
13	4.8	801	1.87	12.01	0.789	9.48	3.63	0.197	1 496	573	1 497	—	573
10	7.8	670	3.04	11.22	0.818	9.18	3.52	0.331	2 036	781	2 037	—	781
7	10.8	858	4.21	9.80	0.857	8.40	3.40	0.501	3 611	1 462	3 612	—	1 462
4	13.8	639	5.38	8.49	0.908	7.71	3.18	0.698	3 439	1 418	3 438	—	1 418
1	16.8	793	6.55	7.98	0.955	7.62	3.10	0.860	5 196	2 114	5 195	—	2 114
-2	19.8	141	7.72	7.47	1.000	7.47	3.02	1.000	1 053	426	1 089	36	462
-5	22.8	89	8.89	6.95	1.000	6.95	2.93	1.000	618	261	791	173	434
-8	25.8	29	10.06	6.48	1.000	6.48	2.85	1.000	188	83	292	104	187
-11	28.8	0	11.23	5.69	1.000	—	—	—	—	—	—	—	—
<b>Totals:</b>									18 125	7 305	18 436	313	7 618

<sup>a</sup>Cycling Capacity Adjustment Factor =  $1 - C_d(1 - x)$ , where  $C_d$  = degradation coefficient (default = 0.25 unless part load factor is known) and  $x$  = building heat loss per unit capacity at temperature bin. Cycling capacity = 1 at the balance point and below. The cycling capacity adjustment factor should be 1.0 at all temperature bins if the manufacturer includes cycling effects in the heat pump capacity (Column E) and associated electrical input (Column H).

<sup>b</sup>Column G = Column E × Column F

<sup>c</sup>Operating Time Factor equals smaller of 1 or Column D/Column G

<sup>d</sup>Column J = Column I × Column G × Column C

<sup>e</sup>Column K = Column I × Column H × Column C

<sup>f</sup>Column L = Column C × Column D

<sup>g</sup>Column M = Column L - Column J

<sup>h</sup>Column N = Column K + Column M

# Annual energy consumption

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- While these methods are good for rough estimates, it is best to perform annual energy simulations using software to get better estimates
- EnergyPlus
- eQUEST
- IES-VE
- TRNSYS
- Many others

# Next time

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- Energy efficiency
- Building diagnostic methods