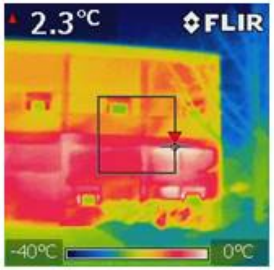
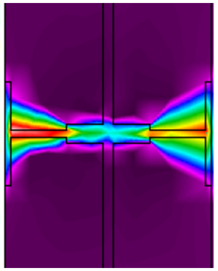
CAE 331/513
Building Science
Fall 2016





Week 9: October 18, 2016
HVAC system components and refrigeration cycles

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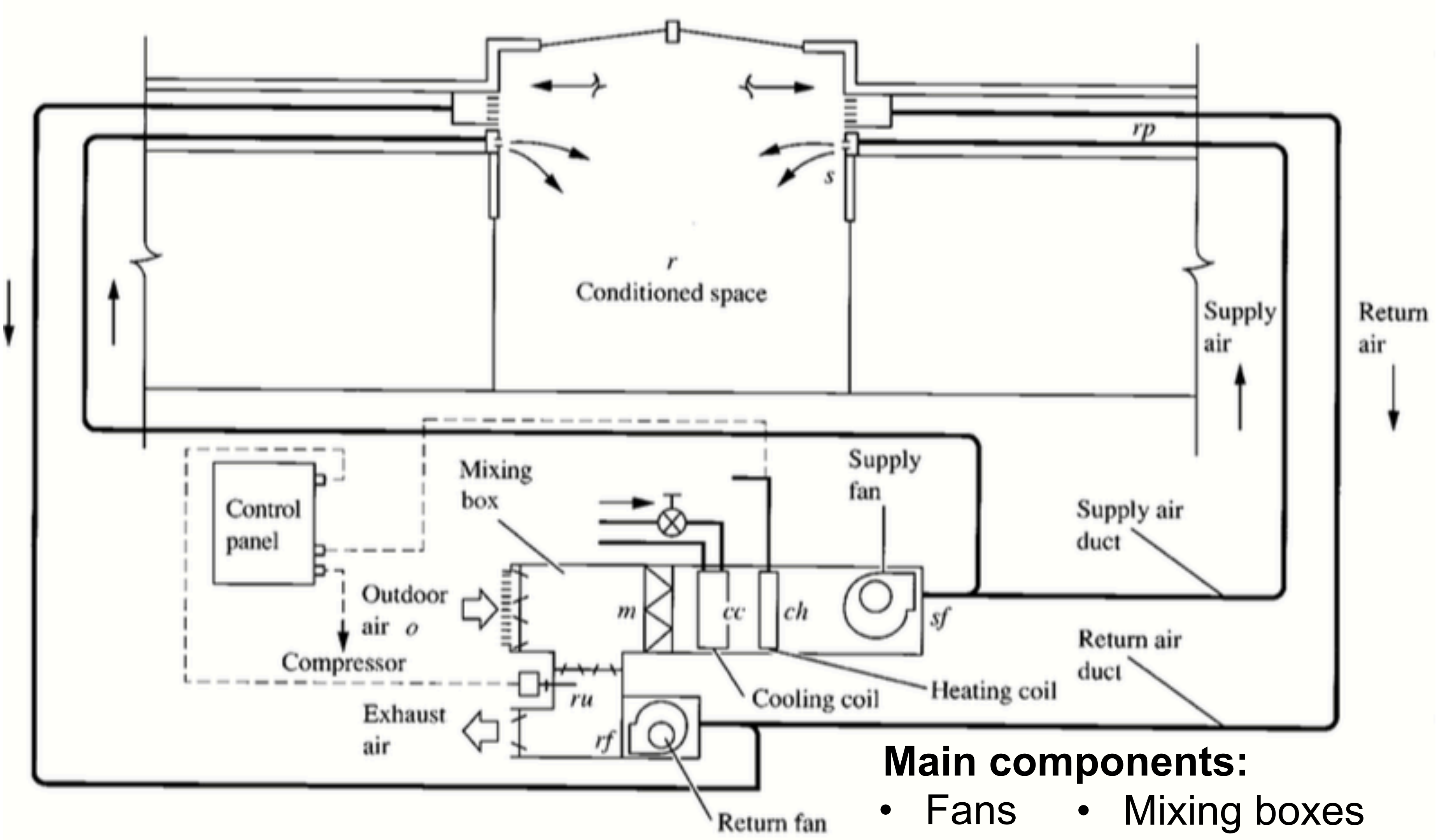
Last time

- Finished psychrometric processes

- Introduced HVAC systems and components
    - Distributed vs. central systems
    - Residential vs. commercial

- HW 4 due today

Typical central commercial air distribution system



Main components:

- Fans
- Coils
- Filters
- Mixing boxes
- Ducts
- Diffusers

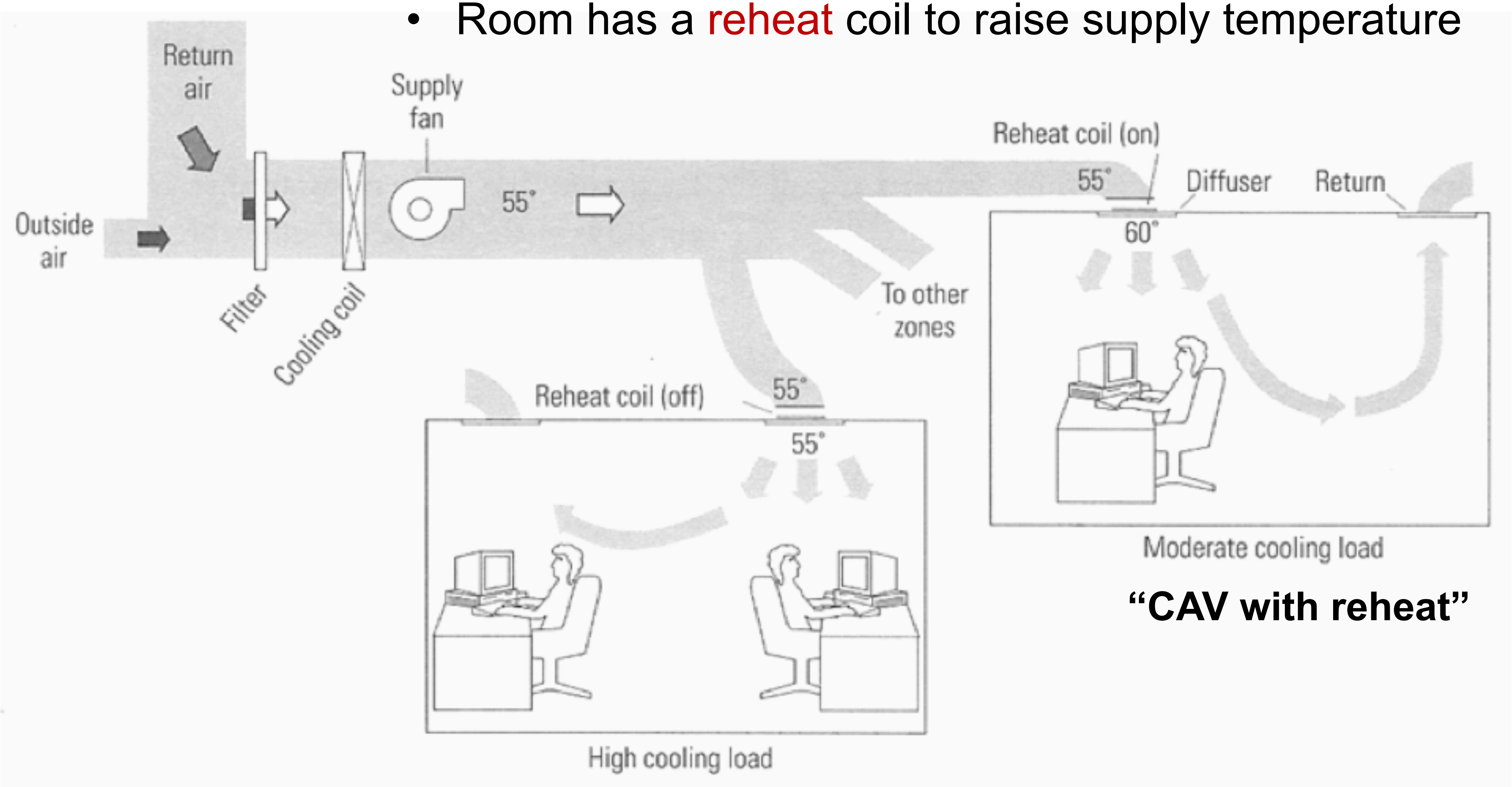
Common commercial air distribution systems

- Constant air volume (**CAV**)
- Variable air volume (**VAV**)
- Dual duct (**DD**)
- Multizone (**MZ**)

Typical constant air volume (CAV) system

Constant airflow rate and temperature to each room

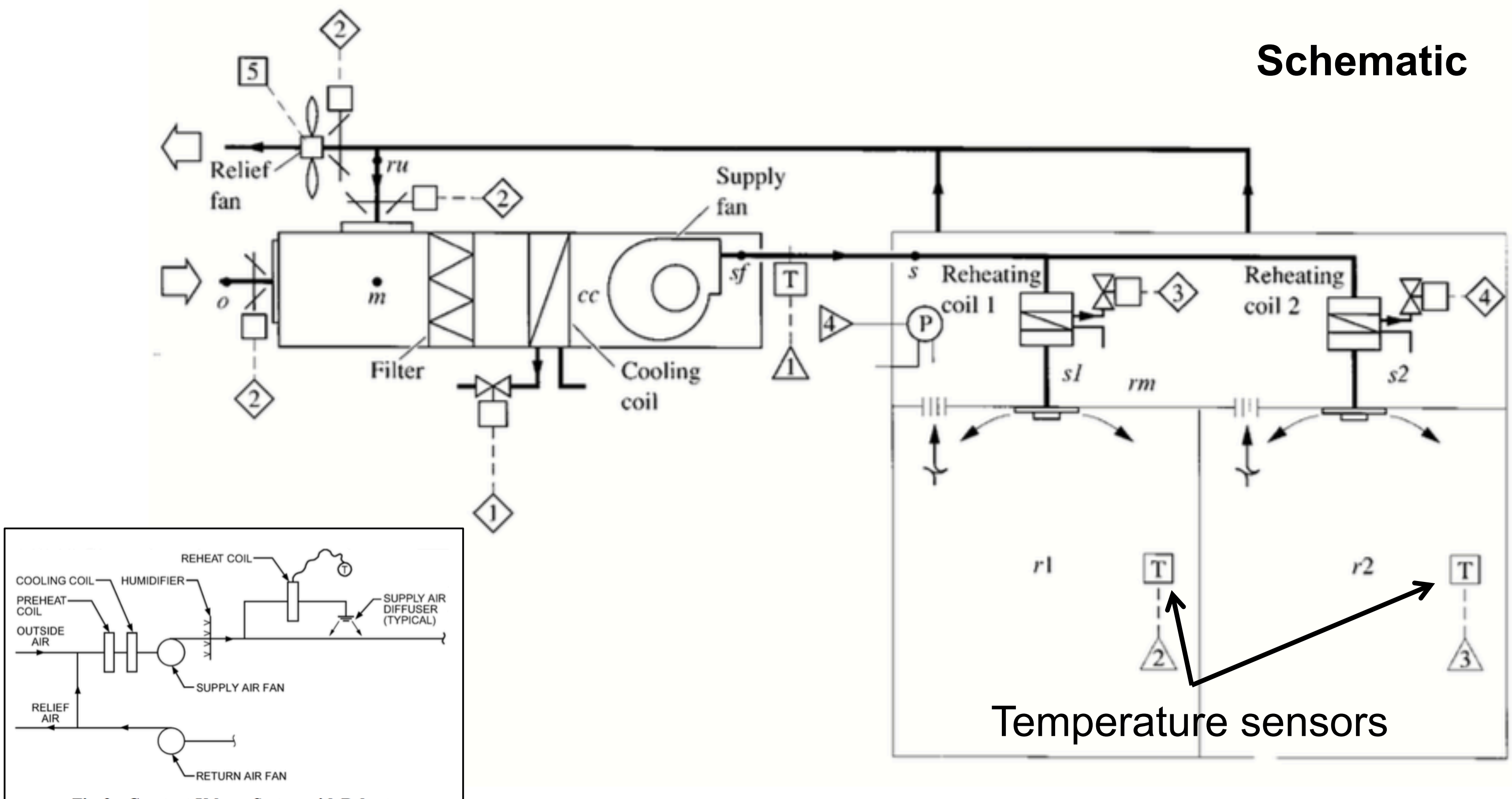
- Cold air delivered to room
- Room has a reheat coil to raise supply temperature



"CAV with reheat"

Typical constant air volume (CAV) system

Schematic

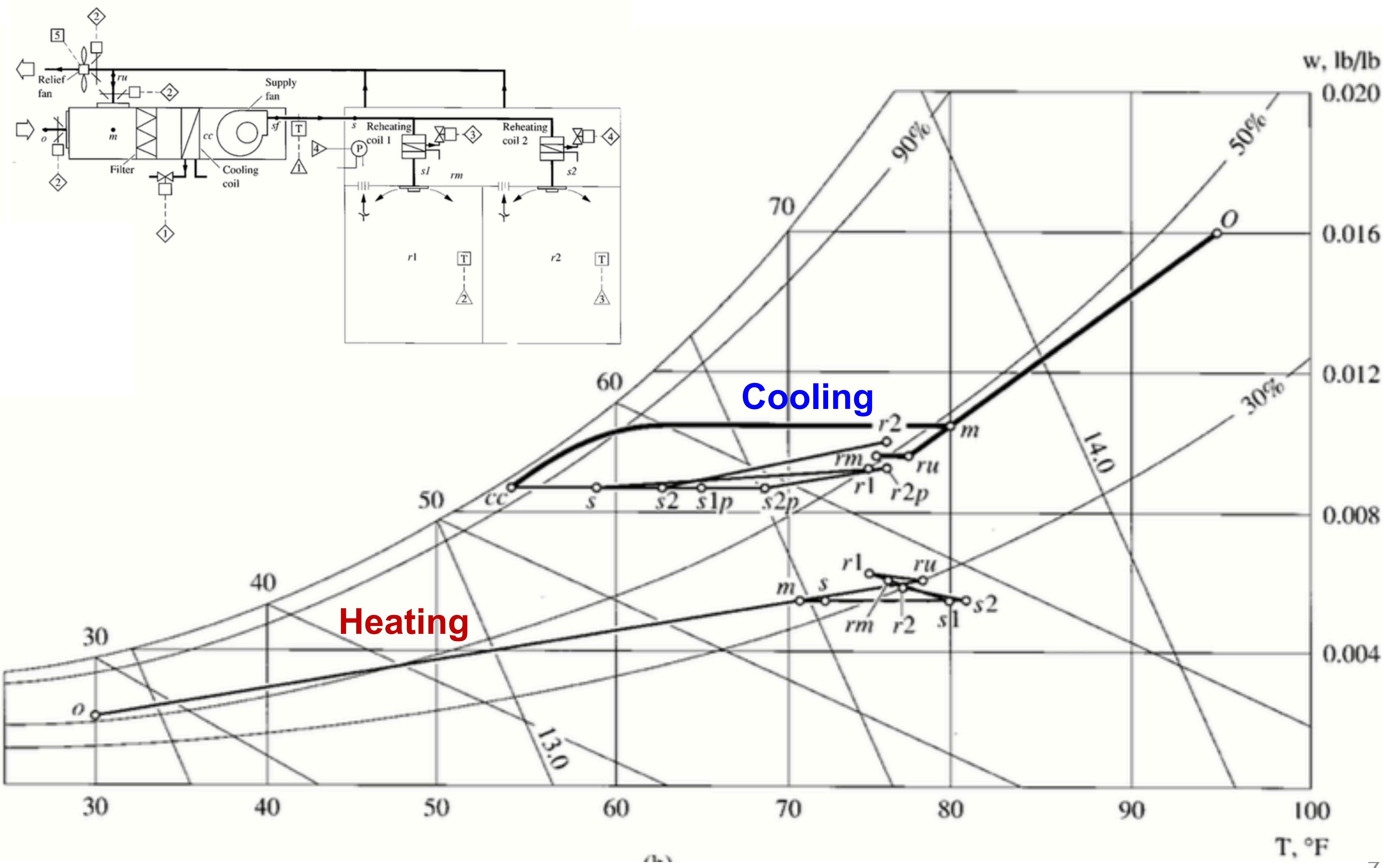


Temperature sensors

Fig. 9 Constant-Volume System with Reheat

ASHRAE Systems and Equipment Handbook

Typical constant air volume (CAV) system



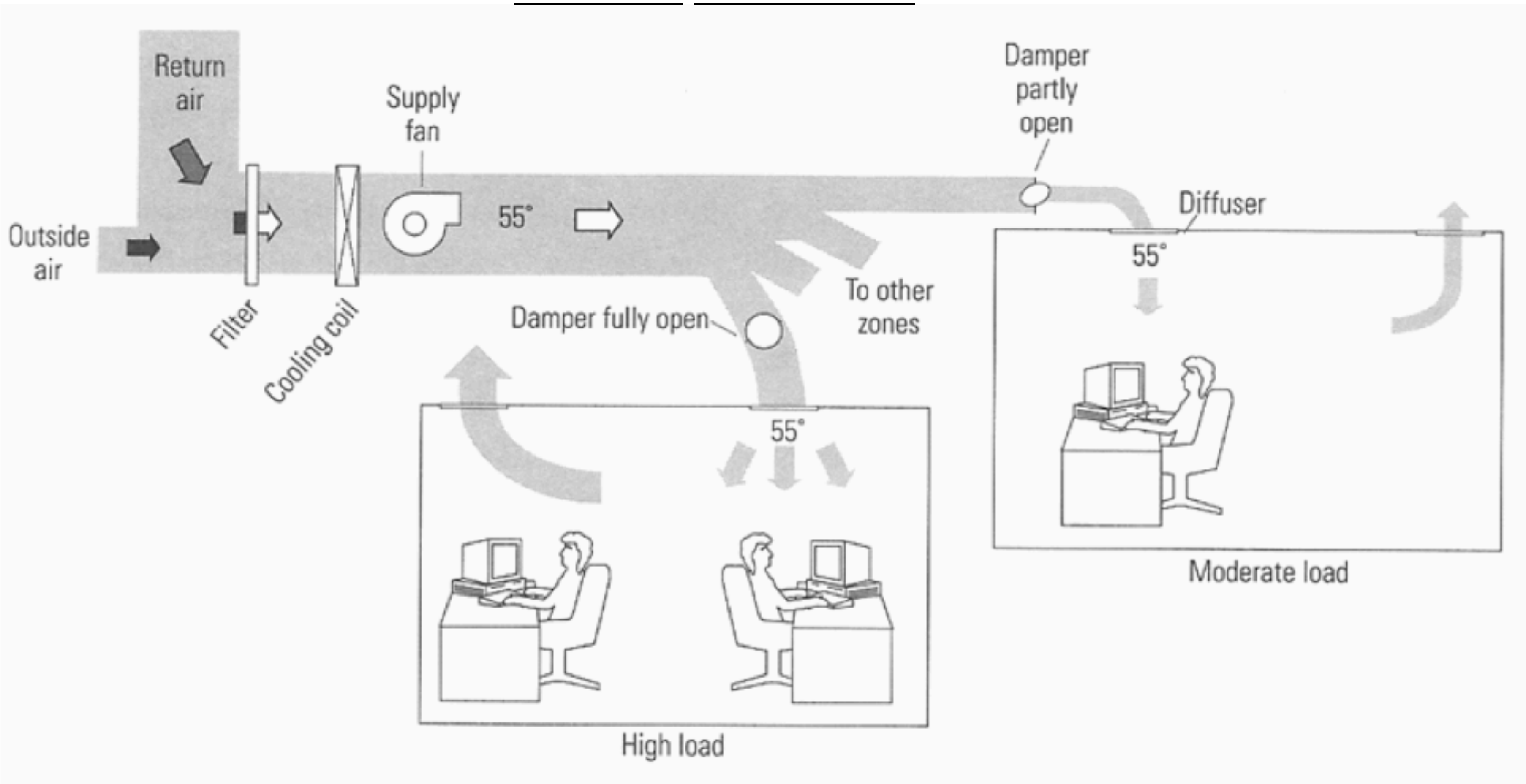
Cooling

Heating

Typical variable air volume (VAV) system

Same temperature air delivered to each room

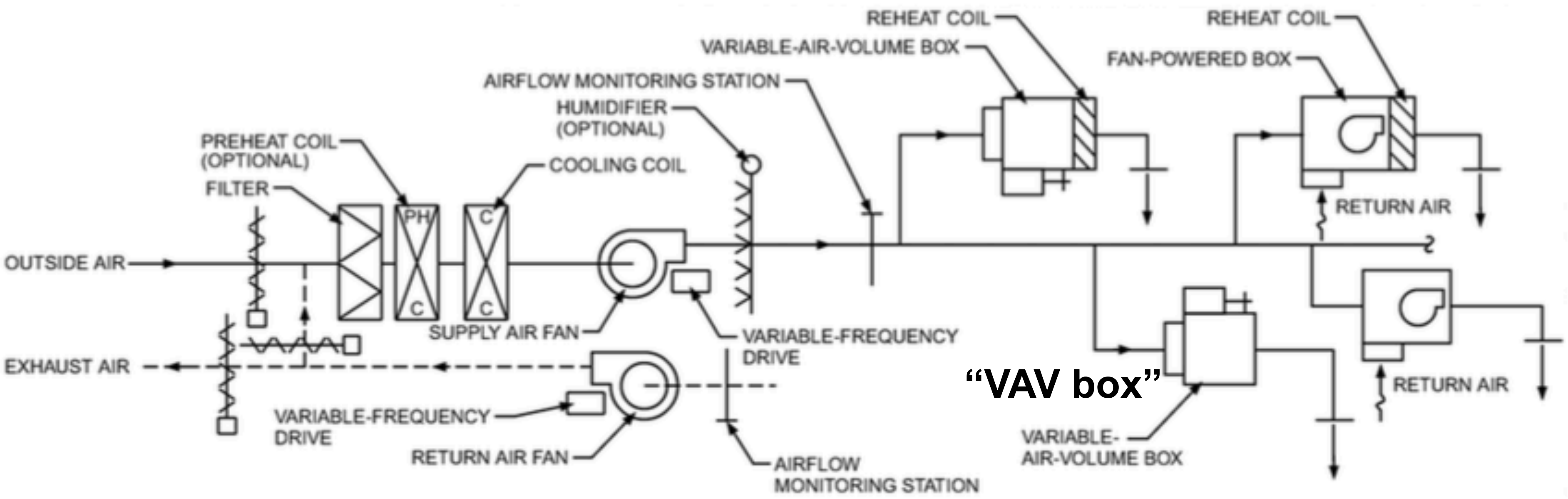
- Different airflow rate delivered to each room



Typical variable air volume (VAV) system

Same temperature air delivered to each room

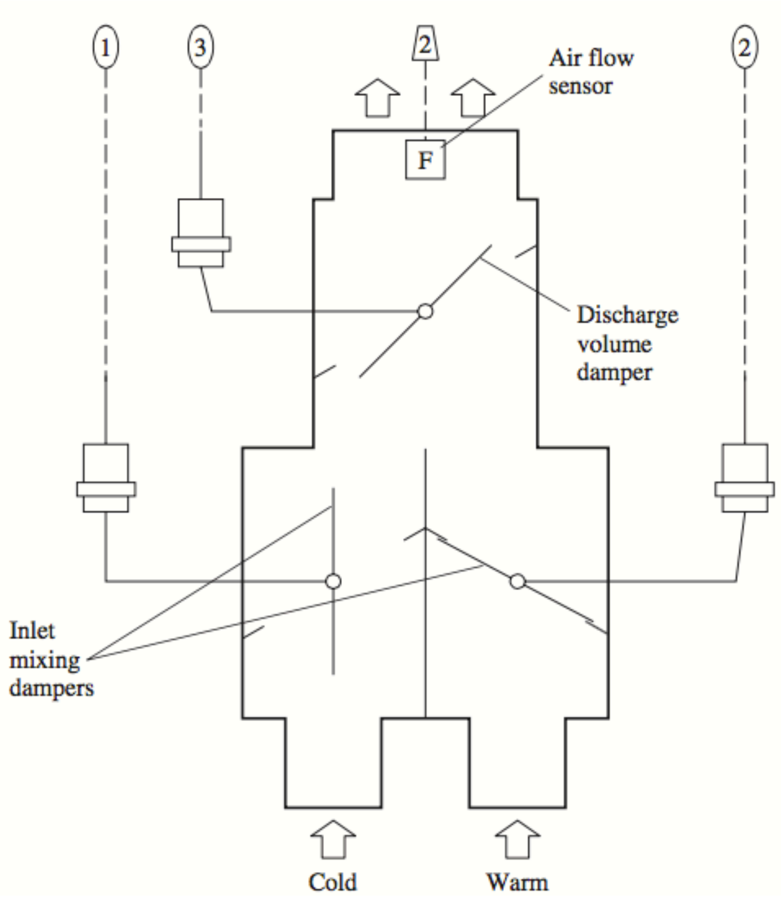
- <u>Different</u> <u>airflow rate</u> delivered to each room



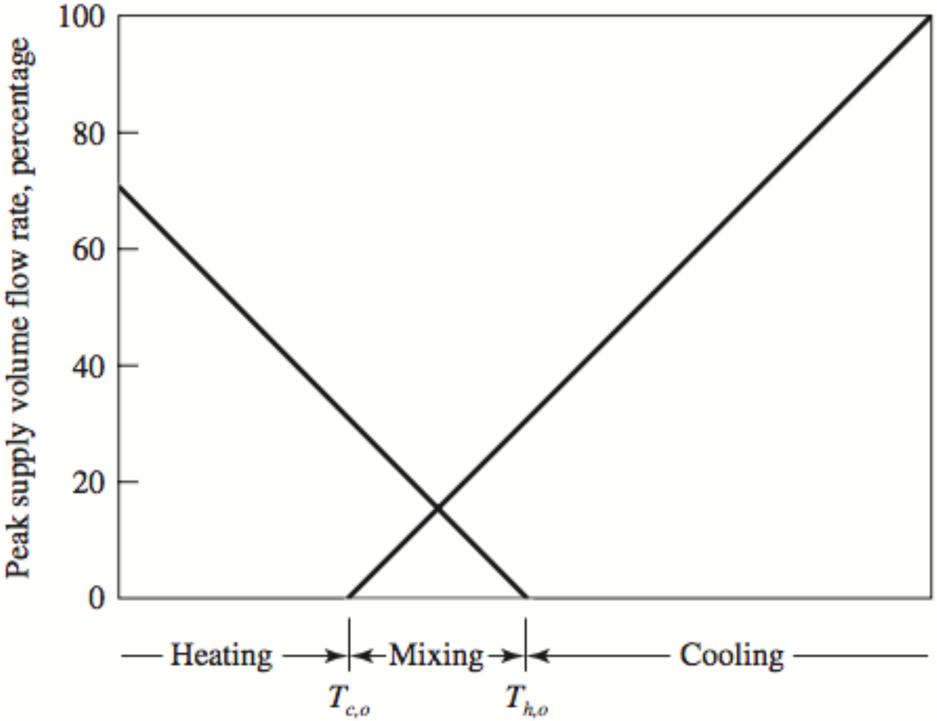
"VAV box"

Fig. 10 Variable-Air-Volume System with Reheat and Induction and Fan-Powered Devices

Typical variable air volume (VAV) system



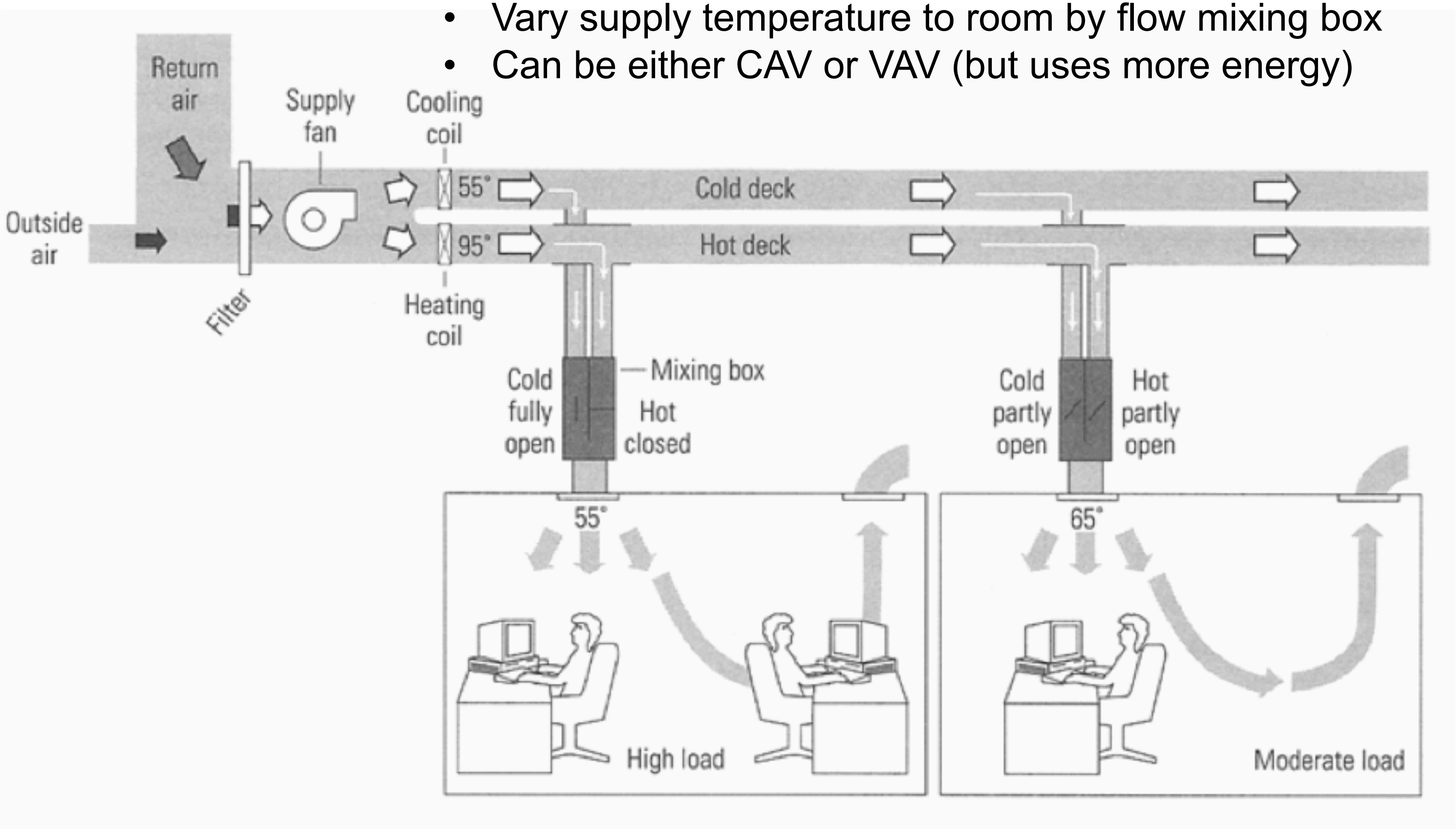
VAV box



Typical dual duct (DD) system (older systems)

1 hot deck and 1 cold deck

- Vary supply temperature to room by flow mixing box
- Can be either CAV or VAV (but uses more energy)



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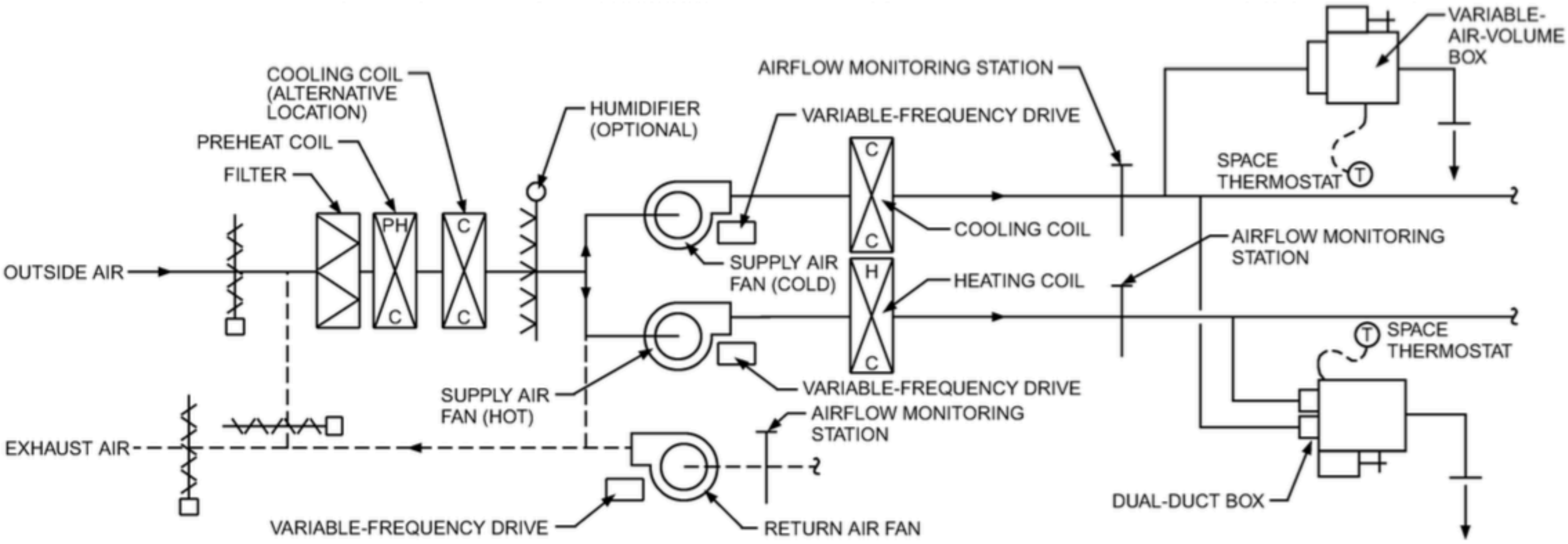
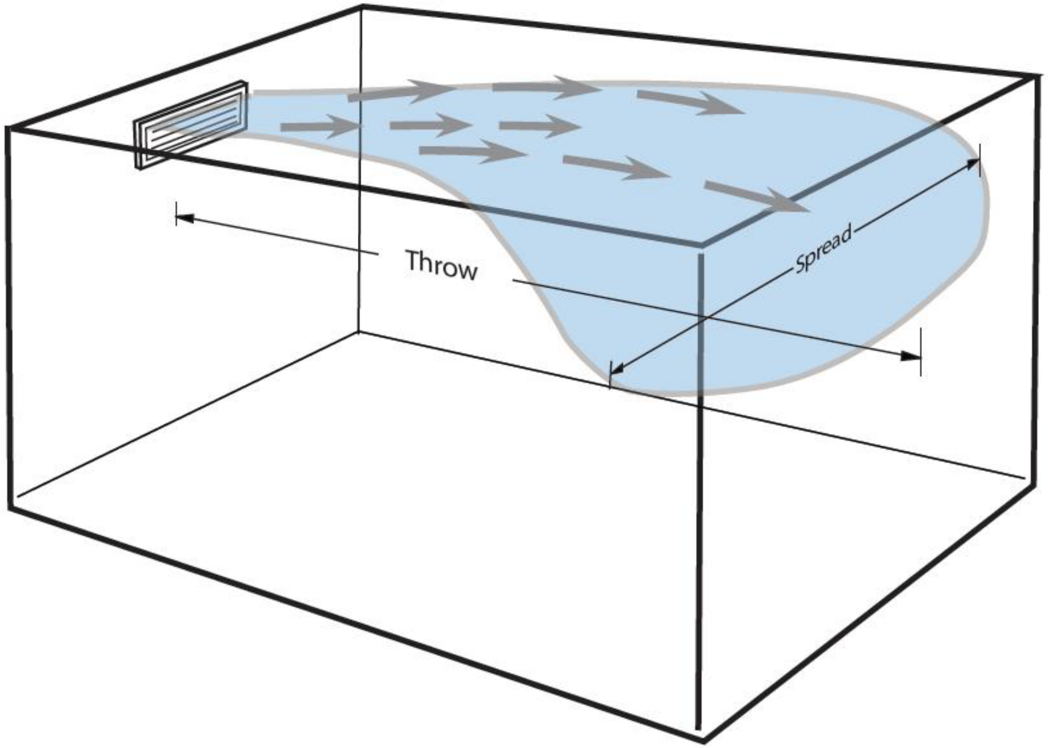
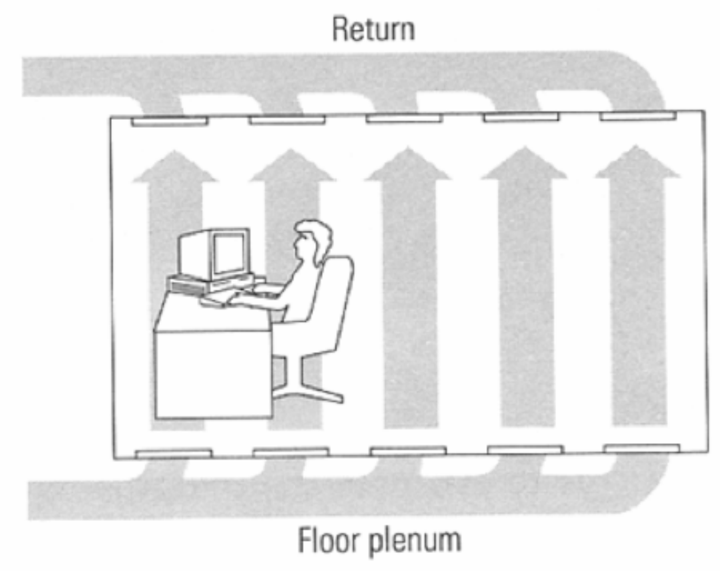


Fig. 12 Dual-Fan, Dual-Duct System

Air supply and diffusers

- Mixed versus displacement ventilation
- Diffuser selection





Air supply and diffusers

- Mixed versus displacement ventilation
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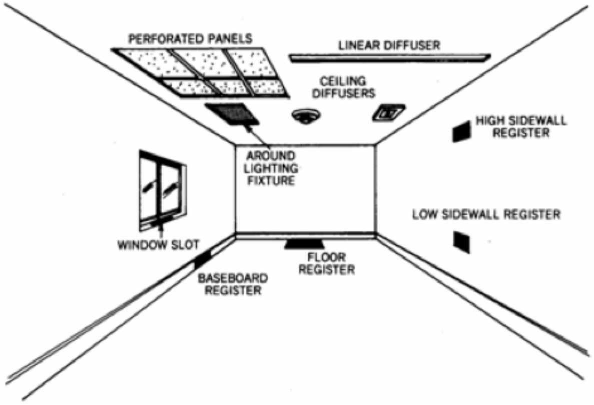
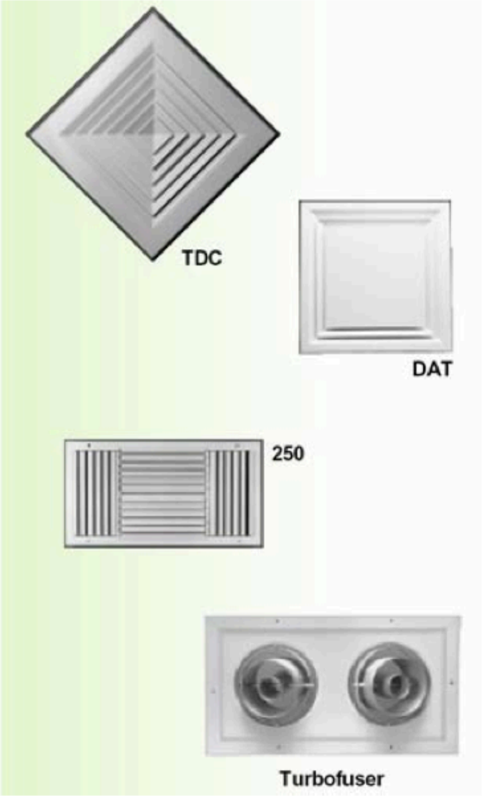
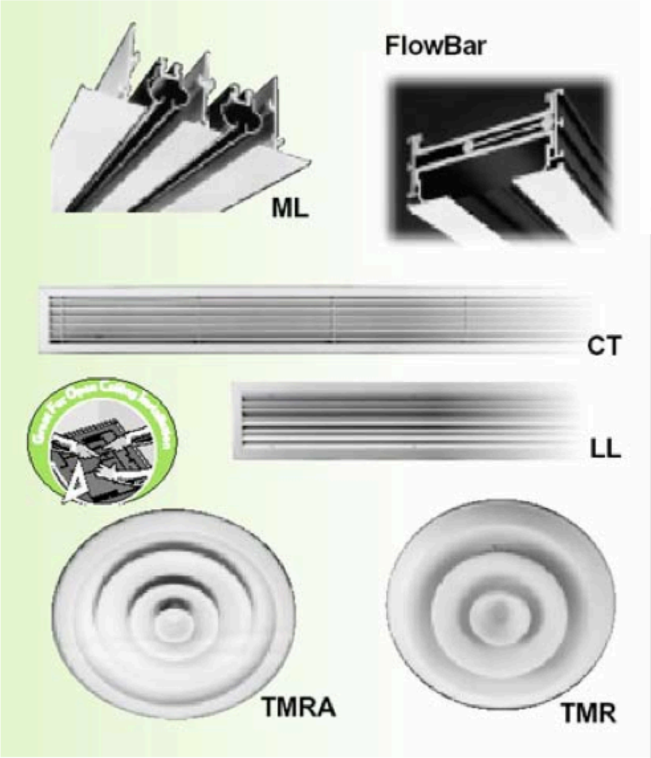
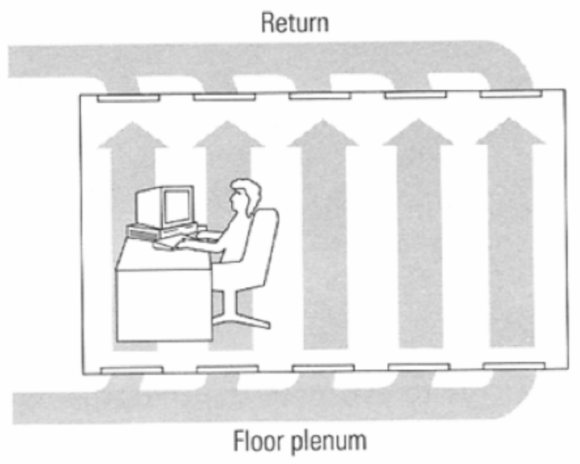






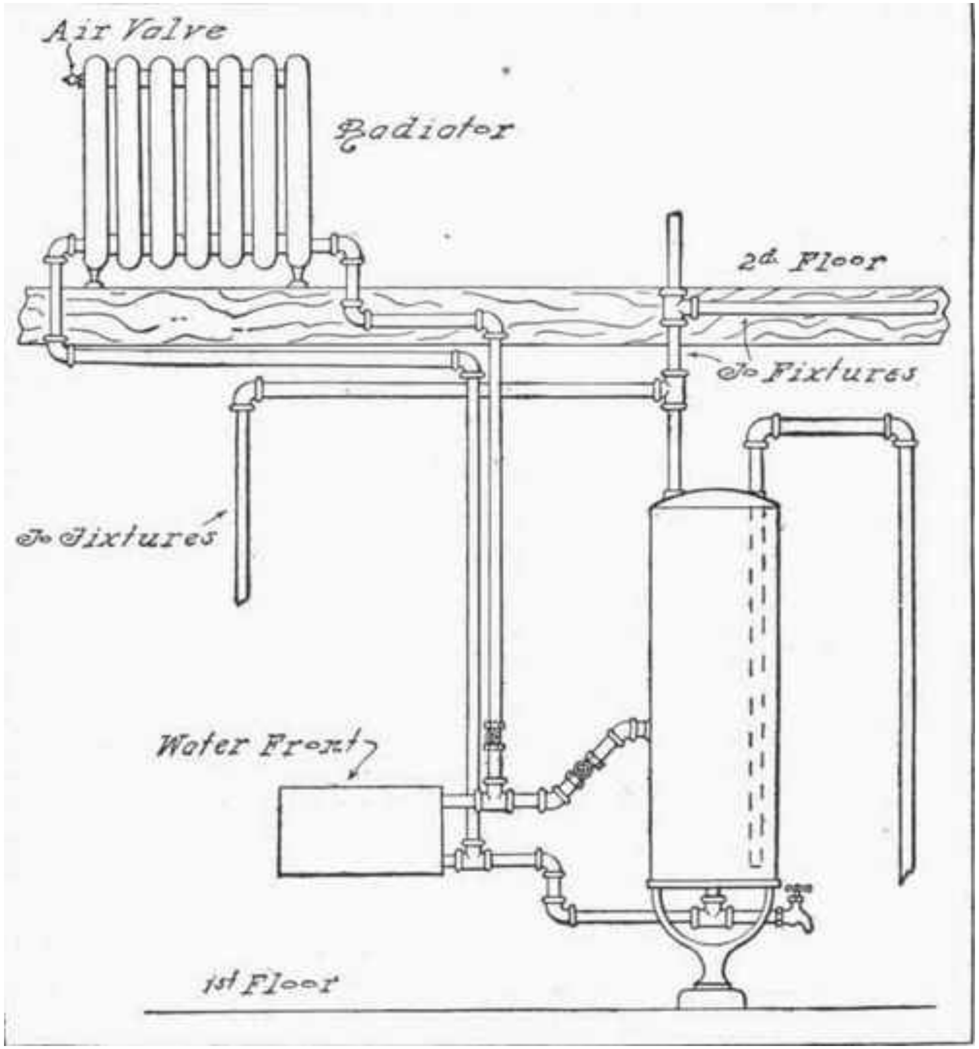


Air + water systems

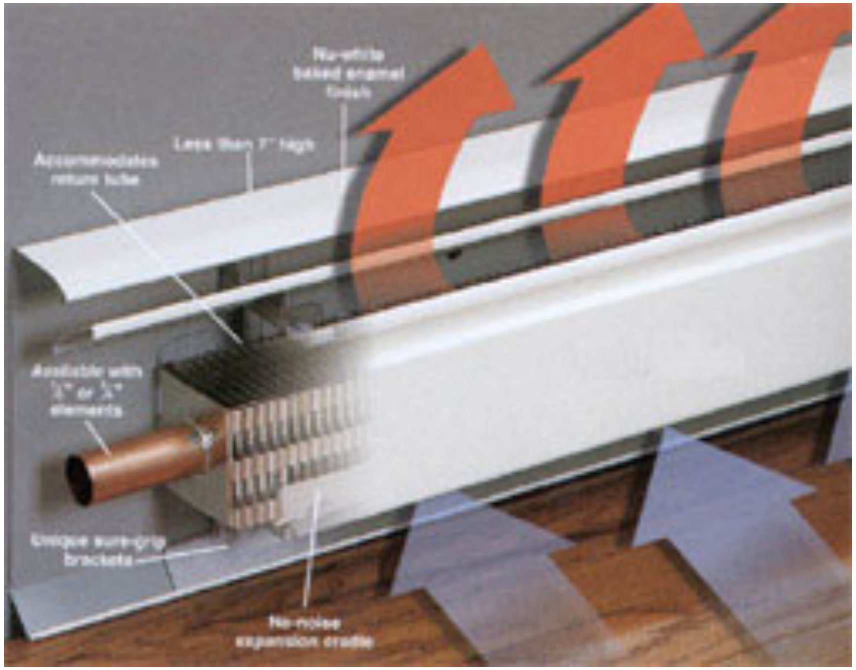
- Many commercial buildings use a combination of conditioned air and zone water coils
- Ventilation requires air movement
- But zone heating and cooling loads can be met with coils
  - We mostly use fan coils now
  - We previously mostly used radiators (like in Alumni Hall)

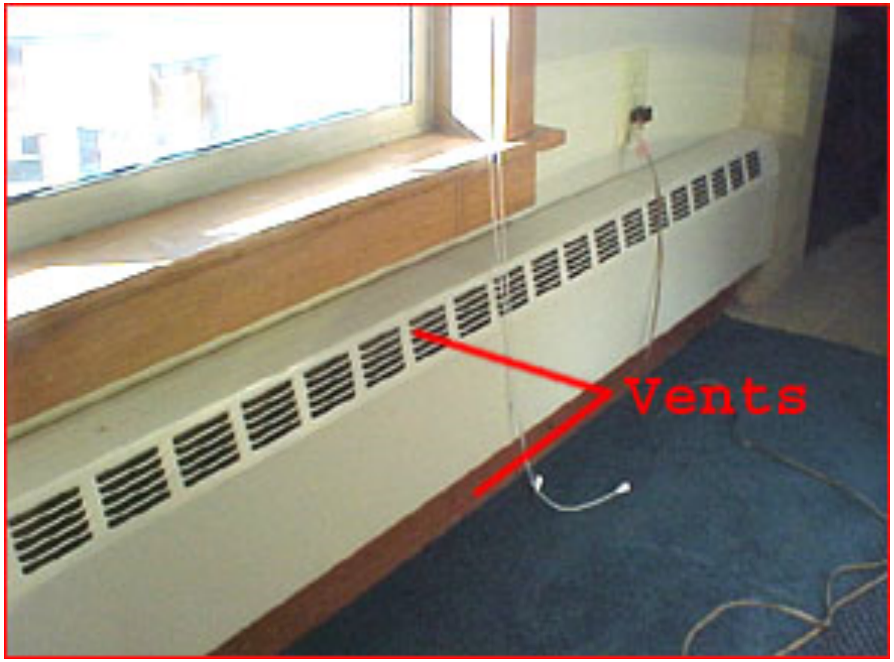
Radiator systems (for heating)

What modes of heat transfer are involved?



Water-based baseboard systems (heating)





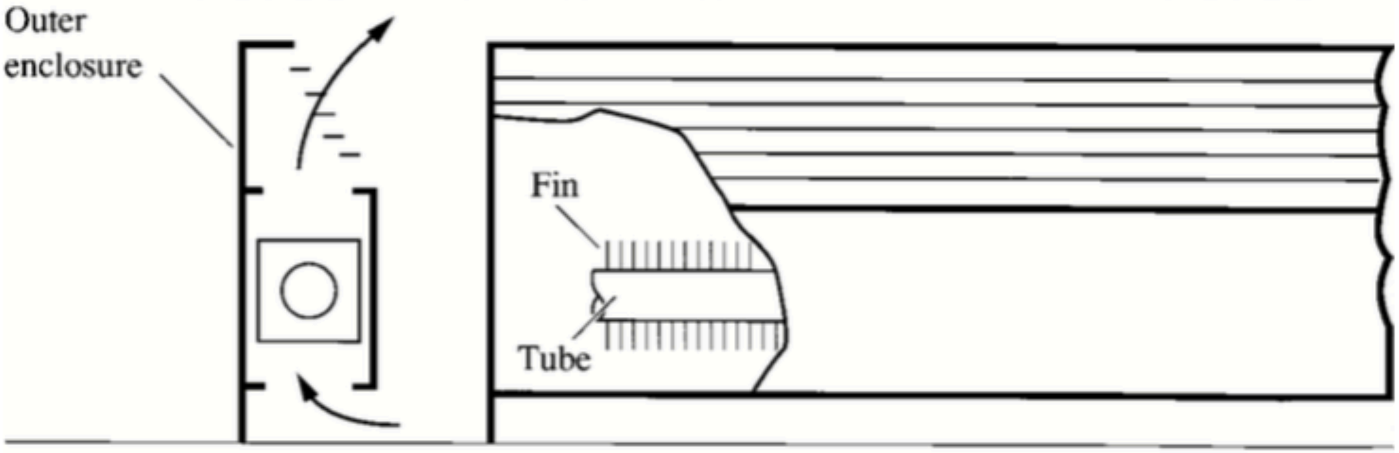


FIGURE 8.8 Baseboard finned-tube heater.

Water-based baseboard systems (heating)

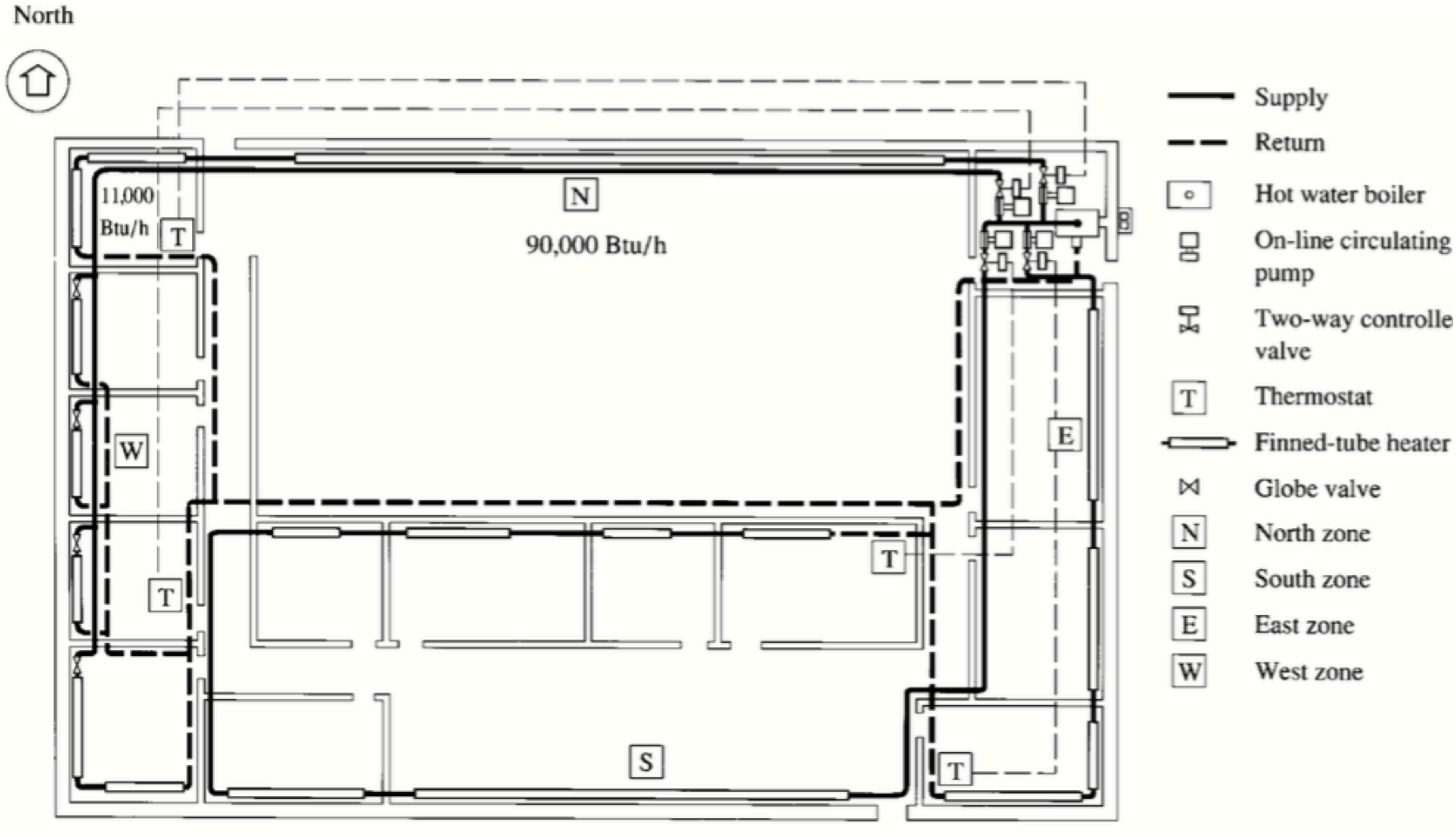
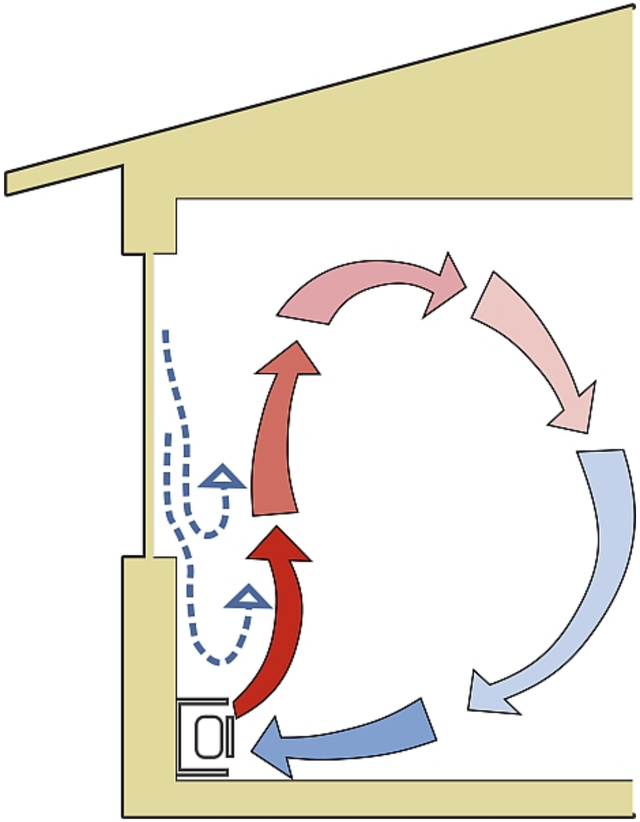
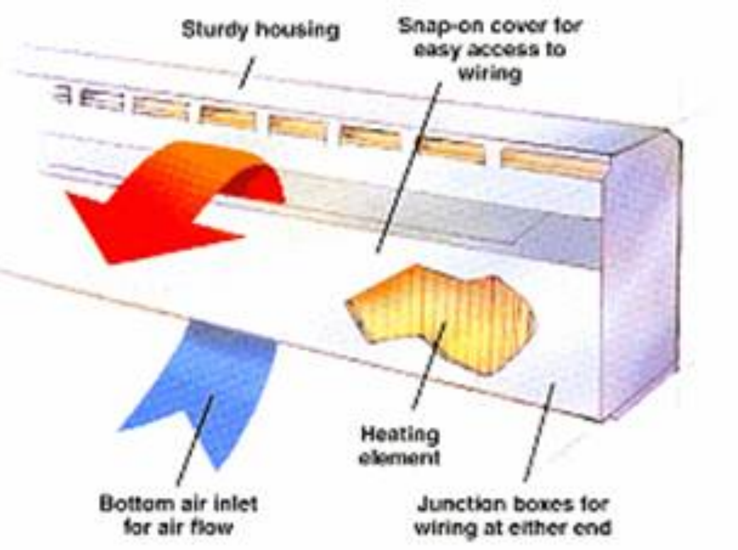


FIGURE 8.7 A two-pipe individual-loop low-temperature hot water heating system for a factory.

Electric baseboard systems (for **heating**)





Fan coils: Modern radiator replacement w/ fan

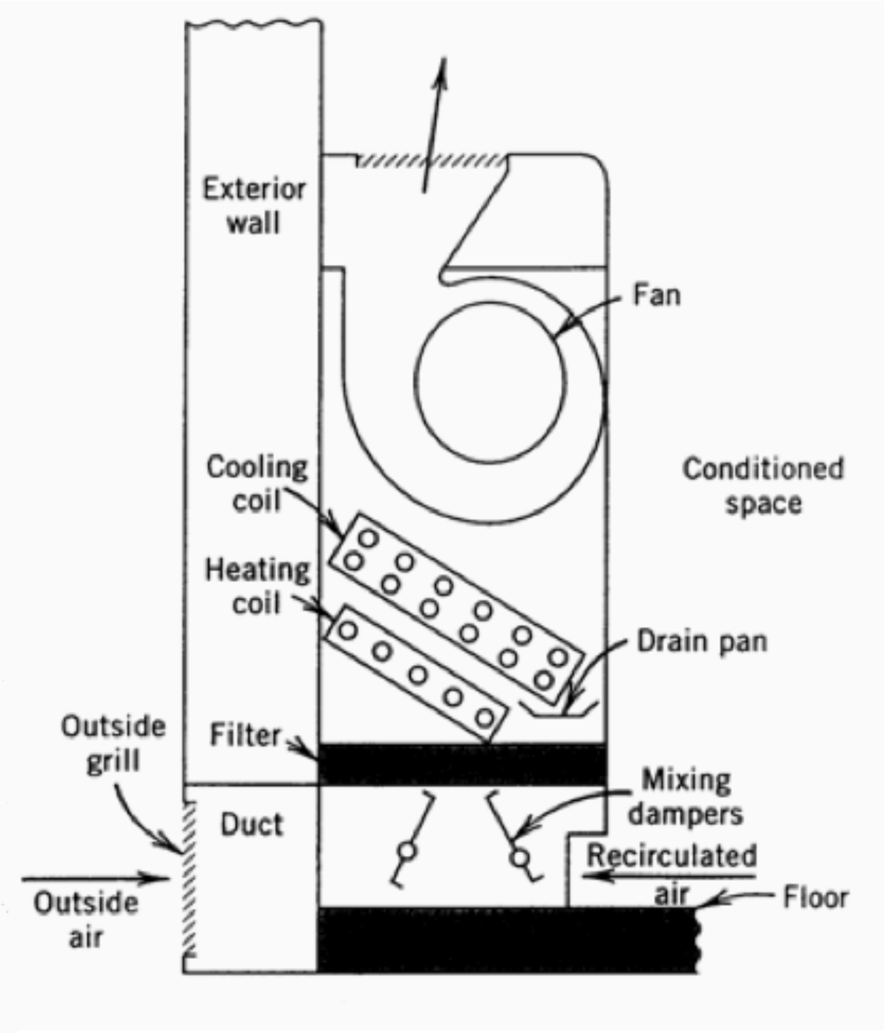
Combines air and water

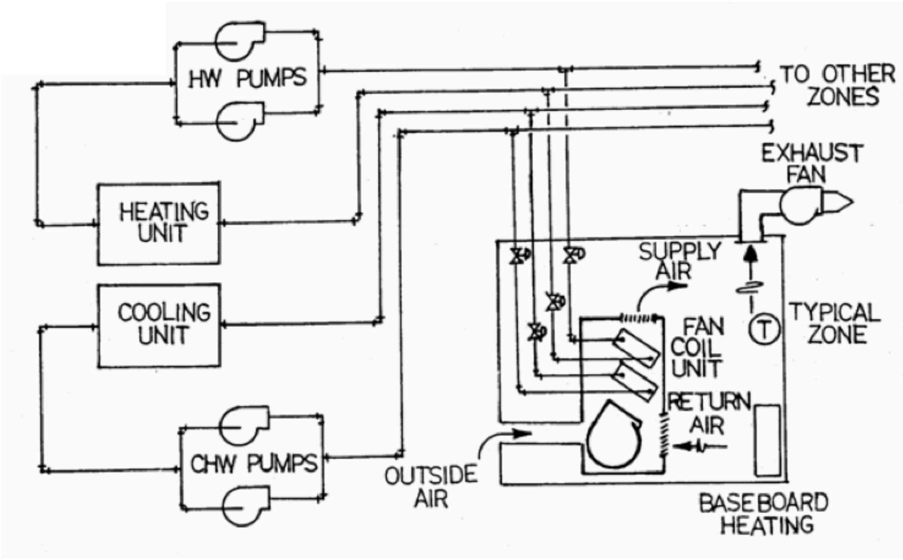
Wall installation

Overhead/ceiling installation

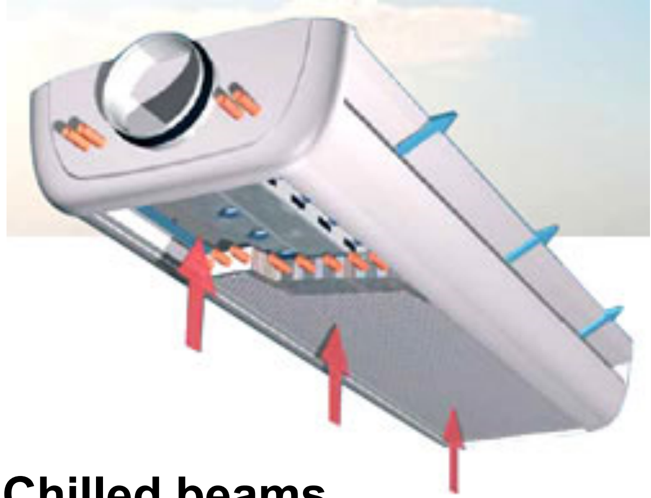
Fan coils: Modern radiator replacement w/ fan

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





Other: Chilled beams and radiant panels



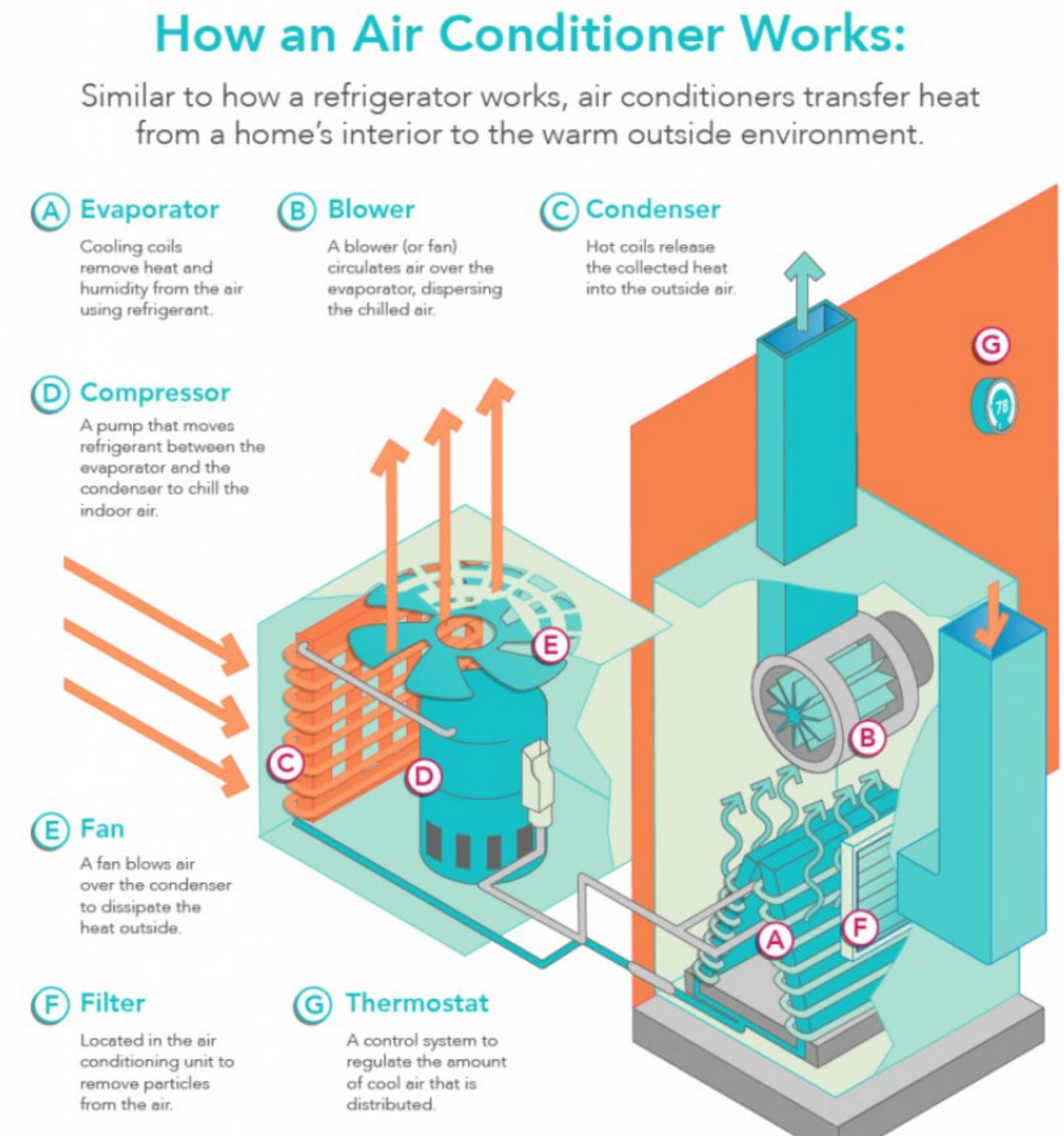
Chilled beams

Radiant panels

HVAC SYSTEMS

How do they actually work?

Typical central residential system



How an Air Conditioner Works:

Similar to how a refrigerator works, air conditioners transfer heat from a home's interior to the warm outside environment.

Ⓐ Evaporator

Cooling coils remove heat and humidity from the air using refrigerant.

Ⓑ Blower

A blower (or fan) circulates air over the evaporator, dispersing the chilled air.

Ⓒ Condenser

Hot coils release the collected heat into the outside air.

Ⓓ Compressor

A pump that moves refrigerant between the evaporator and the condenser to chill the indoor air.

Ⓔ Fan

A fan blows air over the condenser to dissipate the heat outside.

Ⓕ Filter

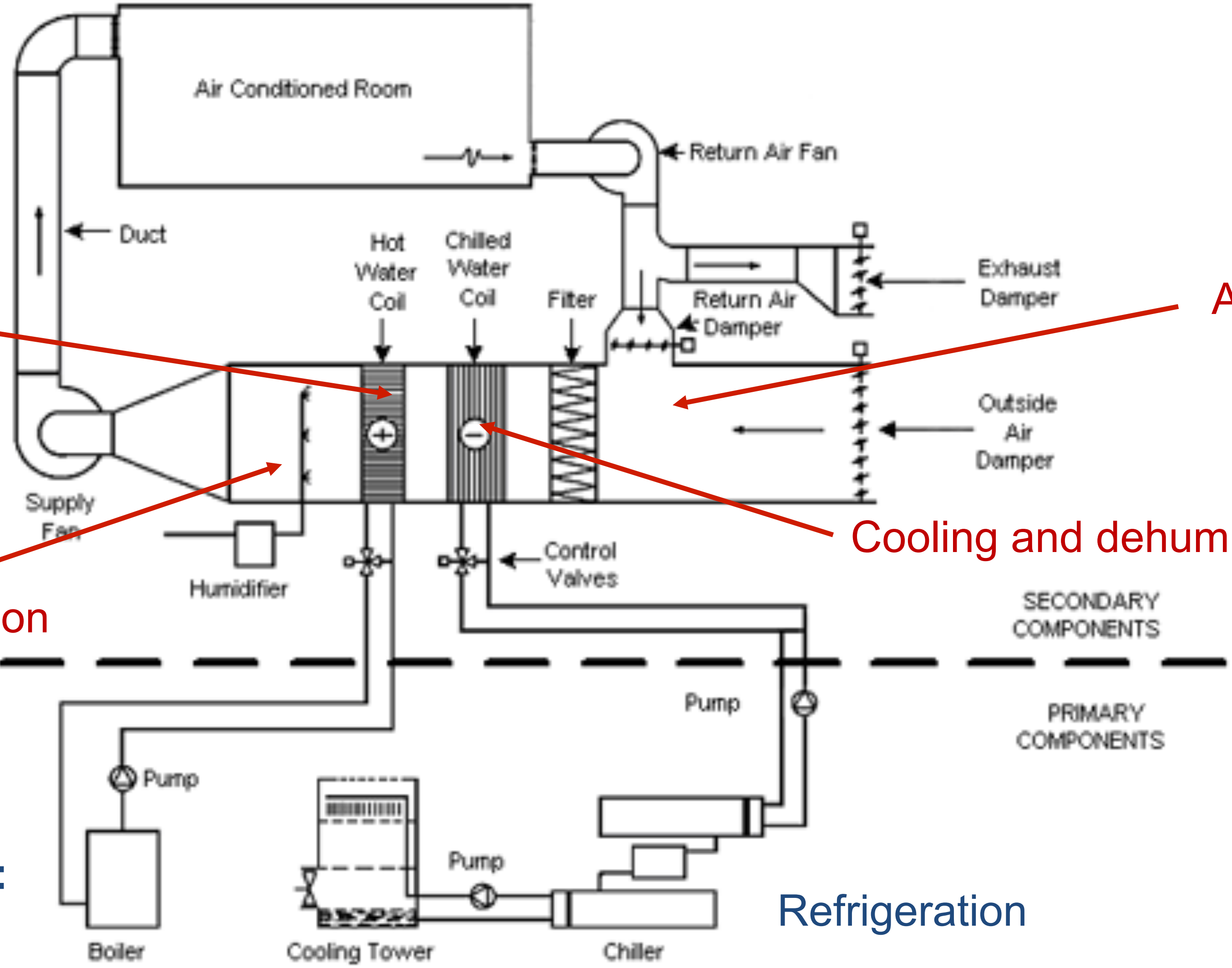
Located in the air conditioning unit to remove particles from the air.

Ⓖ Thermostat

A control system to regulate the amount of cool air that is distributed.

Primary and secondary components of HVAC systems

Some common psychrometric processes:



Heating

Air mixing

Cooling and dehumidification

Humidification

Common primary processes:

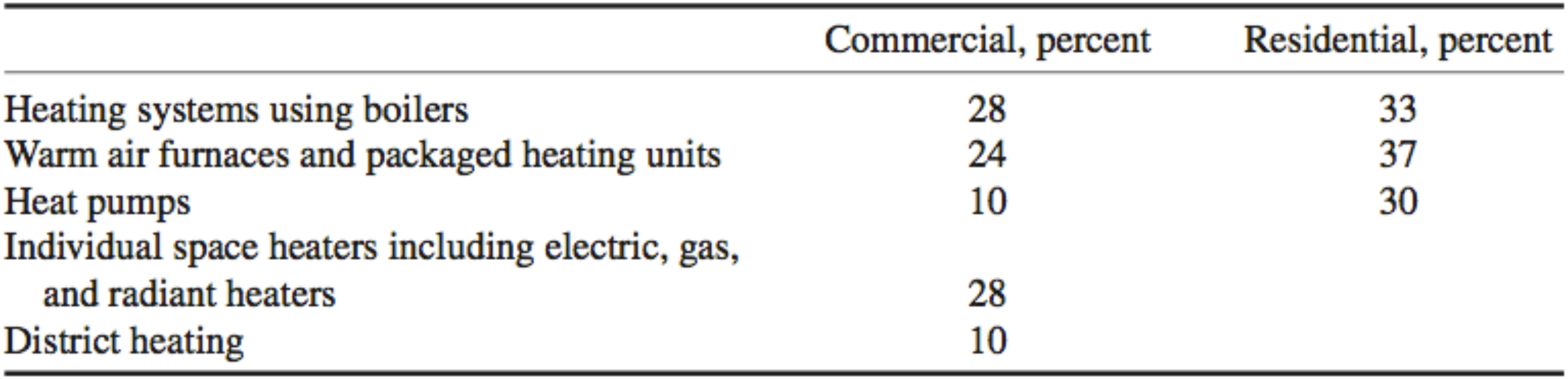
Refrigeration

Heat generation

Heating systems

- Heating systems are pretty straightforward
  - Add energy to heat a medium (e.g., air or water)

- Heating systems vary by building type:



	Commercial, percent	Residential, percent
Heating systems using boilers	28	33
Warm air furnaces and packaged heating units	24	37
Heat pumps	10	30
Individual space heaters including electric, gas, and radiant heaters	28	
District heating	10	

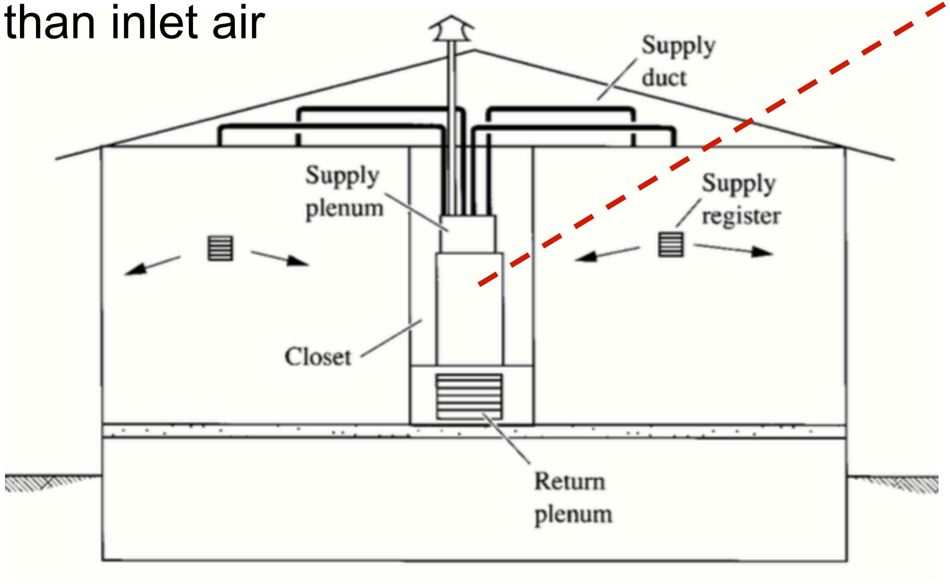
Wang Chapter 8

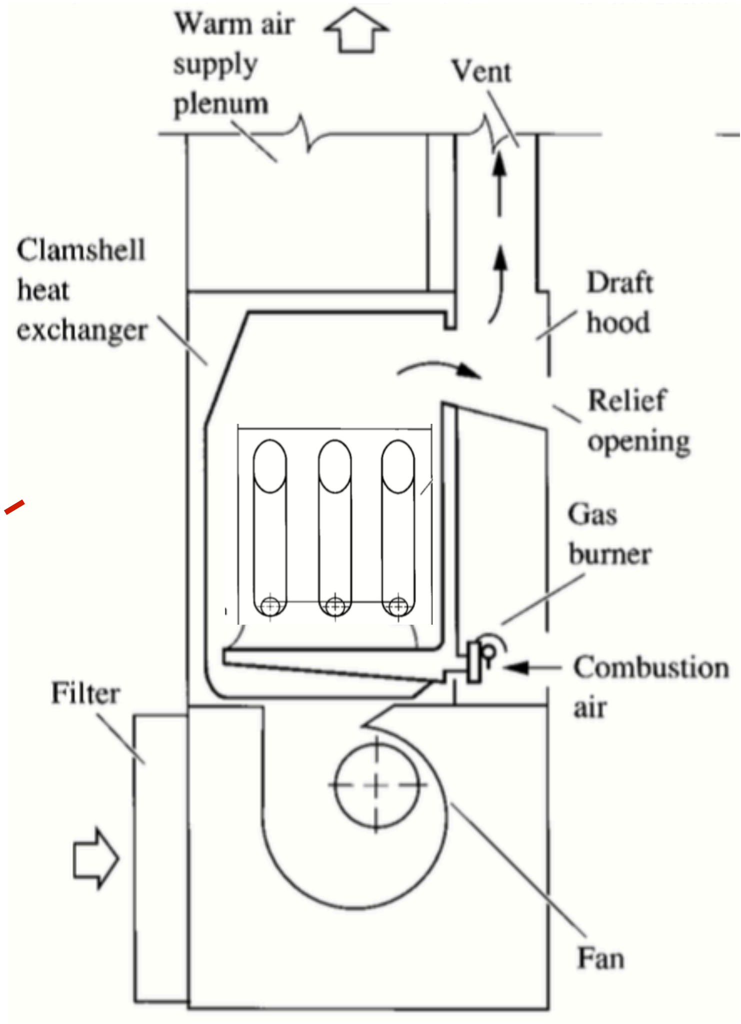
Heating systems: Warm air furnaces

Warm air furnace

– Gas or oil is directly fired (combustion) to heat air passing through a heat exchanger (or air is directly heated by electric resistance elements)

– Most common fuel: Natural gas
  - Capacities up to 175,000 BTU/hr are typical
  - Exit air is typically 50-80°F (28-45°C) higher than inlet air





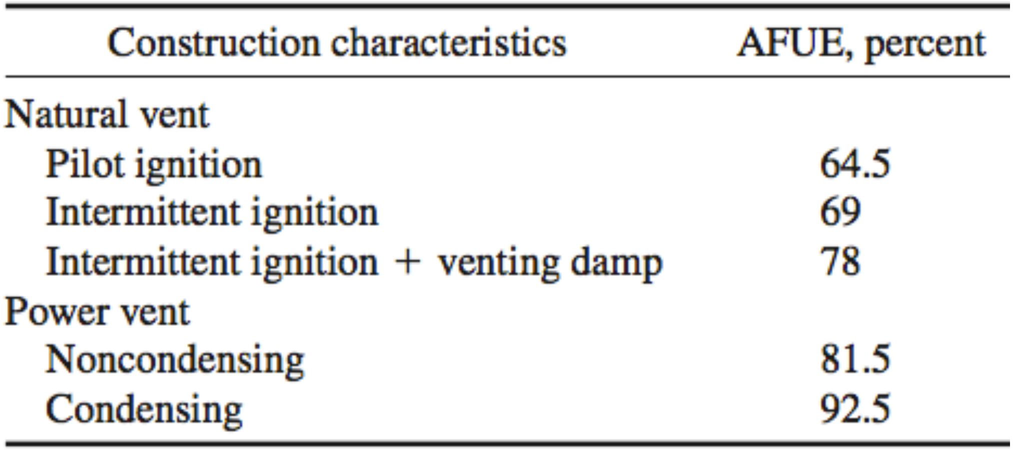
Heating systems: Warm air furnaces

- **Thermal efficiency, E_t**
  - Ratio of energy output of the fluid (air or water) to the fuel energy input

$$E_t = \frac{100\,(\text{fluid energy output})}{\text{fuel energy input}}$$

- **Annual fuel utilization efficiency, AFUE**
  - Ratio of *annual* energy output of the fluid (air or water) to the *annual* fuel energy input (accounts for non-heating season pilot losses)

$$\text{AFUE} = \frac{100\,(\text{annual output energy})}{\text{annual input energy}}$$



Construction characteristics	AFUE, percent
Natural vent	
Pilot ignition	64.5
Intermittent ignition	69
Intermittent ignition + venting damp	78
Power vent	
Noncondensing	81.5
Condensing	92.5

Heating systems: Hot water boilers

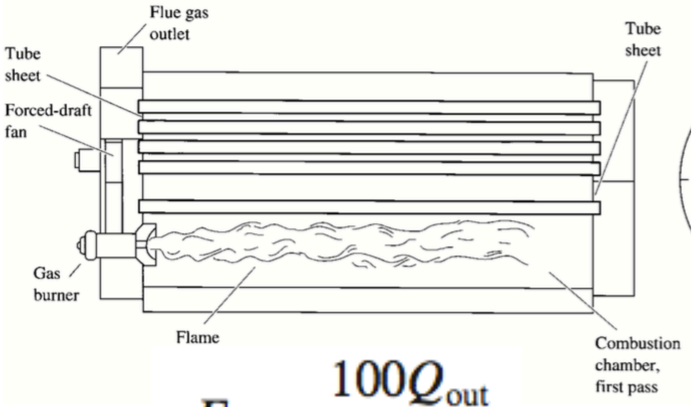
Hot water boiler

- Enclosed pressure vessel in which water is heated to a required temperature and pressure without evaporation
- Most common fuel: Natural gas
  - Capacities up to 50,000 MBTU/hr are typical

Gas-fired boilers	71 percent
Oil-fired boilers	15 percent
Electric boilers	11 percent
Others	2 percent

- Low pressure boilers
  - Working pressure up to 160 psig (1.1 MPa)
  - Working temperature up to 250°F (121°C)
    - Common for low temperature water (e.g., single buildings)
- High pressure boilers
  - Higher temperature and higher pressure (e.g., 300-400°F (150-205°C)
    - Common for large building complexes and campuses

“Fire-tube” boiler



$$E_c = \frac{100Q_{\text{out}}}{Q_{\text{fuel}}}$$

Wang Chapter 8

Cooling: Refrigeration systems

- **Refrigeration** is the process of extracting heat from a lower temperature heat source, substance, or cooling medium, and transferring it to a higher temperature heat sink
  - Refrigeration maintains the temperature of the heat source below that of its surroundings while transferring the extracted heat, and any required energy input, to a heat sink (such as atmospheric air or surface or ground water)

- A **refrigeration system** is a combination of components and equipment connected in a sequential order to produce the refrigeration effect

Types of refrigeration systems

- **Vapor compression systems** (most commonly used)
  - Compressors activate the refrigerant by compressing it to a higher pressure and higher temperature after it has produced its refrigeration effect (high P, high T)
  - The compressed refrigerant transfers its heat energy to the sink (e.g., ambient air) and then is condensed into a liquid
  - The liquid refrigerant is then throttled (i.e., expands) to a low pressure, low temperature vapor (low P, low T) to produce the refrigerating effect during evaporation
  - The refrigeration cycle then repeats itself

Other types of refrigeration systems

- **Absorption systems**
  - The refrigeration effect is produced by thermal energy input
  - After absorbing heat from the cooling medium during evaporation, the vapor refrigerant is absorbed by an absorbent medium
  - The absorbent+refrigerant solution is then heated (by a furnace, waste heat, hot water, or steam), which converts the refrigerant to a vapor again, which then absorbs heat from the medium during evaporation and the cycle repeats
- **Air or gas expansion systems**
  - Air or gas is compressed to a high pressure by mechanical energy
  - It is then expanded to a low pressure
    - Because the temperature of the air or gas drops during expansion, a refrigeration effect is produced

What do these systems all have in common?

Fundamentals of vapor compression systems

Heat of Vaporization

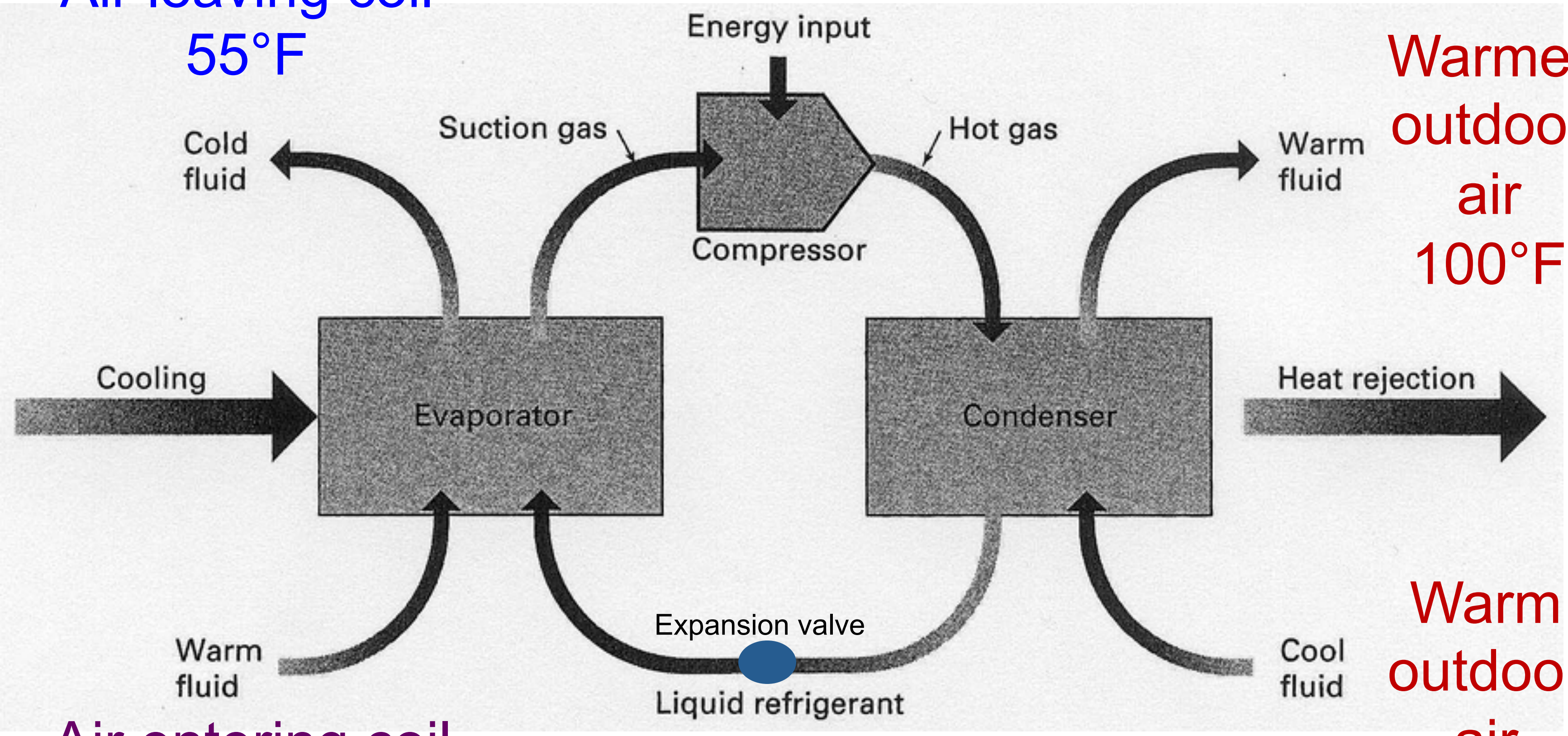
by: Michael Ermann and Clark Coots

https://www.youtube.com/watch?v=2wZb6HgIDE0

Typical vapor compression cycle: Air-conditioning unit

Air leaving coil
55°F

Warmer
outdoor
air
100°F

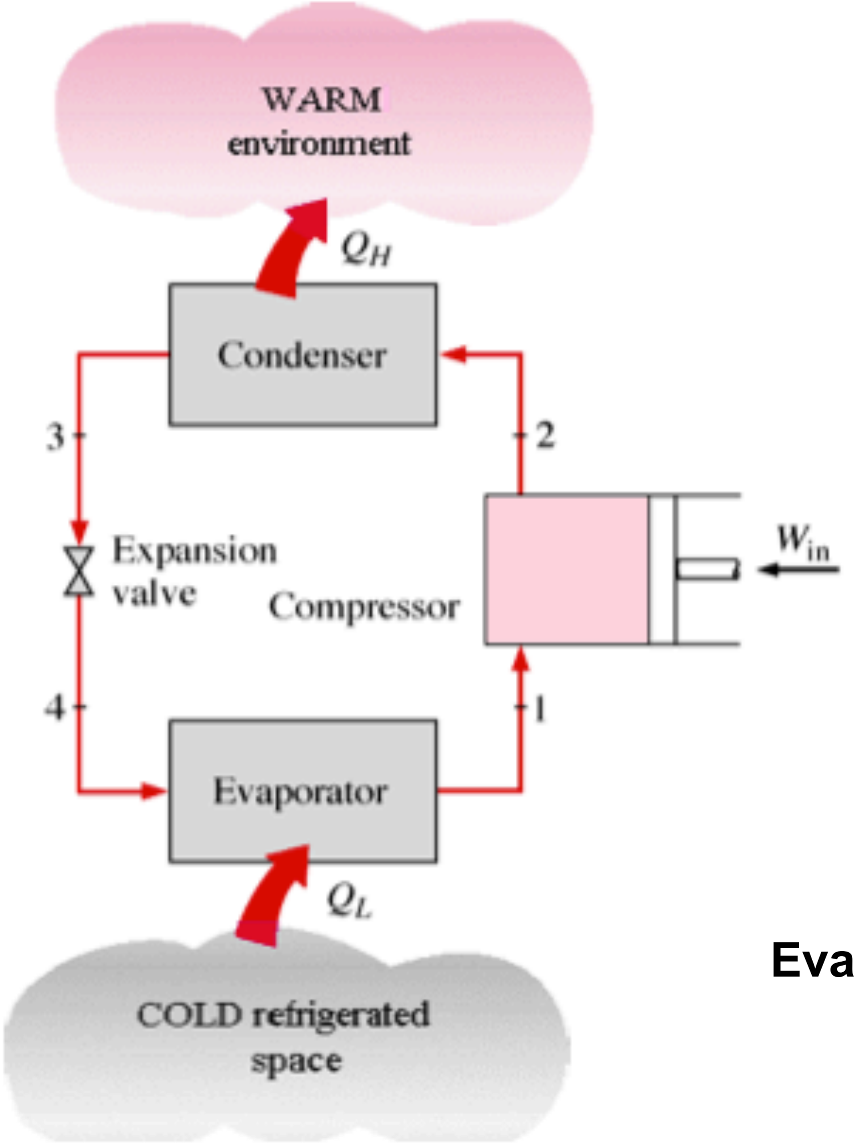


Air entering coil
75°F

Changing refrigerant
T and P

Warm
outdoor
air
90°F

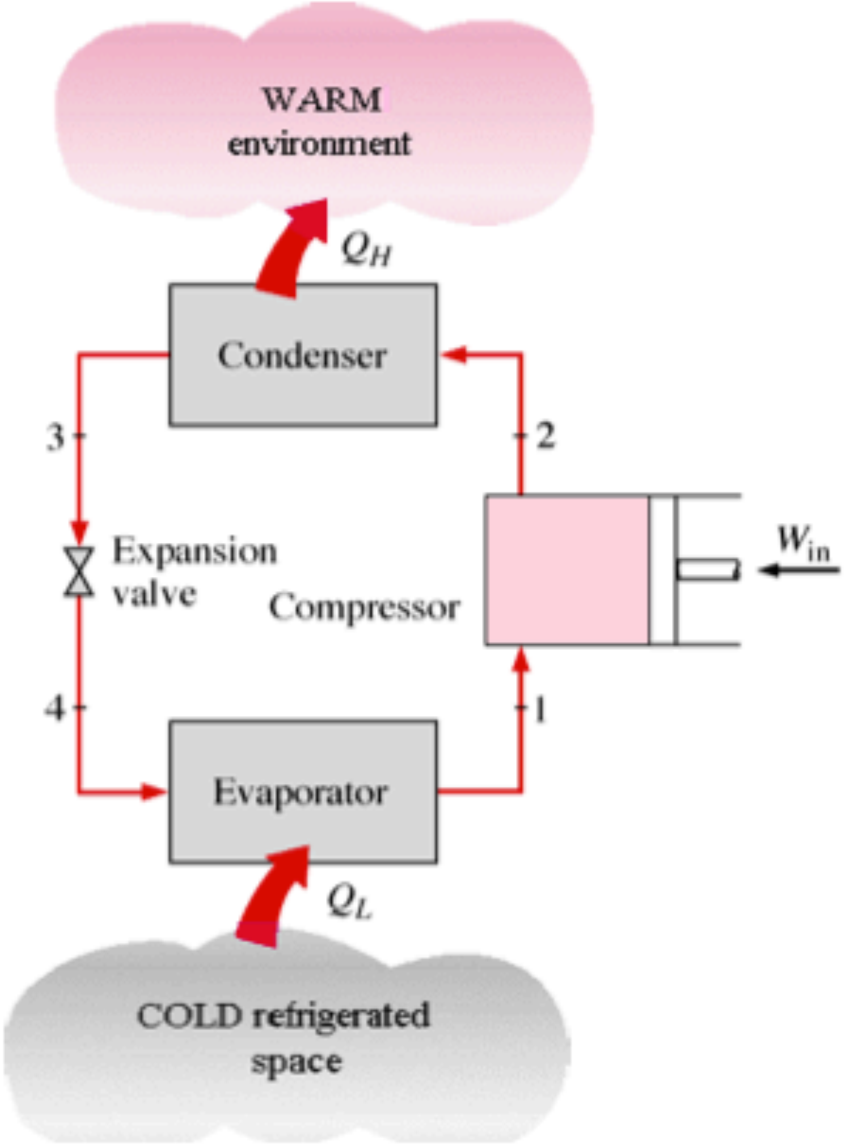
Ideal single-stage vapor compression cycle



Expansion valve
(creates the high P restriction)

Evaporator coil

Ideal single-stage vapor compression cycle

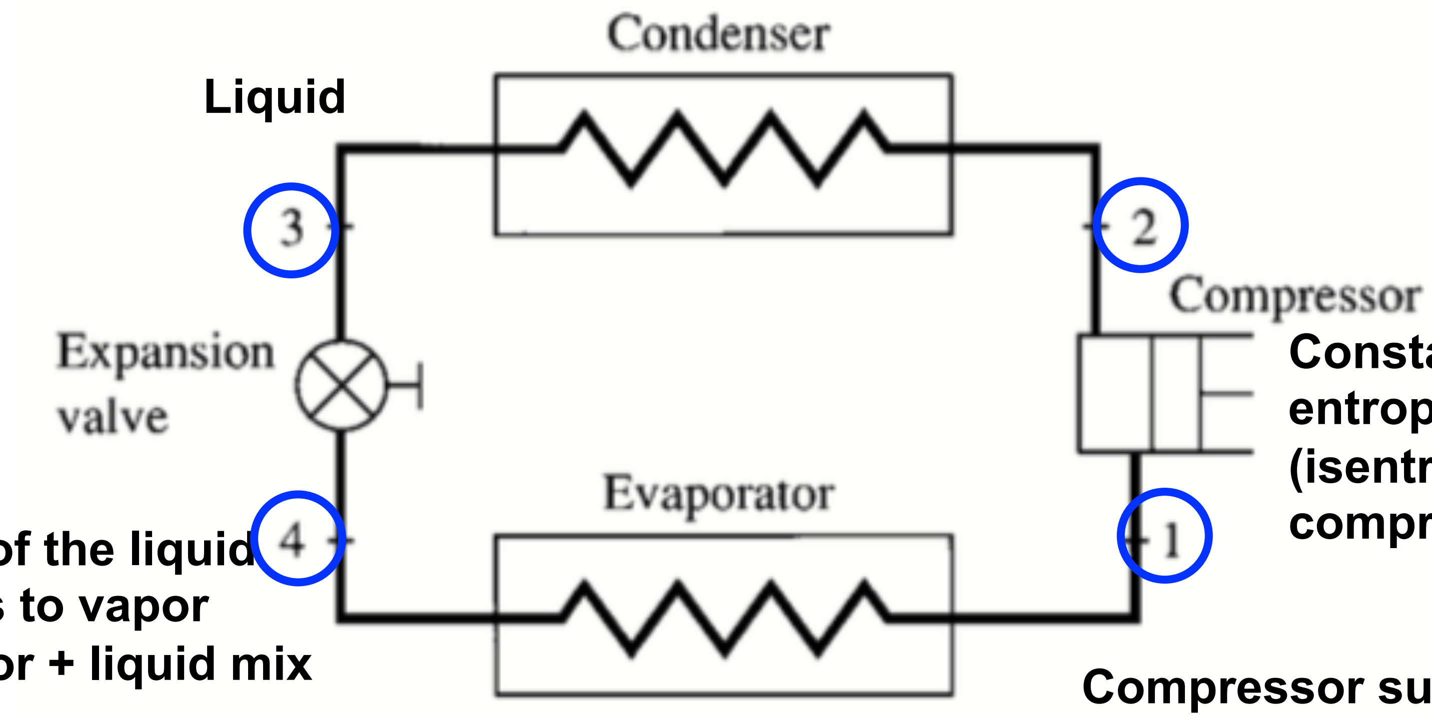


Condenser coil

Compressor

Ideal single-stage vapor compression cycle

Latent heat of condensation
(rejected to heat sink)



Liquid

Constant entropy (isentropic) compression

Some of the liquid flashes to vapor

- Vapor + liquid mix

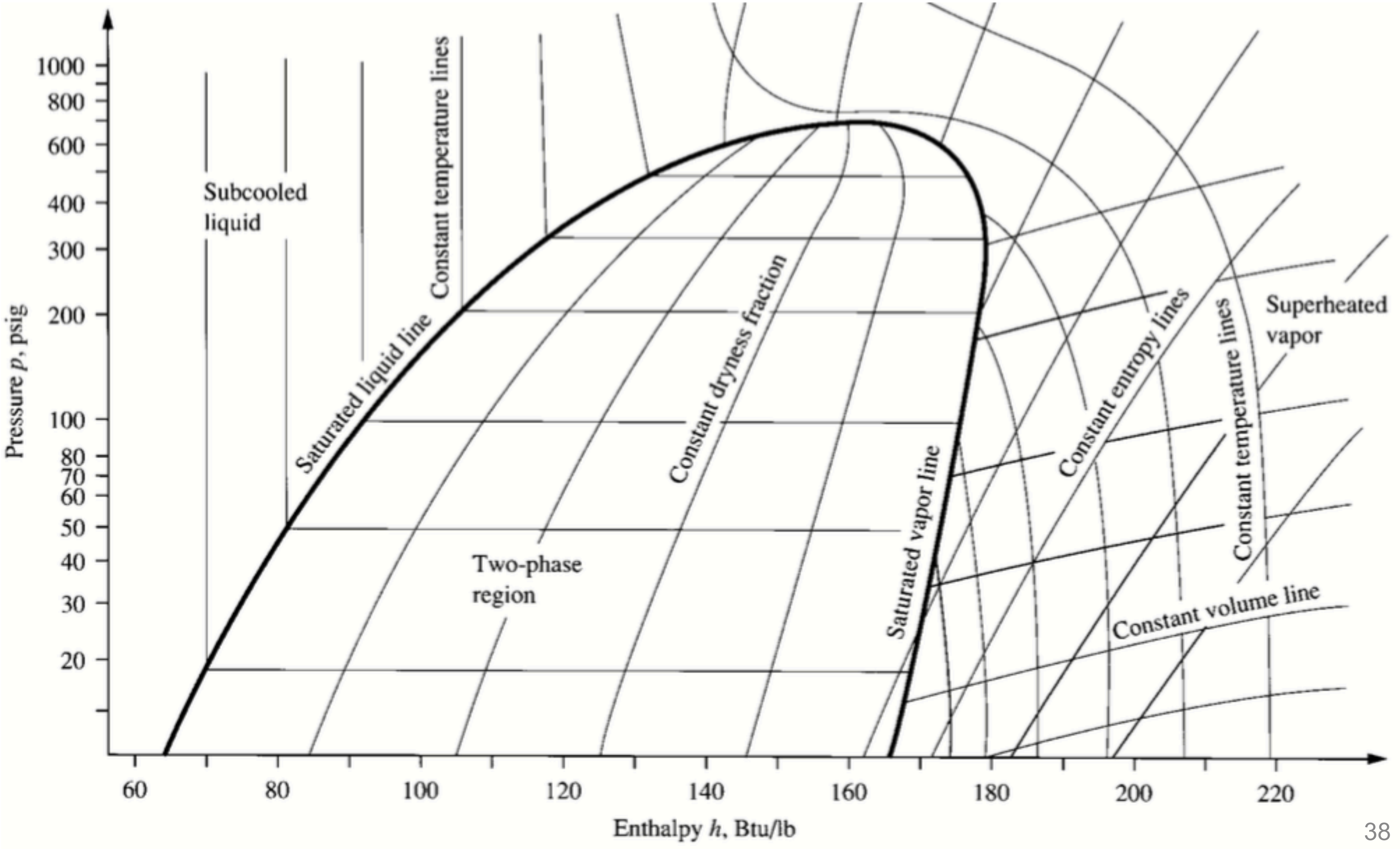
Rest of liquid evaporates at evaporating temperature

Compressor suction

- “suction pressure”

Ideal single-stage vapor compression cycle

Pressure-enthalpy (*p-h*) diagram for a given refrigerant



Ideal single-stage vapor compression cycle

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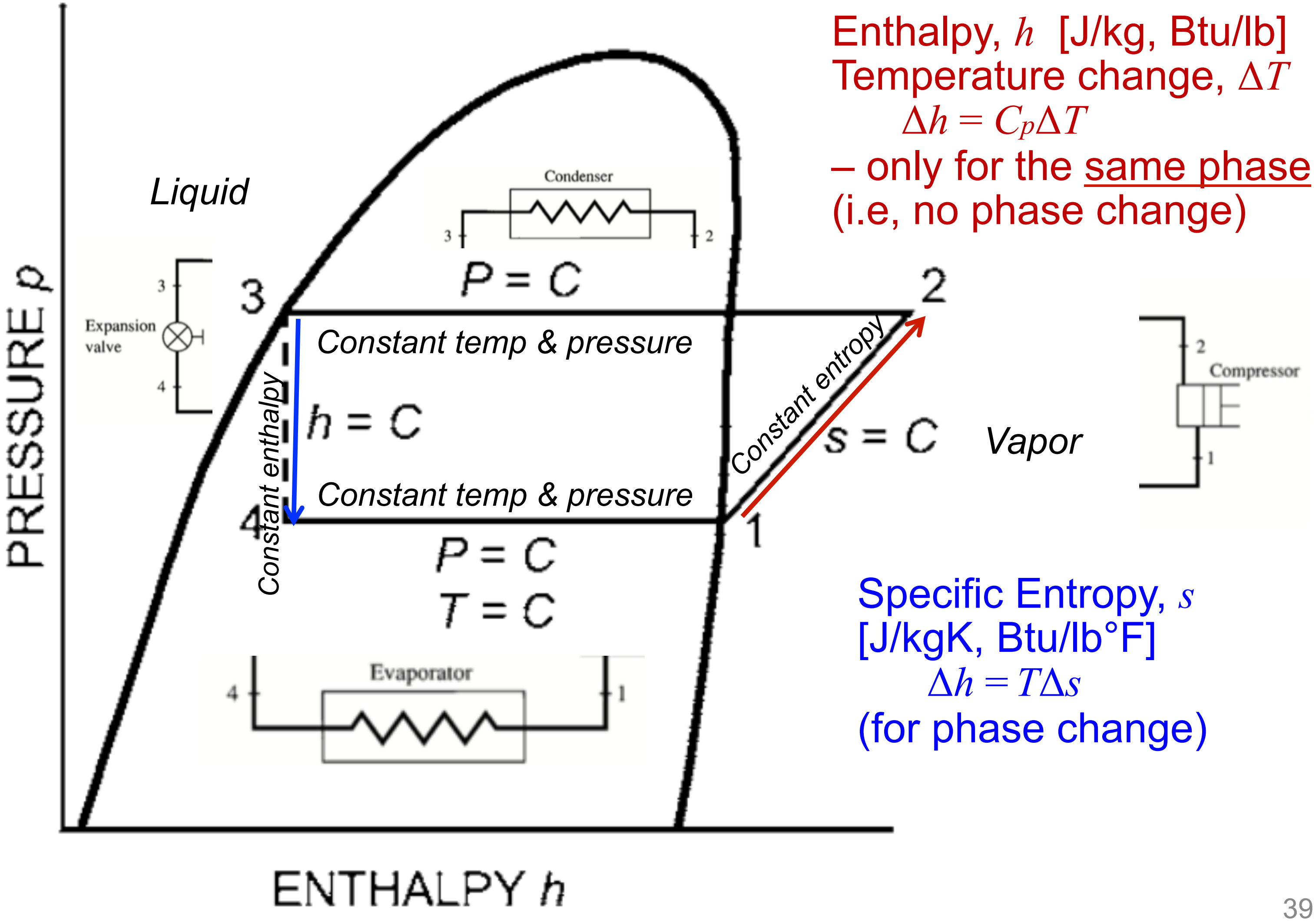


Enthalpy, h [J/kg, Btu/lb]
Temperature change, ΔT

$$\Delta h = C_p \Delta T$$

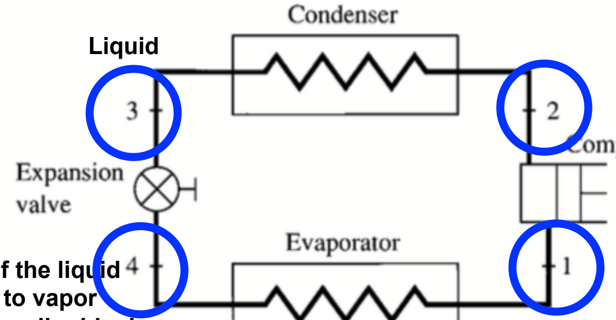
– only for the same phase
(i.e, no phase change)

Specific Entropy, s
[J/kgK, Btu/lb°F]

$$\Delta h = T \Delta s$$

(for phase change)

Ideal single-stage vapor compression cycle



Latent heat of condensation (rejected to heat sink)

Liquid

Constant entropy (isentropic) compression

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- **Vapor + liquid mix**

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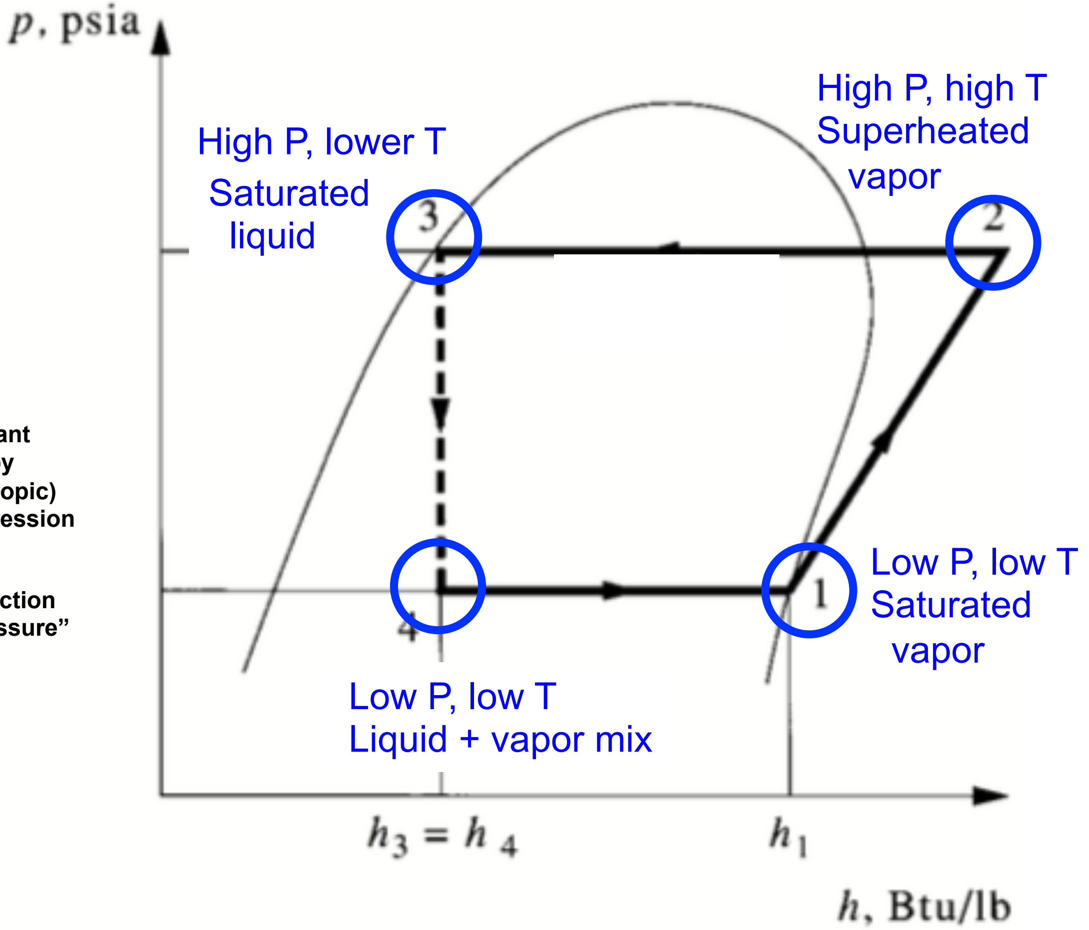
Compressor suction
- **“suction pressure”**

Pressure-enthalpy (*p-h*) diagram



High P, lower T
Saturated liquid

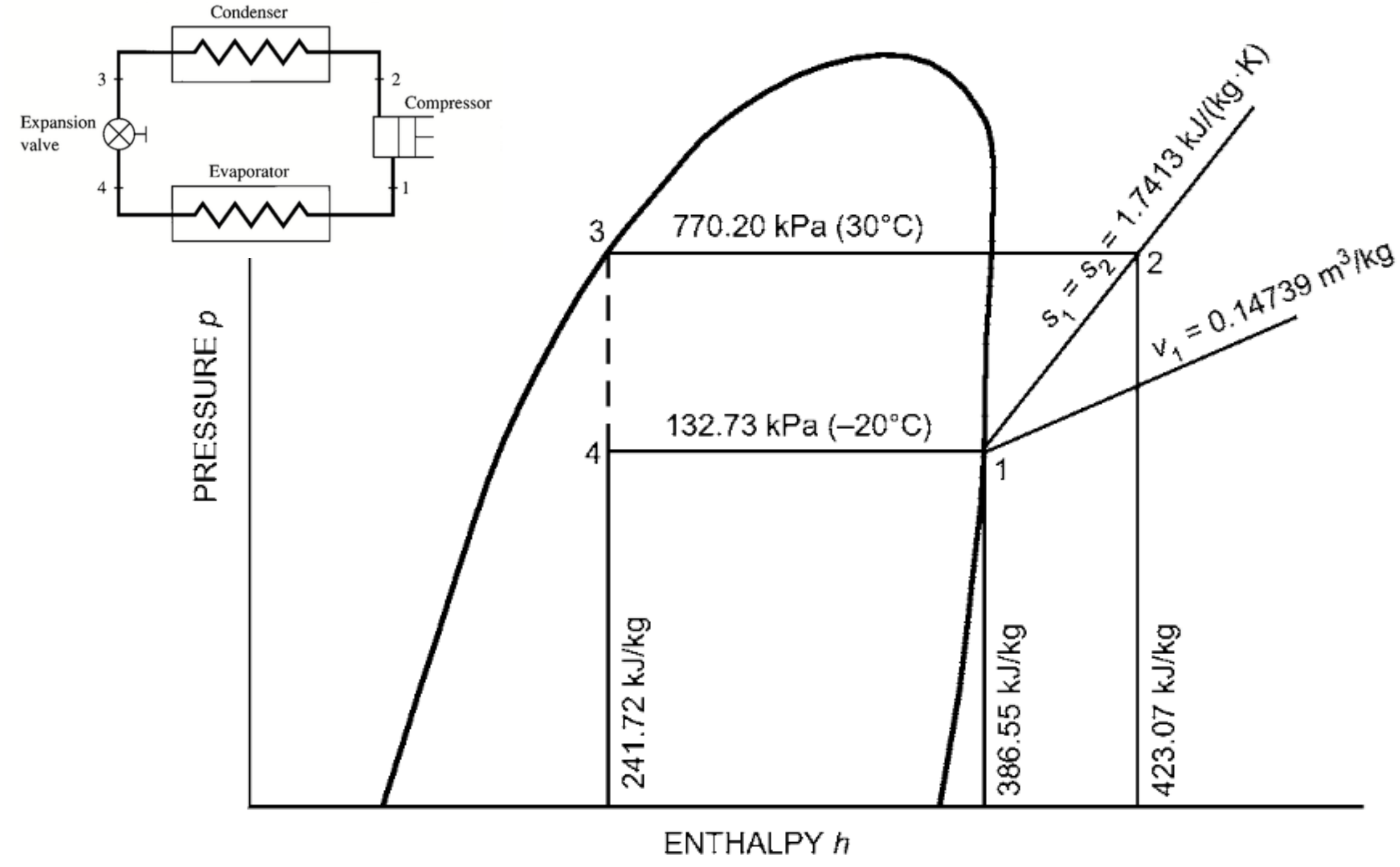
High P, high T
Superheated vapor

Low P, low T
Liquid + vapor mix

Low P, low T
Saturated vapor

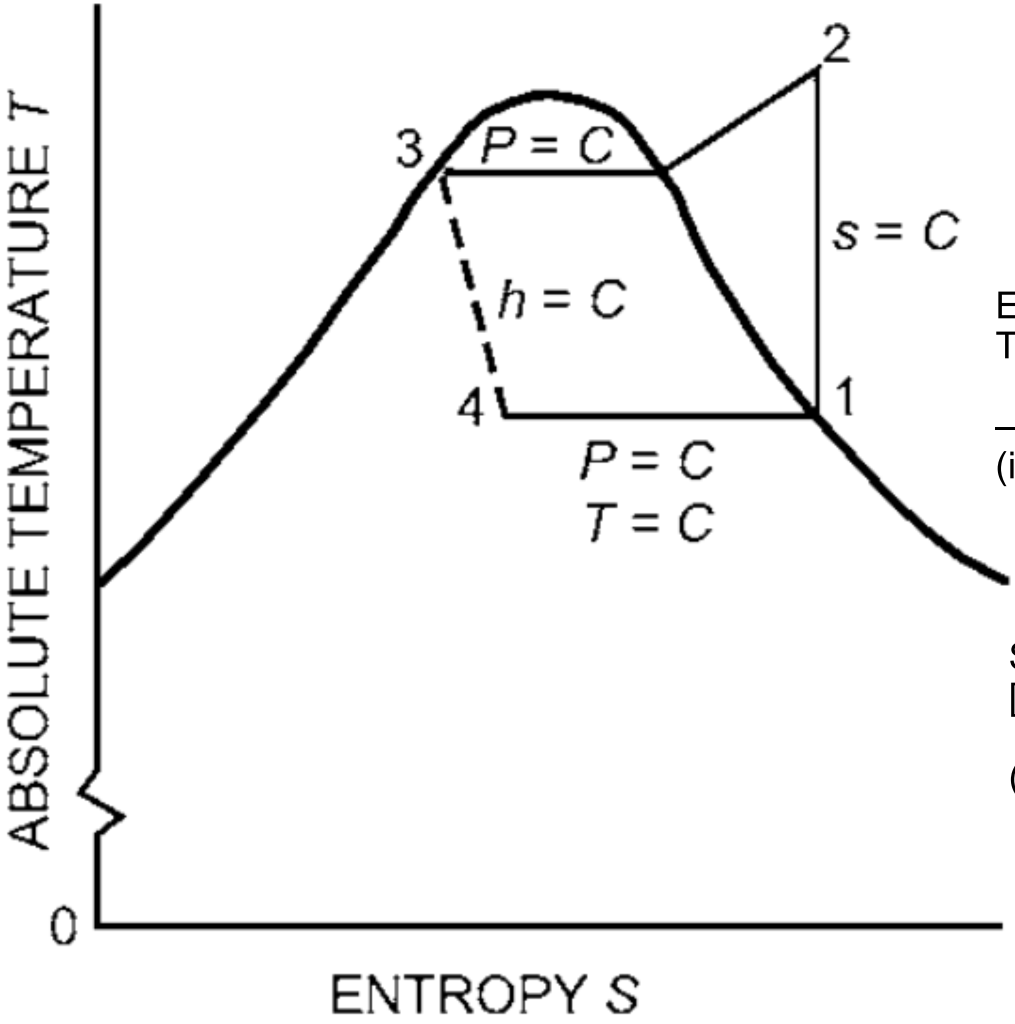
Ideal single-stage vapor compression cycle

Pressure-enthalpy (*p*-*h*) diagram for a given refrigerant



Ideal single-stage vapor compression cycle

Temperature-entropy (*T-s*) diagram for a given refrigerant



Enthalpy, h [J/kg, Btu/lb]
Temperature change, ΔT

$\Delta h = C_p \Delta T$

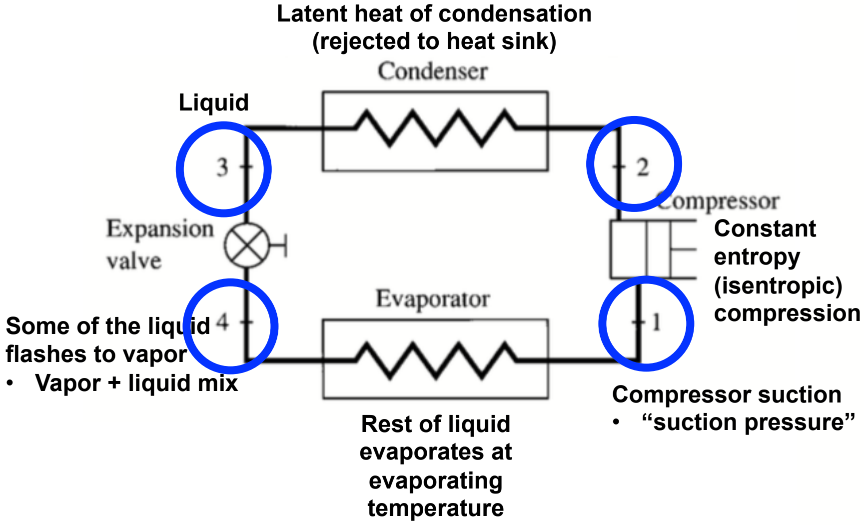
– only for the same phase
(i.e, no phase change)

Specific Entropy, s
[J/kgK, Btu/lb°F]

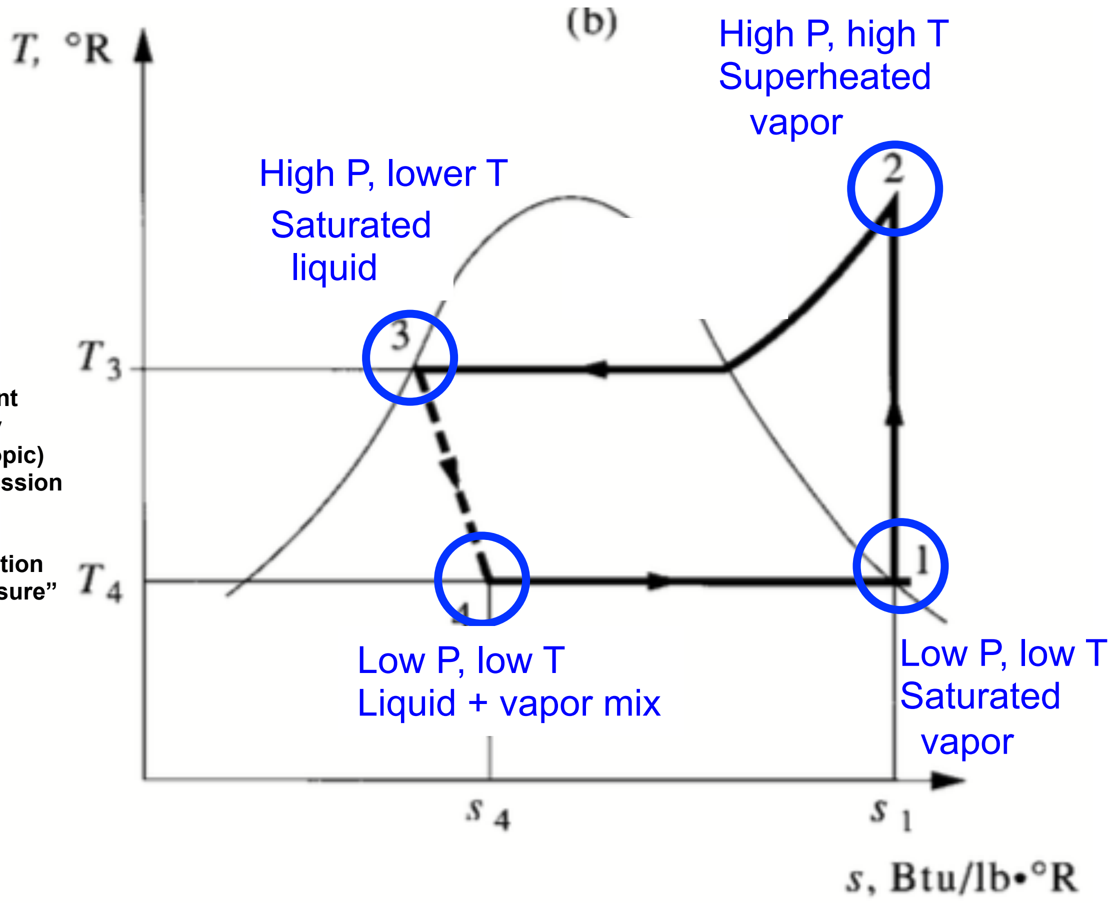
$\Delta h = T \Delta s$

(for phase change)

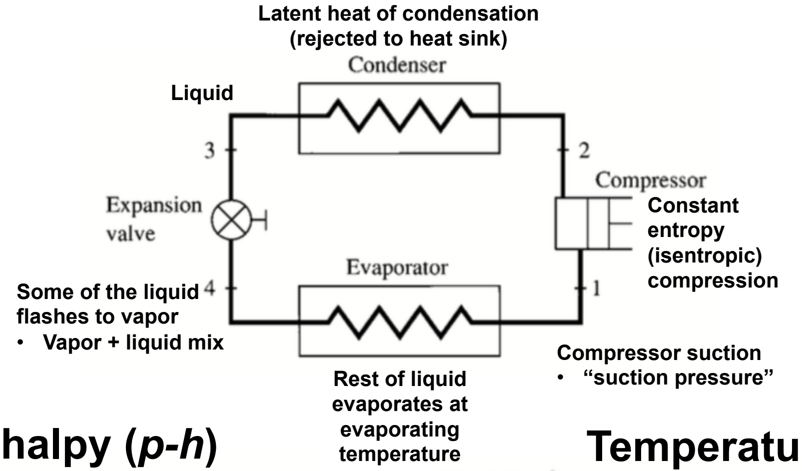
Ideal single-stage vapor compression cycle



Temperature-entropy (*T-s*) diagram



Ideal single-stage vapor compression cycle



Latent heat of condensation (rejected to heat sink)

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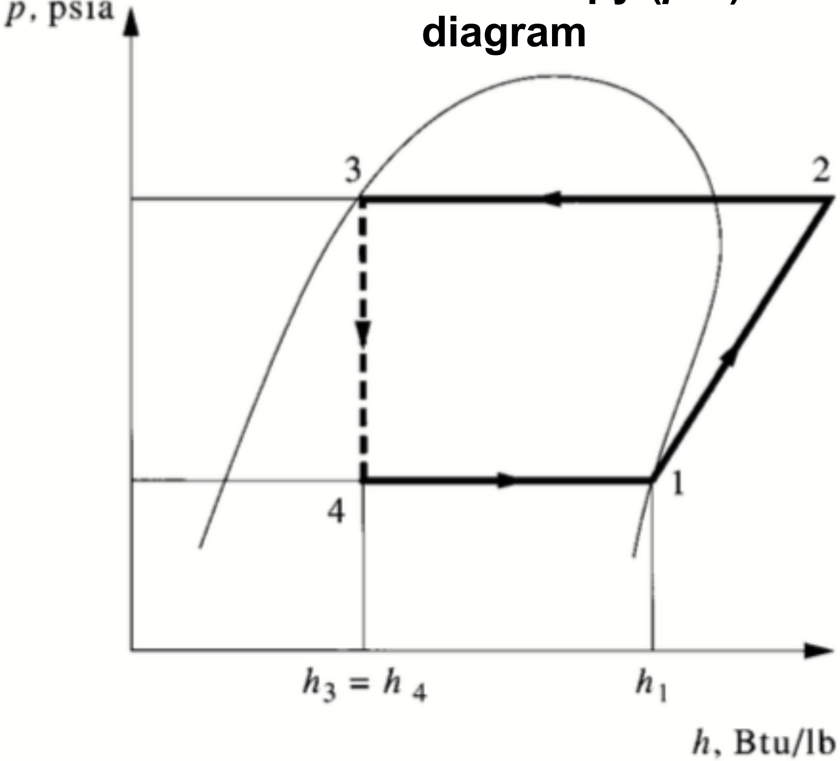
Some of the liquid flashes to vapor
- **Vapor + liquid mix**

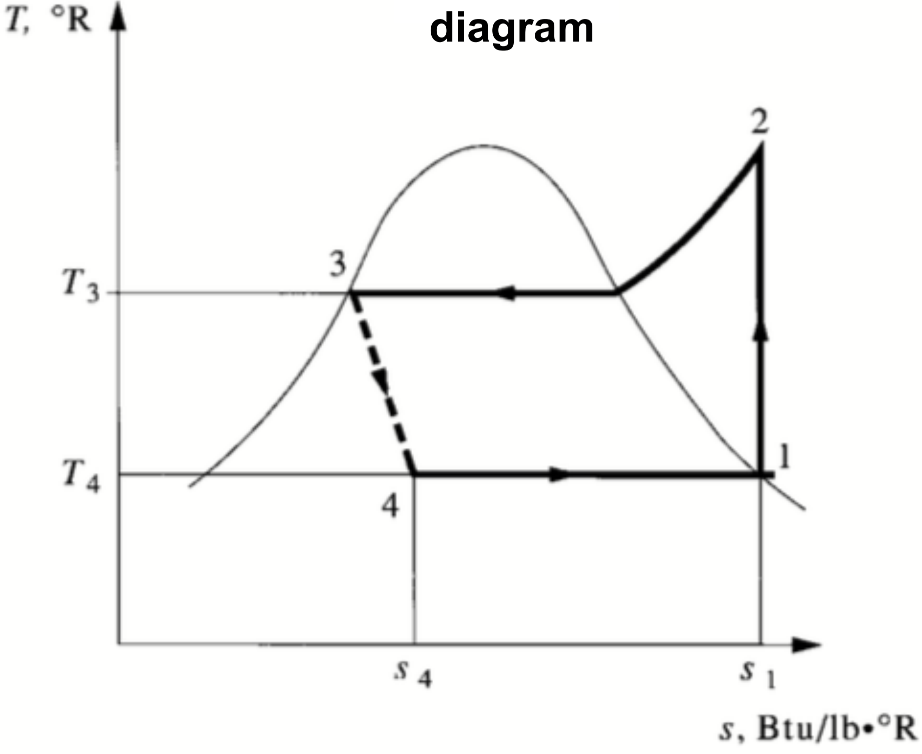
Rest of liquid evaporates at evaporating temperature

Compressor suction
- **"suction pressure"**

Pressure-enthalpy (*p-h*) diagram



Temperature-specific enthalpy (*T-s*) diagram



What makes a good refrigerant?

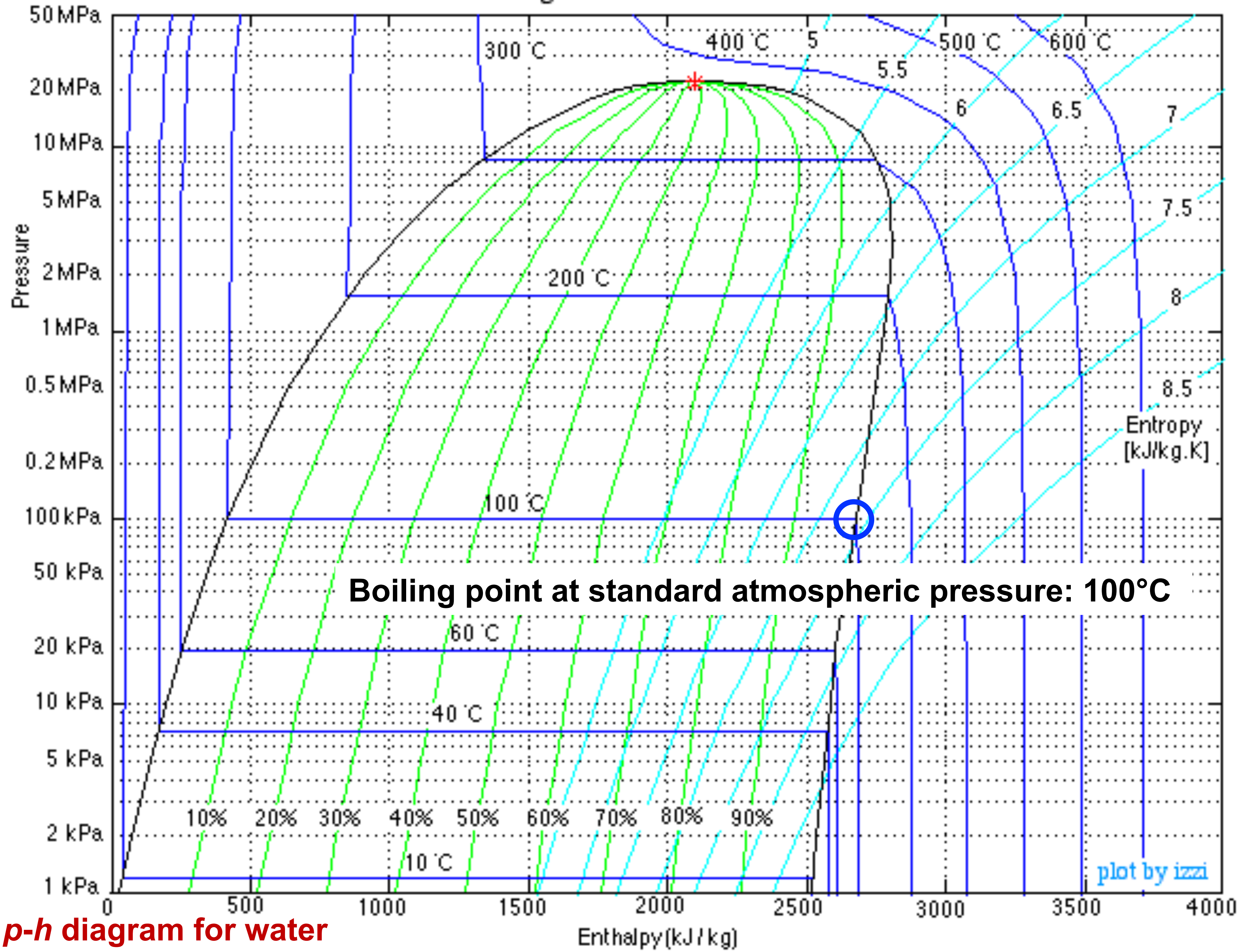
- The goal is to find a fluid that absorbs heat at a low temperature and low pressure and releases heat at a higher temperature and pressure
  - Most refrigerants will undergo phase changes during heat absorption (i.e., evaporation) and heat release (i.e., condensation)
- You want a refrigerant that:
  - Has an evaporating pressure that is higher than that of the atmosphere so that air and other gases will not leak into the system and increase the pressure in the system
  - Is inert (avoids corrosion)
  - Has a high thermal conductivity (increases heat transfer efficiency in heat exchangers)
  - Has a high refrigeration capacity (i.e., a high latent heat of vaporization and specific volume at the suction pressure)

What makes a good refrigerant?

- In the past, we have used ammonia, sulfur dioxide, methyl chloride, and others
  - All are quite toxic

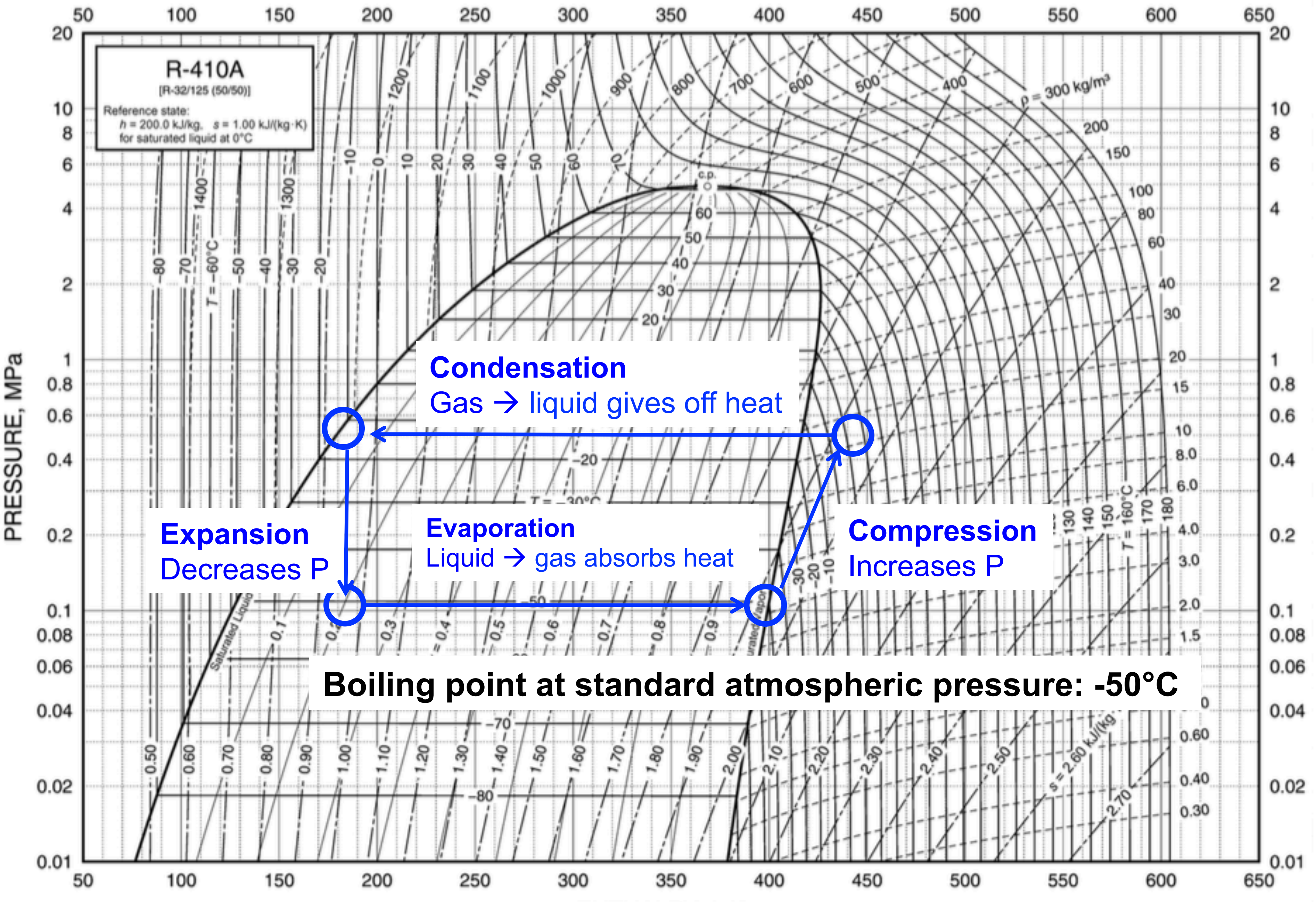
- Then we switched to chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) such as R-22 (freon)
  - But they have high global warming and ozone depletion potentials

- Now phased out in favor of **R-410A** and others (which are being phased out once again for global warming potentials)
  - Boiling point = -55°F
  - Liquid heat capacity = 1.8 kJ/kgK @ STP
  - Gas heat capacity = 0.84 kJ/kgK @ STP



Boiling point at standard atmospheric pressure: 100°C

***p-h* diagram for water**



Condensation
Gas → liquid gives off heat

Expansion
Decreases P

Evaporation
Liquid → gas absorbs heat

Compression
Increases P

Boiling point at standard atmospheric pressure: -50°C

Properties computed with: NIST REFPROP version 7.0

Based on formulation of Lemmon and Jacobsen (2004)

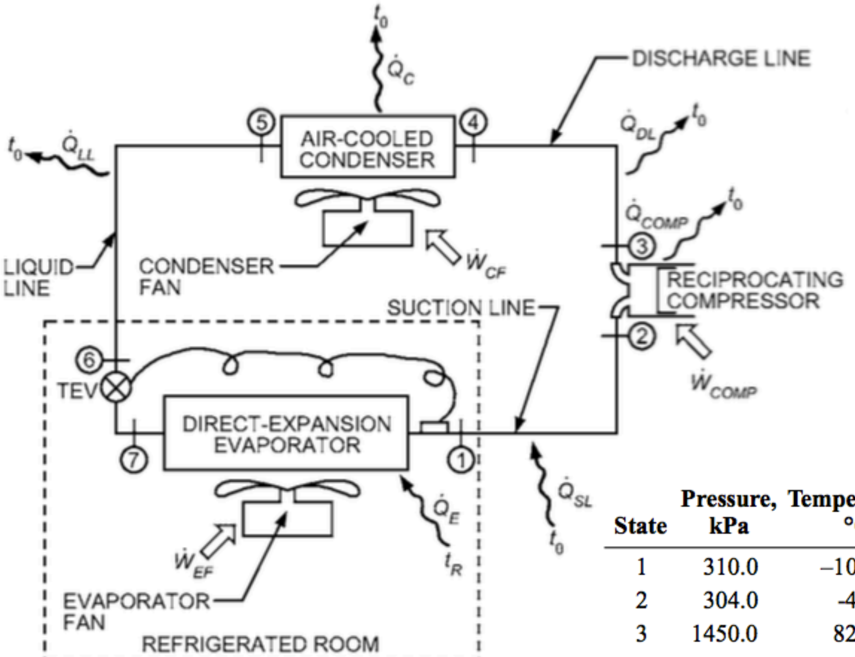
p-h diagram for R-410A

Fig. 16 Pressure-Enthalpy Diagram for Refrigerant 410A

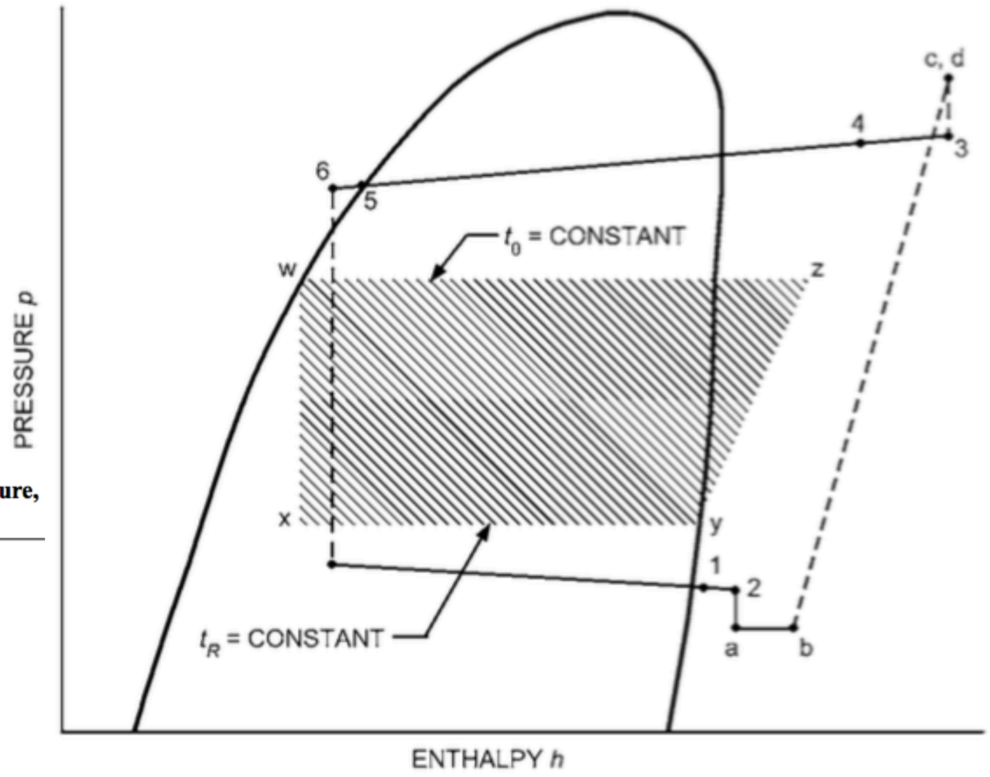
<u>Non</u>-ideal single-stage vapor compression cycle

<u>Actual</u> refrigeration systems differ from ideal cycles

- Pressure drops occur everywhere but the compression process
- Heat transfers between the refrigerant and its environment
- Actual compression process may differ
- Refrigerant might also have some oil mixed in to lubricate
- They all cause irreversibilities in the system that require additional compressor power



State	Pressure, kPa	Temperature, °C
1	310.0	–10.0
2	304.0	-4.0
3	1450.0	82.0
4	1435.0	70.0
5	1410.0	34.0
6	1405.0	33.0
7	320.0	–12.8



Non-ideal single-stage vapor compression cycle

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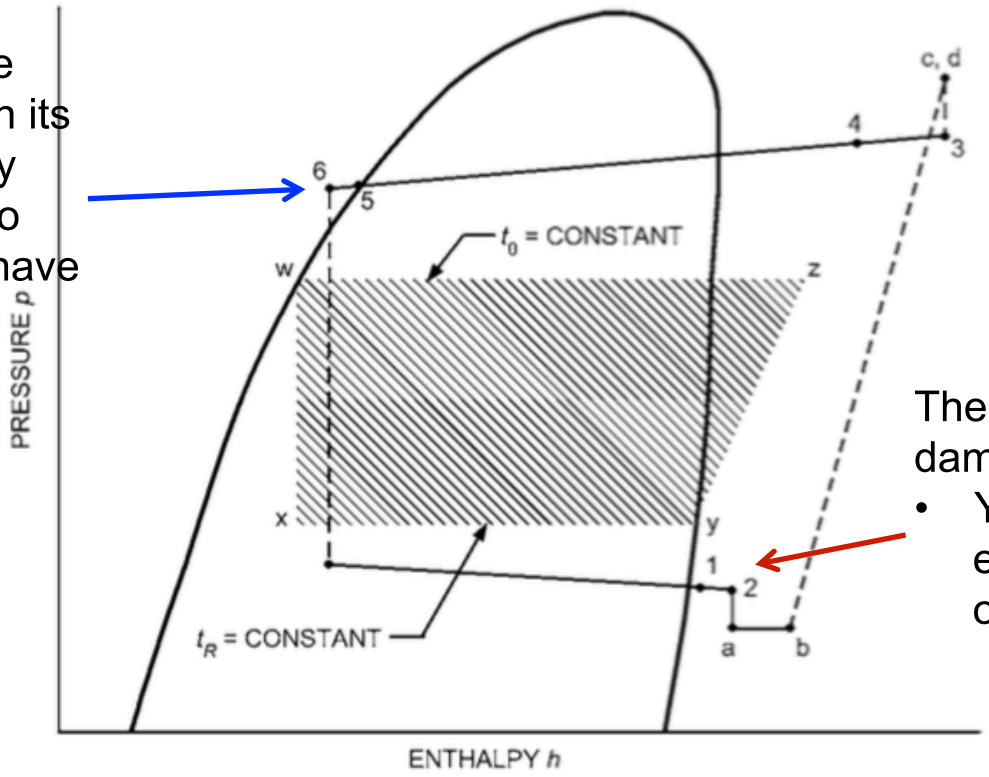


The expansion valve needs 100% liquid in its inlet to work properly

- You “**subcool**” to ensure that you have only liquid

The compressor will be damaged if liquid enters

- You “**superheat**” to ensure that you have only vapor

Question: What is the COP?

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

$$COP = \frac{\text{Provided cooling energy [W or BTU/hr]}}{\text{Used electric energy [W or BTU/hr]}}$$

Equivalent to the efficiency of an air-conditioning unit

Joke courtesy of Jeff Siegel, University of Toronto

Coefficient of performance (COP)

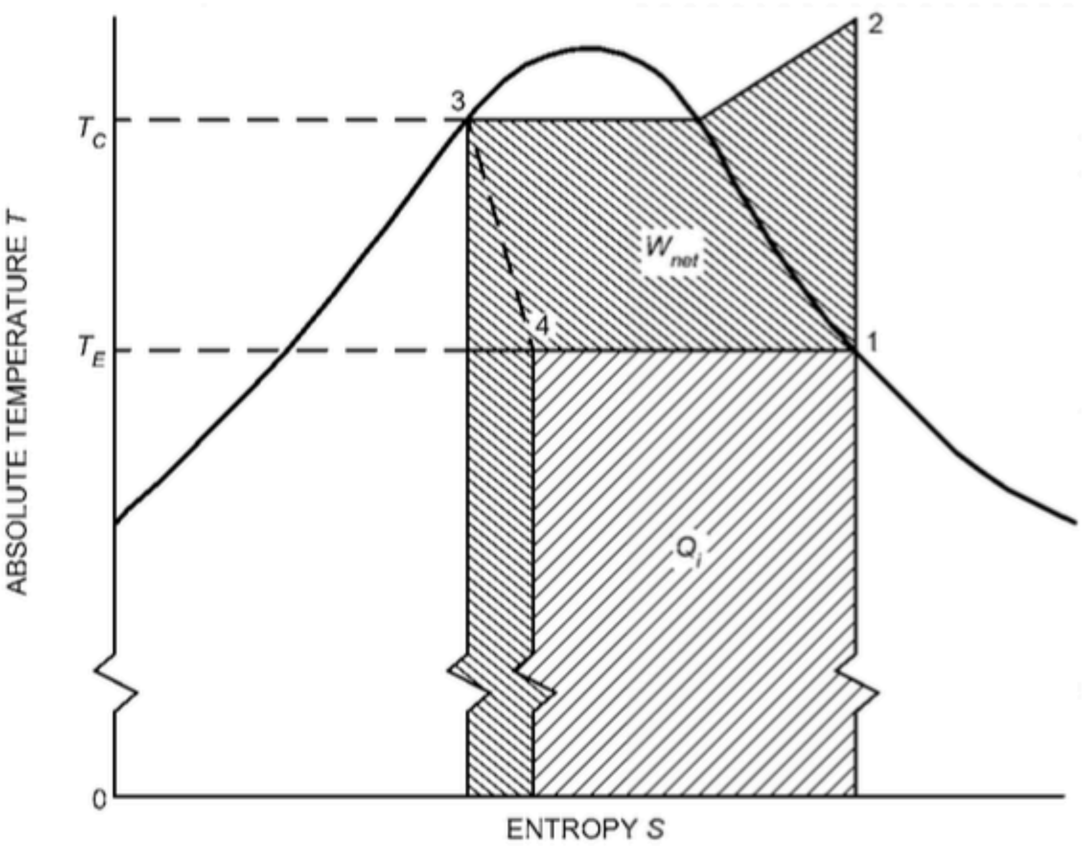
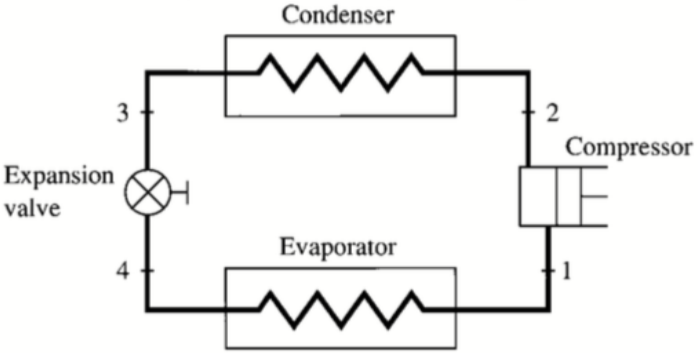


Fig. 10 Areas on *T*- *s* Diagram Representing Refrigerating Effect and Work Supplied for Theoretical Single-Stage Cycle

For an <u>ideal</u> refrigeration cycle:

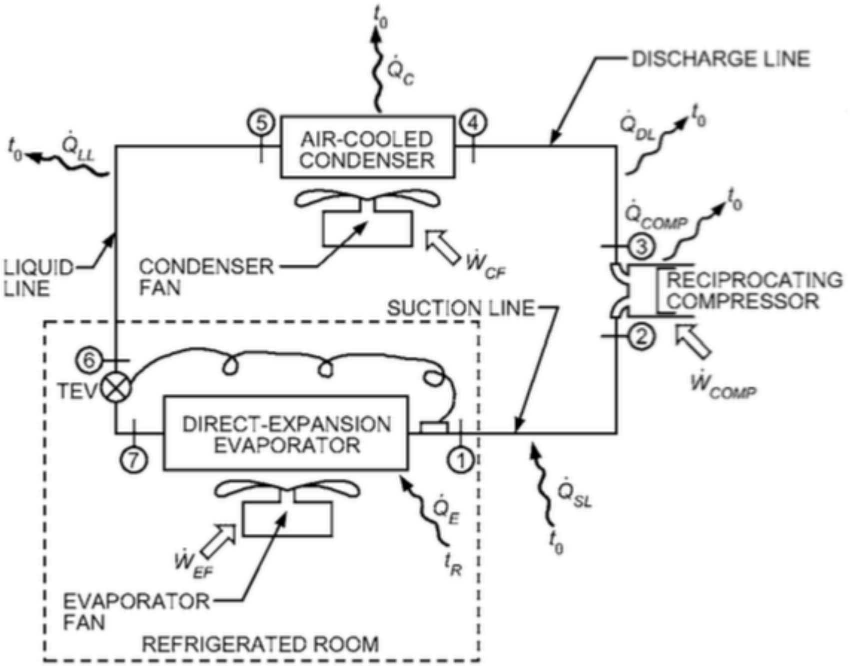
$$COP = \frac{\mathrm{Q_{cool}}}{\mathrm{W_{elec}}} = \frac{h_1 - h_4}{h_2 - h_1}$$

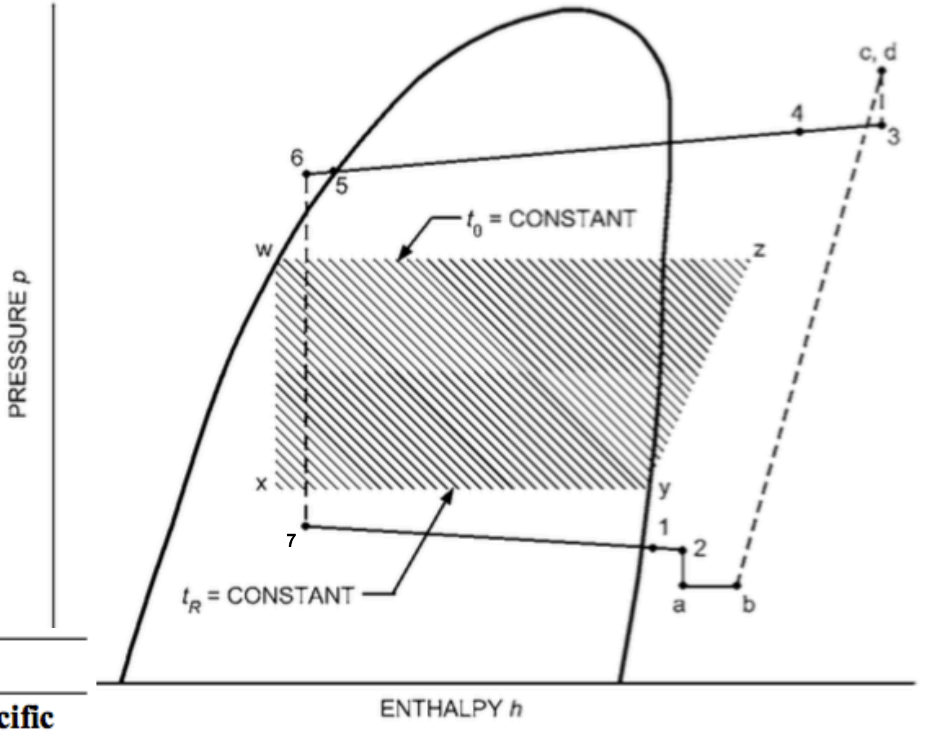


What is the efficiency of a typical residential AC unit?

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

COP example





	Measured		Computed		
State	Pressure, kPa	Temperature, °C	Specific Enthalpy, kJ/kg	Specific Entropy, kJ/(kg·K)	Specific Volume, m^3/kg
1	310.0	–10.0	402.08	1.7810	0.07558
2	304.0	-4.0	406.25	1.7984	0.07946
3	1450.0	82.0	454.20	1.8165	0.02057
4	1435.0	70.0	444.31	1.7891	0.01970
5	1410.0	34.0	241.40	1.1400	0.00086
6	1405.0	33.0	240.13	1.1359	0.00086
7	320.0	–12.8	240.13	1.1561	0.01910

$$COP = \frac{\mathrm{Q_{cool}}}{\mathrm{W_{elec}}} = \frac{h_1 - h_7}{h_3 - h_2}$$

$$COP = \frac{\mathrm{Q_{cool}}}{\mathrm{W_{elec}}} = \frac{402 - 240}{454 - 406} = 3.38$$

Real life COP example: Residential AC unit

- Capacity = 3 tons
  - 36 kBTU/hr
  - 10.5 kW
- Power draw while operating:
  - 3500 W = 3.5 kW

ΔT_{coil} = 12°C - 24°C

Abs(ΔT_{coil}) = 12 K

$\dot{V}_{air}$ = 400 CFM per ton (typical)

$\dot{V}_{air}$ = 1200 CFM

$\dot{V}_{air}$ = 0.566 m^3/s

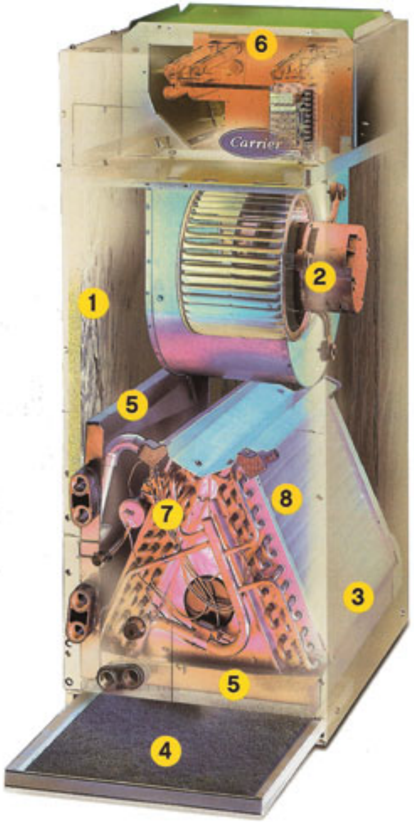
Q_{sens} = (1.15 kg/m^3)(1 kJ/kgK)(0.566 m^3/s)(12K)

Q_{sens} = 7.9 kW

SHR = 0.75 (typical)

Q_{total} = 7.9/0.75 = 10.5 kW

COP = 10.5 kW/3.5 kW = 3.0



What do we need to know about cooling systems?

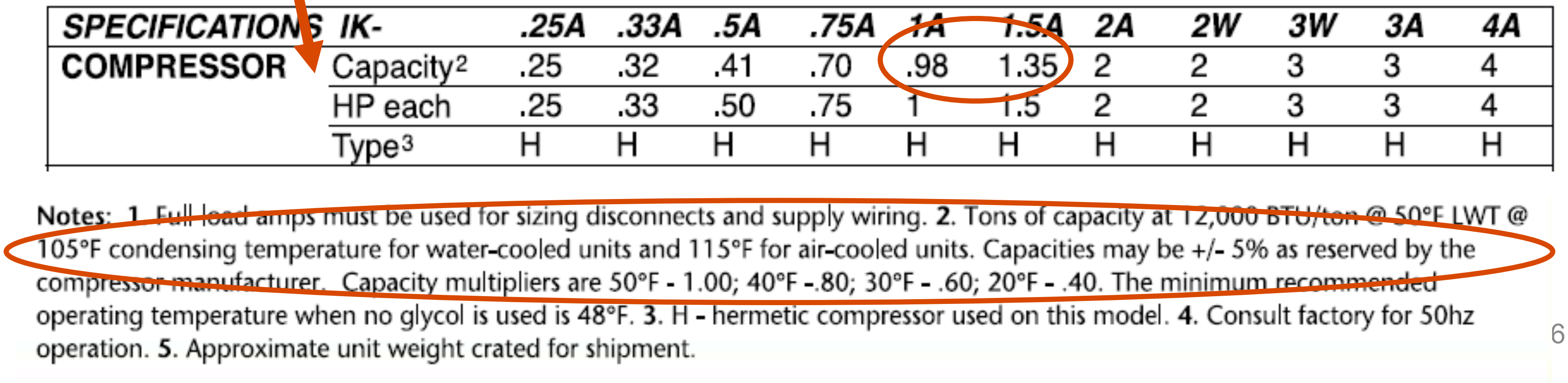
Equipment selection example:

A load calculation determines you need 1.2 tons of water cooling

1 ton = 12000 Btu/hr
1.2 tons = 14,400 Btu/hr

You would choose a 1.35 ton capacity unit

1.35 ton is accurate for:
115°F air condenser temp
and
50°F of leaving water temperature



SPECIFICATIONS	***IK-***	***.25A***	***.33A***	***.5A***	***.75A***	***1A***	***1.5A***	***2A***	***2W***	***3W***	***3A***	***4A***
COMPRESSOR	Capacity[2]	.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[3]	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.

AC capacity and efficiency changes with outdoor T, indoor T/RH, and airflow rates

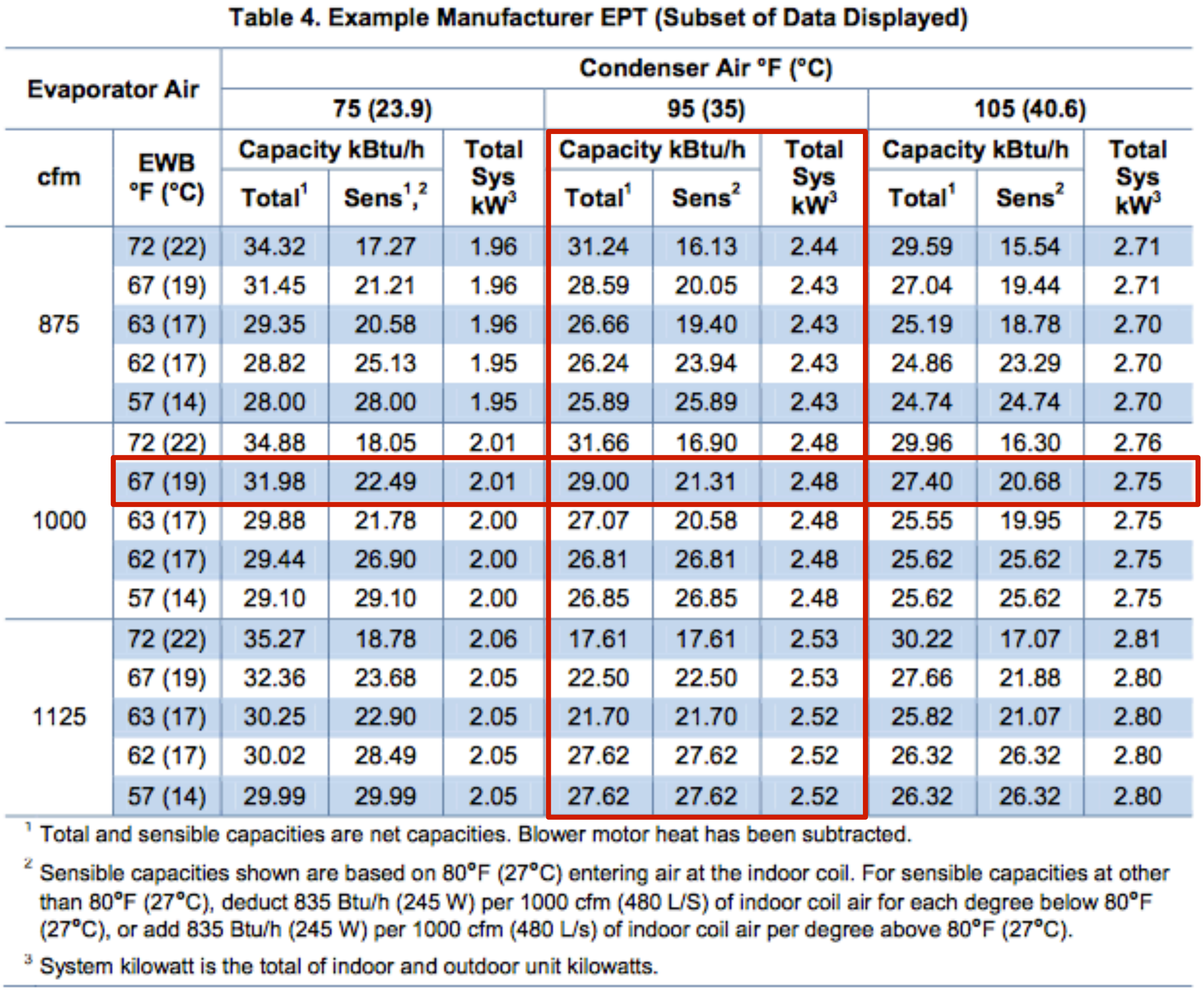


Table 4. Example Manufacturer EPT (Subset of Data Displayed)

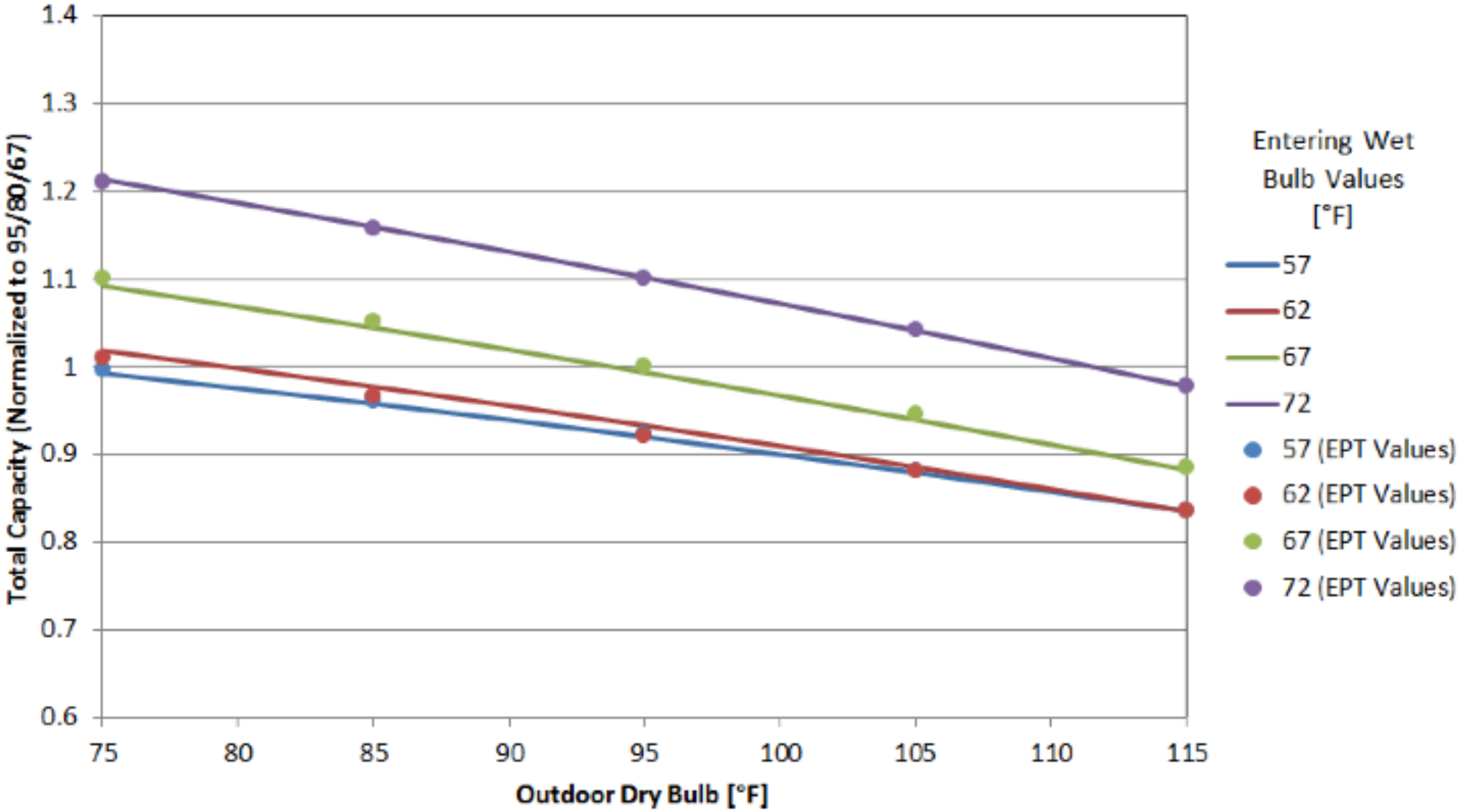
Evaporator Air		Condenser Air °F (°C)								
		75 (23.9)			95 (35)			105 (40.6)		
cfm	EWB °F (°C)	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[1,2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]	Capacity kBtu/h Total[1]	Capacity kBtu/h Sens[2]	Total Sys kW[3]
875	72 (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

[1] Total and sensible capacities are net capacities. Blower motor heat has been subtracted.

[2] 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).

[3] System kilowatt is the total of indoor and outdoor unit kilowatts.

AC 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 mixed units: (Btu/hr)/W
  - Example from previous page:

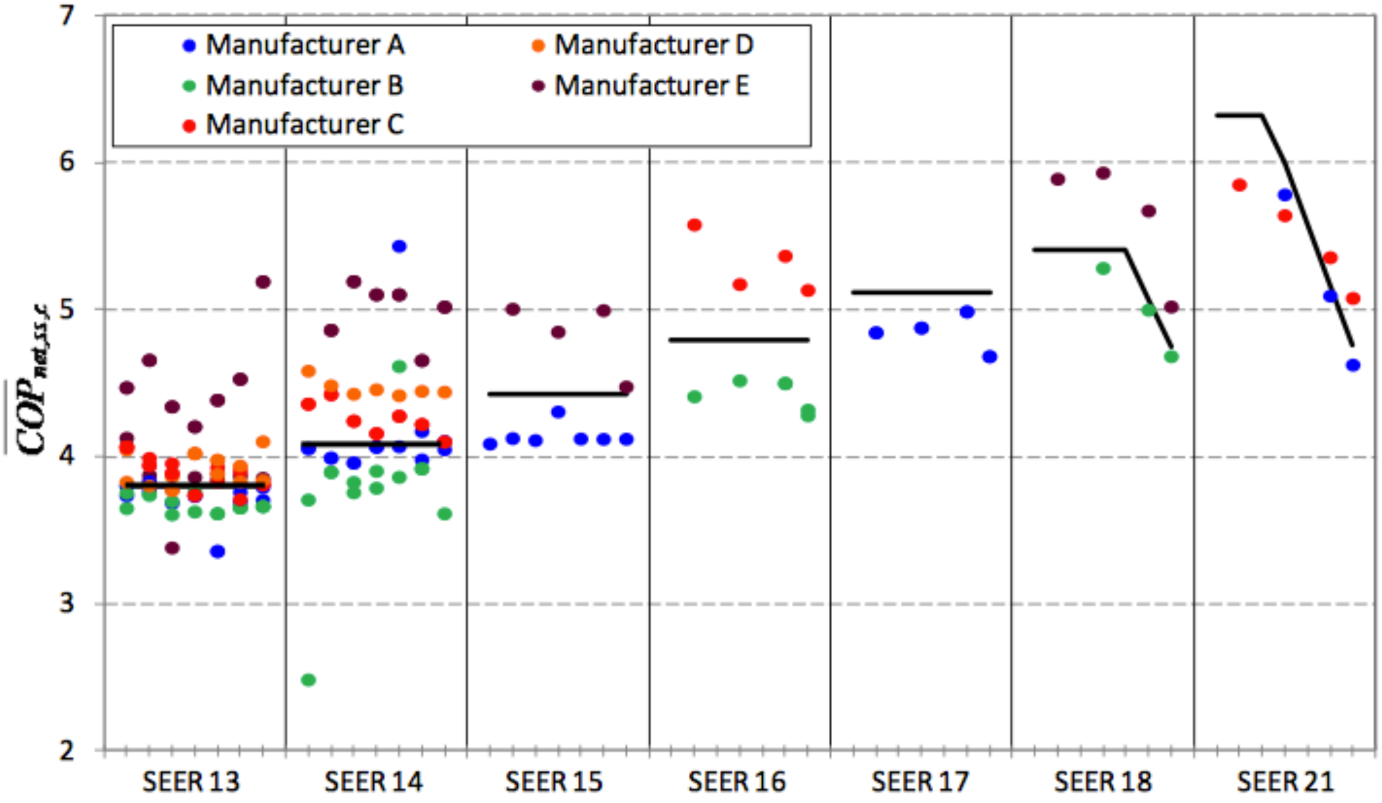
$$COP = \frac{8.5\ [\text{kW}]}{2.48\ [\text{kW}]} = 3.43 \qquad EER = \frac{29.0\ [\text{kBtu/hr}]}{2.48\ [\text{kW}]} = 11.7$$

$$EER = COP \times 3.41$$

- 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



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

Using COP to estimate power draw and energy consumption

- If you know the cooling load and you know the COP, you can estimate the instantaneous electric power draw required to meet the load:

$$\mathrm{P}_{elec} = \frac{Q_{cooling,load}}{COP}$$

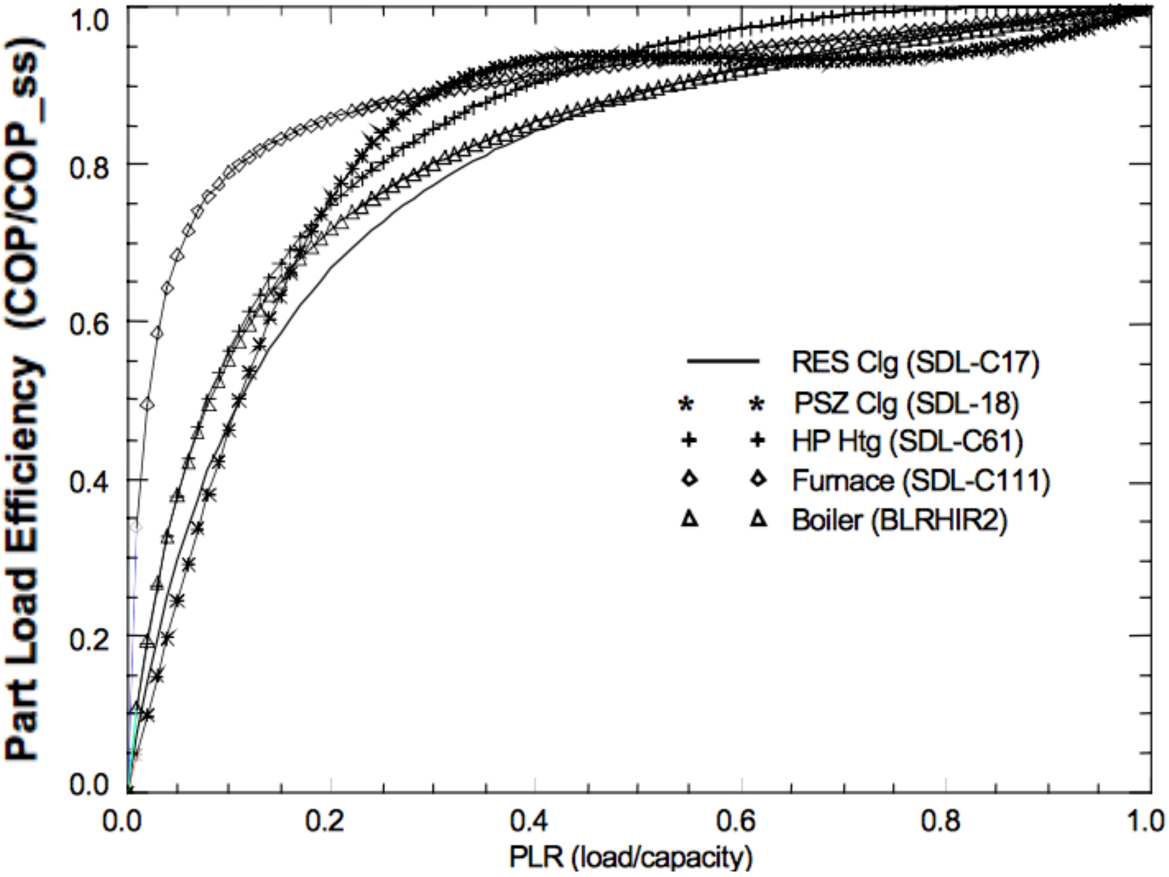
- If you multiply by the number of hours and sum over a period of operating time, you can estimate energy consumption:

$$E = \sum \mathrm{P}_{elec}\,\Delta t$$

- You can also split data into bins if COP/EER changes with varying conditions

Part-load ratio (PLR)

- Many systems operate at their highest efficiency (highest COP) at design load conditions
  - Maximum load
- But systems don't always operate at peak load conditions
  - "Part-load" conditions are common
- The "part-load ratio" quantifies COP at part-load conditions



Part-load ratio (PLR) and entering water temp. (EWT)

- Many systems operate at their highest efficiency (highest COP) at design load conditions
  - Maximum load
- But systems don't always operate at peak load conditions
  - "Part-load" conditions are common
- The "part-load ratio" quantifies COP at part-load conditions