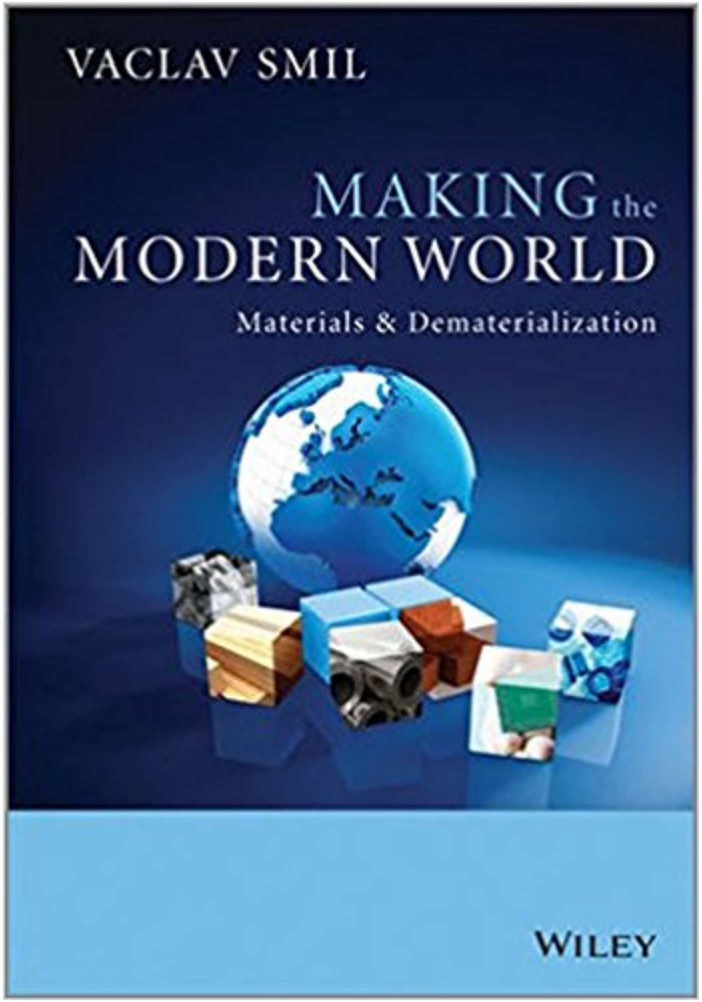
Vaclav Smil Books

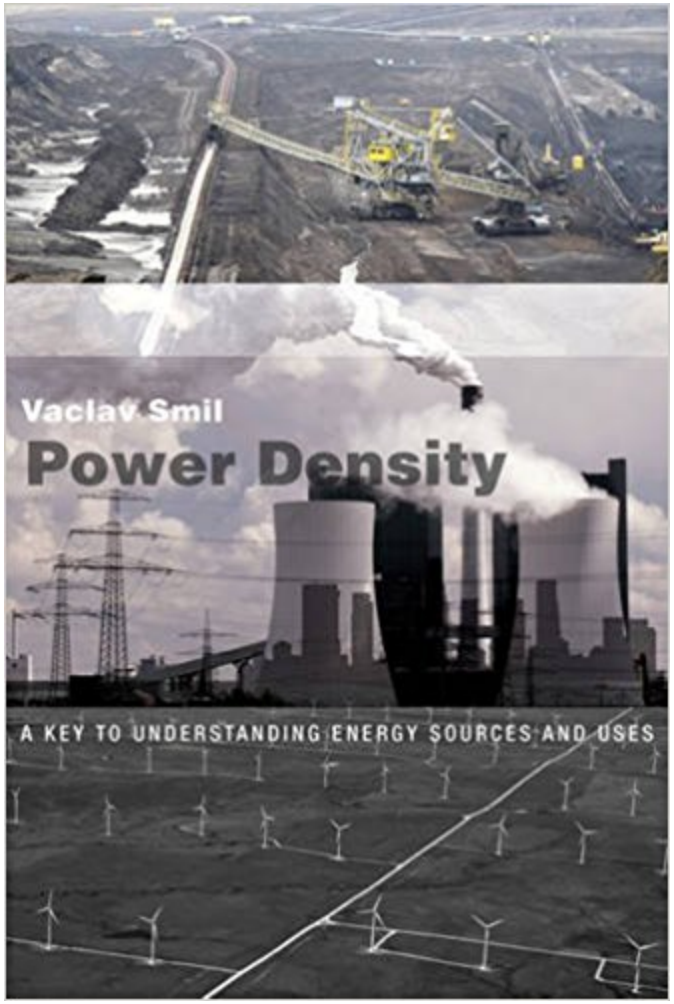


VACLAV SMIL

MAKING the MODERN WORLD

Materials & Dematerialization

WILEY



Vaclav Smil

Power Density

A KEY TO UNDERSTANDING ENERGY SOURCES AND USES

Applied Thermodynamics

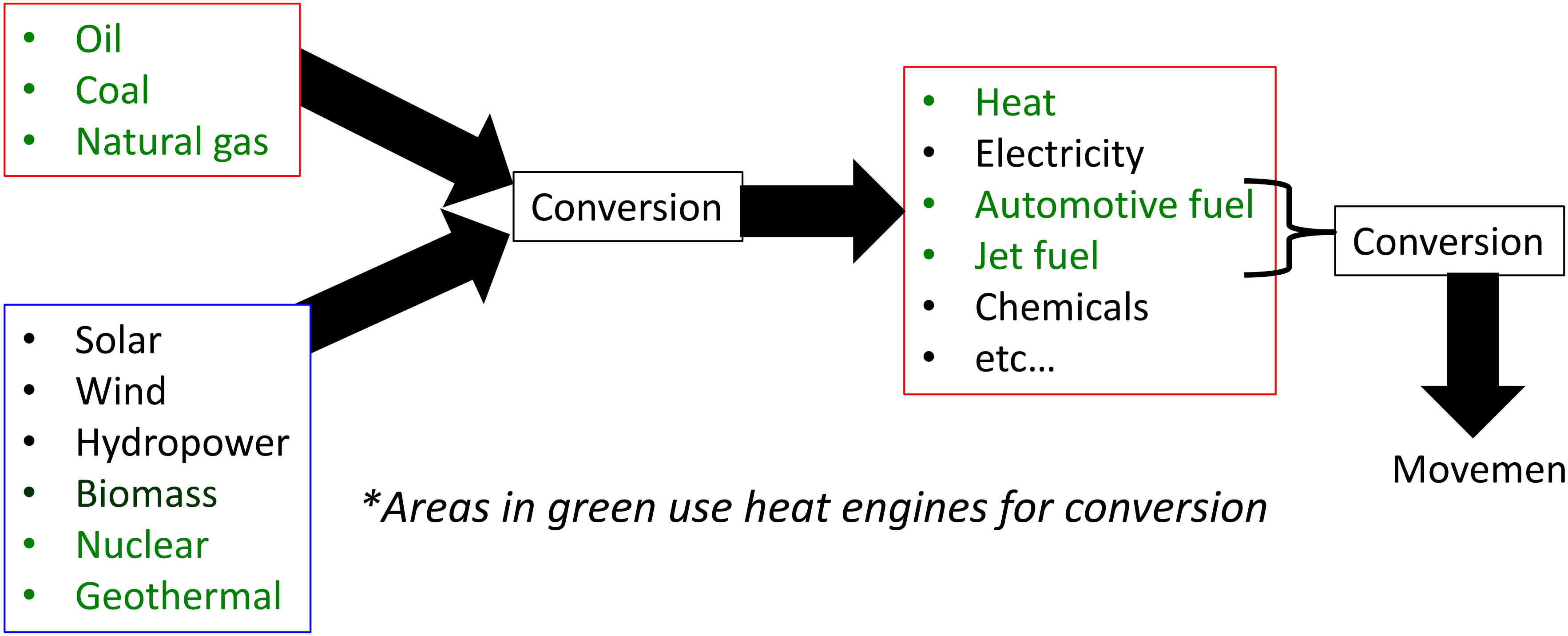
Lecture - Learning Objectives

At the end of this lecture you should be able to:

- Know the thermodynamic limits of heat engines.
- Be able to calculate the power coming from a power plant and know how to modify the conditions to give you more power or efficiency.
- Be able to calculate the heat pulled from a refrigerator and know how to modify the conditions to give you more power or efficiency.
- Know the difference between Rankine cycle devices, Otto and Diesel engines, and steam turbines.

Heat engines related to sustainability

- Currently society's energy conversion approach is almost completely based off of heat engines.
- In a sustainable future there will still be many areas where heat engines will be needed.



- Oil
- Coal
- Natural gas

- Solar
- Wind
- Hydropower
- Biomass
- Nuclear
- Geothermal

Conversion

- Heat
- Electricity
- Automotive fuel
- Jet fuel
- Chemicals
- etc…

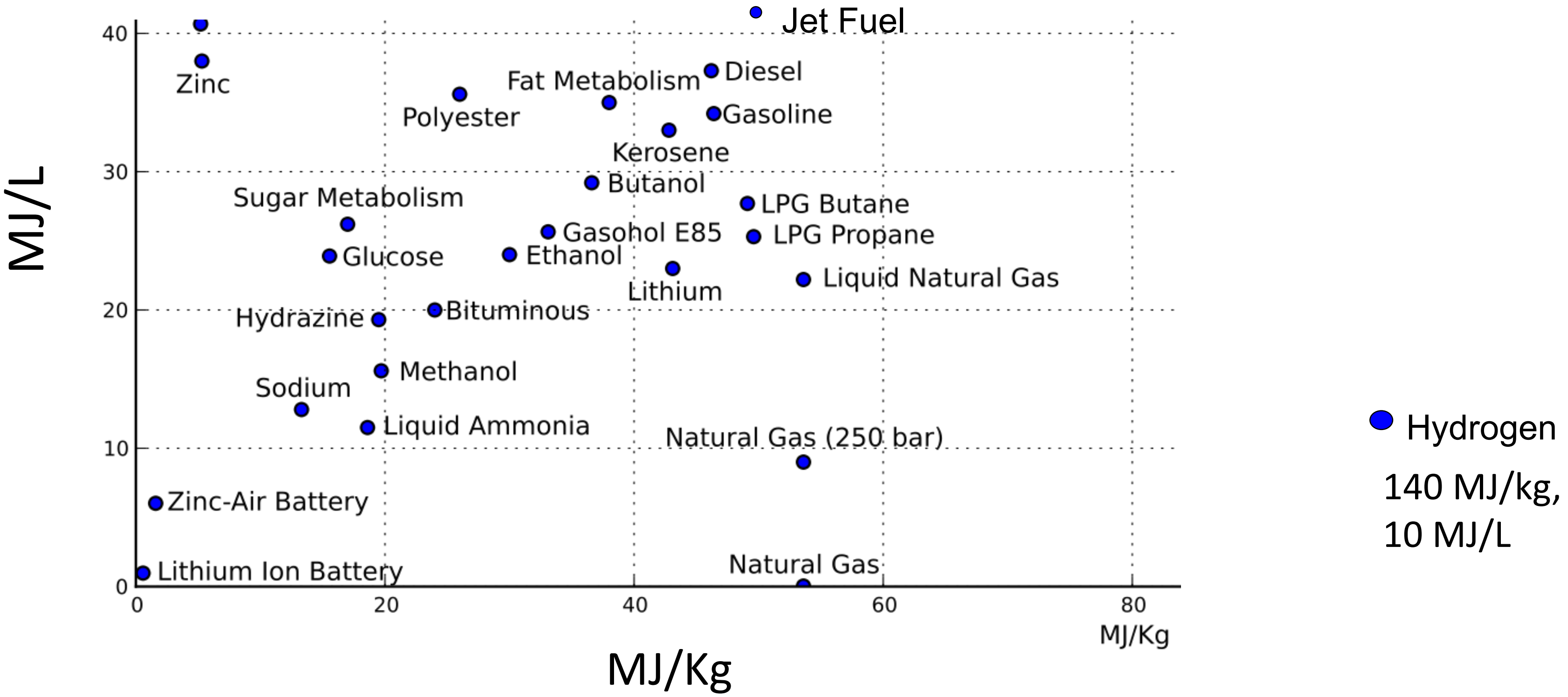
Conversion

Movement

**Areas in green use heat engines for conversion*

Will we burn things in a sustainable society?

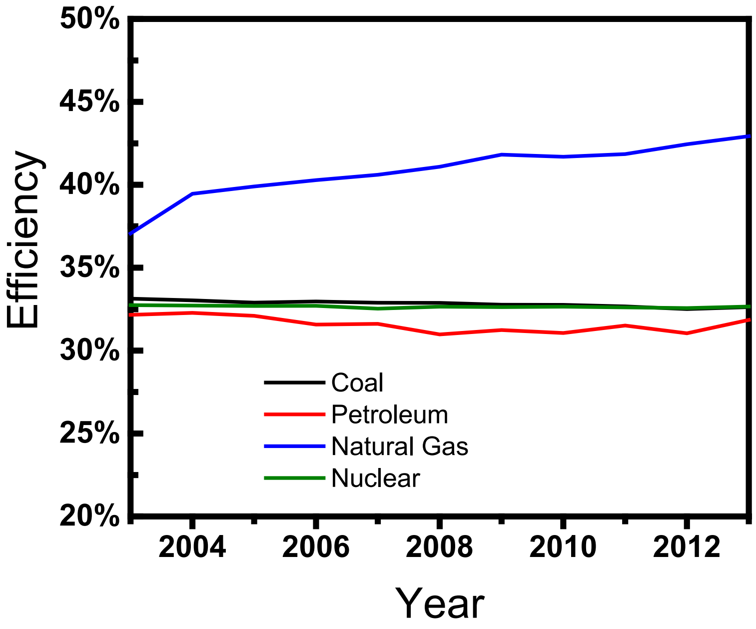
- Airplanes and boats almost certainly will need the energy density from molecules not batteries.
- Hydrogen and Hydrazine are both used in rockets and both can be done sustainably.



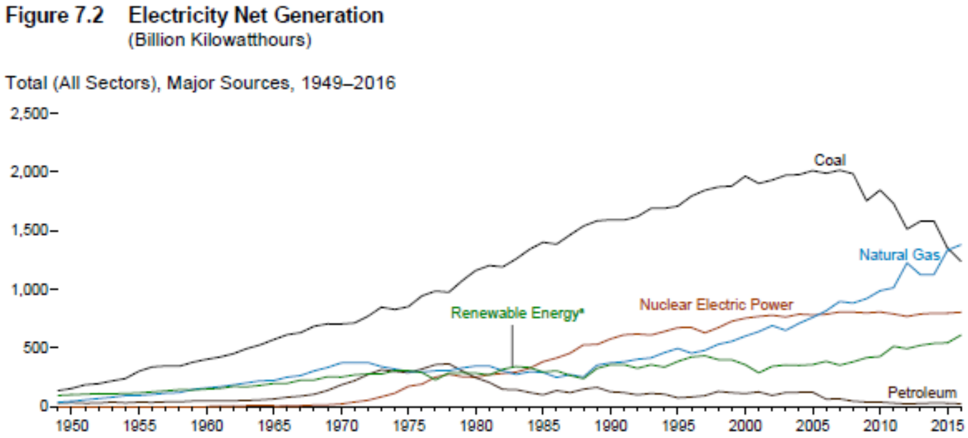
140 MJ/kg,
10 MJ/L

Power plant efficiency and cost

- The electrical generation efficiency is about 33% for most power plants, but natural gas plants can be almost 45% efficient.
- The low price of coal and ample supply (100+ years of reserves) makes this the most dominant electricity generation approach.
- Fracking has greatly decreased the natural gas approach, making this quite competitive recently.



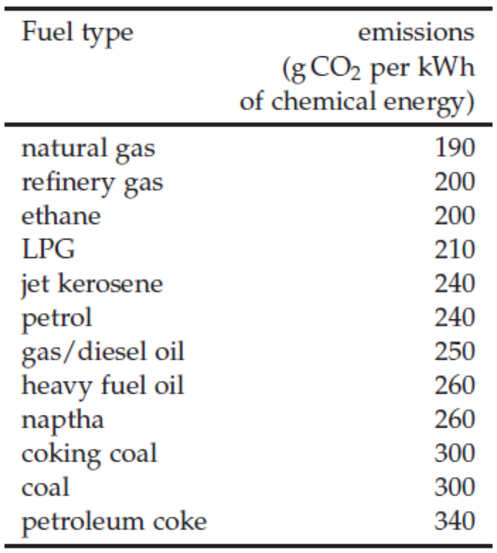
From EIA Data



Source: U.S. EIA. Monthly Energy Review (Sept 2017)

Fossil fuel power plants

- For sustainability:
  - Coal < Oil < Natural gas << geothermal
- Coal is horrible in particulate matter, CO and SO_2. Natural gas is very good in these areas.



Fuel type	emissions ($g\,CO_2$ per kWh of chemical energy)
natural gas	190
refinery gas	200
ethane	200
LPG	210
jet kerosene	240
petrol	240
gas/diesel oil	250
heavy fuel oil	260
naptha	260
coking coal	300
coal	300
petroleum coke	340

Appendix of SE book

Pollutant	Hard coal	Brown coal	Fuel oil	Other oil	Gas
CO_2 (g/GJ)	94,600	101,000	77,400	74,100	56,100
SO_2 (g/GJ)	765	1,361	1,350	228	0.68
NO_x (g/GJ)	292	183	195	129	93.3
CO (g/GJ)	89.1	89.1	15.7	15.7	14.5
Particulate matter (g/GJ)	1,203	3,254	16	1.91	0.1
Flue gas volume total (m^3/GJ)	360	444	279	276	272

Wikipedia

Real Science

Thermodynamics

- Below are the laws of thermodynamics

- Zeroth law of thermodynamics: If two systems are in thermal equilibrium respectively with a third system, they must be in thermal equilibrium with each other.

-Definition of temperature

- First law of thermodynamics: Energy is always conserved.

$$\delta Q = dU + W$$

- Second law of thermodynamics: Useful energy is not conserved. The sum of the entropies of the interacting thermodynamic systems increases.

$$\delta Q = TdS$$

- Third law of thermodynamics: The entropy is equal to the log of the multiplicity of the quantum ground states.

-Definition of entropy

2nd law of thermodynamics

$$\delta Q = TdS$$

Q = Heat
T= Temperature
dV = Entropy change

- **Entropy**- Most easily thought of as disorder in the system.
- Entropy is probably the hardest term to be visualized and see its implications.
- Irreversible processes will increase the entropy, thus a more realistic equation for entropy is:

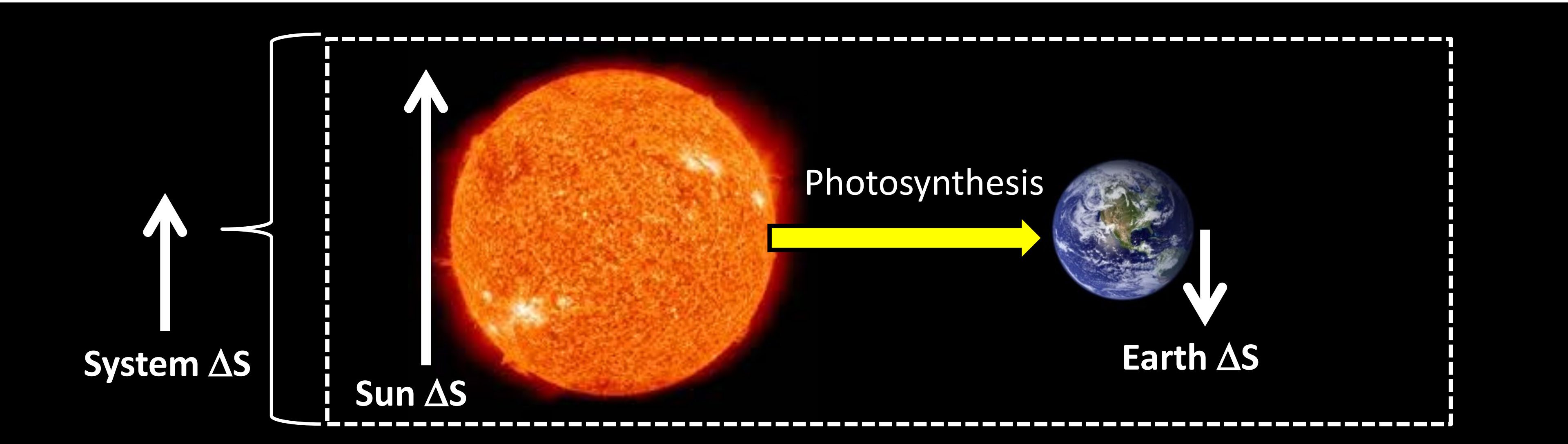
$$\delta Q \leq TdS$$

(Clausius inequality)

- Thus in any system entropy can only increase.
- Question- billions of years ago earth was made of simple bacteria. Now organisms are very complex. It seems the Earth is becoming less disordered. Is this correct?

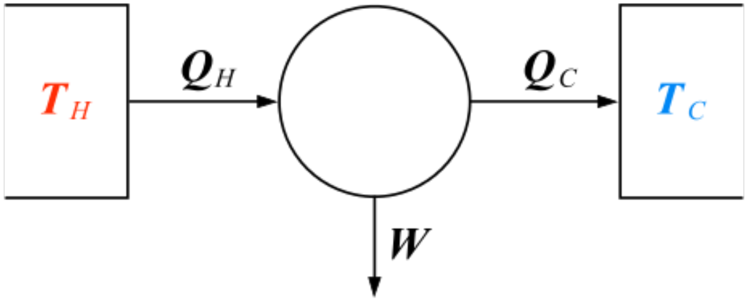
Entropy

- The entropy of the earth is probably decreasing. (Maybe not any more due to our fossil fuel usage.)
- *The key is knowing the system*. The entropy of the sun is increasing, thus the overall system is having an increase in entropy.
- Anytime you think you have broken this law, you probably just don't know what is in your system.



Carnot efficiency

- In a heat engine, you are simply going from a hot temperature source (T_H) to a cold temperature source (T_C).



$$Q_H = W - Q_C$$

$$\eta_{Carnot} = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H} = 1 - \frac{T_C}{T_H}$$

- The Carnot Efficiency is the maximum efficiency you will ever get from a heat engine.
- Realistically your efficiency will be lower.

Heat engine - Realistic

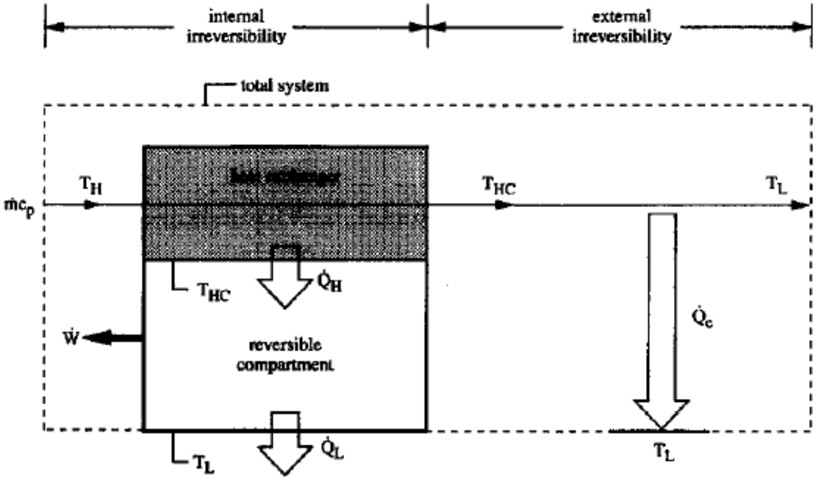
- In any real system we use a working fluid. A coal fired power plant doesn’t use coal flames as a working fluid, but rather steam.
- The effective T_H is actually $T_{H,eff} = \sqrt{T_C T_H}$

(See pg 97-98 in
EP for derivation)

- Thus the endoreversible or irreversible Carnot Efficiency limit is:

$$\eta_{Carnot,irr} = 1 - \sqrt{\frac{T_C}{T_H}}$$

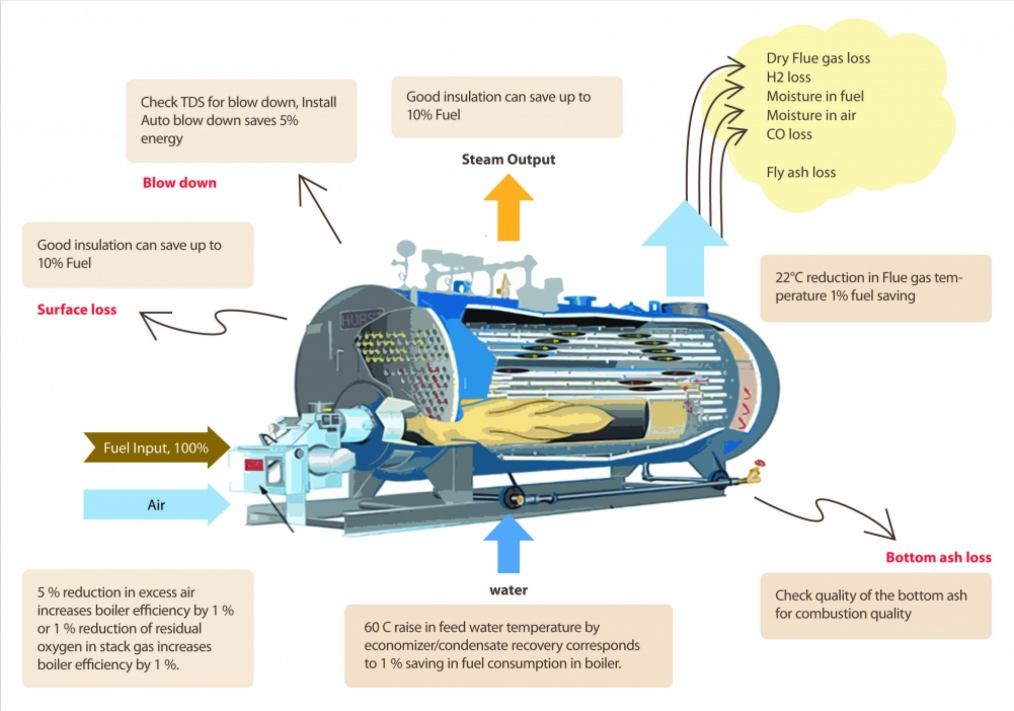
- This is not a fundamental limit, but an accurate practical limit.



Bejan, Rev. Gen. Therm., 1996

Heat engine - Realistic

- Another way of denoting this working fluid heat transfer issue is to say the boilers aren’t perfectly efficient at transferring heat.
- According to the EPA typical boiler efficiencies are:
  - Natural gas- 80%
  - Biomass- 75%
  - Coal- 83%
- These are obviously temperature dependent, but most boilers run near the same temp.



Check TDS for blow down, Install Auto blow down saves 5% energy

Good insulation can save up to 10% Fuel

Good insulation can save up to 10% Fuel

22°C reduction in Flue gas temperature 1% fuel saving

5 % reduction in excess air increases boiler efficiency by 1 % or 1 % reduction of residual oxygen in stack gas increases boiler efficiency by 1 %.

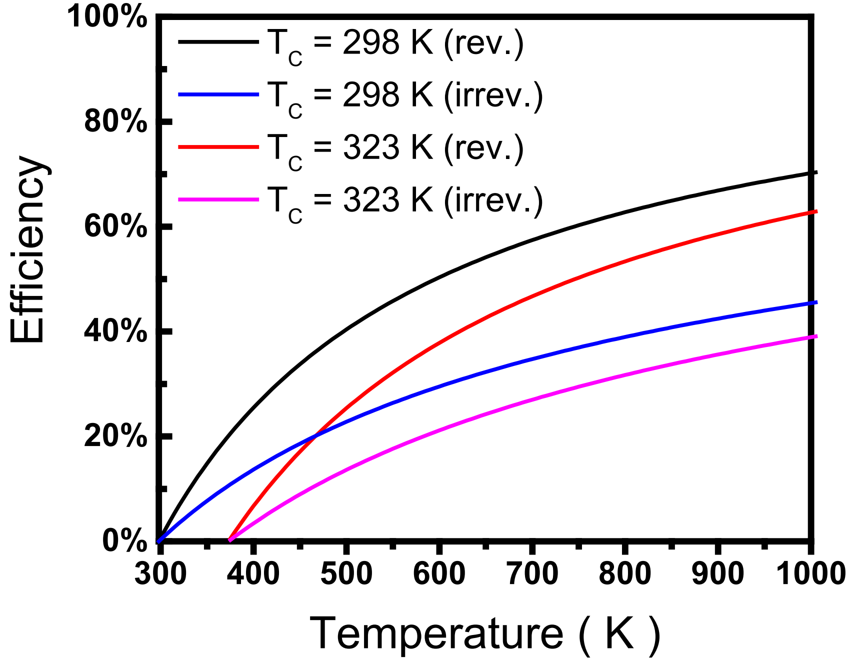
60 C raise in feed water temperature by economizer/condensate recovery corresponds to 1 % saving in fuel consumption in boiler.

Check quality of the bottom ash for combustion quality

Image from: Ginley & Cahen, 2011, Fundamentals of Materials for Energy and Environmental Sustainability

Heat engine

- Obviously the higher temperature you operate at, the more efficient the device will be.
- The atmosphere is a great cold sink and is almost universally used as T_c
- Due to slow heat extraction, realistic T_c's are higher than room temperature.
- At extremely high temperature, materials for engines break down.



Reversible and irreversible Carnot efficiency as a function of temperature for 2 different T_c values.

Heat engine - Limitations

- In theory we are limited by the flame temperature of our energy source.
- In reality we are limited by the materials used for our heat engine.
- Currently boilers operate around 800 K.
- I am not sure what they are made of.

Fuel	Flame Temperature (K)	Carnot Efficiency	Carnot Efficiency with Irreversibility
Coal	2446	87,8%	65,1%
Natural Gas	2327	87,2%	64,2%
Fuel Oil	2302	87,1%	64,0%
Wood	2143	86,1%	62,7%
Hydrogen	2573	88,4%	66,0%

Wikipedia

Material	Max Operating Temperature(K)
Carbon Steel	1023
Ni-Cr Steel	1700
Copper	480
Aluminum	423-523
Titanium	813
Plastics	323-473
Alumina	1700-2000

← Random sources

Heat engine - Limitations

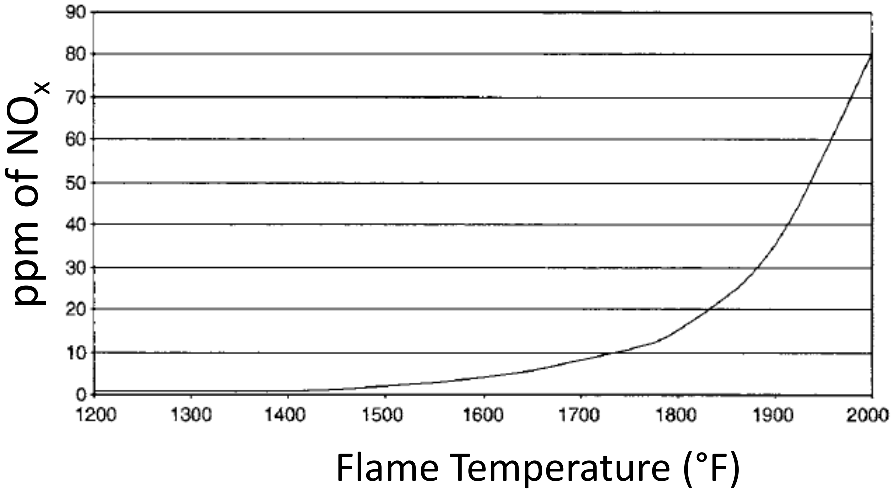
- NO_x is a pollutant that forms increasingly at high temperatures.
- The mechanism is based off an oxygen radical interacting with N_2.

1st step: $O^* + N_2 \rightarrow NO + N^*$

2nd step: $\underline{N^* + O_2 \rightarrow NO + O^*}$

Overall Reaction: $O_2 + N_2 \rightarrow 2NO$

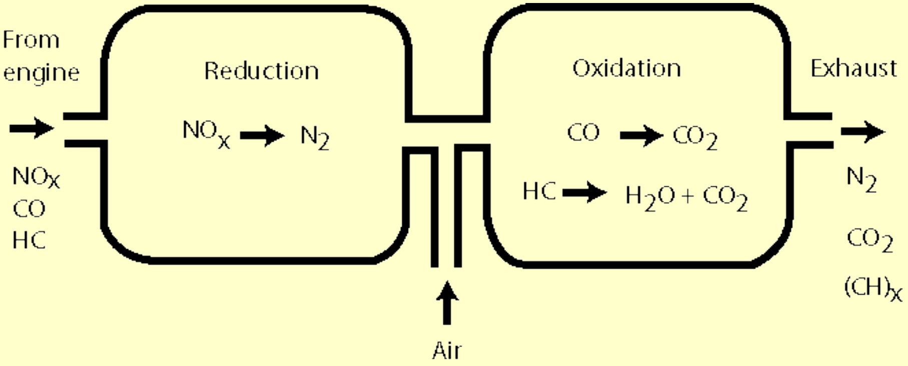
- Since air is 80% N_2 20% O_2, we are kind of stuck with this reaction.
- See here for more details.



Boyce, P. M, 2002, "Gas turbine engineering handbook, pg. 414"

Catalytic converters

- Can we catalyze our way out of the NO_x issue? –Yes !
- 3-way catalytic converters allow us to do this.



- Unburnt hydrocarbons (H_xC_y) react with the water (created during combustion) to form H_2 gas.

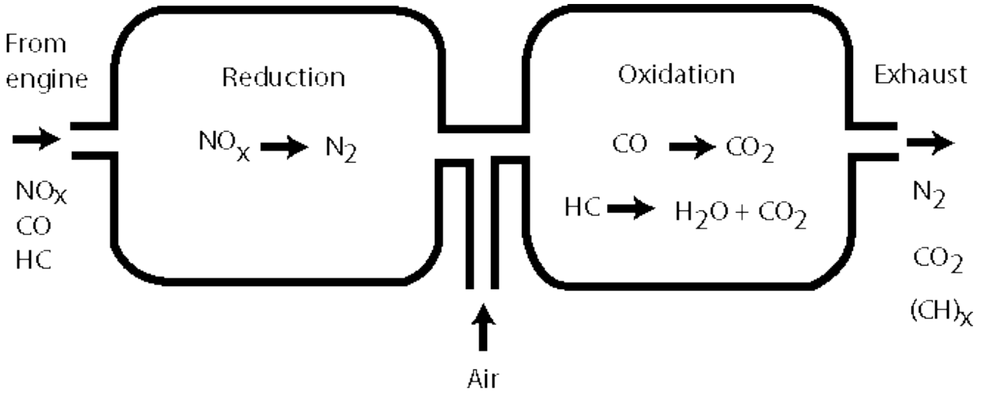
1st step: $H_xC_y + H_2O \rightarrow H_2 + CO_2$

- The H_2 gas then reduces the NO_x.

2nd step: $2H_2 + NO \rightarrow N_2 + 2H_2O$

- Why can’t we add air in from the beginning?

Catalytic converters



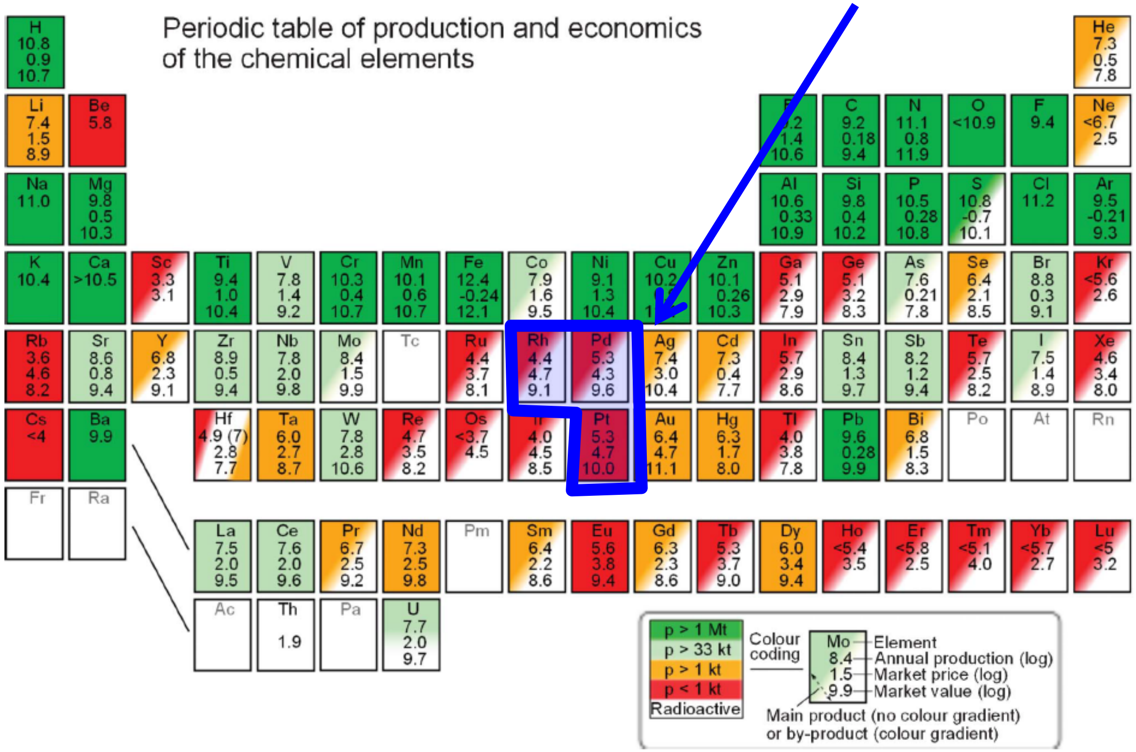
- Further down the line, CO and any remaining hydrocarbons get oxidized from additional air (i.e. O_2).

$$3^{rd}\text{ step: } \begin{cases} H_xC_y + O_2 \rightarrow \frac{x}{2}H_2O + yCO_2 \\ 2CO + O_2 \rightarrow 2CO_2 \end{cases}$$

- While these reactions are quite efficient, the catalysts are quite expensive.

Catalytic converters

- Per car in the EU, catalytic converters contain:
  - 3 g platinum
  - 2.5 g palladium
  - 0.5 g rhodium



Periodic table of production and economics of the chemical elements

- 80% of the world's rhodium supply goes towards catalytic converters.
- Rhodium costs are a major reason why governments don't set lower NO_x emission rates.

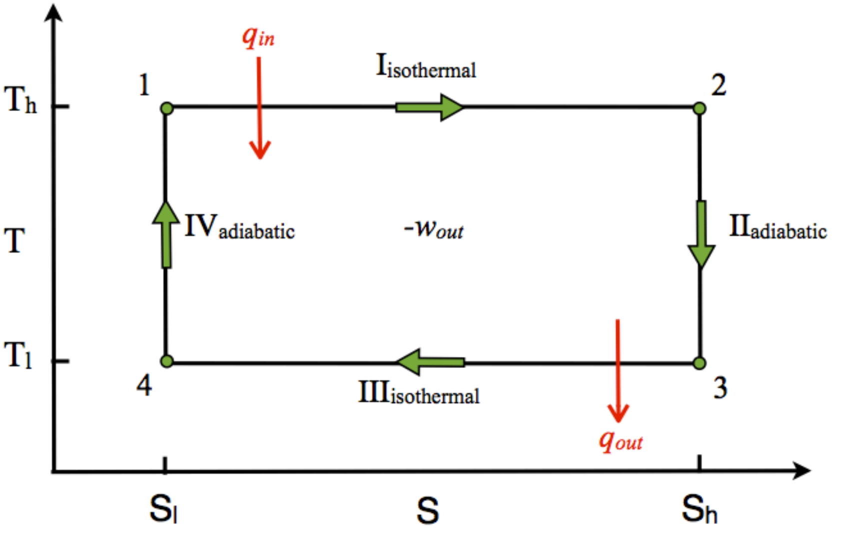
Heat Engines

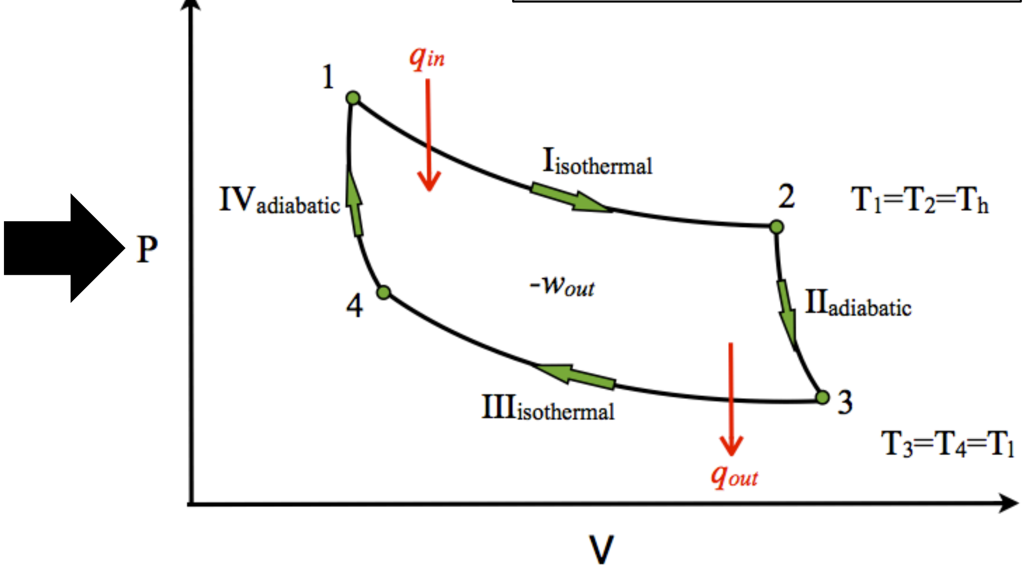
- So due to material costs and NO_x emissions heat engine operating conditions are limited to lower temperatures.
- Water is normally used as a heat transfer medium and the critical temperature of water 647K. Temperatures beyond that complicate the design
- This entails the maximum efficiency is normally < 54% .

Carnot cycle

- How do we operate a cycle to maximize efficiency:
  - 1-2 Isothermal expansion $Q_H = T_H(S_3 - S_2)$
  - 2-3 Adiabatic expansion
  - 3-4 Isothermal compression $Q_C = T_C(S_4 - S_1)$
  - 4-1 Adiabatic compression
  - $W = Q_H - Q_C = (T_H - T_C)(S_2 - S_1)$

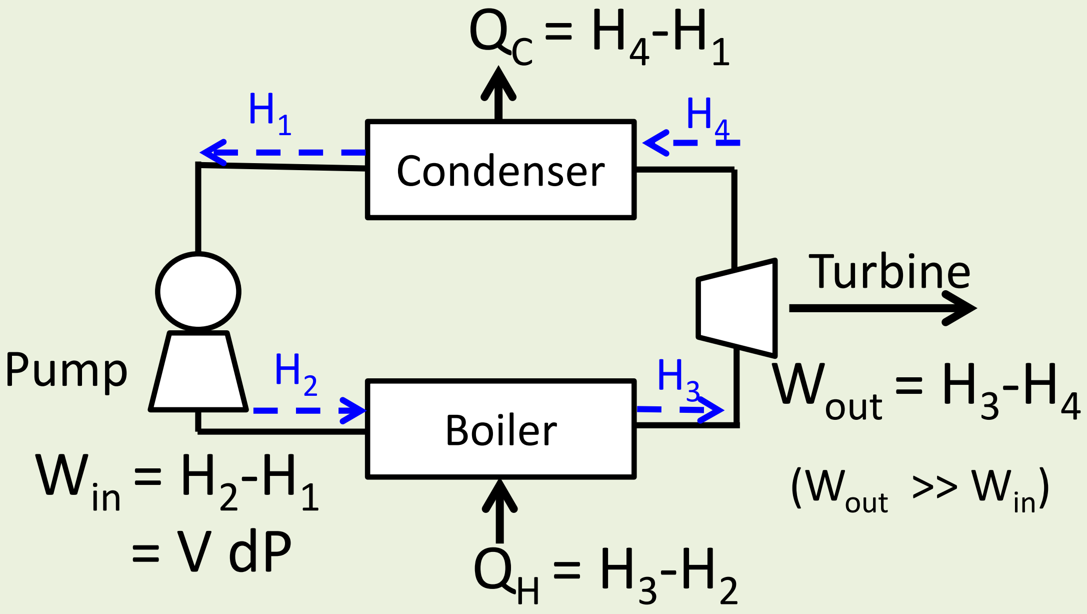
Isothermal- Constant T
Adiabatic - Q = 0
Isentropic- ΔS = 0





Rankine cycle

- The Rankine Cycle is what is used in power plants
  - 1-2 Working fluid (liquid) is pumped, thus increasing pressure.
  - 2-3 The liquid is boiled (typically to a superheated gas) at constant pressure.
  - 3-4 The gas goes through a turbine, which reduced the pressure and temperature of the fluid.
  - 4-1 The wet vapor is then condensed (at constant P) to a liquid.



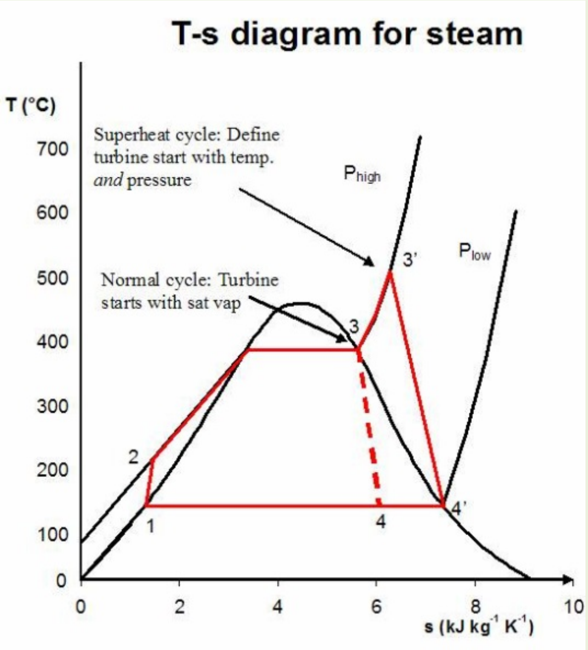
$Q_C = H_4 - H_1$

$W_{out} = H_3 - H_4$

$(W_{out} >> W_{in})$

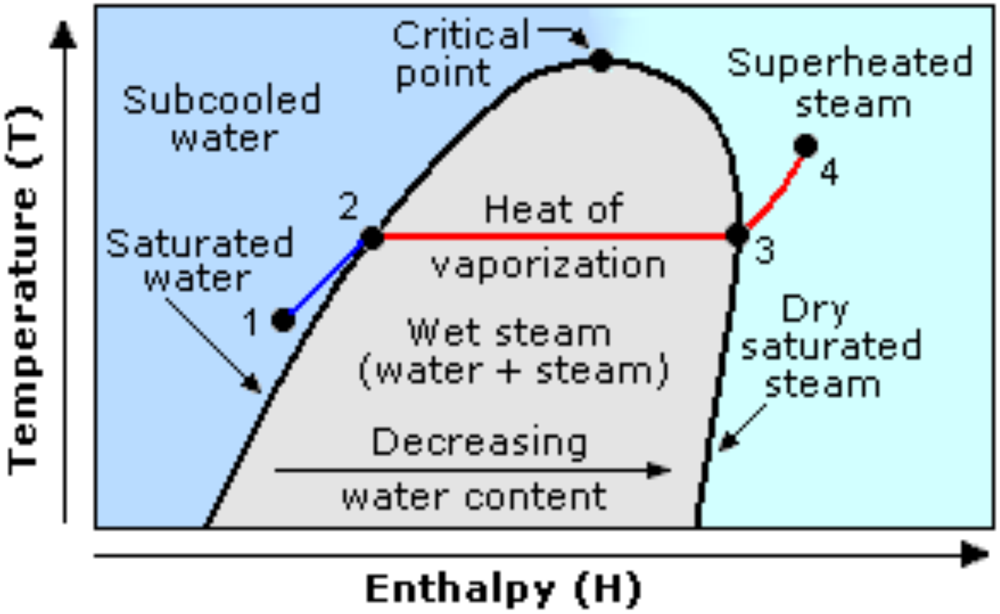
$W_{in} = H_2 - H_1$
$= V\,dP$

$Q_H = H_3 - H_2$


T-s diagram for steam

Phase diagrams

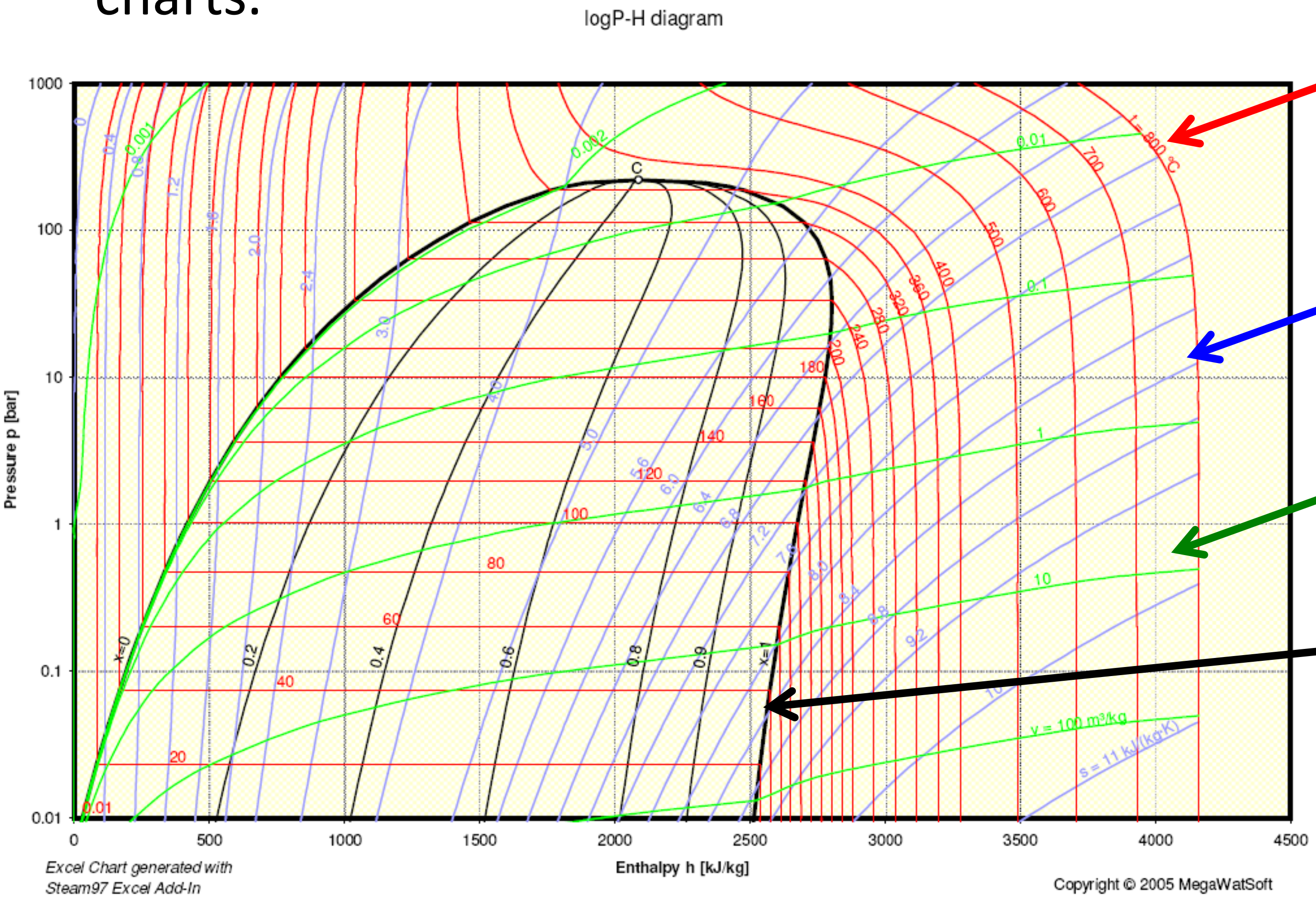
- Phase diagrams are helpful in analyzing this system.



T-H DIAGRAM OF WATER TO STEAM
(Converting water into superheated steam)

Phase diagram

- There are tables for steam and other common heat engine fluids that give all the thermodynamic data you need.
- Calculating power plants efficiencies are much easier with these charts.



Excel Chart generated with Steam97 Excel Add-In

Copyright © 2005 MegaWatSoft

Isotherms
(constant T lines)

Isentropic lines
(constant S lines)

Isochoric
(constant V lines)

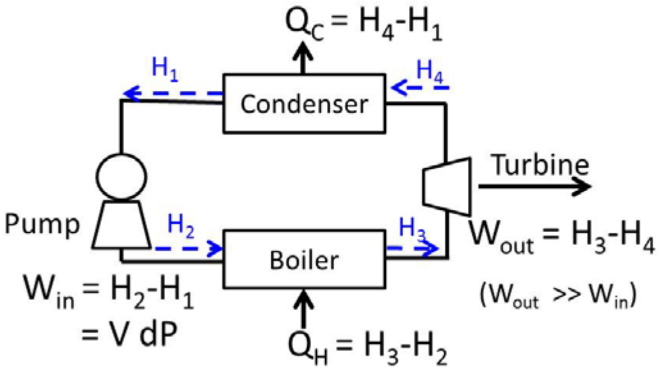
Boiling Point Curve

Power plant- realistic issues

- Pumps and turbines aren’t 100% efficient.
- Incorporating their efficiencies is quite easy though.

$$W_{in,actual} = \frac{H_2 - H_1}{\eta_{pump}}$$

$$W_{out,actual} = \eta_{Turbine}(H_3 - H_4)$$



- Thus the overall efficiency is:

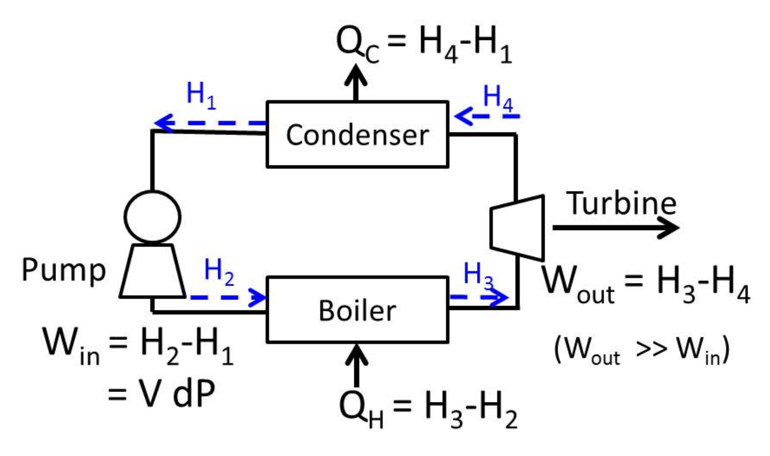
$$\eta = \frac{W_{out} - W_{in}}{Q_H} = \frac{\eta_{Turbine}(H_3 - H_4) - \dfrac{H_2 - H_1}{\eta_{pump}}}{H_3 - H_2}$$

- In general pumps are about 75-85% efficient and turbines are 60-90% efficient. Typically the larger the turbine, the higher the efficiency.

Power plant- example

- Your 75% efficient pump takes water at atmospheric pressure and pumps it to 100 bar. Your boiler outputs superheated steam at 700 °C. Your turbine converts this to saturated steam at 1atm and the condenser converts this to water at 1 atm.
  - What is the power plant efficiency?
  - If you had a 100% efficient pump, what would the efficiency be?
  - Assuming you get 24 MJ/kg of coal, how much coal (kg/day) would you need to power a typical 100 MW power coal plant?
  - How much water/steam in kg/s would you need to accomplish this?

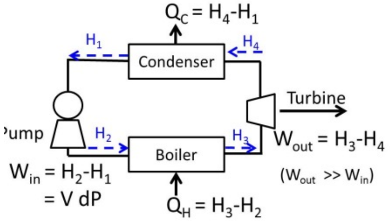
$$\eta = \frac{W_{out} - W_{in}}{Q_H}$$



Assuming no transmission loss, a 100 MW plant could support 155,000 Danes.

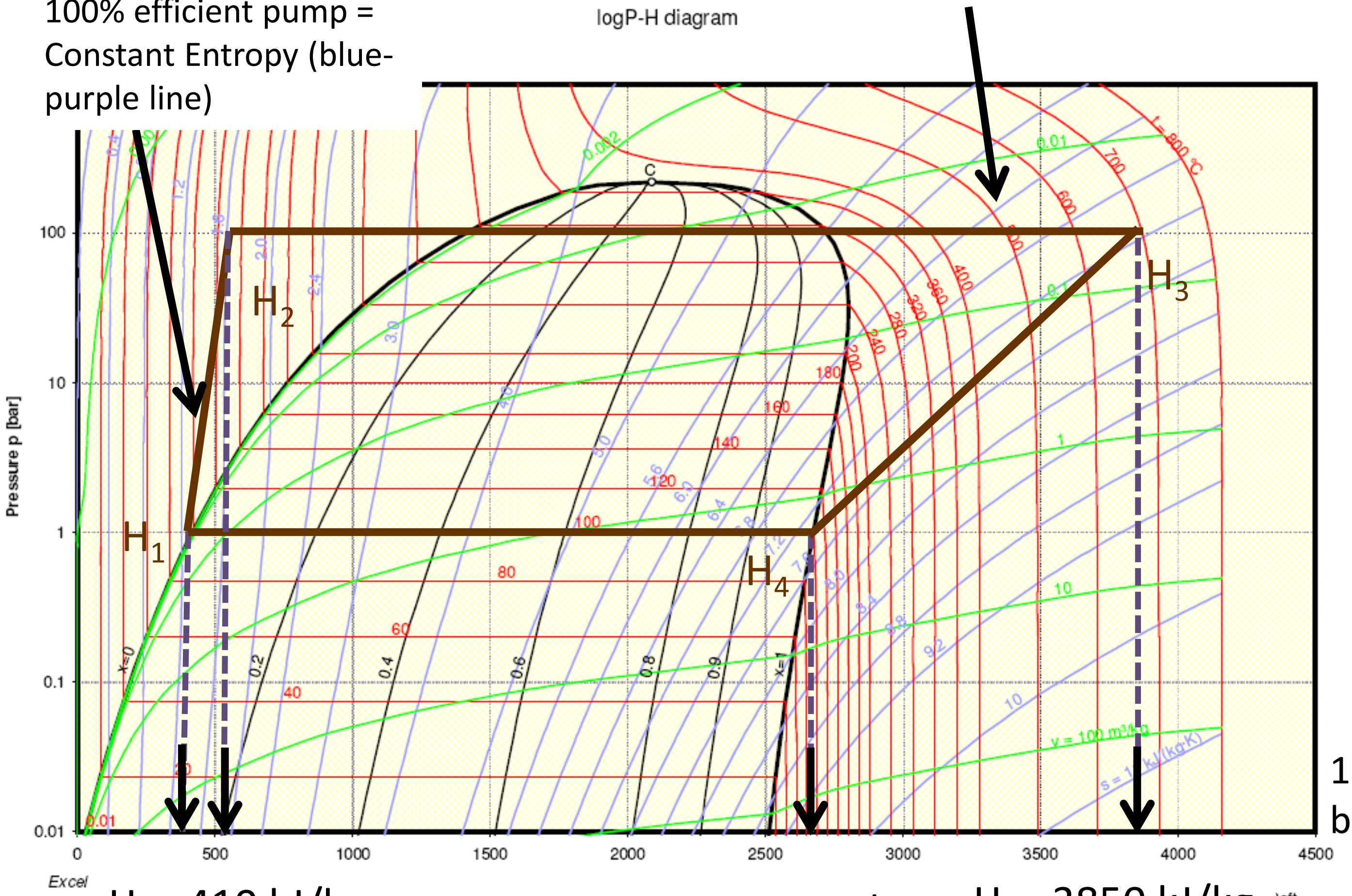
Break

Power plant- solution



100% efficient pump = Constant Entropy (blue-purple line)

If the tubine is 100% efficient, we follow blue line from H3 to H4.



H_1= 410 kJ/kg

H_2= 520 kJ/kg

H_4= 2710 kJ/kg

H_3= 3850 kJ/kg

Q_C= 2300 kJ/kg

Q_H= 3330 kJ/kg

W_{Out}= 1140 kJ/kg

W_{In}= 110 /0.75 kJ/kg
= 147 kJ/kg

$$\eta = \frac{1140 - 147}{3330}$$

= 30 %

100% efficient pump would be about 30.9% efficient

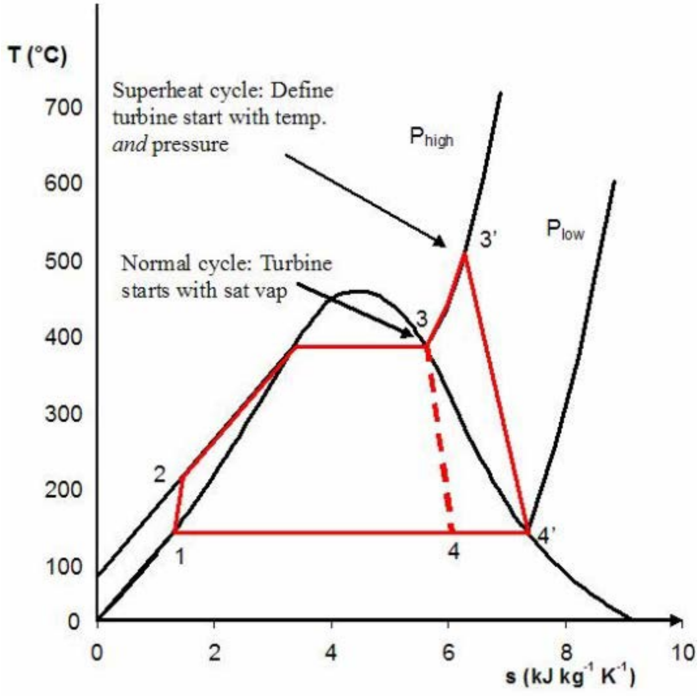
Coal needed =100 MW=(100 MJ/s)*(3600 s/hr)* (24 hour/day)/ (24 MJ/kg * 33%) = 1,200,000 kg/day

Amount of water/steam needed: W_{out} = (100 MJ/s) = (100,000 kJ/s) / (800 kJ/kg) =88 kg/s

Modified designs

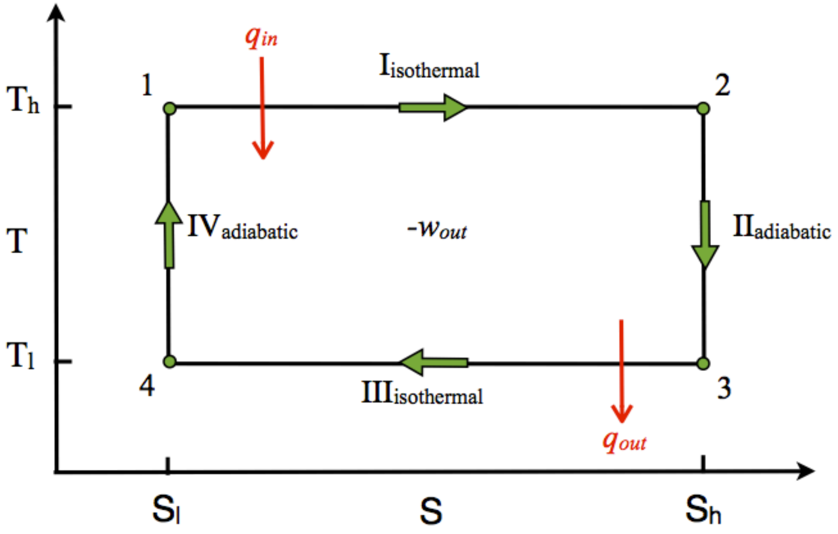
- There are a fair amount of modifications of the rankine cycle.
- All of them try to get the Rankine cycle to more closely match the Carnot cycle.

<u>Rankine Cycle</u>



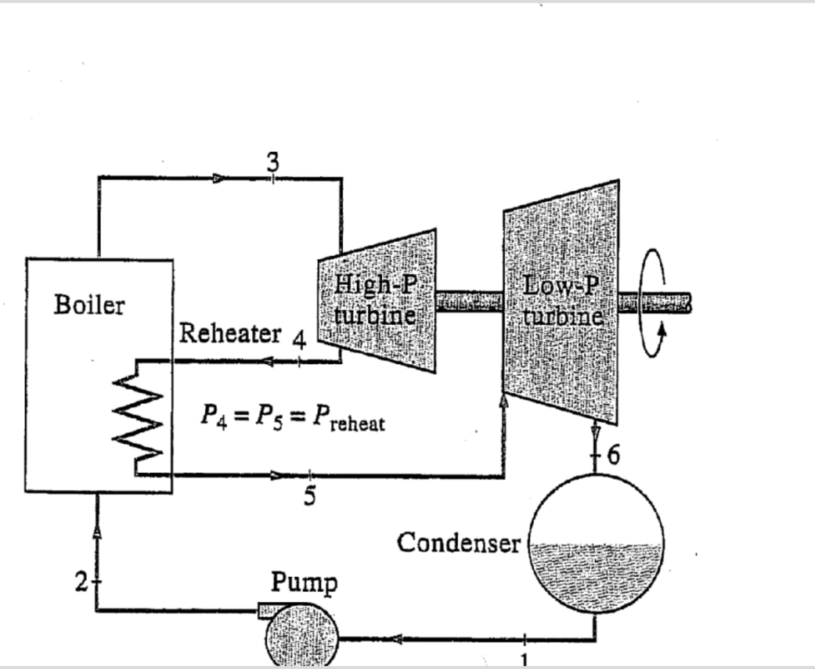
Modify

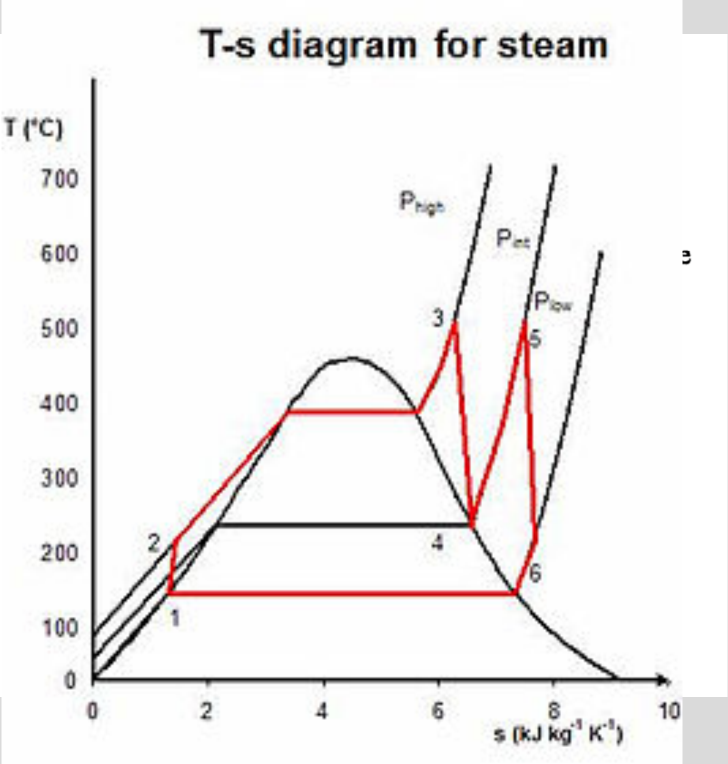
<u>Carnot Cycle</u>



Modified designs- reheat cycle

- If you are worried about wet vapor in your turbine using a re-heat cycle prevents that for one turbine.
- This end result is this allows you to run one turbine at higher pressure.

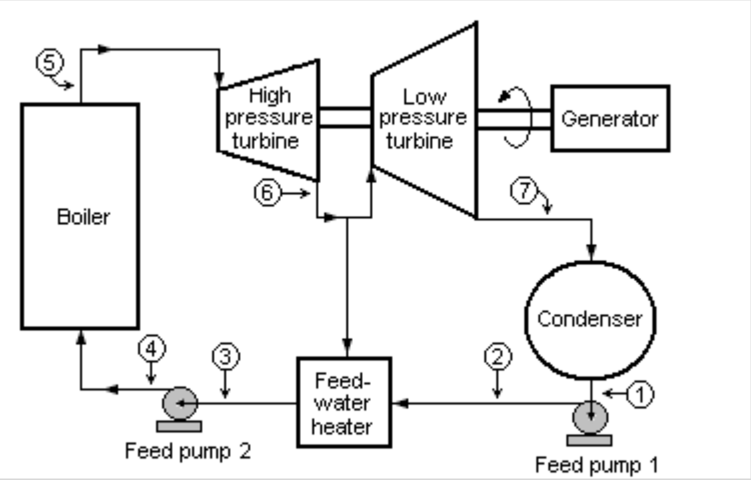




- Figure on left from Cengel and Boles, Thermodynamics, An Engineering Approach, 6th ed., McGraw Hill, 2008.

Modified designs- regeneration

- Preheats steam entering boiler using a feedwater heater, improving efficiency.
- The turbine has a high and low pressure like the reheat design.
- Some of the steam leaving the high pressure turbine gets leaked to preheat the feed to the boiler.



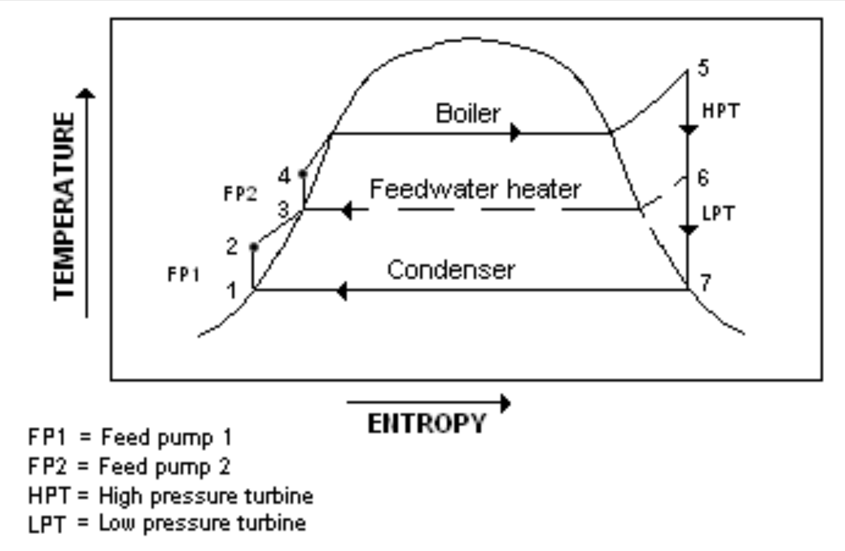


Figure from Wikipedia

Modified designs

- OK, this is just getting ridiculous.

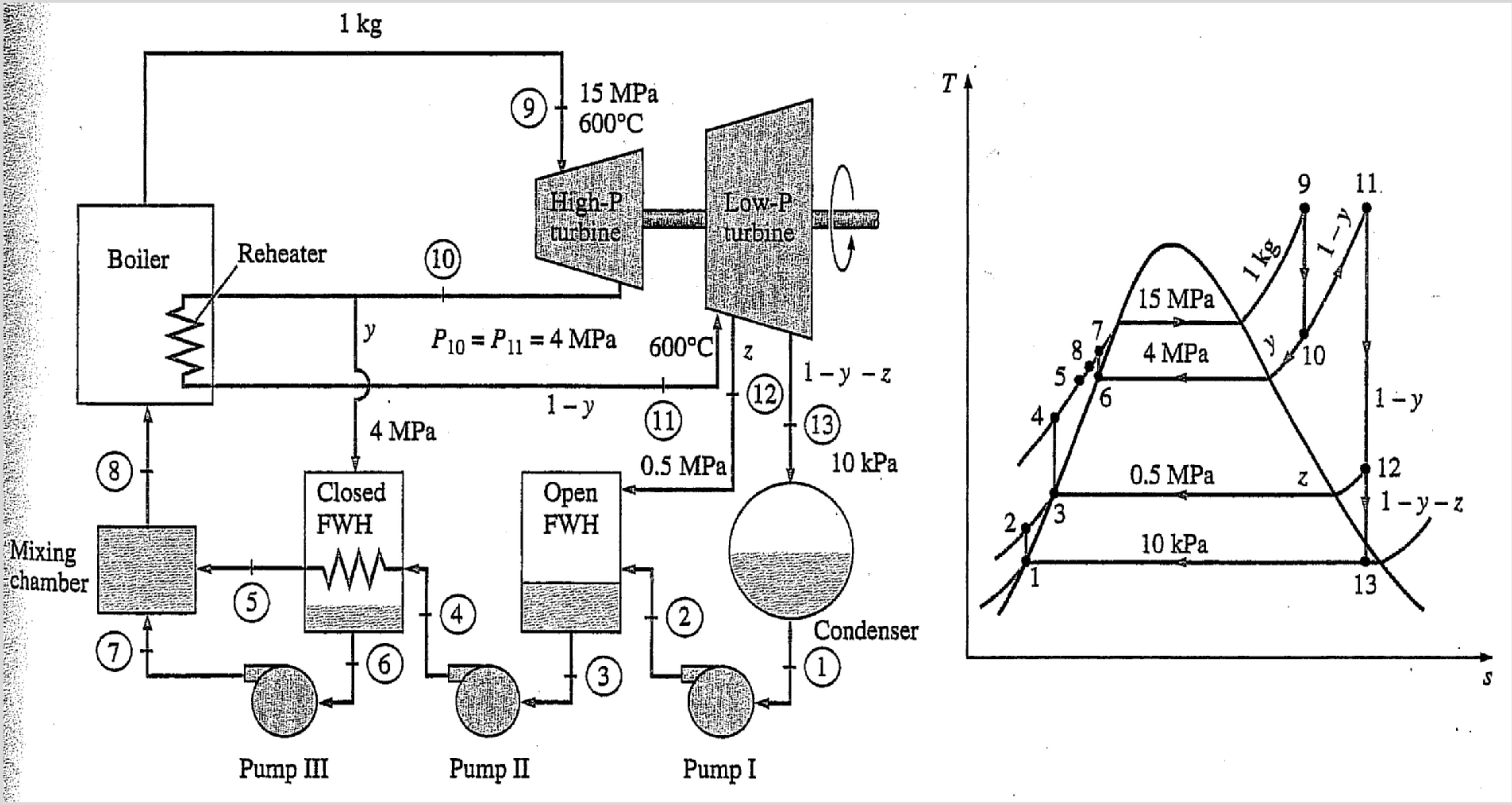
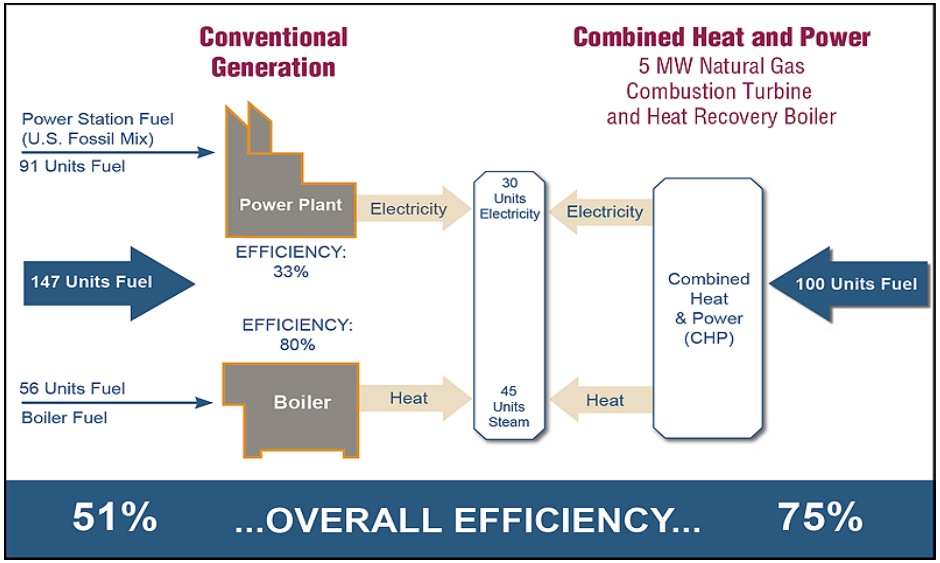


Figure from Cengel and Boles, Thermodynamics, An Engineering Approach, 6th ed., McGraw Hill, 2008.

Co-generation

- Good power plants get 33% efficiency, which means 67% is wasted as heat.
- Why don't we use this heat for home heating (as we do in Denmark).



EPA.gov

$$\eta_{Total} = \frac{W_{el} + \sum Q_{Therm}}{Q_H}$$

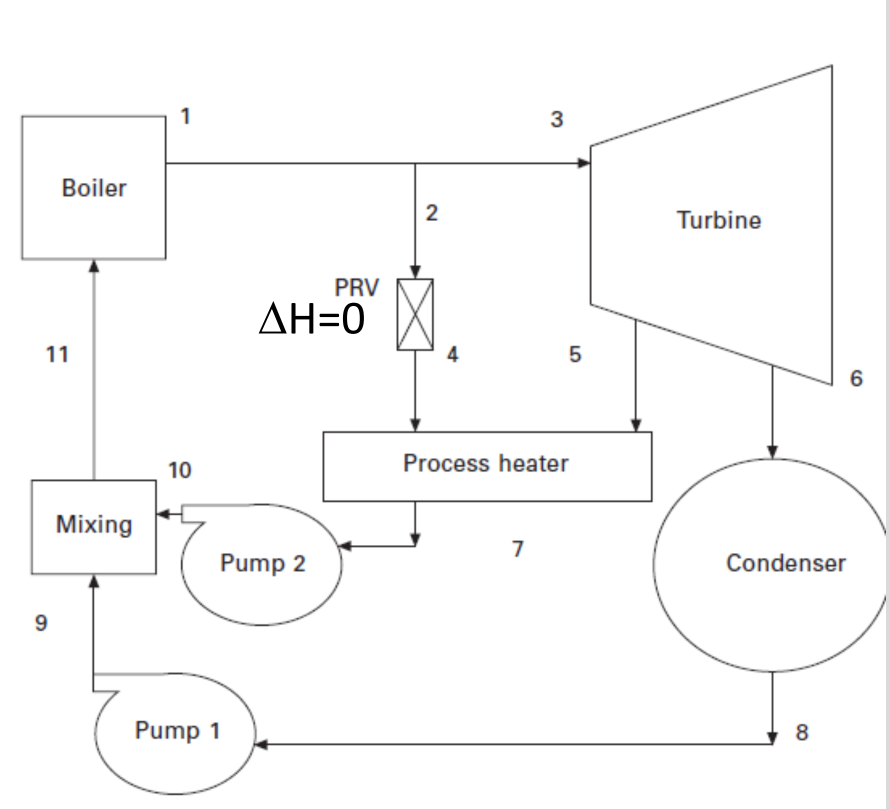
W_{el} – Electrical work (W)

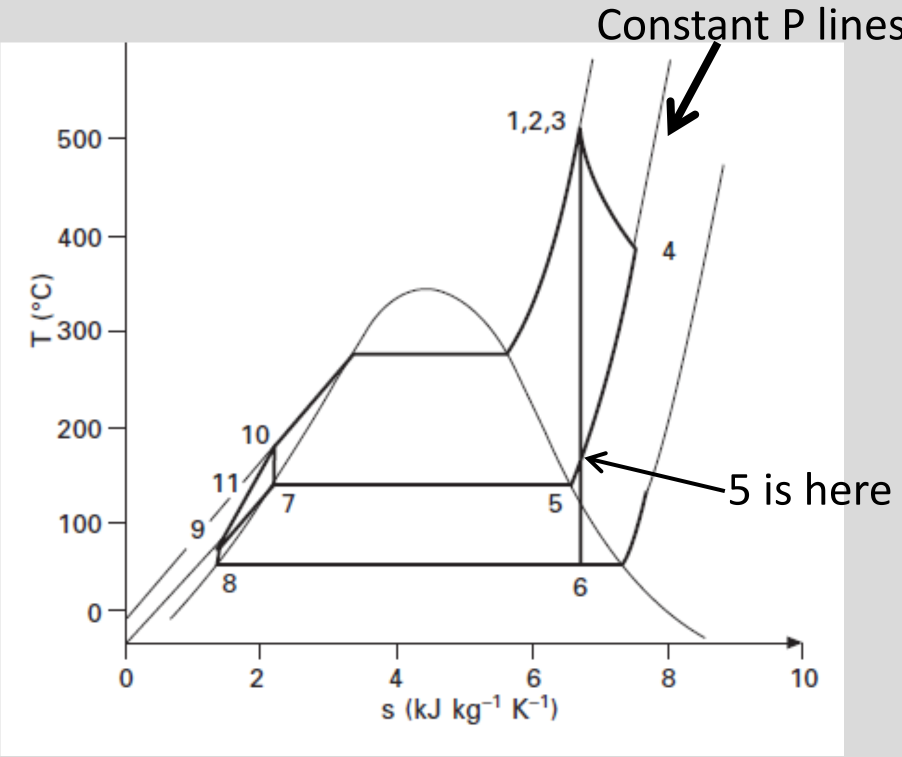
Q_{Therm} – Net useful thermal units (J/S)

Very vague description, but it works

Co-generation- Brian’s Notes

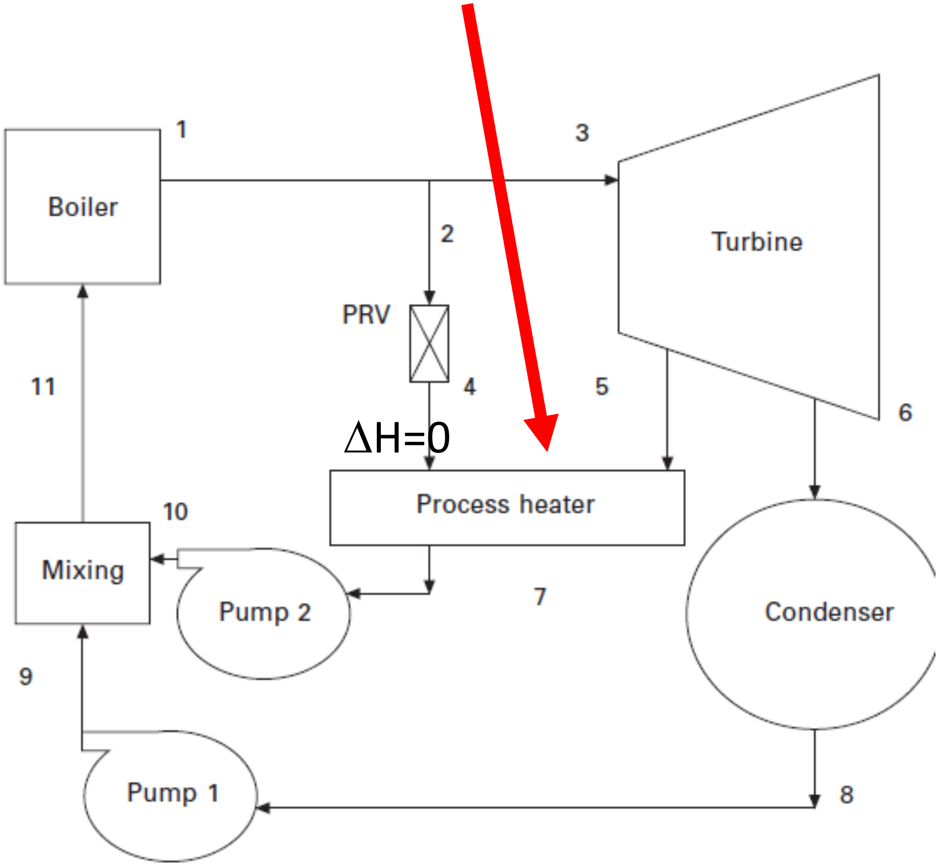
- Line 5 is a diversion line midway through the turbine (actually between the multitude of turbines.) This allows for steam to be diverted to heat when needed.
- The pressure reducing valve (PRV) is an expansion valve that is isoenthalpic. It will be set to the same pressure as line 5 so they can both operate simultaneously. It gives more flexibility to heat:electric ratio.
- The process heater is just a condenser, but in the diagram it operates at around 100C, thus allowing it to heat anything 99C and colder. (Obviously you set this temperature to match your heating needs.)
- The stream leaving the process heater will be at a lower pressure than the stream leaving the condenser (Look at wikipedia T-S phase diagram- this is correct, but not intuitive). Is this right?
- Pump 1 and Pump 2 bring them both to the same pressure, and then they go in the boiler.



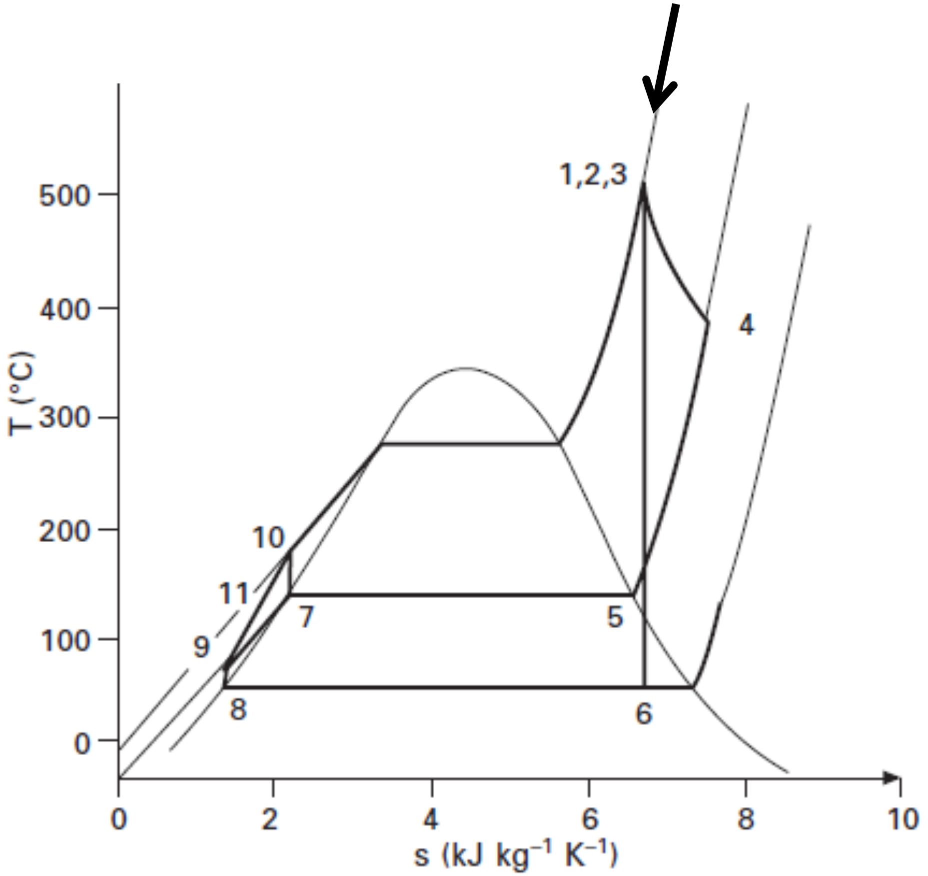


Co-generation

Extra condenser to pull out heat



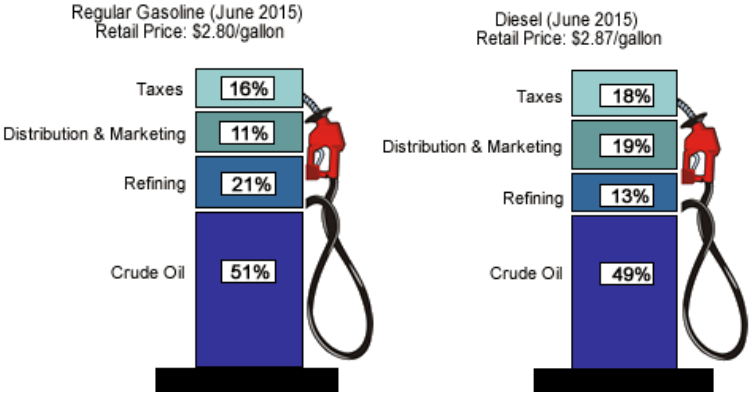
Constant pressure lines



Engines in Cars

Average Car

- 74% of the gasoline energy is lost due to engine's inefficiencies.
- 4% is friction in the driveline.
- 6% is simply idleing.
- We have 16% to actually use.
- The losses due to movement correspond to:
  - 7 % braking
  - 5 % rolling resistance
  - 4 % aerodynamic drag



Energy Information Agency

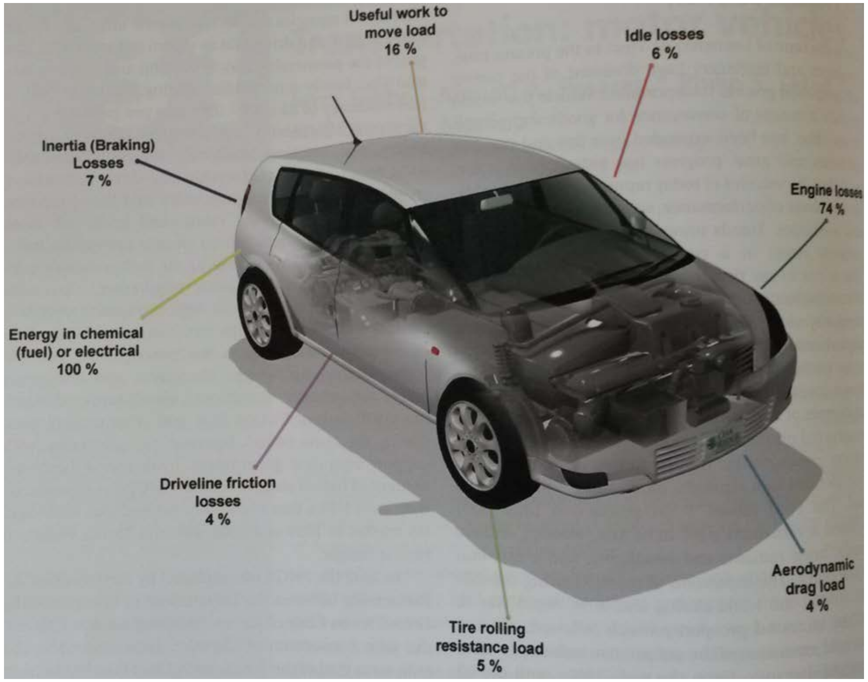


Figure from Ginley and Cahen

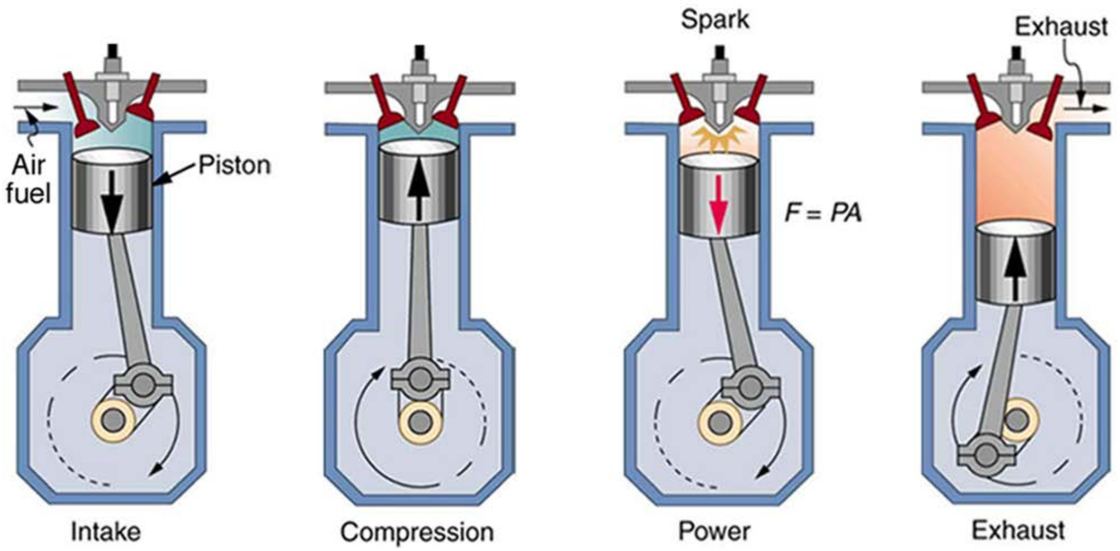
Car Engines

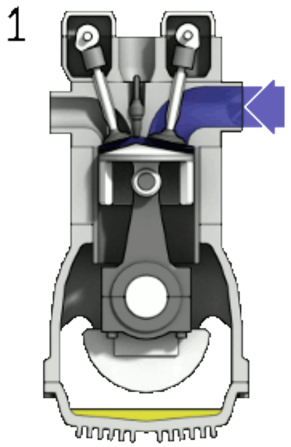
- In cars we have internal combustion engines instead of steam engines.
- Gasoline vs. coal

Property	**Gasoline (ICE)**	**Coal (Rankine)**
Energy density (MJ/L)	32.4	31.7
Specific Energy (MJ/kg)	44.4	24.0
Efficiency	30%	33%
Cheaper		✓
Low pollutants (fly ash, particulate)	✓	
Easier transport (Liquid)	✓	
Ability to make process compact	✓	
Better at transients (stop/start)	✓	

Otto cycle- *(In coordination with next slide)*

- The Otto cycle is similar to the Carnot cycle and Rankine cycle in that it has 4 steps:
  - (0) Initially we add a gas-air mixture into our chamber.
  - From 1-2 the fuel is compressed adiabatically.
  - From 2-3 the fuel is ignited, thus instantaneously increasing the pressure.
  - From 3-4 the hot gases expand adiabatically.
  - From 4-1 the high pressure forces most of the exhaust gas/heat out.
  - (5) the residual exhaust is forced out.
  - Steps 0 and 5 add an extra ‘energy dead’ revolution to the cycle





Otto cycle- *(In coordination with previous slide)*

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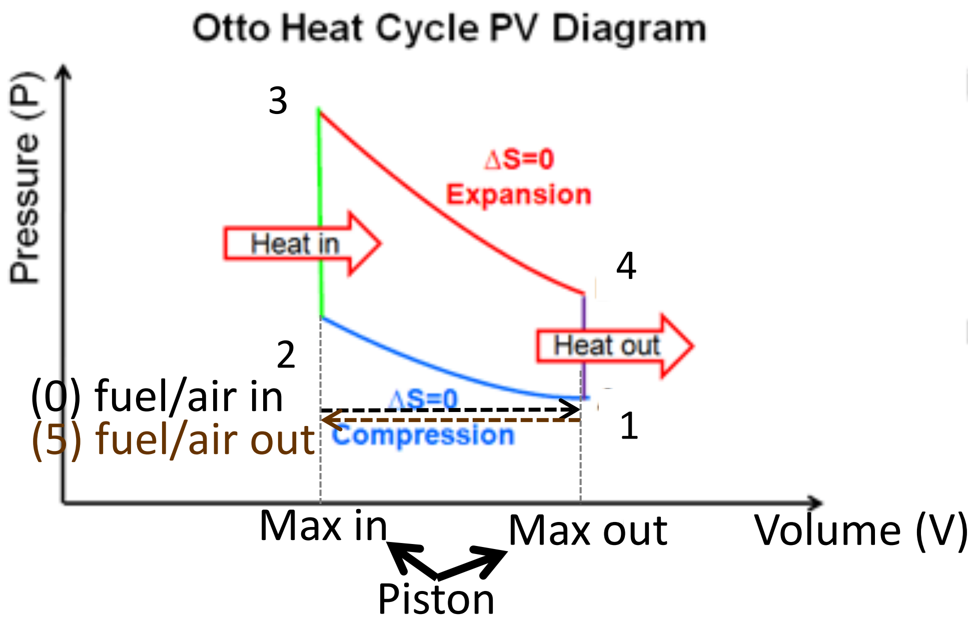
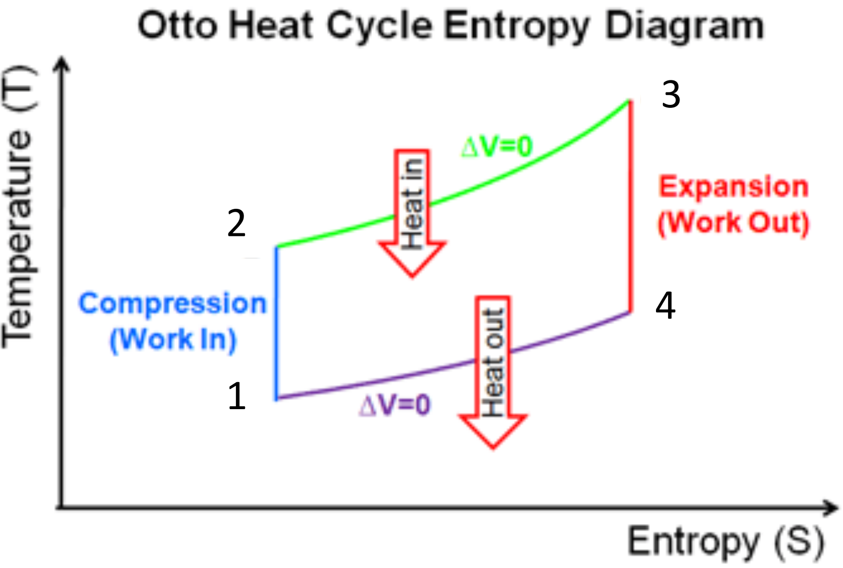




Adiabatic compression

- Steps 1-2 is adiabatic compression.
- Poisson's relationship tells us: pV^{κ} =constant

κ - is c_p/c_v

$$\Downarrow$$

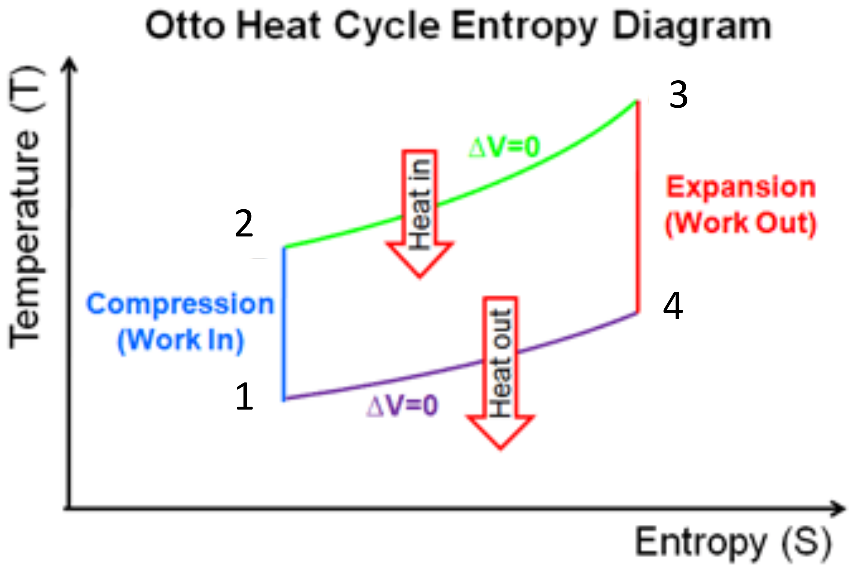
(Derivation pg. 108 EP)

$$T_1 {V_1}^{\kappa-1} = T_2 {V_2}^{\kappa-1}$$

- Since our variation in volume is limited by our engine size, this also sets T_2 as a function of κ (assuming T_1 is ambient temperature).

- Step 2-3 is our combustion reaction which produces a certain Q_H.
- This lets us determine T_3, since $\Delta V = 0$ for this step.

$$Q_H = c_v(T_3 - T_2)$$


Otto Heat Cycle Entropy Diagram

Adiabatic compression and combustion

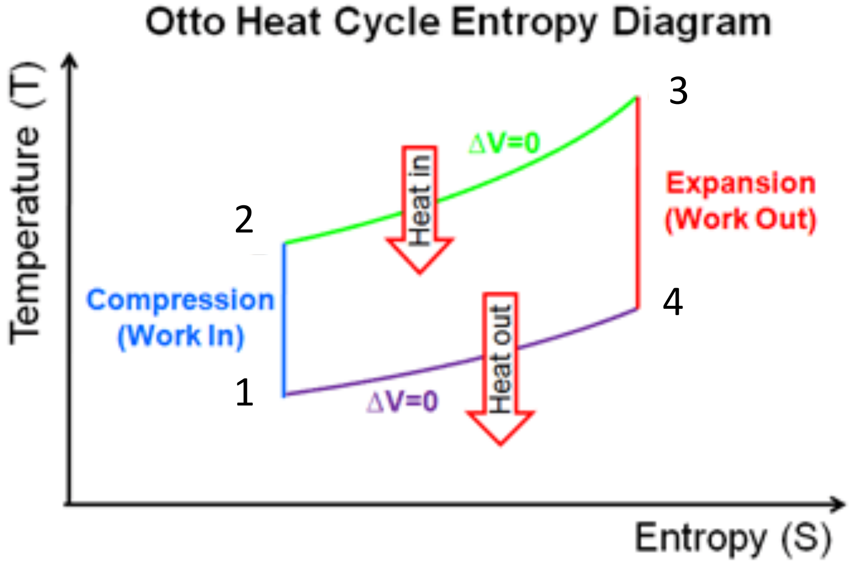
- Steps 3-4 is adiabatic expansion, until the piston maxes out.
- Again Poisson's relationship tells us: $T_3 {V_3}^{\kappa-1} = T_4 {V_4}^{\kappa-1}$

Note: Since $V_1 = V_4$, we can also say → $= T_4 {V_1}^{\kappa-1}$

- In step 4-1, we simply open the vent valve and release the pressure (@ constant volume). The exhaust releases heat via:

$$Q_C = c_v(T_4 - T_1)$$

- We can assume that replacing the volume of exhaust air with fuel air is almost an energy free process.



Efficiency

- Our efficiency is given by: $\eta = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$

- By defining $r \equiv \frac{V_1}{V_2}$ and remembering $\left\{ \begin{aligned} T_1 {V_1}^{\kappa-1} &= T_2 {V_2}^{\kappa-1} \\ T_3 {V_3}^{\kappa-1} &= T_4 {V_1}^{\kappa-1} \end{aligned} \right.$

⬇ Boring derivation

V_1= Max Open
V_2 = Min Open

$$\eta_{Otto} = 1 - \frac{1}{r^{\kappa-1}}$$

- κ is typically dominated by air (κ=1.3), with a typical air-fuel mixture being 1.4. This variable is hard to change.

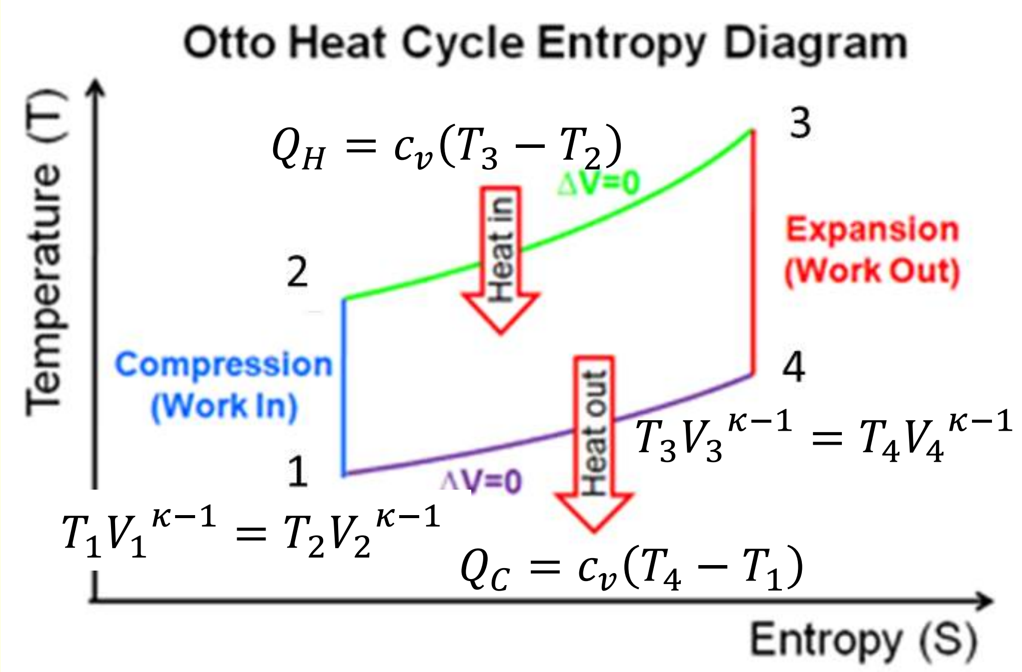
- r can be increased up to about 13. Above that point the fuel self-ignites. 8-11 is normal in cars.

Exercise

- With a compression ratio of 10 and a κ of 1.4, what is the efficiency of an Otto-engine?
- How much power can you get from 4 mL of gasoline/s? (Gasoline has an energy density of 32.4 MJ/L.)
- If after expansion your gas temperature is 500 °C, and you have a r=10, and κ =1.4,

Could you make this engine out of carbon steel (T_{max} = 750 °C)?

$$\eta = \frac{W}{Q_H} =$$



$$Q_H = c_v(T_3 - T_2)$$

$$T_3 {V_3}^{\kappa-1} = T_4 {V_4}^{\kappa-1}$$

$$T_1 {V_1}^{\kappa-1} = T_2 {V_2}^{\kappa-1}$$

$$Q_C = c_v(T_4 - T_1)$$

Exercise- Solution

- Efficiency is: $\eta_{Otto} = 1 - \frac{1}{r^{\kappa-1}} = 1 - \frac{1}{10^{1.4-1}} = 60\%$

$$Work = \eta Q_H = 60\% \times (32.4MJ/L \times 4mL/s) = 78kW$$

- 65kW is about 40% maximum power of a large car.

- Could you make this engine out of carbon steel (T_{max} = 750 °C)?

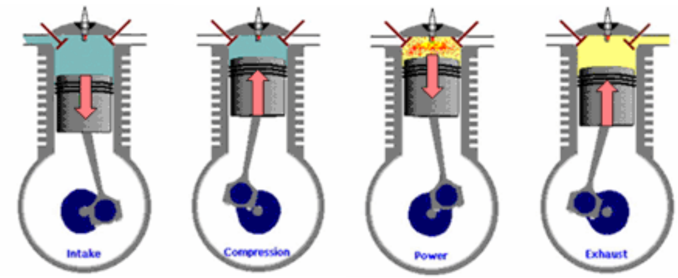
$$T_3{V_3}^{\kappa-1} = T_4{V_4}^{\kappa-1} \Longrightarrow T_3 = T_4\left(\frac{V_4}{V_3}\right)^{\kappa-1} = 773K \times 10^{1.4-1} = 1949\ K$$

= 1669 °C

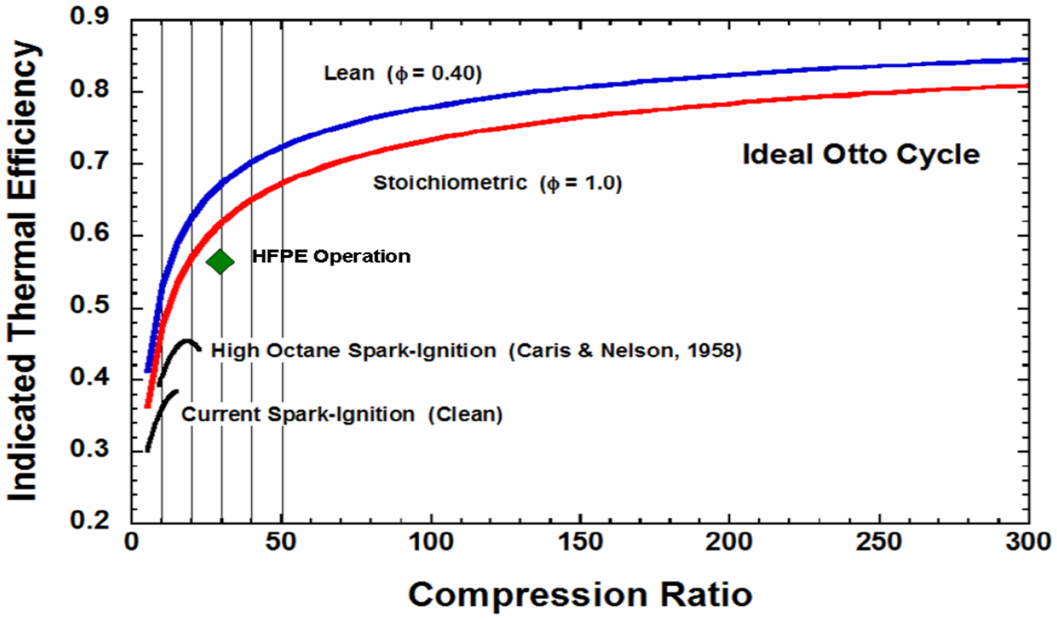
No, you need alloyed steel

Real efficiency

- We should get around 60% efficiency, but we actually get close to 30-40%.
- All the moving parts and associated friction prevents us from getting these high efficiencies.
- A simple look at the rotating shaft makes is apparent that there will be friction.



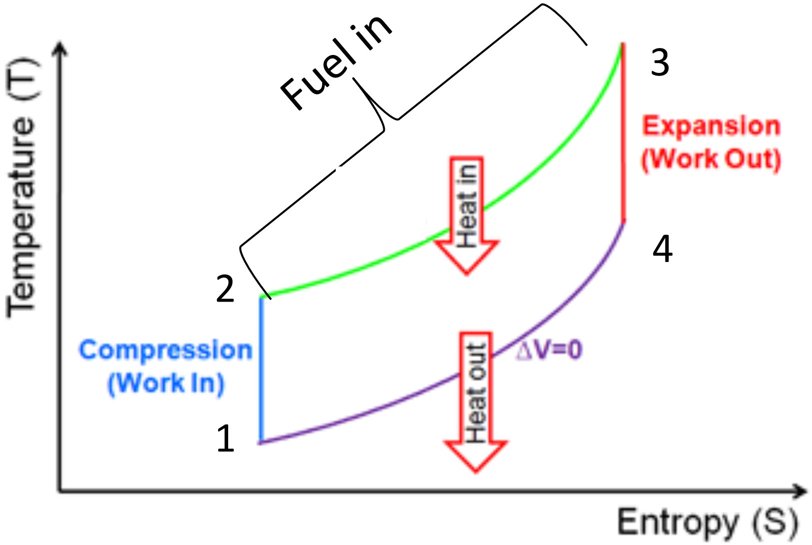
Four-Stroke Engine Cycle

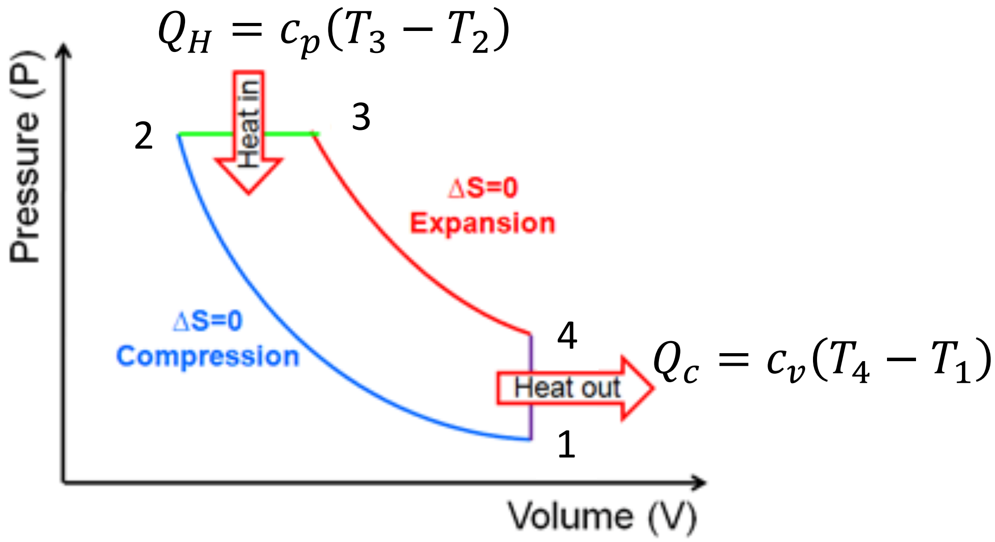


Paul Miles, 2010

Diesel engine

- The diesel engine gets around the auto-ignition issue, by compressing the gas without fuel in it. Once compressed, the fuel is let in.
- The steps are:
  - From 1-2 the fuel is compressed adiabatically.
  - From 2-3 the fuel is added/ignited, isobarically ($\Delta P = 0$).
  - From 3-4 the hot gases expand adiabatically.
  - From 4-1 the high pressure forces most of the exhaust gas/heat out.
  - There still is a dead cycle that removes the excess gas and adds air




$$Q_H = c_p(T_3 - T_2)$$

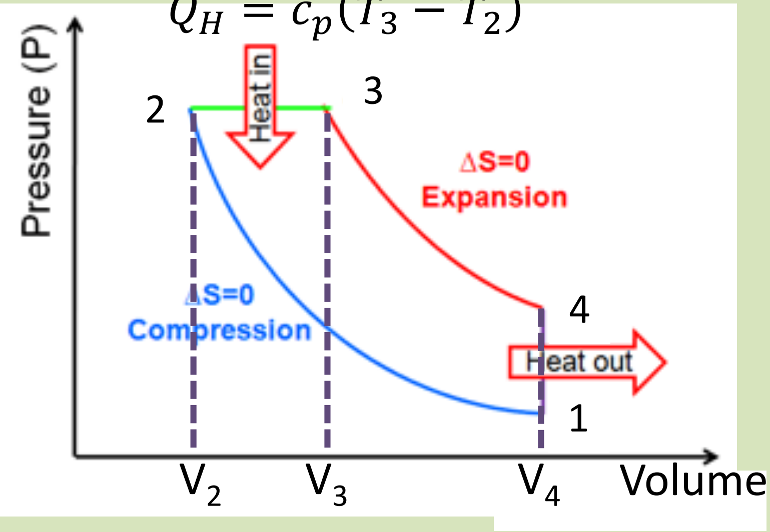
$$Q_c = c_v(T_4 - T_1)$$

Diesel engine

- The key to making this efficient is choosing when to stop adding fuel. (This is at point 3)
  - If $V_3 \rightarrow V_2$ the heat (Q_H) in is minimized.
  - If $V_3 \rightarrow V_4$ then our work (W) is minimized.
  - V_3 and V_4 are related via Poisson's Equation

$$\eta = \frac{W}{Q_H}$$

$$Q_H = c_p(T_3 - T_2)$$



- By defining an cut-off ratio as:

$$r_{cf} \equiv \frac{V_3}{V_2}$$

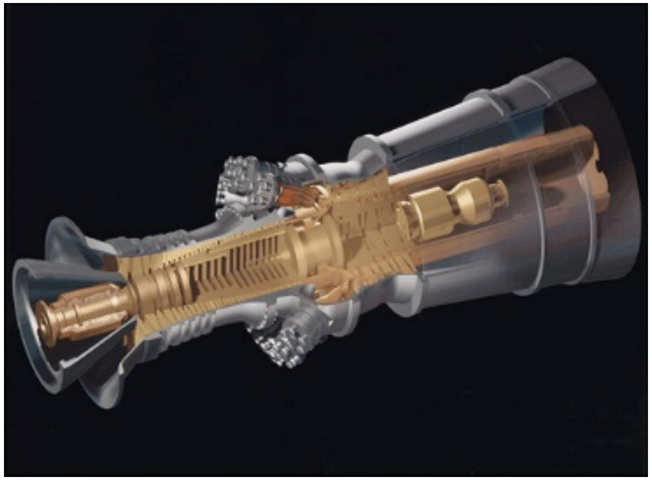
- We can derive the following:

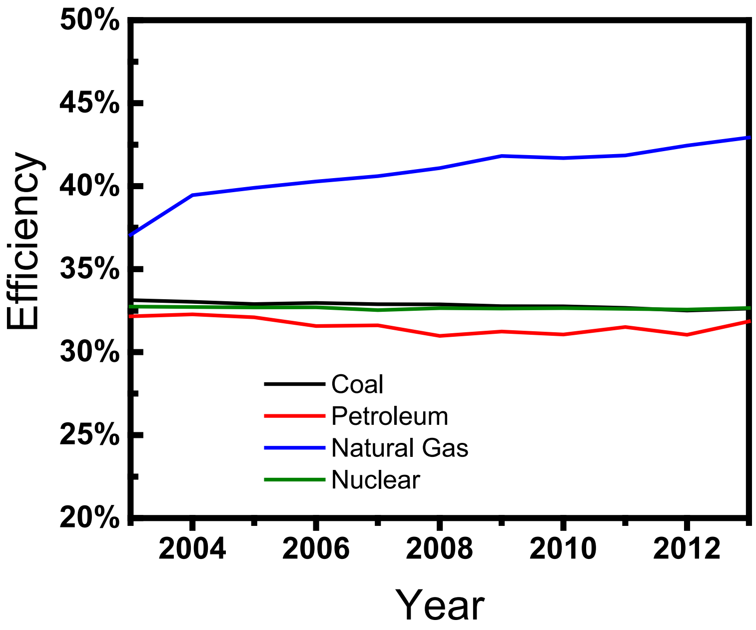
$$\eta_{Diesel} = 1 - \frac{1}{\kappa}\frac{1}{r^{\kappa-1}}\frac{{r_{cf}}^{\kappa} - 1}{r_{cf} - 1}$$

Why don’t we use Otto Engine / Diesel Engine cycle for power generation ?

Gas Turbine

- The gas turbine does not need an intermediate medium to transfer heat.
- Thus this is no limited by the endoreversible Carnot efficiency limit.
- This is why natural gas has the highest efficiency.

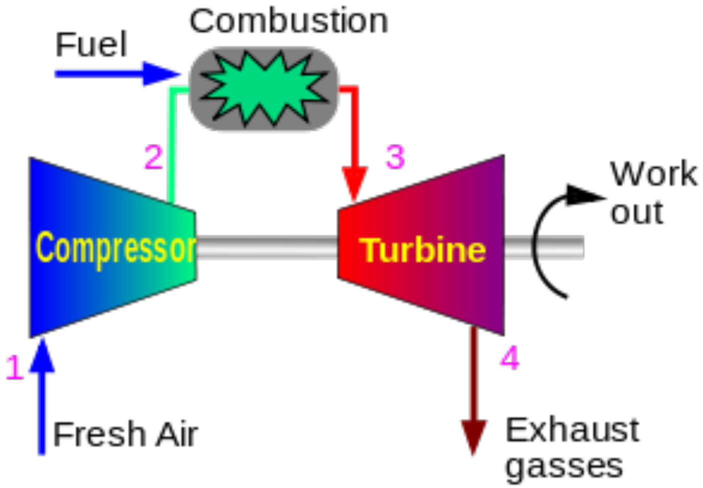


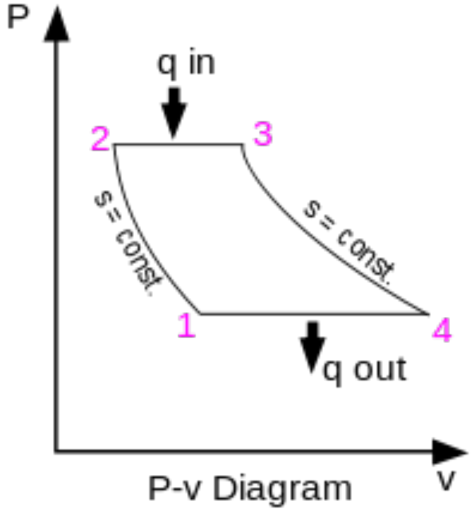


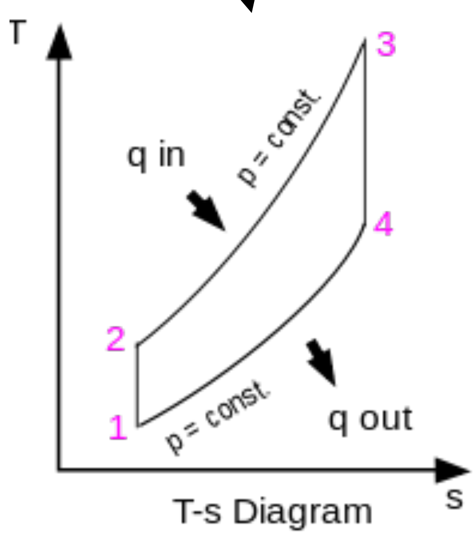
Gas Turbine- Thermodynamics

- The gas turbine follows the Brayton Cycle
  - 1-2 Isentropic compression ($\Delta S = 0$)
  - 2-3 Isobaric combustion ($\Delta P = 0$, Q_H)
  - 3-4 In theory Isentropic expansion ($DS = 0$, W)
  - 4 Removal of gas/heat (Q_c)

Just like the Otto Cycle, except without the 'dead cycle'

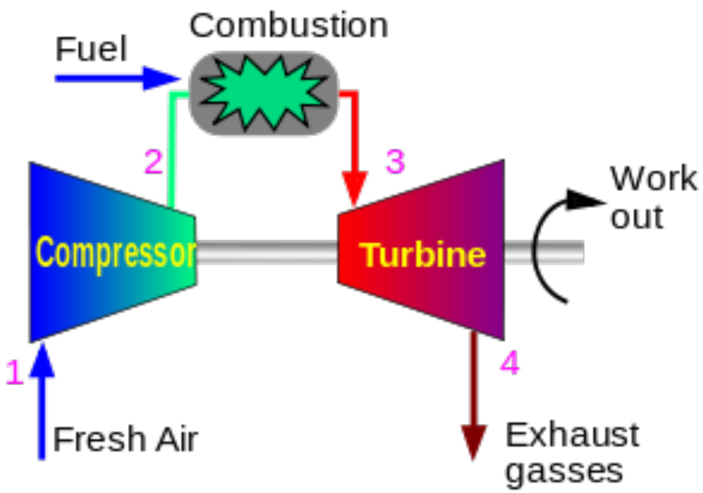


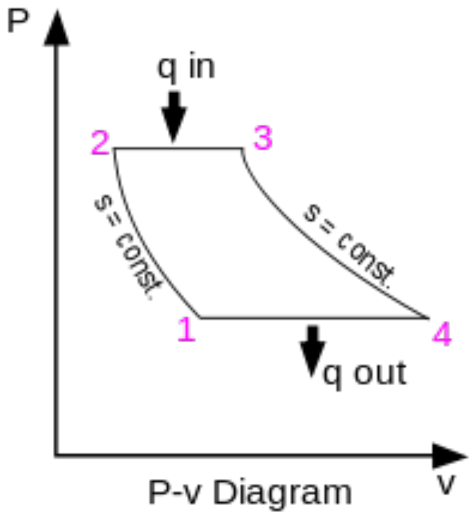




Gas Turbine- Thermodynamics

- One of the limiting factors in gas turbines is getting enough pressure drop across the turbine.
- The pressure drop is dependent upon how fast the turbine blades can spin.
- Micro-turbines can spin at 500k rpm whereas power plant turbines run at 10k-15k rpm.





Gas Turbine- Materials

- Due to the simplicity, companies operate these at higher temperatures.
- Turbines have been shown to run at over 1500C.
  - For how long that is another question…
- Durability and finding the right alloy to work spinning at 10,000rpm is not easy.
- Here are the 4 major companies producing turbines:
  - General Electric
  - Siemens
  - Mitsubishi
  - Ansalado Energia

Gas Turbine- Practical considerations

- Thermodynamically you always want the outgoing pressure to be almost the same as incoming pressure.
- For turbine based propeller airplanes though, you need thrust, which is derived from high pressure coming from your exhaust gas.
- Thus a comprise is made between power to spin the blades versus thrust from exiting gas

- Jet engines are based solely on thrust, thus the only power used is that for compressors and auxiliary equipment.

Advantages vs. Disadvantages

- Advantages:
  - More efficient
  - Simpler
  - Cheaper for power plant
  - Fast start/stop compared to steam based processes
- Disadvantages
  - Needs gas fuel
  - Slow start/stop compared to internal combustion engine
  - Complicated materials issues due to high temperature operation

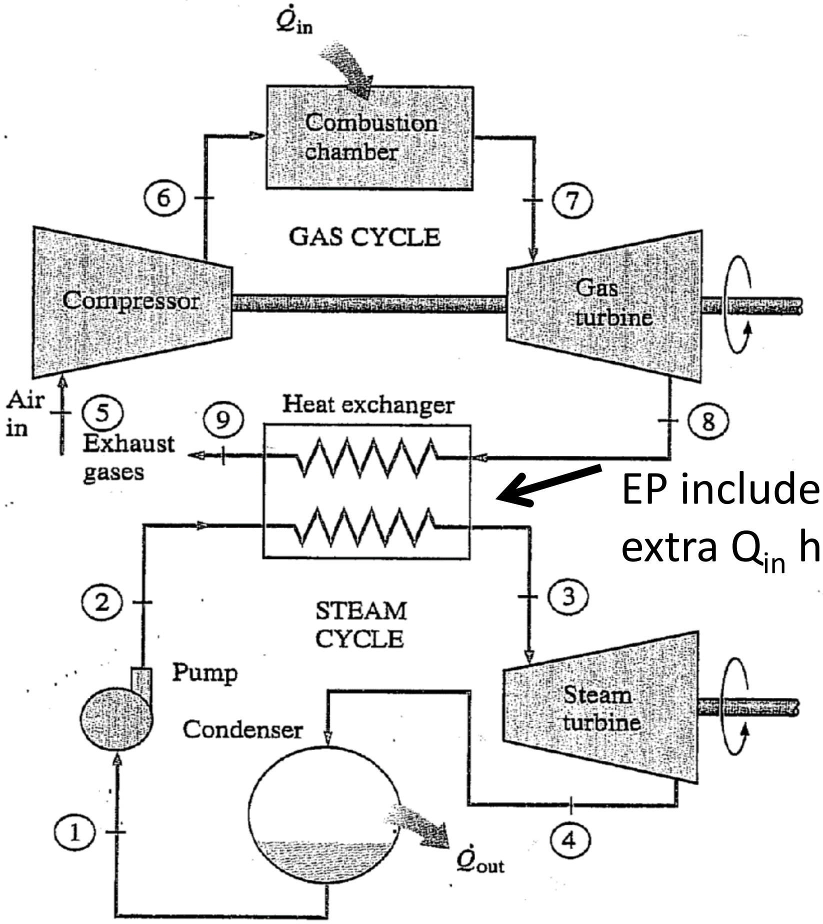
- Conclusion: This is the best way to do things unless you need quick start/ stop. Thus great for power generation, bad for automobiles.

Combined Cycle

- The combined cycle uses inefficiencies in the turbine to run a secondary Rankine cycle.
- This increases the efficiency, but also increases capital costs.
- The efficiency for this approach is:

$$\eta_{Total} = \eta_{gas} + \eta_{steam} - \eta_{gas}\eta_{steam}$$

(Derivation is in EP)



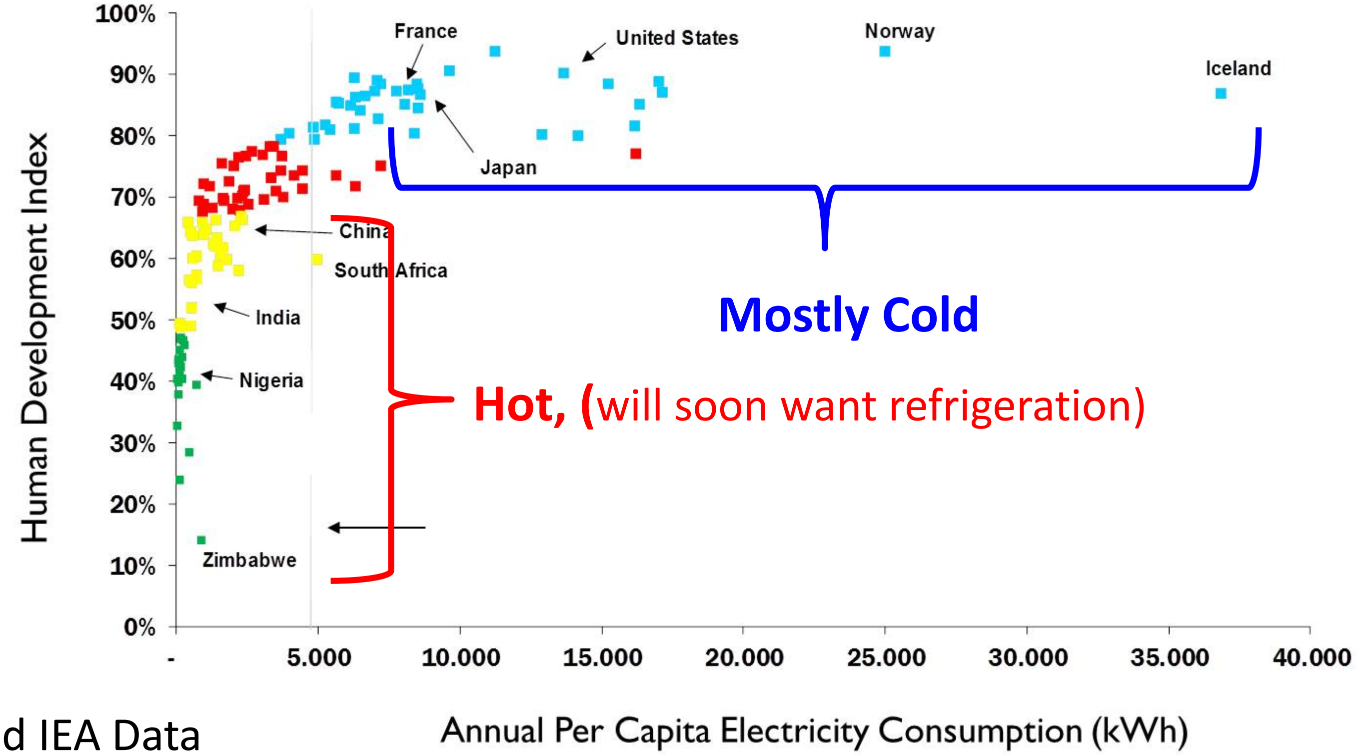
EP includes extra Q_{in} here

Figure from Cengel and Boles, Thermodynamics, An Engineering Approach, 6th ed., McGraw Hill, 2008.

Break

Refrigeration

- Air conditioning, refrigerators and freezers use refrigeration cycles.
- Worldwide refrigeration accounts for ~ 0.1 TW.
- The refrigeration market is set to increase dramatically though.



Based off of UN and IEA Data

Refrigerants

- Typically the biggest sustainability issue with refrigeration's have been the environmental impact of the refrigerants.

- Water is no good since it freezes at 0 °C.

- Initially we used:
  - Sulfur dioxide- toxic
  - Methyl chloride – toxic
  - Ammonia- very strong odor

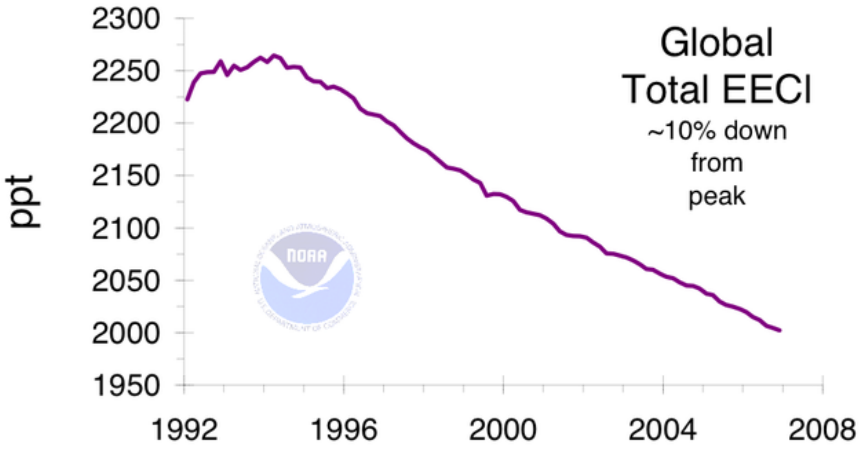
- More recently we used:
  - $CFCl_3$
  - CF_2Cl_2
  - $C_2F_3Cl_3$
  - $C_2F_4Cl_2$

- The biggest problem is fluid leaking and disposal of waste refrigerants.

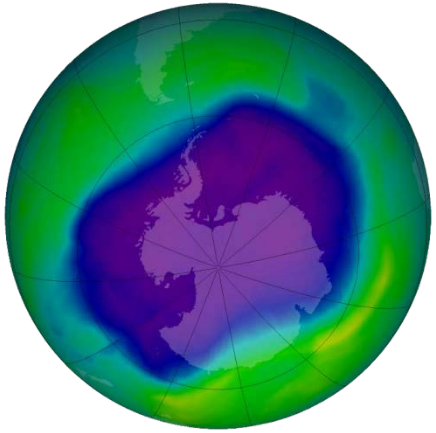
Montreal Protocol

- Scientists showed that many materials were destroying the ozone layer.
  - The ozone layer basically absorbs high energy/destructive photons.
- The Montreal Protocol was ratified in 1987 and was put into practice in 1989.
- Basically this phased out chlorofluorocarbons.

$CFCl_3$
CF_2Cl_2
$C_2F_3Cl_3$
$C_2F_4Cl_2$
C_2F_5Cl



Ozone depleting materials in the atmosphere



Ozone hole, 2006

Climate change

- Leaking refrigerants are a major greenhouse gas.

- There is actually a pretty big engineering push to find 'green' refrigerants.

- Ammonia is returning to favor since it has no global warming potential.

- CO_2 is also looking very promising. Leaky CO_2 won't contribute significantly to climate change.

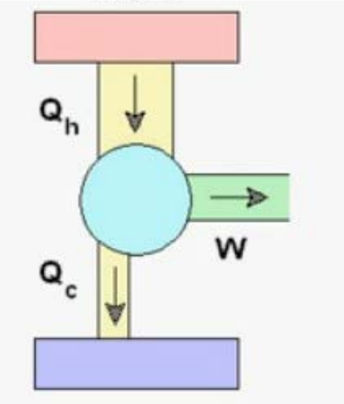
Molecule	**CO_2 Equivalent**
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous oxide (N_2O)	298
Hydrofluorocarbons (HFCs)	2,000-11,000
Perfluorocarbons (PFCs)	7,000-12,000
Sulphur hexafluoride (SF_6)	22,800
$CHClF_2$ (Most popular refrig., R22)	1810

100 year global warming potential (Wikipedia)

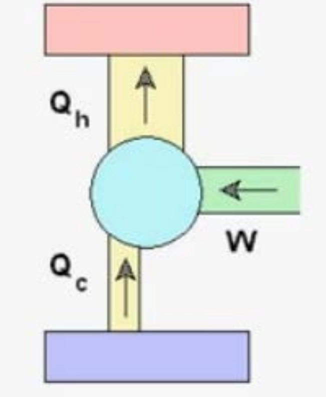
Refrigeration cycle

- Refrigeration is simply the reverse of a heat engine.

Heat engine



Refrigerator



Efficiency

$$\eta_{Carnot} = \frac{W}{Q_H} = 1 - \frac{T_C}{T_H}$$

Coefficient of performance (COP)

$$COP = \frac{Q_c}{W}$$

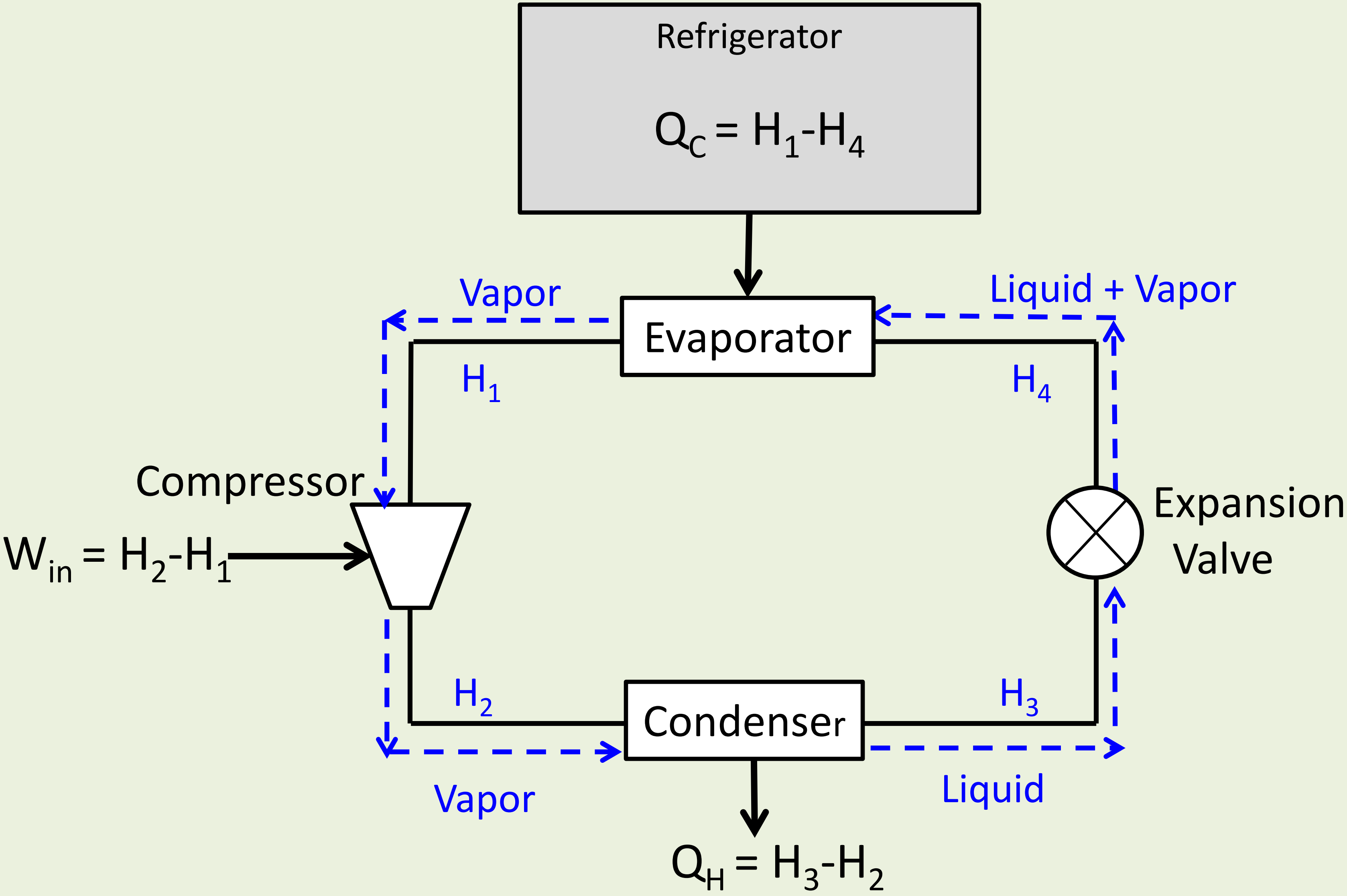
Key to efficiency

Run at high temperatures

Key to high COP

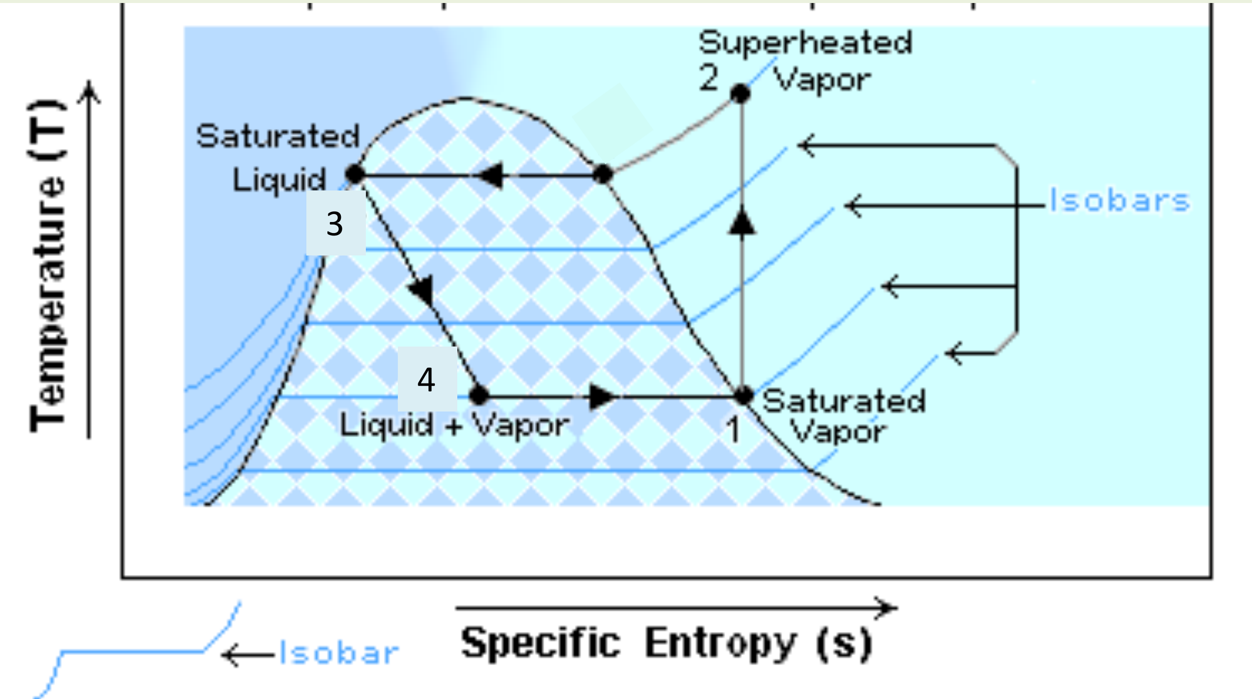
Small variation in temperature

Refrigeration cycle

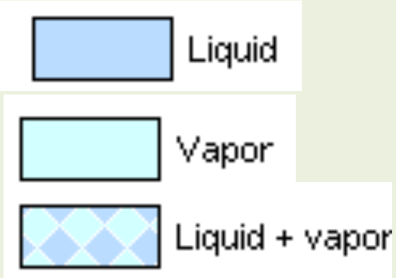


Refrigeration cycle

- Operation of a refrigeration cycle:
  - Adiabatic compression of vapor from H_1 to H_2. $W_{in} = H_2 - H_1$
  - Condensing superheated vapor isobarically to saturated vapor. Then isothermally to saturated liquid. $Q_H = H_3 - H_2$
  - Liquid flashes into liquid + vapor mixture across an expansion valve. $\Delta H = 0$
  - Liquid + vapor is evaporated to saturated vapor. $Q_C = H_1 - H_4$



$$COP = \frac{H_1 - H_4}{H_2 - H_1}$$

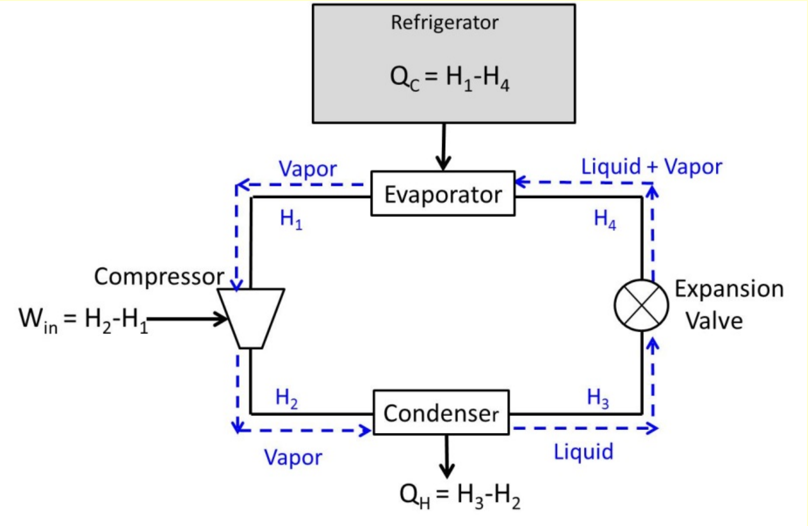


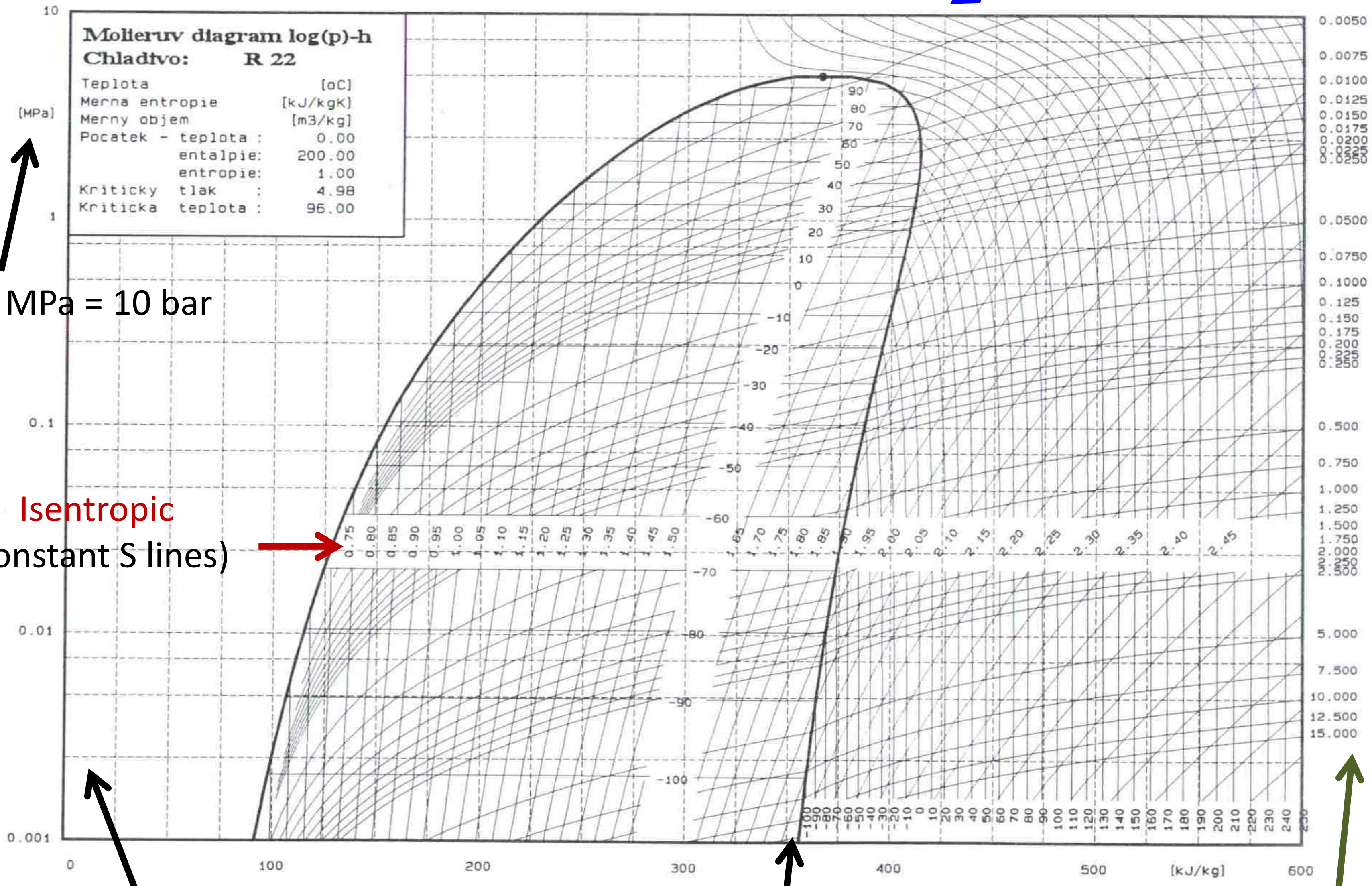
Refrigeration example

- You are given 2 options for an air conditioner:
  - Group A- You use R-22 as a coolant. You compress your fluid from atmospheric pressure to 20 bar at 100% efficiency $(\Delta S) = 0$. You then let it condense at a constant pressure to saturated liquid. Next you use your expansion valve to take it back to atmospheric pressure. You then let it evaporate until it is a saturated vapor.
  - Group B- You use CO_2 as a coolant. You compress your fluid from 10 bar to 65 bar at 100% efficiency $(\Delta S) = 0$. You then let it condense at a constant pressure to saturated liquid. Next you use your expansion valve to take it 10 bar. You then let it evaporate until it is a saturated vapor.

<u>Questions:</u>

- What is your COP?
- How much work do you need to put in to get 5 kW of cooling with an 85% efficient compressor?
- What is your vapor flow rate at H_1?
- How could you improve efficiency?





Isotherms
(constant T lines)

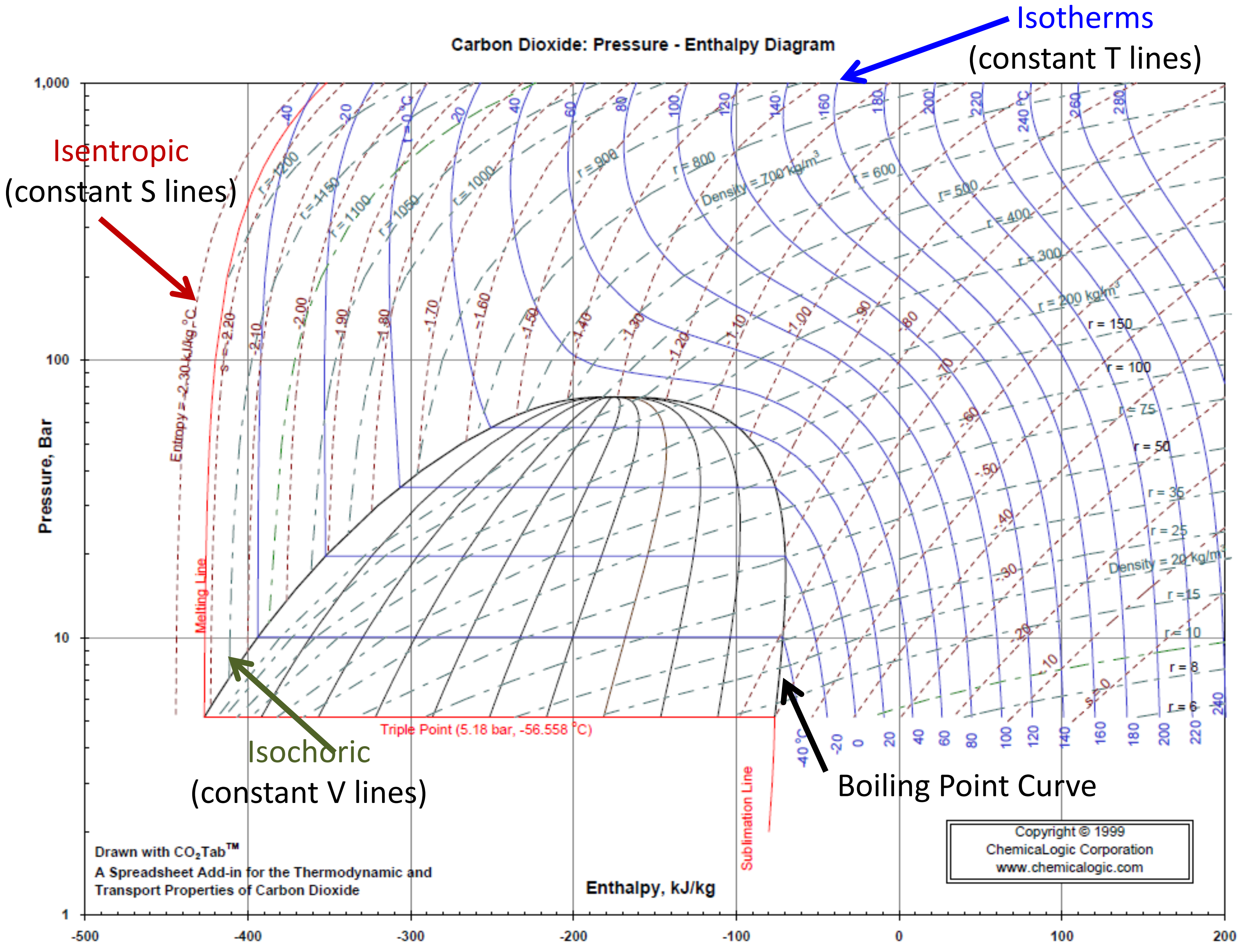
1 MPa = 10 bar

Isentropic
(constant S lines)

Each line is an increase of 25%

Boiling Point Curve

Isochoric
(constant V lines)



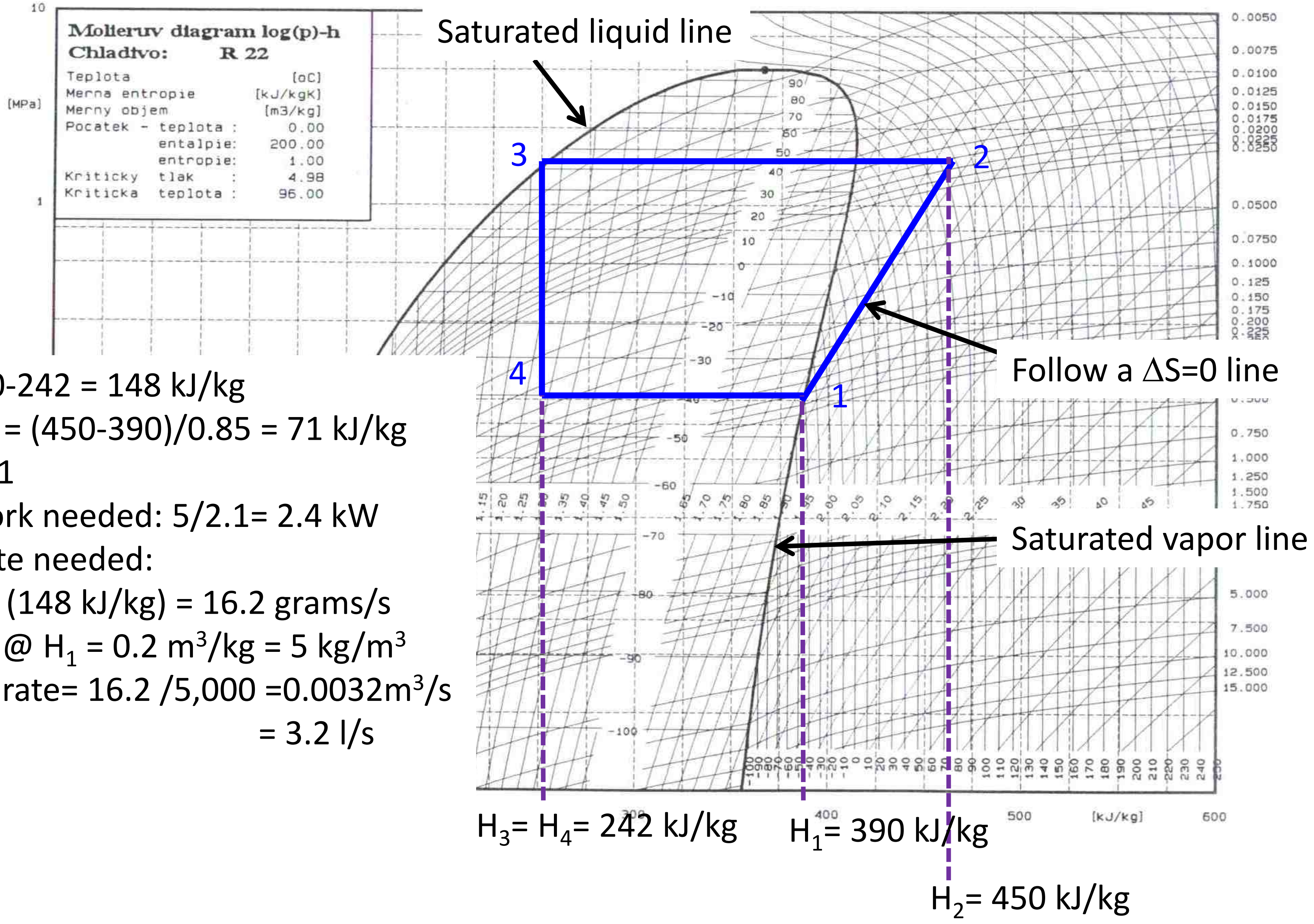
Isotherms
(constant T lines)

Isentropic
(constant S lines)

Isochoric
(constant V lines)

Boiling Point Curve

Refrigeration example R22 Solution



Saturated liquid line

Follow a $\Delta S=0$ line

Saturated vapor line

$H_3 = H_4 = 242$ kJ/kg

$H_1 = 390$ kJ/kg

$H_2 = 450$ kJ/kg

$Q_c = 390-242 = 148$ kJ/kg

Work in = (450-390)/0.85 = 71 kJ/kg

COP= 2.1

Total work needed: 5/2.1= 2.4 kW

Mass rate needed:

2.4 kW/ (148 kJ/kg) = 16.2 grams/s

Volume @ $H_1 = 0.2\ m^3/kg = 5\ kg/m^3$

Volume rate= 16.2 /5,000 =0.0032m^3/s

= 3.2 l/s

Refrigeration example CO_2 solution

Q_c = 20- -220 = 240 kJ/kg

Work in = (10- -70)/0.85 = 106 kJ/kg

COP= 2.3

Total work needed: 5/2.3= 2.2 kW

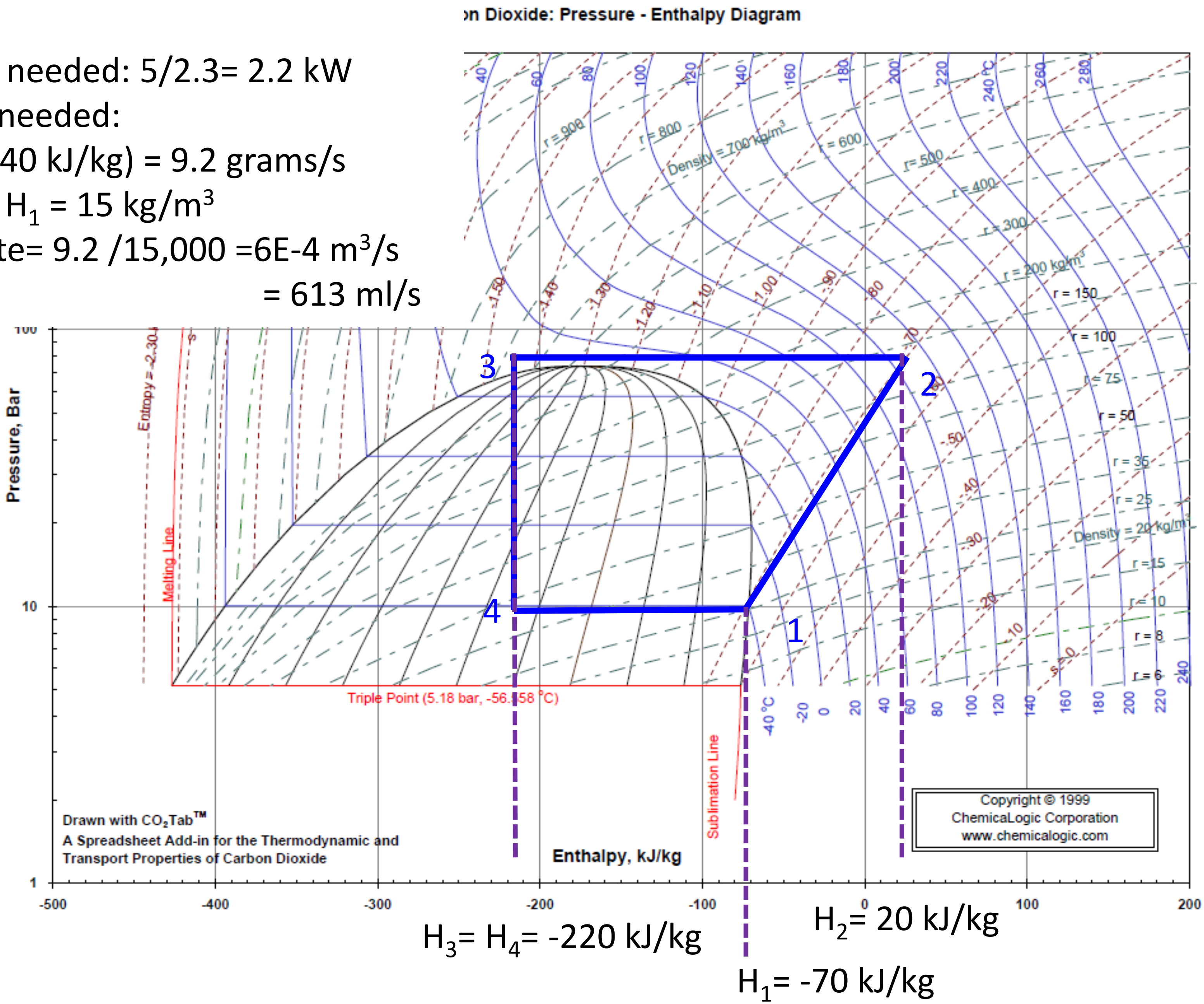
Mass rate needed:

2.2 kW/ (240 kJ/kg) = 9.2 grams/s

Density @ H_1 = 15 kg/m^3

Volume rate= 9.2 /15,000 =6E-4 m^3/s

= 613 ml/s



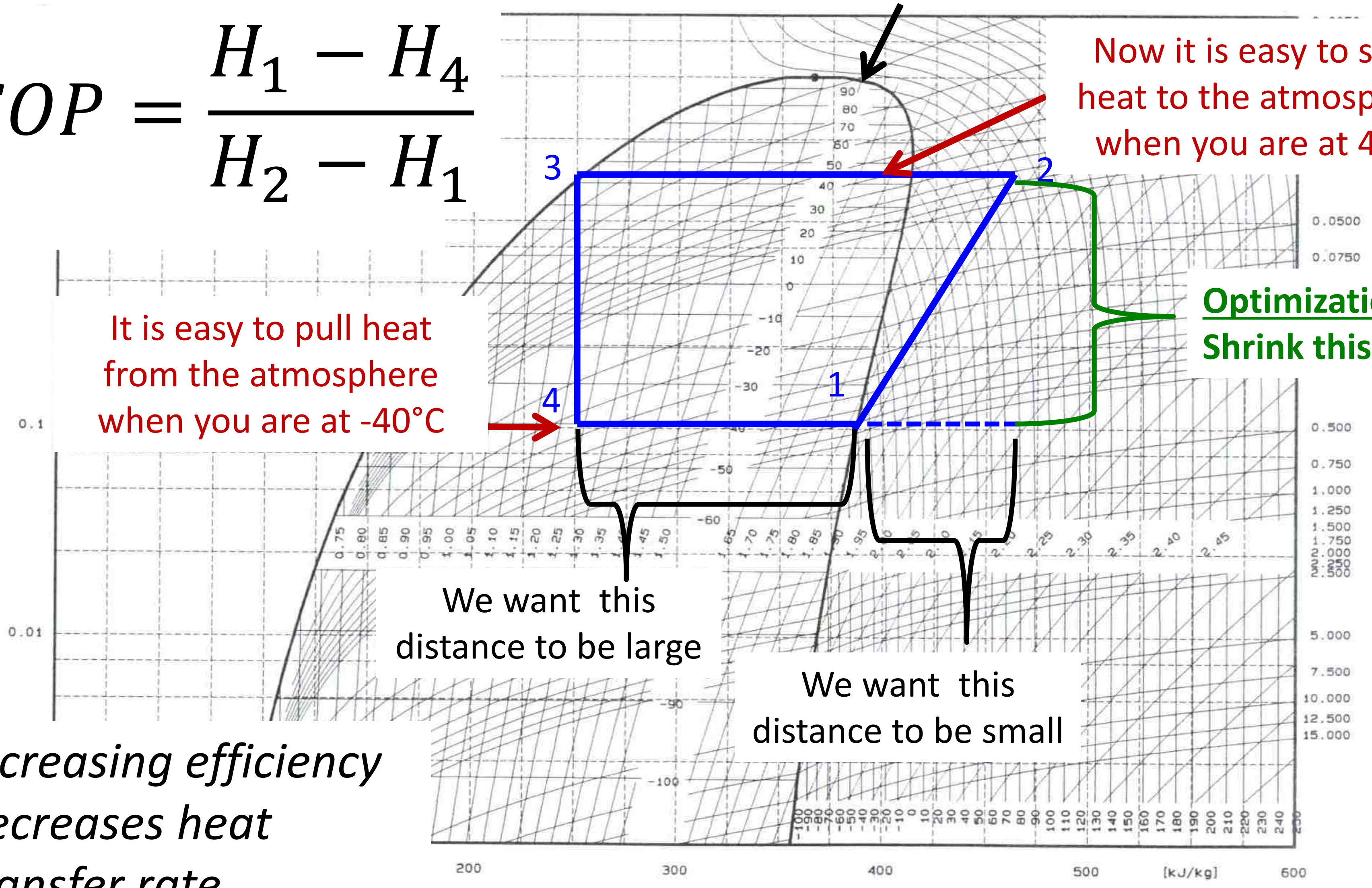
H_3= H_4= -220 kJ/kg

H_2= 20 kJ/kg

H_1= -70 kJ/kg

Refrigeration example R22 Solution

$$COP = \frac{H_1 - H_4}{H_2 - H_1}$$



Temperature Isotherms

Now it is easy to send heat to the atmosphere when you are at 45°C

Optimization:
Shrink this area

It is easy to pull heat from the atmosphere when you are at -40°C

We want this distance to be large

We want this distance to be small

Increasing efficiency decreases heat transfer rate

Options

Now

Later

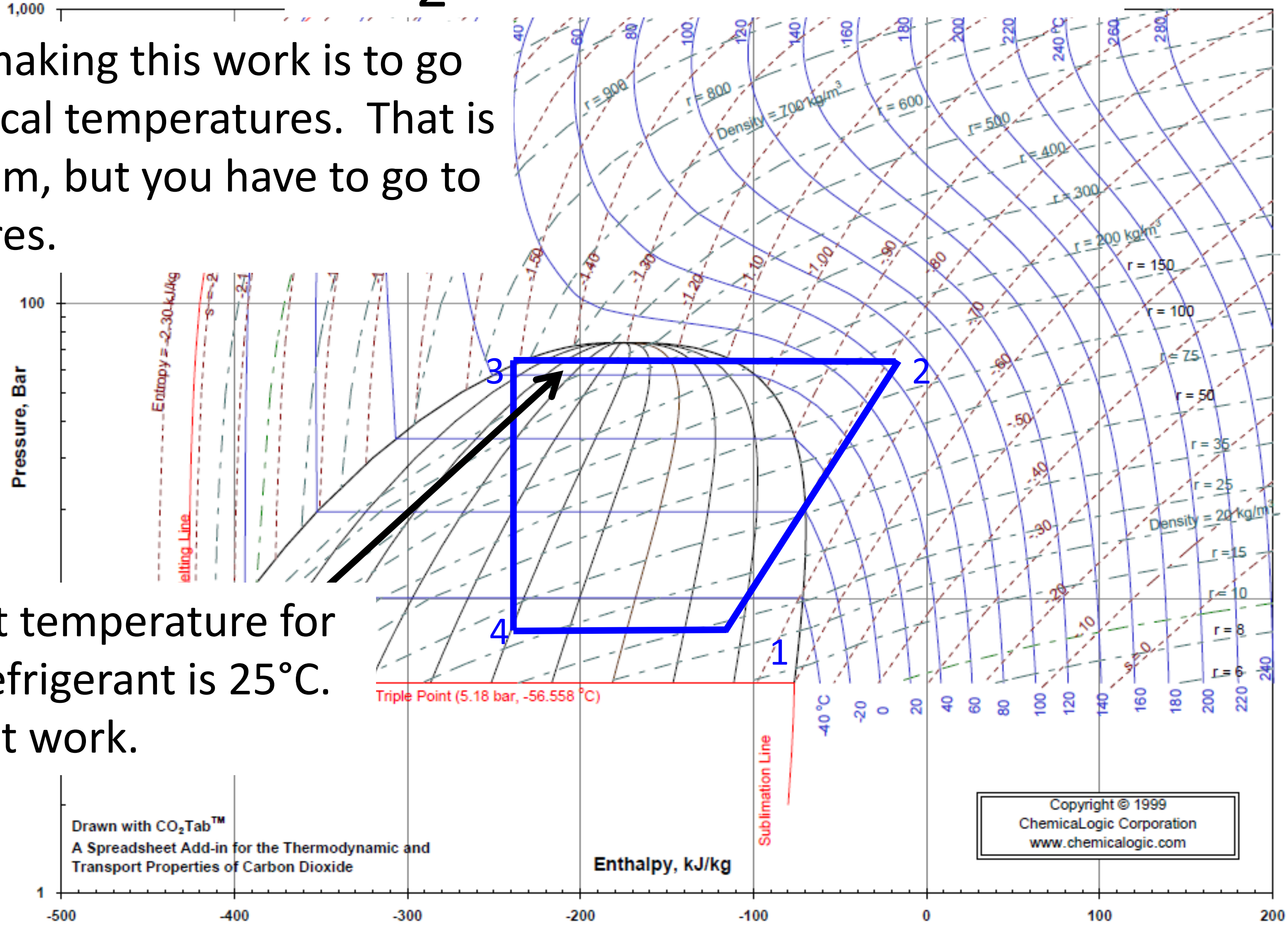
Or

Now

Later

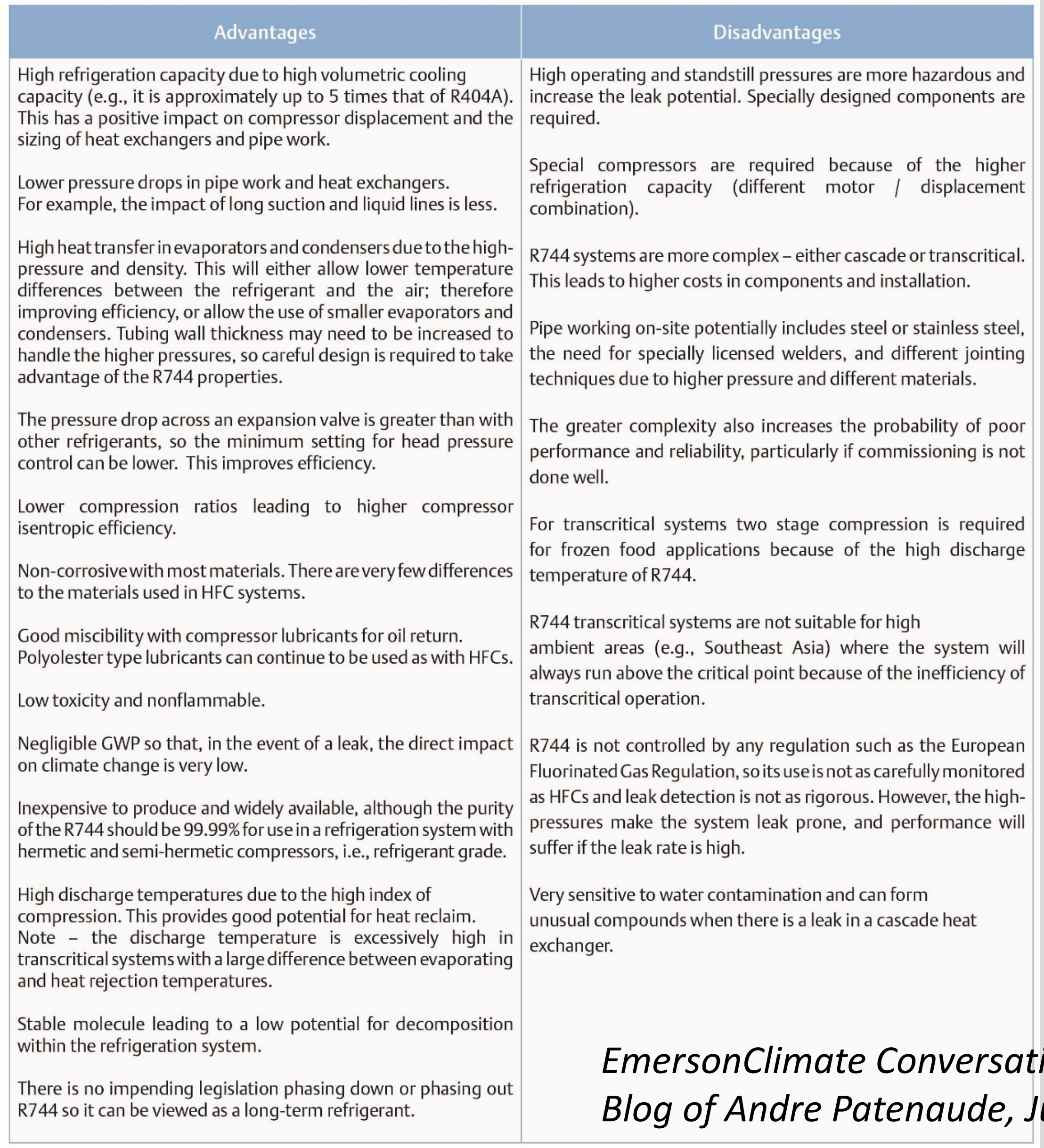
CO_2 as a Refrigerant

The key to making this work is to go to supercritical temperatures. That is not a problem, but you have to go to high pressures.



Our outlet temperature for the CO_2 refrigerant is 25°C. That won't work.

Pro's and Con's of CO_2



Advantages	Disadvantages
High refrigeration capacity due to high volumetric cooling capacity (e.g., it is approximately up to 5 times that of R404A). This has a positive impact on compressor displacement and the sizing of heat exchangers and pipe work.	High operating and standstill pressures are more hazardous and increase the leak potential. Specially designed components are required.
Lower pressure drops in pipe work and heat exchangers. For example, the impact of long suction and liquid lines is less.	Special compressors are required because of the higher refrigeration capacity (different motor / displacement combination).
High heat transfer in evaporators and condensers due to the high-pressure and density. This will either allow lower temperature differences between the refrigerant and the air; therefore improving efficiency, or allow the use of smaller evaporators and condensers. Tubing wall thickness may need to be increased to handle the higher pressures, so careful design is required to take advantage of the R744 properties.	R744 systems are more complex – either cascade or transcritical. This leads to higher costs in components and installation.
The pressure drop across an expansion valve is greater than with other refrigerants, so the minimum setting for head pressure control can be lower. This improves efficiency.	Pipe working on-site potentially includes steel or stainless steel, the need for specially licensed welders, and different jointing techniques due to higher pressure and different materials.
Lower compression ratios leading to higher compressor isentropic efficiency.	The greater complexity also increases the probability of poor performance and reliability, particularly if commissioning is not done well.
Non-corrosive with most materials. There are very few differences to the materials used in HFC systems.	For transcritical systems two stage compression is required for frozen food applications because of the high discharge temperature of R744.
Good miscibility with compressor lubricants for oil return. Polyolester type lubricants can continue to be used as with HFCs.	R744 transcritical systems are not suitable for high ambient areas (e.g., Southeast Asia) where the system will always run above the critical point because of the inefficiency of transcritical operation.
Low toxicity and nonflammable.	R744 is not controlled by any regulation such as the European Fluorinated Gas Regulation, so its use is not as carefully monitored as HFCs and leak detection is not as rigorous. However, the high-pressures make the system leak prone, and performance will suffer if the leak rate is high.
Negligible GWP so that, in the event of a leak, the direct impact on climate change is very low.	Very sensitive to water contamination and can form unusual compounds when there is a leak in a cascade heat exchanger.
Inexpensive to produce and widely available, although the purity of the R744 should be 99.99% for use in a refrigeration system with hermetic and semi-hermetic compressors, i.e., refrigerant grade.	
High discharge temperatures due to the high index of compression. This provides good potential for heat reclaim. Note – the discharge temperature is excessively high in transcritical systems with a large difference between evaporating and heat rejection temperatures.	
Stable molecule leading to a low potential for decomposition within the refrigeration system.	
There is no impending legislation phasing down or phasing out R744 so it can be viewed as a long-term refrigerant.	

EmersonClimate Conversations.com
Blog of Andre Patenaude, July 30th, 2015

Summary

CO_2 is great, as long as you can handle high pressures.

Lecture - Learning Objectives

At the end of this lecture you should be able to:

- Know the thermodynamic limits of heat engines
- Be able to calculate the power coming from a power plant and know how to modify the conditions to give you more power or efficiency.
- Be able to calculate the heat pulled from a refrigerator and know how to modify the conditions to give you more power or efficiency.
- Know the difference between Rankine cycle devices, Otto and Diesel Engines, and Steam turbines.

Exercises

- Assume you are running a coal fired power plant at 33% efficiency. You could take this coal and heat it up with steam to produce syngas (H_2 + CO) and then burn this in a gas turbine at 45% efficiency. What is the maximum amount of energy you could lose in the conversion for this approach to be worthwhile? Find a syngas energy density and determine if this is a good idea?

- Assume that you have geothermal heat you want to run using a Rankine cycle. You were given a free powerplant with a 80% efficient pump and a 100% efficient turbine that can handle 100 kg/s, however operating costs to run the plant are 30,000 Euro/day. The steam coming from the geothermal well is at 300C and wholesale electricity prices are at 60 Euro/MWh. Should you run the power plant or keep it shut down?

Concept Check

The primary way to set the efficiency of an internal combustion engine is to:

a) Use fuels that burn hotter

b) Increase the compression ratio

c) Cool the exit exhaust

d) Use piston materials that can handle higher temperatures

Concept Check

In a Rankine cycle, what unit produces the work:

a) Boiler

b) Turbine

c) Condenser

d) Pump

Concept Check

What are some practical limits, preventing higher thermodynamic efficiencies (may be more than one right answer:

a) Material costs needed to go to higher temperatures

b) Flame temperature

c) Excess CO_2 output

d) Excess NO_x output

e) Limitations due to heat of combustion enthalpies

f) Heat transfer loss switching from different operating fluids.

Concept Check

What is an advantage and a disadvantage of using CO_2 as a coolant:

a) Advantage: Small greenhouse gas effect if leaked
   Disadvantage: Need to go to high pressures

b) Advantage: Relatively free to get
   Disadvantage: Large greenhouse gas effect if leaked

c) Advantage: Can do it at reasonable pressures
   Disadvantage: Is highly reactive

d) Advantage: Relatively free to get
   Disadvantage: Is highly reactive

Bonus Slides

- These slides/ topics didn’t make the cut this year (i.e. not on exam), but at least you can have them for reference.

Heat transfer

- Heat will only transfer from an area of high temperature to one of low temperature.
- Heat can transfer 1 of 3 ways:
  - Conductively:

Fick's Law of Difusion

$$q = Ak\nabla T$$

1st Law

$$\frac{\partial T}{\partial t} = D\Delta T$$

2nd Law

A - Area

k – Thermal conductivity ($\mathrm{W\cdot m^{-1}\cdot K^{-1}}$)

D – Thermal diffusivity ($\mathrm{m^2\cdot s}$)

$$D = \frac{k}{\rho C_p}$$

ρ – Density($\mathrm{Kg\cdot m^{-3}}$)

C_p – Specific heat capacity ($\mathrm{J\cdot Kg^{-1}\cdot K^{-1}}$)

  - Convectively:

$$q = hA\nabla T$$

h – Heat transfer coefficient ($\mathrm{W\cdot m^{-2}\cdot K^{-1}}$)

Empirical experimentally derived number

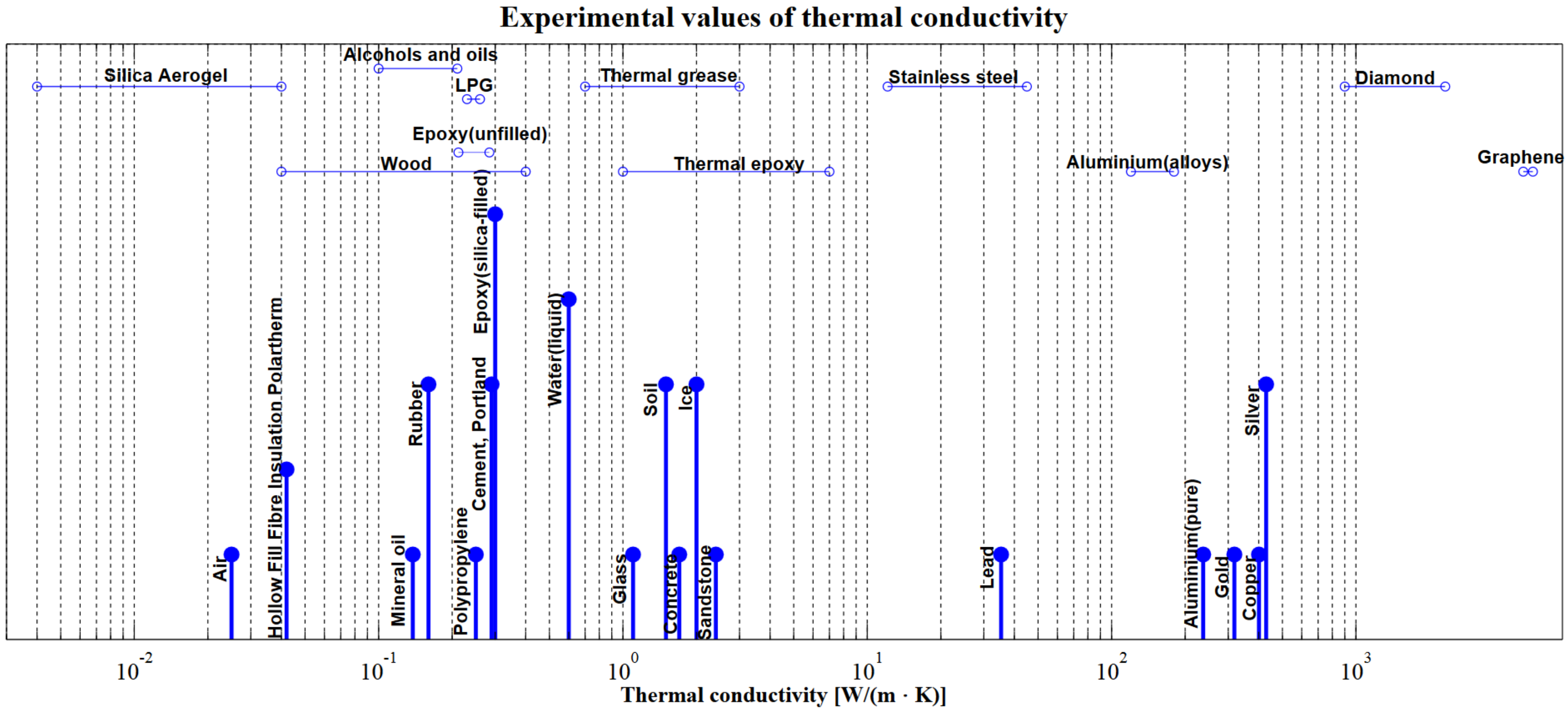
  - Radiatively: $q = \varepsilon\sigma T^4$

ε – emissivity

σ – Stefan Boltzmann constant (5.7×10^{-8} W m^{-2} K^{-4})

Heat transfer

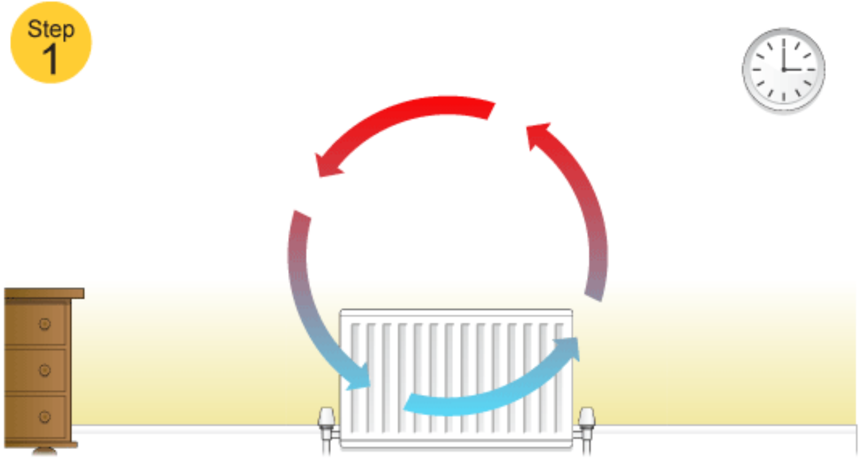
- Conductive heating is a function of the material. $q = Ak\nabla T$
- We want to transfer heat to our homes with a material with a high k and insulate it with a low k value.
- Conductivity of vacuum is 0, and a typical commercial vacuum panel for insulation is 0.007 W m^{-1} K^{-1}.



Y-axis that has no meaning

Heat transfer-Convection

- Convection is basically ‘warm air rises’ via the ideal gas law.
- Convection is why air is not used as an insulator on it’s own.
- Since air is such a good conductive insulator, the goal of most insulations is to simply have a material that minimizes convection in air.



$$\mathrm{PV} = nRT \Rightarrow \frac{1}{T} = \overbrace{\frac{R}{P}}^{\text{Constant}} \overbrace{\frac{n}{V}}^{\text{Density}}$$

-Due to gravity, higher density (Low T) drops, while lower density rises (High T).

Heat transfer-radiation

- This relates back to the Stefan-Boltzmann's law.

$$Q = A\sigma T^4 \qquad \sigma \text{– } 5.67 \text{ x } 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$$

- With regards to a radiative heater, net radiative heat flux is related to the differences in temperature.

$$Q_{Net} = A\sigma\left({T_{Rad}}^4 - {T_{room}}^4\right)$$

- Since most radiators are in contact with air, conductive heat transfer is basically 0.