

Supercritical sCO₂ Symposium 2022



- ❑ Welcome
- ❑ 12:00-6:00 pm – Tutorials:
 - sCO₂ Power Cycles Fundamentals Tutorial (SwRI)
 - sCO₂ Cycles Tutorial (SwRI/Echogen)
 - sCO₂ Oxy-Combustion Tutorial (UCF / SwRI)
 - sCO₂ Turbomachinery Tutorial (SwRI)
 - sCO₂ Materials Tutorial (GTI / Carleton/Epri)
 - sCO₂ Heat Exchanger Tutorial (SwRI / Heatric/Thar)
- ❑ 6:30 pm - Industry Sponsored Reception –
Speaker #1: Karl Wygant – Elliott Group)
- ❑ 7:00 pm - Welcome – Klaus Brun, Elliott Group /
Tim Allison, Southwest Research Institute

Tutorial:

Fundamentals of Supercritical CO₂

Feb 26, 2024

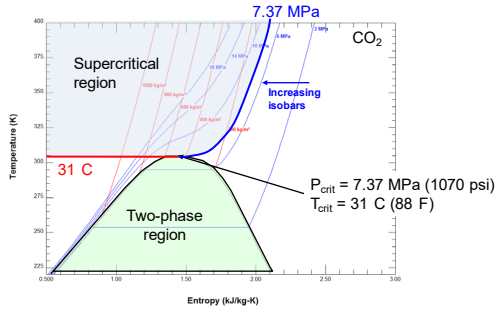
Jason C. Wilkes, Ph.D.

jason.wilkes@swri.org

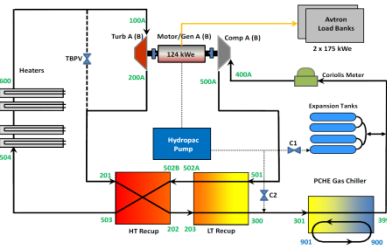
Southwest Research Institute



This tutorial provides an introduction to sCO₂ in power cycle applications



CO₂ and supercritical CO₂ (sCO₂)



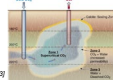
sCO₂ loop hardware & Cycles



Concentrated Solar Power



Fossil Fuel



Geothermal



Ship-board Propulsion

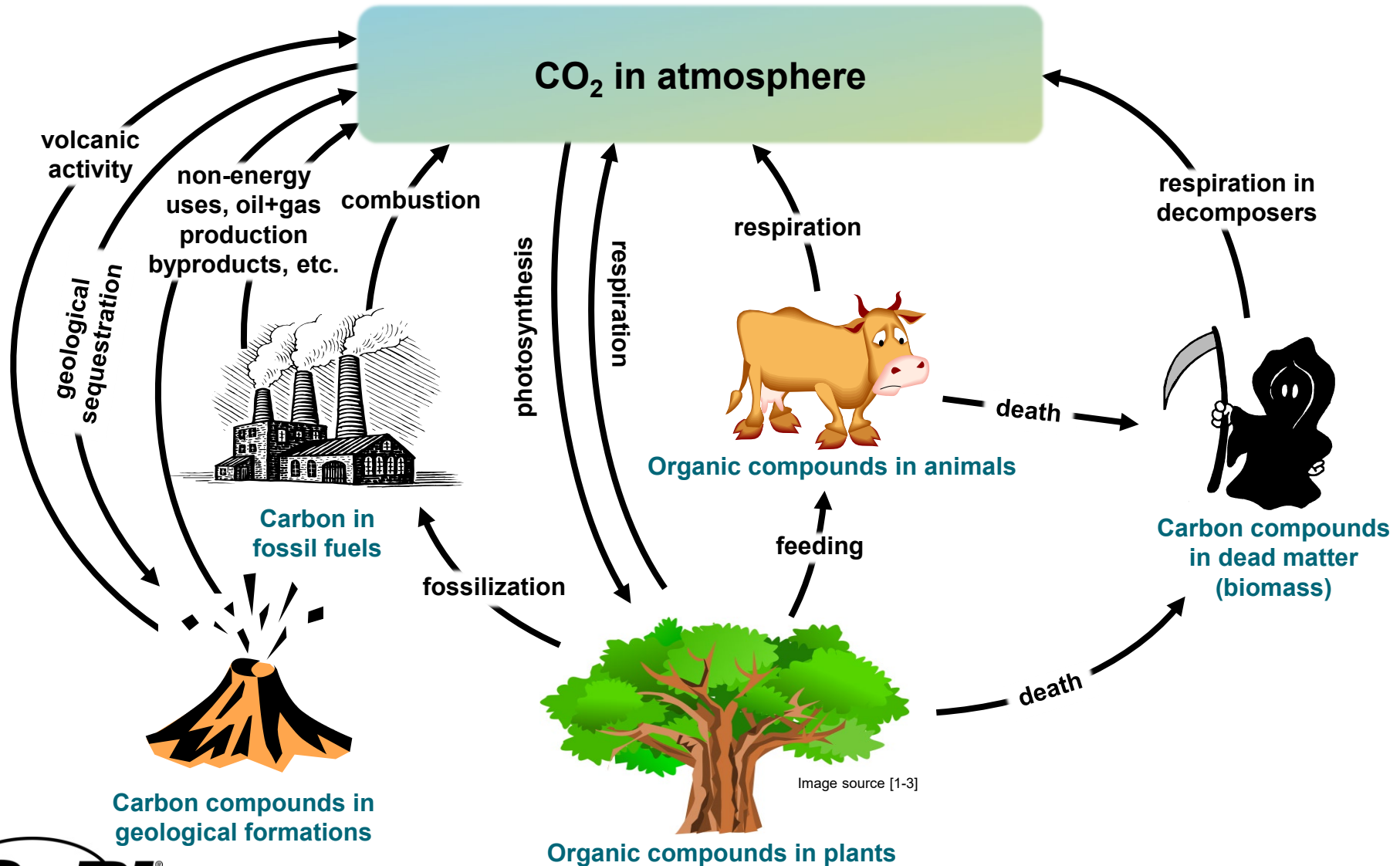
Power cycle applications

Research and future trends

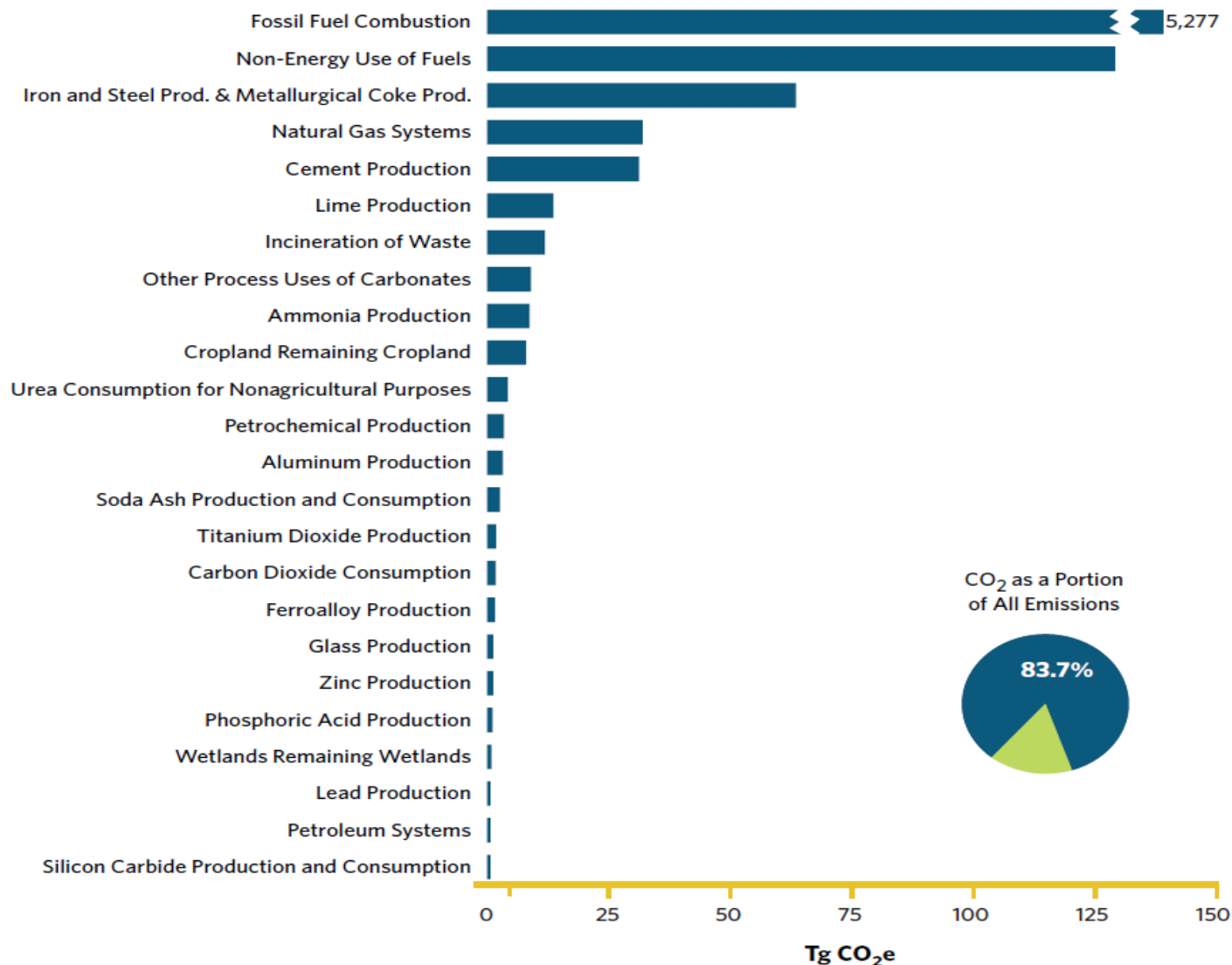
CO₂ General Information



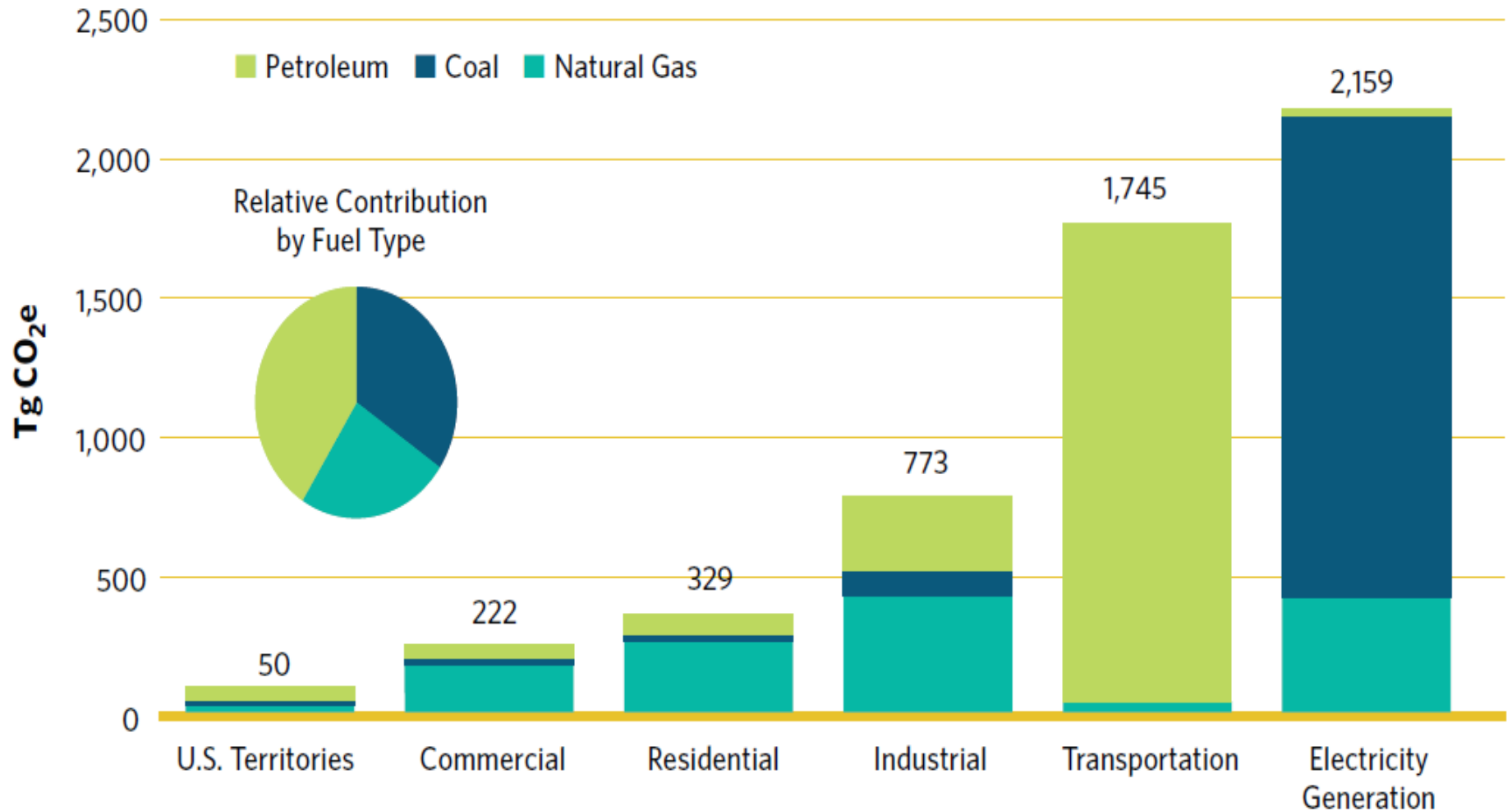
There are both industrial and natural contributors and consumers of CO₂ in our atmosphere



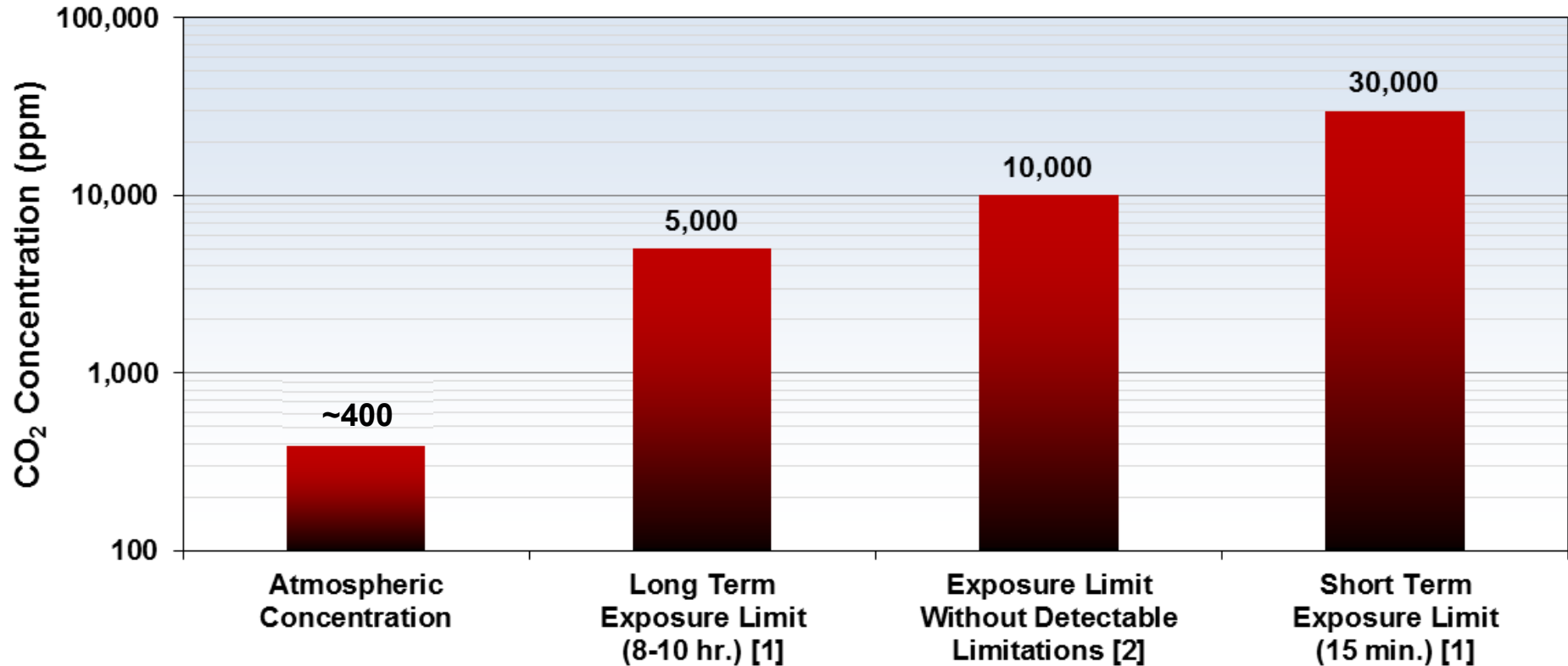
Fossil fuel combustion is the largest industrial contributor to CO₂ production



Transportation (petroleum) and electricity generation (coal) majority contributors of CO₂



CO₂ has human exposure limits, but is classified at “non-toxic”



Notes:

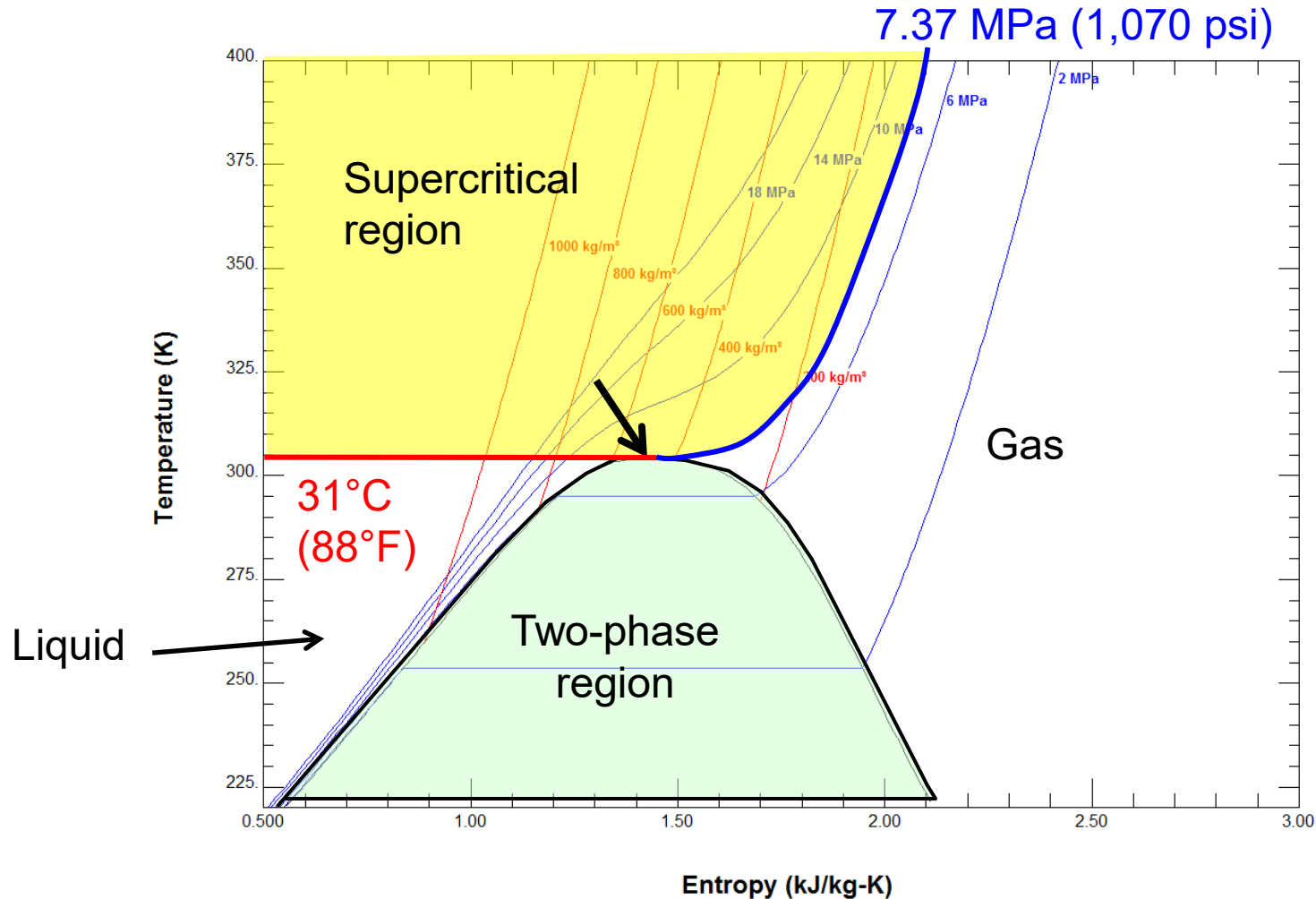
[1] Reference safety standards: OSHA, ACGIH, NIOSH (USA)

[2] Reference study by Lambertsen (1971)

What is Supercritical CO₂?

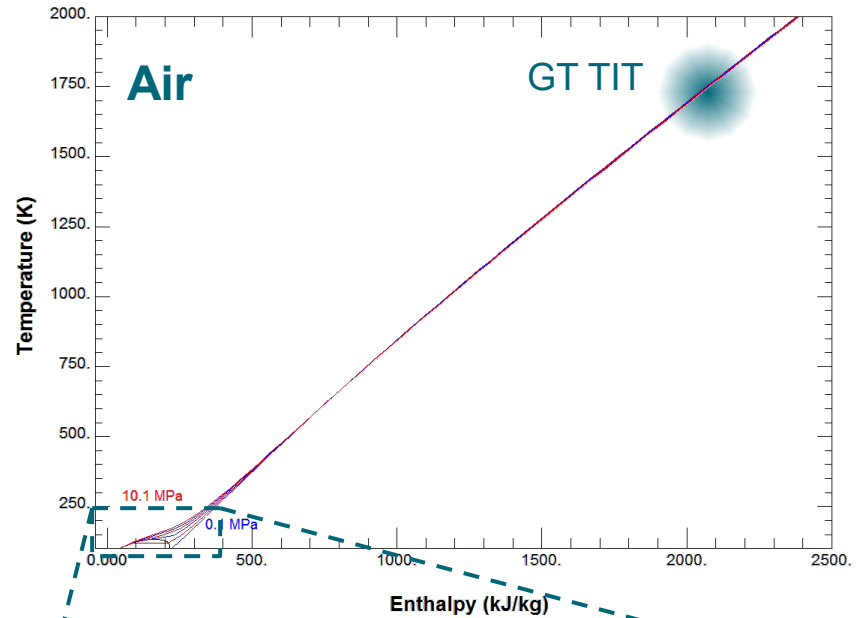
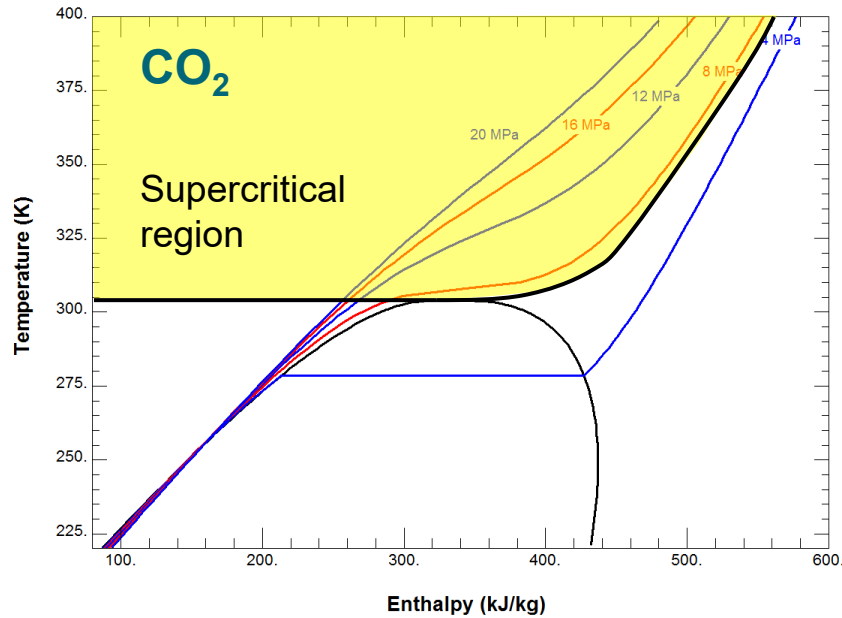


CO₂ is supercritical if the pressure and temperature are greater than the critical values

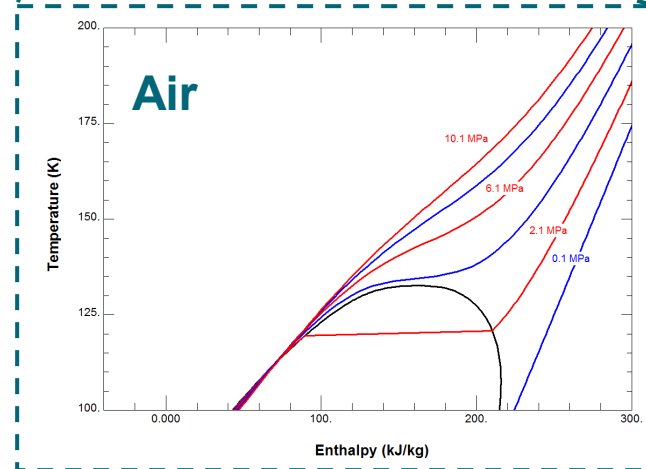
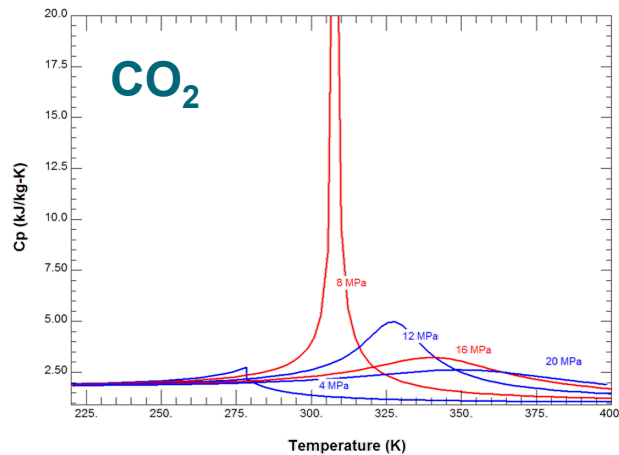


REFPROP (2007), EOS CO₂: Span & Wagner (1996)

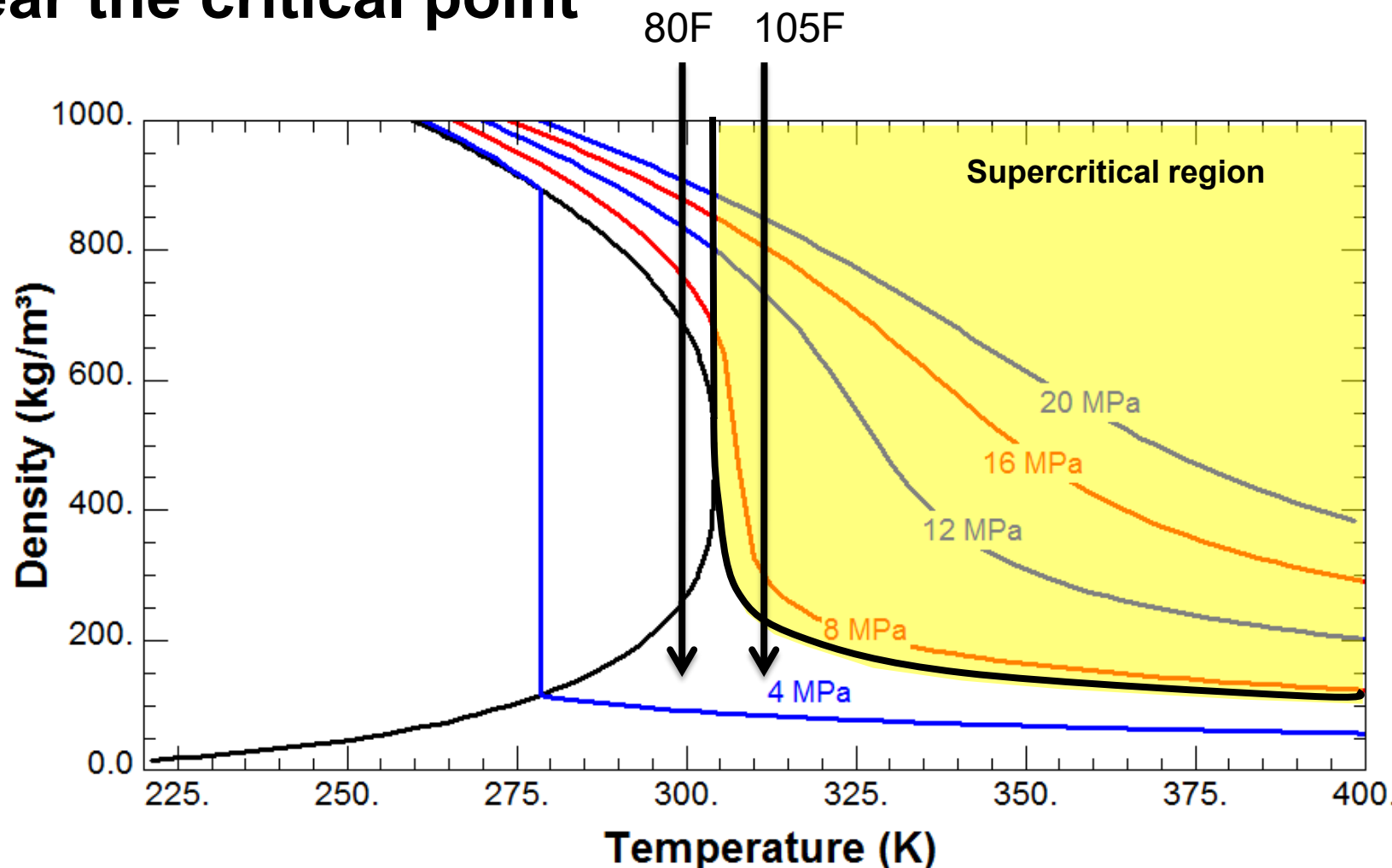
Fluids operating near their critical point have dramatic changes in enthalpy



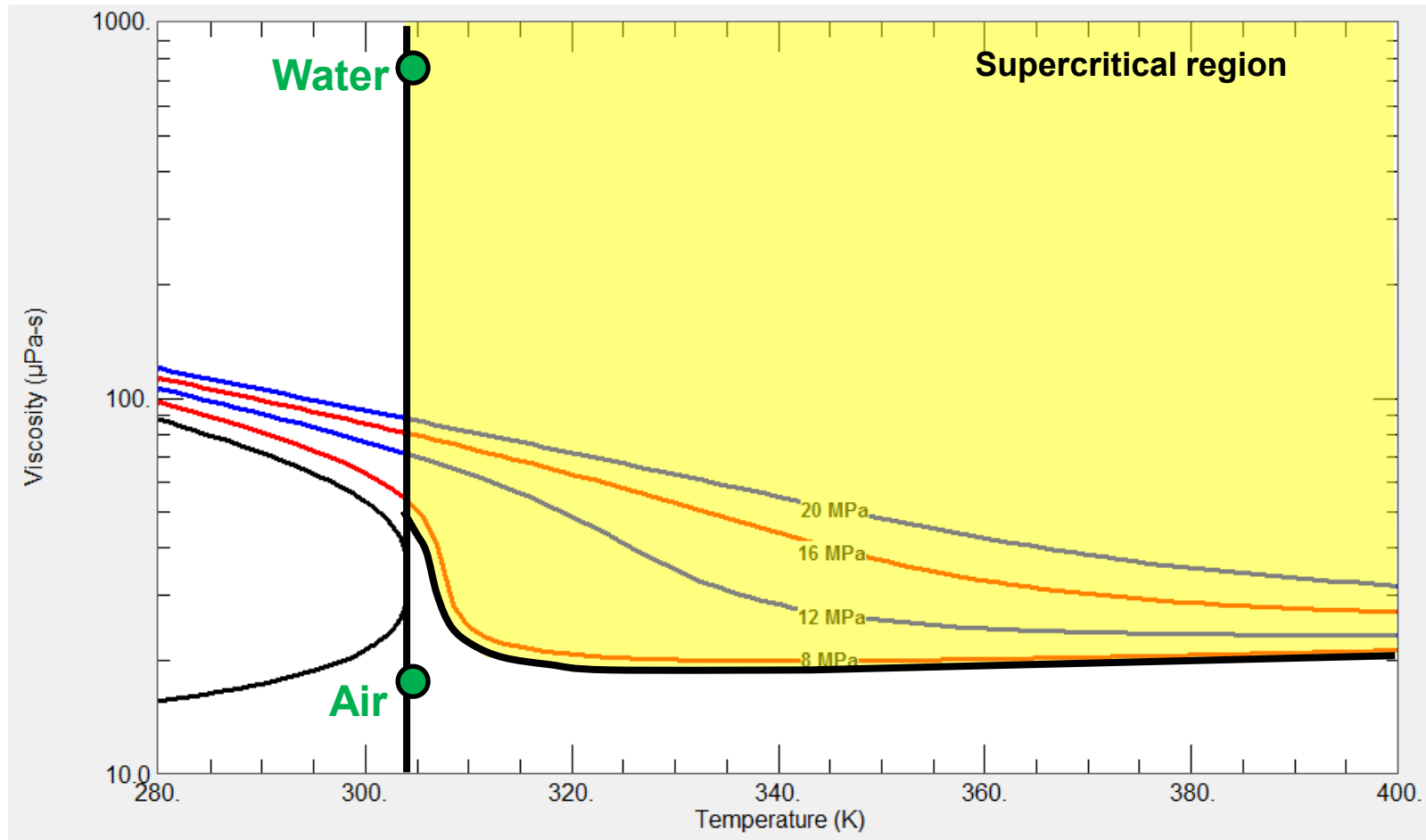
$$C_p = \left(\frac{\partial h}{\partial T} \right)_p$$



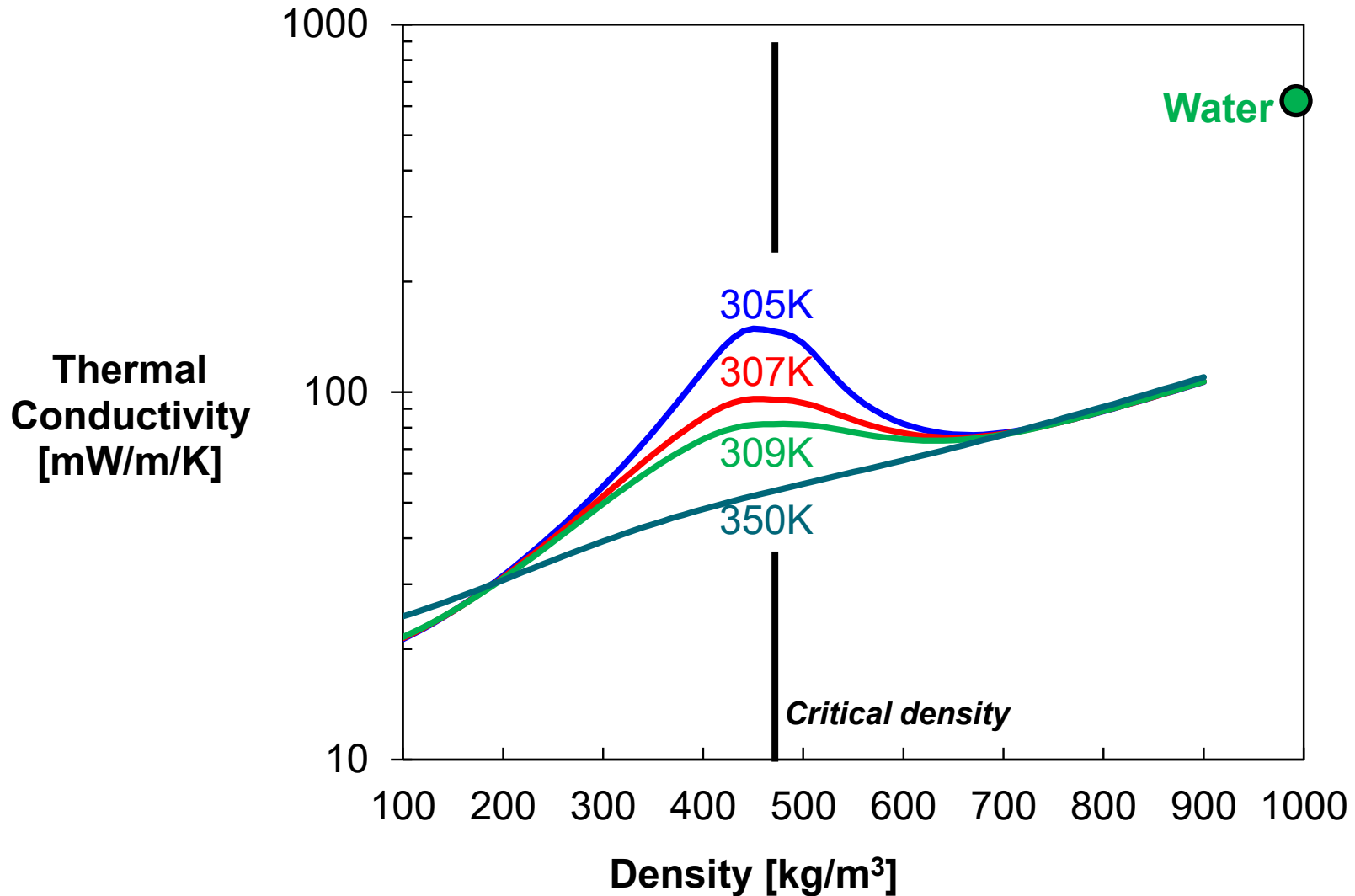
CO₂ density sharply decreases near the critical point



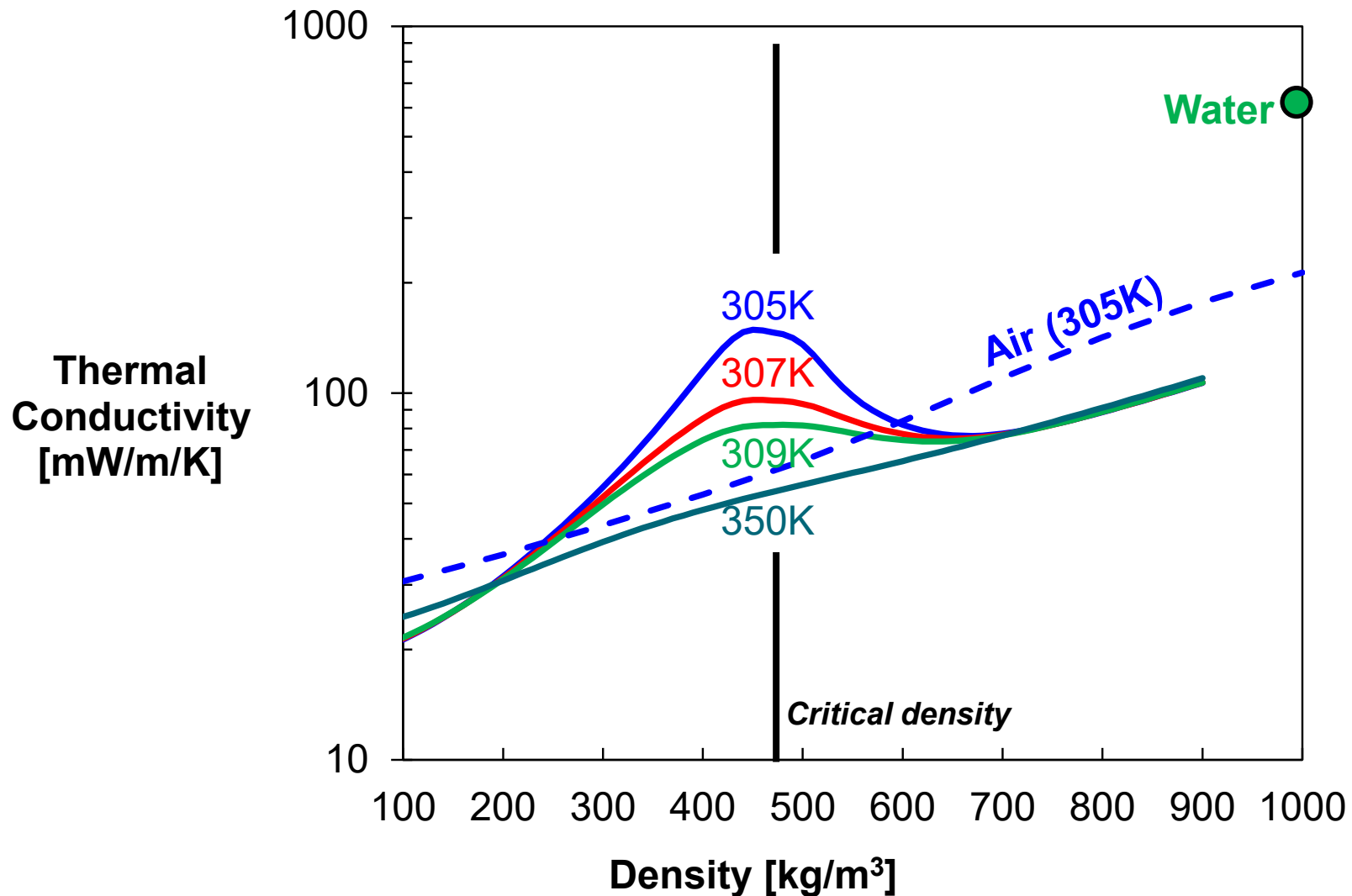
CO₂ viscosity decreases through the critical point



CO₂ thermal conductivity is enhanced near the critical region



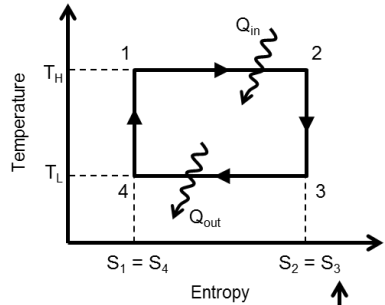
CO₂ thermal conductivity is enhanced near the critical region



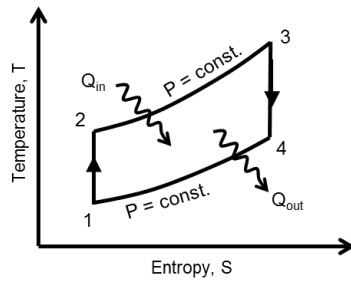
Power Cycle Basics



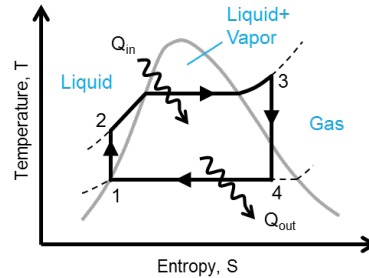
Power Cycle Basics Overview



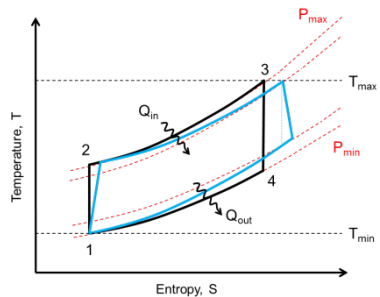
Carnot – “the standard”



Brayton – gas cycle

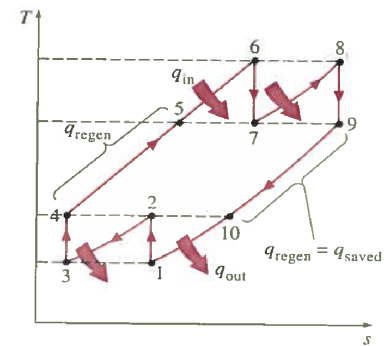


Rankine – vapor cycle



Ideal vs. actual cycle

Cycle variations



Carnot Cycle

Processes

- (1-2) Isothermal heat addition
- (2-3) Isentropic expansion
- (3-4) Isothermal heat rejection
- (4-1) Isentropic compression

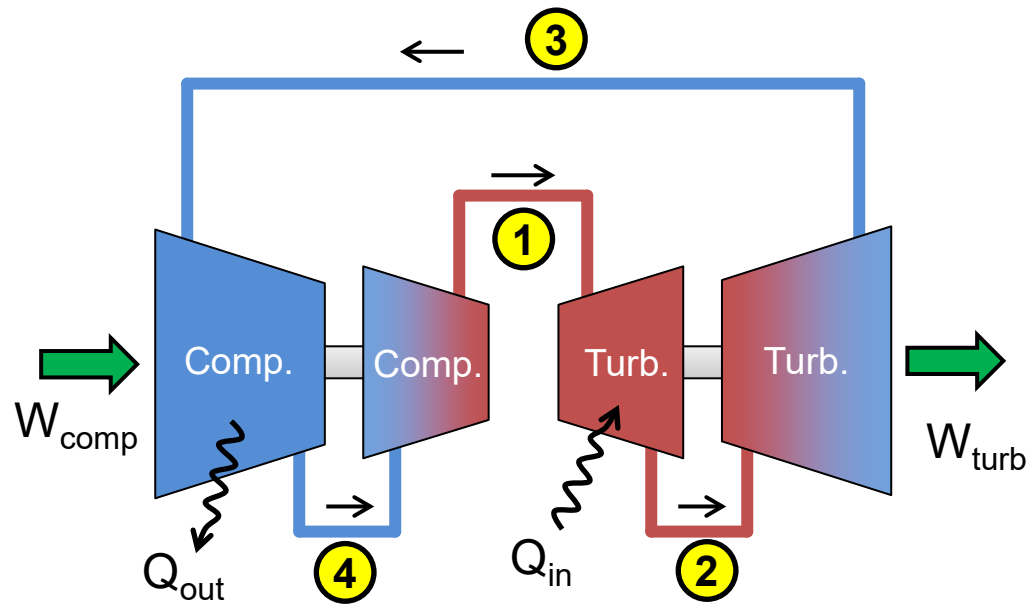
Not practical to build

Most efficient heat engine

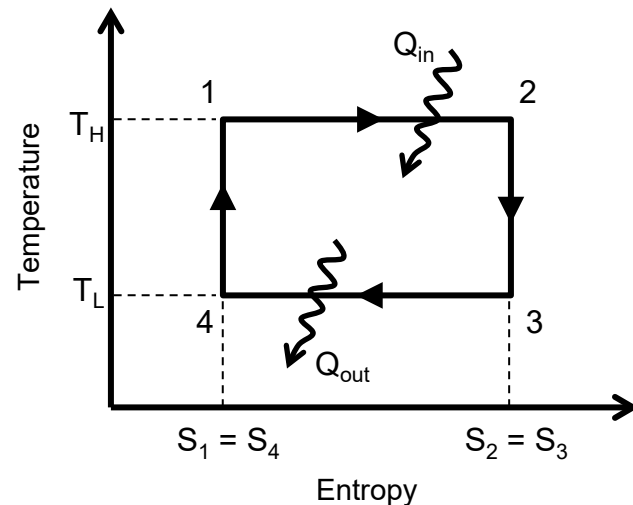
$$\eta_{th,Carnot} = 1 - T_L/T_H$$

↓ T_L : Available heat sink?

↑ T_H : Available heat source?
Materials?



$$W_{net} = W_{turb} - W_{comp}$$



Brayton Cycle (Ideal)

Processes

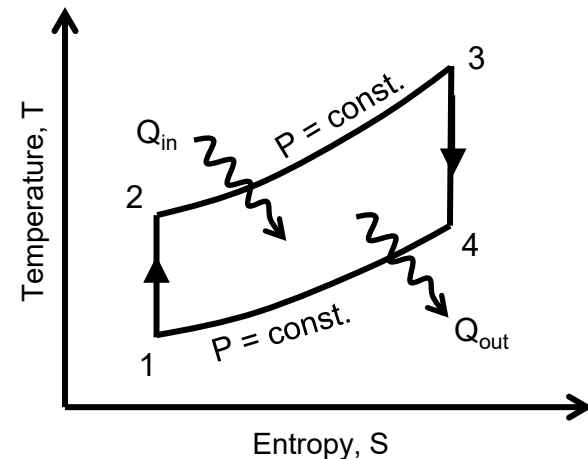
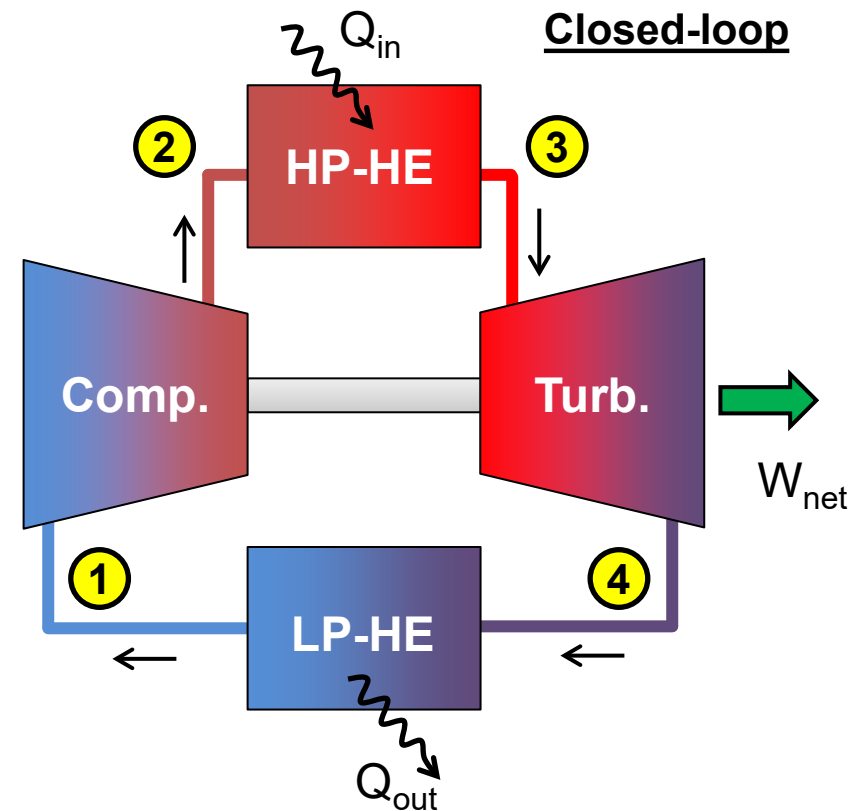
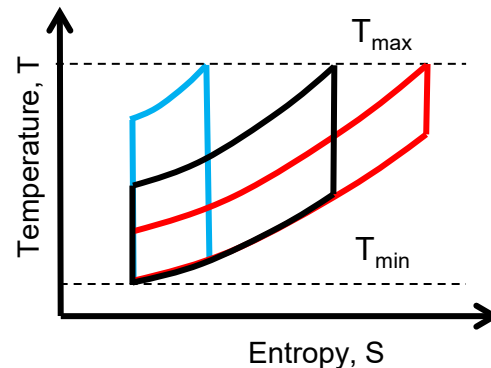
- (1-2) Isentropic compression
- (2-3) Const. pres. heat addition
- (3-4) Isentropic expansion
- (4-1) Const. pres. heat reject.

Open- or closed-loop

$$\eta_{th,Brayton} = 1 - PR^{(1-k)/k}$$

$$\uparrow PR, \uparrow k : \uparrow \eta_{th}$$

Optimal PR
for net work



Rankine Cycle (Ideal)

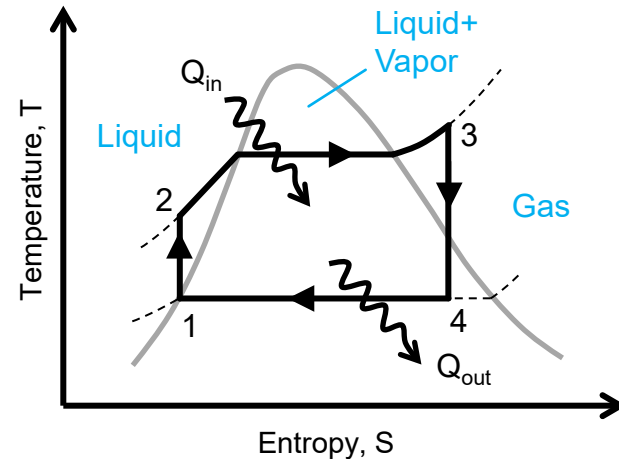
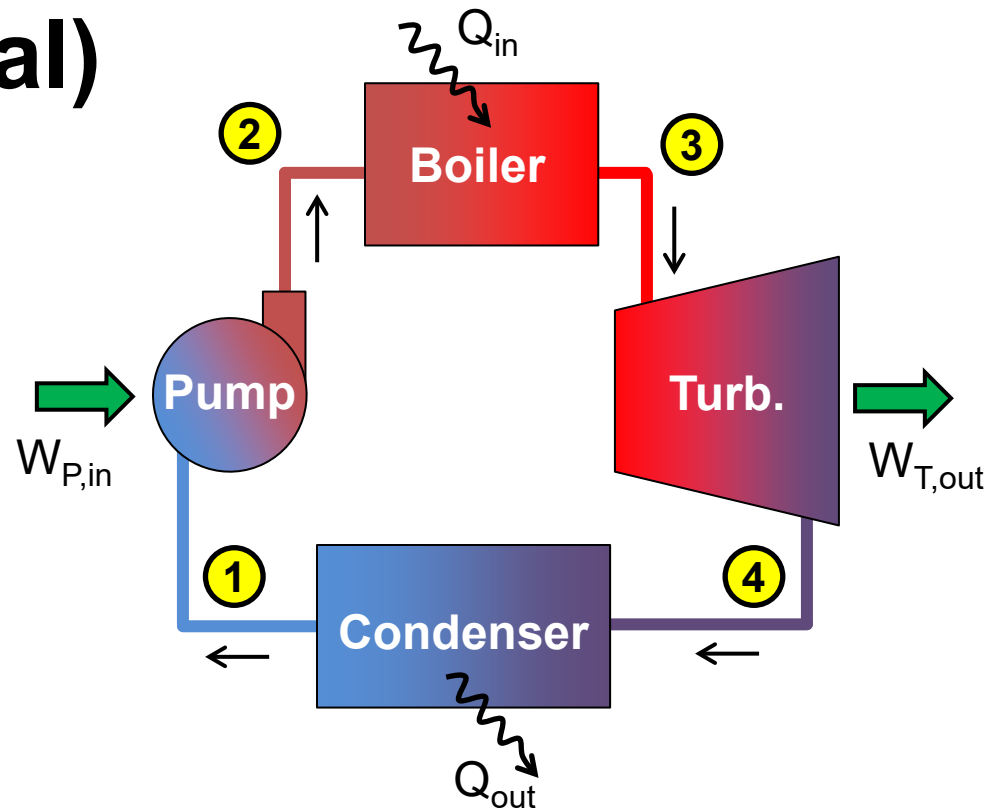
□ Processes

- (1-2) Isentropic compression
- (2-3) Const. pres. heat addition
- (3-4) Isentropic expansion
- (4-1) Const. pres. heat reject.

□ Same processes as Brayton; different hardware

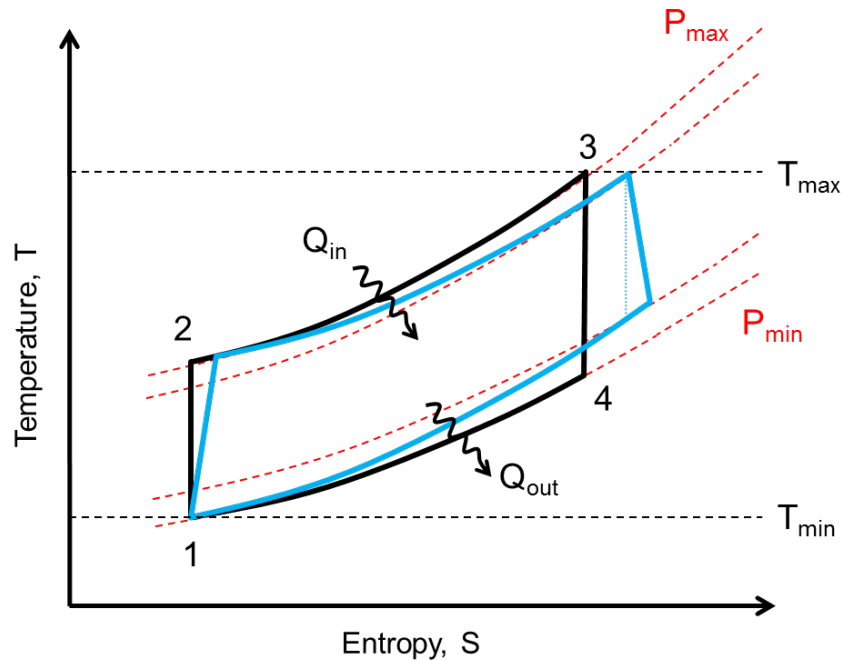
□ Phase changes

□ E.g., steam cycle

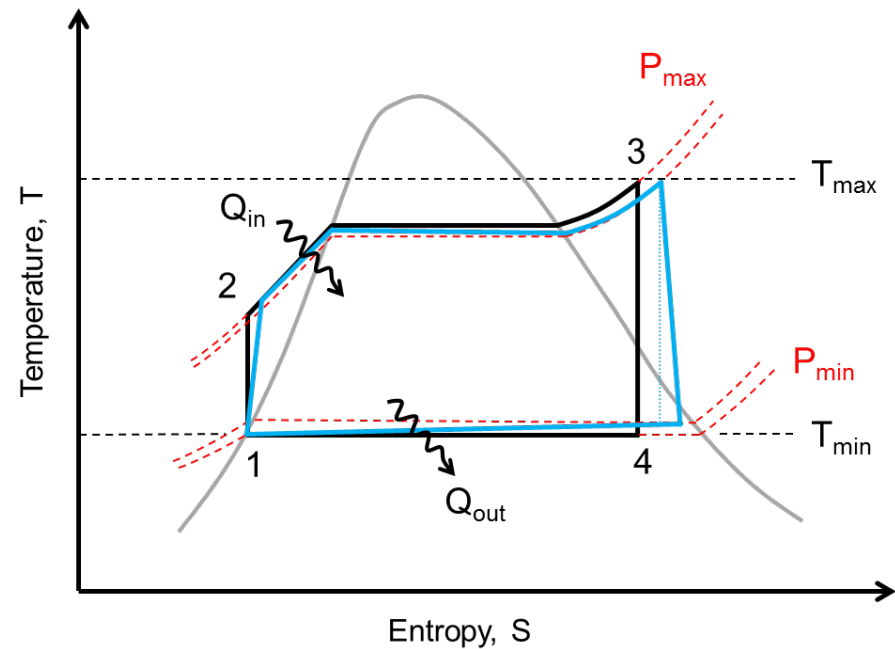


Ideal vs. Actual Processes

Brayton



Rankine

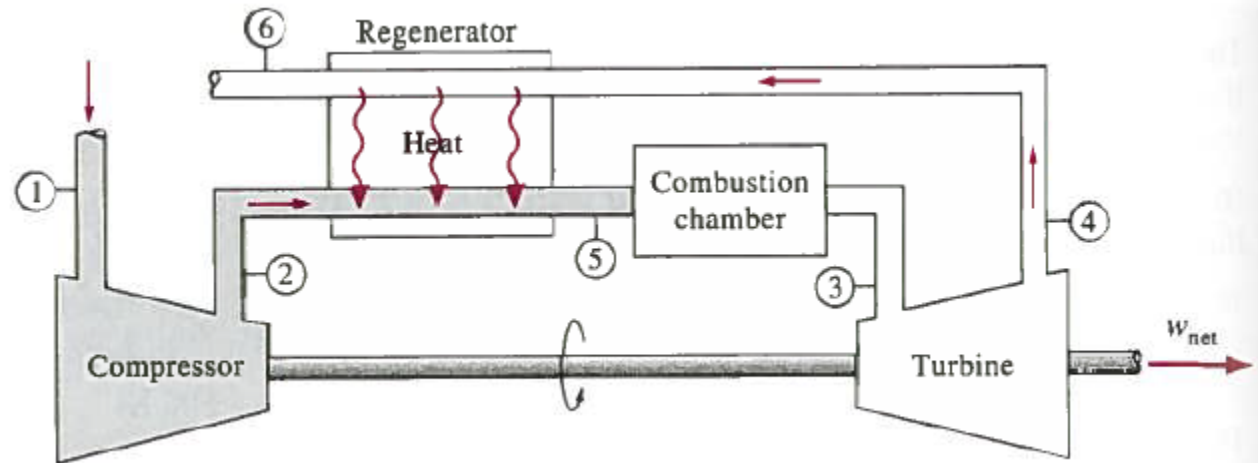


1-2, 3-4: Irreversibilities

2-3, 4-1: Pressure losses

Brayton Cycle + Regeneration

Regenerator
= recuperator



Effectiveness:
 $\varepsilon = (h_5 - h_2) / (h_4 - h_2)$

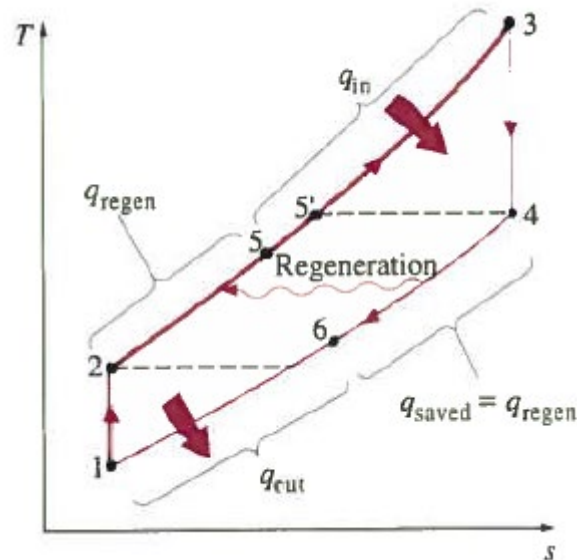
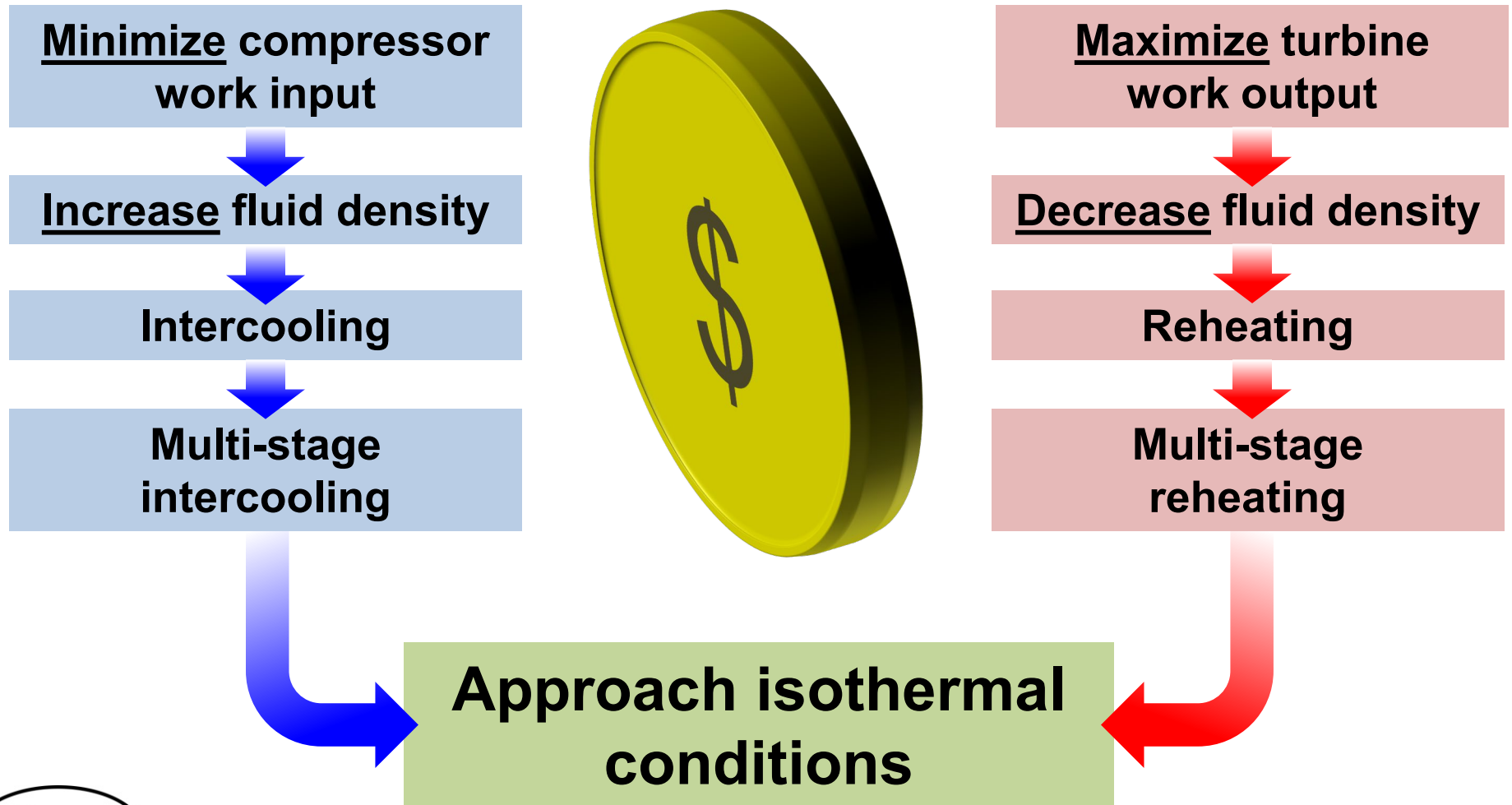


Figure reference: Cengel and Boles (2002)

Intercooling & Reheating...

Two Sides of the Same Coin



Brayton Cycle + Regeneration + Intercooling + Reheating

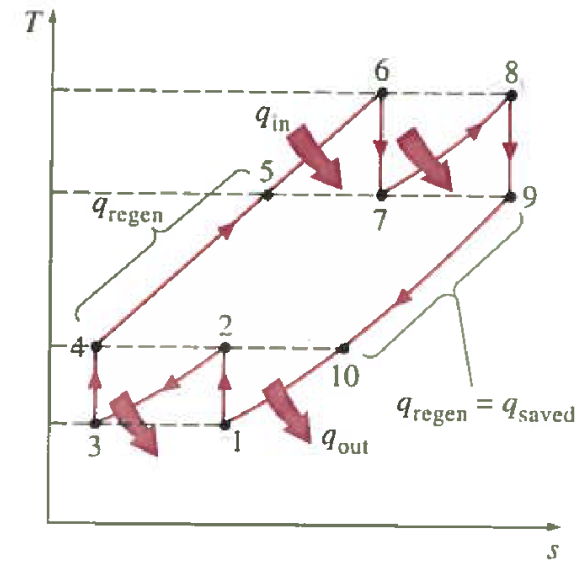
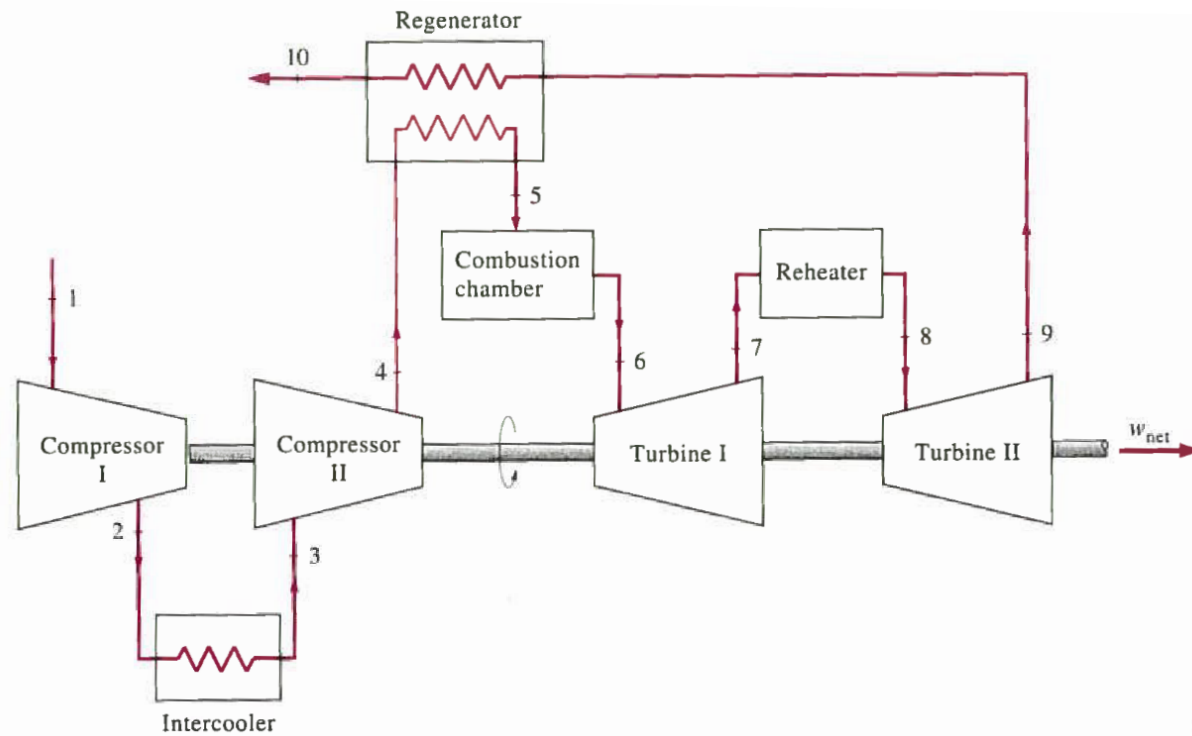


Figure reference: Cengel and Boles (2002)

Example: Compare Effect of Brayton Variations

Gas turbine cycle (air)

Temp. = 300-1300 K

PR = 8

For real GT

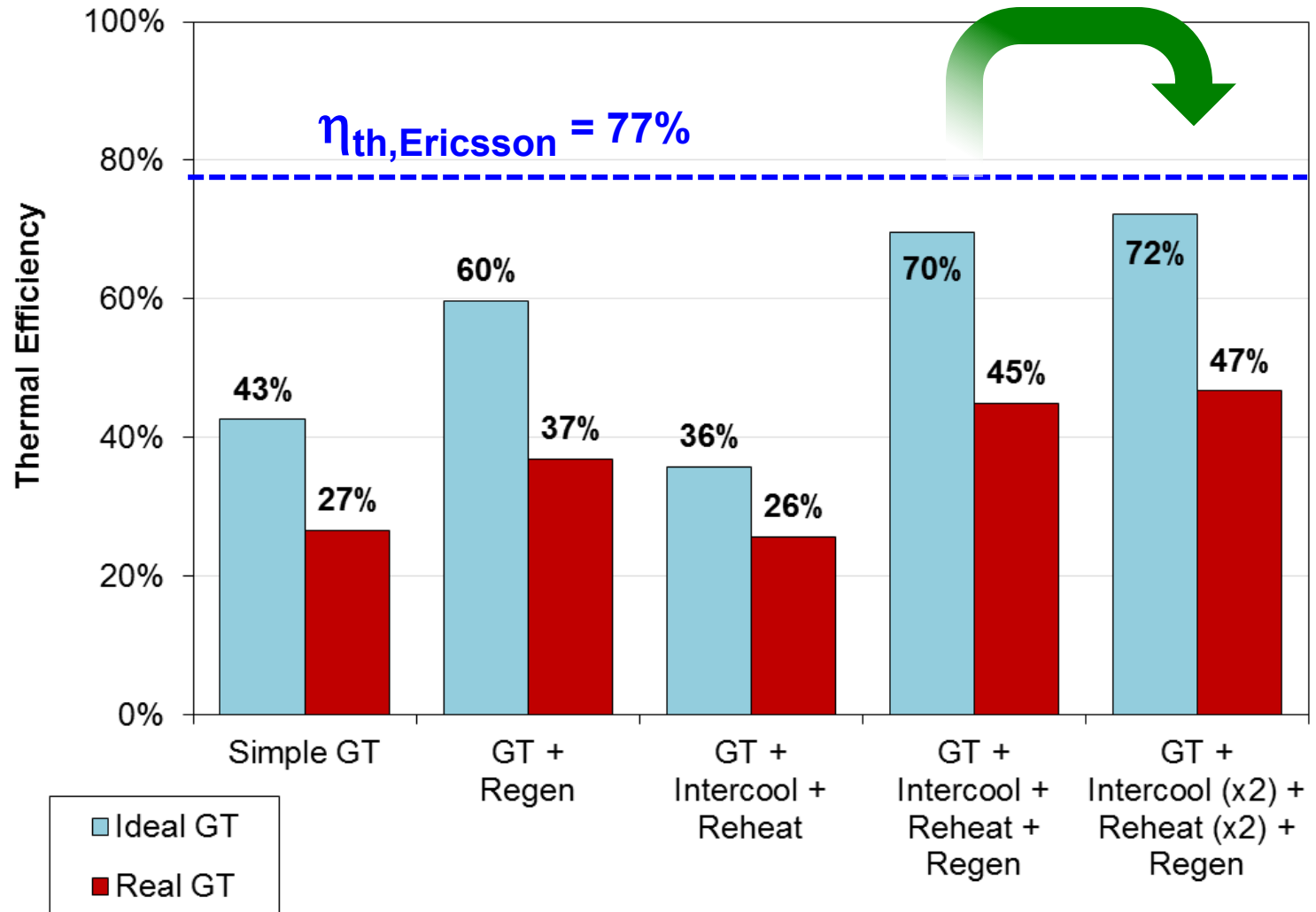
$\eta_{\text{comp}} = 80\%$

$\eta_{\text{turb}} = 85\%$

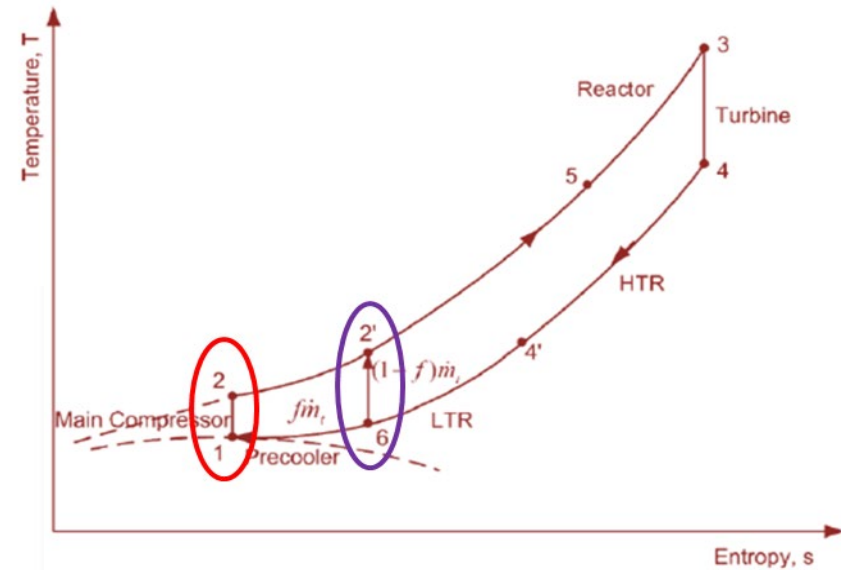
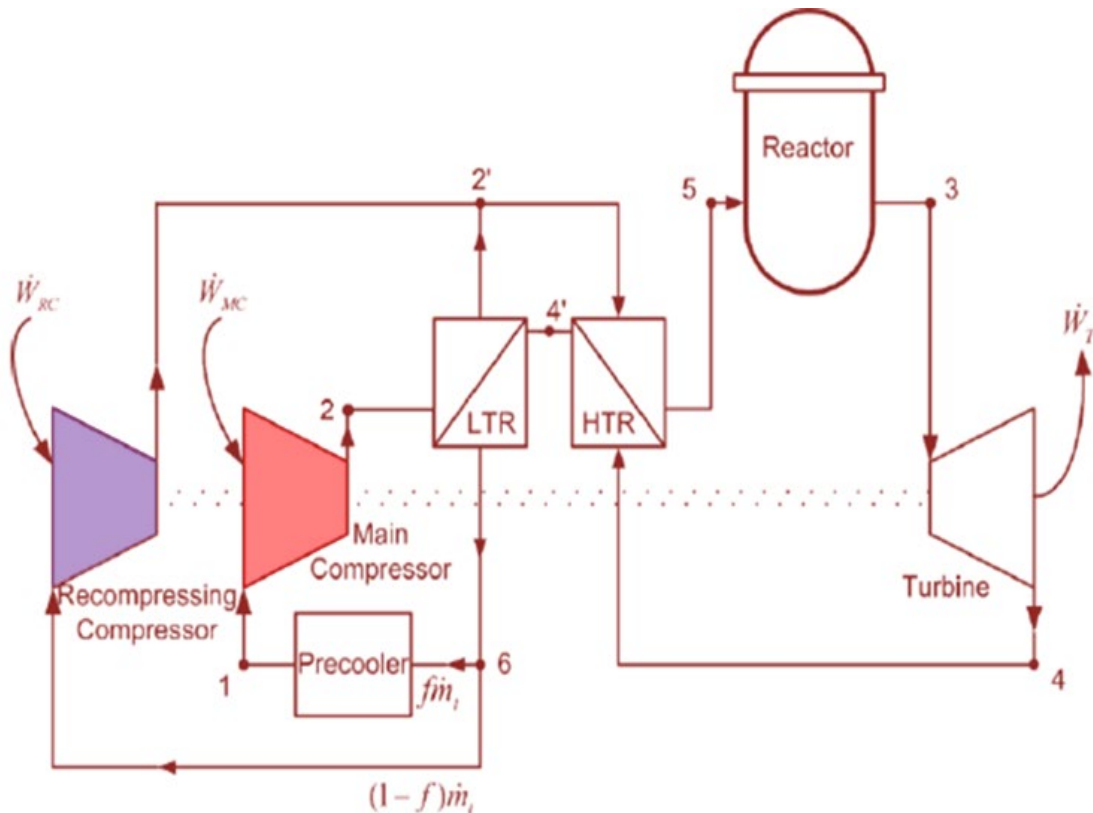
$\epsilon_{\text{regen}} = 80\%$

$\Delta P \approx \text{negligible}$

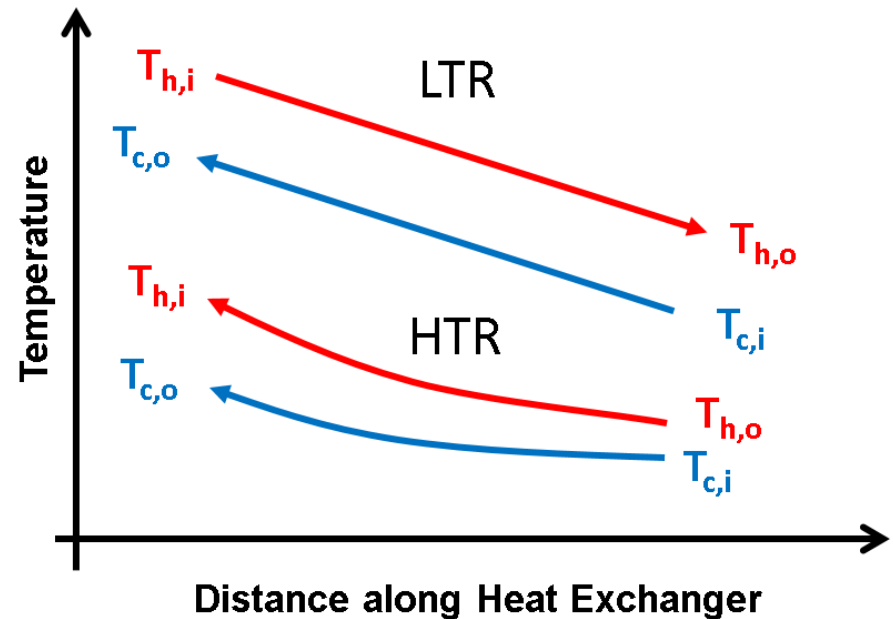
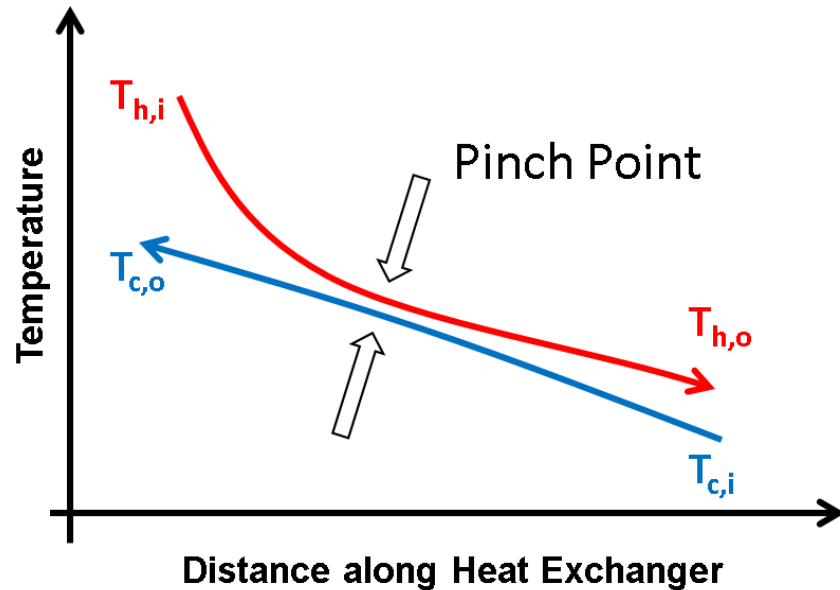
Cost-benefit analysis...



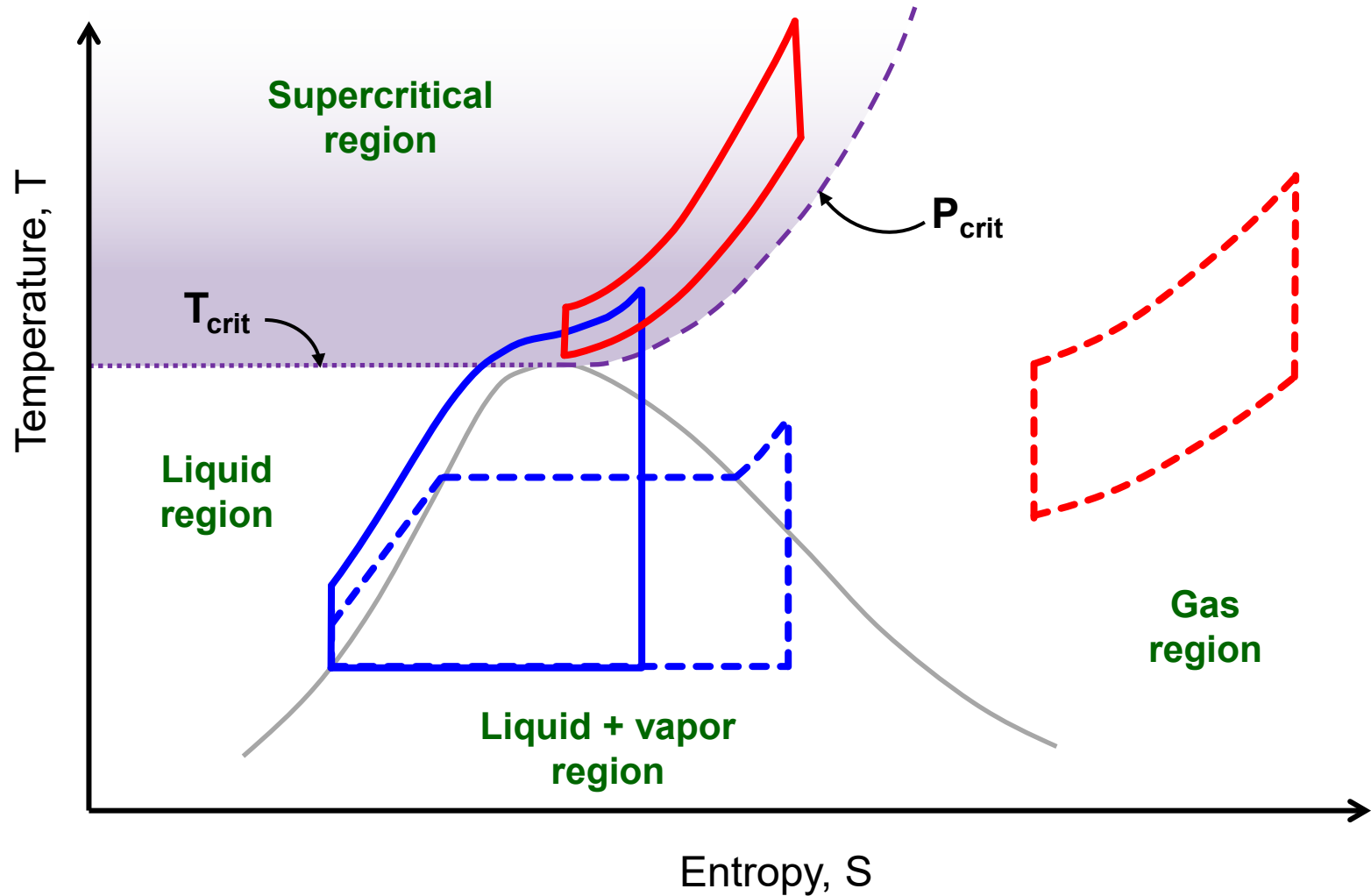
Recompression in Brayton Cycle



Split Recuperators can be used to avoid pinch points



What is a Supercritical Power Cycle?



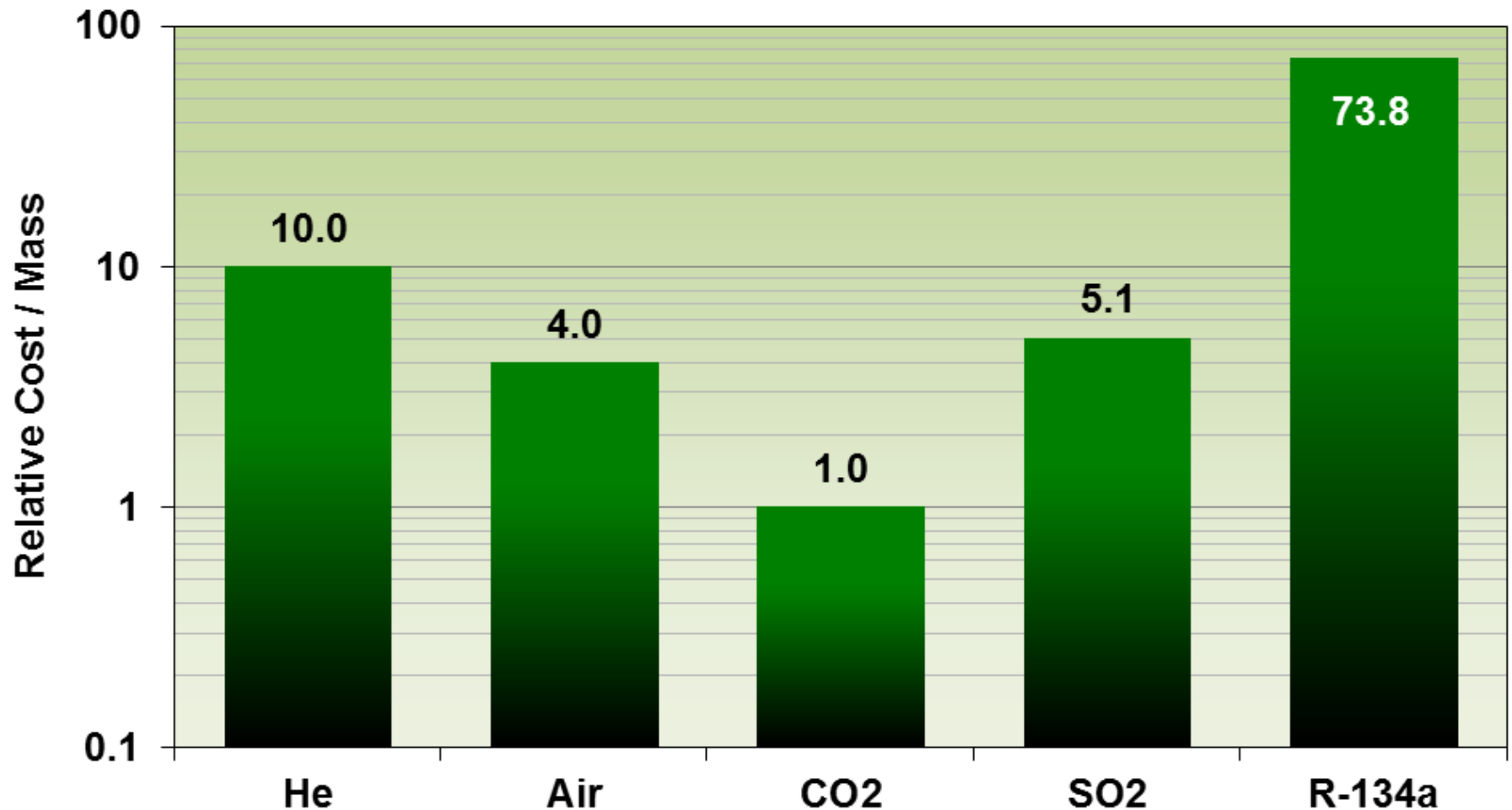
sCO₂ Power Cycles



Why sCO₂ for Power Cycles?

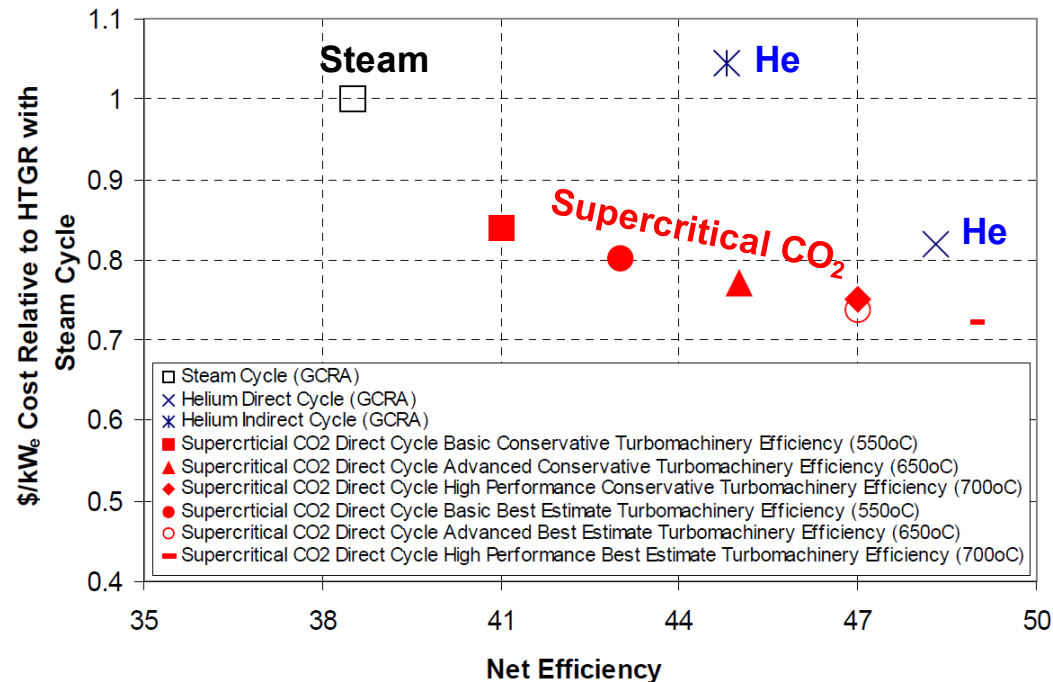
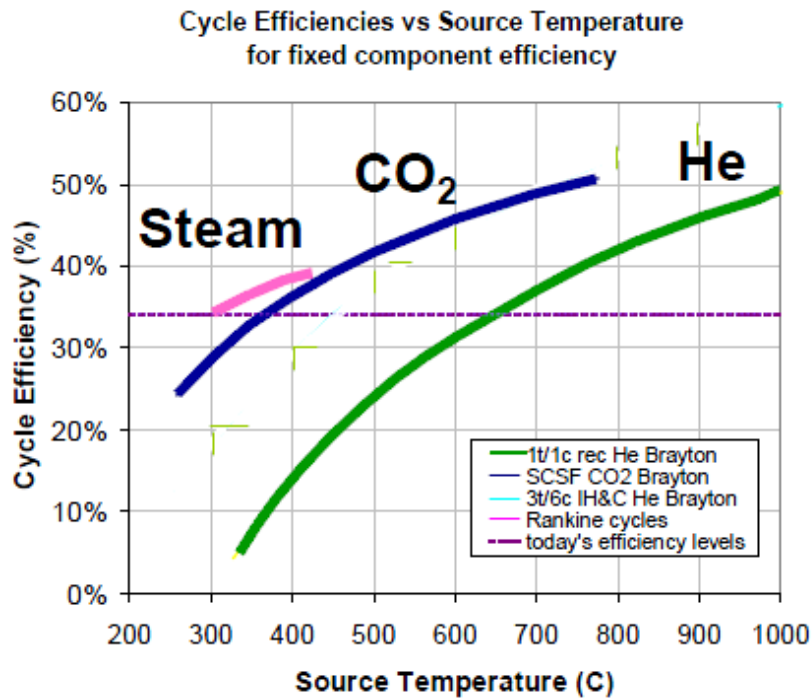
Property	Effect
High density, low viscosity, high C_p near C.P.	<ul style="list-style-type: none">• Reduced compressor work, increased W_{net}• Allow more-compact turbomachinery to achieve same power• Less complex – e.g., fewer compressor and turbine stages, may not need intercooling
Near-ambient T_{crit}	<ul style="list-style-type: none">• Good availability for most temperature sinks and sources
Abundant fluid with low GWP	<ul style="list-style-type: none">• Low cost
Familiar	<ul style="list-style-type: none">• Experience with standard materials, though not necessarily at high temp. & high pressure

CO₂ Cost Comparison*

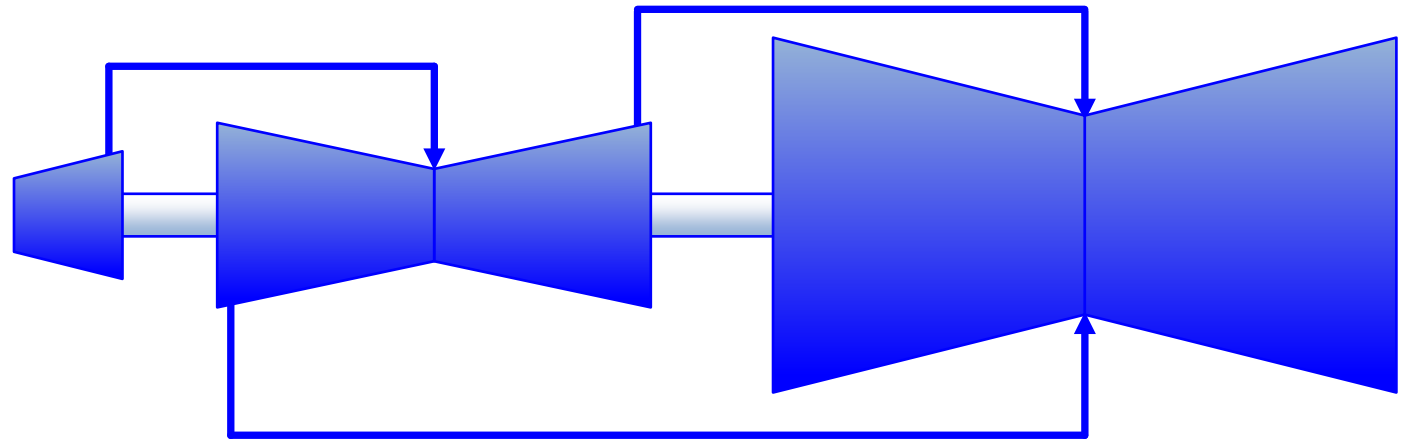


*Based on market pricing for laboratory-grade substance

Calculated sCO₂ efficiencies close to a steam cycle for potentially less \$/kW



Relative Size of Components



5 m

Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries (with casing)

Helium turbine: 17 stages / 333 MW (167 MW_e)
X.L. Yan, L.M. Lidsky (MIT) (without casing)

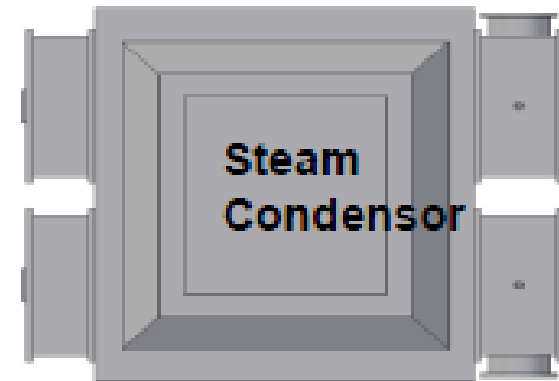
sCO₂ turbine: 4 stages / 450 MW (300 MW_e)
(without casing)

Note: Compressors are
comparable in size

Adapted from Dostal (2004)

S-CO₂
Cooler

1 m



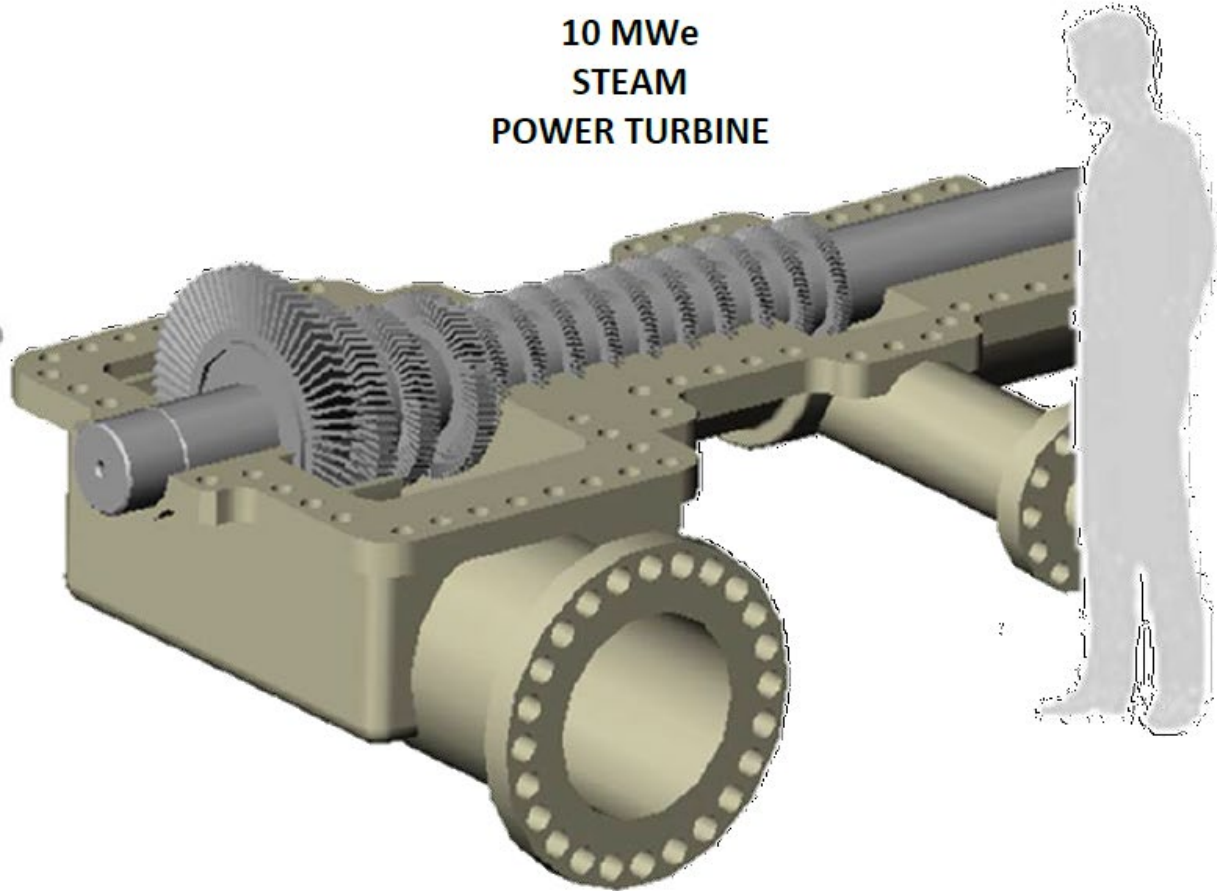
Source: Wright (2011)

Example: 10 MWe Turbine Comparison

10 MWe
SUPERCRITICAL CO₂
POWER TURBINE



10 MWe
STEAM
POWER TURBINE



sCO₂ in Power Cycle Applications



Supercritical CO₂ in Power Cycle Applications



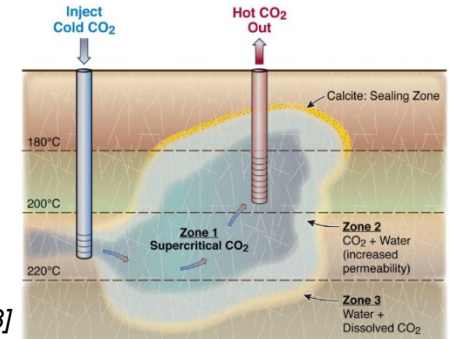
[6-1]

Concentrated
Solar Power



[6-2]

Fossil Fuel



[6-3]

Geothermal



[6-4]

Nuclear



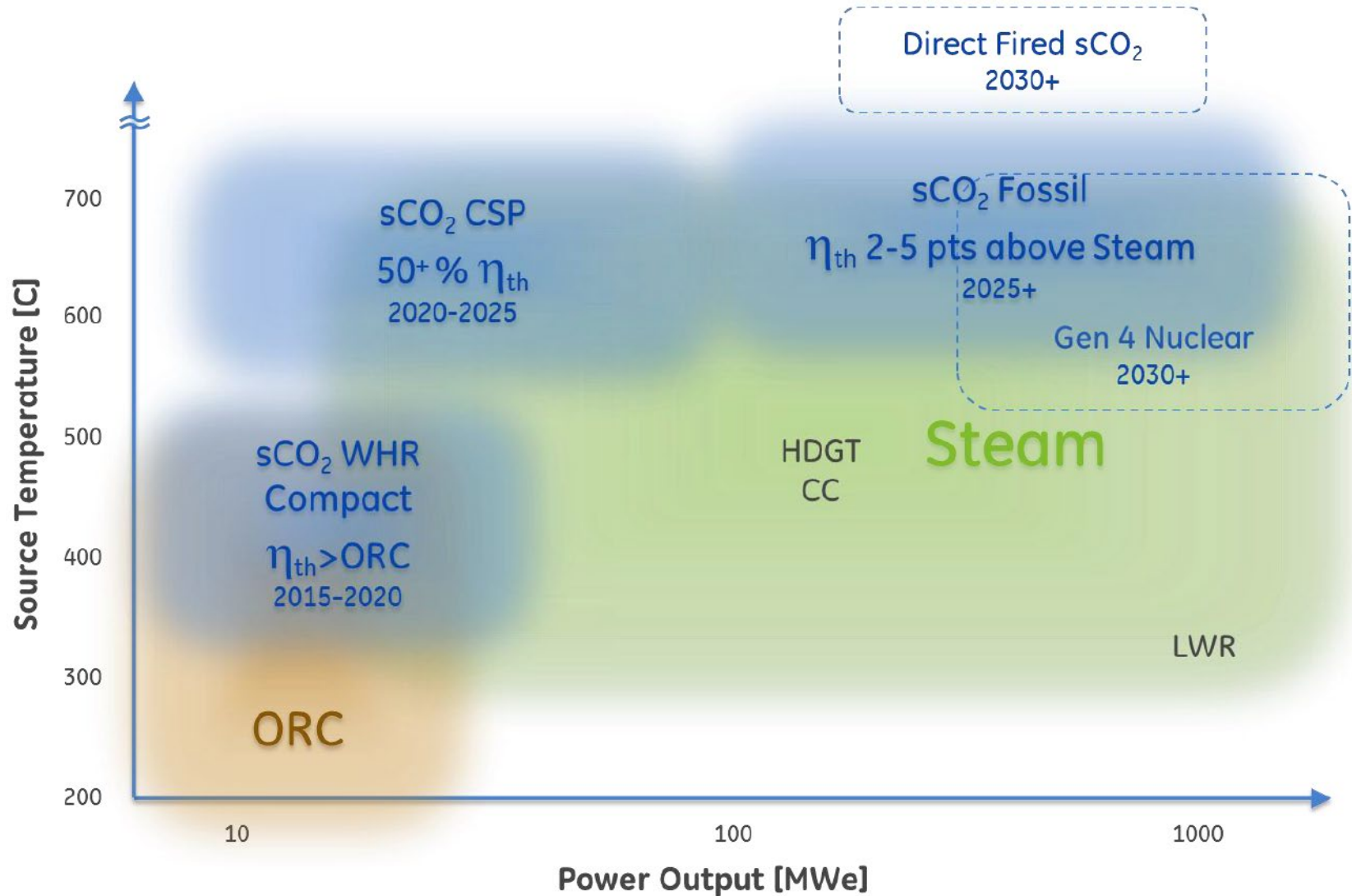
[6-5]

Ship-board
Propulsion



Waste Heat
Recovery [6-11]

Supercritical CO₂ Power Cycle Applications



Supercritical CO₂ in Power Cycle Applications



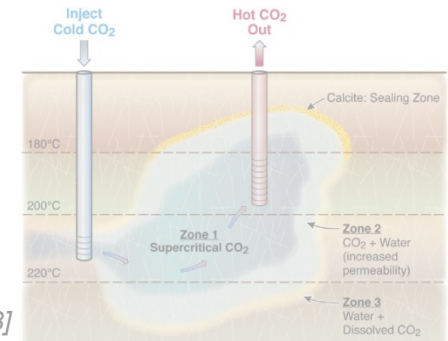
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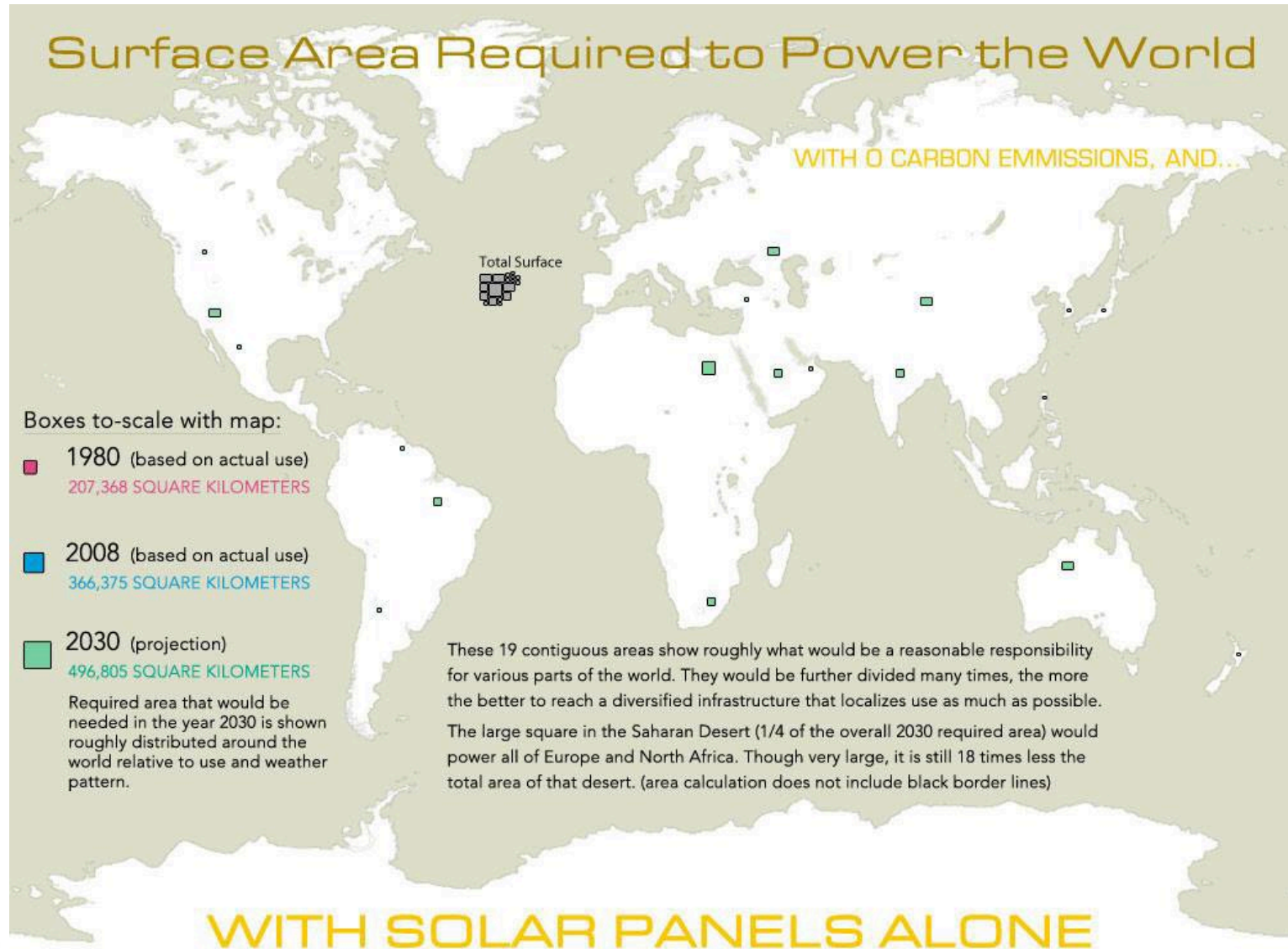
[6-5]

Ship-board
Propulsion



Waste Heat
Recovery [6-11]

Why would we use solar power?



Concentrated Solar Power (CSP)

- ❑ The Sun-Motor (1903)
 - Steam Cycle
 - Pasadena, CA
 - Delivered 1400 GPM of water
- ❑ Solar One (1982)
 - 10 MW_e water-steam solar power tower facility
 - Barstow, CA
 - Achieved 96% availability during hours of sunshine
- ❑ Solar Two (1995)
 - Incorporated a highly efficient (~99%) molten-salt receiver and thermal energy storage system into Solar One.

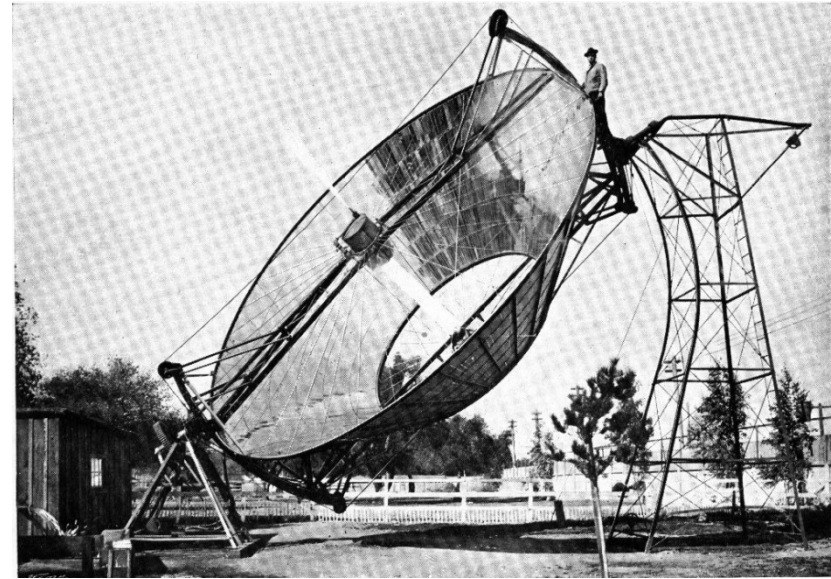
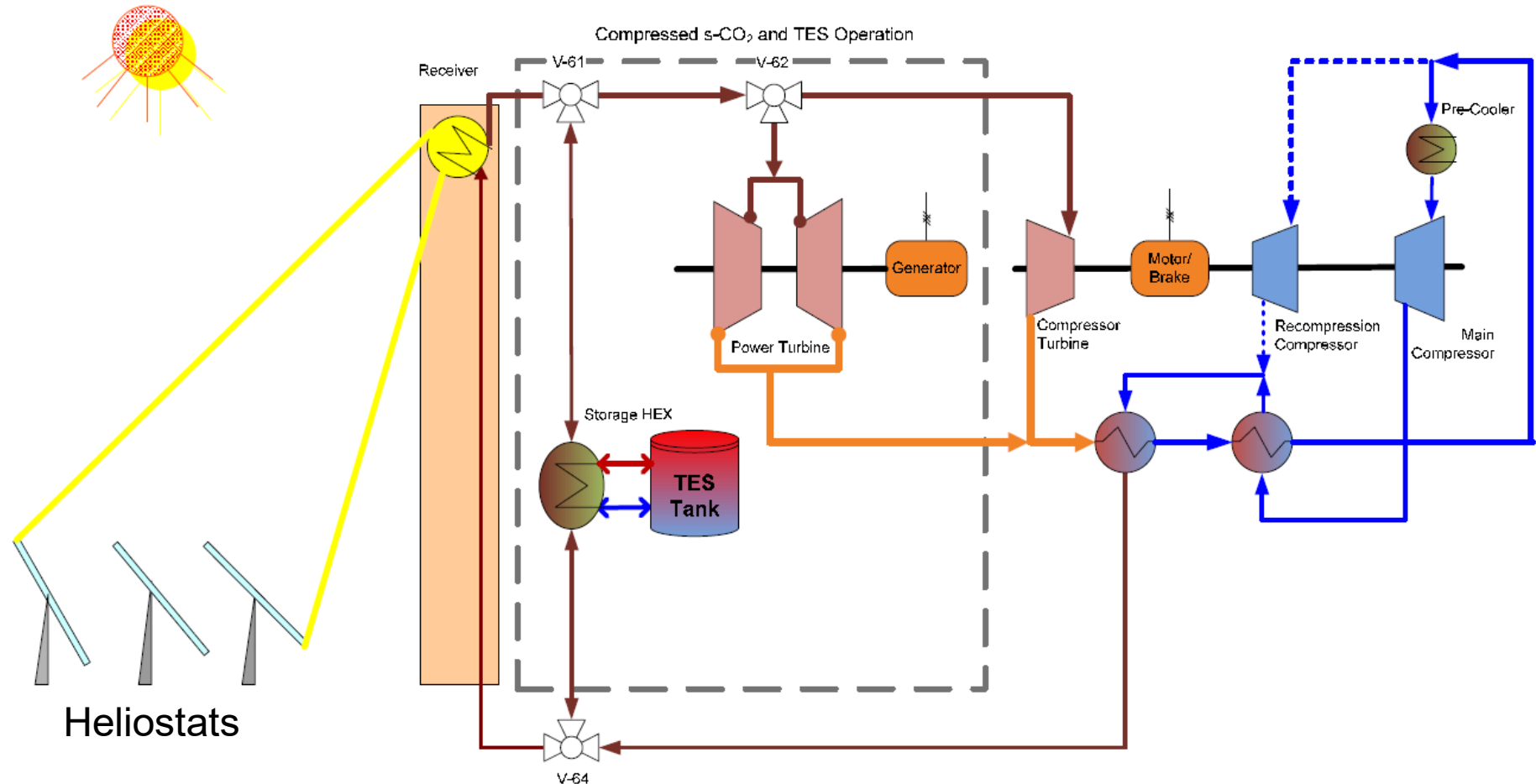


Image source: [6-6]



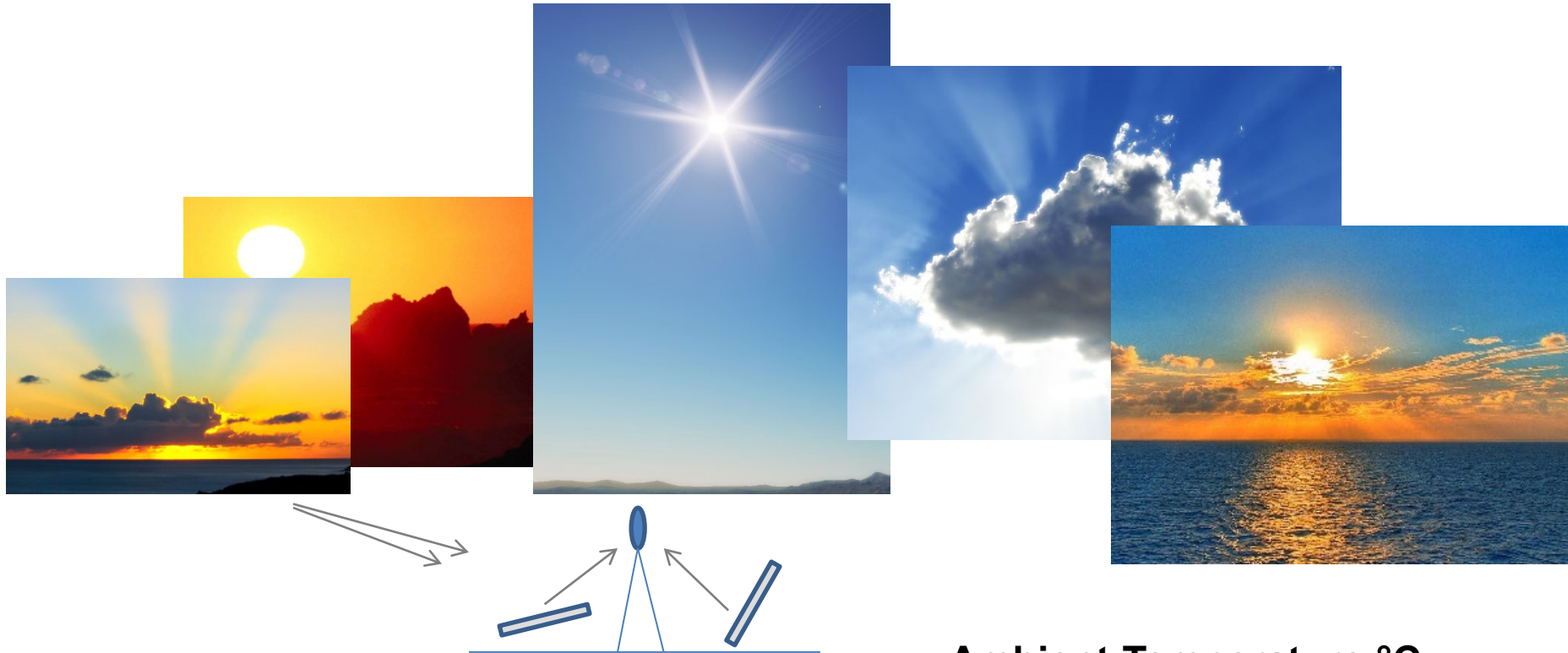
Image source: [6-7]

sCO₂ CSP Process Diagram

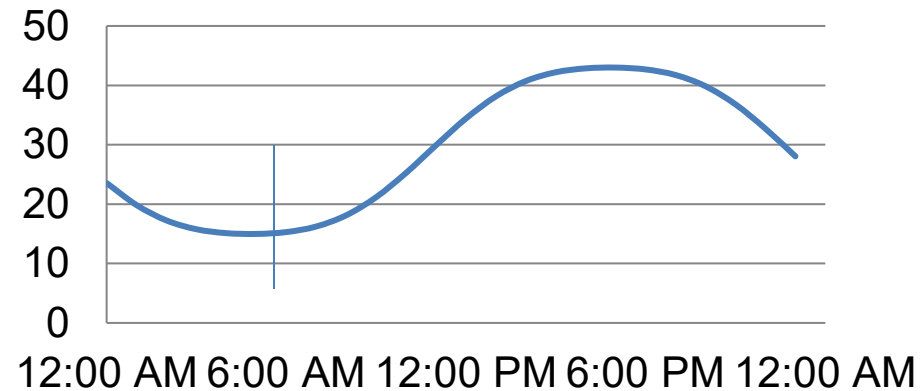


Dual-shaft, tower receiver sCO₂ Brayton Cycle solar thermal power system with thermal energy storage, Zhiwen and Turchi (2011)

The transient challenges of a concentrated solar power plant are significant

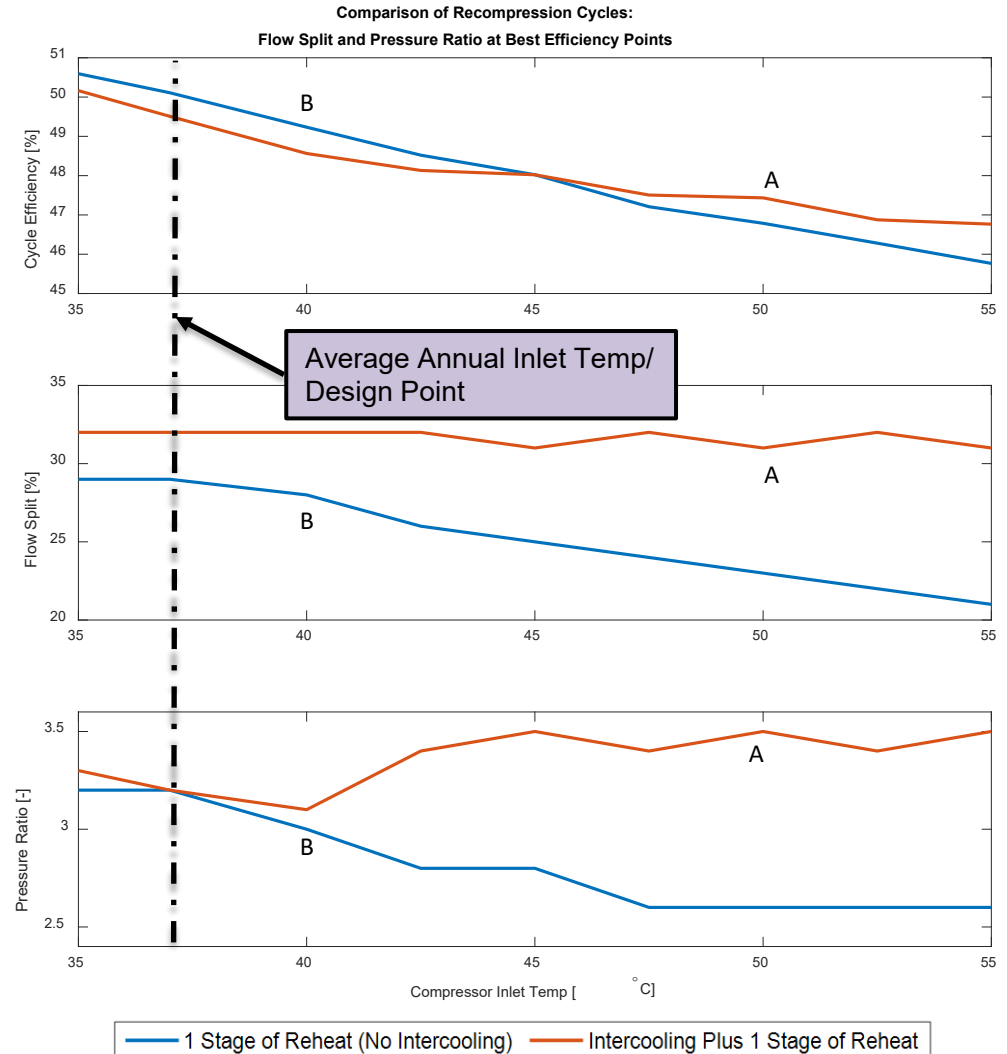


Ambient Temperature °C

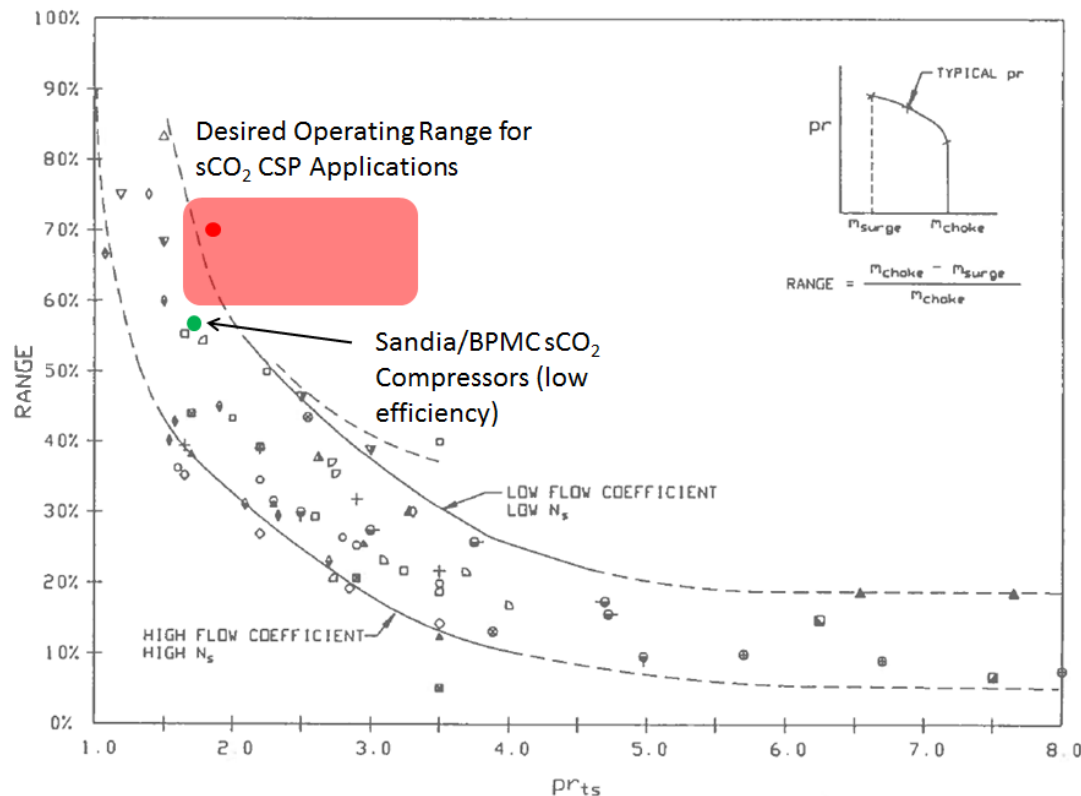


Optimal Cycle Configuration with varying Compressor Inlet Temperature

- SAM modeling of typical sites shows an annual average compressor inlet temperature to be 37-38°C assuming 15°C approach temperature in the cooler
- Cycle Modeling
 - Optimal flow split
 - 22-33%
 - Heavily dependent on CIT
 - Optimal PR
 - Varies with use of intercooling
 - Intercooled cycles are more efficient on hot days, and less efficient on cool days



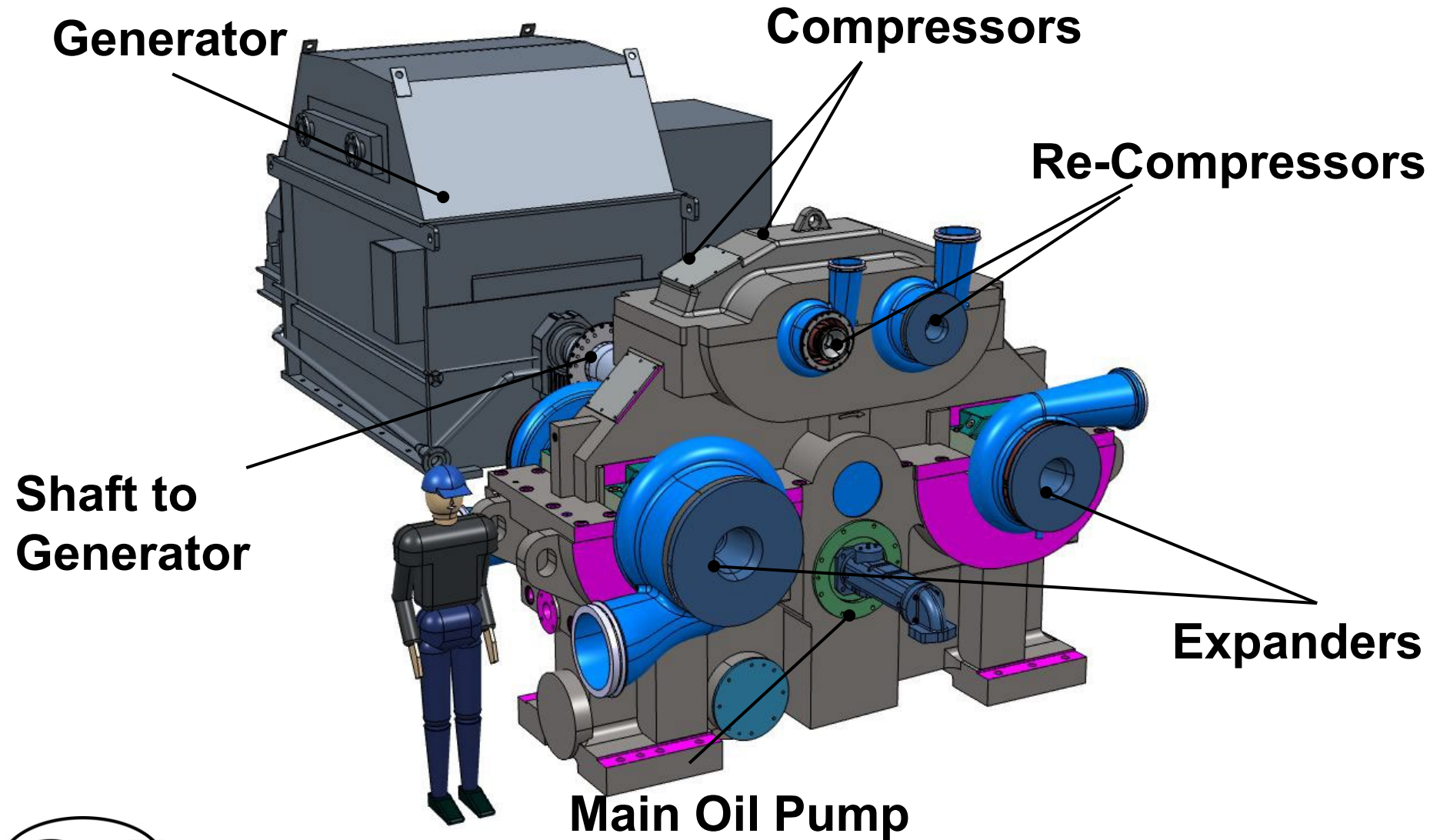
CSP Compressor Inlet Variation and Turbomachinery Performance



- To manage this challenge, numerous strategies will be required
 - Inventory Control
 - Inlet Guide Vanes
 - Variable Diffuser Vanes
 - Variable Speed Compression
 - Novel Control Features

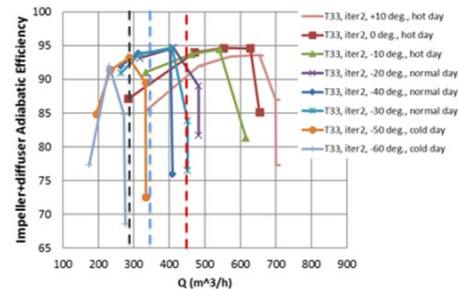
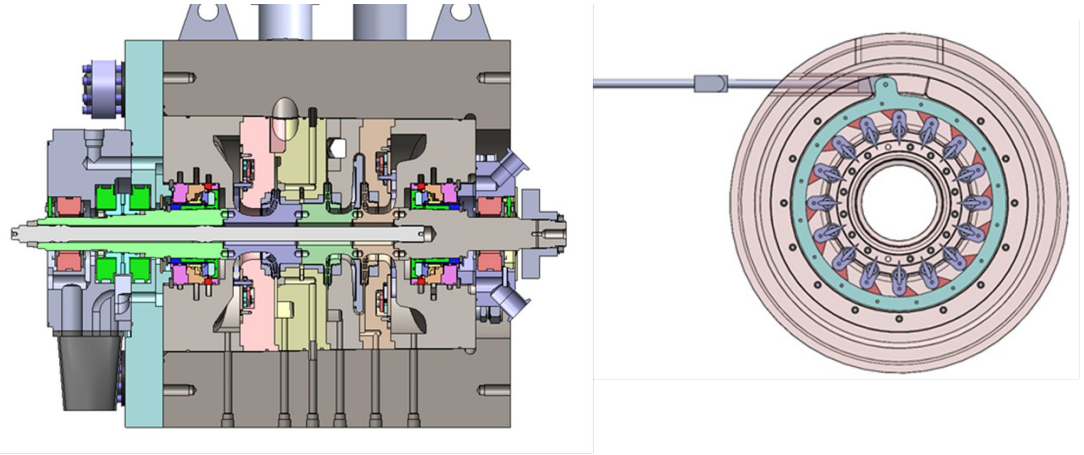
Figure 5: Comparison of Operating Range and Pressure Ratio Requirements [Modified from Japikse^[5]]

Conceptual 10 MW_e Integrally Geared Compressor Applied to Recuperated Brayton Cycle



APOLLO Compressor Development

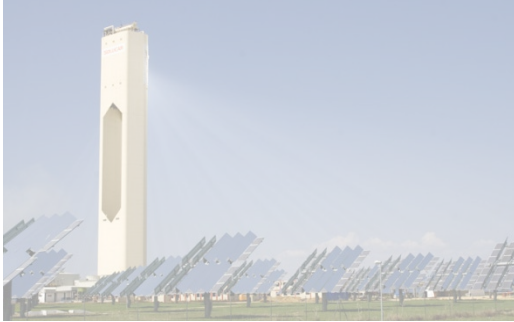
- ❑ Develop and test an sCO₂ compressor for power cycles
- ❑ GE, SwRI, BHGE (Funded by EERE)
- ❑ Compressor targets
 - 10 MWe net module size
 - >80% net thermal efficiency
 - Operation across wide range of ambient temperatures



What are the key challenges to CSP sCO₂ cycles

- ❑ Variable inlet temperature creates numerous cycle challenges
 - Dry cooling mandatory
 - Compressor operation near the critical point requires careful cycle control (not yet demonstrated)
- ❑ Heat addition to the sCO₂ while incorporating thermal energy storage is challenging
- ❑ Turbine inlet temperatures approaching 750° with very high cycle efficiency requirements expected.

Supercritical CO₂ in Power Cycle Applications



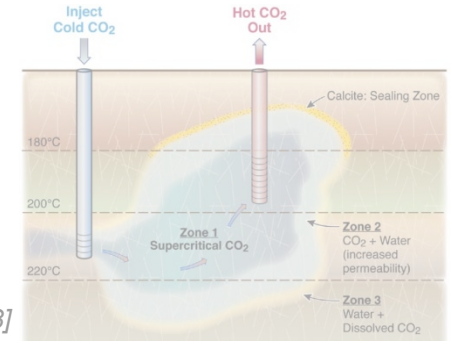
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Solar Power



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Fossil Fuel



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[6-5]

Ship-board
Propulsion



Waste Heat
Recovery [6-11]

Rankine Cycle Application: Nuclear Power Generation

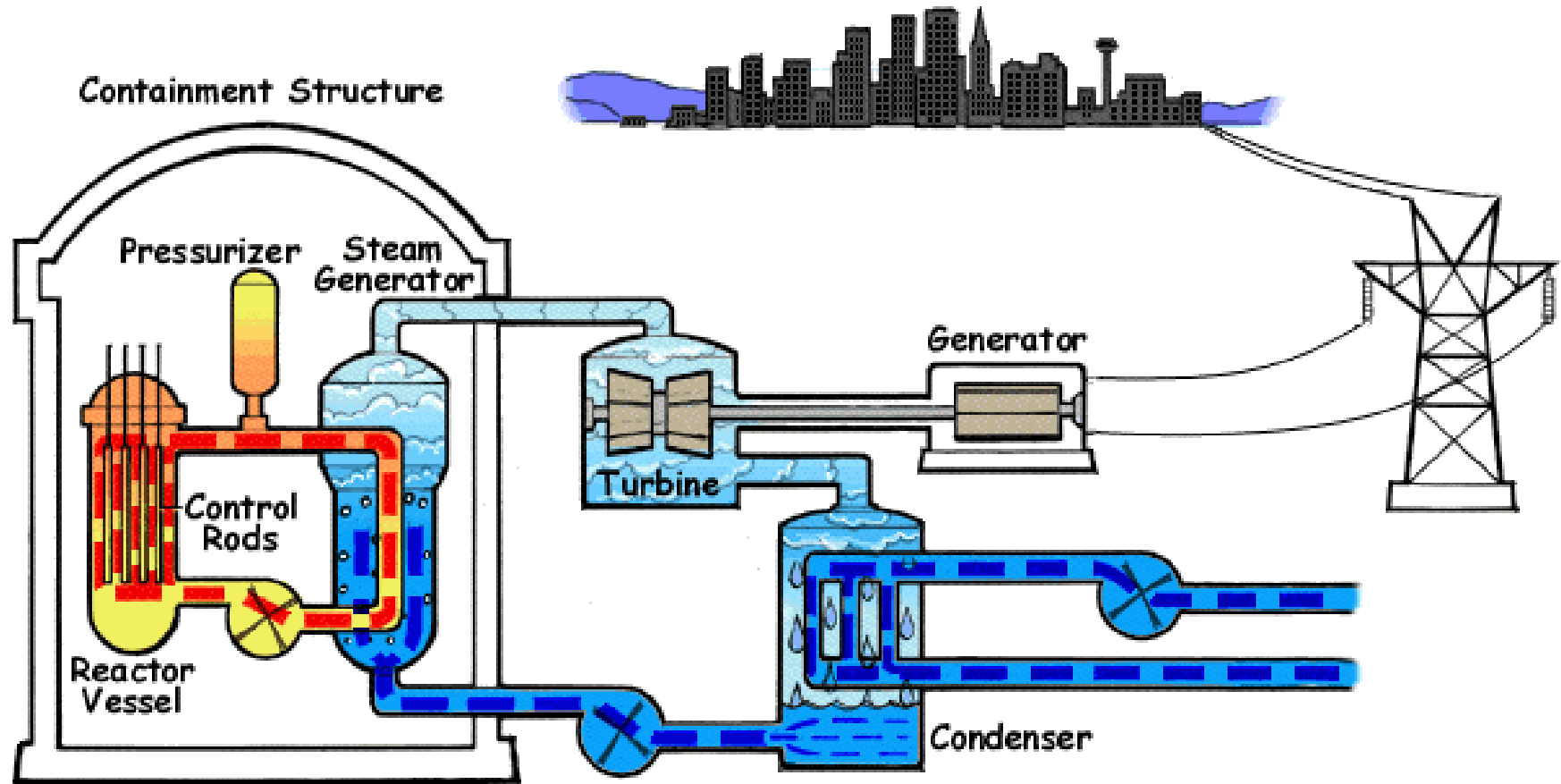


Image source: [6-8]

sCO₂ for Nuclear Applications (550°C-700°C, 34 MPa)

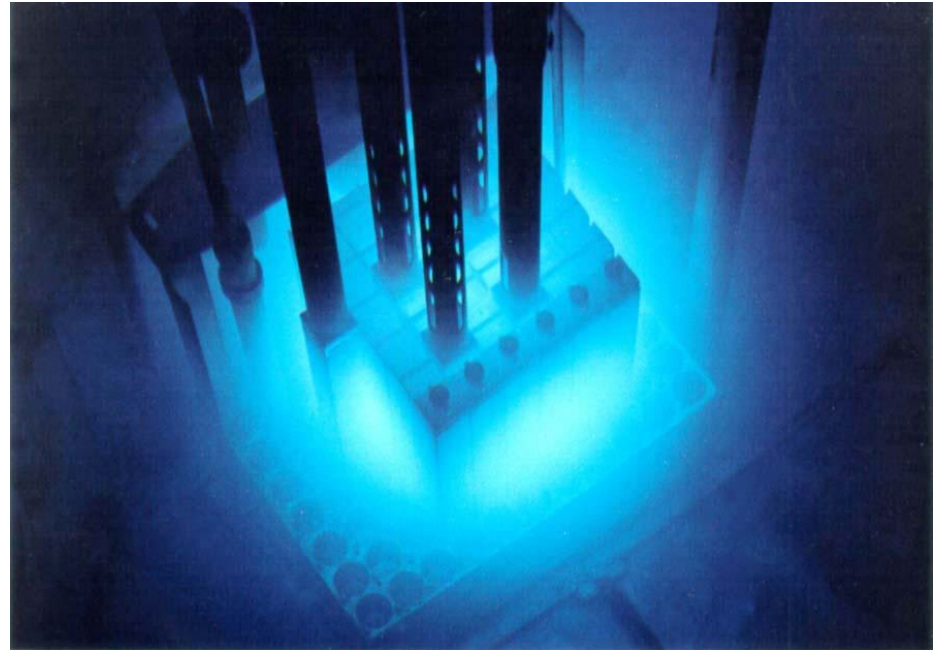


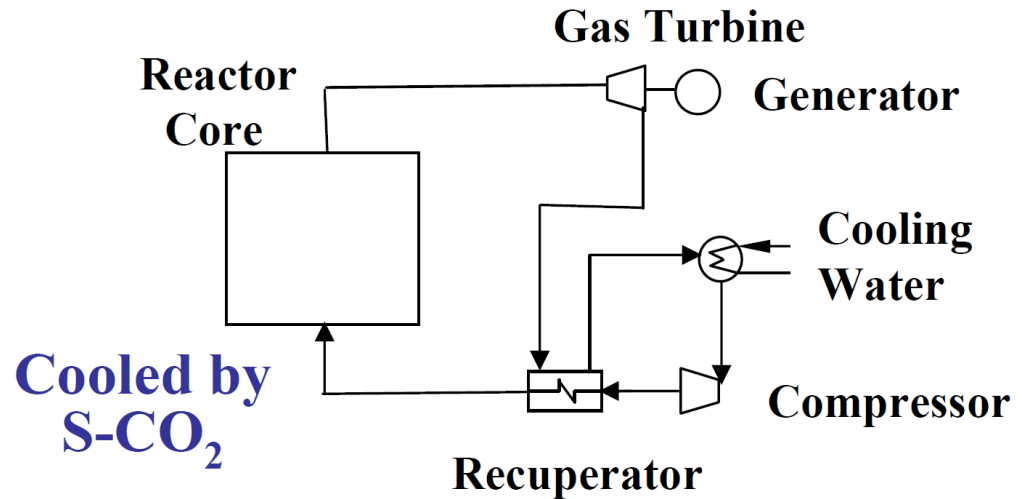
Image source: [6-9]

Image source: [6-4]

Proposed Nuclear sCO₂ Cycles

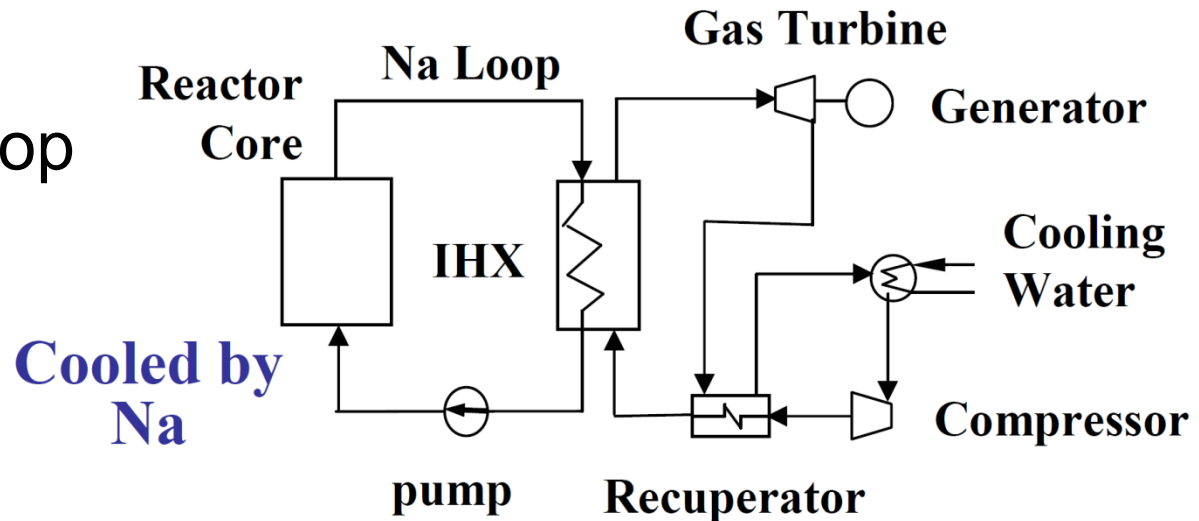
❑ Direct Cycle

- No primary and secondary Na loops
- Lower Void Reactivity

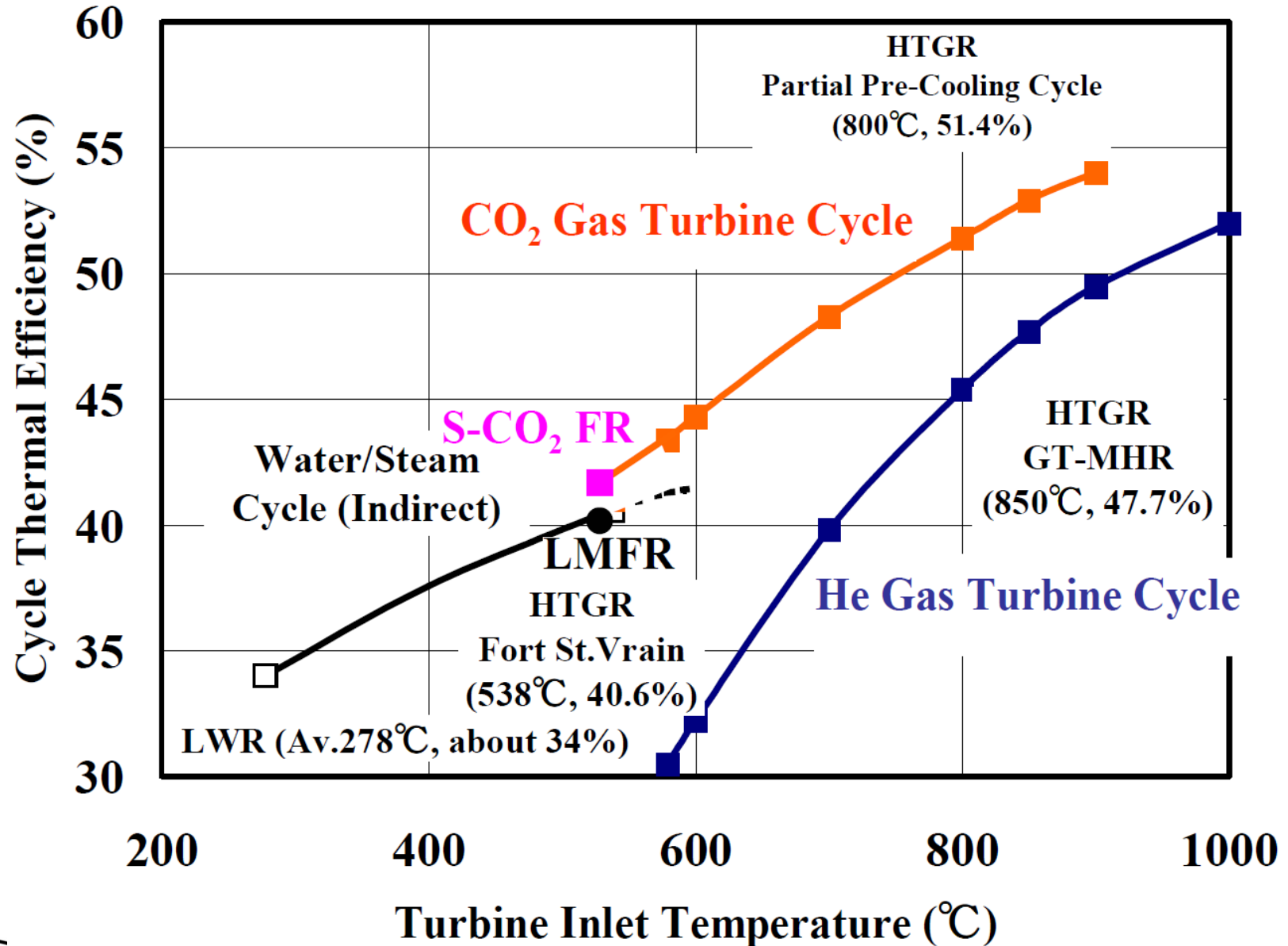


❑ Indirect Cycle

- Primary Na loop
- Smaller core size



Nuclear Plant Efficiency vs. Cycle Prop.



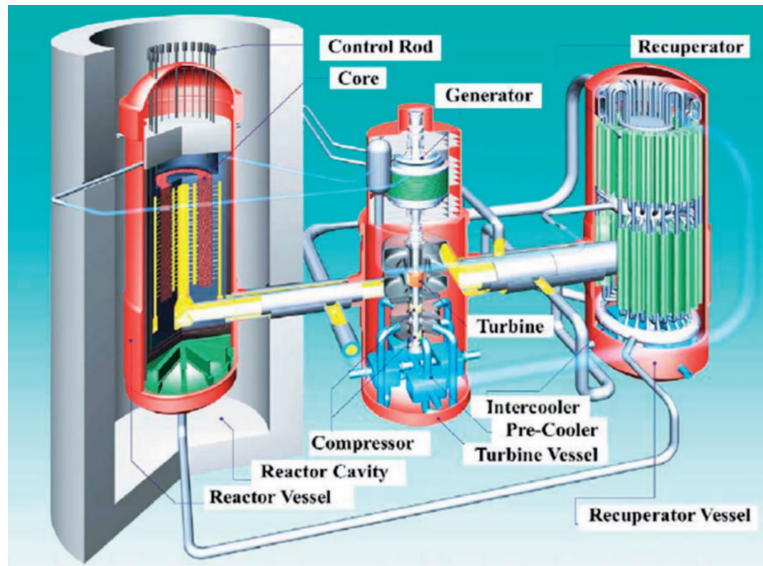
Modular

vs.

Consolidated

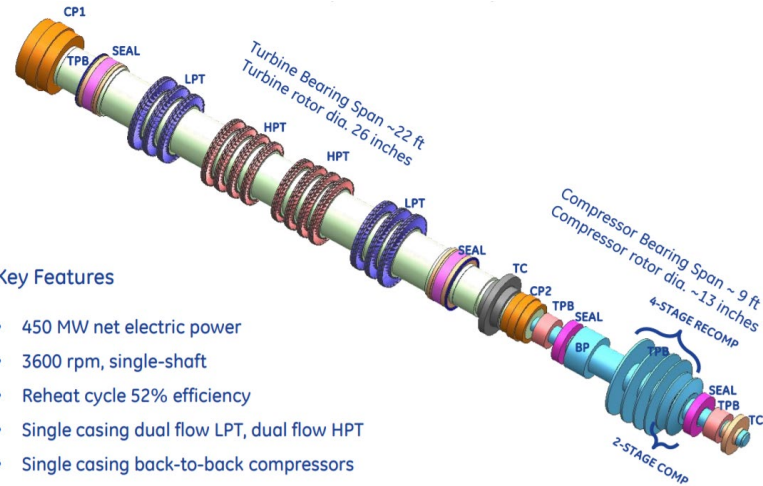
❑ 10-20 MW

- Multiple High-Speed Trains
- Smaller Capital Investment
- Intrinsically Safe Cooling
- Mass Scale Production
- Smaller Environmental Risk



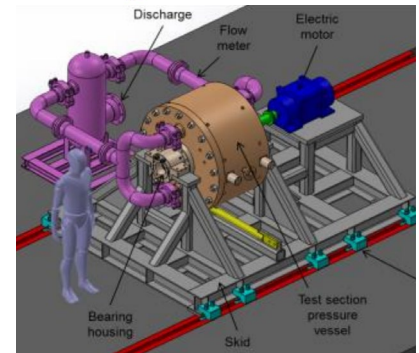
❑ 200 MW-1 GW

- Single Low Speed Train
- Larger Capital Investment
- Larger Environmental Risk
- Intensive NRE



Key Features

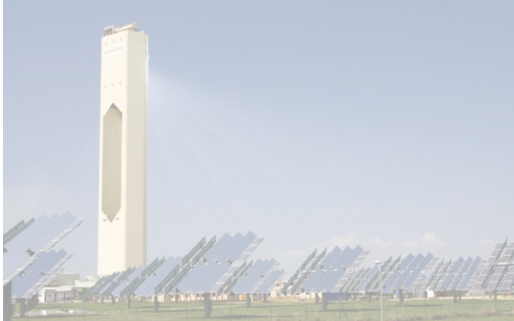
- 450 MW net electric power
- 3600 rpm, single-shaft
- Reheat cycle 52% efficiency
- Single casing dual flow LPT, dual flow HPT
- Single casing back-to-back compressors



What are the key challenges to Nuclear sCO₂ cycles

- ❑ Aversion to risk likely to push this out past waste heat recovery, solar, and fossil implementations; however, modular 10-30 MW sodium reactors are a key topic of research in Korea.

Supercritical CO₂ in Power Cycle Applications



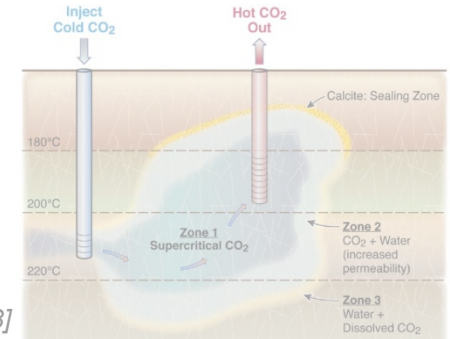
[6-1]

Concentrated
Solar Power



[6-2]

Fossil Fuel



[6-3]

Geothermal



[6-4]

Nuclear



[6-5]

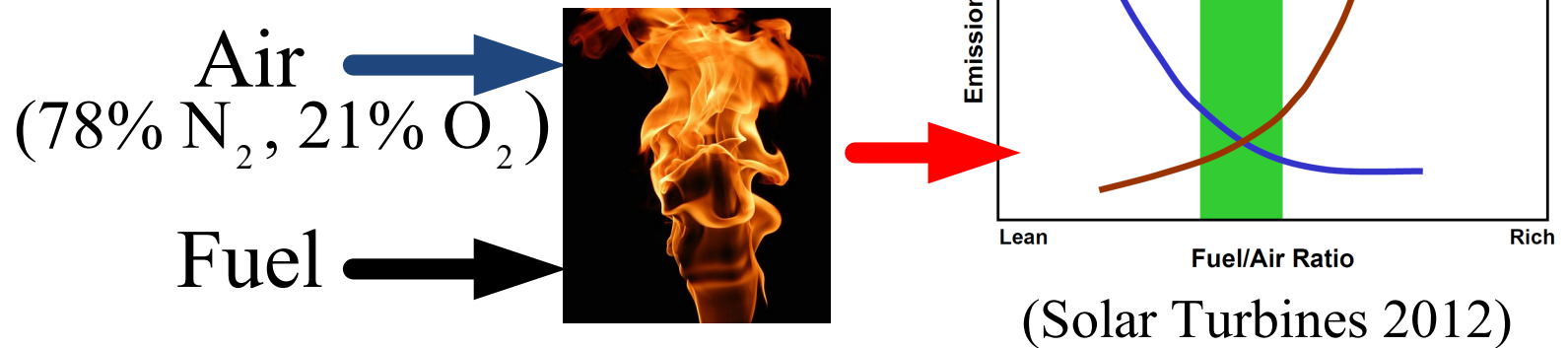
Ship-board
Propulsion



Waste Heat
Recovery [6-11]

Oxy-Fuel Combustion

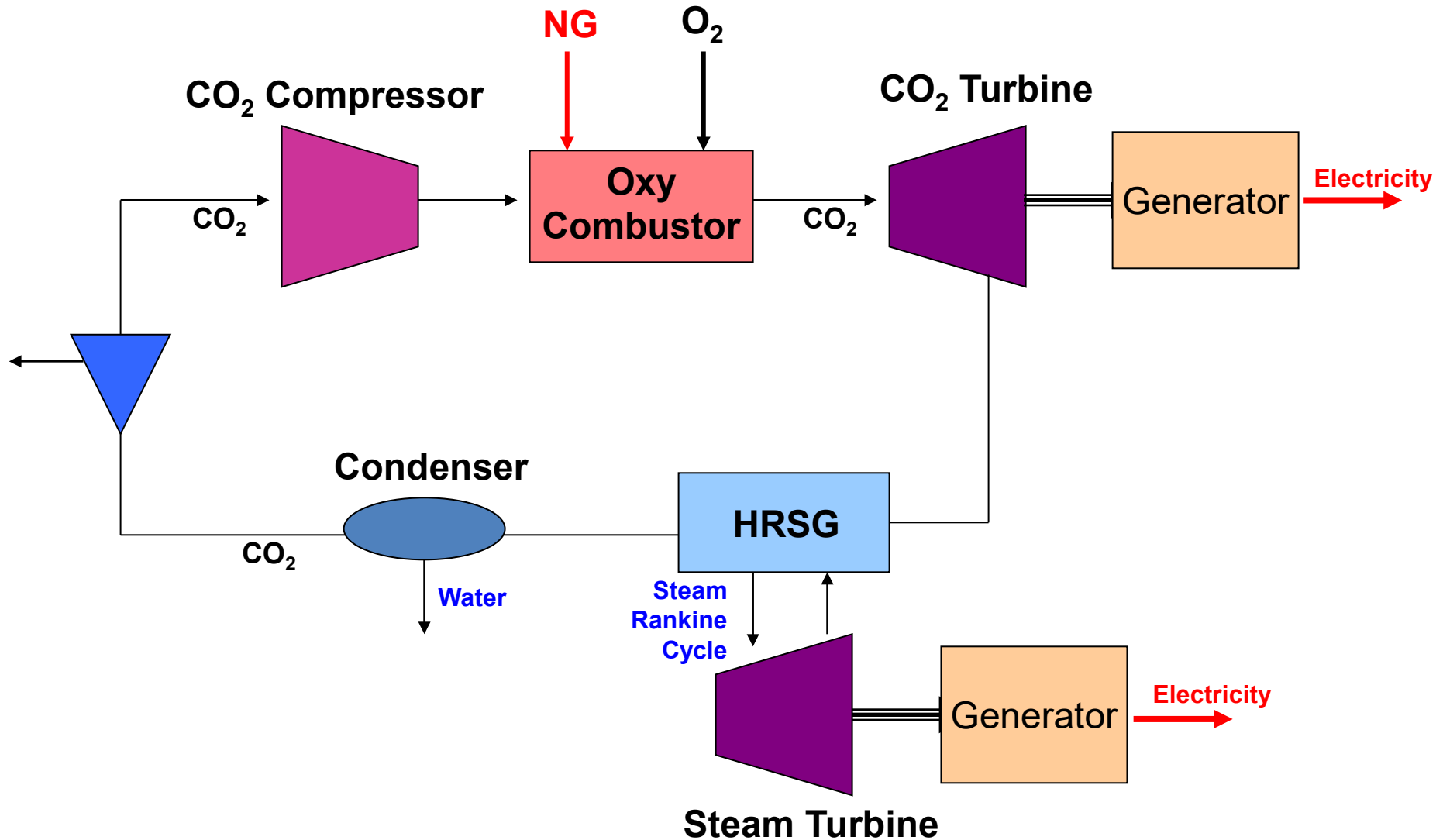
Conventional Combustion



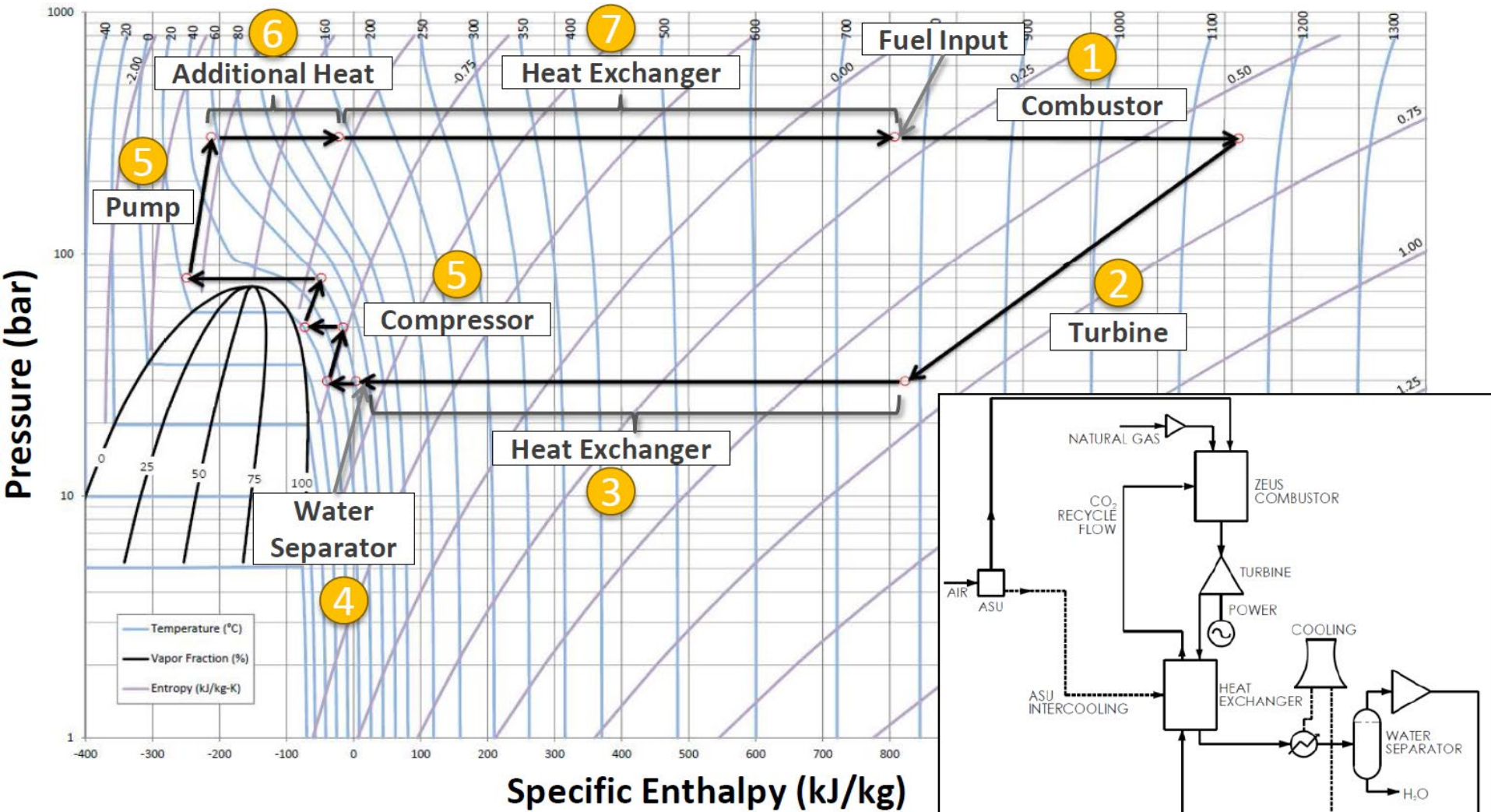
Oxy-Fuel Combustion



Direct Oxy-Fuel Combustion



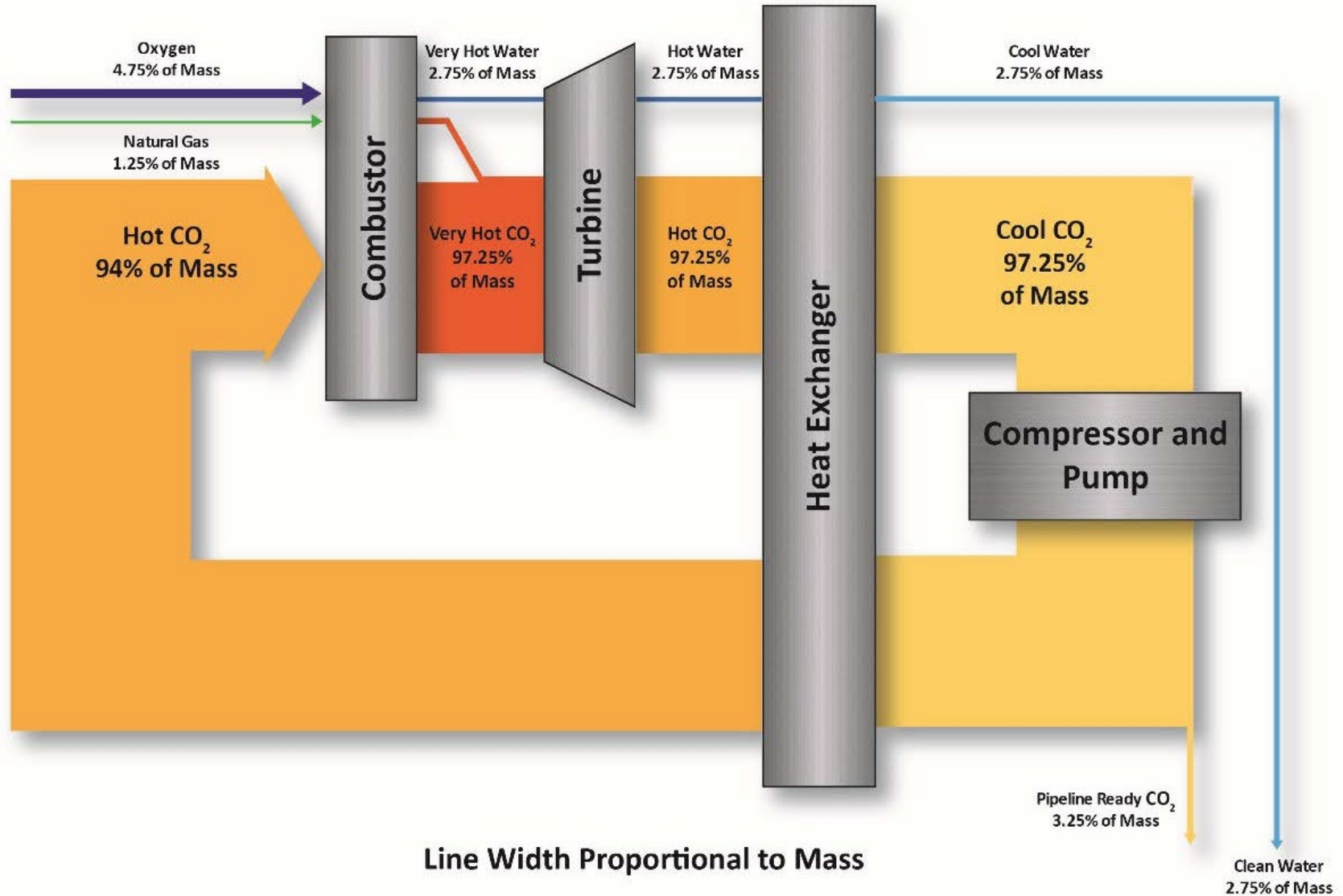
Allam Cycle (NetPOWER)



Net Efficiency 58.9%

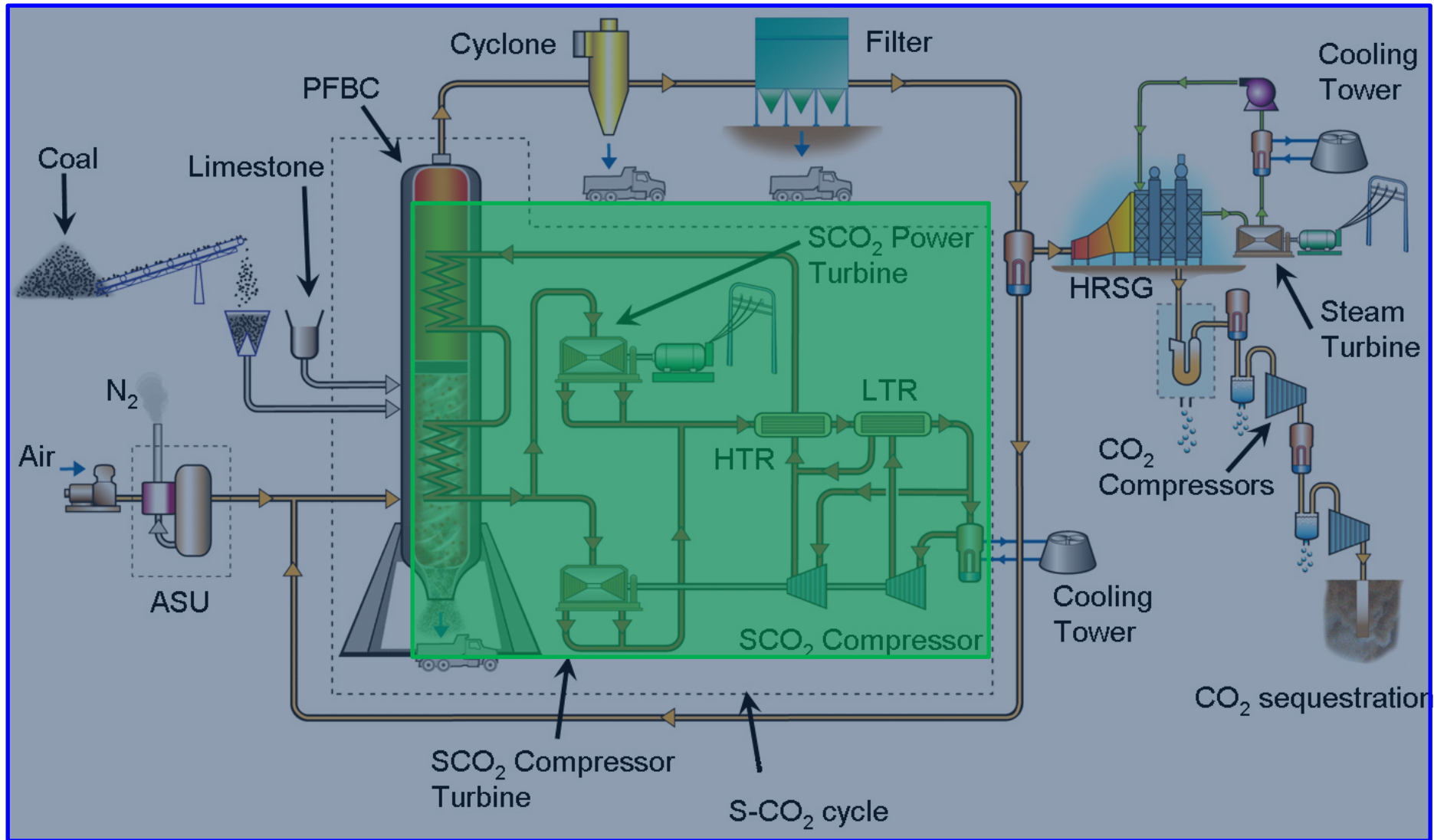
[Fetvedt 2016]

The Allam Cycle (NetPOWER)





Indirect Oxy-Fuel Combustion

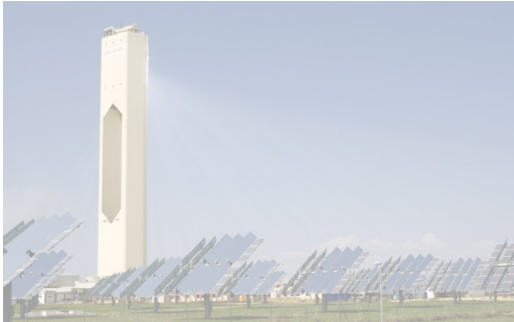


Zero Emission Oxy-Coal Power Plant with Supercritical CO₂ Cycle, Johnson et al. (2012)

What are the key challenges for oxy-fuel sCO₂ cycles

- ❑ Very high combustor and expander temperatures (1,200°C)
 - Film cooling mandatory
 - Containment challenges
 - Sealing challenges
- ❑ Unproven combustion dynamics
- ❑ Complex auxiliary hardware

Supercritical CO₂ in Power Cycle Applications



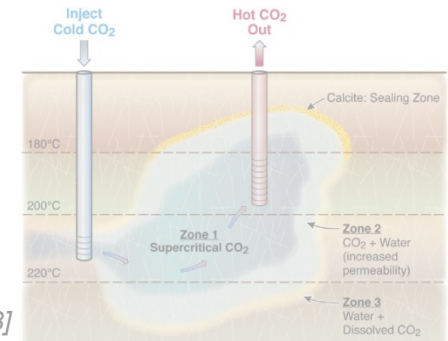
[6-1]

Concentrated
Solar Power



[6-2]

Fossil Fuel



[6-3]

Geothermal



[6-4]

Nuclear



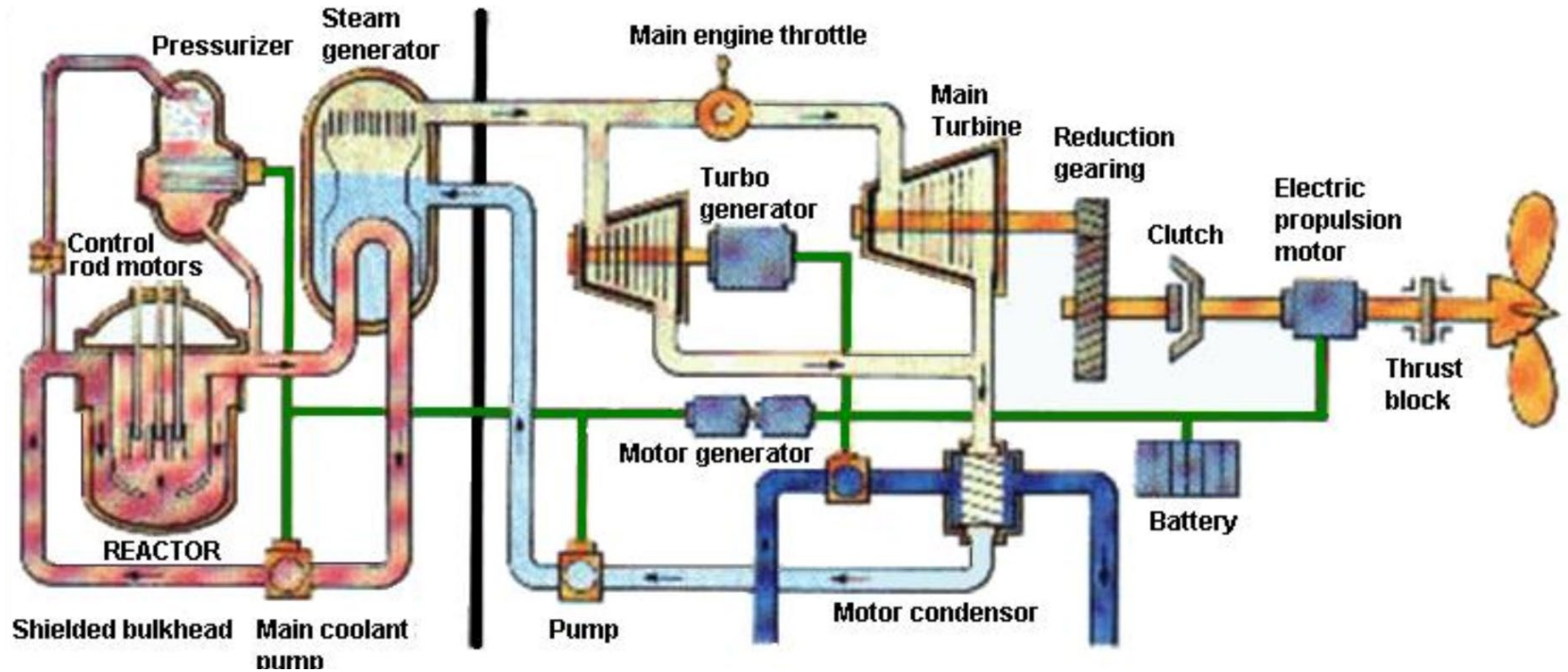
[6-5]

Ship-board
Propulsion



Waste Heat
Recovery [6-11]

Pressurized-Water Naval Nuclear Propulsion System

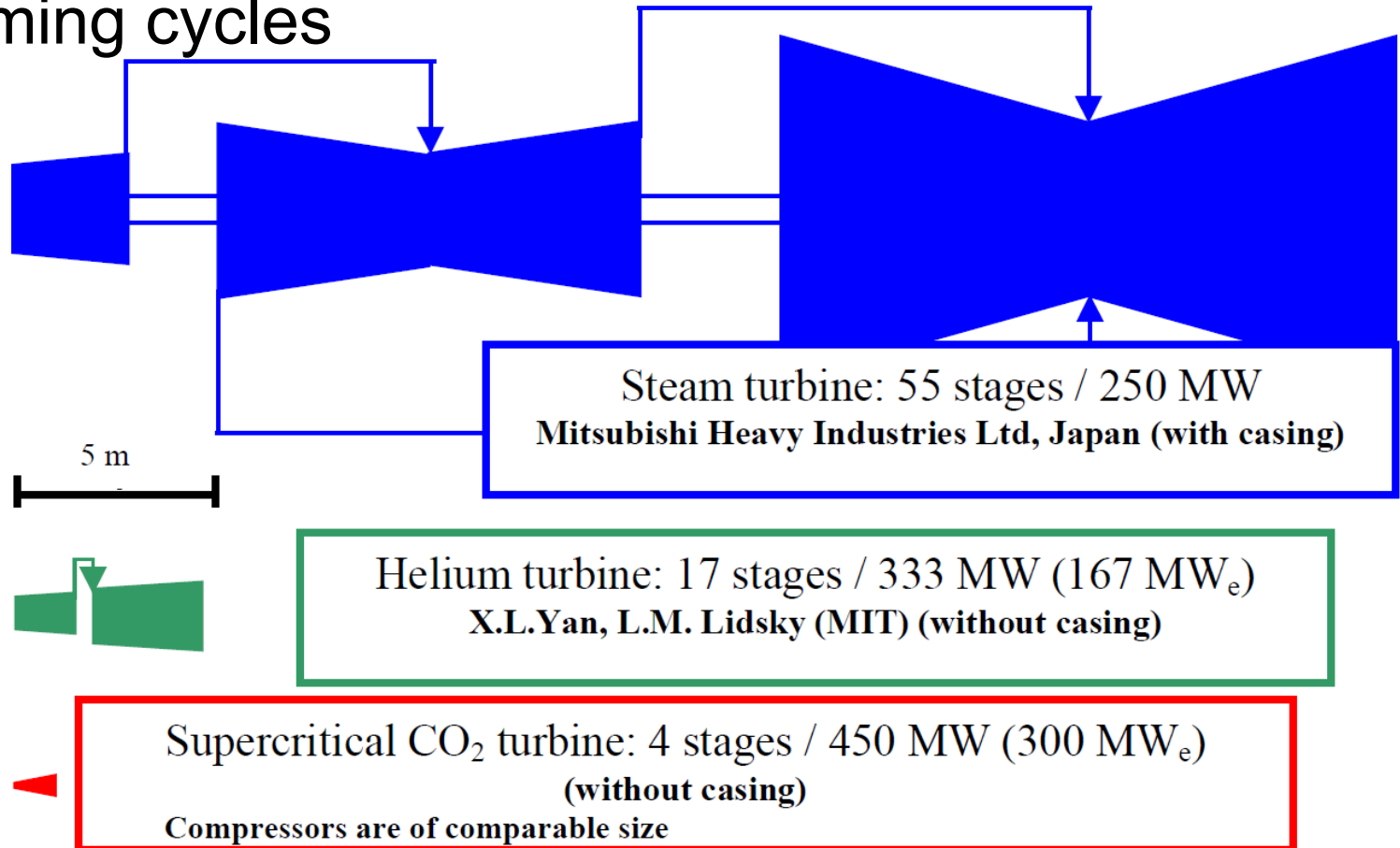


Ship-board Propulsion

- ❑ Nuclear sCO₂ cycles?
- ❑ Improved power to weight
- ❑ Rapid startup
- ❑ Bottoming cycles



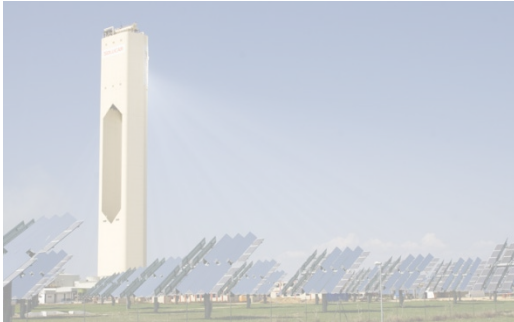
Image source: [6-10]



Key challenges to sCO₂ nautical applications

- ❑ Weight
- ❑ Startup transient response times
- ❑ Impulse load robustness
- ❑ Containment (ships do get hit)

Supercritical CO₂ in Power Cycle Applications



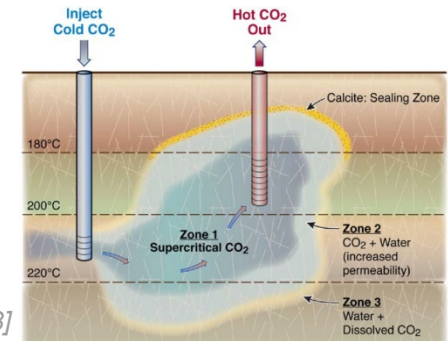
[6-1]

Concentrated
Solar Power



[6-2]

Fossil Fuel



[6-3]

Geothermal



[6-4]

Nuclear



[6-5]

Ship-board
Propulsion

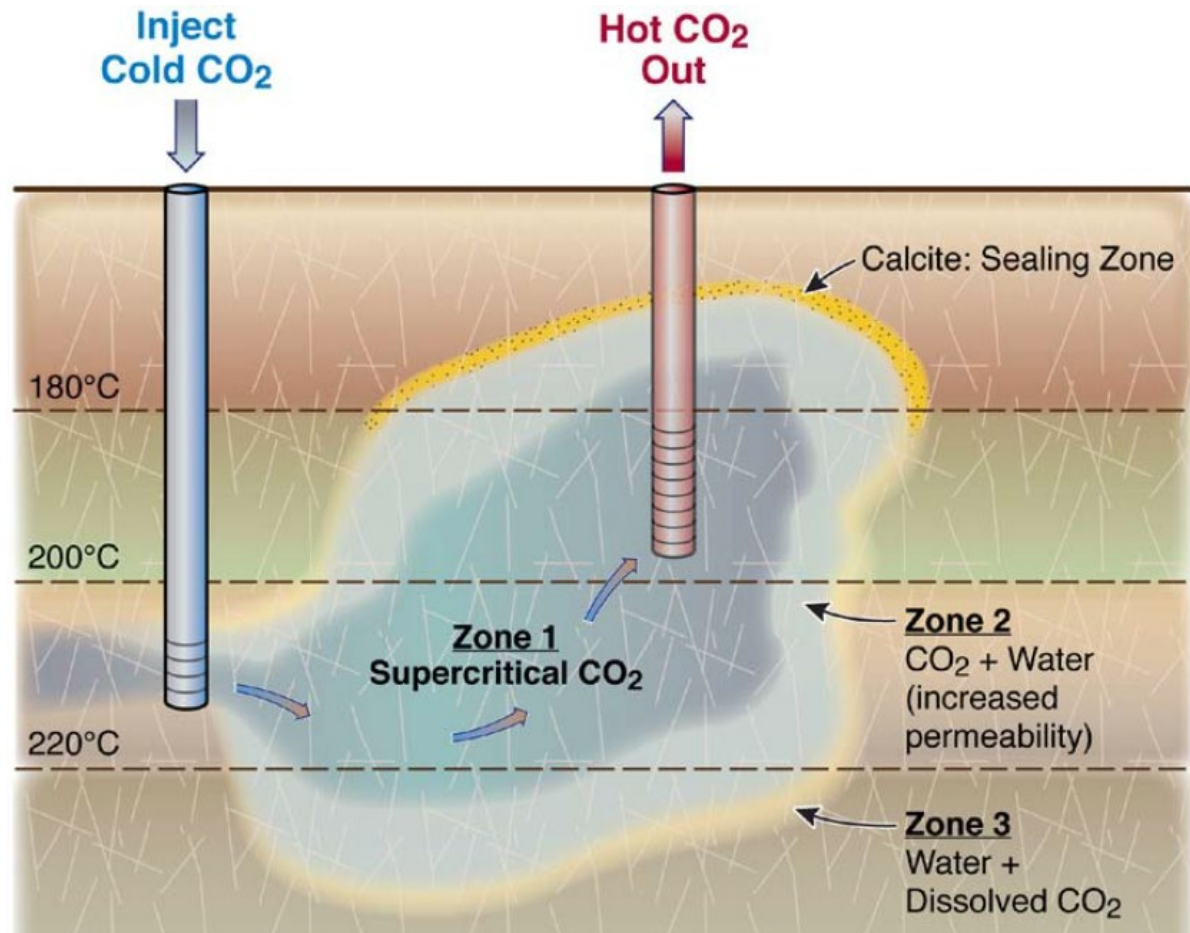


Waste Heat
Recovery [6-11]

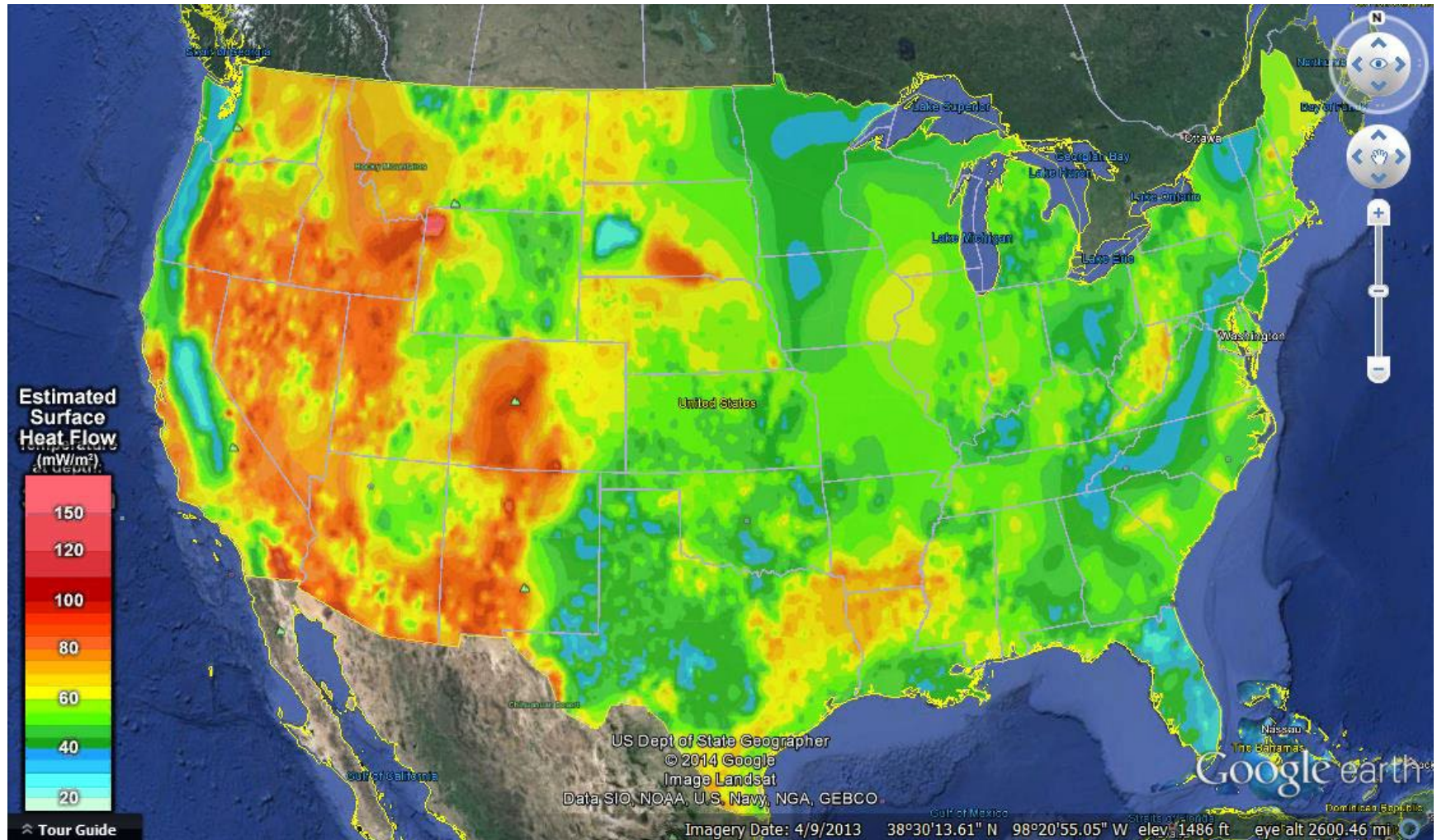
Geothermal

□ Low Temperature Heat Source

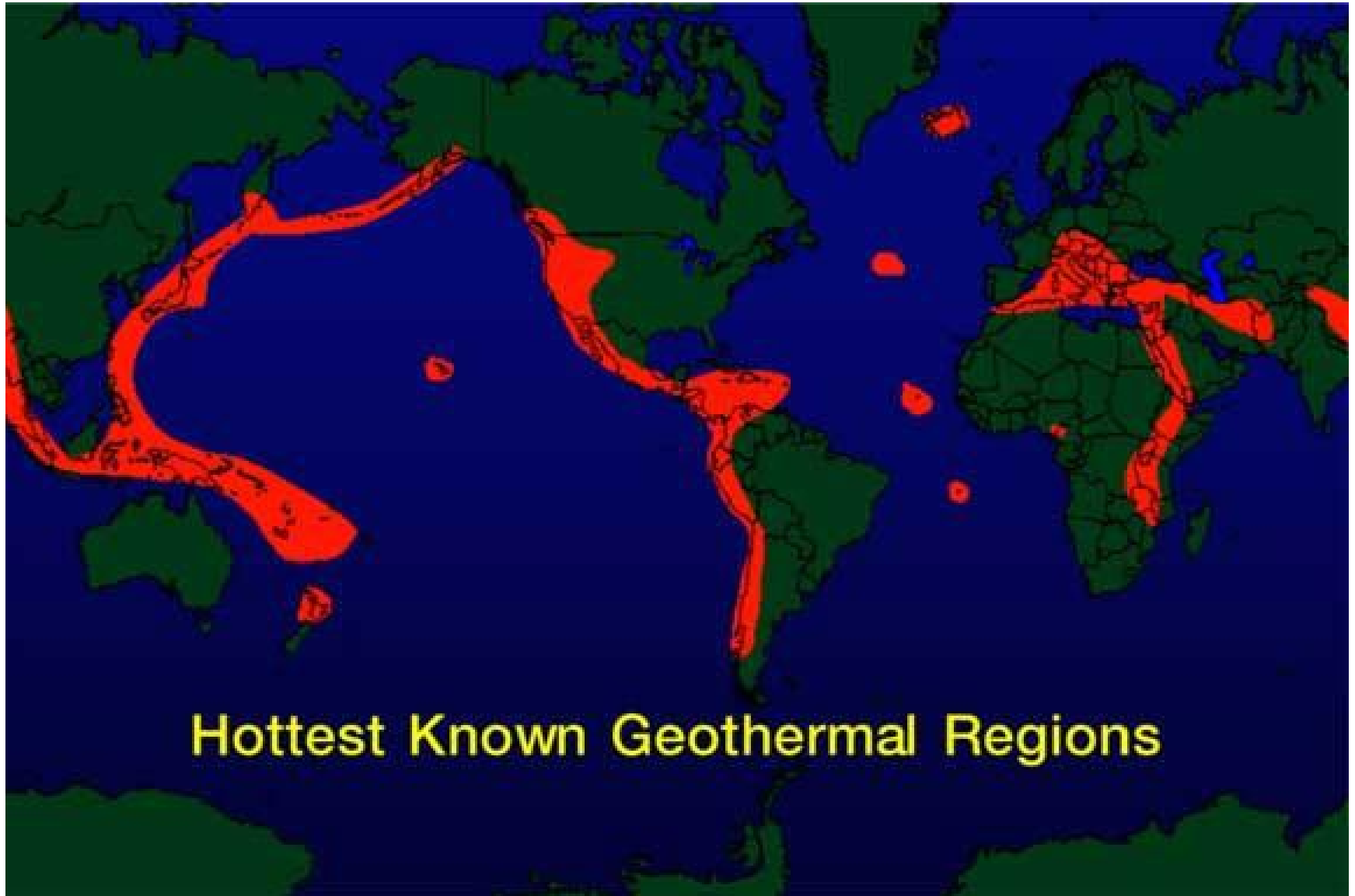
- $T \approx 210^{\circ}\text{C}$, $P \approx 100$ bar



US Geothermal Resources

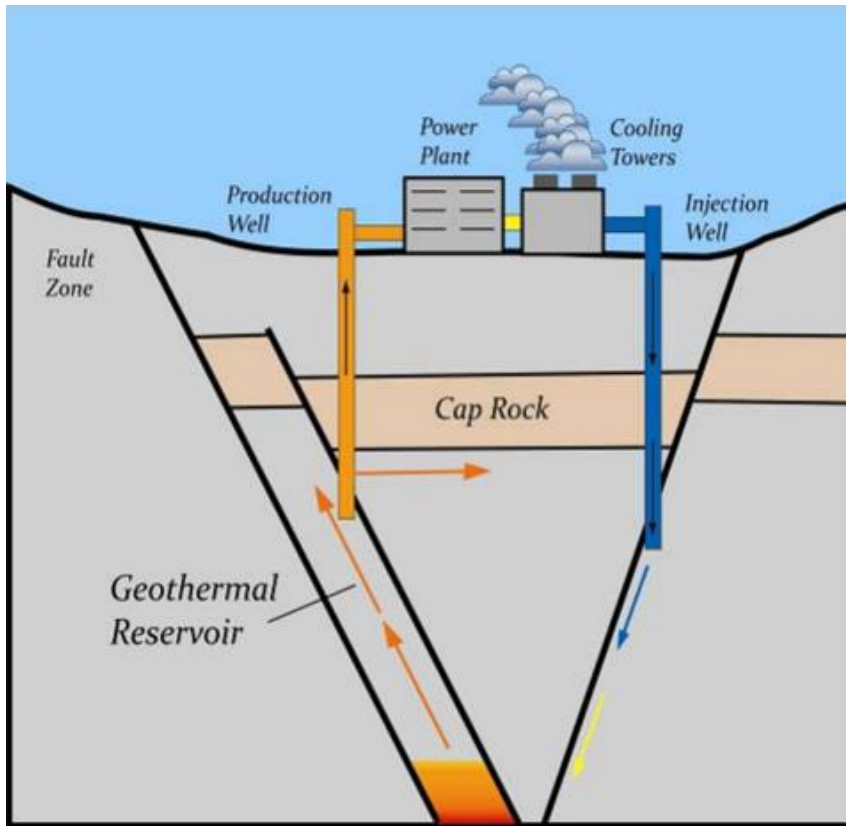


Global Geothermal Resources

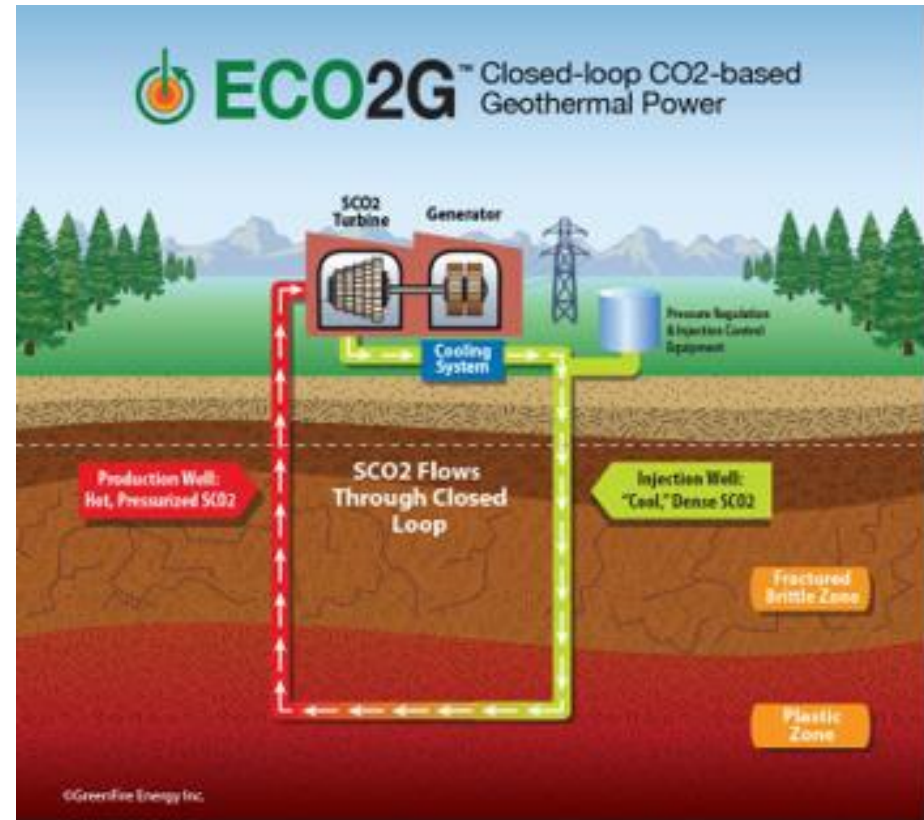


ECO2G

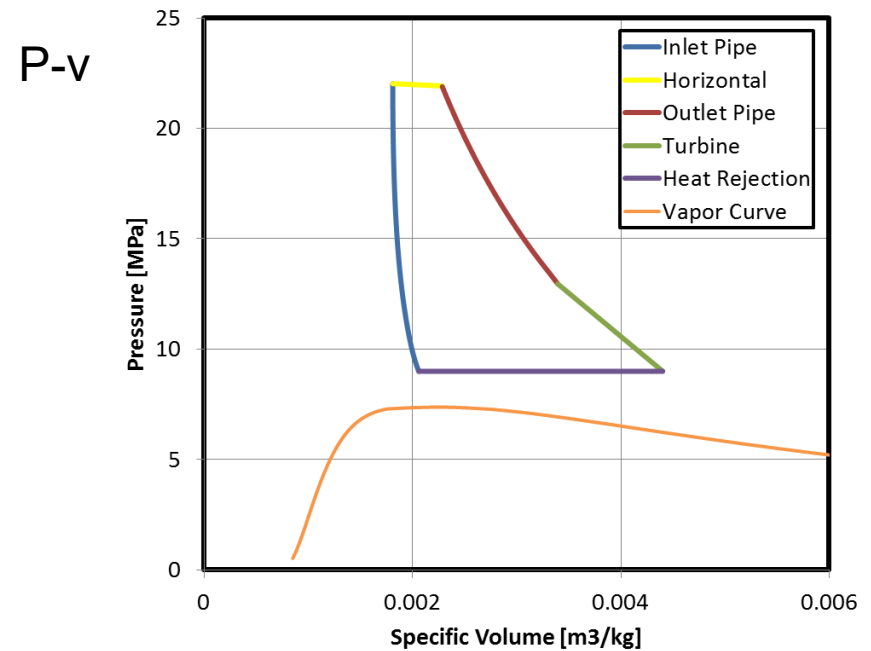
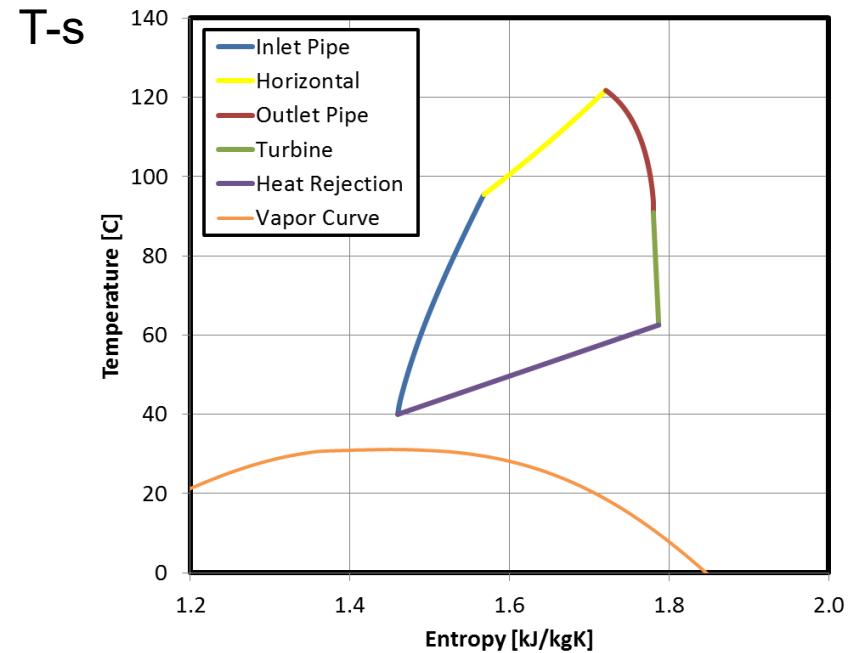
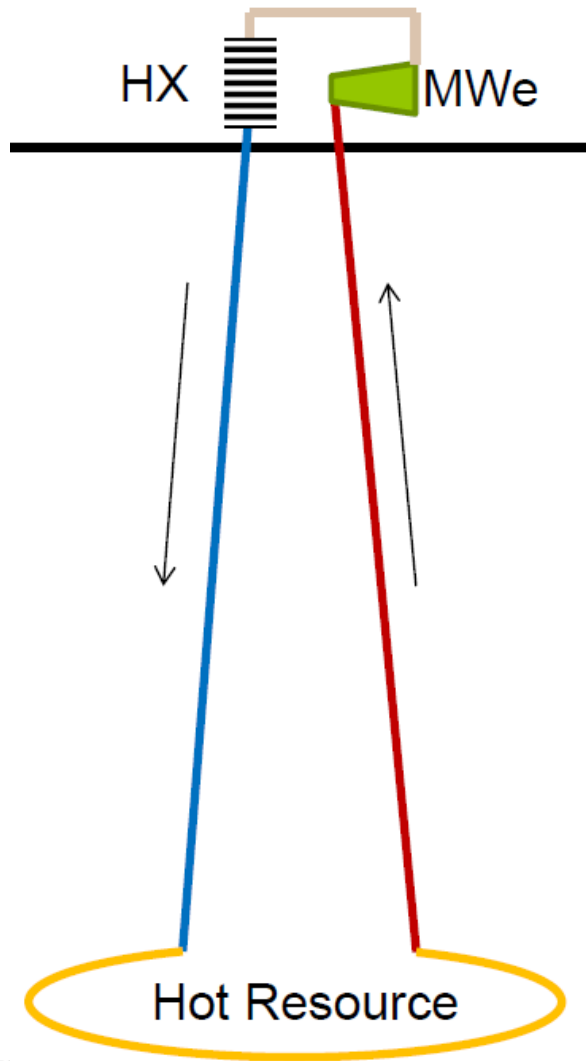
Conventional Hydrothermal



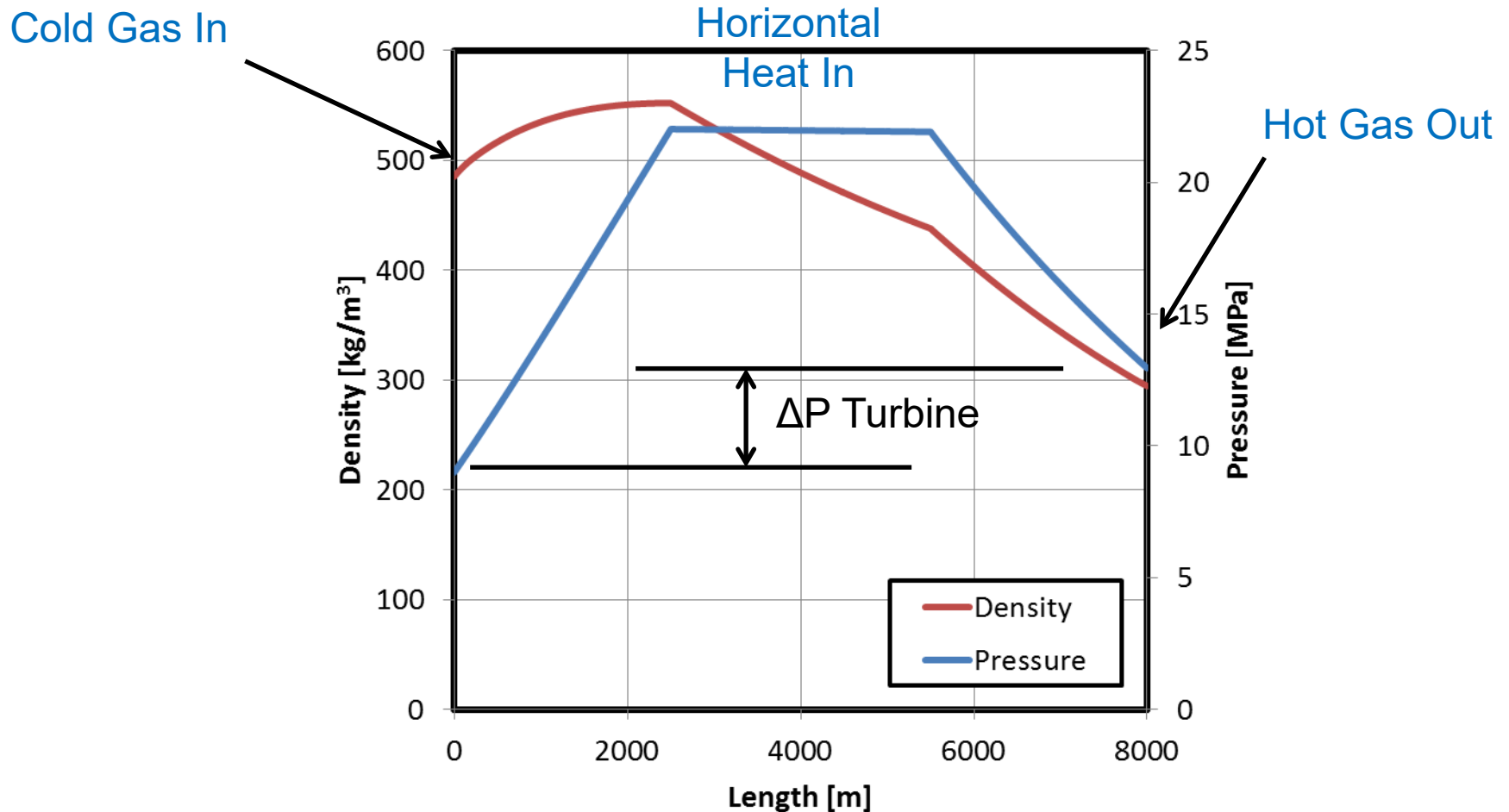
Closed-Loop Supercritical CO₂



P-v & T-s Diagram



How does a Thermosiphon Work



Performance ECO2G

- ❑ Power Production
- ❑ Electrical power is typically 1 to 2 MWe per well
- ❑ Electrical power can exceed 5 MWe for some cases
- ❑ Financial Projections
- ❑ •25 Year LCOE ranges from \$0.05 - \$0.10/kWh

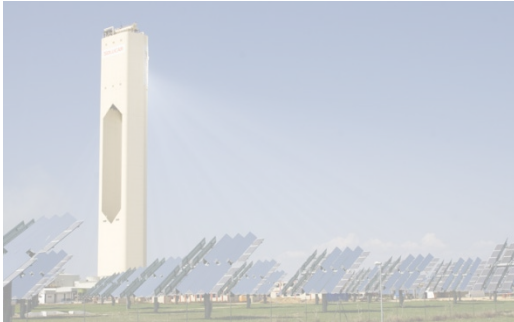
Benefits of sCO₂ Based Geothermal

- ❑ Highly Compressible
 - Produces a strong thermosiphon
- ❑ Inexpensive
- ❑ High-Efficiency, Small Turbines
- ❑ No Process Water
- ❑ Outperforms Hydrothermal
 - Steam (flash tank) and binary (ORC) cycles
- ❑ Environmentally Friendly
 - Relatively Inert
 - No Process Water
 - Zero Emissions
 - Small Footprint

Challenges to sCO₂ geothermal

- ❑ Drilling technology is very expensive and (probably) not a sure thing.

Supercritical CO₂ in Power Cycle Applications



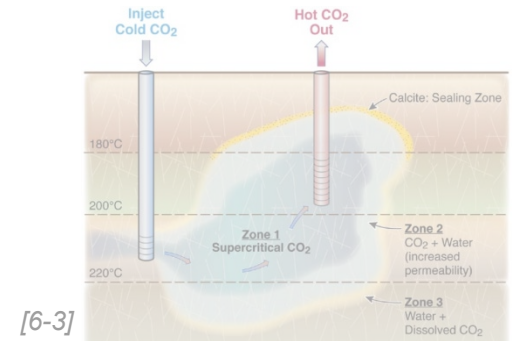
[6-1]

Concentrated
Solar Power



[6-2]

Fossil Fuel



[6-3]

Geothermal



[6-4]

Nuclear



[6-5]

Ship-board
Propulsion



Waste Heat
Recovery

Waste Heat Recovery (Bottoming)

□ Rankine Cycle Description

1. Liquid CO_2 is pumped to supercritical pressure
2. sCO_2 accepts waste heat at recuperator and waste heat exchanger
3. High energy sCO_2 is expanded at turbo-alternator producing power
4. Expanded sCO_2 is cooled at recuperator and condensed to a liquid at condenser



Image source: [6-11]

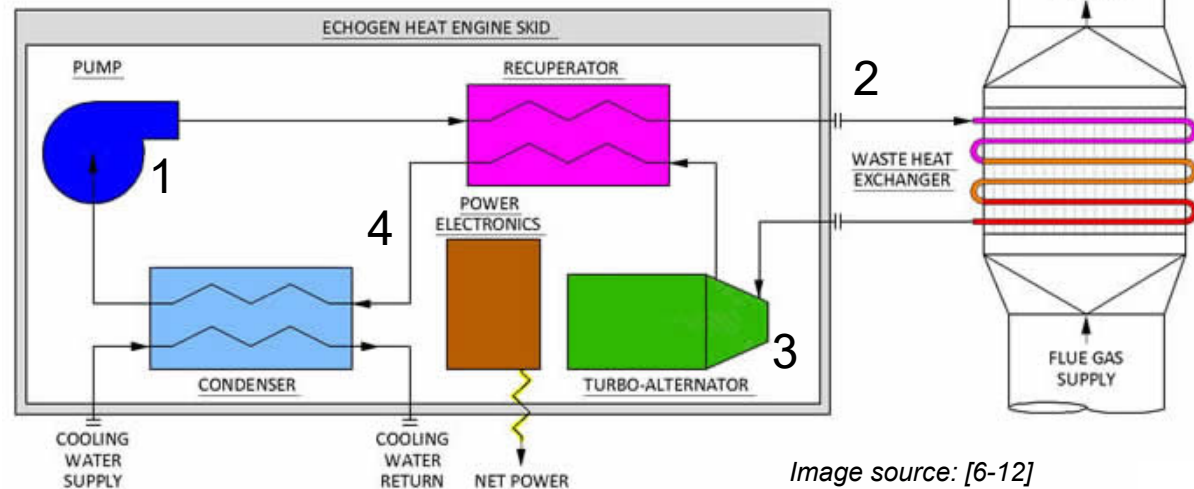


Image source: [6-12]

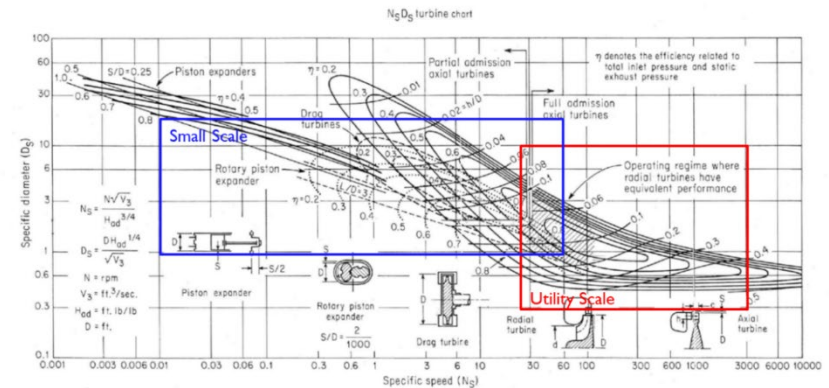
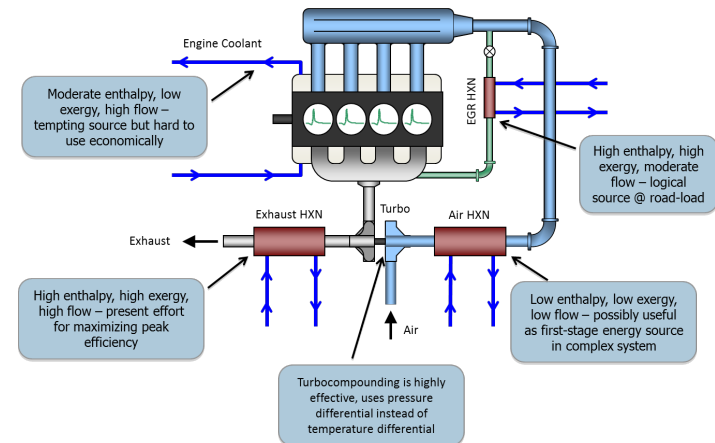
Sub-1 MWe sCO₂ Waste Heat Recovery

Diesel IC Engine WHR Applications

- Stationary power
- Class 8 long haul trucks
- Locomotive
- Marine

Fundamental machinery technology break.

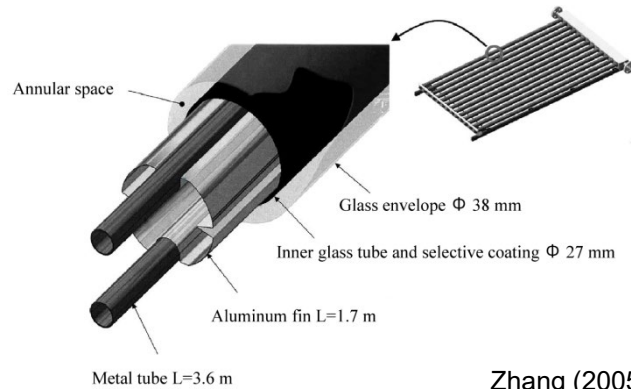
- sCO₂ power density results in turbomachines that are too fast and small for practical implementation at high efficiency
- Requires the development of reciprocating sCO₂ machines



Key challenges to sCO₂ bottoming cycles

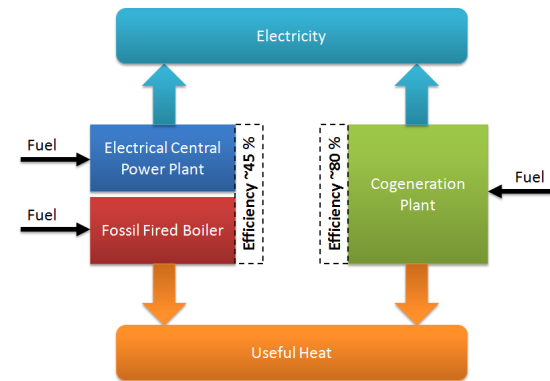
- ❑ Efficiencies and costs must compete with steam/ORC at relevant temperatures
- ❑ Unproven technology must move into a field with proven WHR solutions (steam/ORC)
 - Since WHR is not the primary asset in nearly any implementation, shutting down production or heat generation for an unproven benefit is challenging.

Other sCO₂ Power Cycle Applications



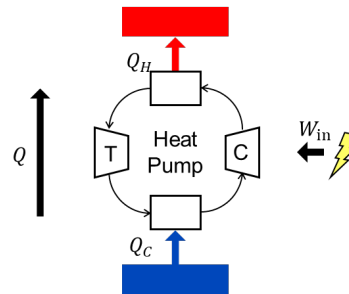
Zhang (2005)

Non-Concentrated Solar Power



Combined Heat & Power

Charge Mode
Use excess energy to run heat pump
and store energy in hot and cold reservoirs



PTES

sCO₂-based Pumped Thermal Energy Storage

PTES Technology Benefits

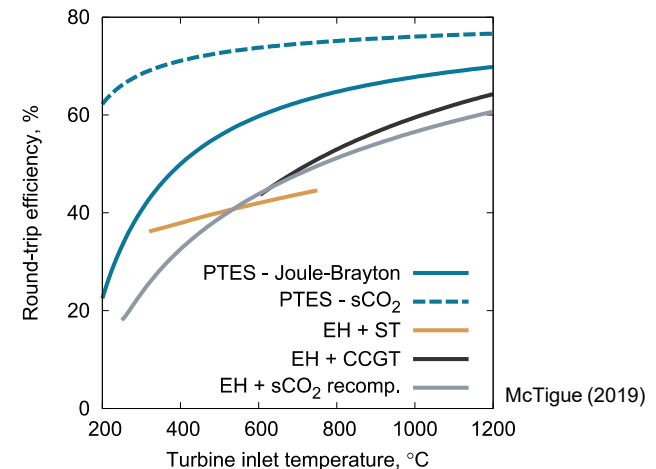
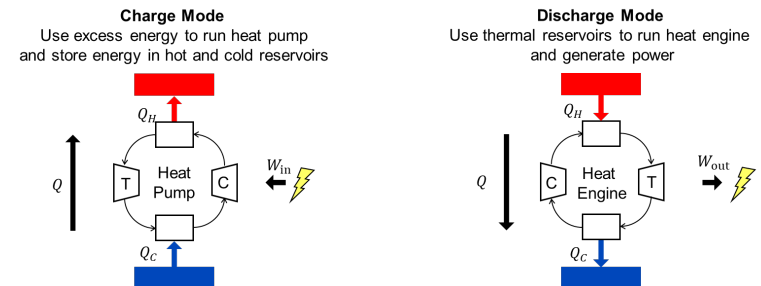
- Up to 50-70% RTE
- No geographical constraints
- Leverages many existing technologies
- Safer than other Thermal ES

Theoretically, sCO₂ PTES has the potential out-perform ideal gas based PTES (in terms of RTE)

- Leverage the high power density of sCO₂
- Charge Cycle: Supercritical or transcritical cycles
- Discharge Cycle: Supercritical or transcritical cycles, recompression cycle

Developing technology area

- Echogen
- Heliogen
- MAN



Future Trends for sCO₂ Power Cycles



Future trends and research needs

Intermediate-scale is needed to demonstrate commercial viability of full-scale technologies (i.e. 10 Mwe)

Materials

- ☐ Long term corrosion testing (10,000 hrs)
- ☐ Corrosion of diffusion-bonded materials (PCHE HX)
- ☐ Coatings to limit/delay corrosion
- ☐ Corrosion tests under stress

Heat Exchangers

- ☐ Improved heat transfer correlations near the critical region for varying geometries
- ☐ Improve resolution of local heat transfer measurements
- ☐ Heat exchanger durability – studying effects of material, fabrication, channel geometry, fouling, corrosion, and maintenance

Rotordynamics

- ☐ Analysis of rotor-dynamic cross-coupling coefficients for sCO₂

Pulsation analysis

- ☐ Development of transient pipe flow analysis models for sCO₂

Future trends and research needs

Control System and Simulation

- ☐ Detailed models of turbo machinery
- ☐ Improved transient analysis – surge, shutdown events

Fluid properties

- ☐ Mixture of sCO₂ and other fluids
- ☐ Physical property testing of CO₂ mixtures at extreme conditions with significantly reduced uncertainties (i.e. $\leq 1\%$)

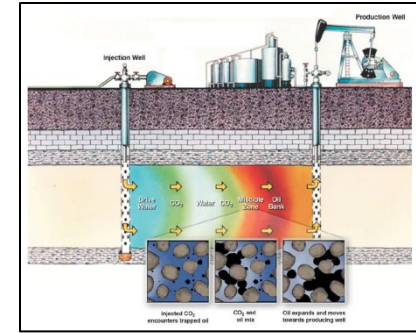
10 MW Scale Pilot Plant

Summary

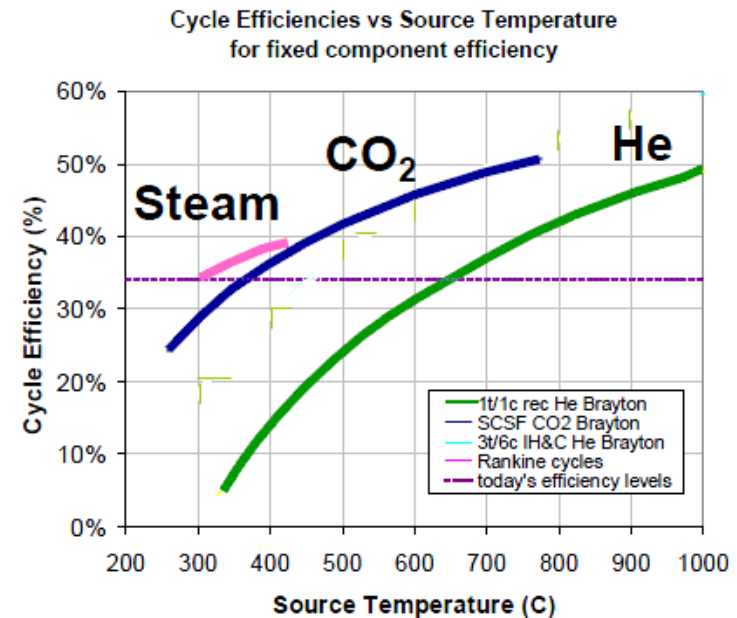
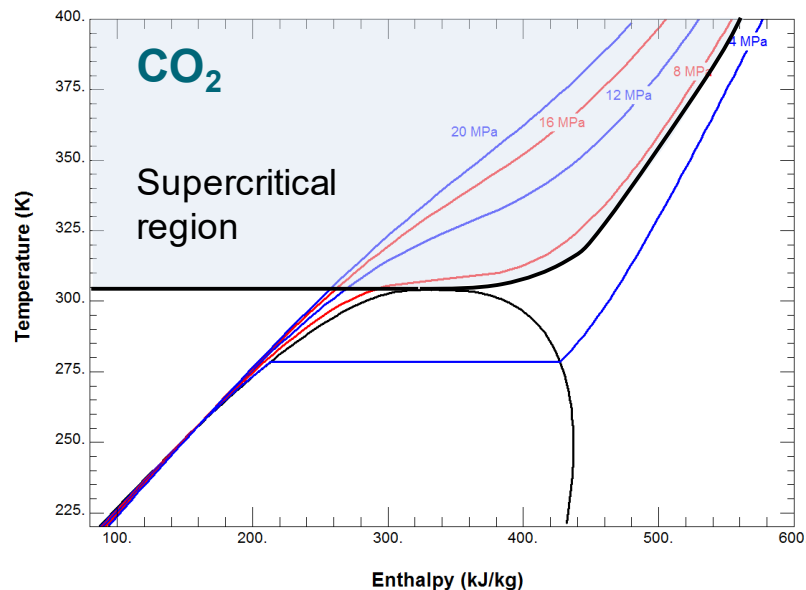


Both supercritical power cycles and the use of sCO_2 are not new concepts

sCO_2 is used in a variety of industries as a solvent

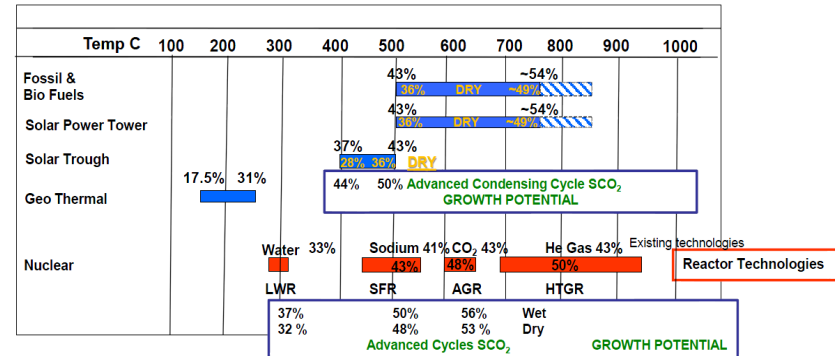
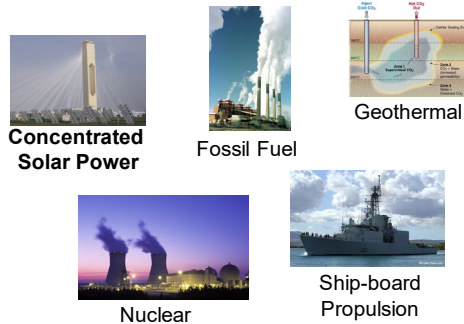


sCO_2 is desirable for power cycles because of its near-critical fluid properties

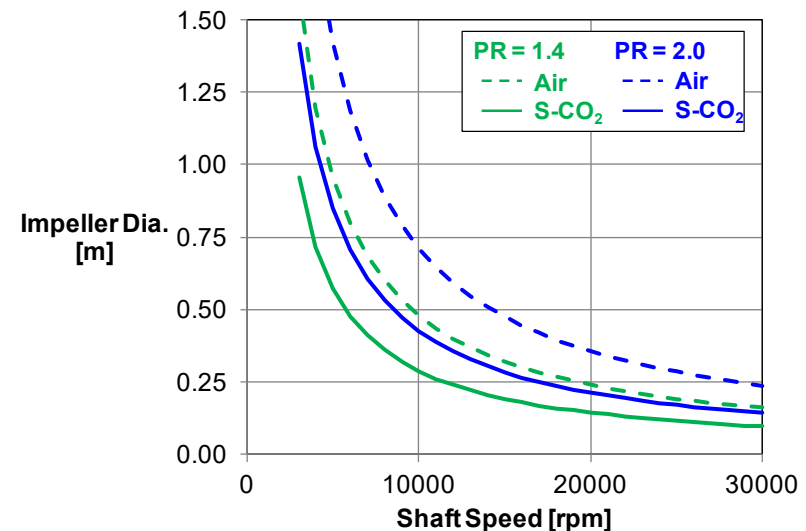
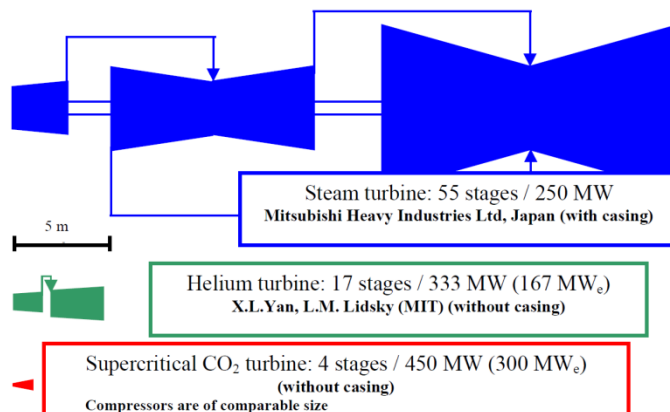


sCO₂ power cycles can be applied to many heat sources and have a small footprint

The near ambient critical temperature of CO₂ allows it to be matched with a variety of thermal heat sources



The combination of favorable property variation and high fluid density of sCO₂ allows small footprint of machinery



The near future goal is to improve understanding and develop commercial-scale power

International sCO₂ power cycle research is ongoing

Power production test loops

Materials corrosion test facilities

Machinery component test loops

Fluid property testing

More research is needed sCO₂ power cycle applications

Intermediate scale (10MW) demonstration

Materials testing at high temperature, pressure and stress

Property testing with sCO₂ mixtures

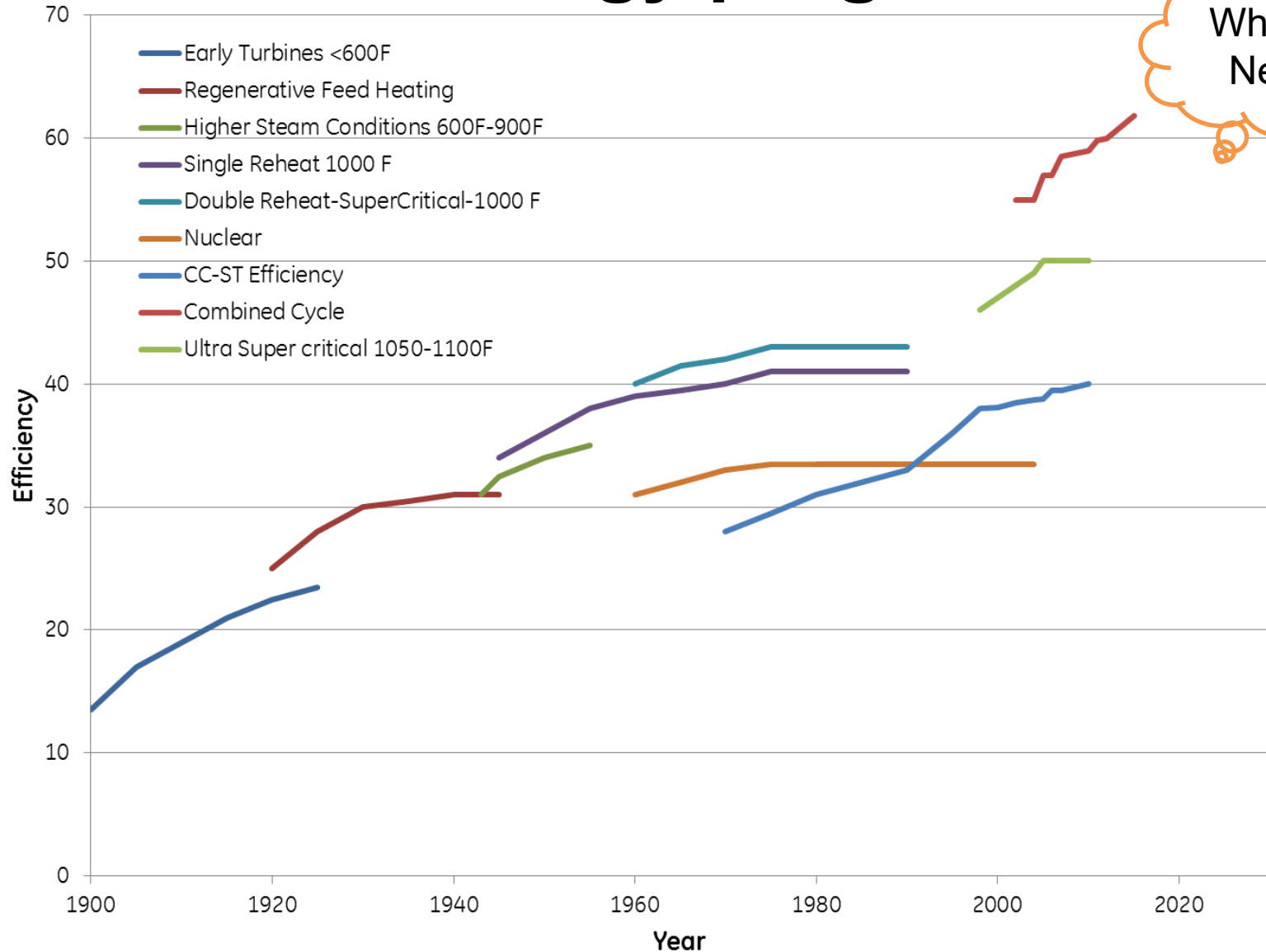
Rotordynamics with sCO₂

sCO₂ heat transfer and heat exchangers

More detailed dynamic simulation and control systems

Questions?

How has technology progressed



What's
Next