Supercritical CO$_2$
Power Cycles
Symposium

Tutorial:
Fundamentals of Supercritical CO$_2$

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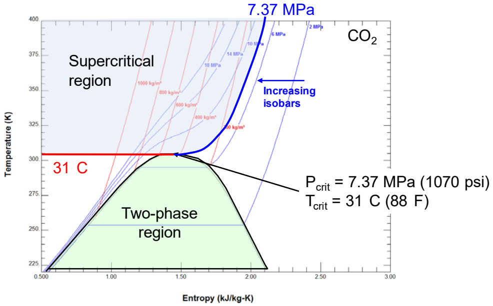
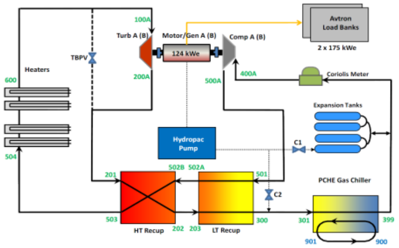
This tutorial provides an introduction to sCO_2 in power cycle applications



CO_2 and supercritical CO_2 (sCO_2)



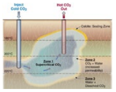
sCO_2 loop hardware & Cycles


[6-1]

Concentrated Solar Power


[6-2]

Fossil Fuel


[6-3]

Geothermal


[6-4]


[6-5]

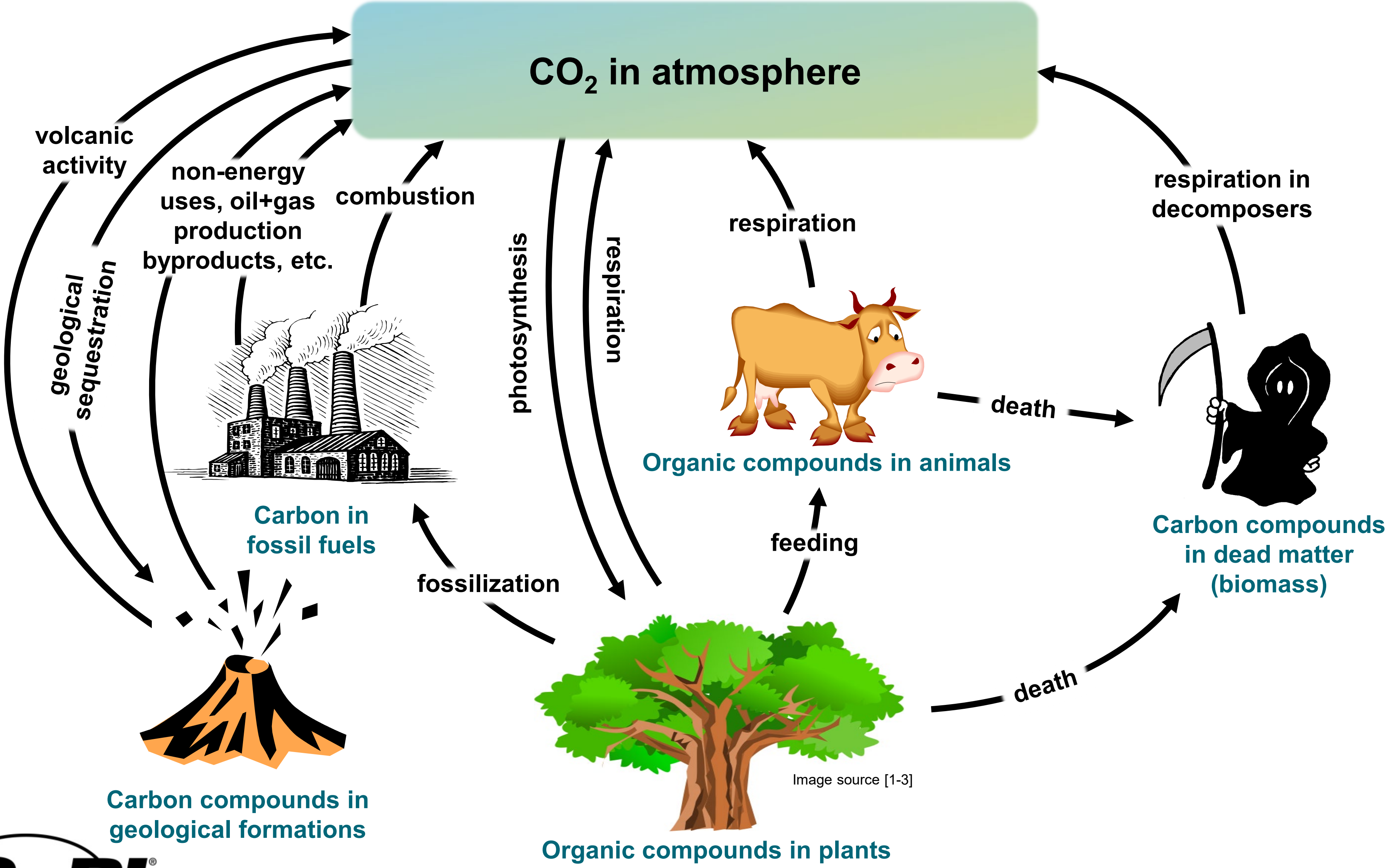
Ship-board Propulsion

Power cycle applications

Research and future trends

CO_2 General Information

There are both industrial and natural contributors and consumers of CO_2 in our atmosphere



CO_2 in atmosphere

volcanic activity

geological sequestration

non-energy uses, oil+gas production byproducts, etc.

combustion

photosynthesis

respiration

respiration

respiration in decomposers

death

Organic compounds in animals

Carbon in fossil fuels

feeding

Carbon compounds in dead matter (biomass)

fossilization

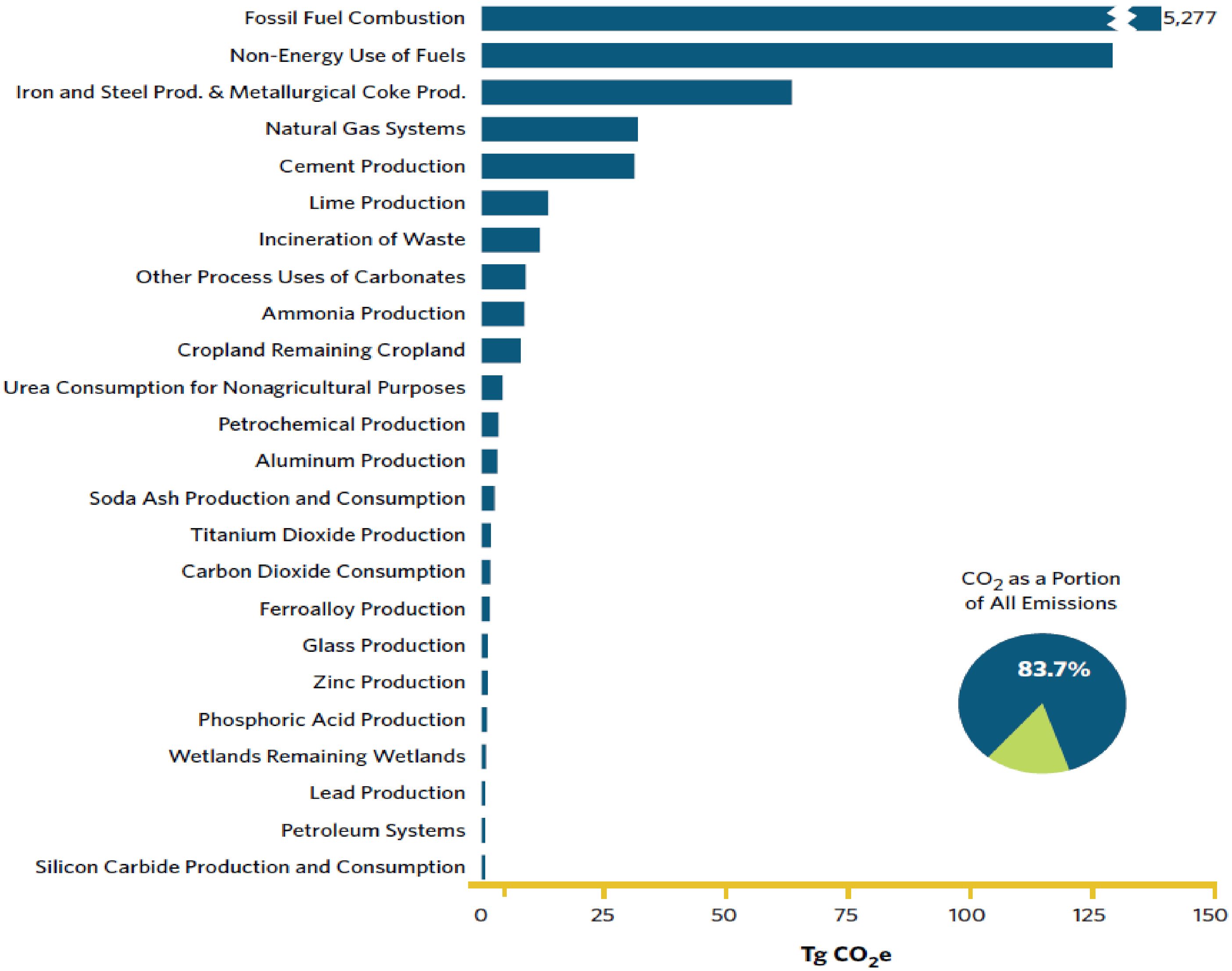
death

Carbon compounds in geological formations

Image source [1-3]

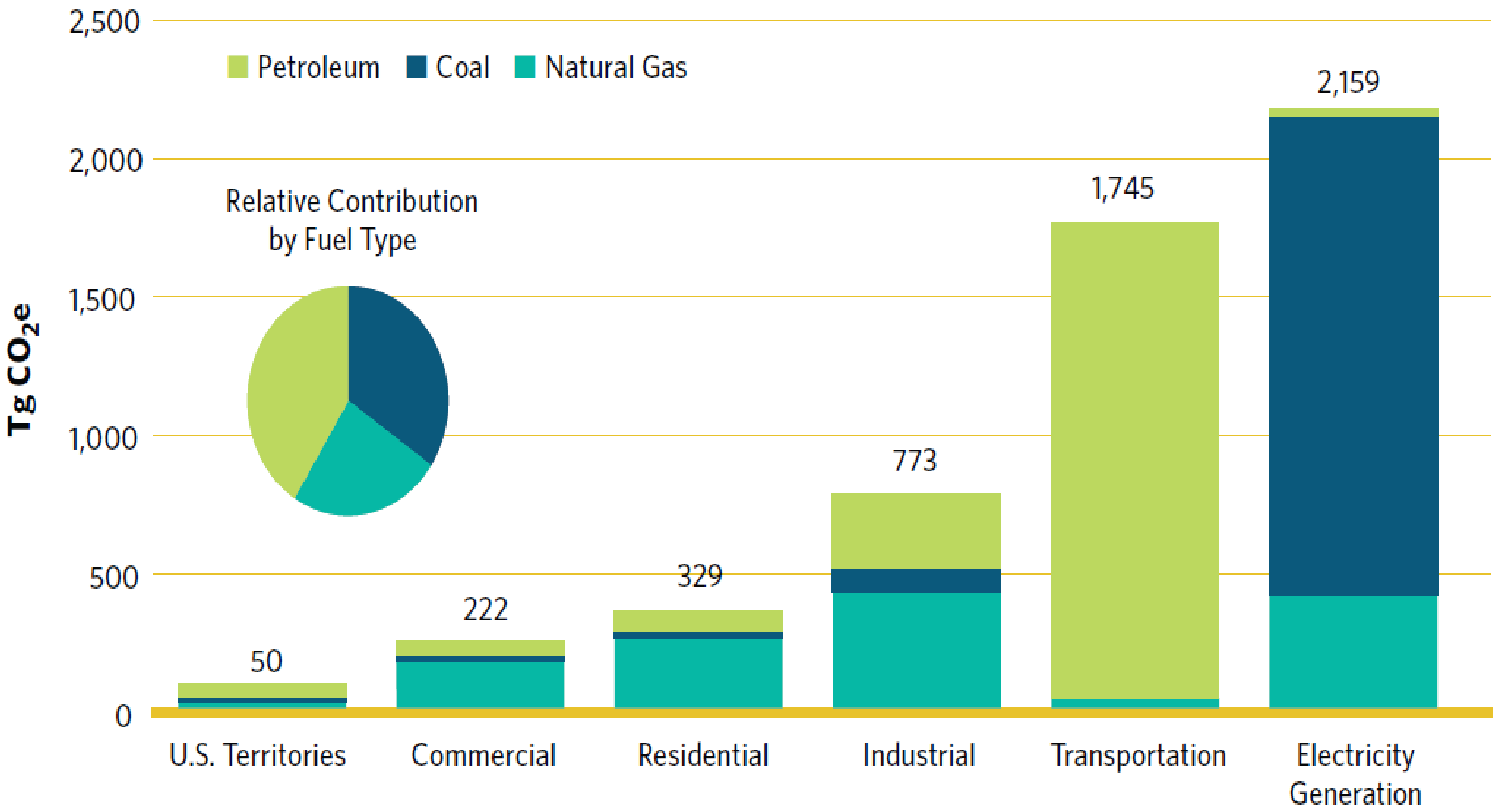
Organic compounds in plants

Fossil fuel combustion is the largest industrial contributor to CO_2 production



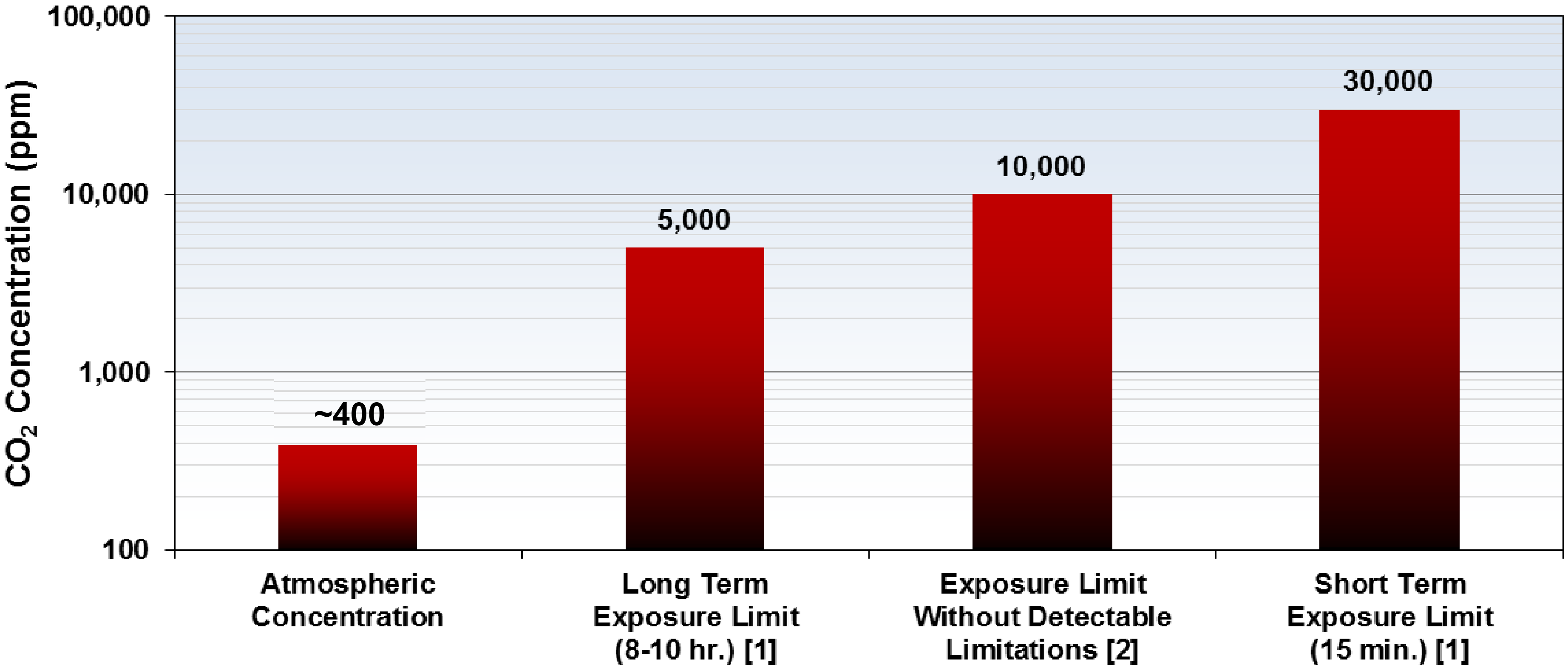
Source: “U.S. Climate Action Report 2014”

Transportation (petroleum) and electricity generation (coal) majority contributors of CO_2



Source: "U.S. Climate Action Report 2014"

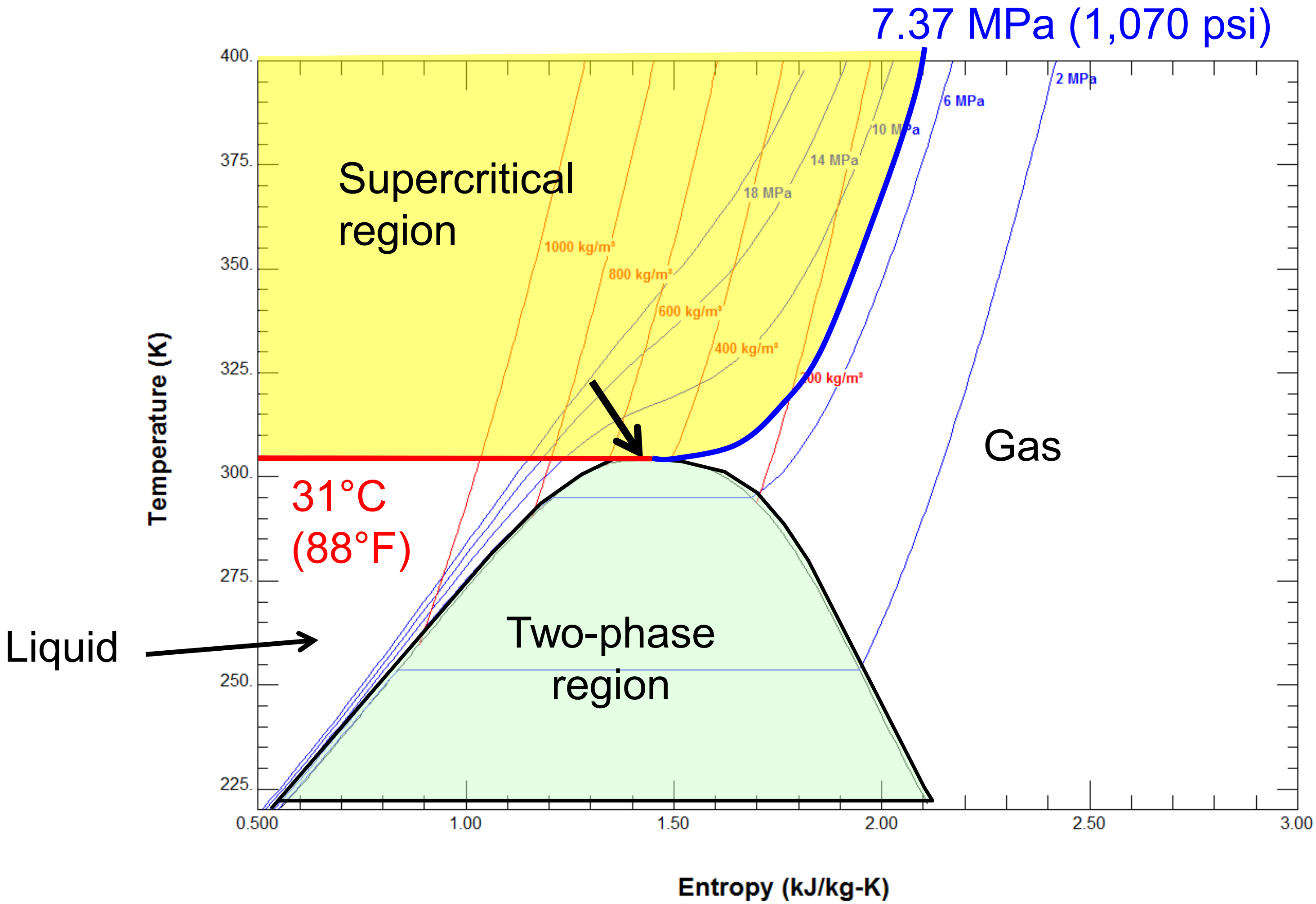
CO_2 has human exposure limits, but is classified at "non-toxic"



Notes:
[1] Reference safety standards: OSHA, ACGIH, NIOSH (USA)
[2] Reference study by Lambertsen (1971)

What is Supercritical CO_2?

CO_2 is supercritical if the pressure and temperature are greater than the critical values



7.37 MPa (1,070 psi)

Supercritical region

31°C (88°F)

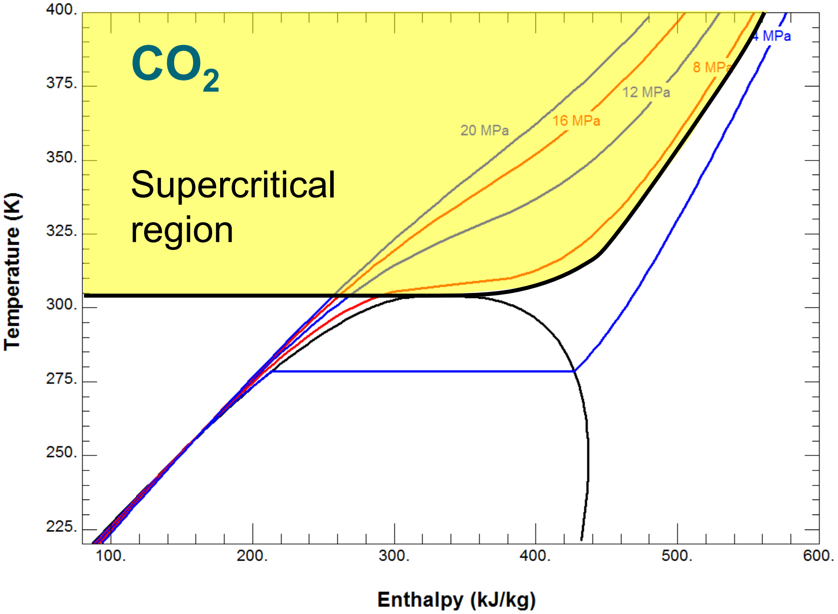
Liquid

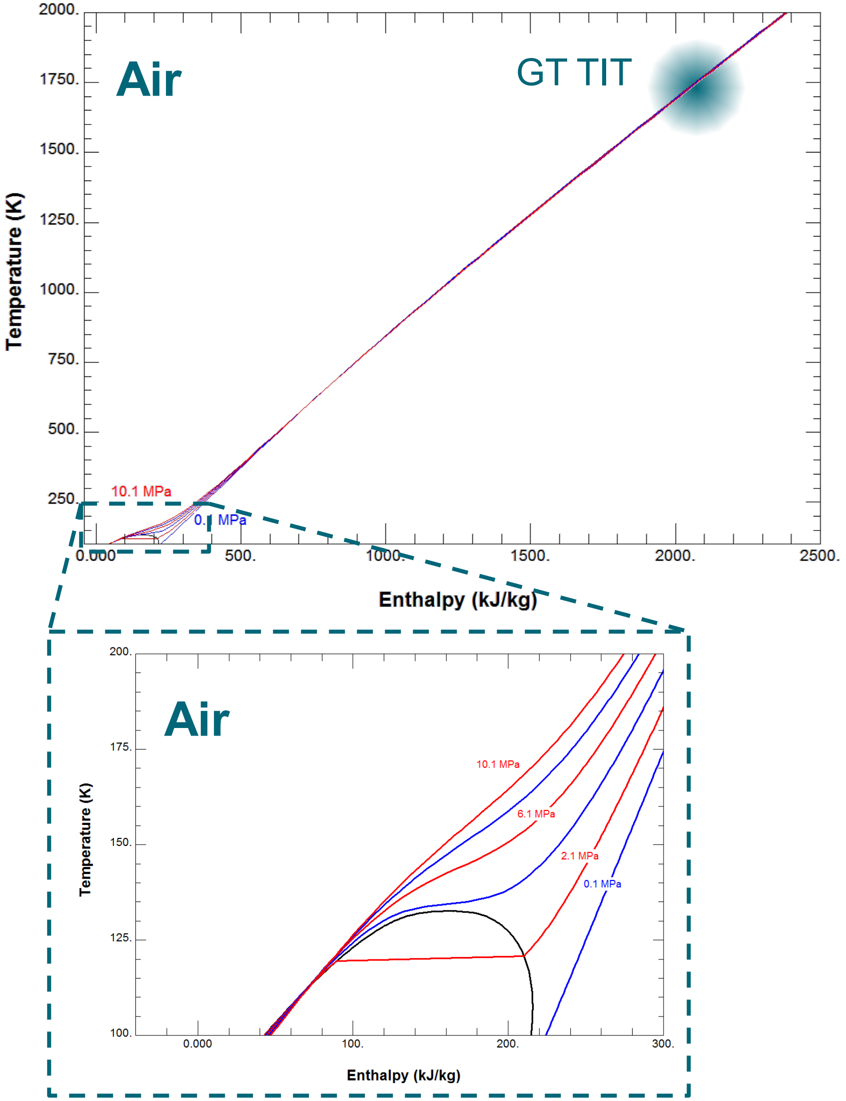
Two-phase region

Gas

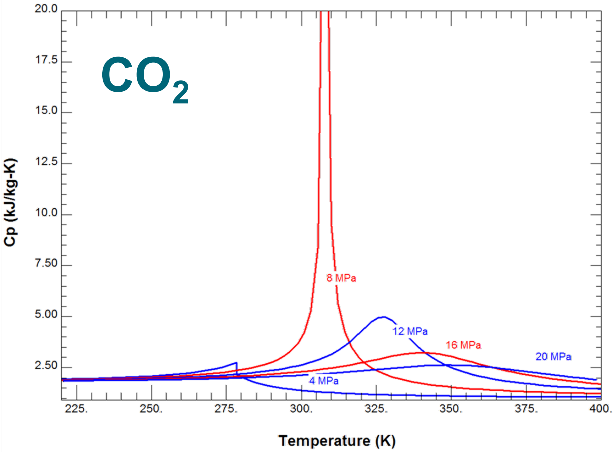
REFPROP (2007), EOS CO_2: Span & Wagner (1996)

Fluids operating near their critical point have dramatic changes in enthalpy



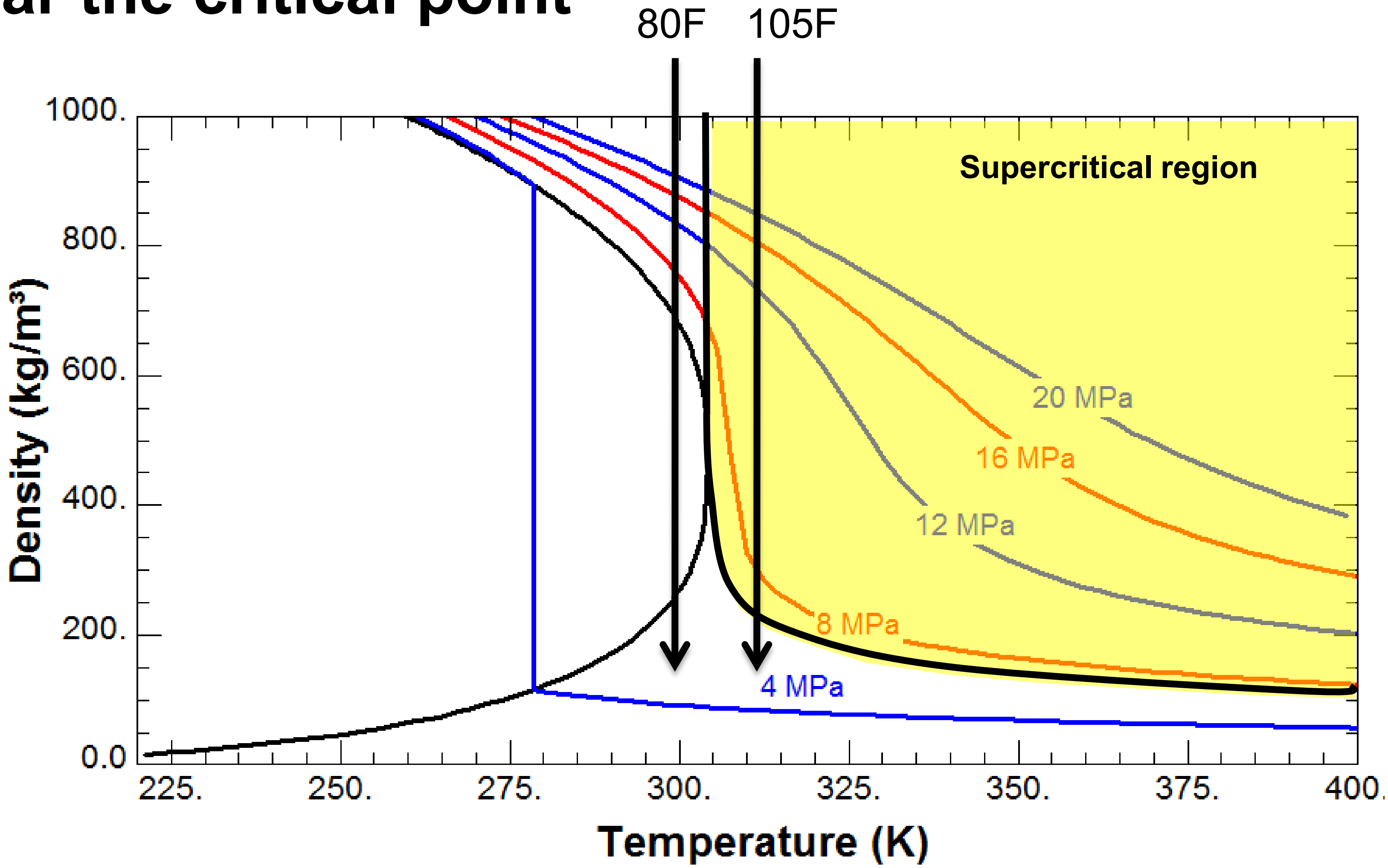


$$C_p = \left.\frac{\partial h}{\partial T}\right)_p$$



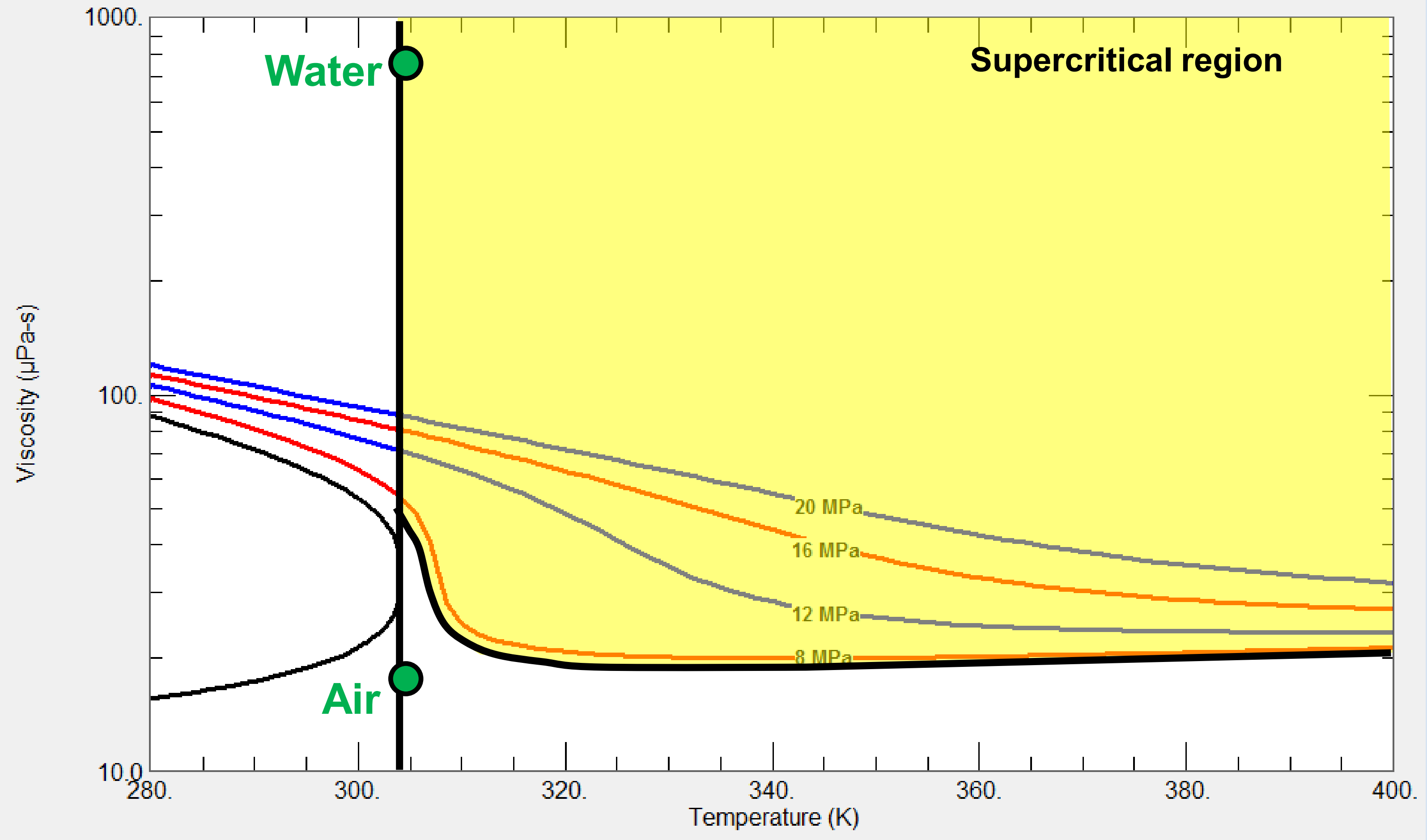
REFPROP (2007)

CO_2 density sharply decreases near the critical point



REFPROP (2007)

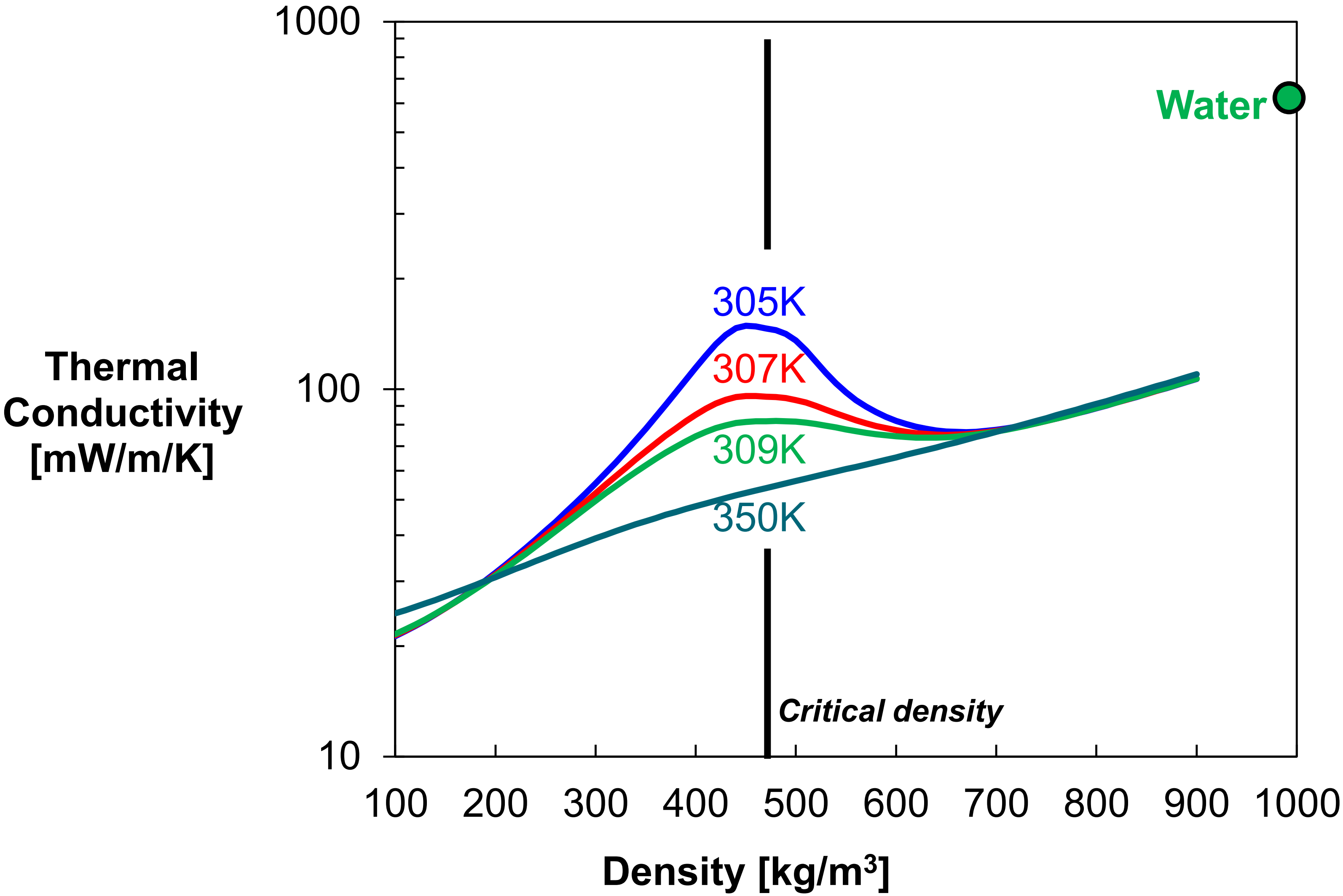
CO_2 viscosity decreases through the critical point



REFPROP (2007)

1 μPa-s = 10^{-6} kg/m/s

CO_2 thermal conductivity is enhanced near the critical region



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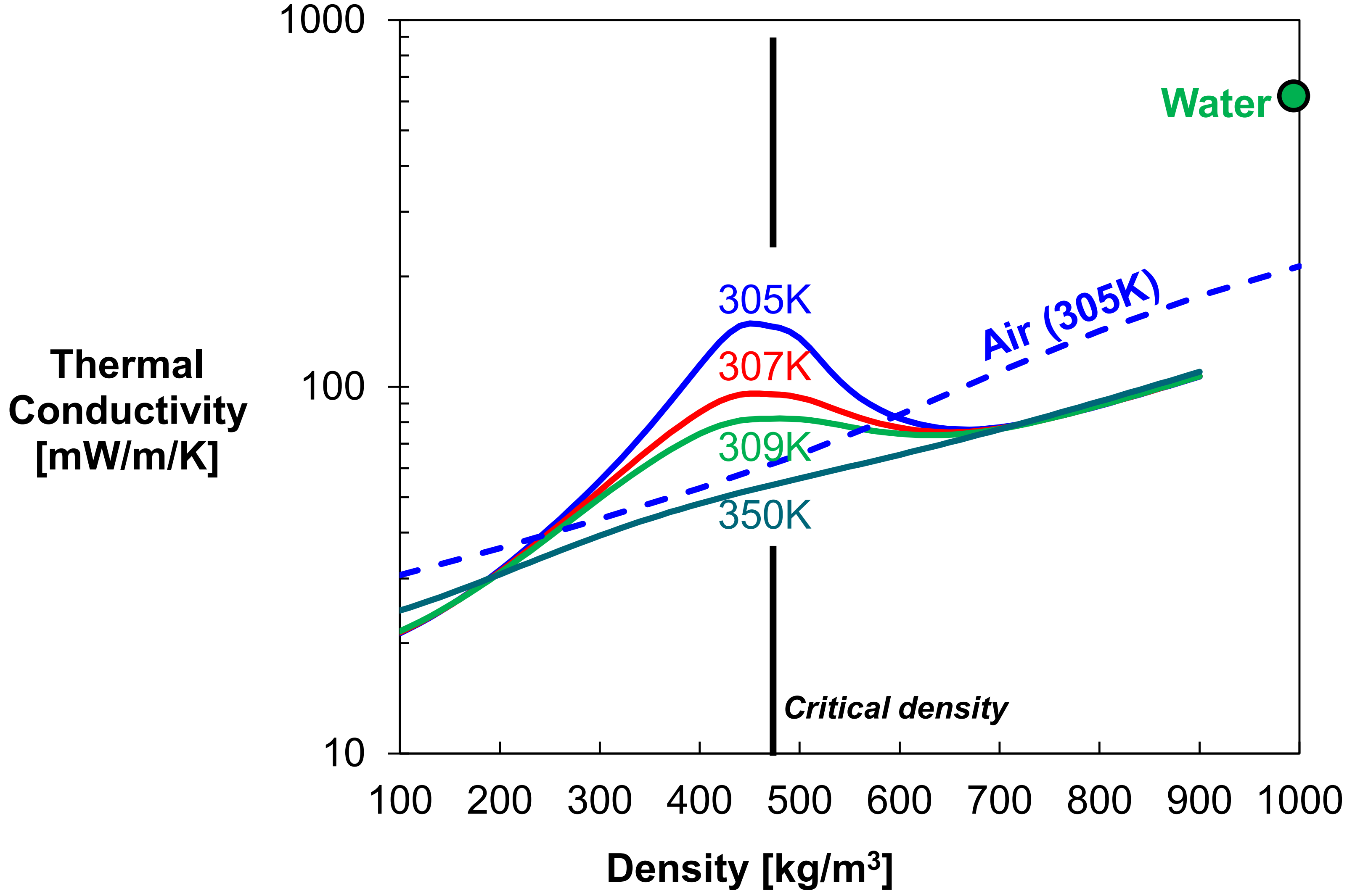
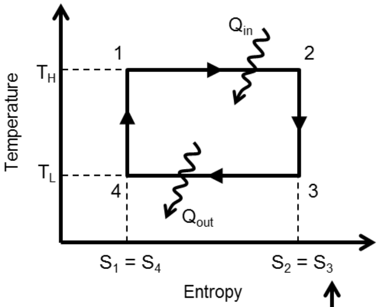
CO_2 thermal conductivity is enhanced near the critical region



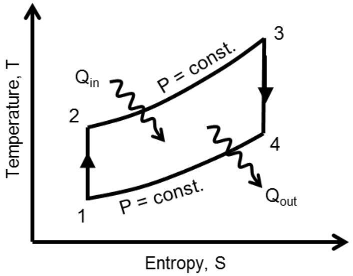
REFPROP (2007)

Power Cycle Basics

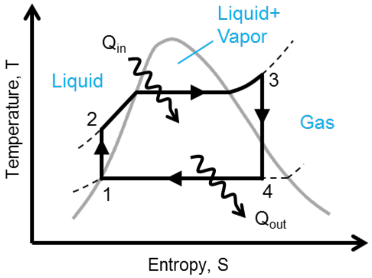
Power Cycle Basics Overview



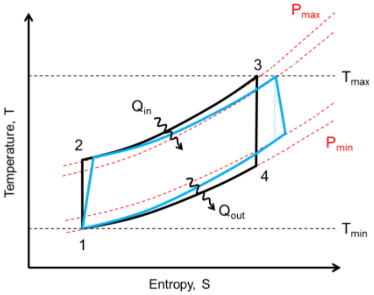
Carnot – “the standard”



Brayton – gas cycle

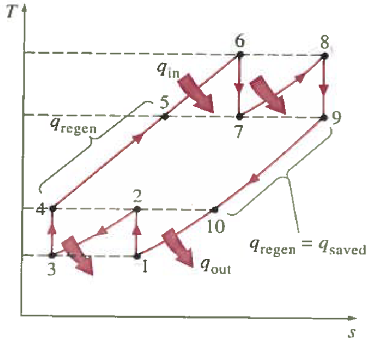


Rankine – vapor cycle



Ideal vs. actual cycle

Cycle variations



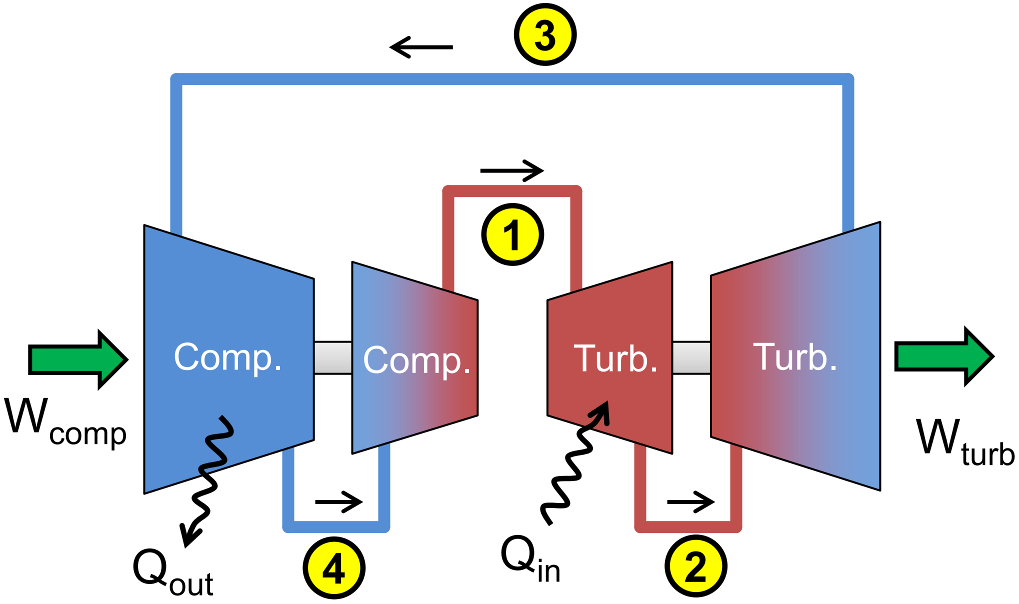
Carnot Cycle

- ❑ 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

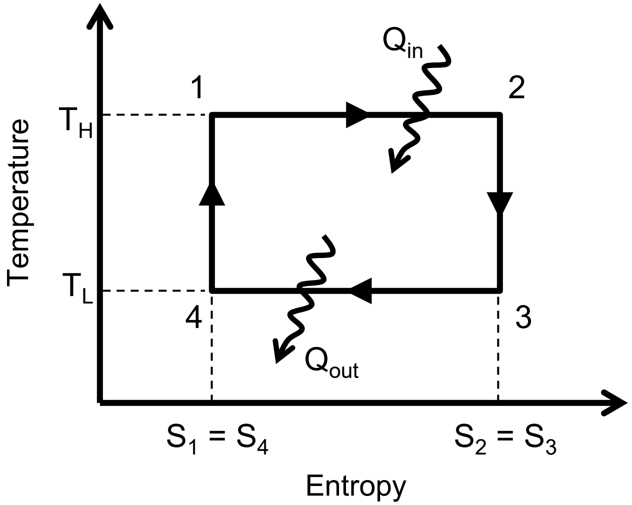
$$\eta_{th,Carnot} = 1 - T_L/T_H$$

$\downarrow T_L$: Available heat sink?

$\uparrow T_H$: Available heat source? Materials?



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



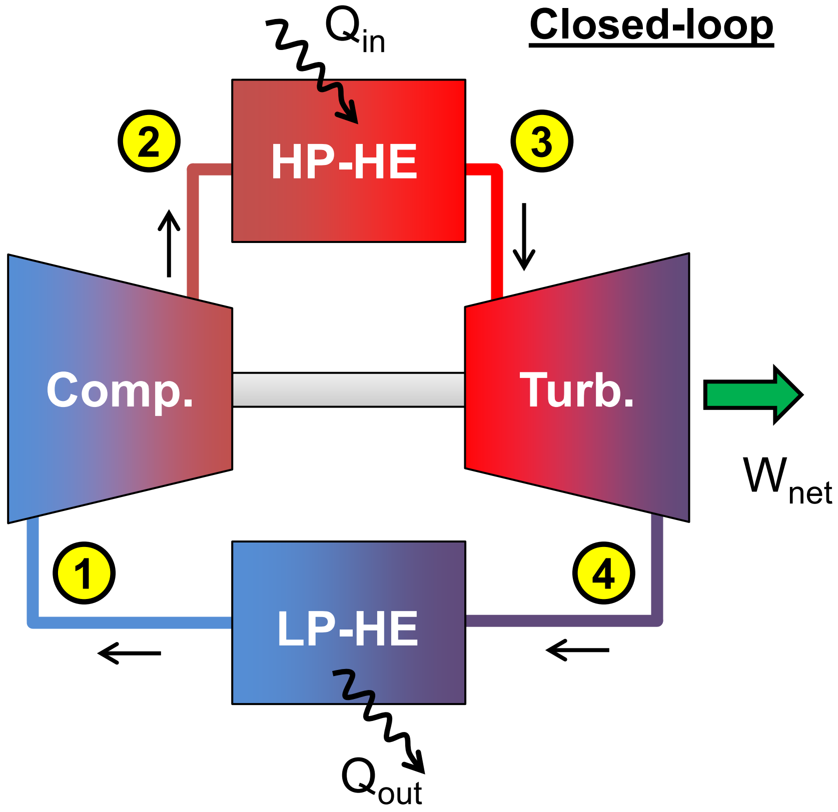
Brayton Cycle (Ideal)

- ❑ 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

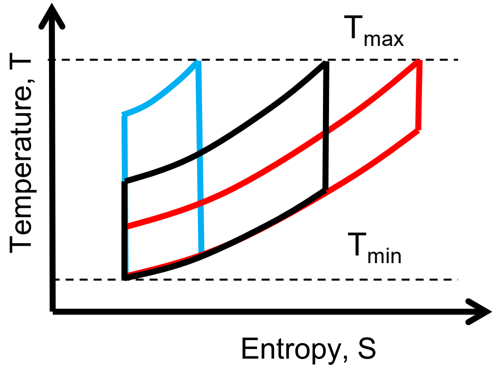
$$\eta_{th,Brayton} = 1 - PR^{(1-k)/k}$$

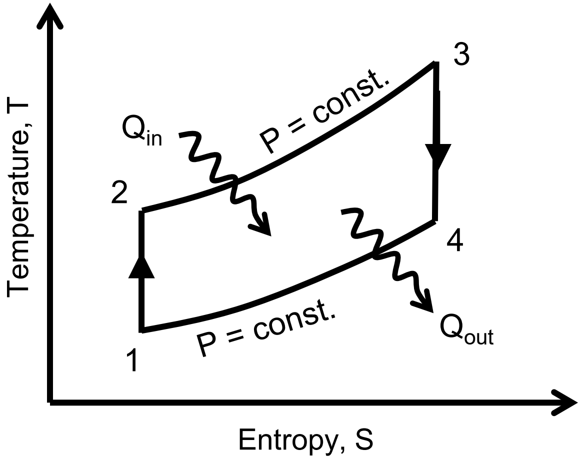
$$\uparrow PR, \uparrow k : \uparrow \eta_{th}$$

Closed-loop



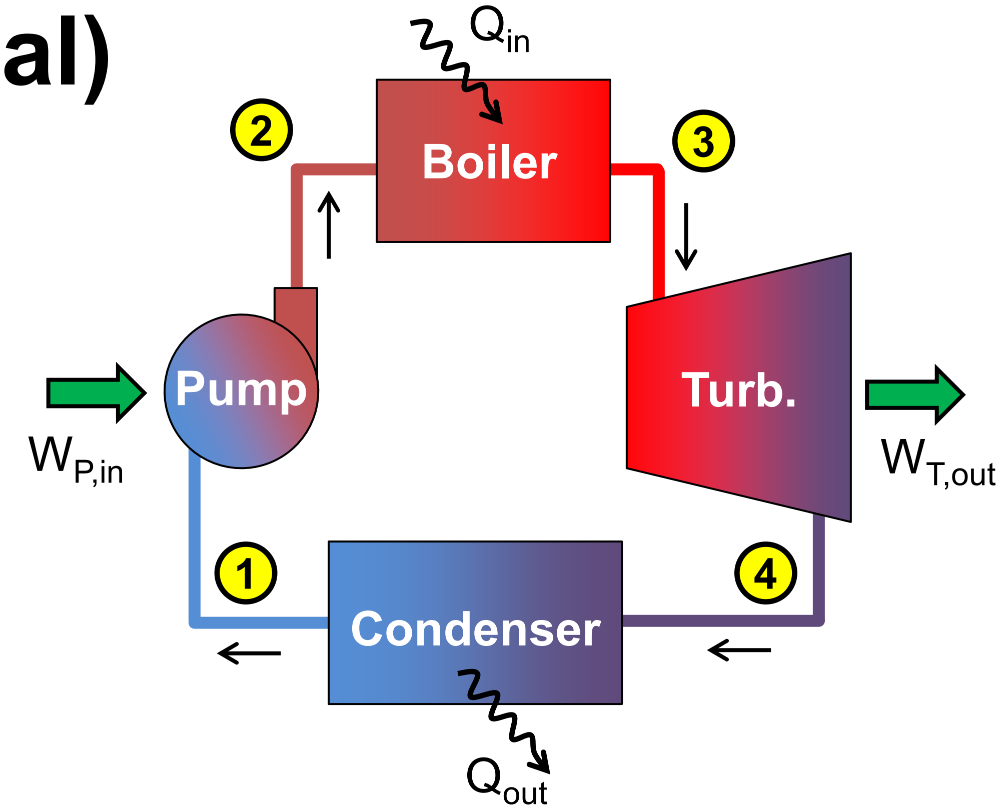
Optimal PR for net work

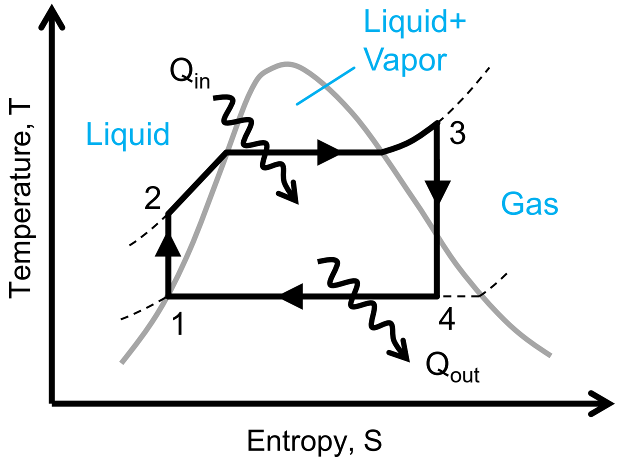




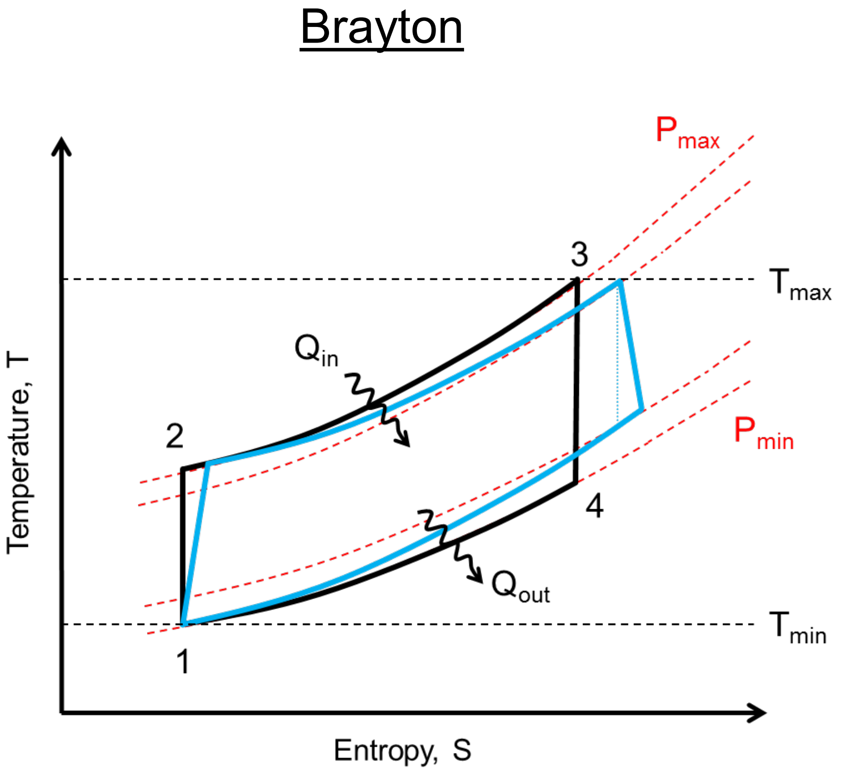
Rankine Cycle (Ideal)

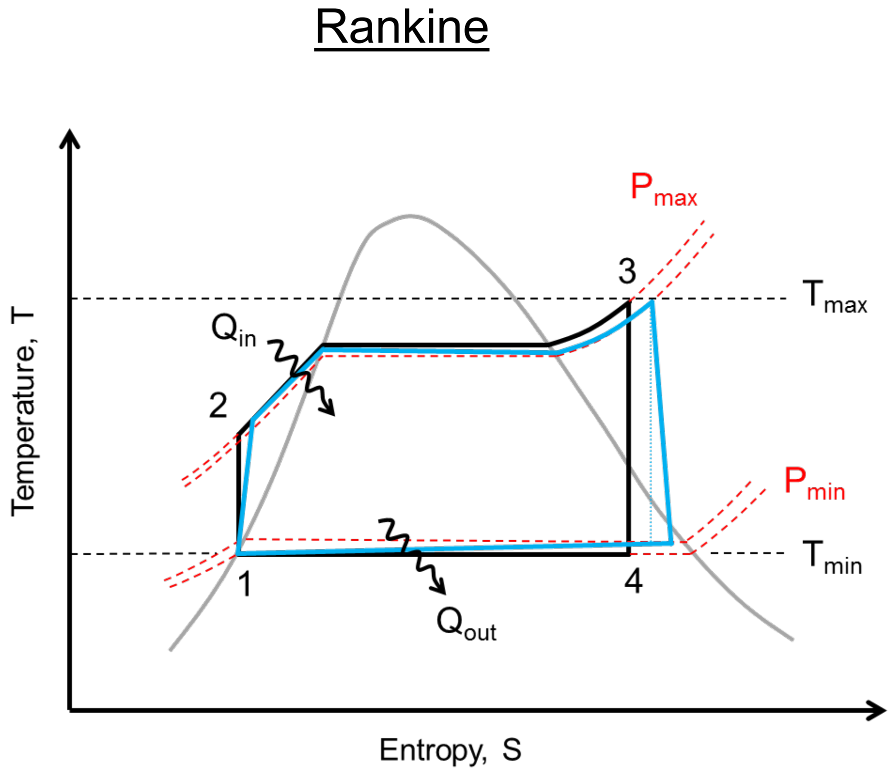
- ☐ Processes
  - (1-2) Isentropic compression
  - (2-3) Const. pres. heat addition
  - (3-4) Isentropic expansion
  - (4-1) Const. pres. heat reject.
- ☐ Same processes as Brayton; different hardware
- ☐ Phase changes
- ☐ E.g., steam cycle





Ideal vs. Actual Processes



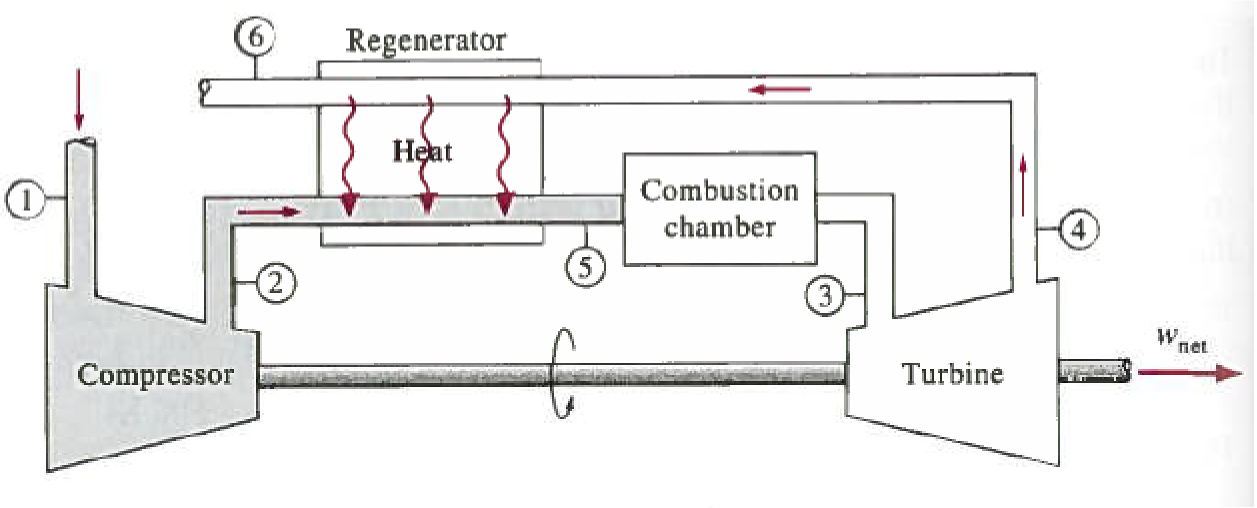


1-2, 3-4: Irreversibilities

2-3, 4-1: Pressure losses

Brayton Cycle + Regeneration

Regenerator
= recuperator



Effectiveness:

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

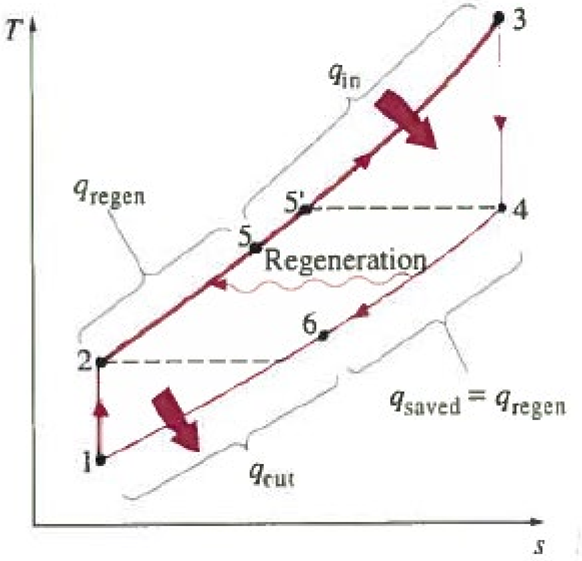


Figure reference: Cengel and Boles (2002)

Intercooling & Reheating…
Two Sides of the Same Coin

Minimize compressor work input

Increase fluid density

Intercooling

Multi-stage intercooling

Maximize turbine work output

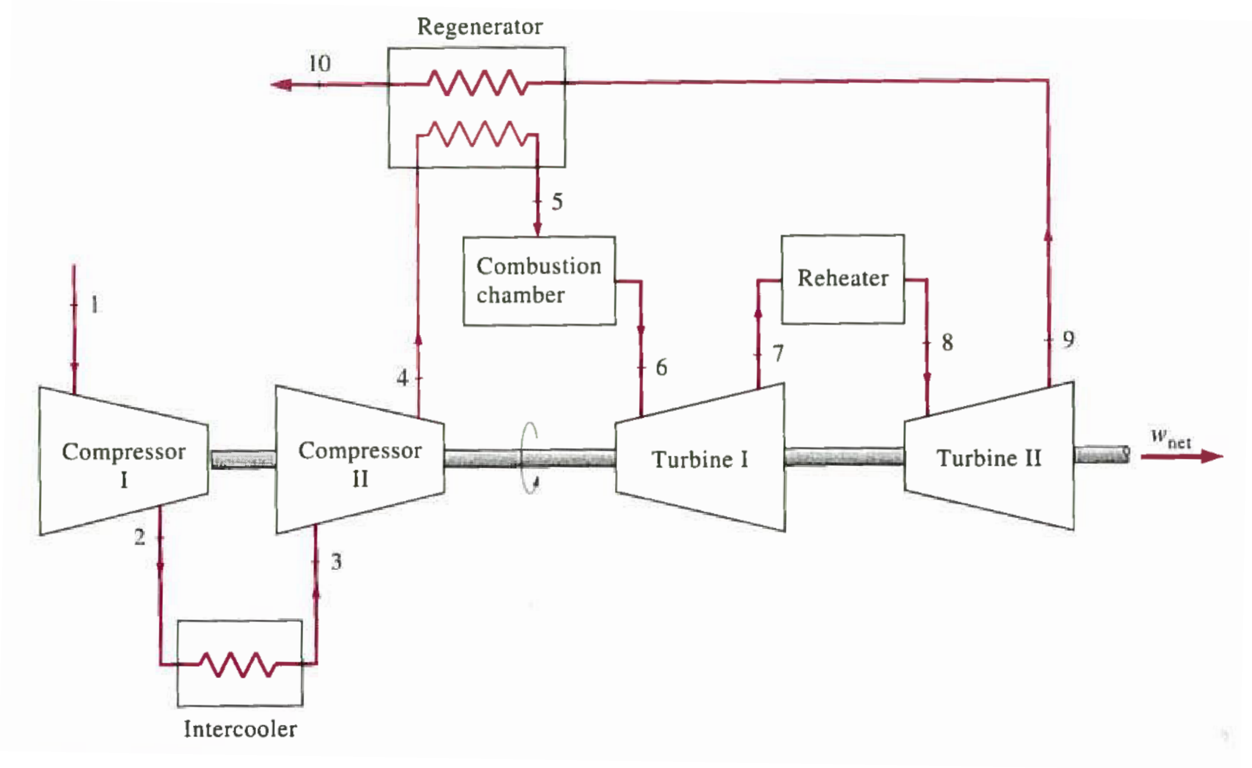
Decrease fluid density

Reheating

Multi-stage reheating

Approach isothermal conditions

Brayton Cycle + Regeneration + Intercooling + Reheating



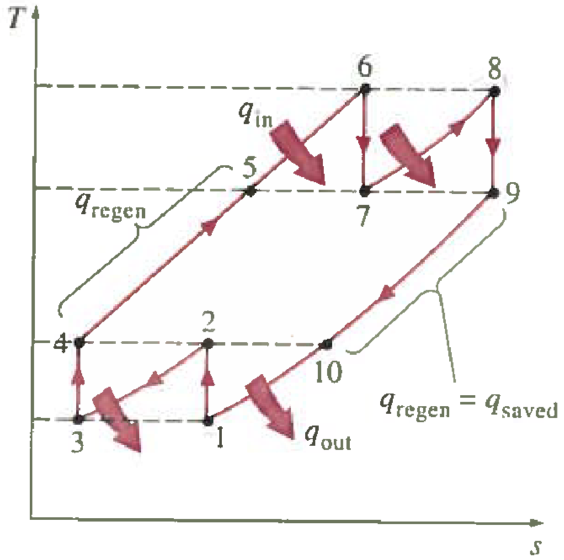


Figure reference: Cengel and Boles (2002)

Example: Compare Effect of Brayton Variations

<ins>Gas turbine cycle (air)</ins>
Temp. = 300-1300 K
PR = 8

<ins>For real GT</ins>

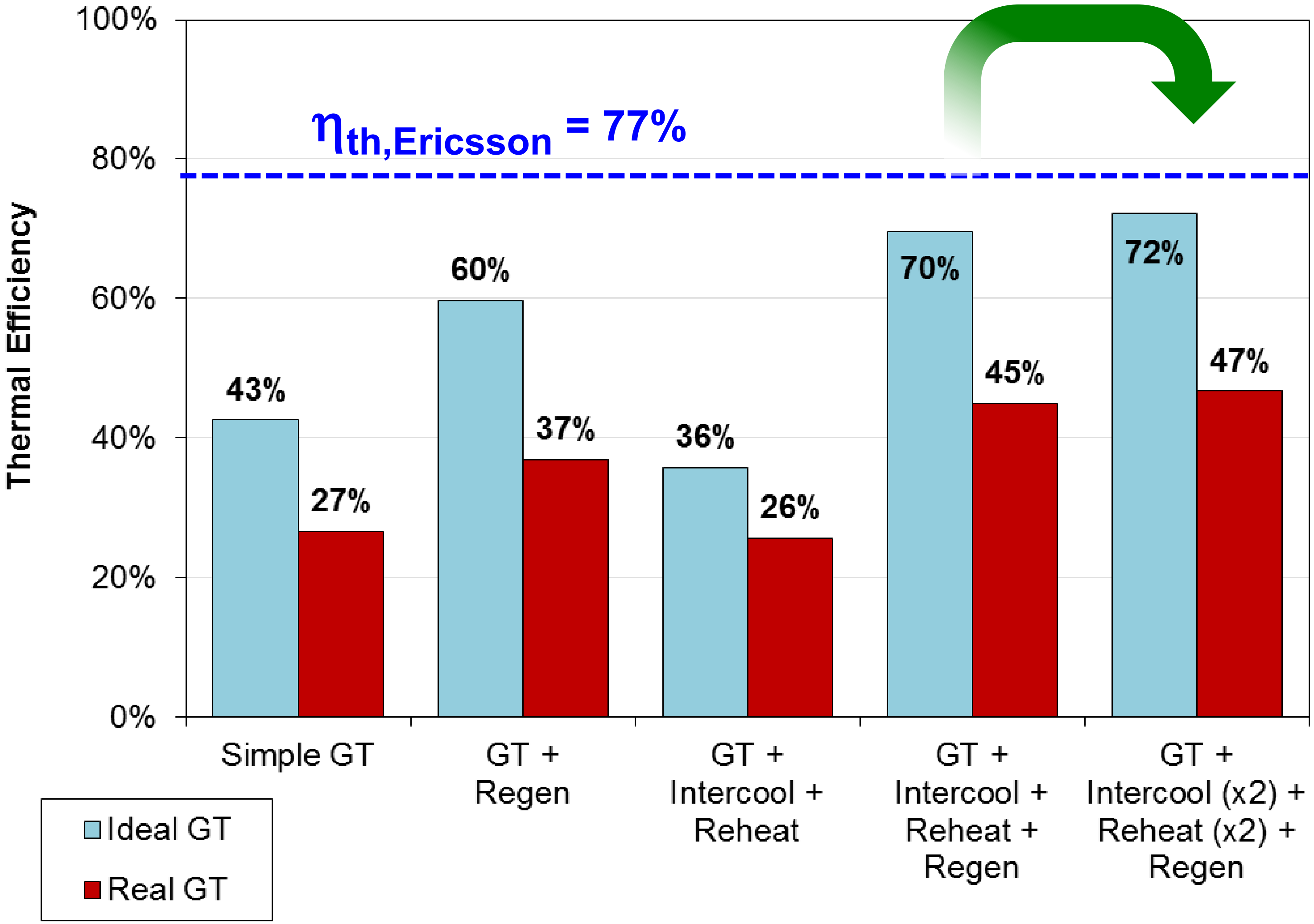
η_{comp} = 80%

η_{turb} = 85%

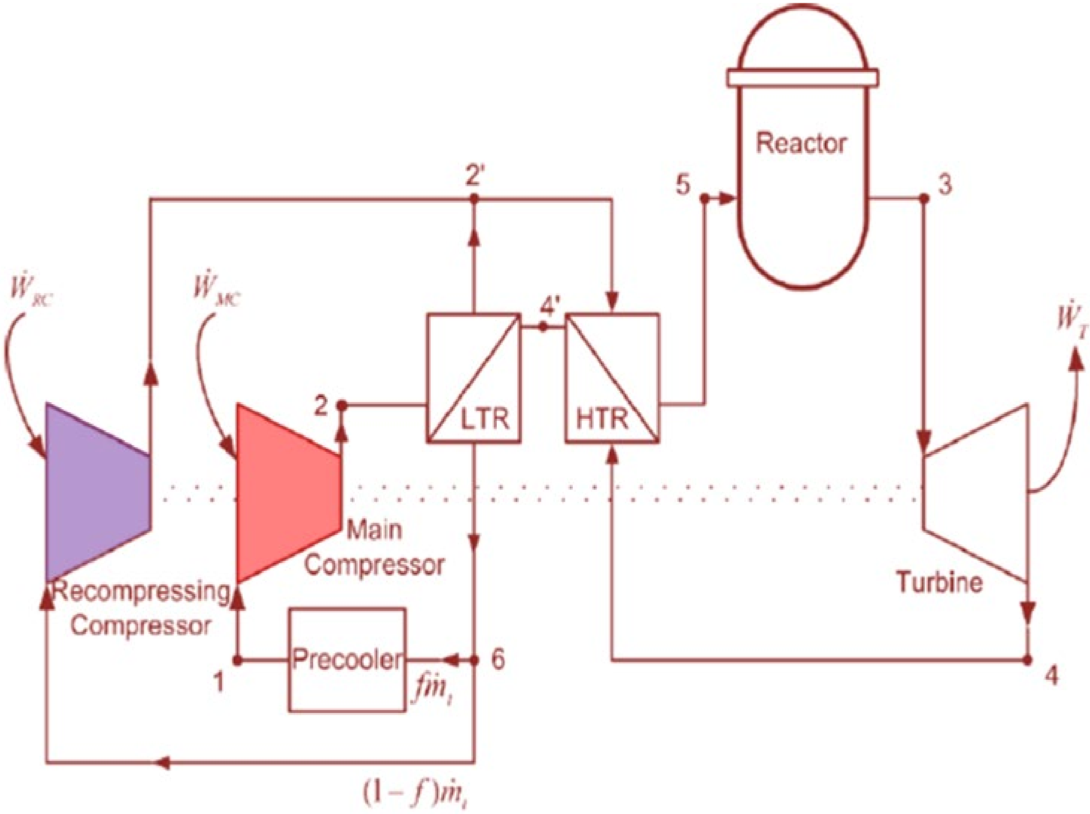
ε_{regen} = 80%

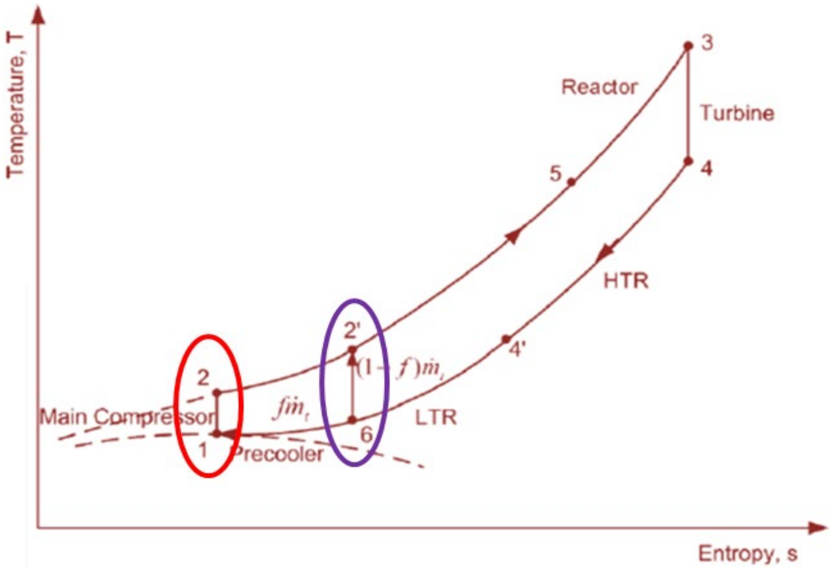
ΔP ≈ negligible

Cost-benefit analysis…



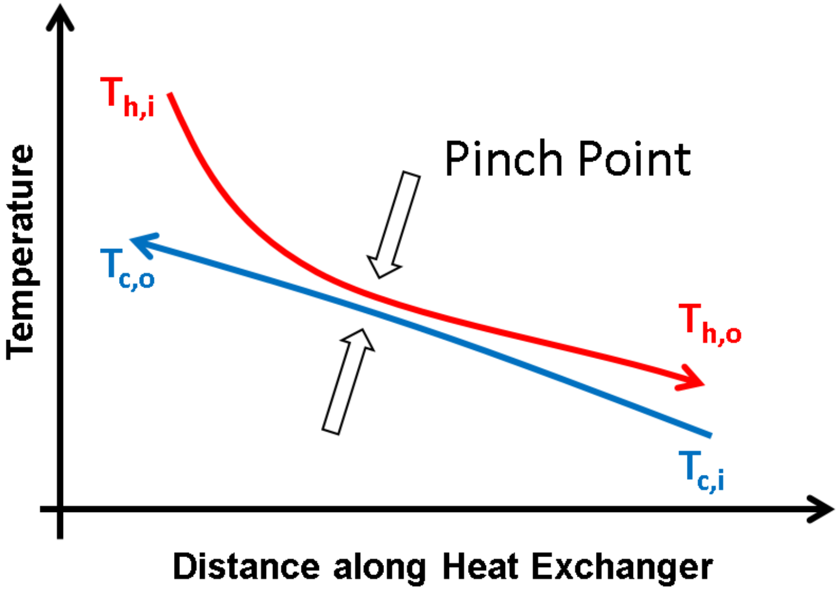
Recompression in Brayton Cycle

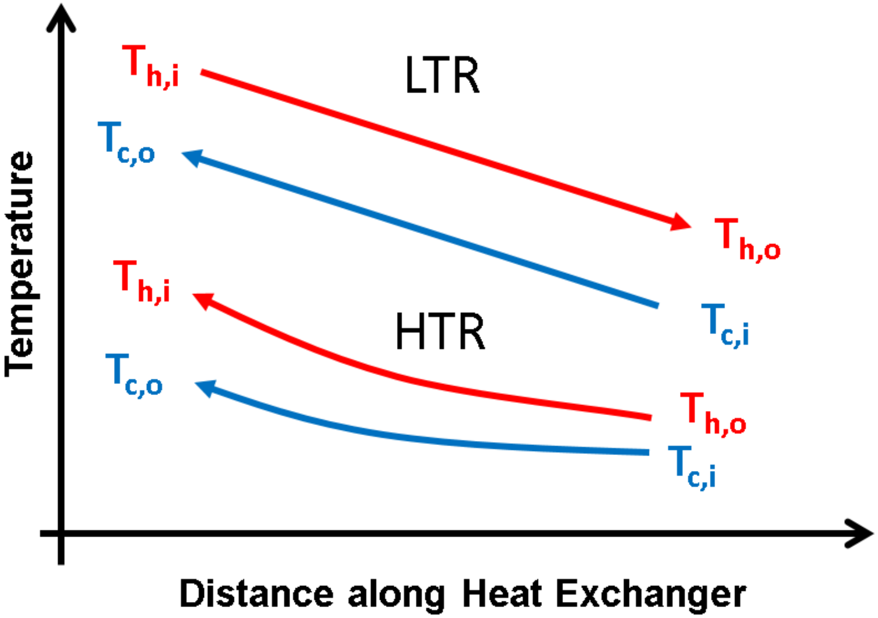




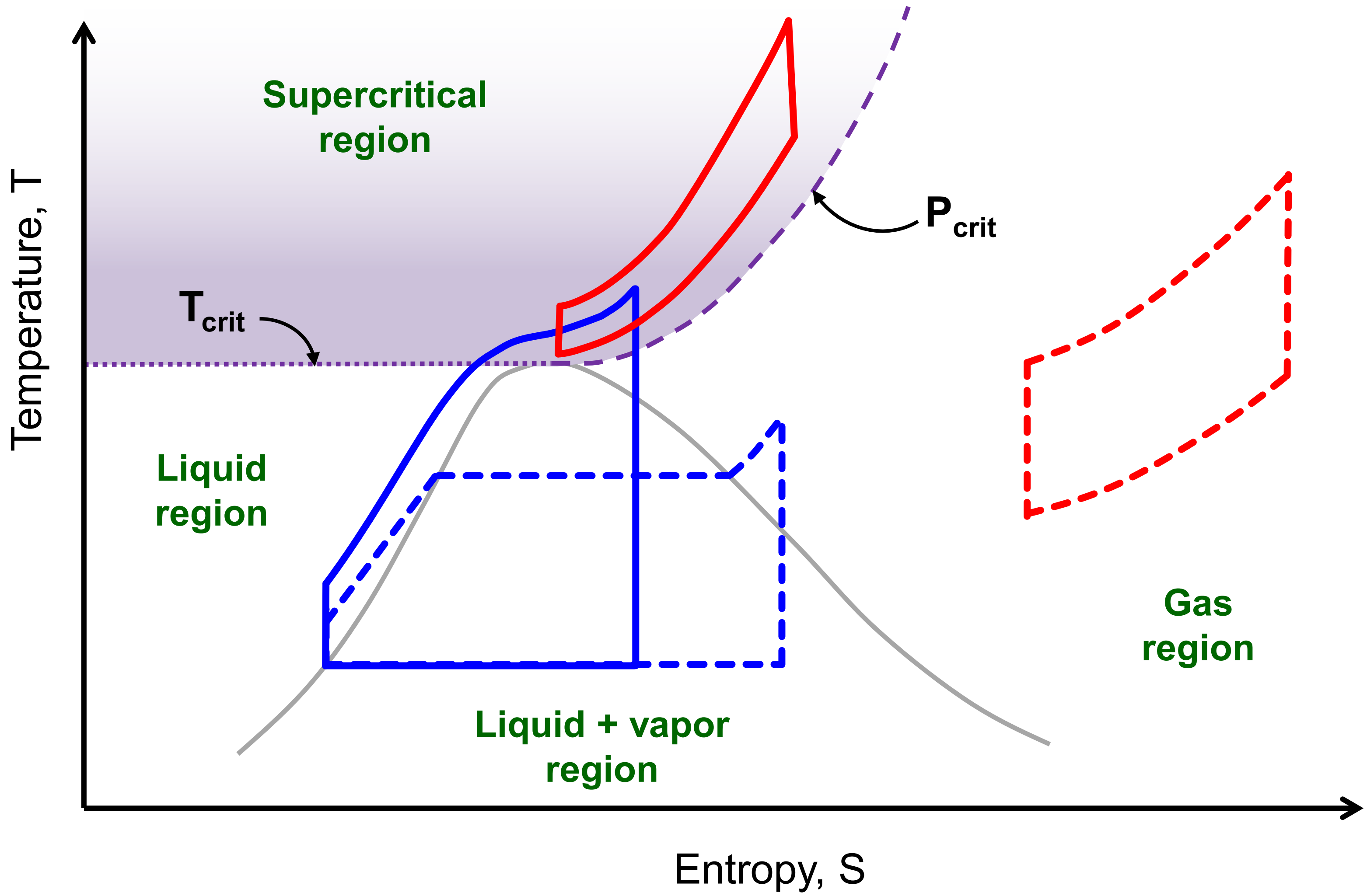
Source: Ludington (2009)

Split Recuperators can be used to avoid pinch points





What is a Supercritical Power Cycle?

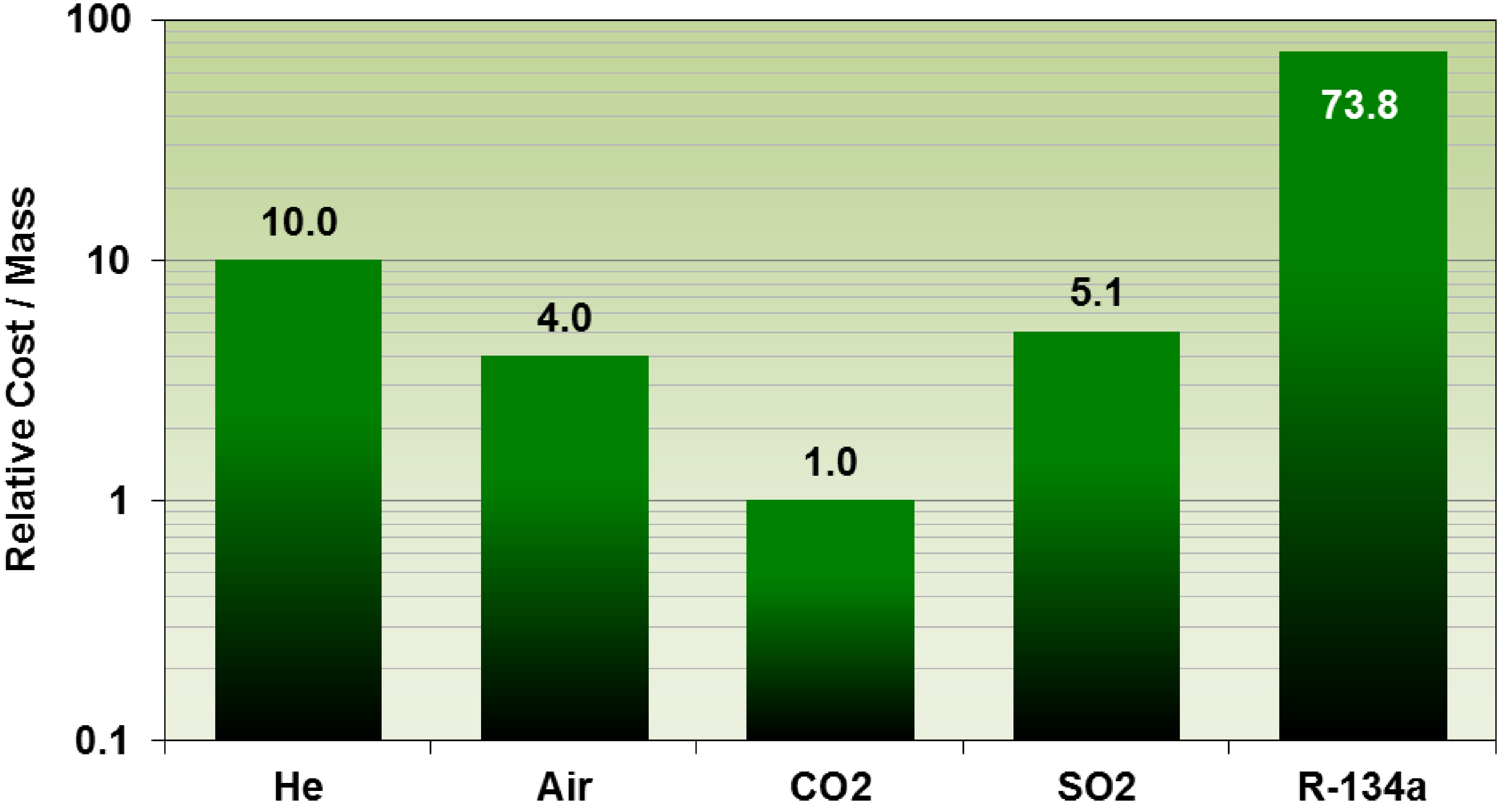


sCO_2 Power Cycles

Why sCO_2 for Power Cycles?

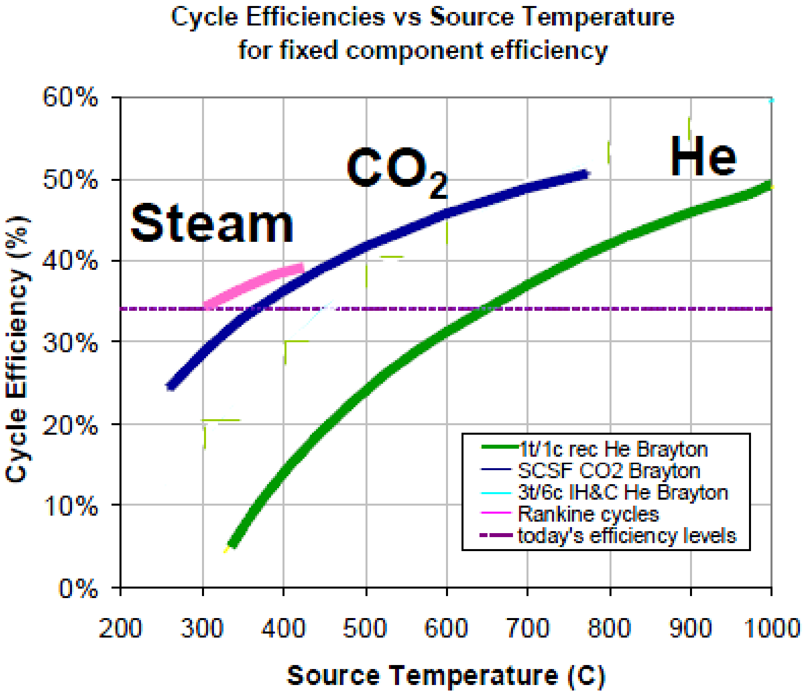
Property	Effect
High density, low viscosity, high C_P near C.P.	• Reduced compressor work, increased W_{net} • Allow more-compact turbomachinery to achieve same power • Less complex – e.g., fewer compressor and turbine stages, may not need intercooling
Near-ambient T_{crit}	• Good availability for most temperature sinks and sources
Abundant fluid with low GWP	• Low cost
Familiar	• Experience with standard materials, though not necessarily at high temp. & high pressure

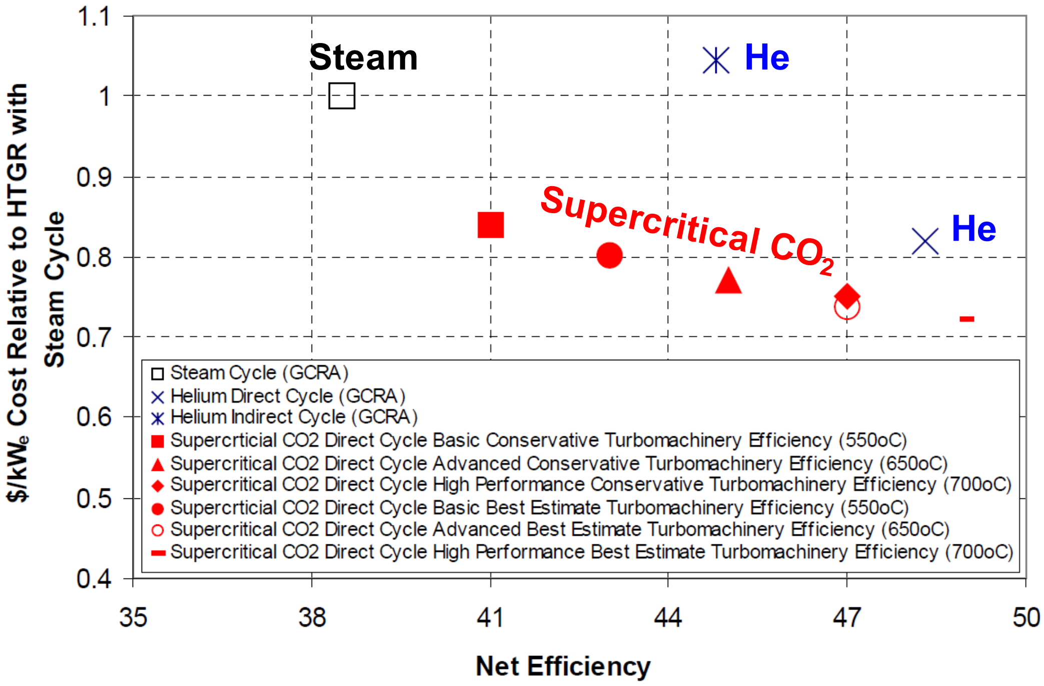
CO_2 Cost Comparison*



*Based on market pricing for laboratory-grade substance

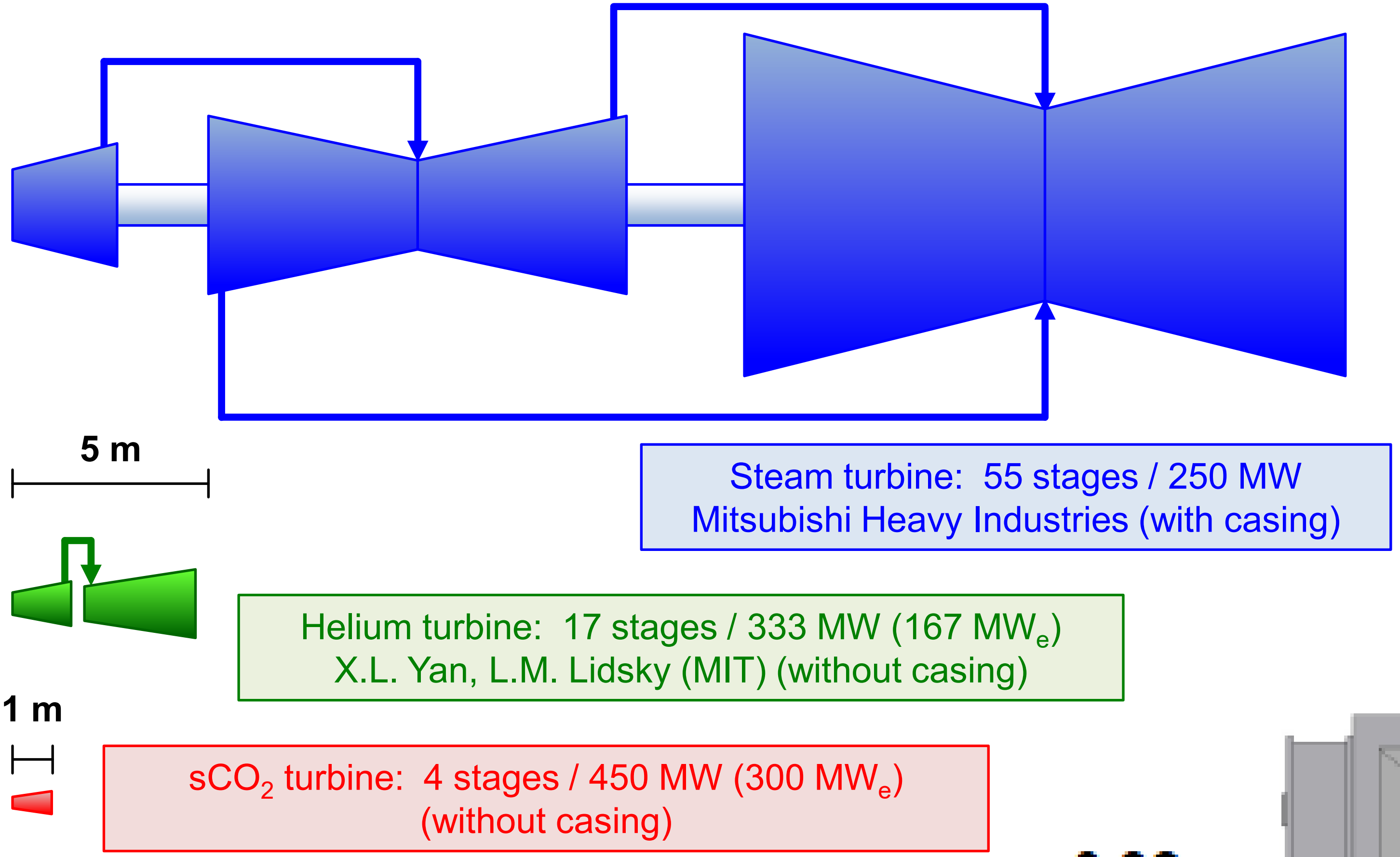
Calculated sCO_2 efficiencies close to a steam cycle for potentially less $/kW





Source: Wright (2011) and Dostal (2004)

Relative Size of Components



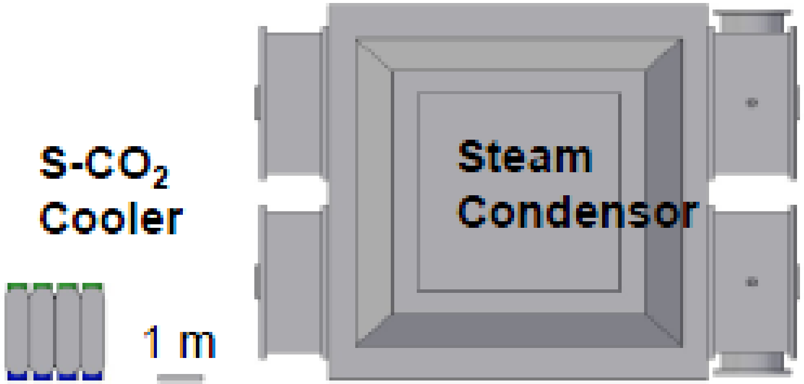
Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries (with casing)

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

sCO_2 turbine: 4 stages / 450 MW (300 MW_e)
(without casing)

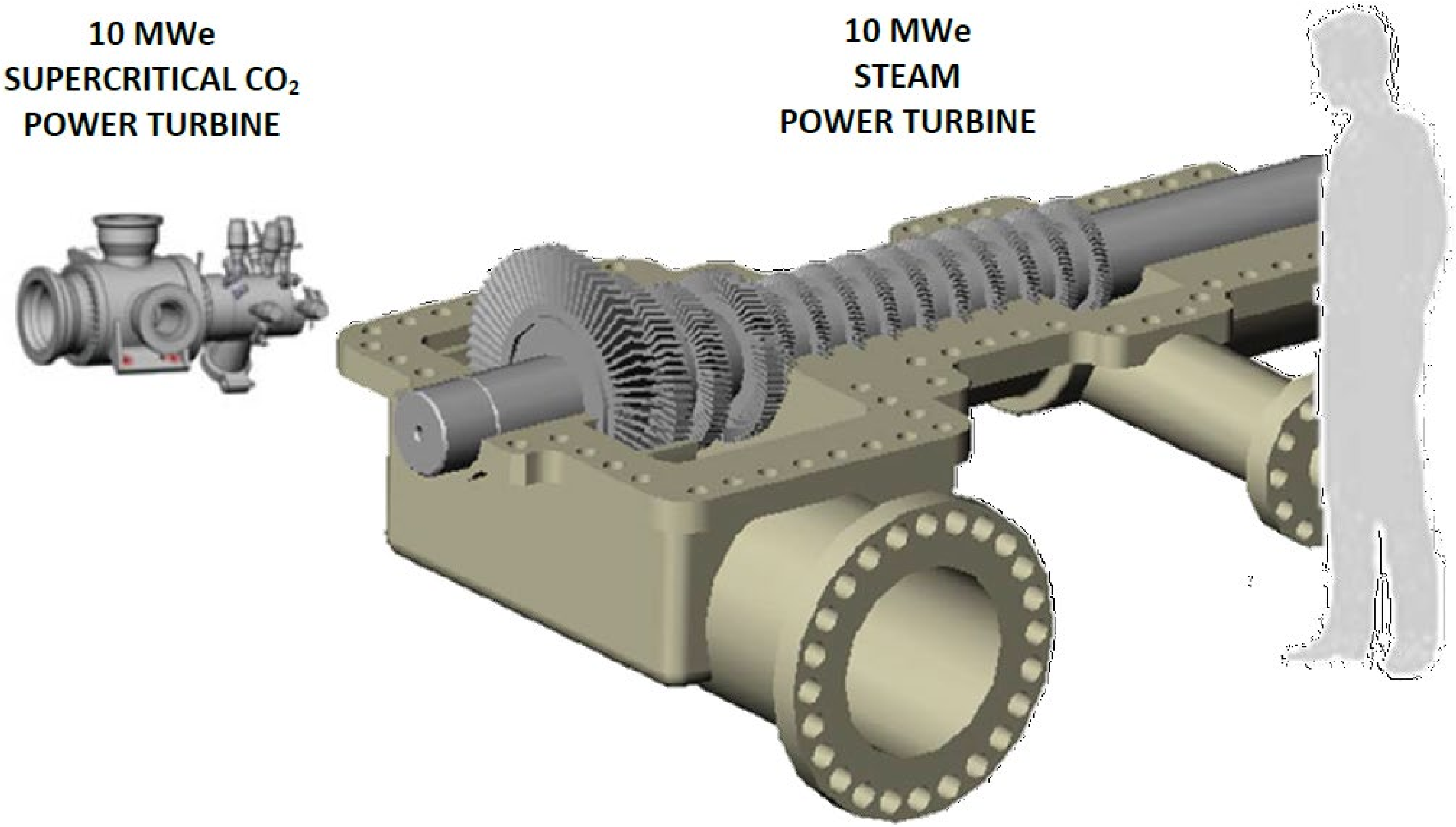
Note: Compressors are comparable in size

Adapted from Dostal (2004)



Source: Wright (2011)

Example: 10 MWe Turbine Comparison



Source: Persichilli et al. (2012)

sCO_2 in Power Cycle Applications

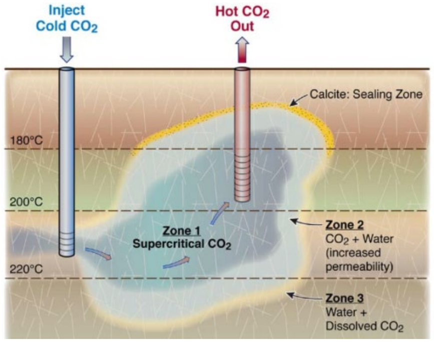
Supercritical CO_2 in Power Cycle Applications

[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

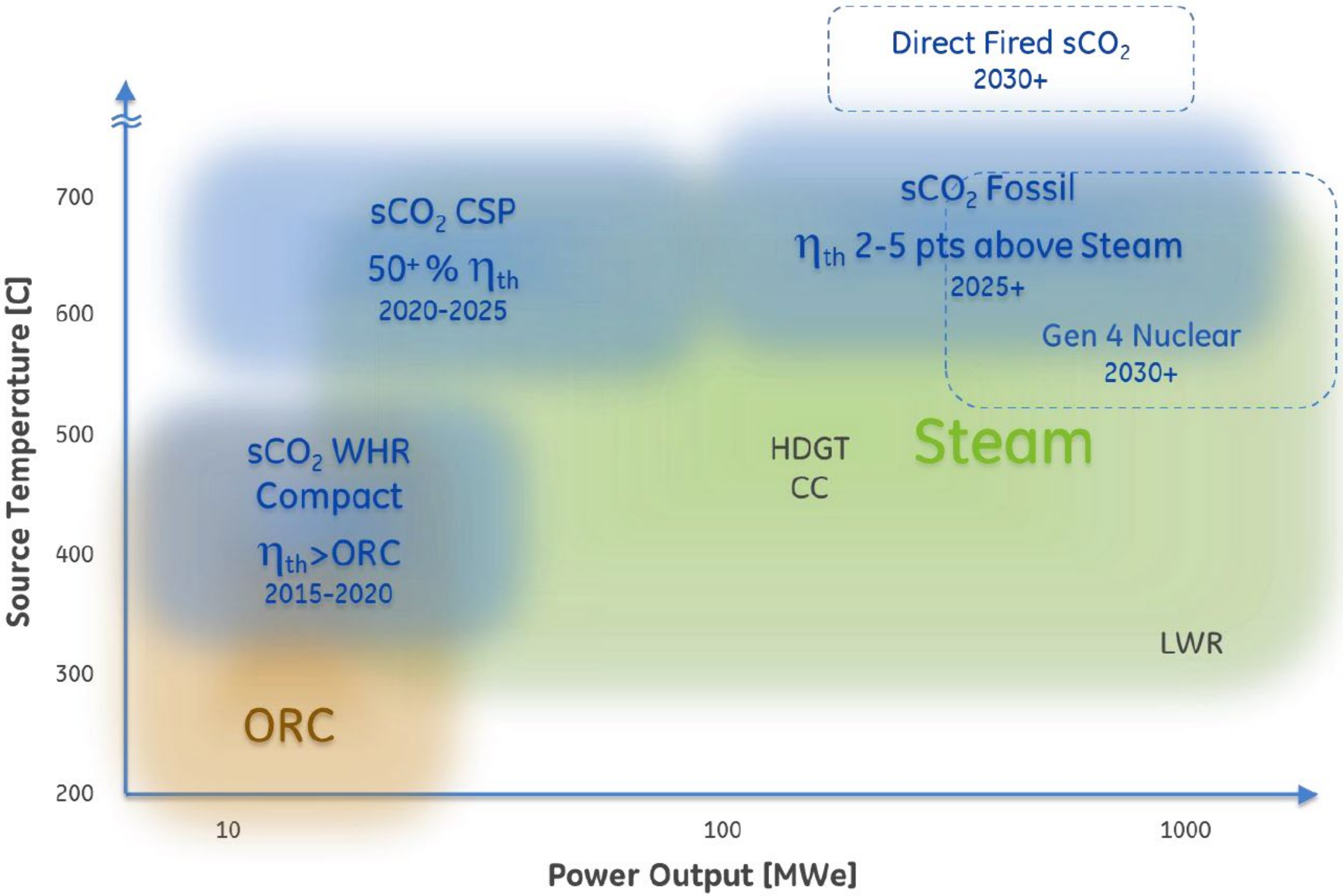
Nuclear

[6-5]

Ship-board Propulsion

Waste Heat Recovery [6-11]

Supercritical CO_2 Power Cycle Applications



[Bowman 2016]

Supercritical CO_2 in Power Cycle Applications

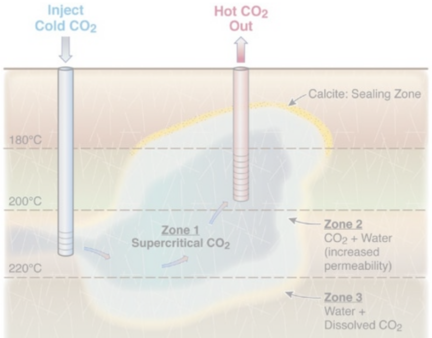
[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel

[6-3]



Geothermal

[6-4]

Nuclear

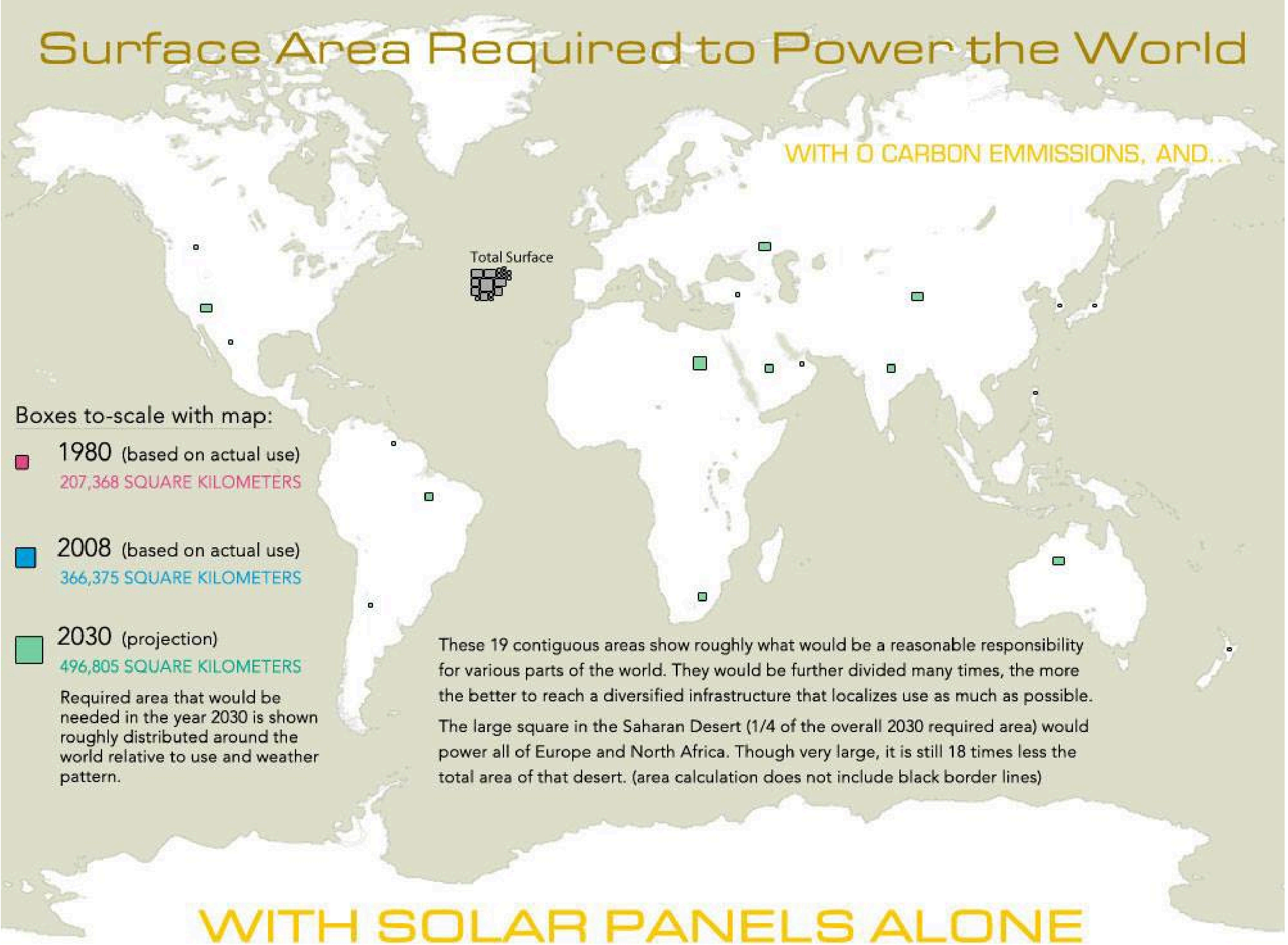
Ship-board Propulsion

[6-5]

Waste Heat Recovery

[6-11]

Why would we use solar power?



Surface Area Required to Power the World

WITH 0 CARBON EMMISSIONS, AND...

Boxes to-scale with map:

🟥 1980 (based on actual use)
207,368 SQUARE KILOMETERS

🟦 2008 (based on actual use)
366,375 SQUARE KILOMETERS

🟩 2030 (projection)
496,805 SQUARE KILOMETERS

Required area that would be needed in the year 2030 is shown roughly distributed around the world relative to use and weather pattern.

These 19 contiguous areas show roughly what would be a reasonable responsibility for various parts of the world. They would be further divided many times, the more the better to reach a diversified infrastructure that localizes use as much as possible.

The large square in the Saharan Desert (1/4 of the overall 2030 required area) would power all of Europe and North Africa. Though very large, it is still 18 times less the total area of that desert. (area calculation does not include black border lines)

WITH SOLAR PANELS ALONE

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.

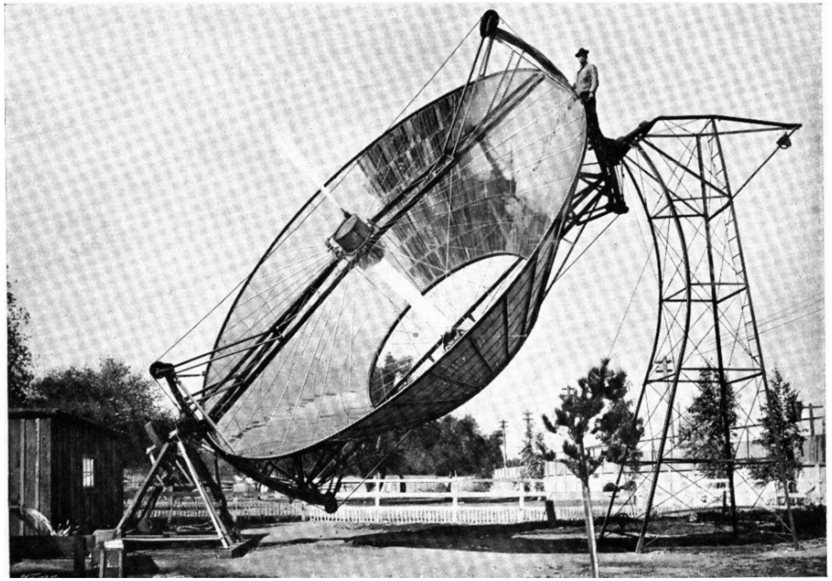
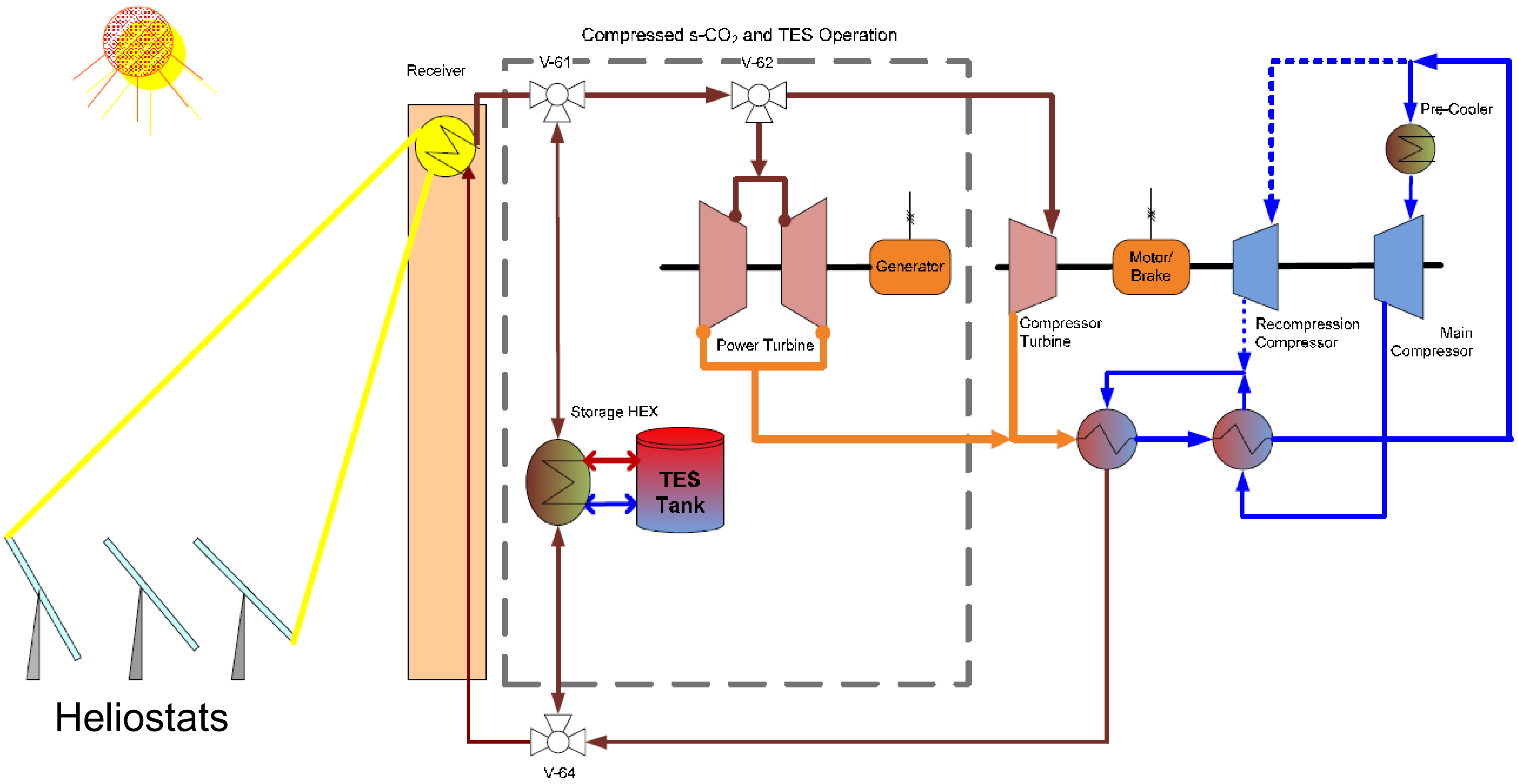


Image source: [6-6]

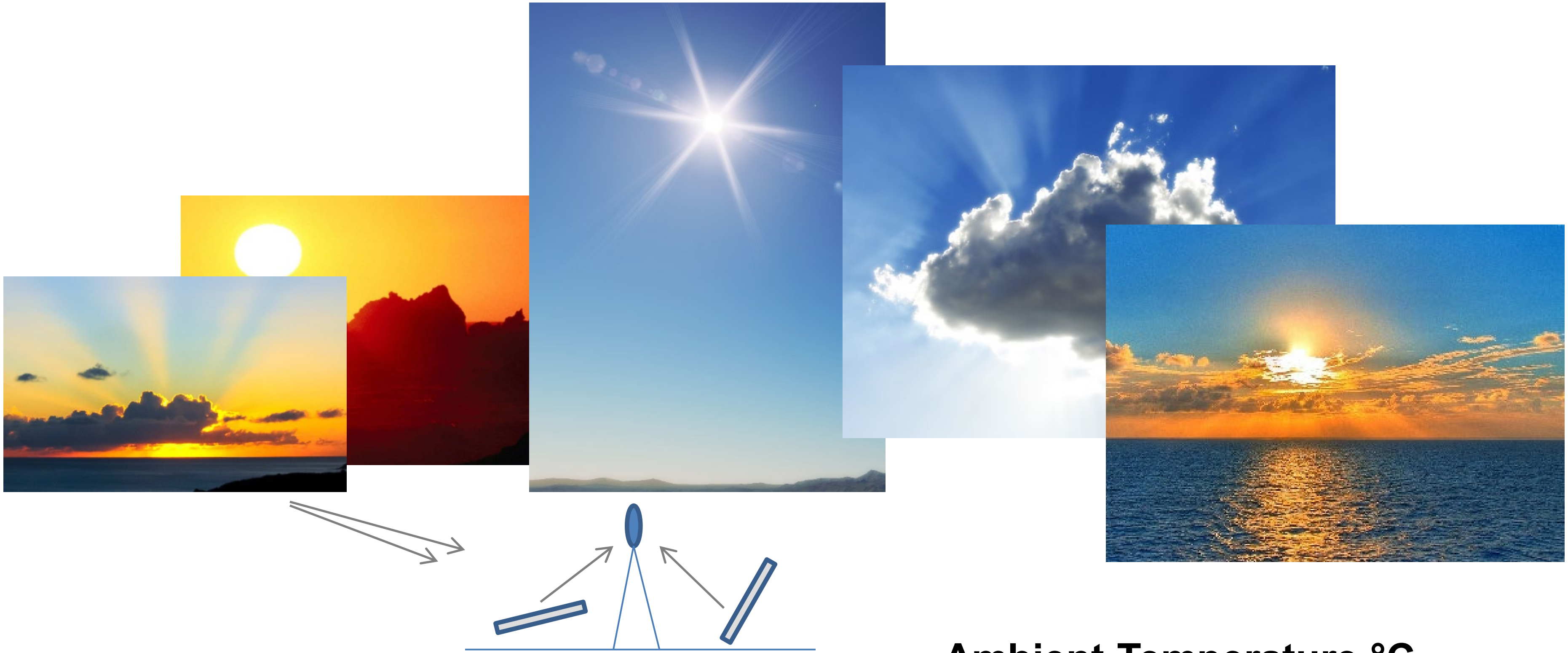
Image source: [6-7]

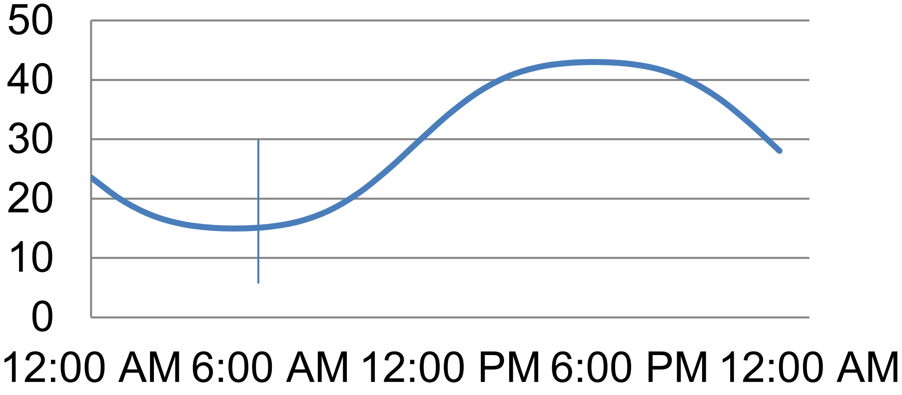
sCO_2 CSP Process Diagram



Dual-shaft, tower receiver sCO_2 Brayton Cycle solar thermal power system with thermal energy storage, Zhiwen and Turchi (2011)

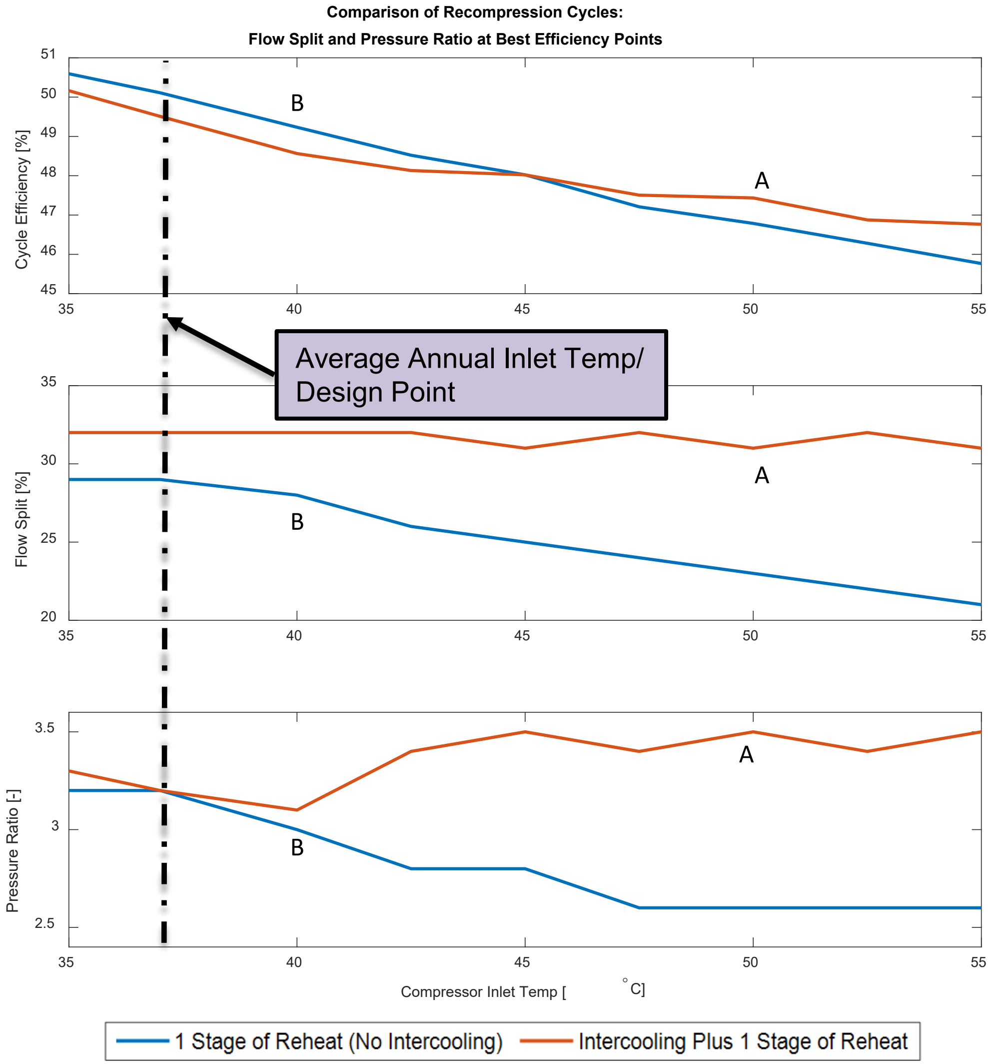
The transient challenges of a concentrated solar power plant are significant



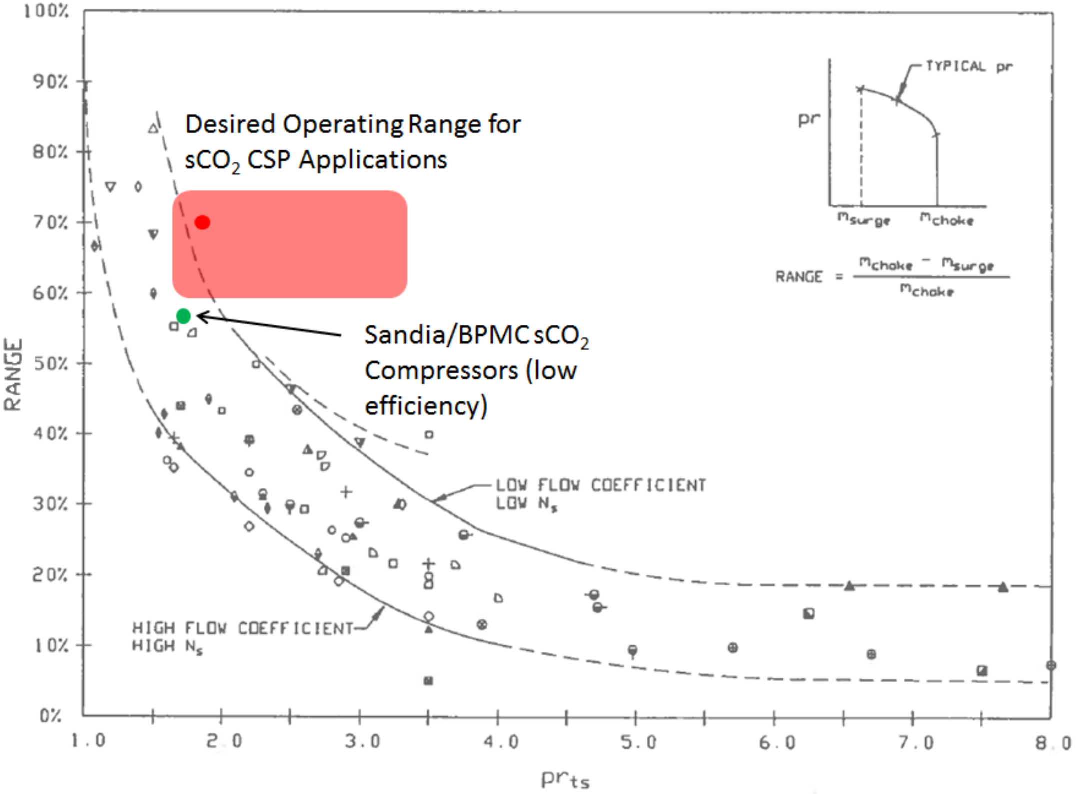


Optimal Cycle Configuration with varying Compressor Inlet Temperature

- SAM modeling of typical sites shows an annual average compressor inlet temperature to be 37-38ºC assuming 15ºC 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



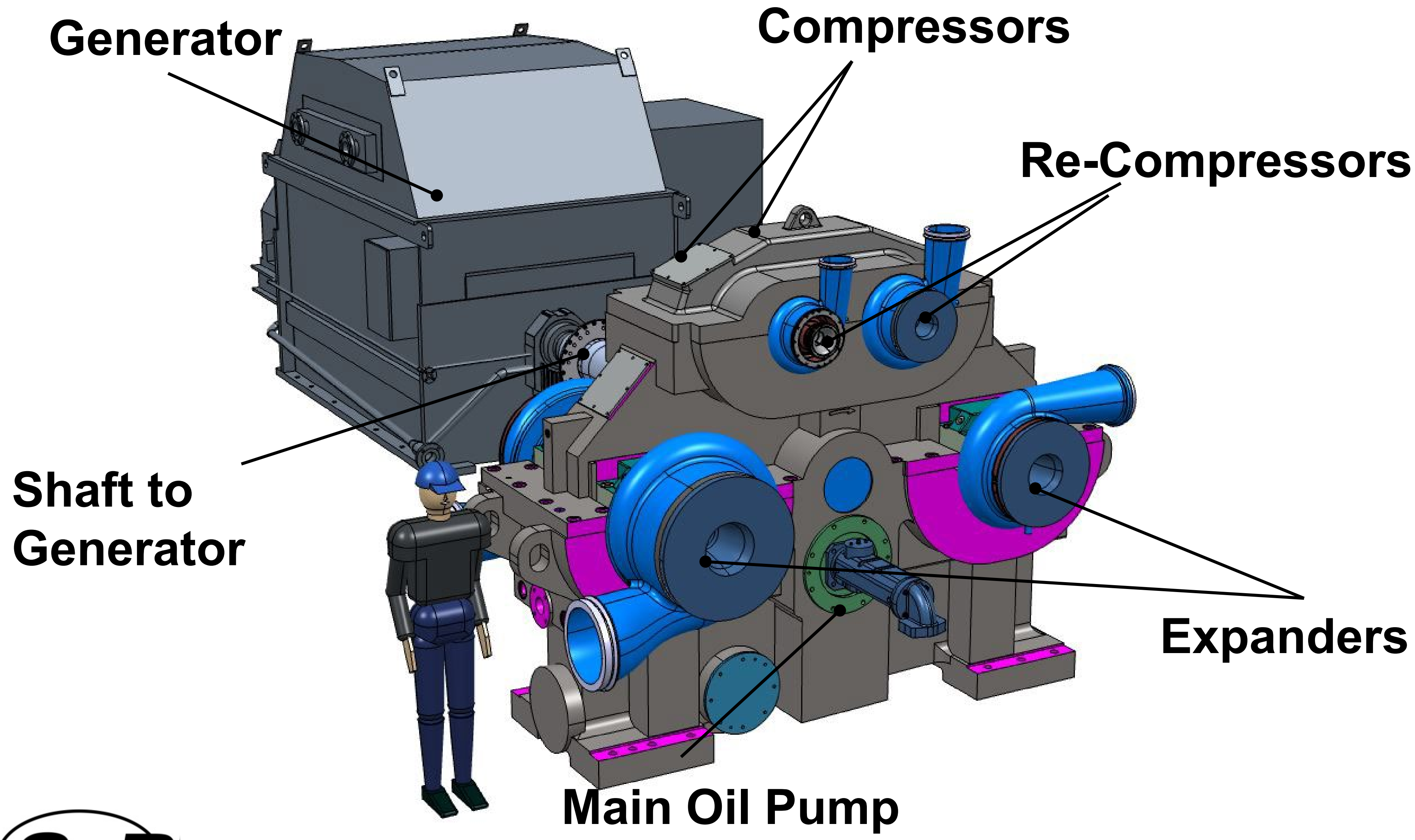
Desired Operating Range for sCO_2 CSP Applications

Sandia/BPMC sCO_2 Compressors (low efficiency)

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

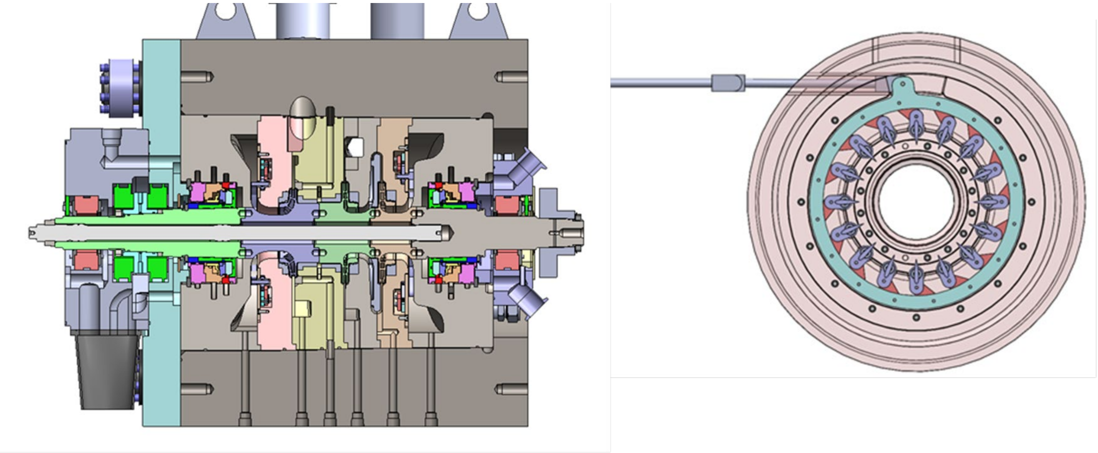
- To manage this challenge, numerous strategies will be required
  - Inventory Control
  - Inlet Guide Vanes
  - Variable Diffuser Vanes
  - Variable Speed Compression
  - Novel Control Features

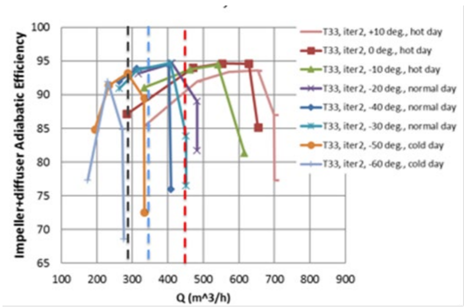
Conceptual 10 MW_e Integrally Geared Compressor Applied to Recuperated Brayton Cycle



APOLLO Compressor Development

- ❑ Develop and test an sCO_2 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

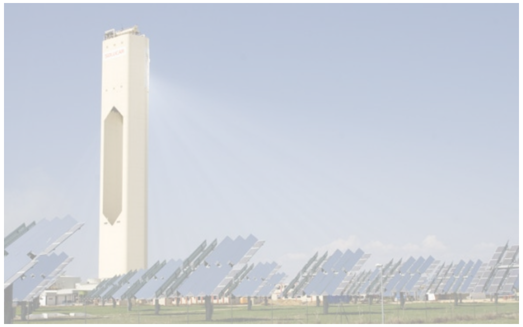




What are the key challenges to CSP sCO_2 cycles

- ❑ 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 sCO_2 while incorporating thermal energy storage is challenging
- ❑ Turbine inlet temperatures approaching 750° with very high cycle efficiency requirements expected.

Supercritical CO_2 in Power Cycle Applications



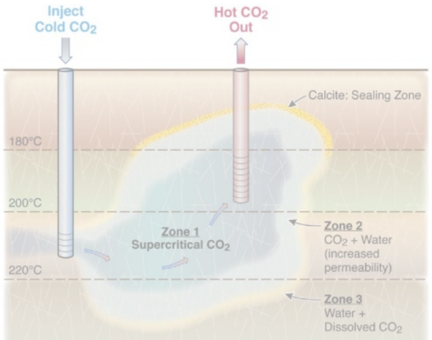
[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel

[6-3]



Geothermal

[6-4]

Nuclear

[6-5]

Ship-board Propulsion

Waste Heat Recovery [6-11]

Rankine Cycle Application: Nuclear Power Generation

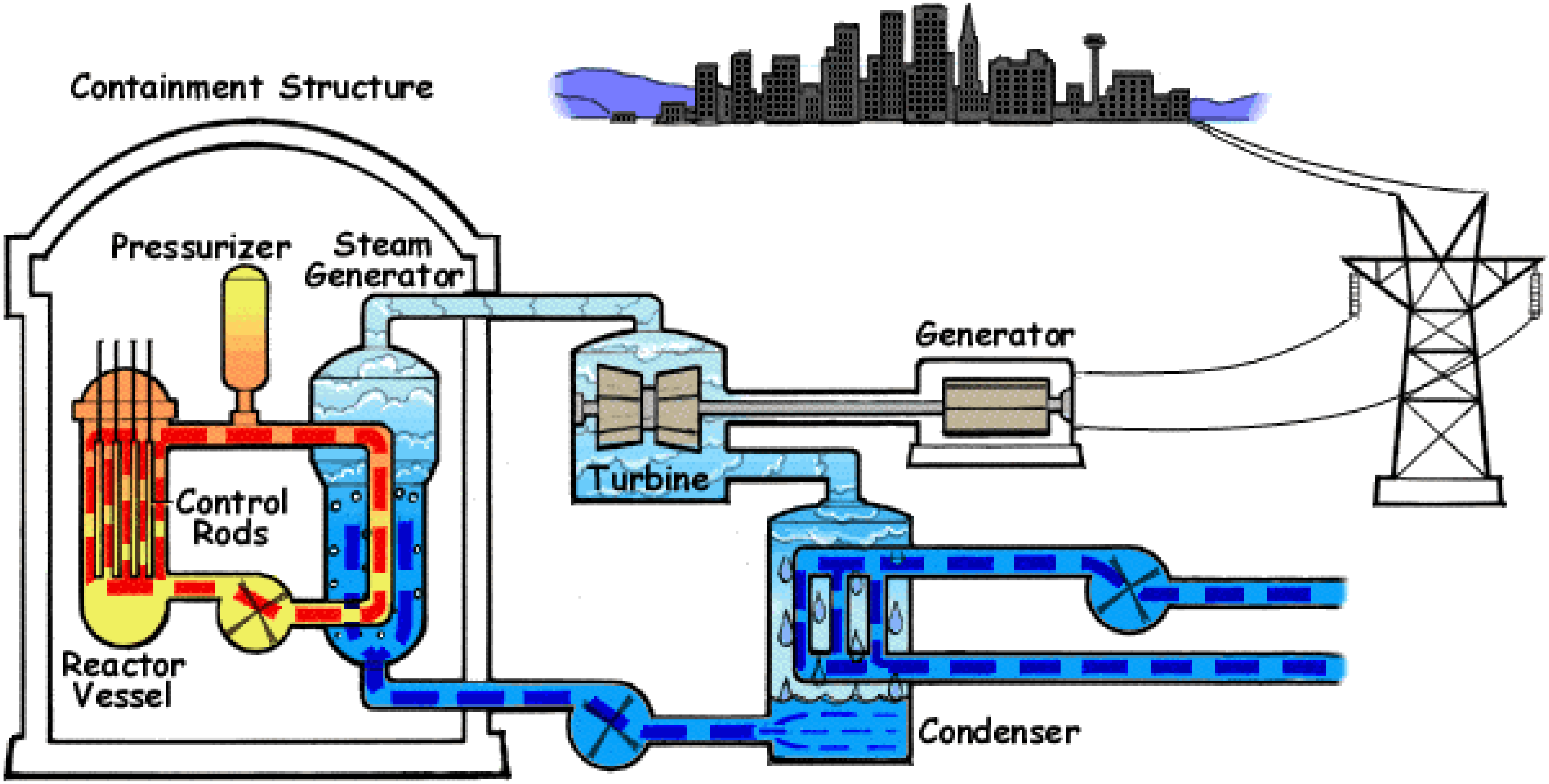


Image source: [6-8]

sCO_2 for Nuclear Applications (550°C-700°C, 34 MPa)

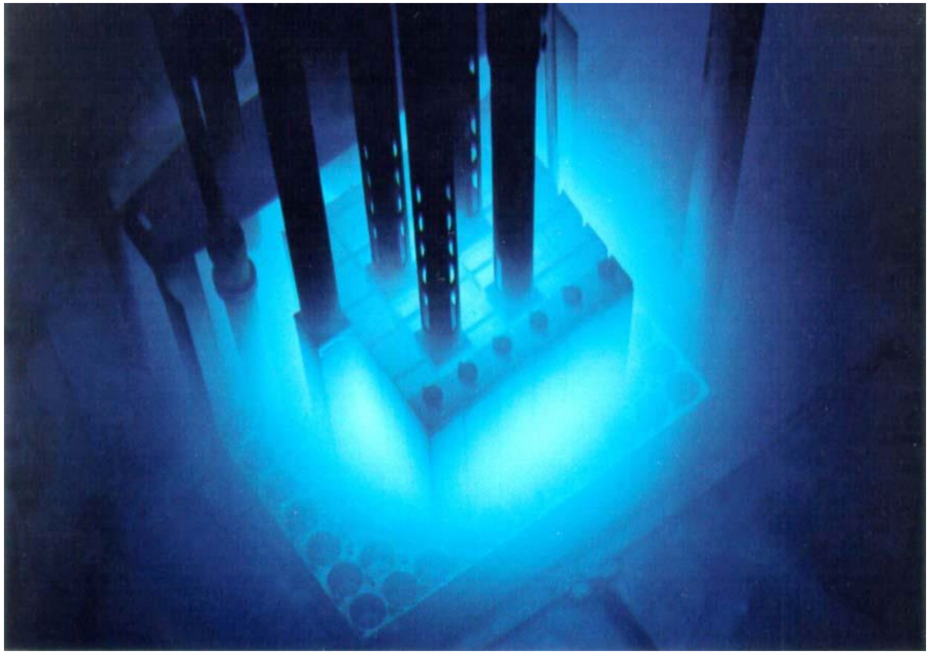
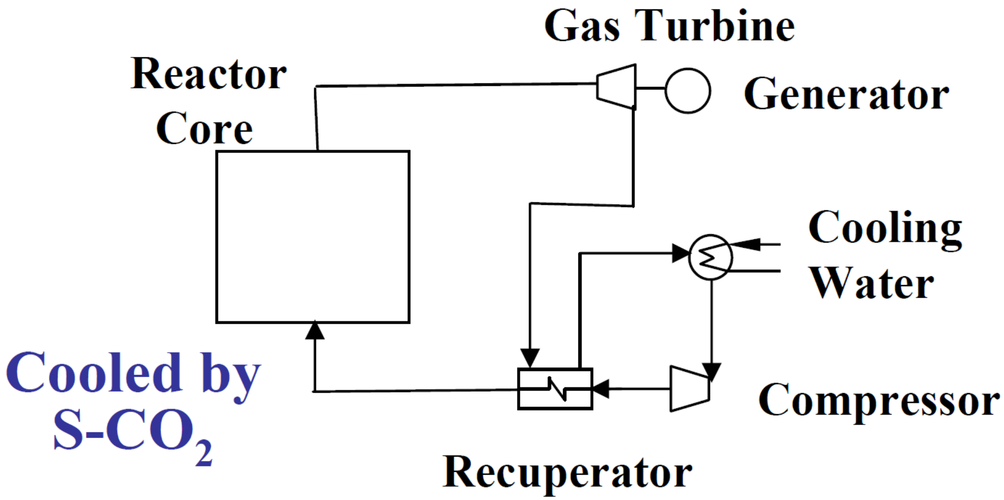


Image source: [6-9]

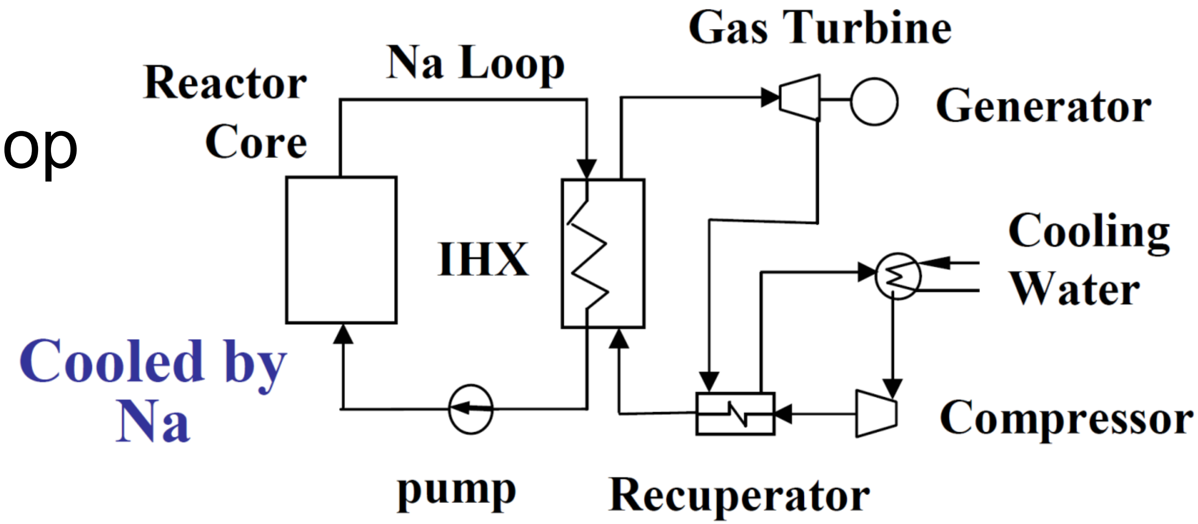
Image source: [6-4]

Proposed Nuclear sCO_2 Cycles

- ❑ Direct Cycle
  - No primary and secondary Na loops
  - Lower Void Reactivity

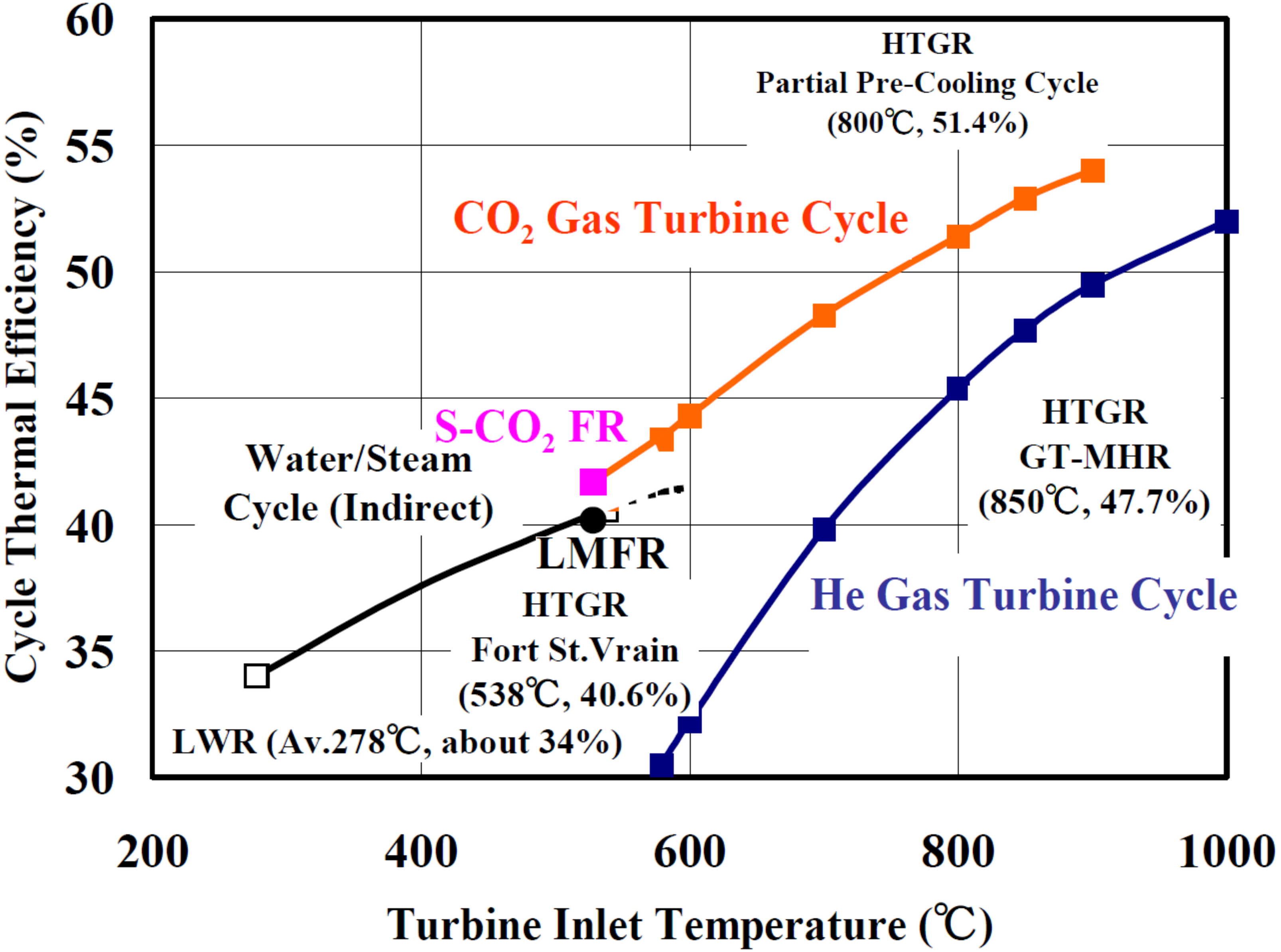


- ❑ Indirect Cycle
  - Primary Na loop
  - Smaller core size



Kato et al. (2007)

Nuclear Plant Efficiency vs. Cycle Prop.

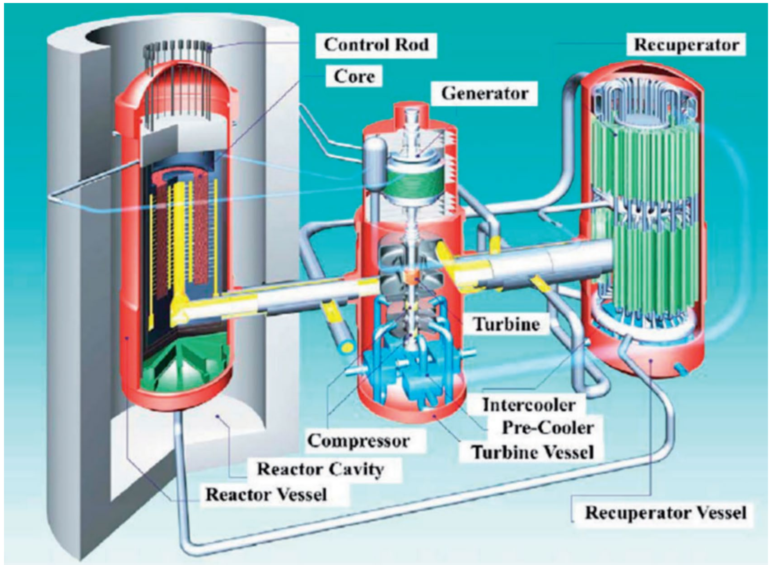


Kato et al. (2007)

Modular vs. Consolidated

☐ 10-20 MW

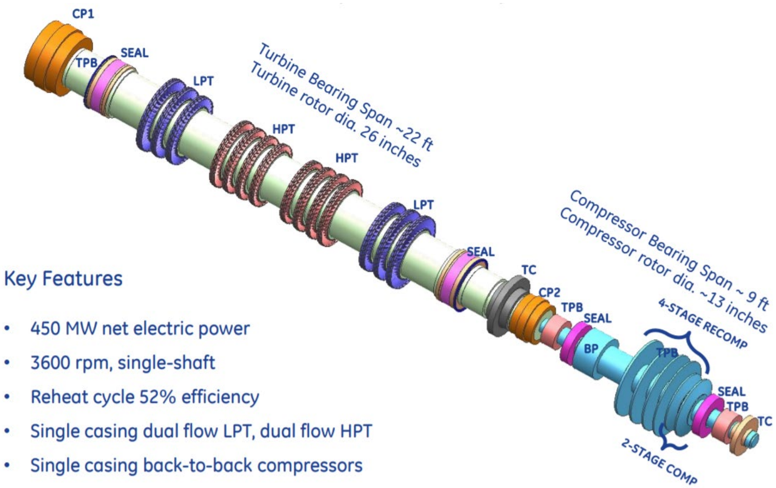
- Multiple High-Speed Trains
- Smaller Capital Investment
- Intrinsically Safe Cooling
- Mass Scale Production
- Smaller Environmental Risk



Gui, H. et al, The application of supercritical CO2 in nuclear engineering: A review, J. Comp. Multiphase Flow, V10-4, 2018

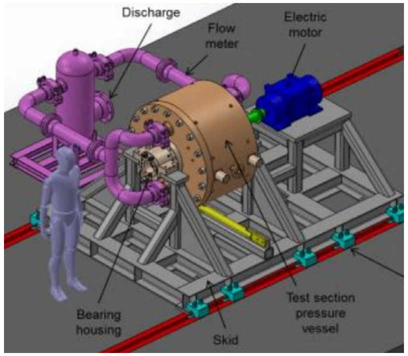
☐ 200 MW-1 GW

- 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

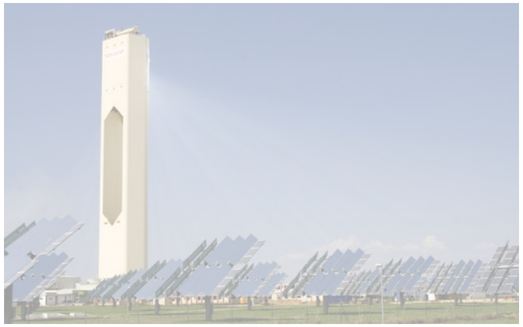


Bidkar et al., sCO2 turbomachinery and Low-Leakage sCO2 End Seals, UTSR (2015)

What are the key challenges to Nuclear sCO_2 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 CO_2 in Power Cycle Applications



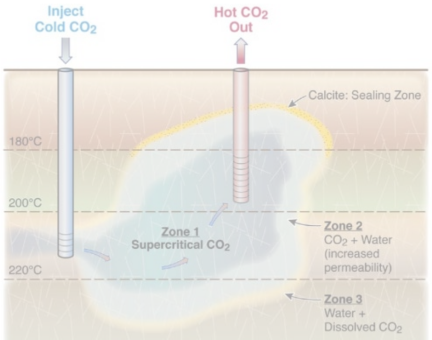
[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel

[6-3]



Geothermal

[6-4]

Nuclear

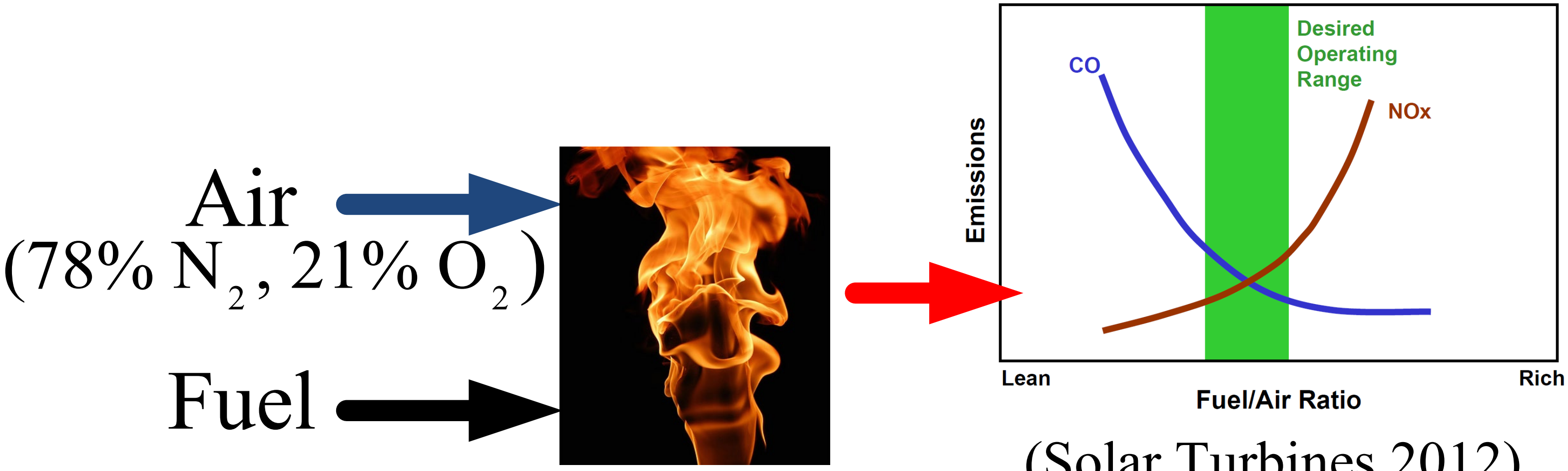
[6-5]

Ship-board Propulsion

Waste Heat Recovery [6-11]

Oxy-Fuel Combustion

Conventional Combustion



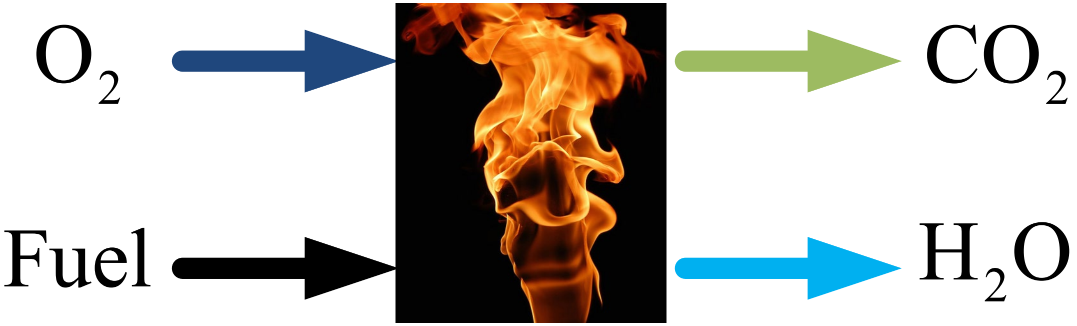
Air

(78% N_2, 21% O_2)

Fuel

(Solar Turbines 2012)

Oxy-Fuel Combustion



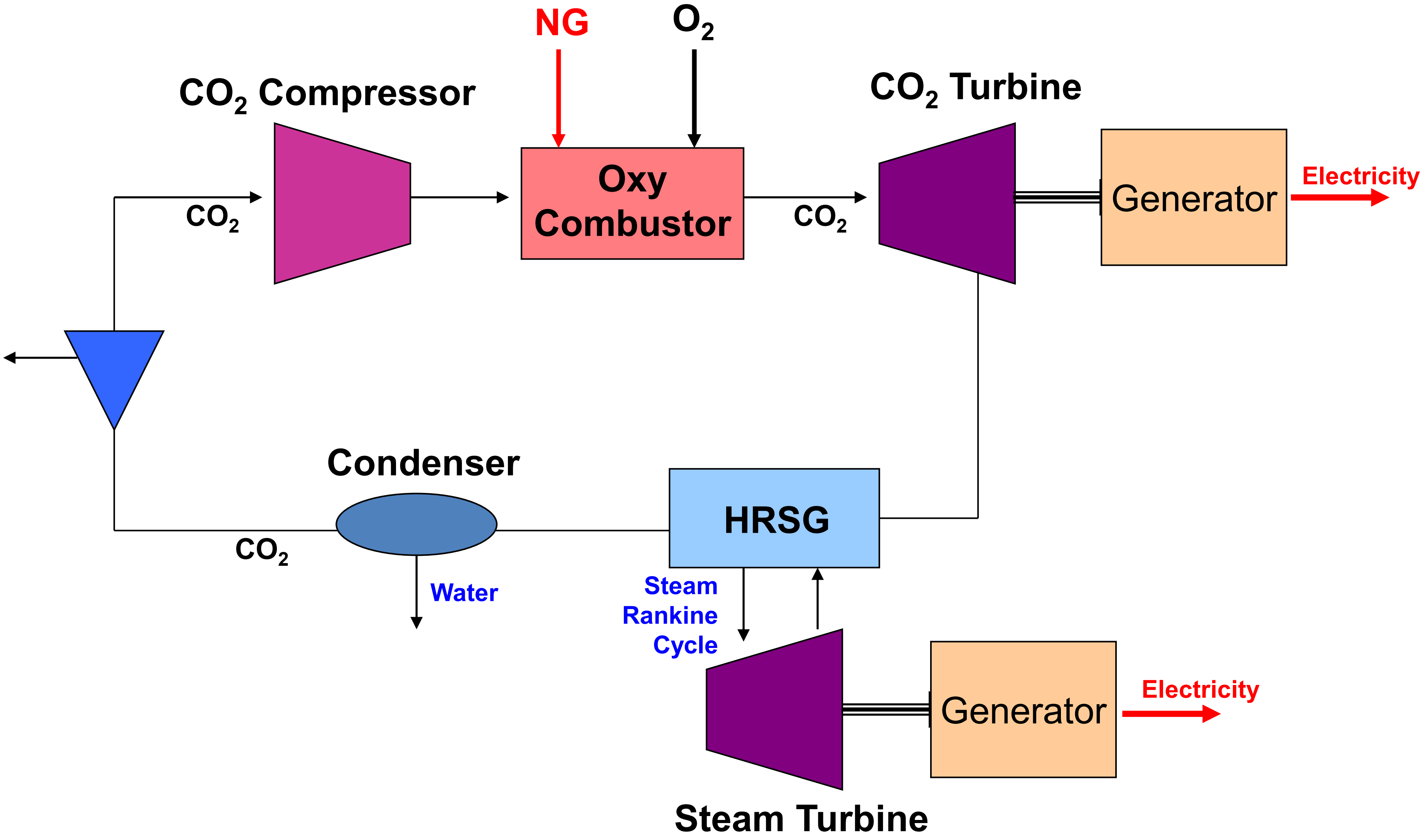
O_2

Fuel

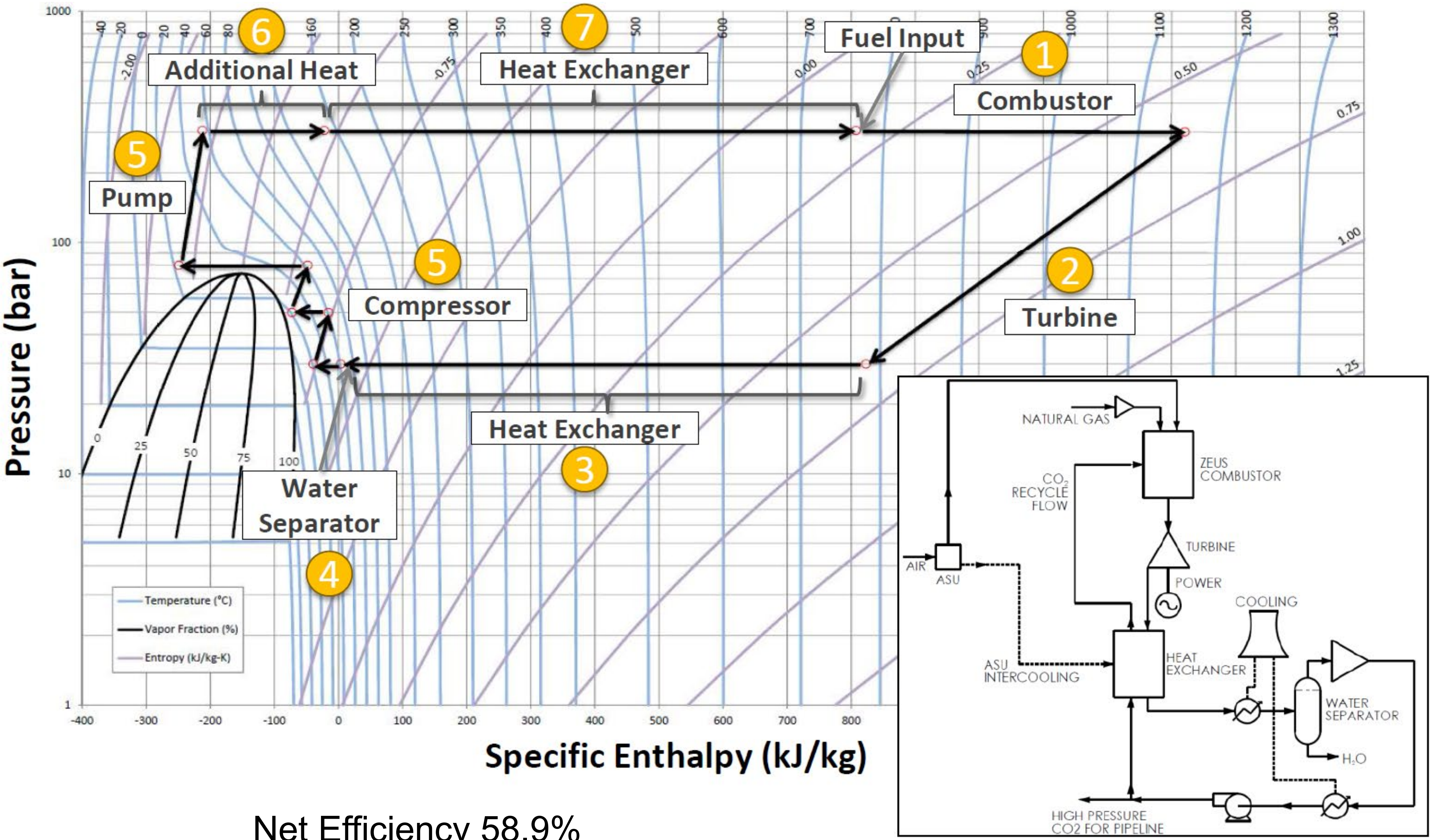
CO_2

H_2O

Direct Oxy-Fuel Combustion



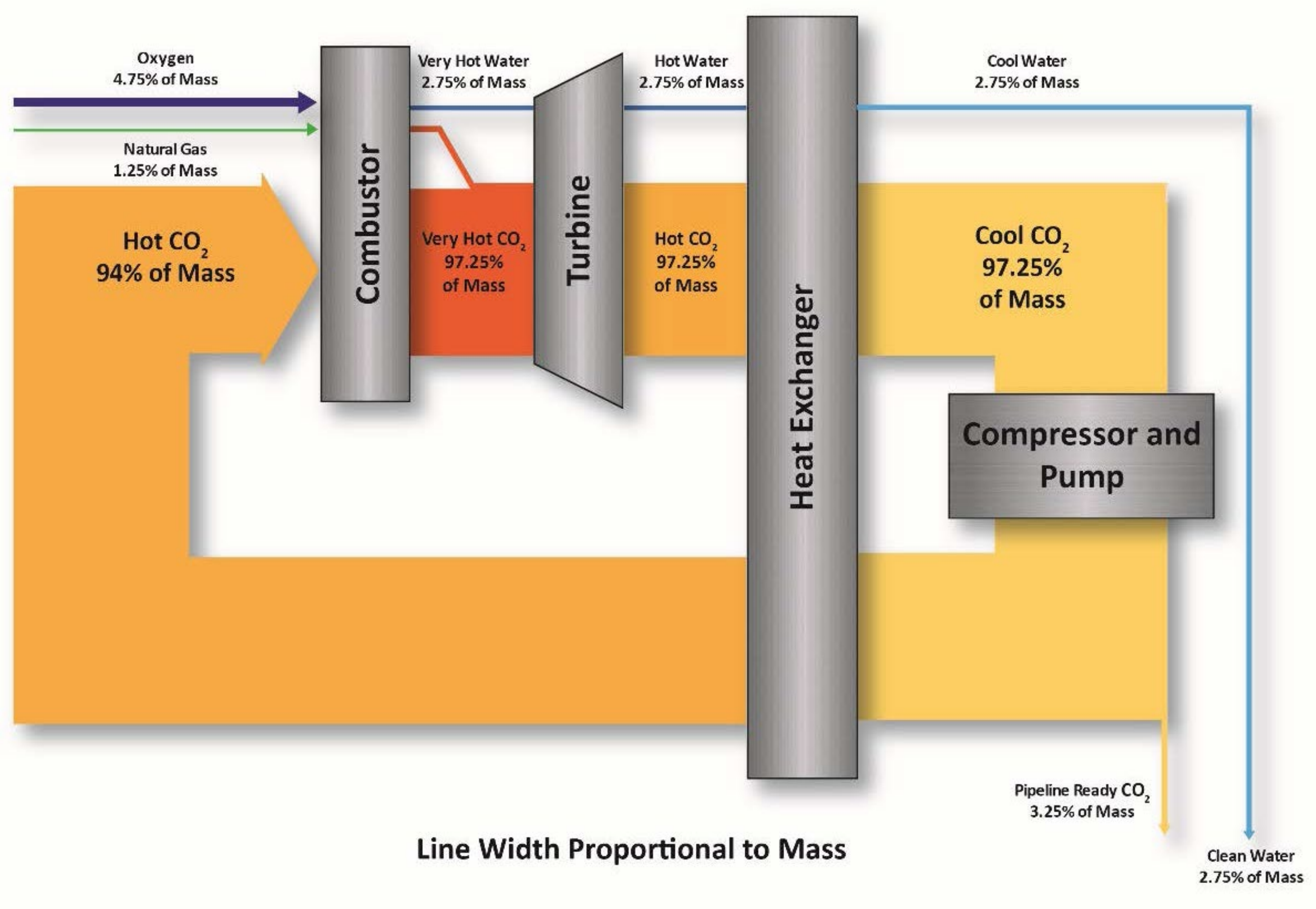
Allam Cycle (NetPOWER)



Net Efficiency 58.9%

[Fetvedt 2016]

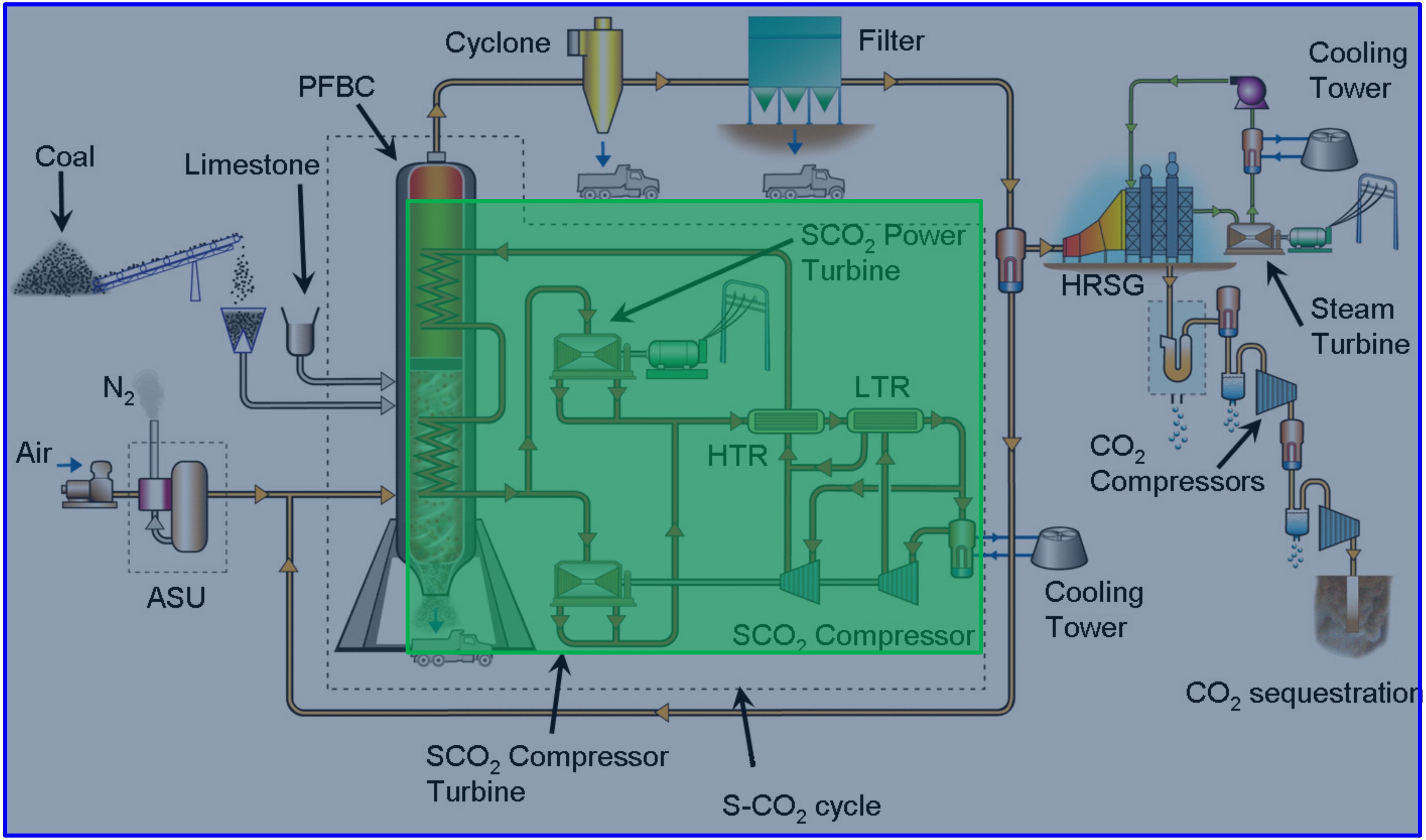
The Allam Cycle (NetPOWER)



[Fetvedt 2016]

[Fetvedt 2016]

Indirect Oxy-Fuel Combustion

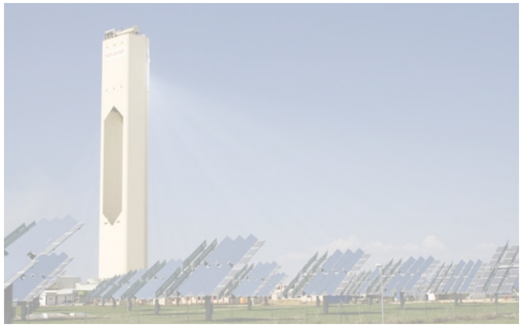


Zero Emission Oxy-Coal Power Plant with Supercritical CO$_2$ Cycle, Johnson et al. (2012)

What are the key challenges for oxy-fuel sCO_2 cycles

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

Supercritical CO_2 in Power Cycle Applications

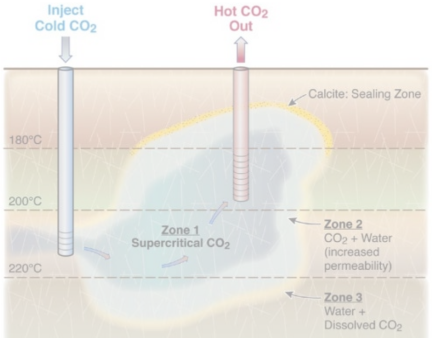


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

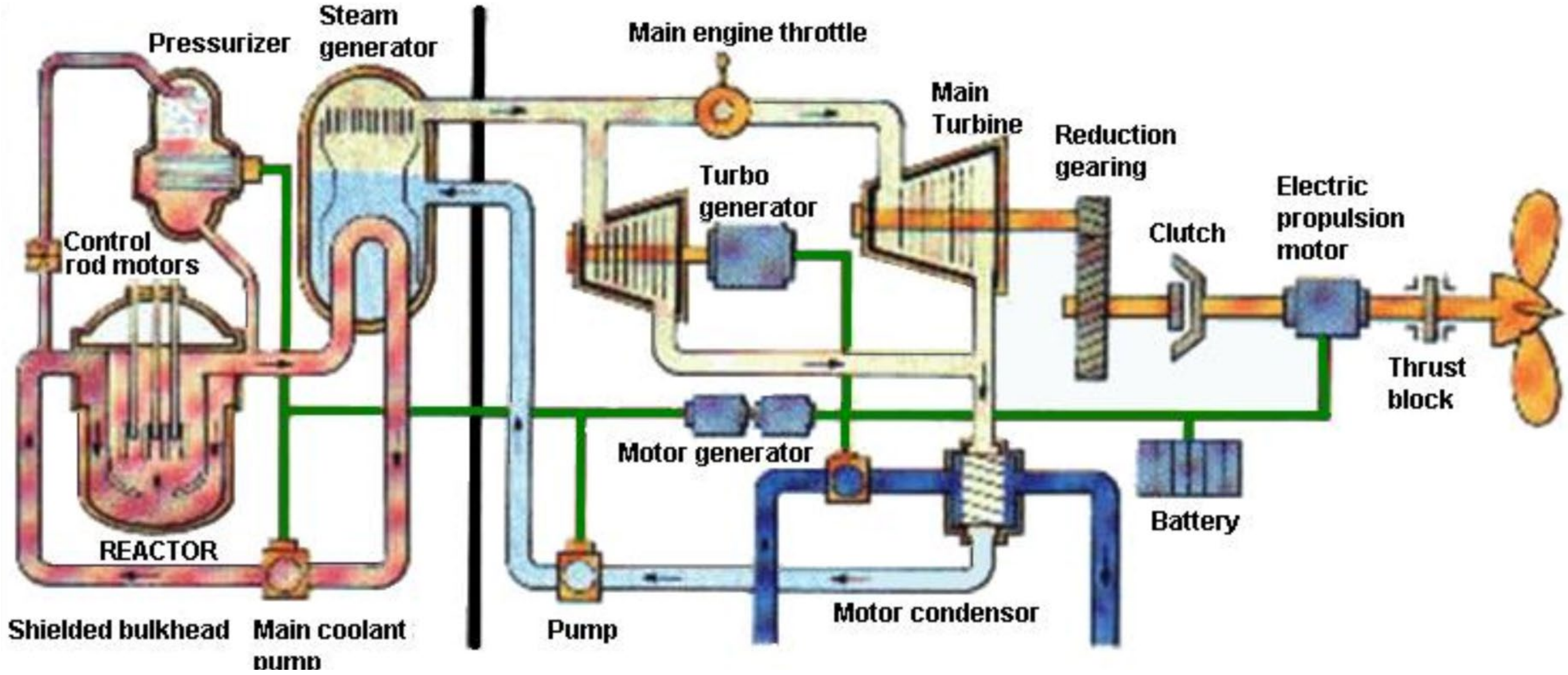
Nuclear

[6-5]

Ship-board Propulsion

Waste Heat Recovery [6-11]

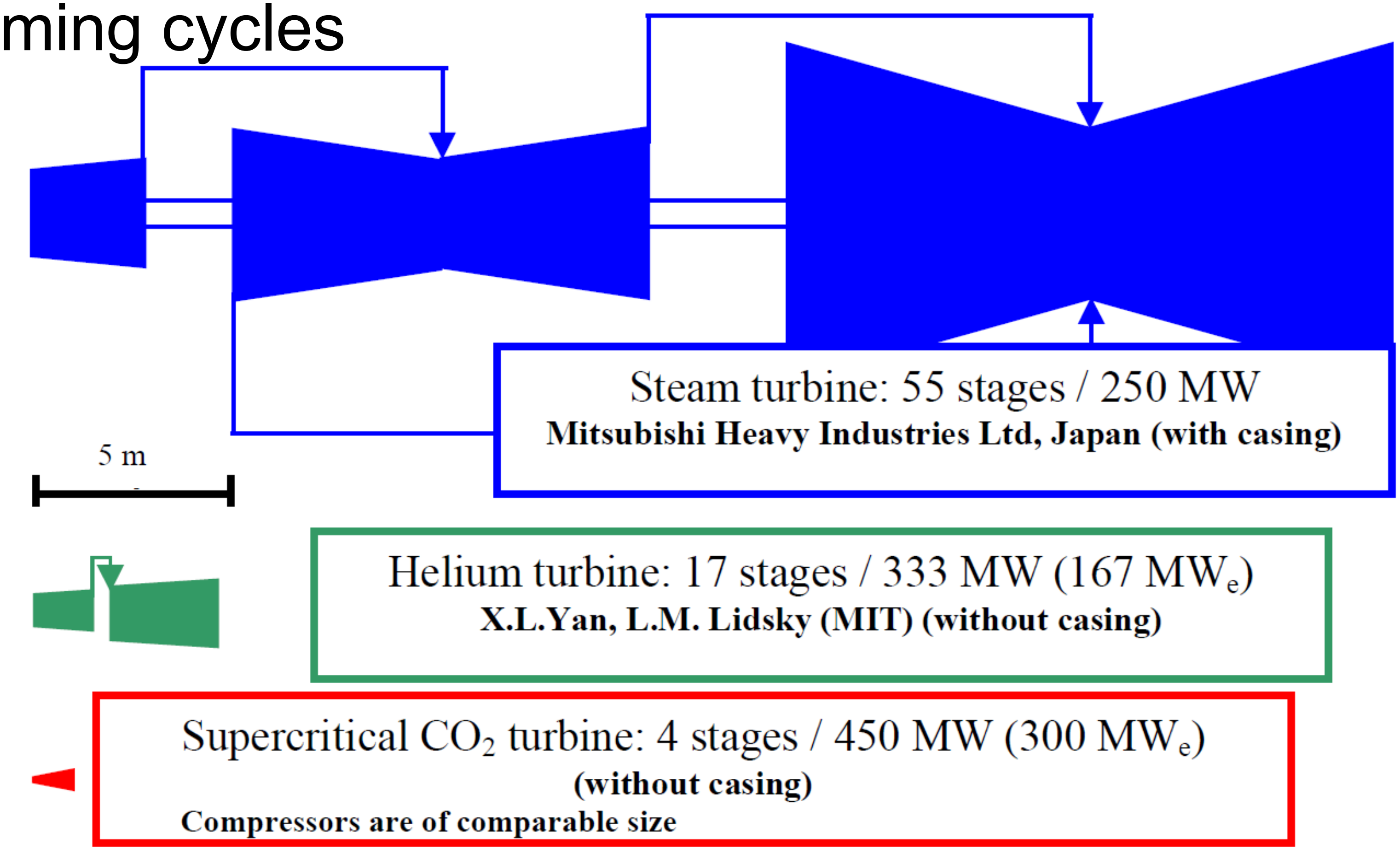
Pressurized-Water Naval Nuclear Propulsion System



Ship-board Propulsion

- ❑ Nuclear sCO_2 cycles?
- ❑ Improved power to weight
- ❑ Rapid startup
- ❑ Bottoming cycles

Image source: [6-10]



Steam turbine: 55 stages / 250 MW

Mitsubishi Heavy Industries Ltd, Japan (with casing)

Helium turbine: 17 stages / 333 MW (167 MW_e)

X.L.Yan, L.M. Lidsky (MIT) (without casing)

Supercritical CO_2 turbine: 4 stages / 450 MW (300 MW_e)

(without casing)

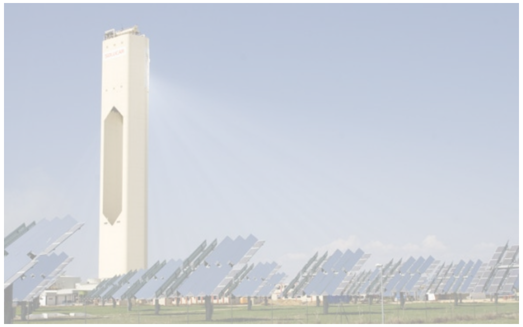
Compressors are of comparable size

Source: Dostal (2004)

Key challenges to sCO_2 nautical applications

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

Supercritical CO_2 in Power Cycle Applications

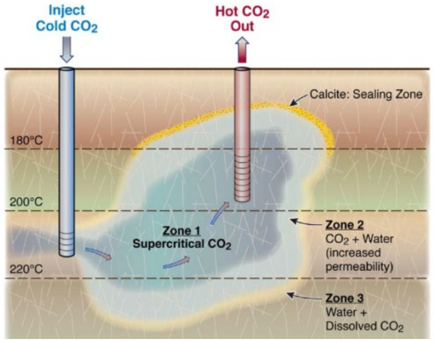


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

Nuclear

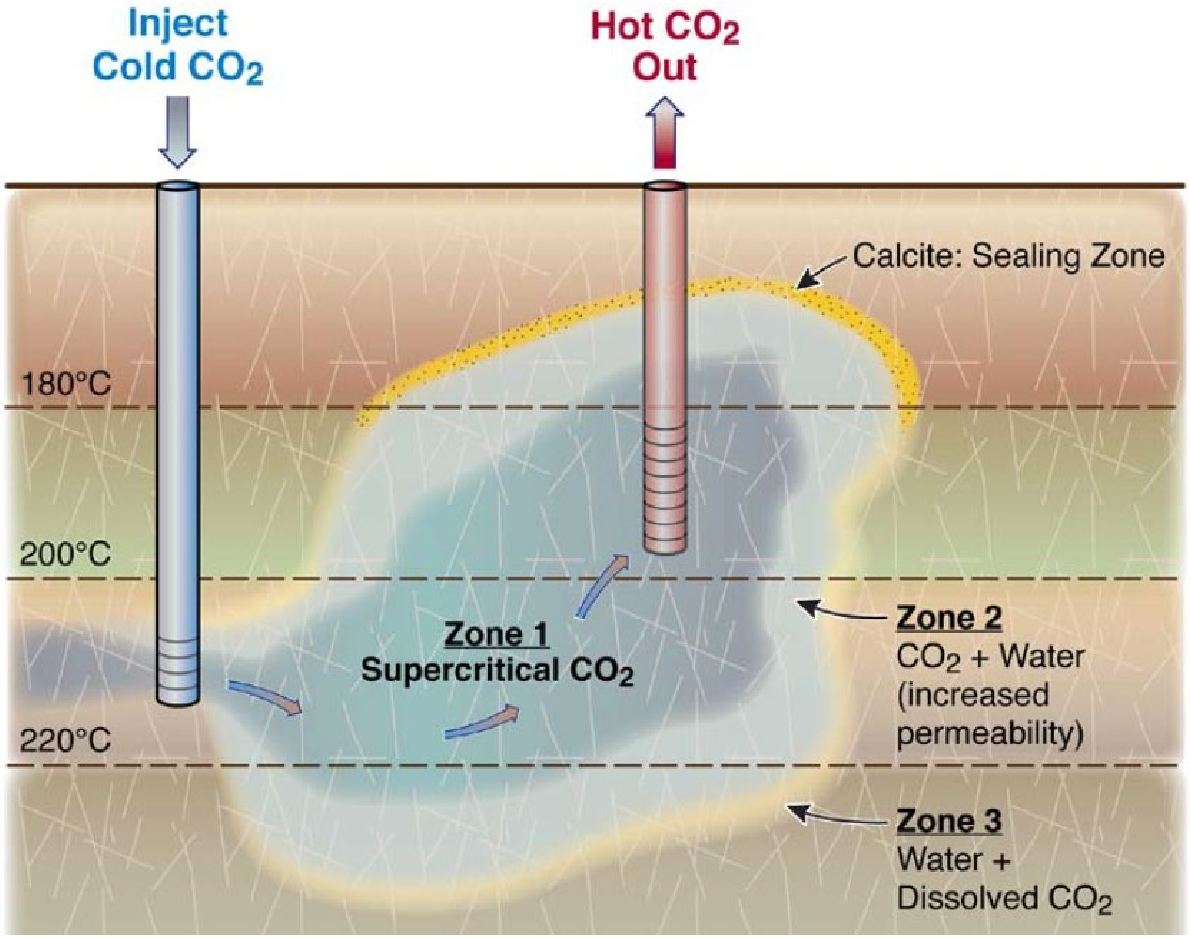
[6-5]

Ship-board Propulsion

Waste Heat Recovery [6-11]

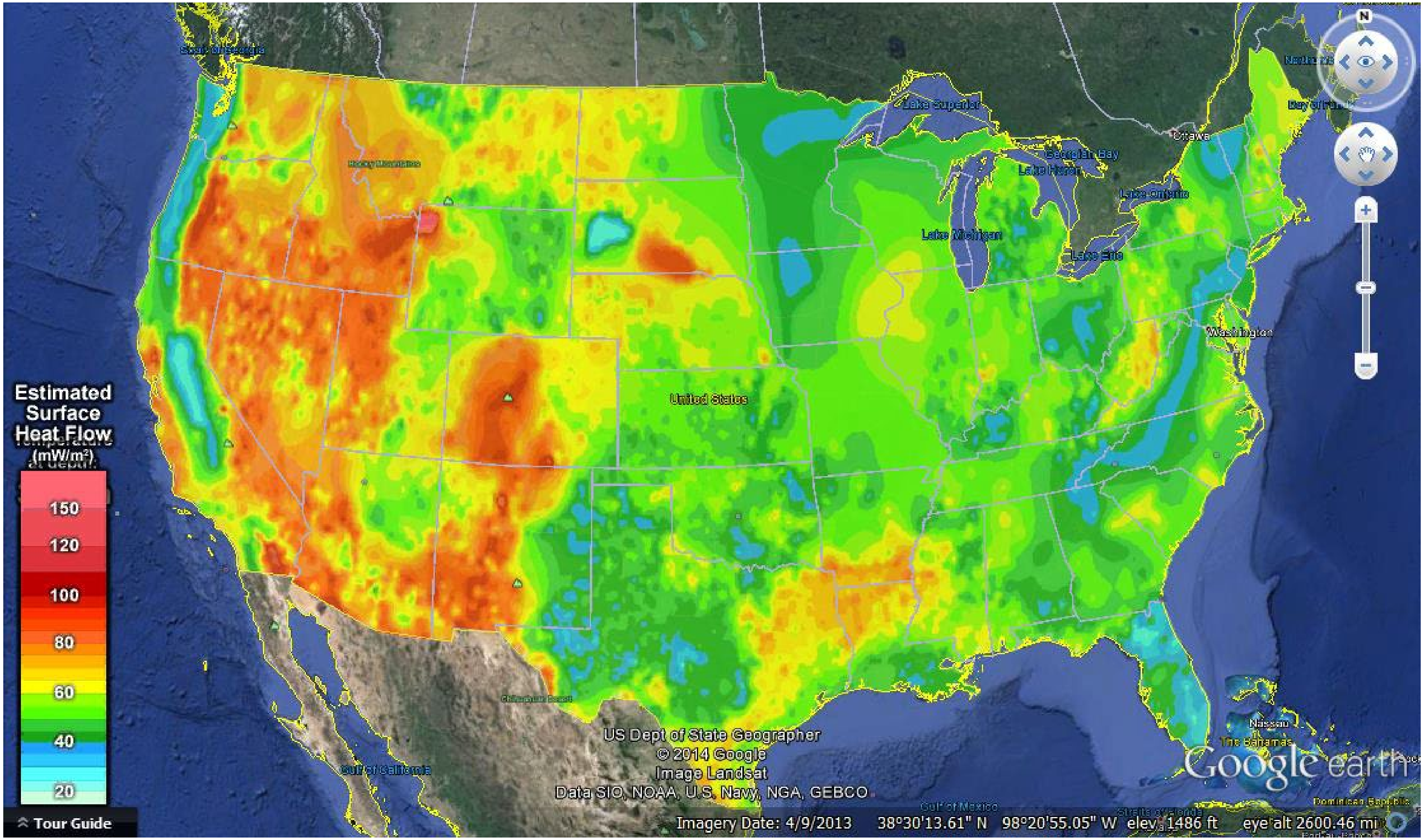
Geothermal

- ❑ Low Temperature Heat Source
  - T ≈ 210°C, P ≈ 100 bar



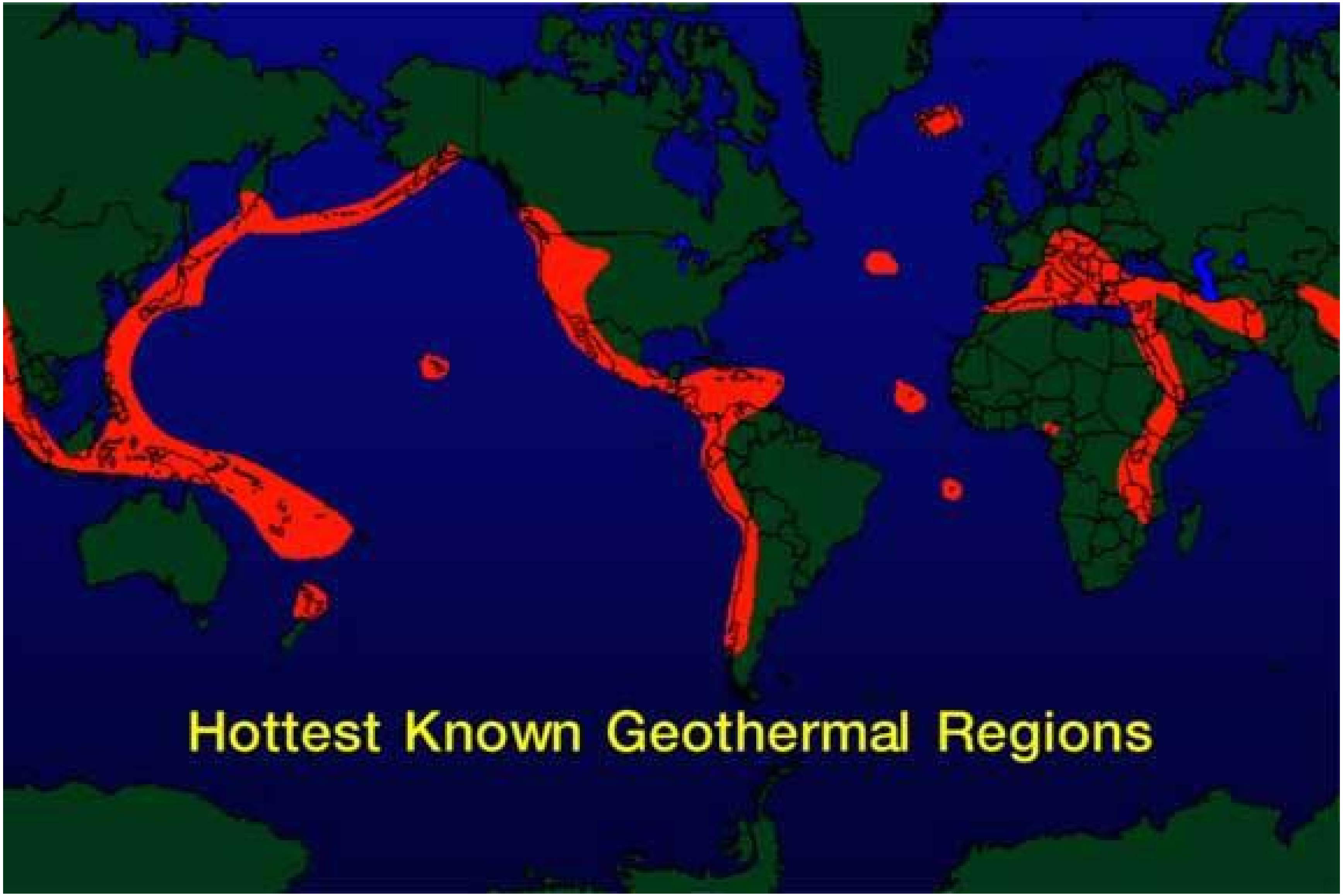
Pruess (May 19, 2010)

US Geothermal Resources



Courtesy: GreenFire Energy [Higgins 2016]

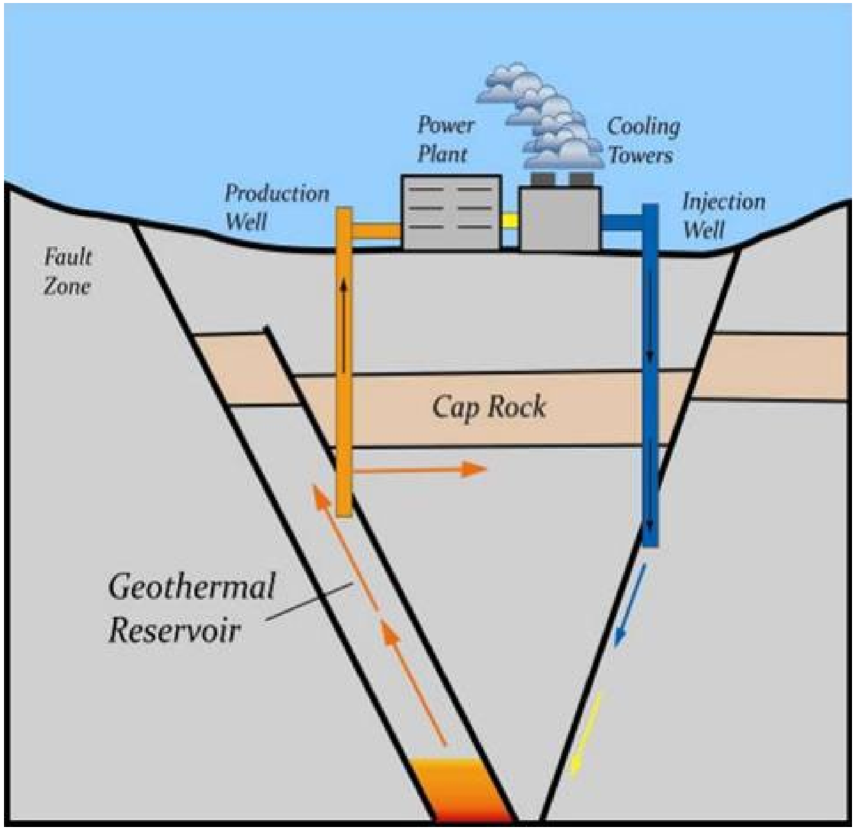
Global Geothermal Resources



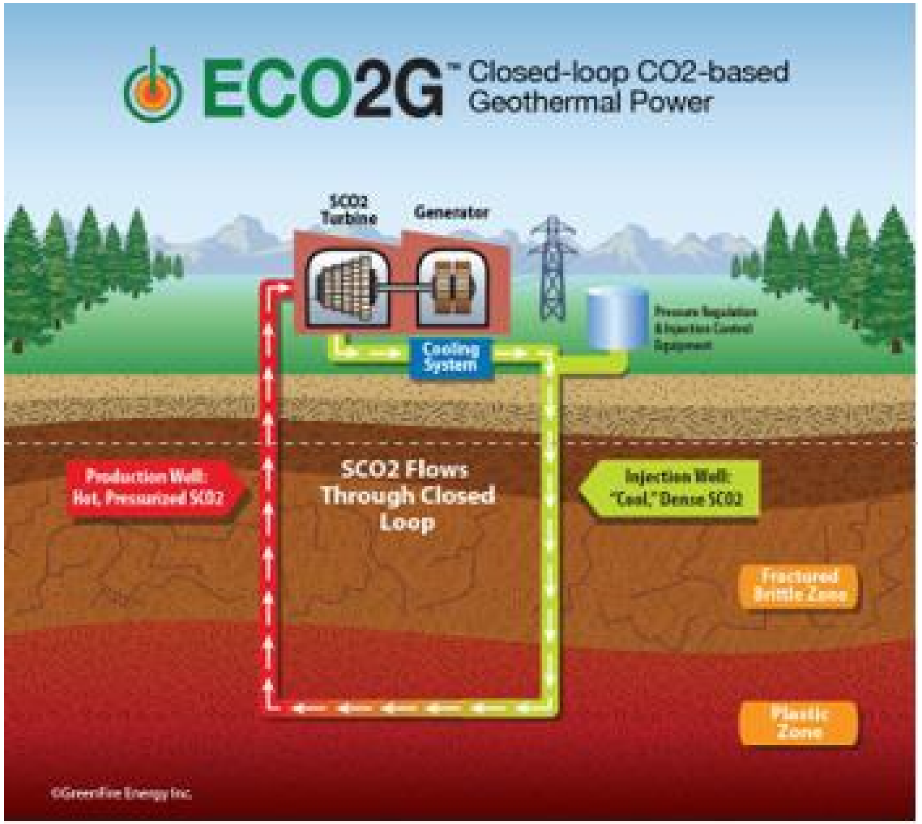
Courtesy: GreenFire Energy [Higgins 2016]

ECO2G

Conventional Hydrothermal

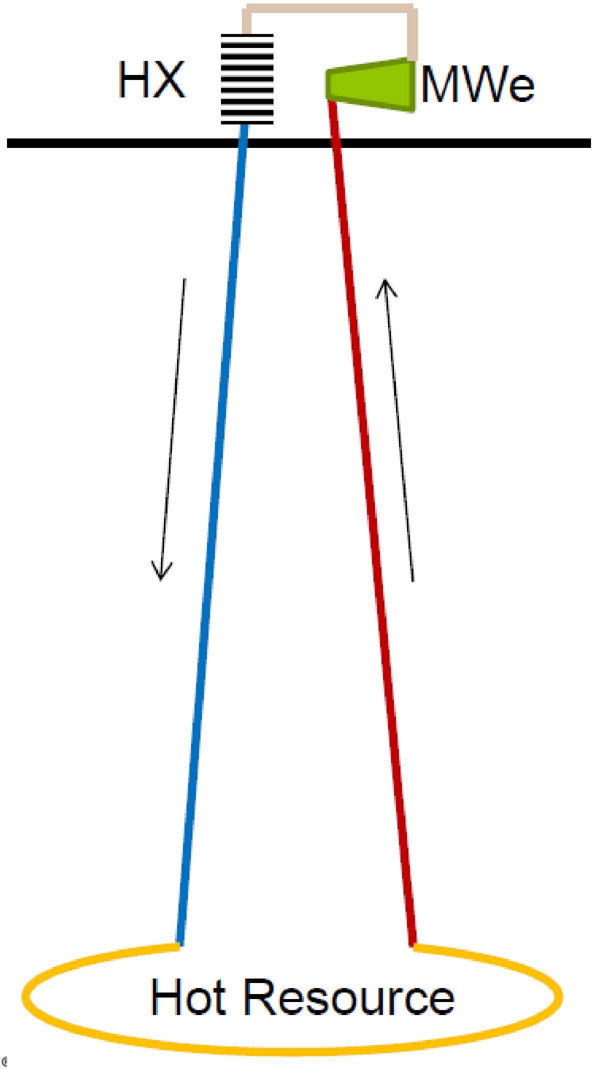


Closed-Loop Supercritical CO_2

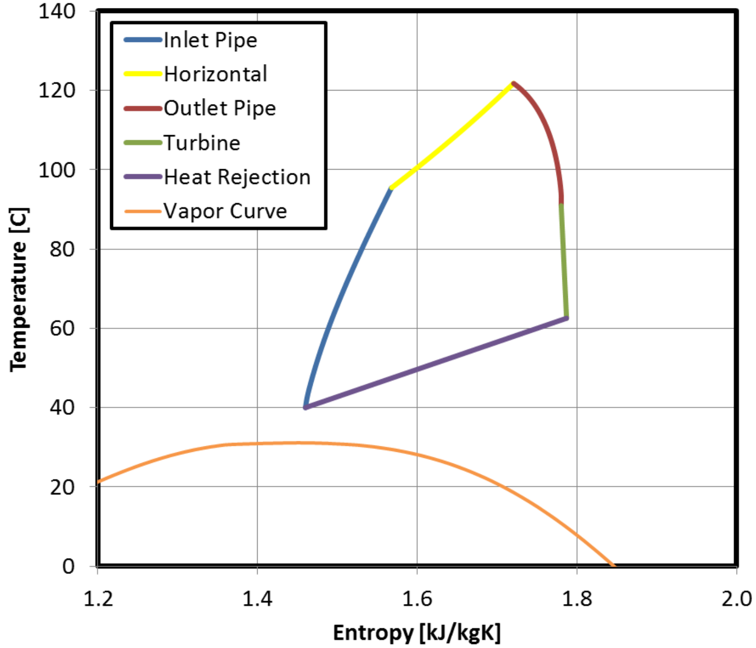


Courtesy: GreenFire Energy [Higgins 2016]

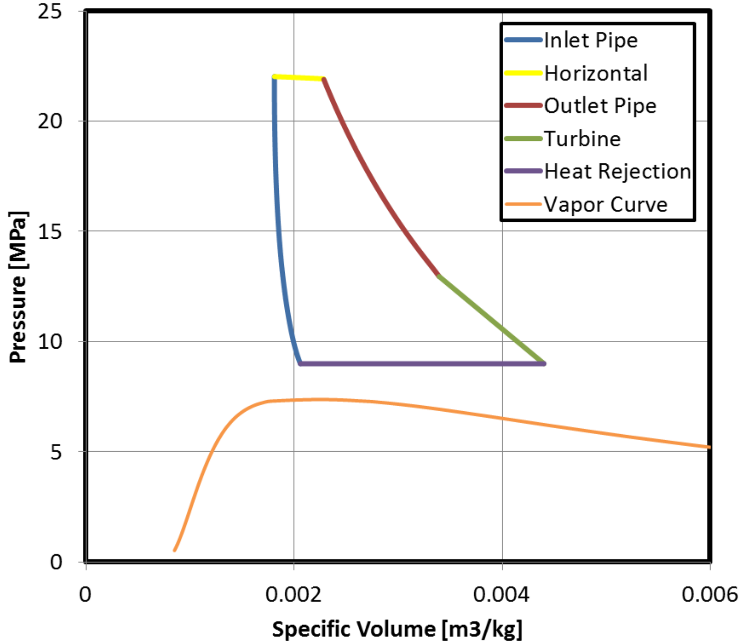
P-v & T-s Diagram



T-s

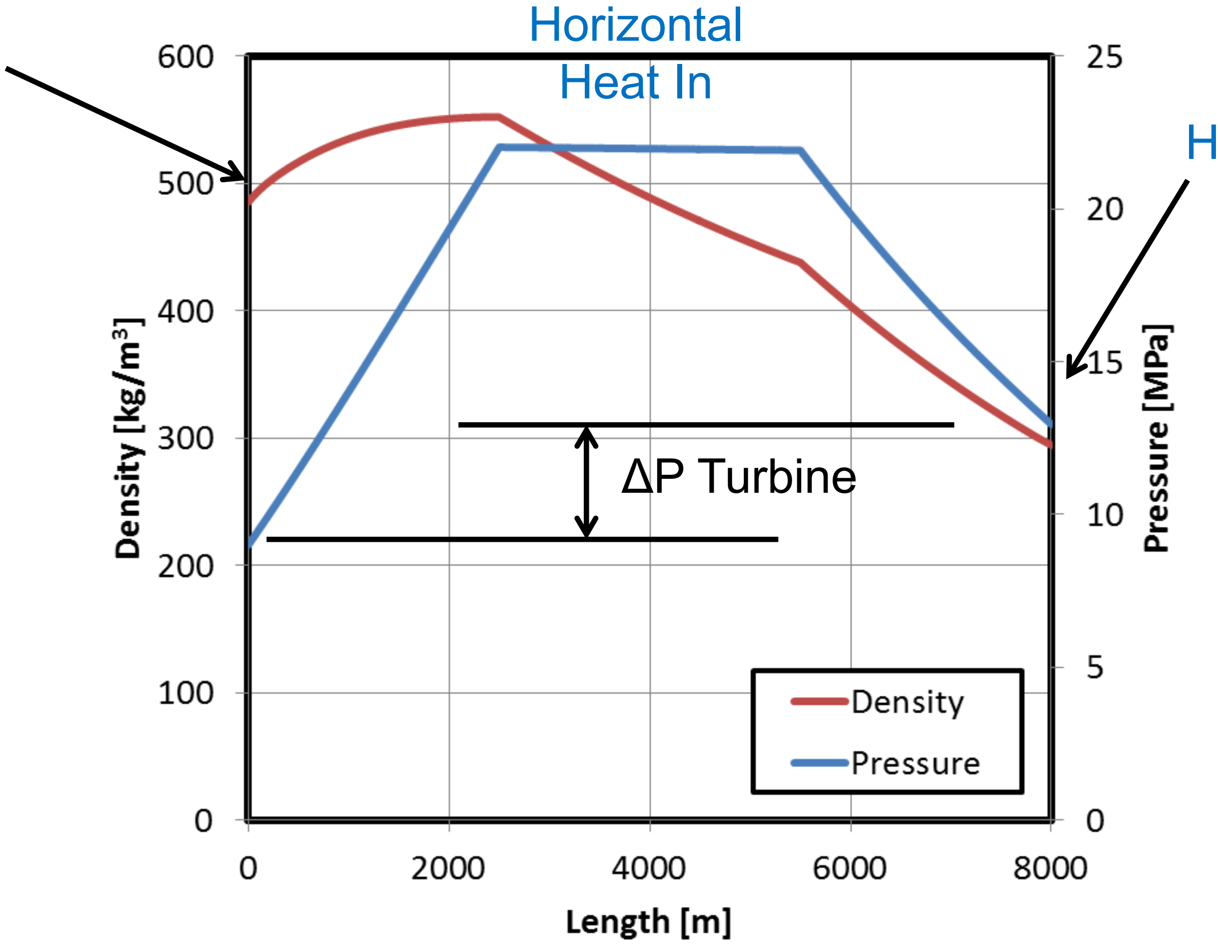


P-v



Courtesy: GreenFire Energy [Higgins 2016]

How does a Thermosiphon Work



Cold Gas In

Horizontal Heat In

Hot Gas Out

Courtesy: GreenFire Energy [Higgins 2016]

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

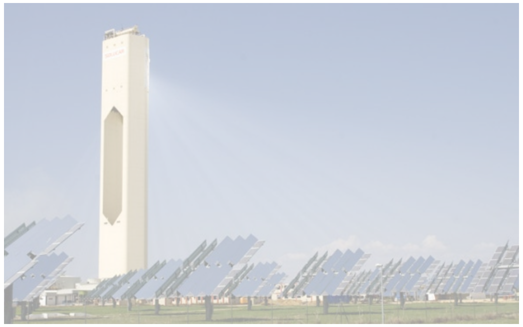
Benefits of sCO_2 Based Geothermal

- 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 sCO_2 goethermal

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

Supercritical CO_2 in Power Cycle Applications

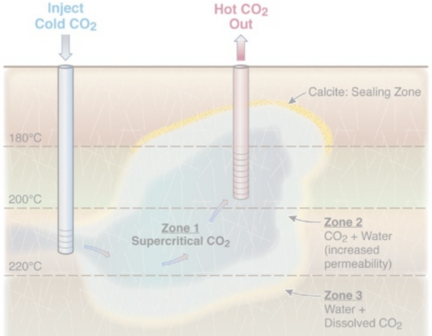


[6-1]

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. sCO2 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]

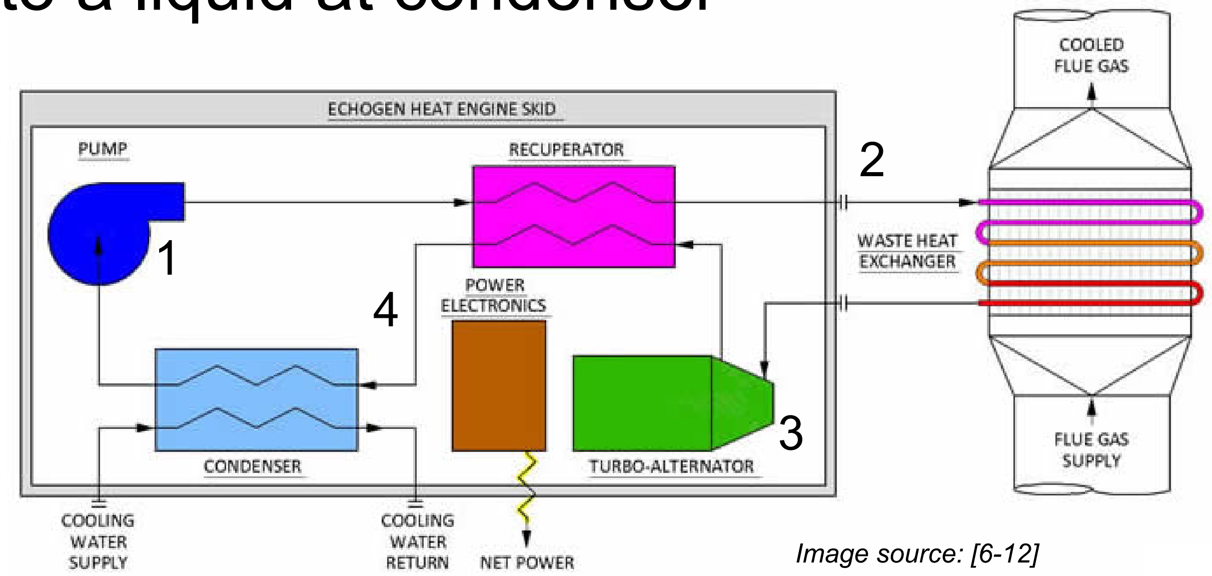
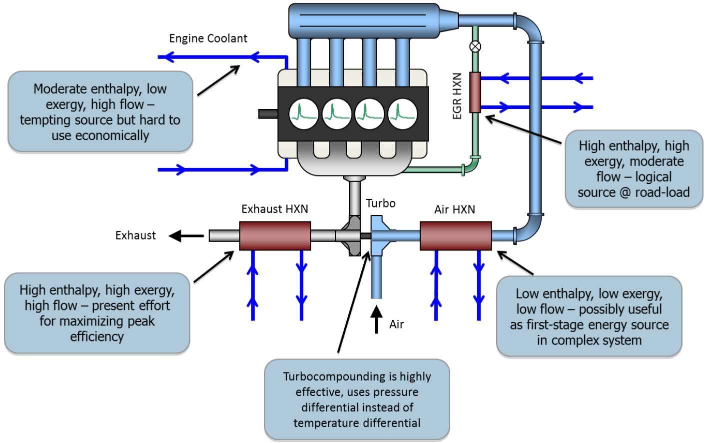


Image source: [6-12]

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



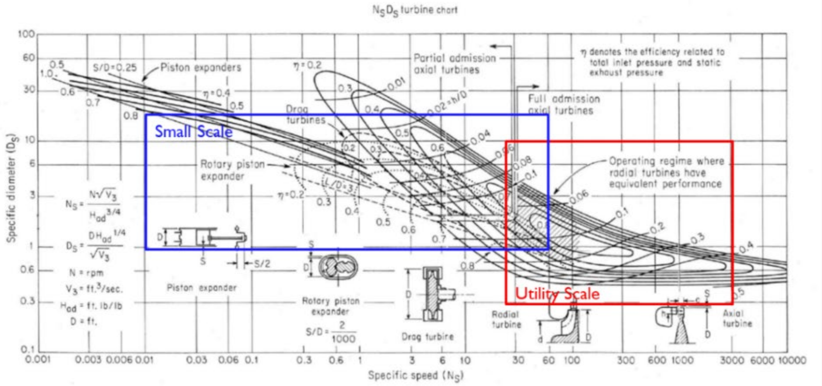
Moderate enthalpy, low exergy, high flow – tempting source but hard to use economically

High enthalpy, high exergy, moderate flow – logical source @ road-load

High enthalpy, high exergy, high flow – present effort for maximizing peak efficiency

Low enthalpy, low exergy, low flow – possibly useful as first-stage energy source in complex system

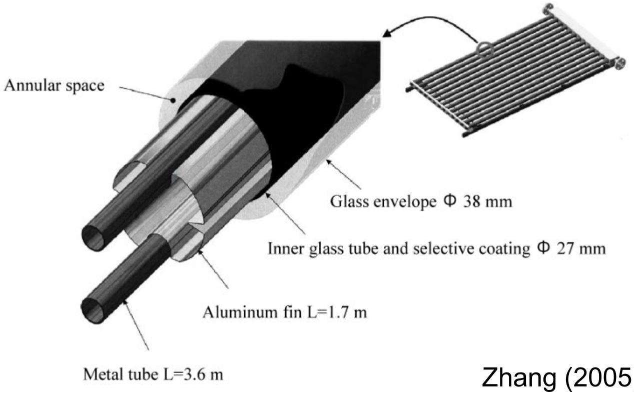
Turbocompounding is highly effective, uses pressure differential instead of temperature differential



Key challenges to sCO_2 bottoming cycles

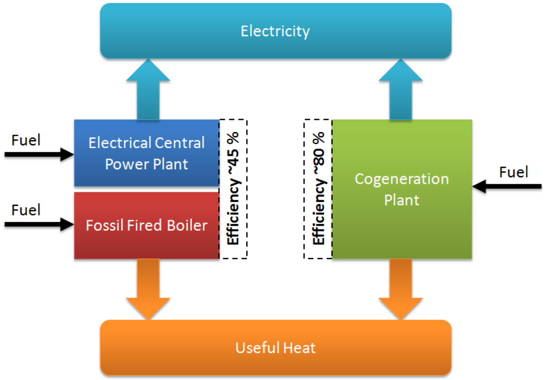
- ❑ Efficiencies and costs must compete with with steam/ORC at relevant temperatures
- ❑ Unproven technology must move into a field with proven WHR solutions (steam/ORC)
    - Since WHR is not the primary asset in nearly any implementation, shutting down production or heat generation for an unproven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

Other sCO_2 Power Cycle Applications



Zhang (2005)

Non-Concentrated Solar Power


Electricity

Fuel

Electrical Central Power Plant

Fuel

Fossil Fired Boiler

Efficiency ~45 %

Efficiency ~80 %

Cogeneration Plant

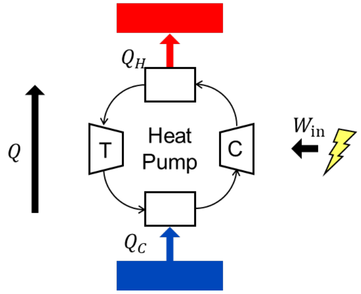
Fuel

Useful Heat

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

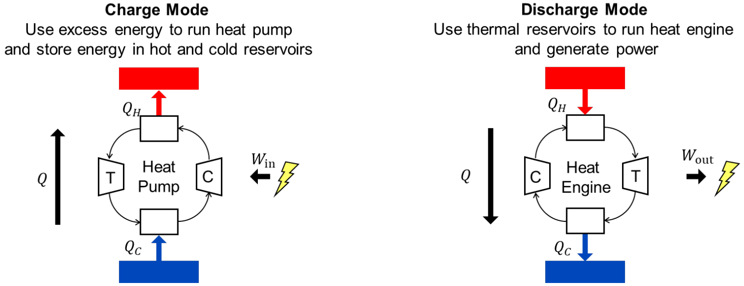
- Up to 50-70% RTE
- No geographical constraints
- Leverages many existing technologies
- Safer than other Thermal ES

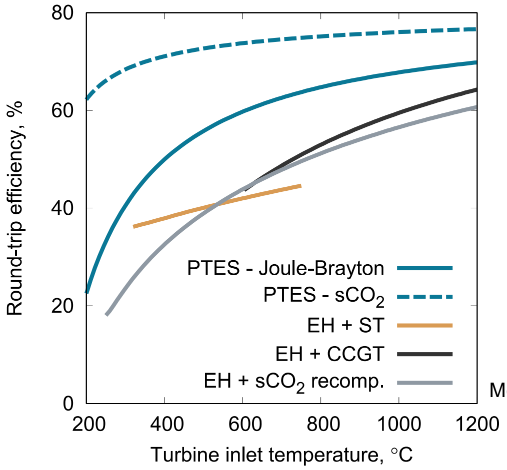
Theoretically, sCO2 PTES has the potential out-perform ideal gas based PTES (in terms of RTE)

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

Developing technology area

- Echogen
- Heliogen
- MAN





McTigue (2019)

Future Trends for sCO_2 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 sCO_2

Pulsation analysis

- ❑Development of transient pipe flow analysis models for sCO_2

Future trends and research needs

Control System and Simulation

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

Fluid properties

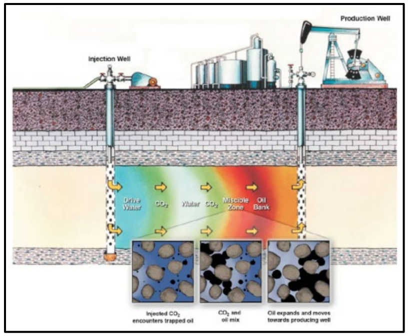
- ❑Mixture of sCO_2 and other fluids
- ❑Physical property testing of CO_2 mixtures at extreme conditions with significantly reduced uncertainties (i.e. $\leq$ 1%)

10 MW Scale Pilot Plant

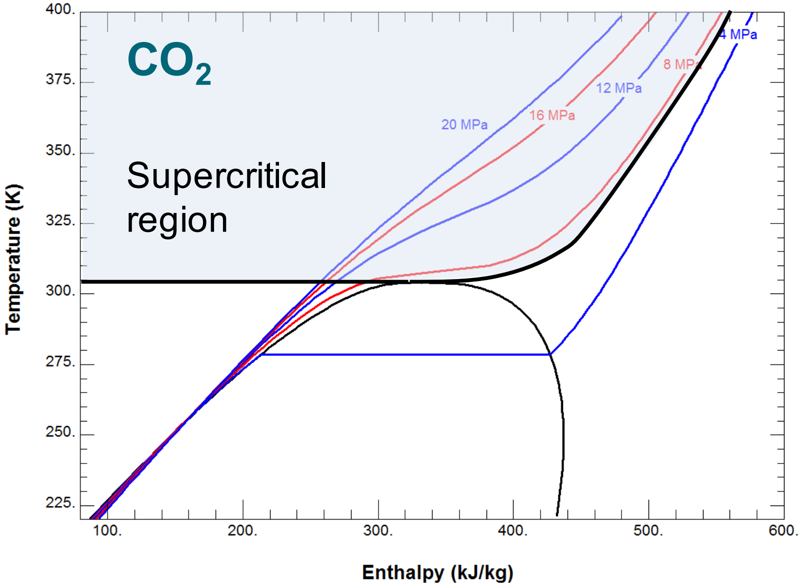
Summary

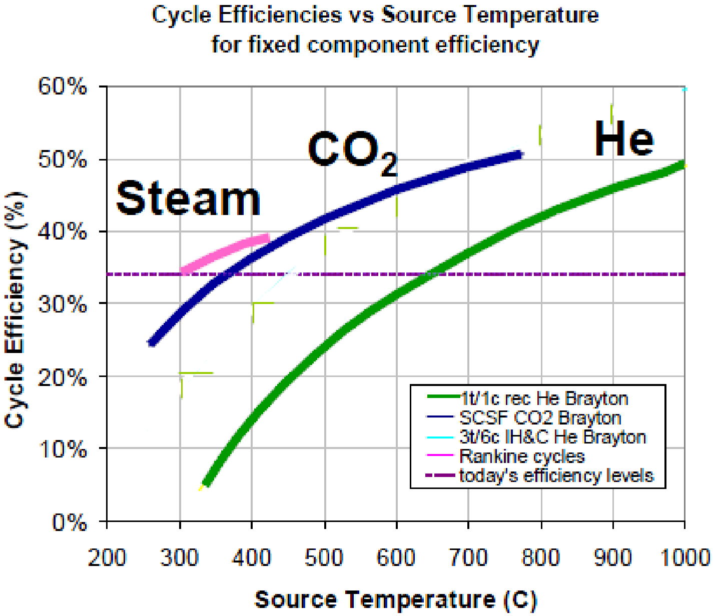
Both supercritical power cycles and the use of sCO_2 are not new concepts

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

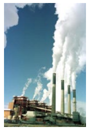


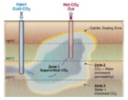


sCO_2 power cycles can be applied to many heat sources and have a small footprint

The near ambient critical temperature of CO_2 allows it to be matched with a variety of thermal heat sources

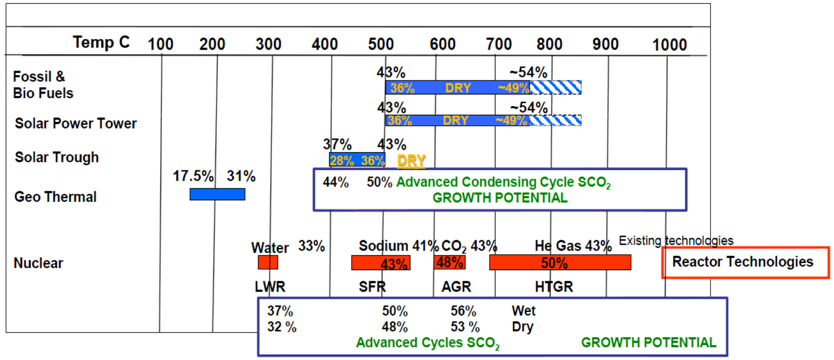

Concentrated Solar Power


Fossil Fuel

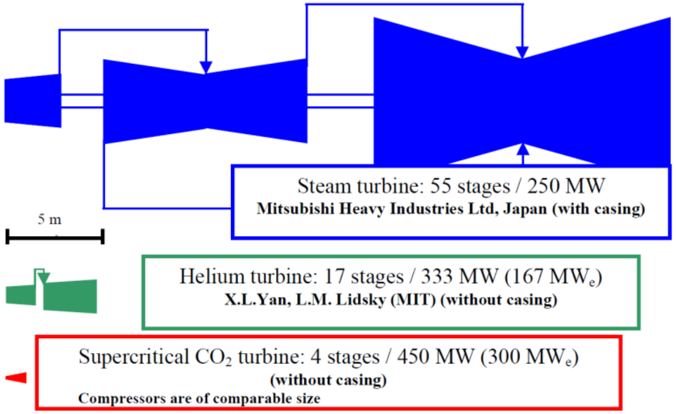

Geothermal


Nuclear


Ship-board Propulsion



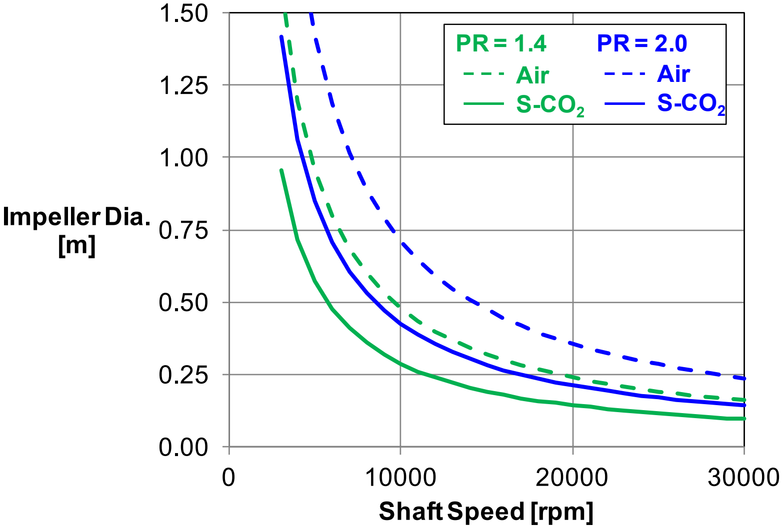
The combination of favorable property variation and high fluid density of sCO_2 allows small footprint of machinery



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

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

Supercritical CO_2 turbine: 4 stages / 450 MW (300 MW_e)
(without casing)
Compressors are of comparable size



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

International sCO_2 power cycle research is ongoing

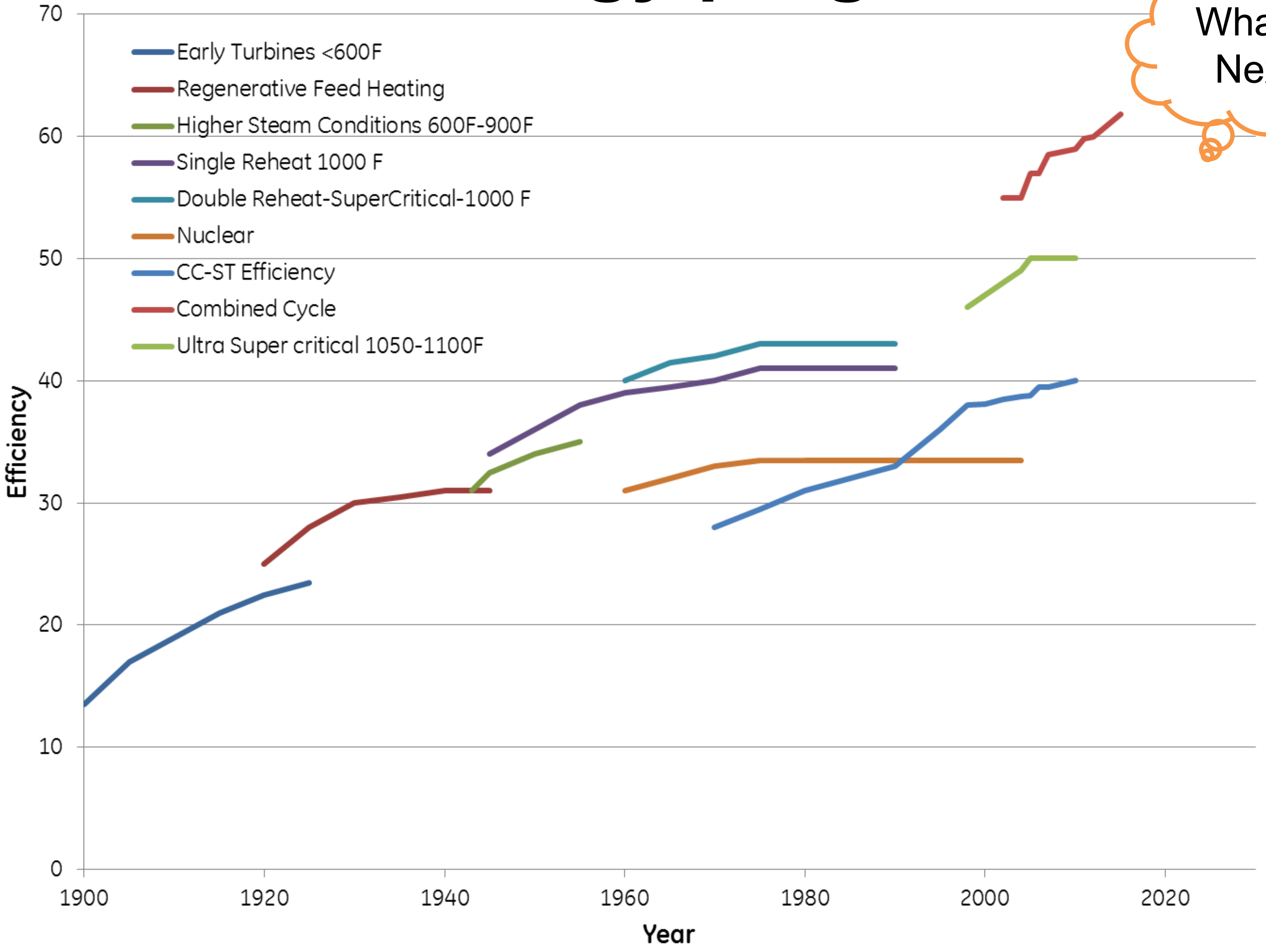
- Power production test loops
- Machinery component test loops
- Materials corrosion test facilities
- Fluid property testing

More research is needed sCO_2 power cycle applications

- Intermediate scale (10MW) demonstration
- Materials testing at high temperature, pressure and stress
- Property testing with sCO_2 mixtures
- Rotordynamics with sCO_2
- sCO_2 heat transfer and heat exchangers
- More detailed dynamic simulation and control systems

Questions?

How has technology progressed



What's Next

[Bowman 2016]