Tutorial:
Fundamentals of Supercritical CO_2

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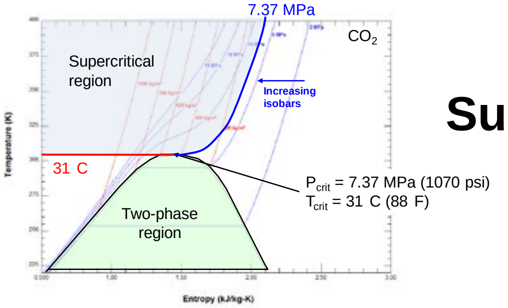
Abstract

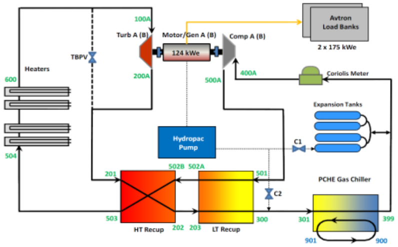
The recent interest to use supercritical CO_2 (sCO_2) in power cycle applications over the past decade has resulted in a large amount of literature that focuses on specific areas related to sCO_2 power cycles in great detail. Such focus areas are demonstration test facilities, heat exchangers, turbomachinery, materials, and fluid properties of CO_2 and CO_2 mixtures, to name a few. As work related to sCO_2 power cycles continues, more technical depth will be emphasized in each focus area, whereas those unfamiliar with the topic are left to undertake the large task of understanding fundamentals on their own.

The following content provides an introductory tutorial on sCO_2 used in power cycle applications, aimed at those who are unfamiliar or only somewhat familiar to the topic. The tutorial includes a brief review of CO_2 and its current industrial uses, a primer on thermodynamic power cycles, an overview of supercritical CO_2 power cycle applications and machinery design considerations, and a summary of some of the current research and future trends.

This tutorial provides an introduction to sCO_2 in power cycle applications



Supercritical CO_2 (sCO_2)



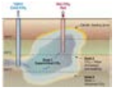
sCO_2 loop hardware


[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

CO_2 is a gas at atmospheric conditions with a concentration of ≈ 400 ppm

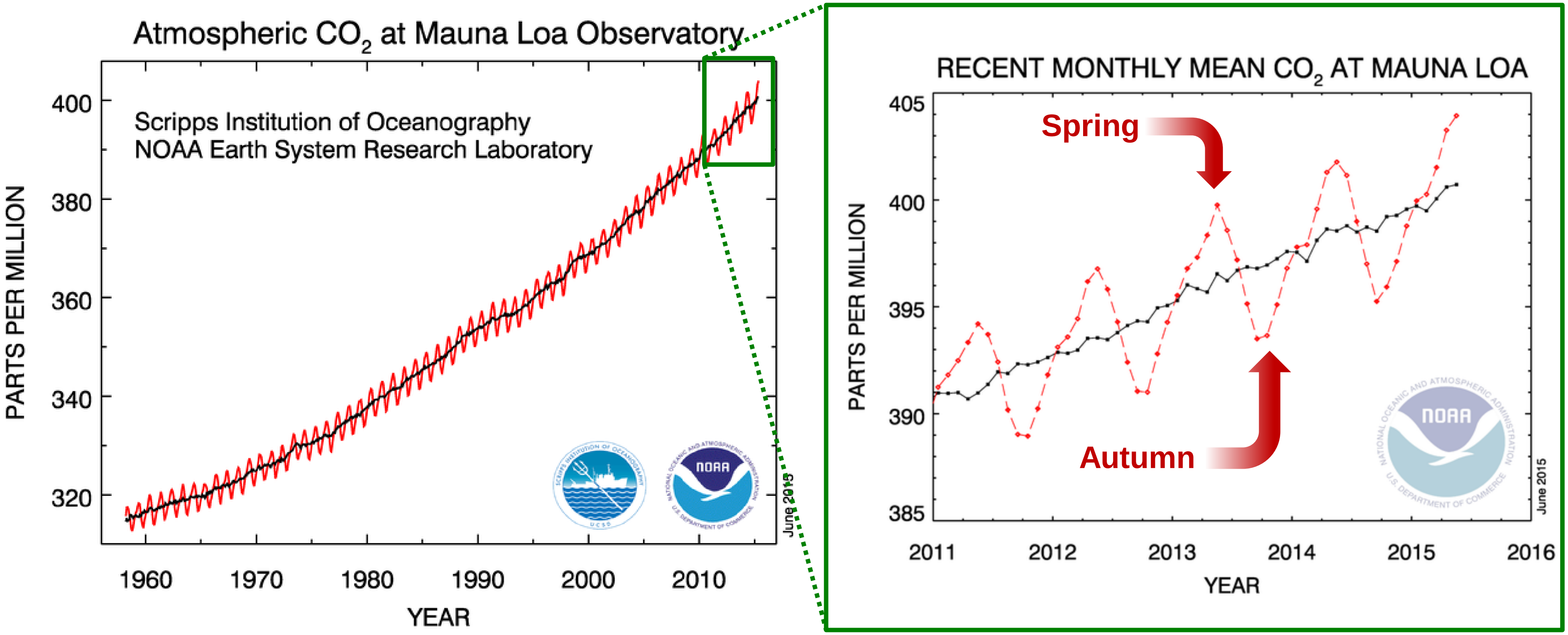


Image source [1-1]

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

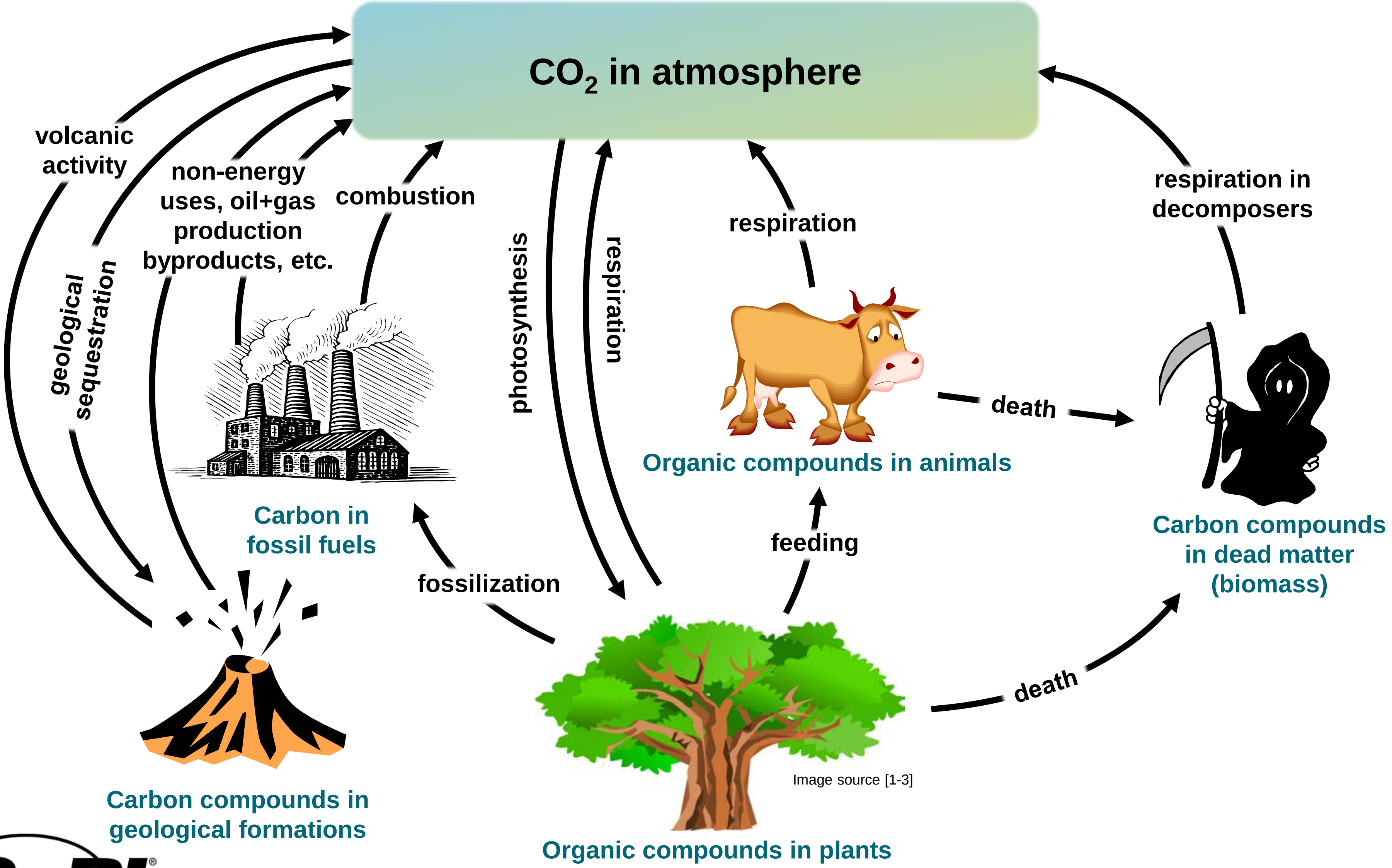
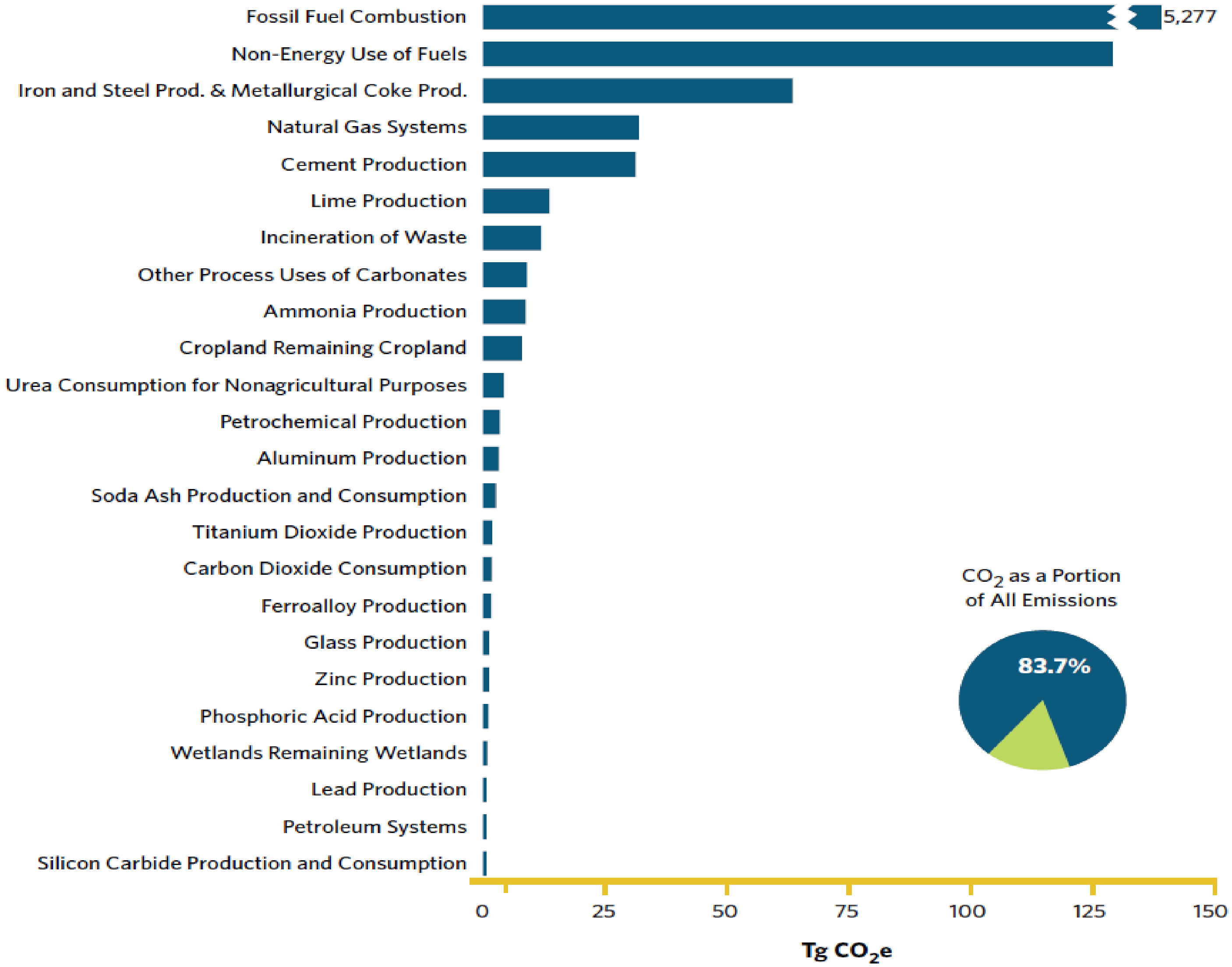


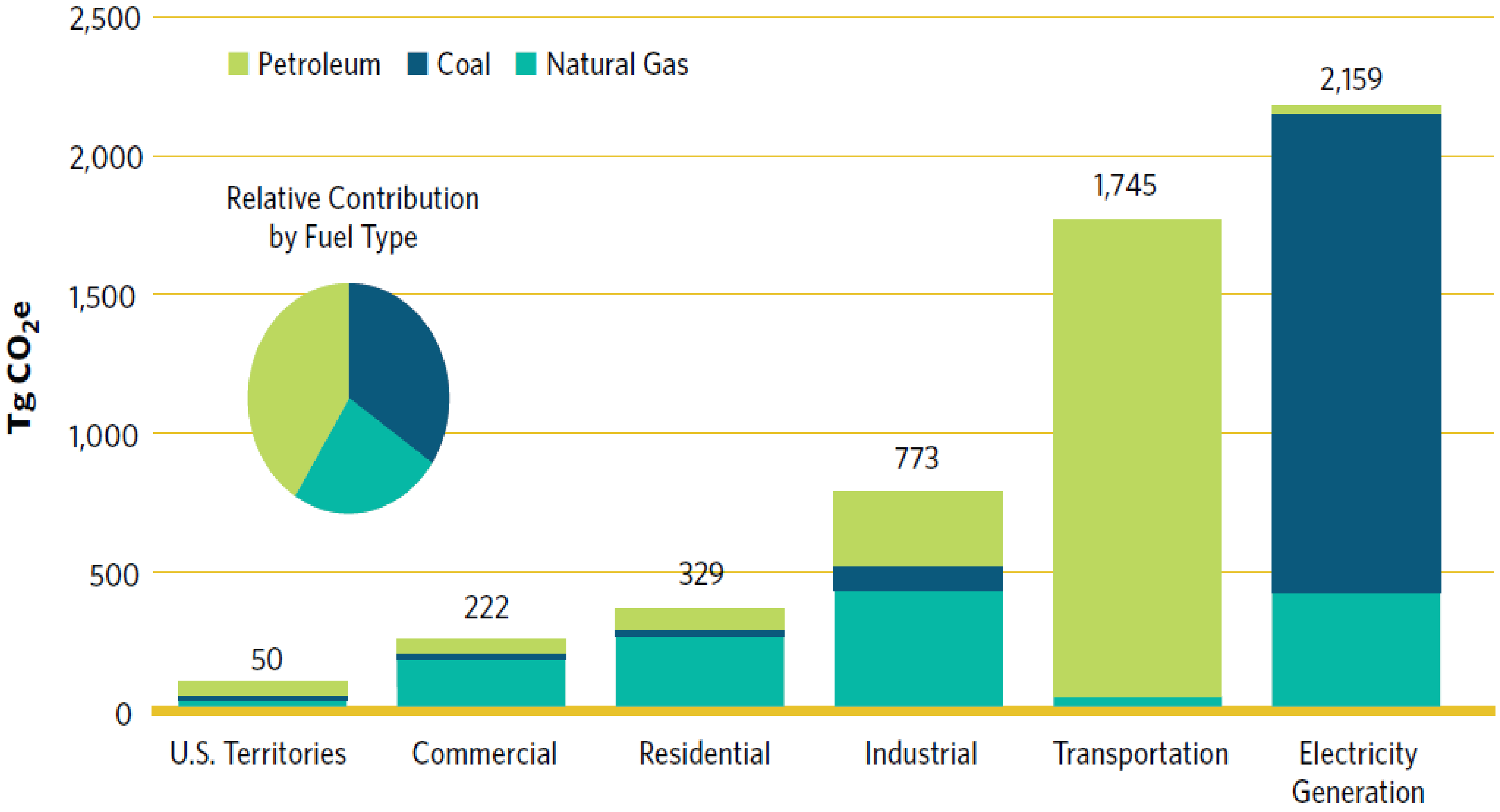
Image source [1-3]

Fossil fuel combustion is the largest industrial contributor to CO_2 production



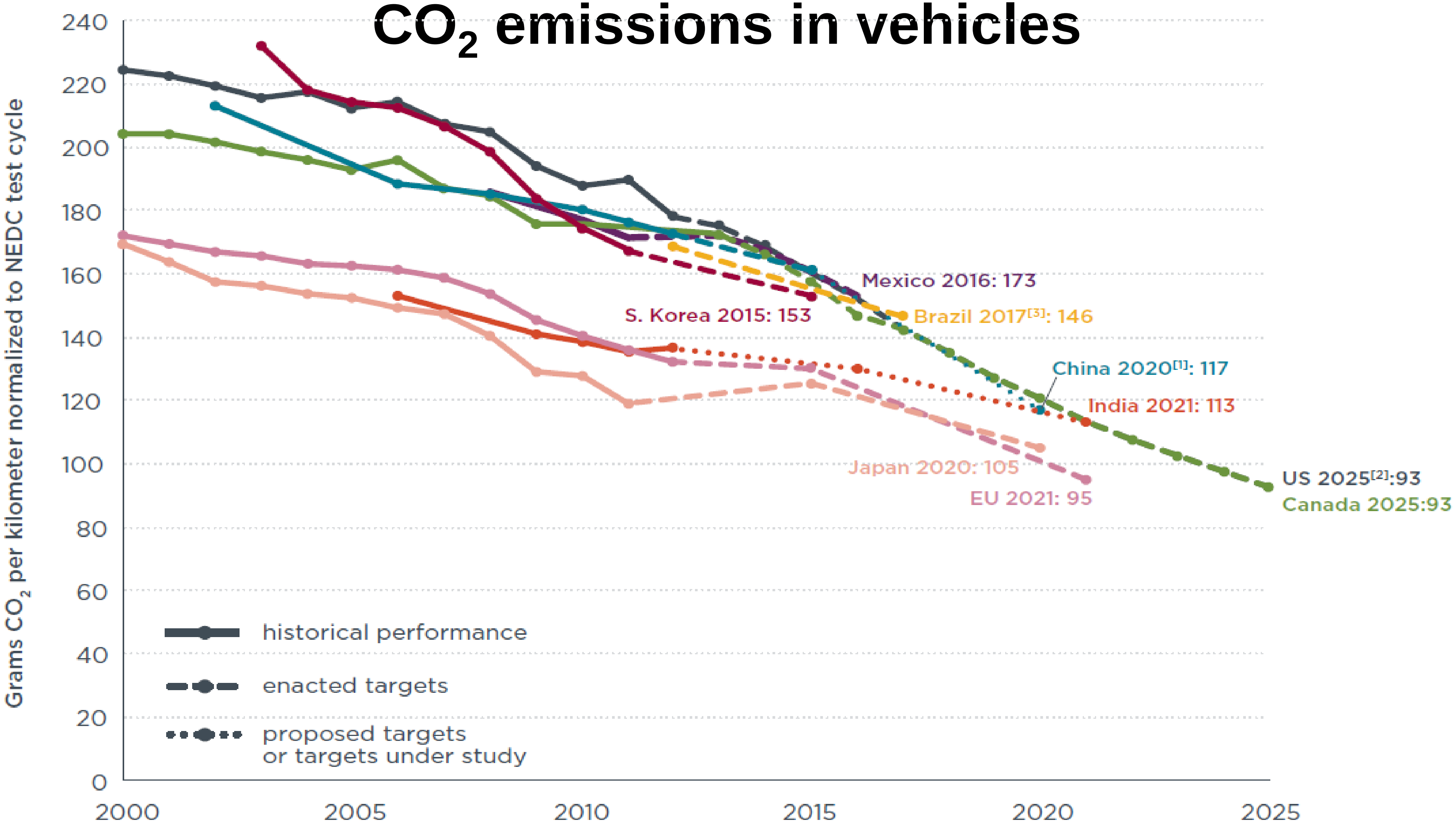
Source: “U.S. Climate Action Report 2014”

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



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

International regulations are continually reducing CO_2 emissions in vehicles



[1] China's target reflects gasoline vehicles only. The target may be higher after new energy vehicles are considered.
[2] US standards GHG standards set by EPA, which is slightly different from fuel economy stadards due to low-GWP refrigerant credits.
[3] Gasoline in Brazil contains 22% of ethanol (E22), all data in the chart have been converted to gasoline (E00) equivalent
[4] Supporting data can be found at: http://www.theicct.org/info-tools/global-passenger-vehicle-standards

Source: International Council on Clean Transportation, Policy Update 2014

CO_2 Industrial Applications

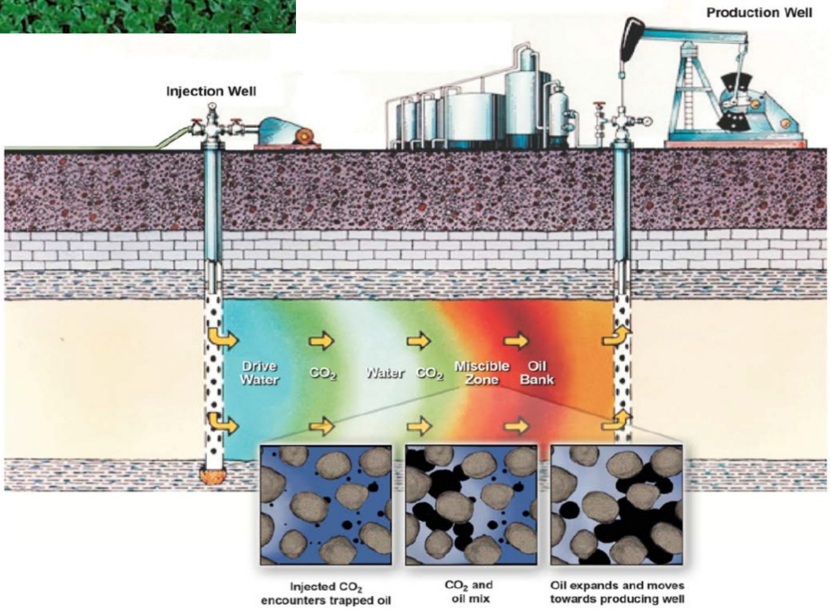
Food & beverage

Agriculture

Welding (shield gas)

Fire extinguishers

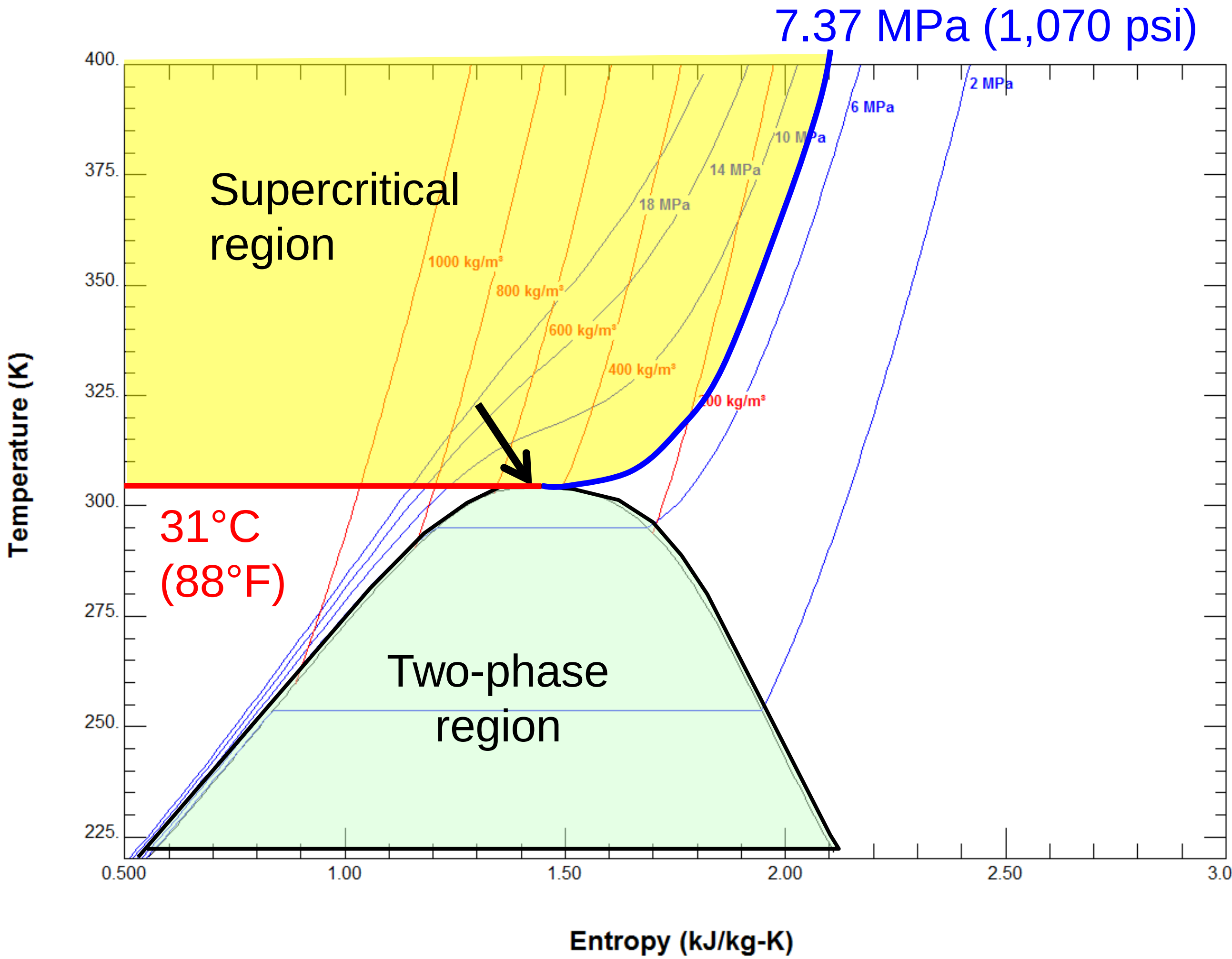
Oil & gas production (more info with sCO_2)



Various image sources [1-4]

What is Supercritical CO_2?

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

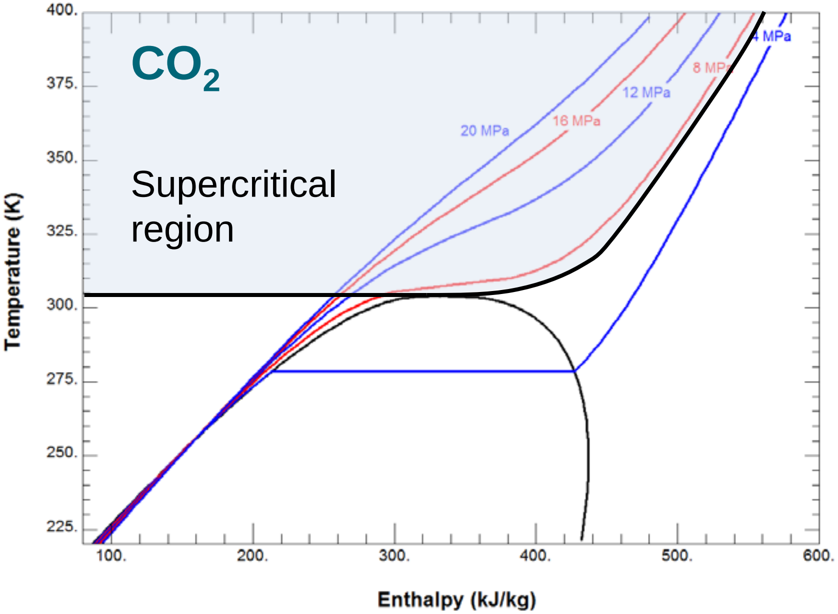


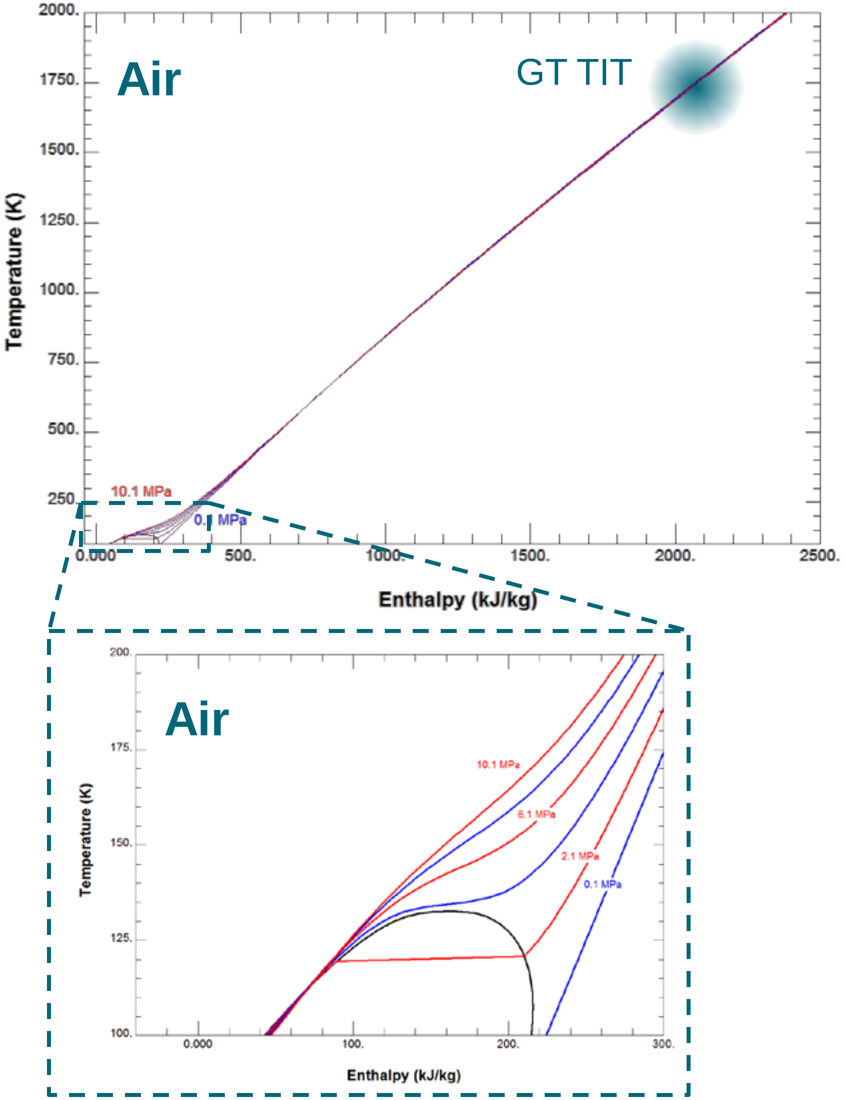
REFPROP (2007), EOS CO_2: Span & Wagner (1996)

Video of Supercritical CO_2

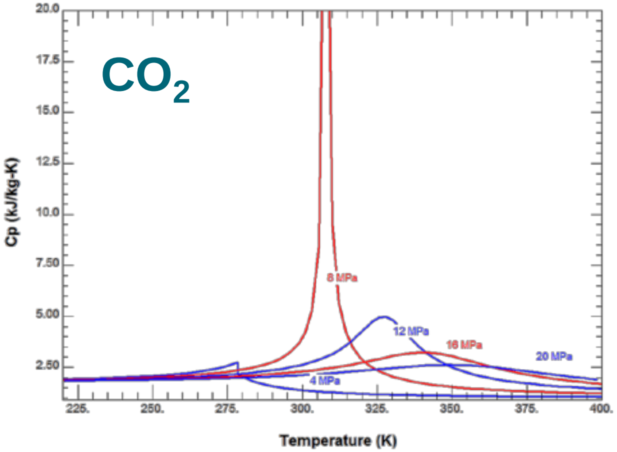
Image source: [2-2]

Fluids operating near their critical point have dramatic changes in enthalpy



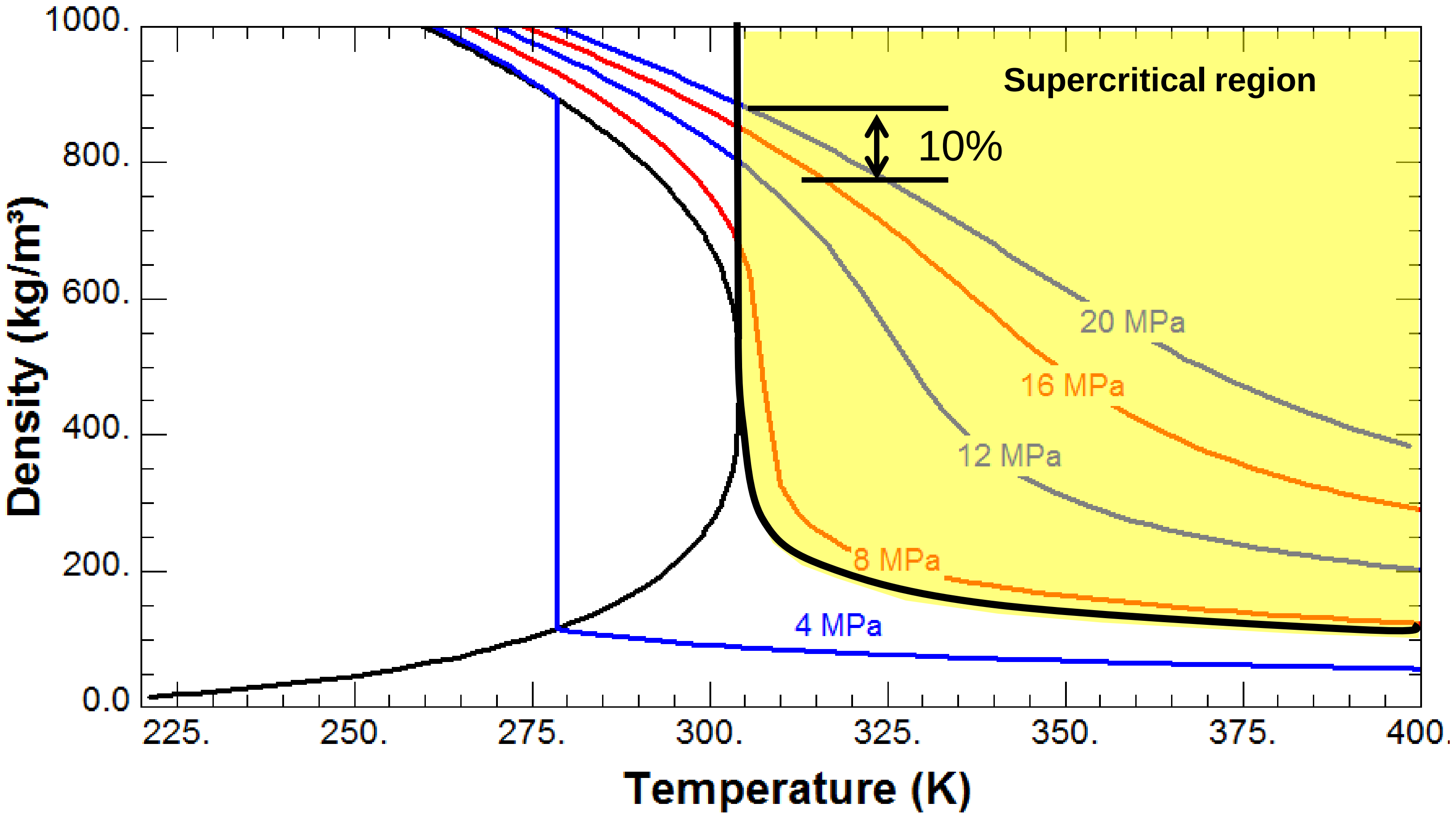


$$C_p = \left.\frac{\partial h}{\partial T}\right)_p$$



REFPROP (2007)

CO_2 density sharply decreases near the critical point



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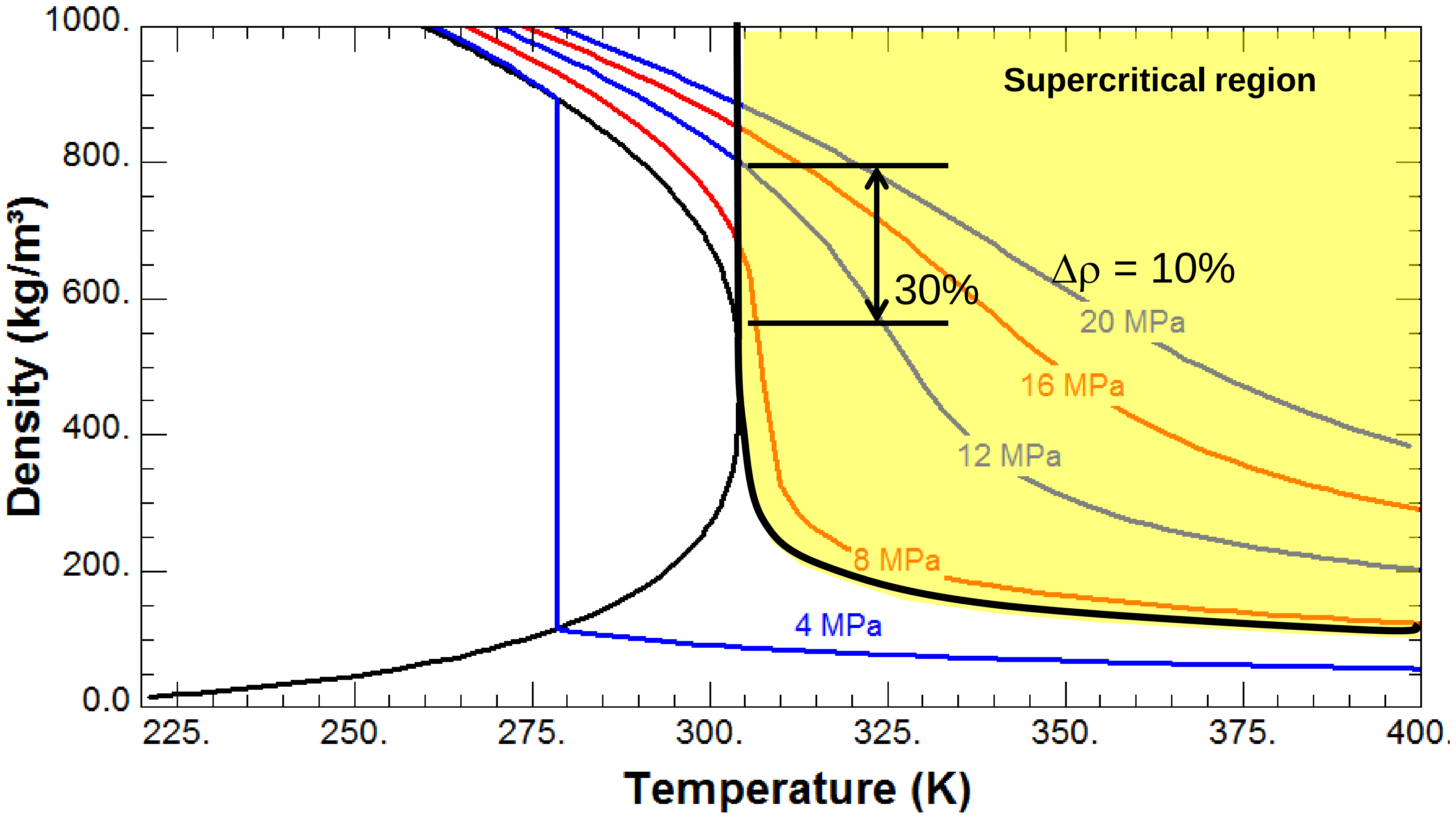

REFPROP (2007)

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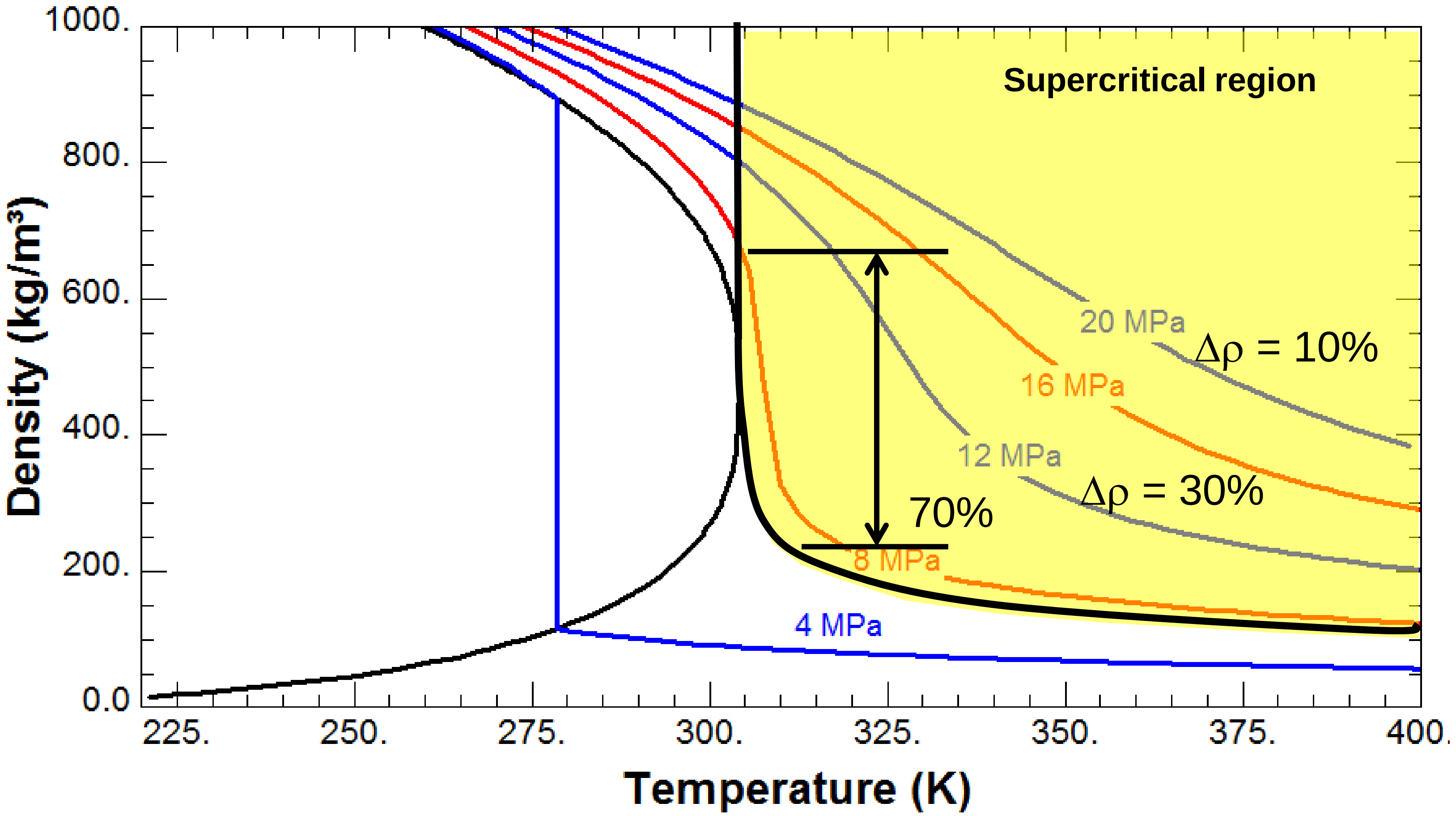
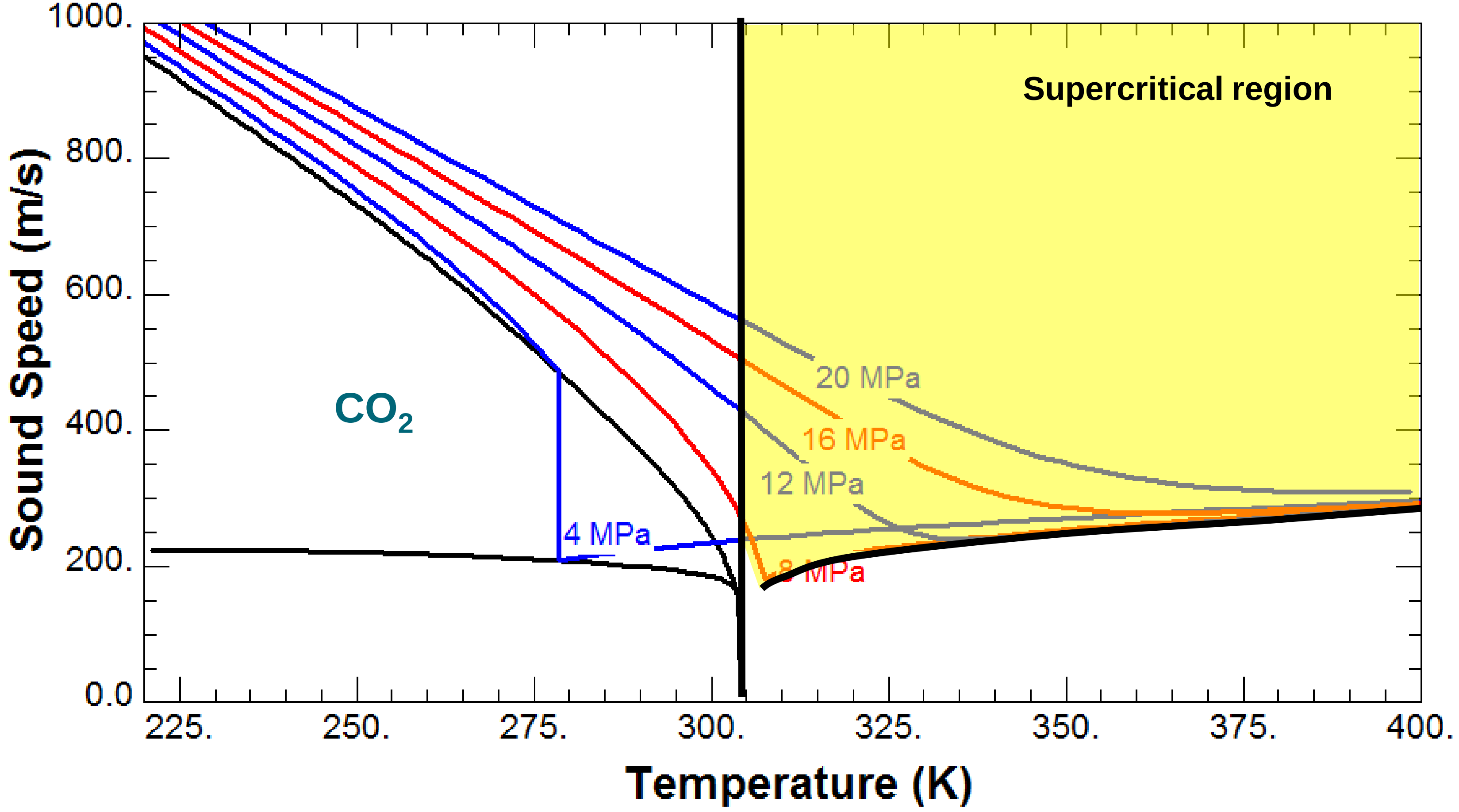


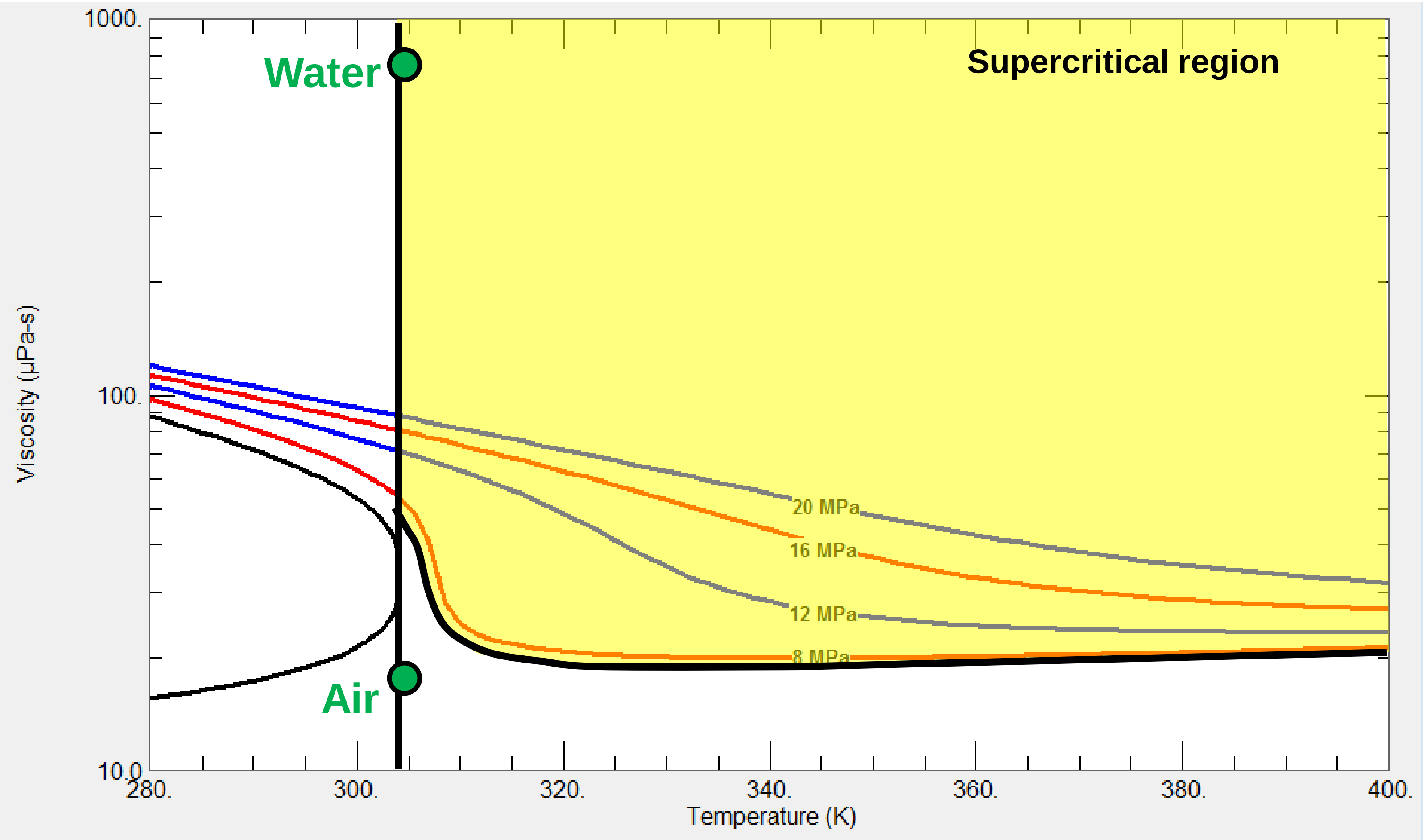
REFPROP (2007)

CO_2 speed of sound decreases through the critical point



REFPROP (2007)

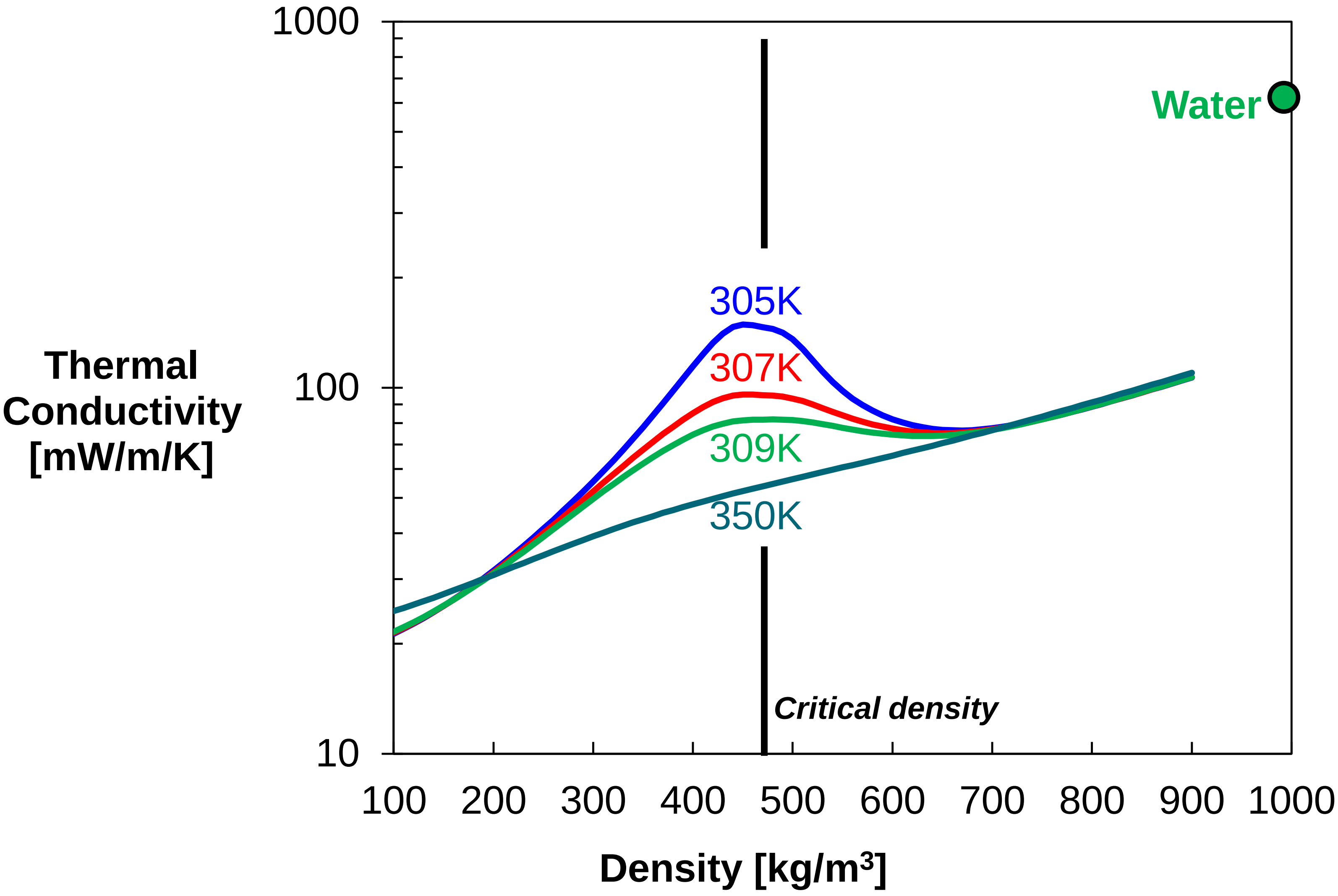
CO_2 viscosity decreases through the critical point



REFPROP (2007)

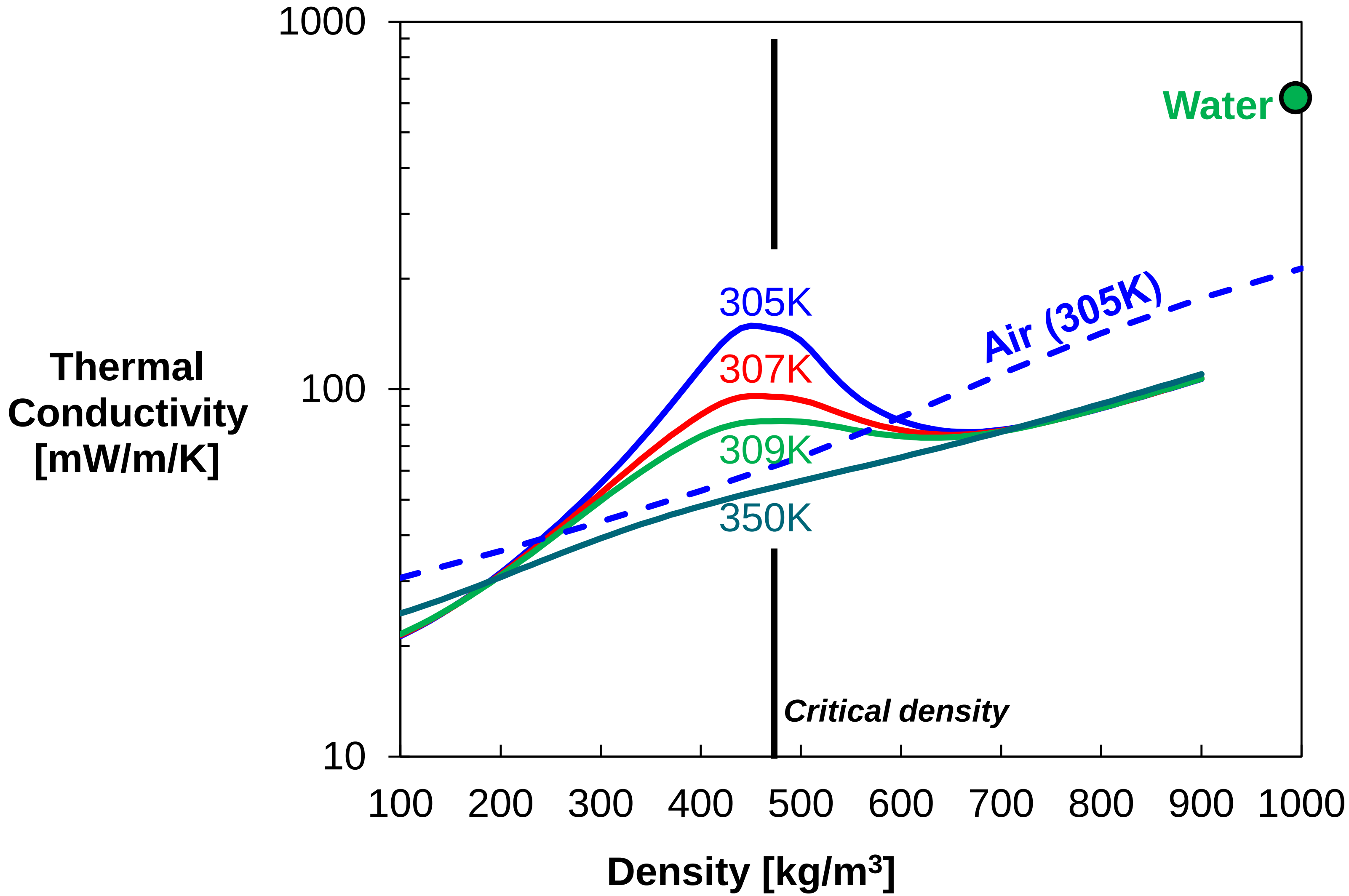
1 µPa-s = 10^{-6} kg/m/s

CO_2 thermal conductivity is enhanced near the critical region



REFPROP (2007)

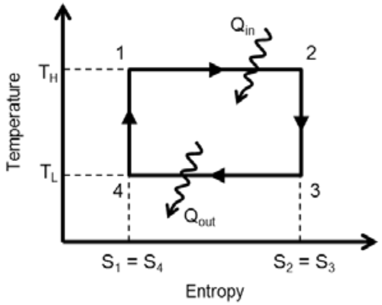
CO_2 thermal conductivity is enhanced near the critical region



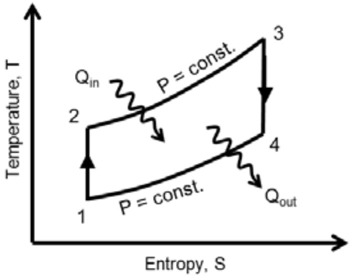
REFPROP (2007)

Power Cycle Basics

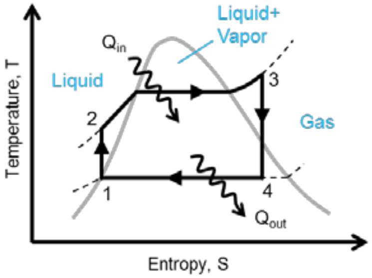
Power Cycle Basics Overview



Carnot – "the standard"



Brayton – gas cycle



Rankine – vapor cycle

Also… *Differences between ideal and actual cycles*

Improvements to simple cycle

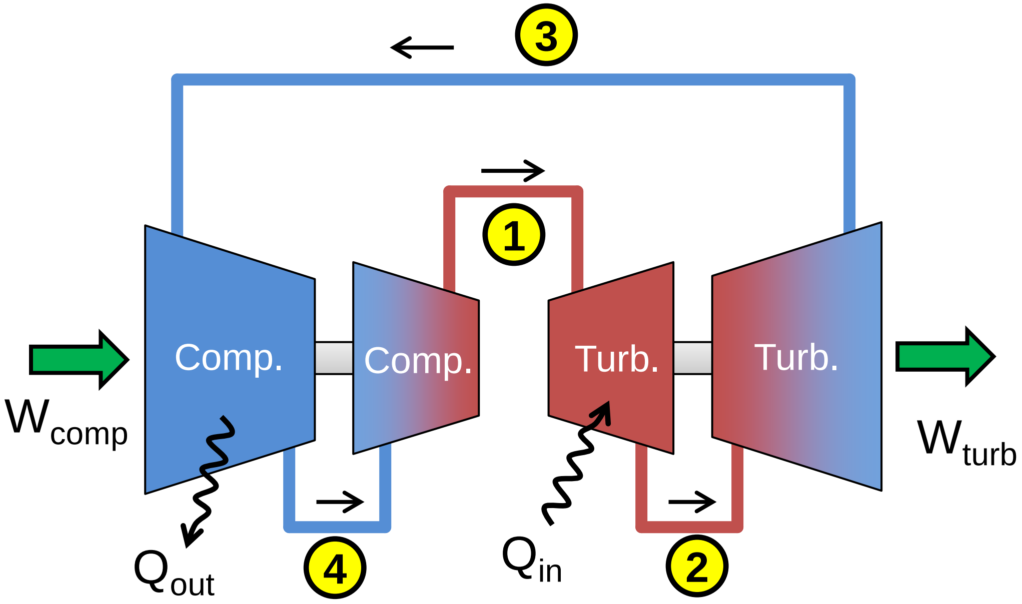
Carnot Cycle

- 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

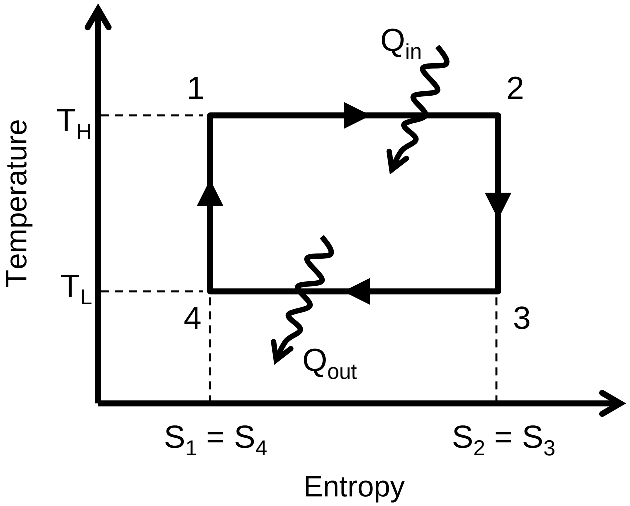
$$\eta_{th,Carnot} = 1 - T_L/T_H$$

↓T_L : Limited by available sink

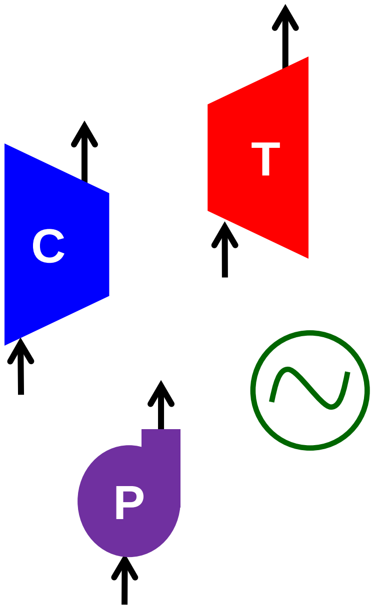
↑T_H : Limited by materials



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



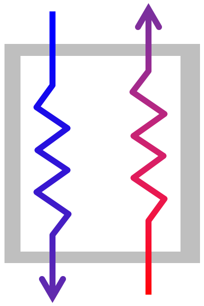
Thermodynamics Aside… 1st Law

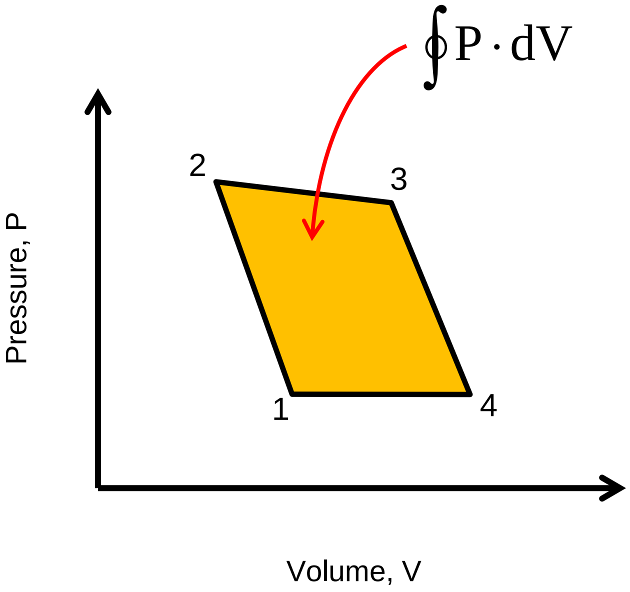


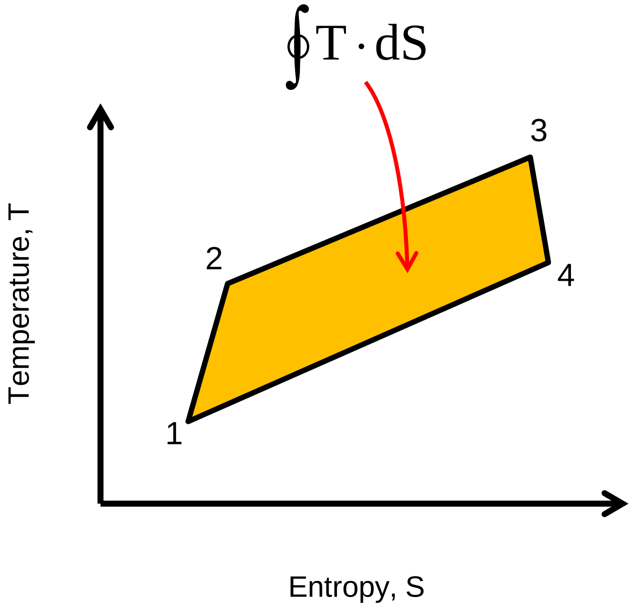
Net Mechanical Work Produced = **Net Heat Utilized**

$$W_{in} - W_{out} = Q_{in} - Q_{out}$$

$$\oint P \cdot dV = \oint T \cdot dS$$







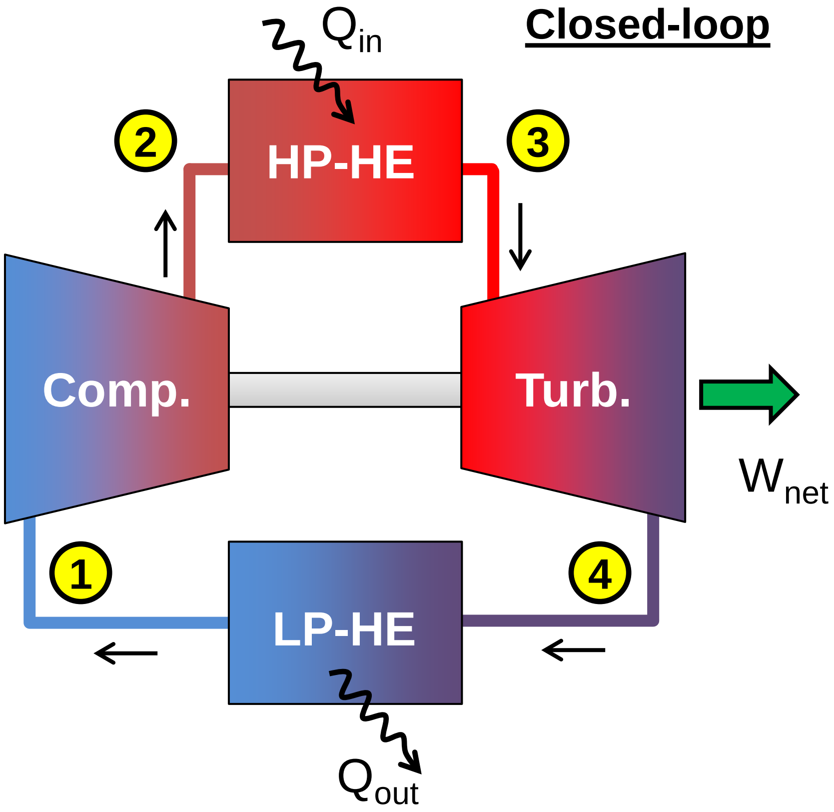
Brayton Cycle (Ideal)

- 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

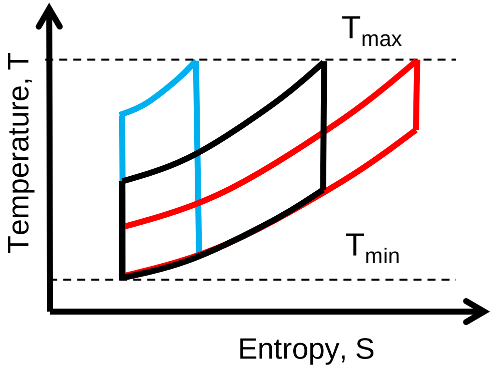
$$\eta_{th,Brayton} = 1 - PR^{(1-k)/k}$$

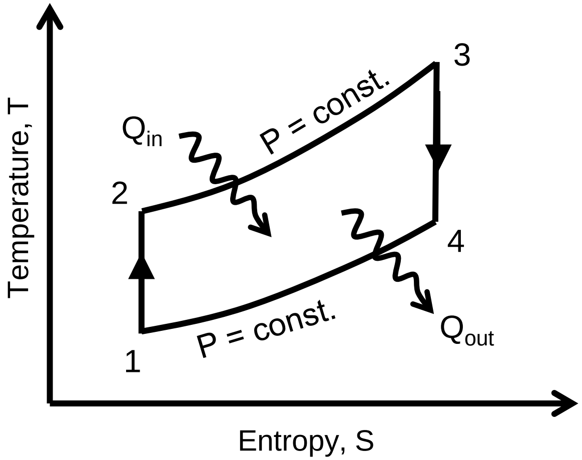
$$\uparrow PR,\ \uparrow k : \uparrow \eta_{th}$$

Closed-loop



Optimal PR for net work

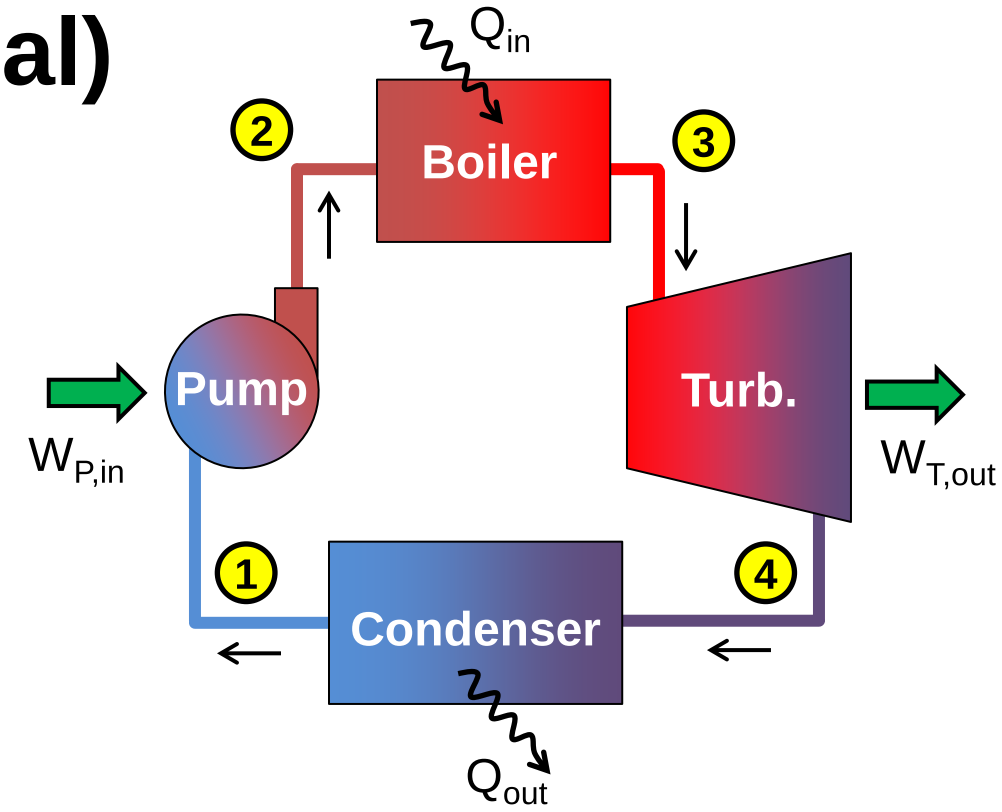


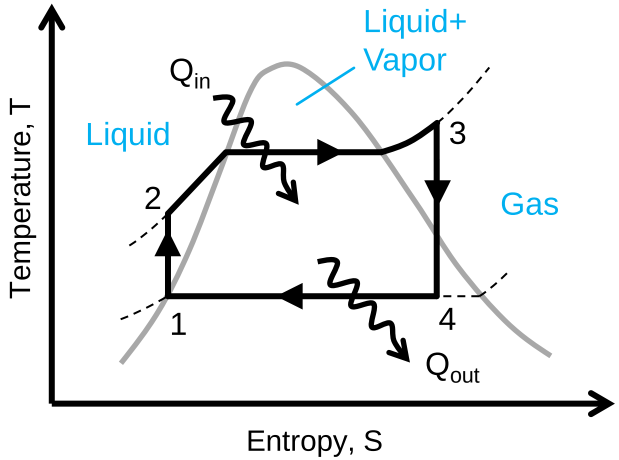


Rankine Cycle (Ideal)

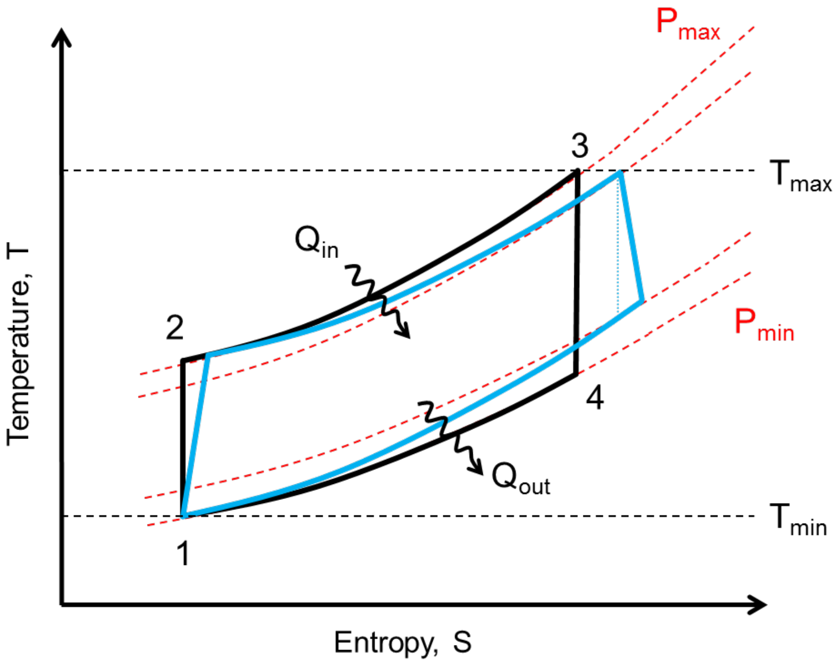
- Processes
  - (1-2) Isentropic compression
  - (2-3) Const. pres. heat addition
  - (3-4) Isentropic expansion
  - (4-1) Const. pres. heat reject.
- Same processes as Brayton; different hardware
- Phase changes
- E.g., steam cycle

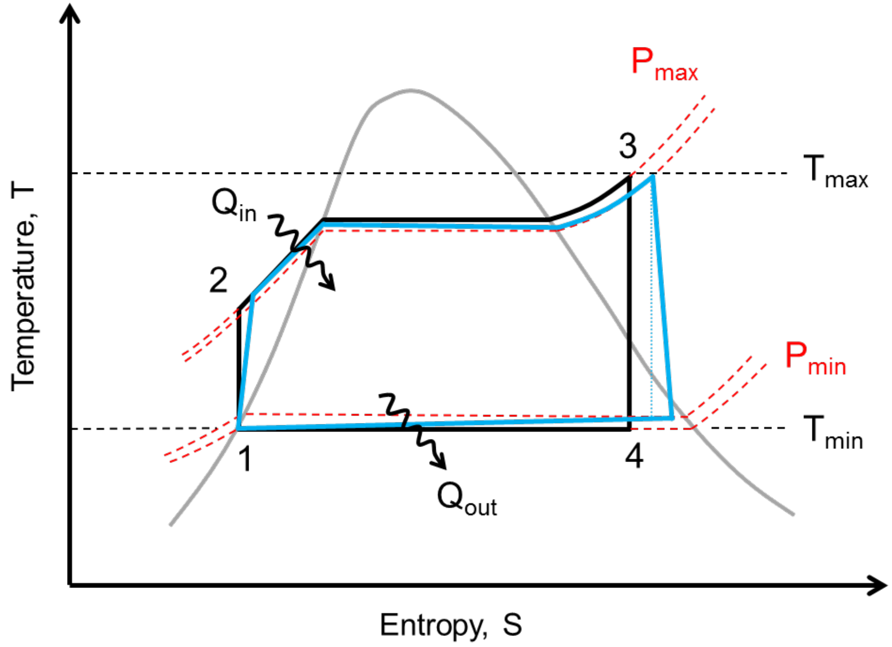
$$\eta_{th} = 1 - Q_{in}/Q_{out}$$





Ideal vs. Actual Processes


Brayton


Rankine

1-2, 3-4: Irreversibilities

2-3, 4-1: Pressure losses

Power Cycle Variations

- ☐ Regeneration
- ☐ Intercooling
- ☐ Reheating
- ☐ Recompression

⋮

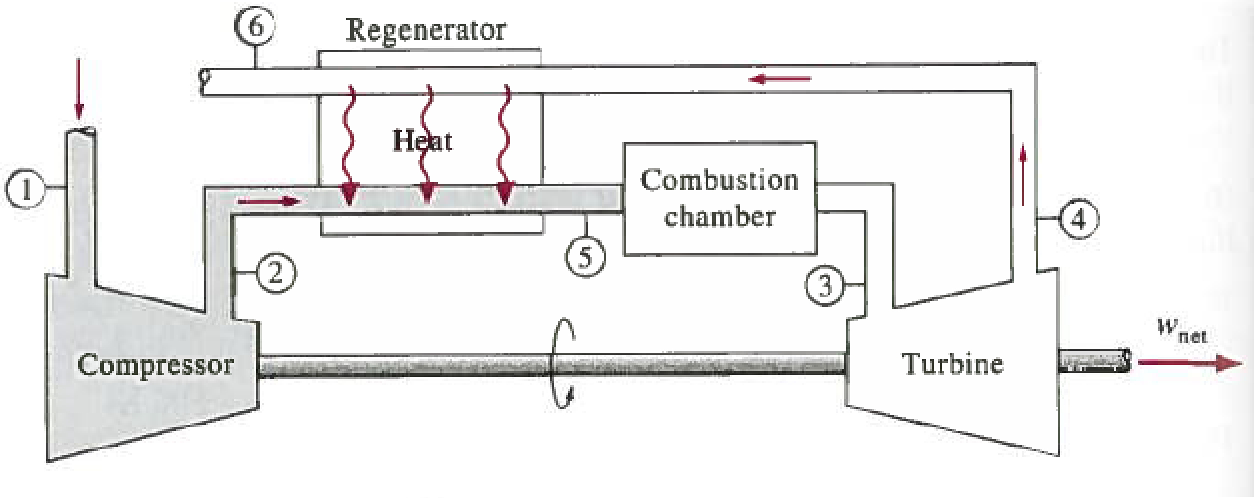
- ☐ What is supercritical power cycle?

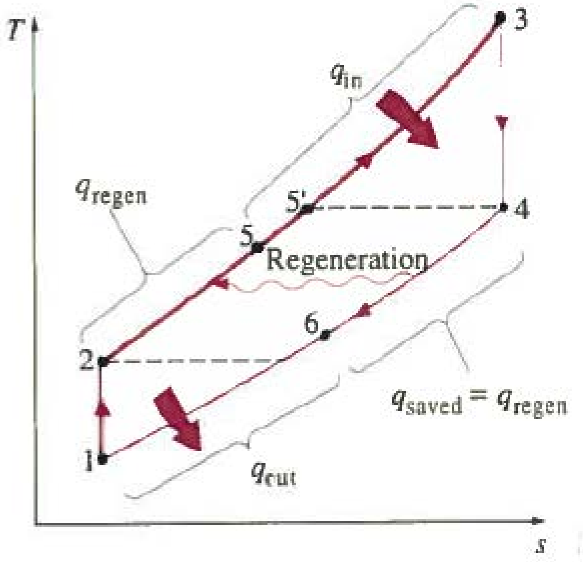
Brayton Cycle + Regeneration

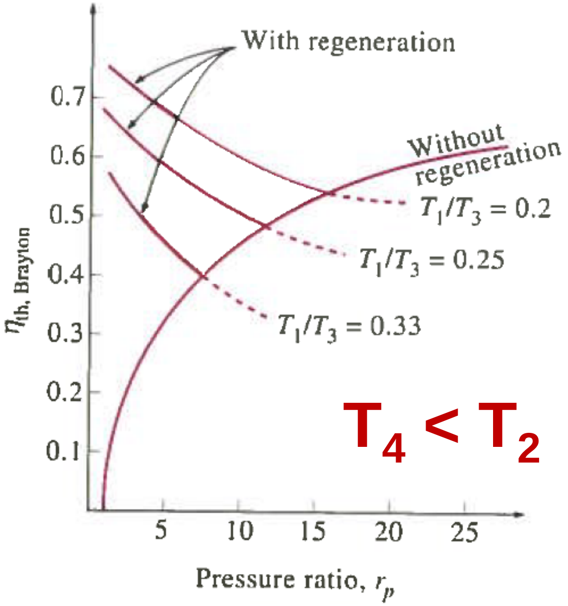
Regenerator = counter-flow HE (a.k.a. recuperator)

Effectiveness:

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







$T_4 < T_2$

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

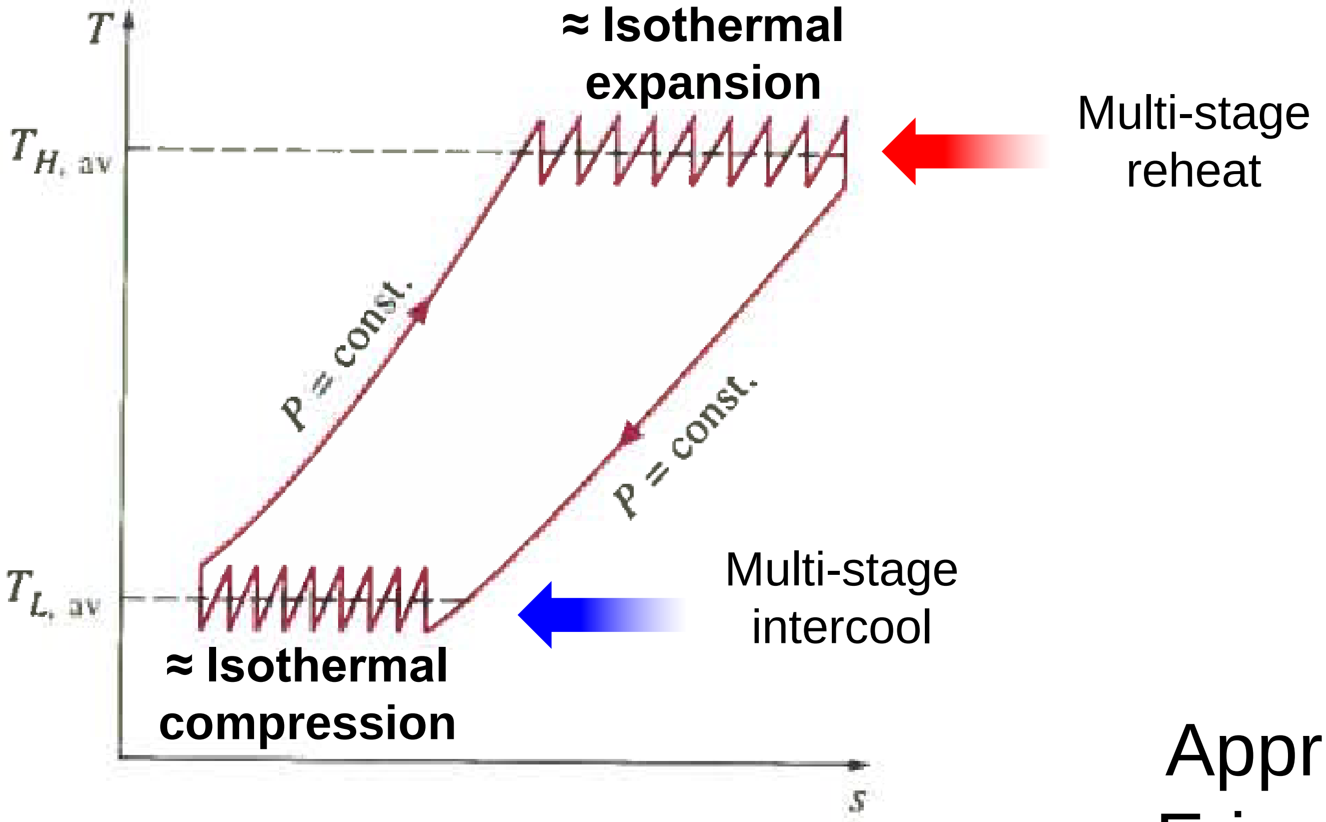
Decrease fluid density

Reheating

Multi-stage reheating

Approach isothermal conditions

Multi-Stage Intercooling & Reheating



≈ Isothermal expansion

Multi-stage reheat

Multi-stage intercool

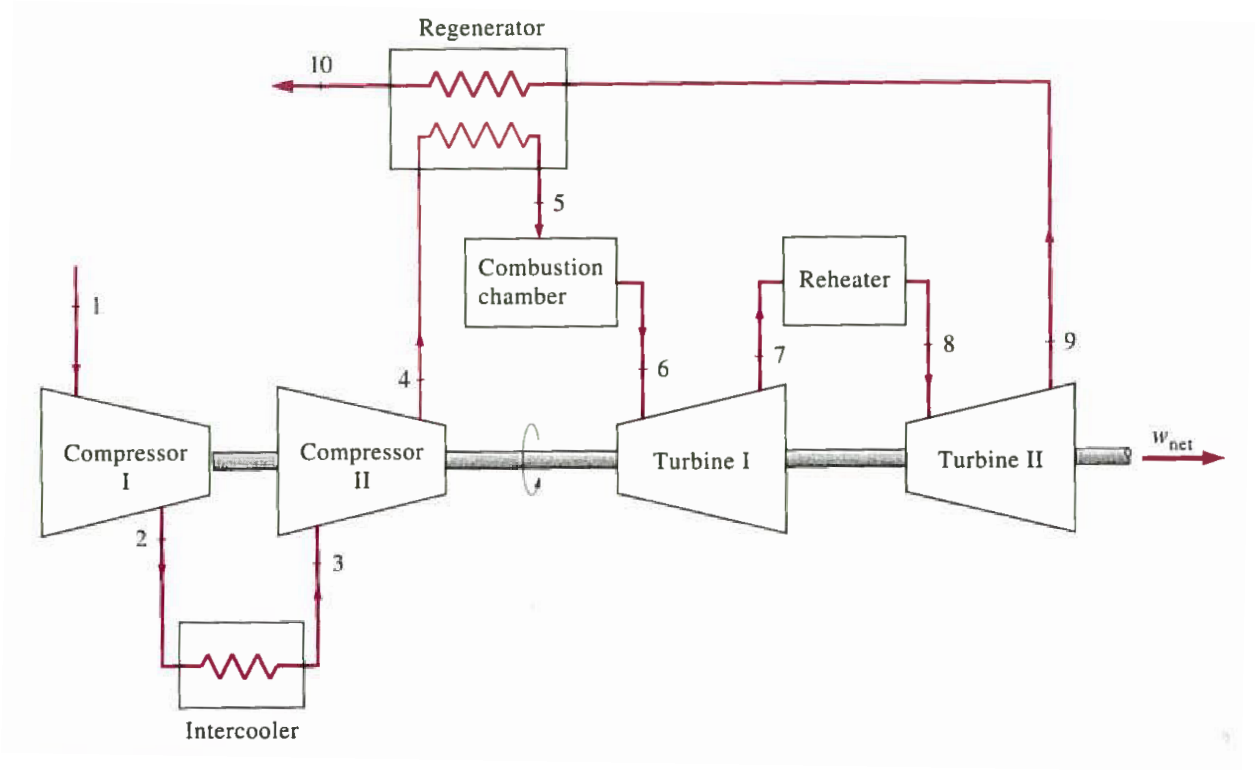
≈ Isothermal compression

Figure reference: Cengel and Boles (2002)

Approximates Ericsson cycle

$$\eta_{th,Ericsson} = \eta_{th,Carnot}$$

Brayton Cycle + Regeneration + Intercooling + Reheating



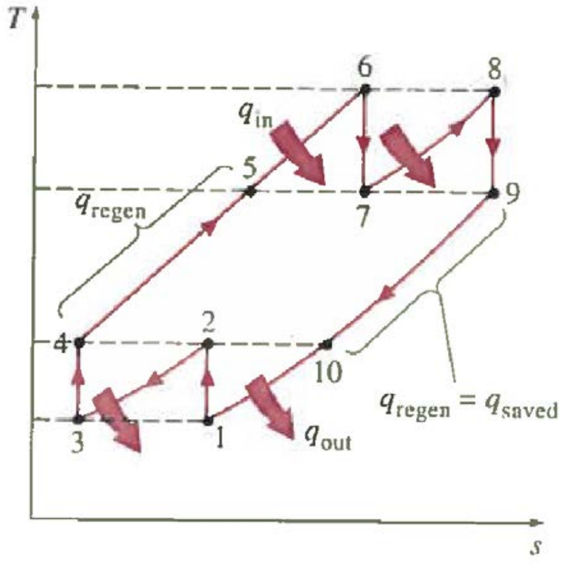
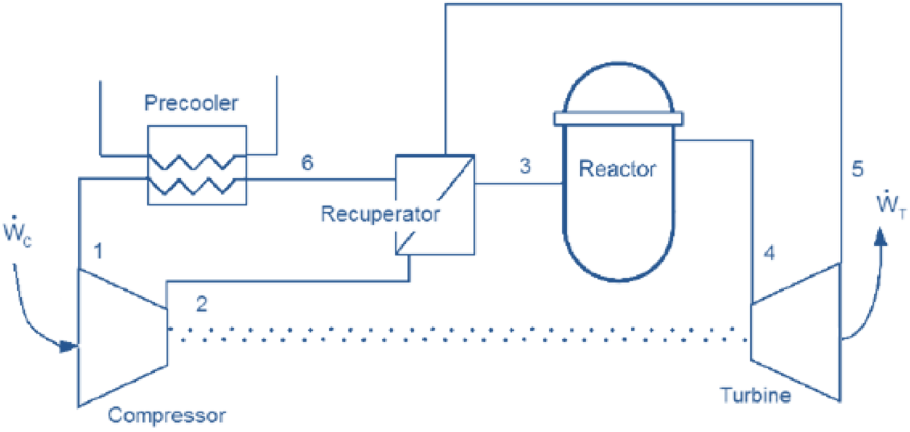
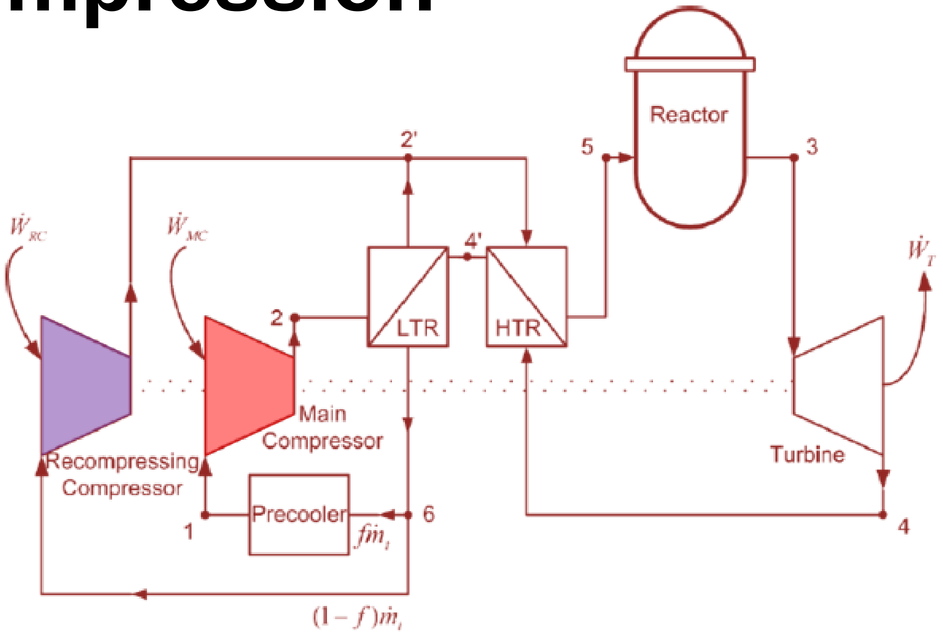
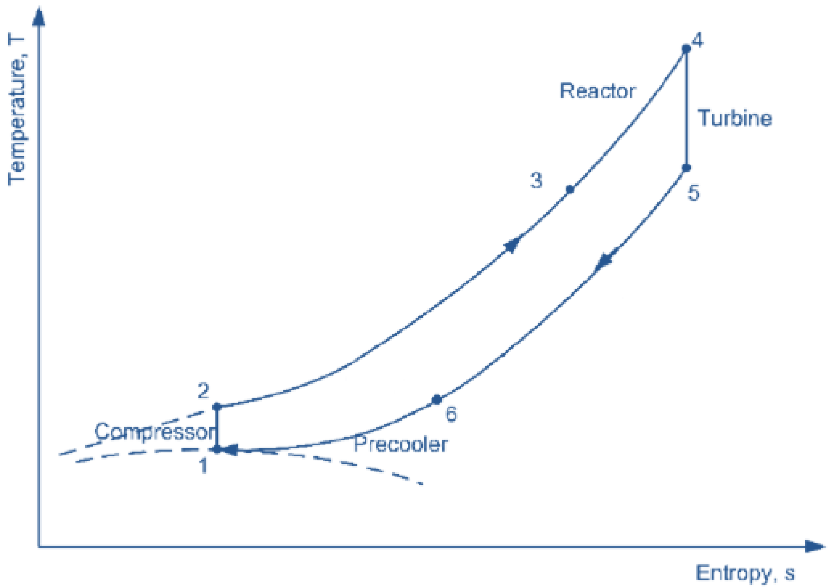


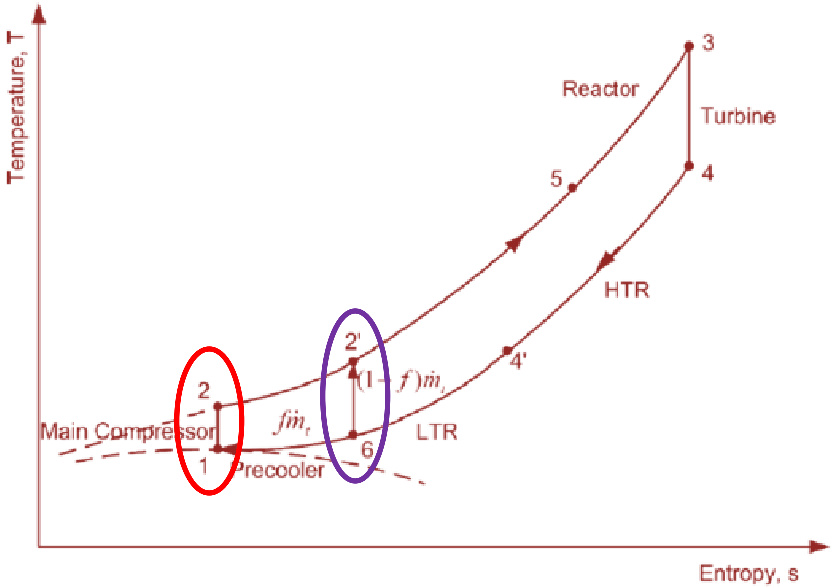
Figure reference: Cengel and Boles (2002)

Regeneration vs. Recompression in Brayton Cycle



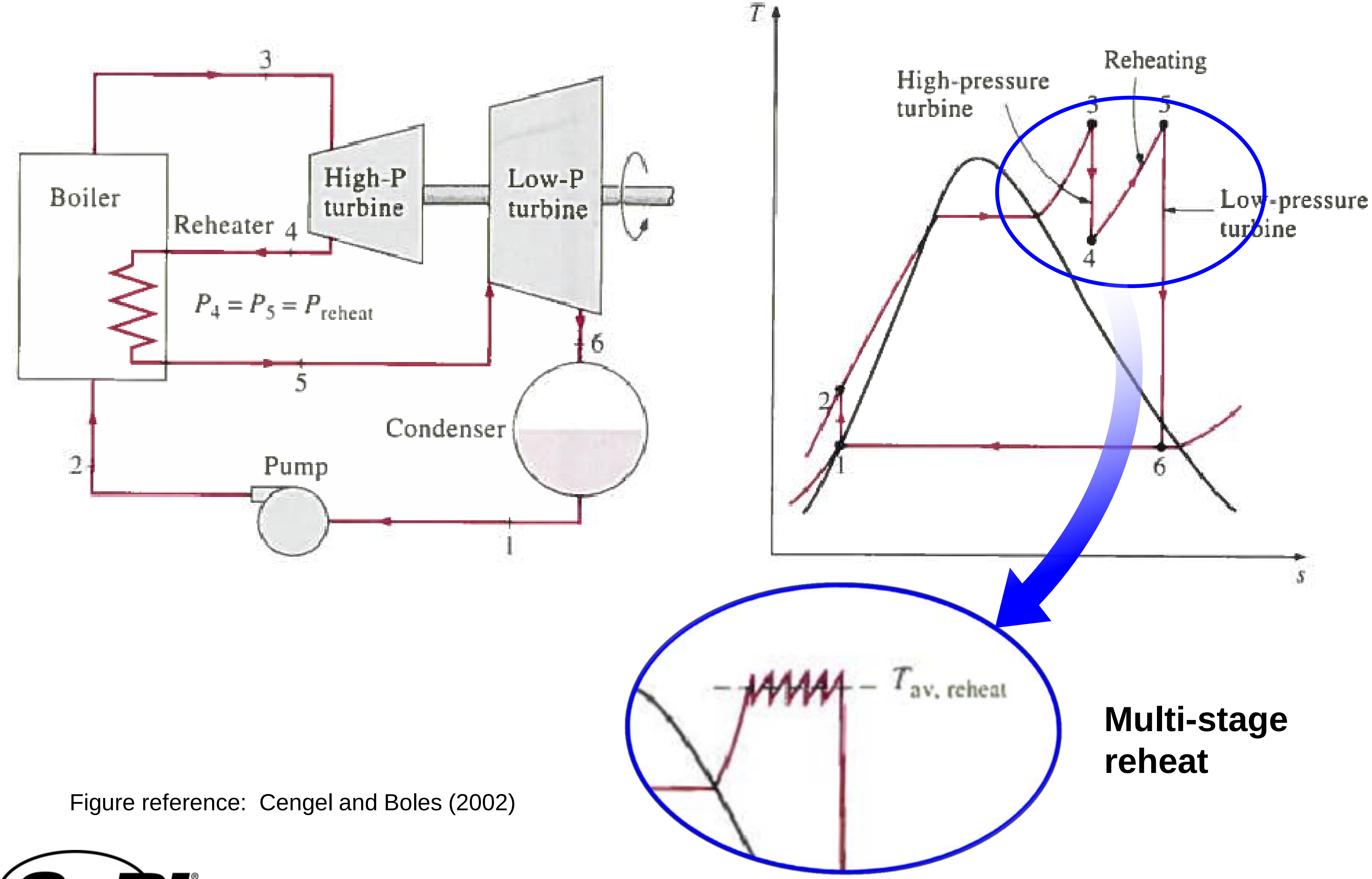






Source: Ludington (2009)

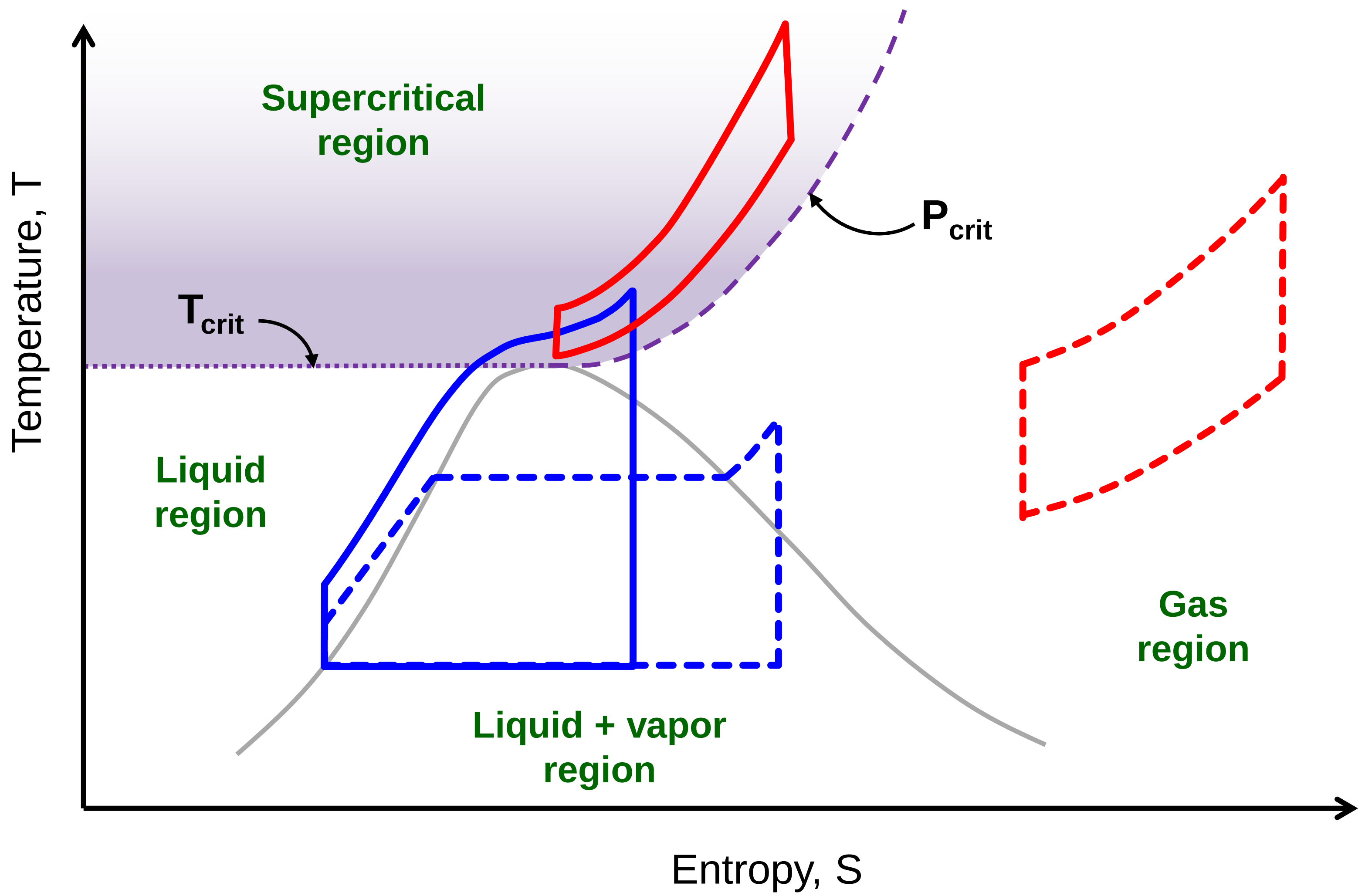
Rankine Cycle + Reheating



Multi-stage reheat

Figure reference: Cengel and Boles (2002)

What is a Supercritical Power Cycle?

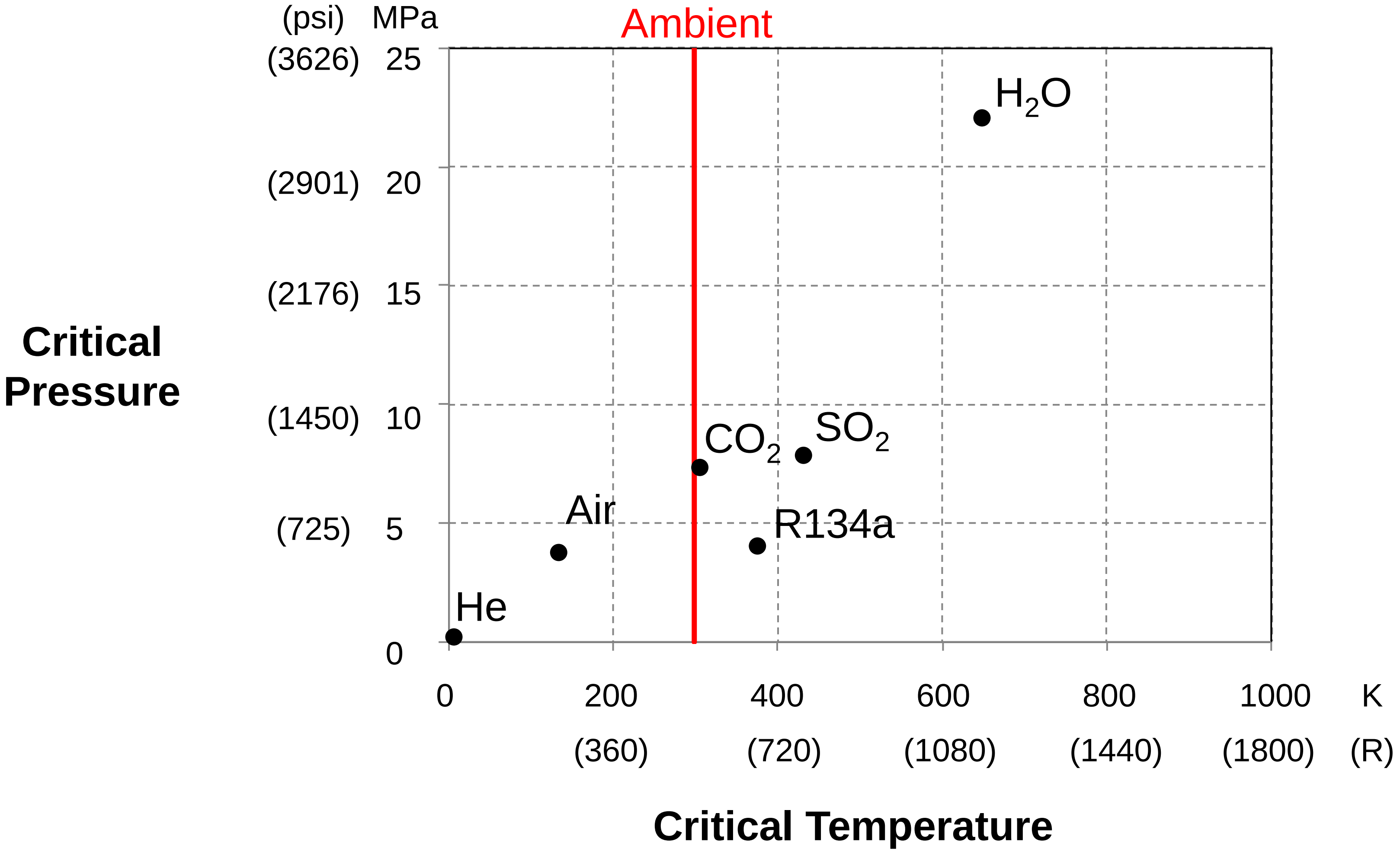


sCO_2 Power Cycles

Why sCO_2 for Power Cycles?

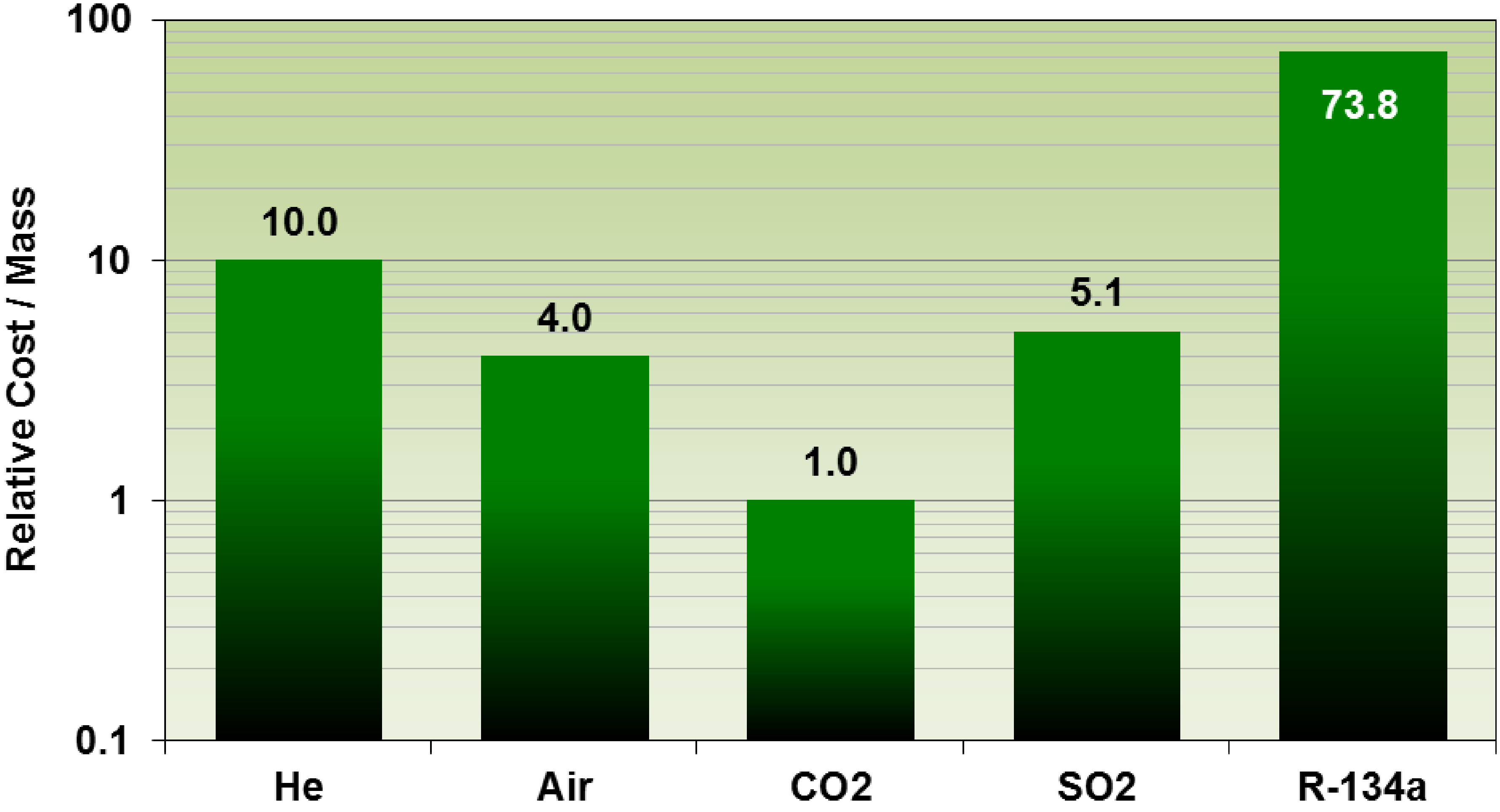
Property	Effect
High density near C.P.	• Reduced compressor work, large W_{net} • Allow more-compact turbomachinery to achieve same power • Less complex – e.g., fewer compressor and turbine stages, may not need intercooling
Near-ambient T_{crit}	• Good availability for most temperature sinks and sources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

CO_2 Critical Point Comparison



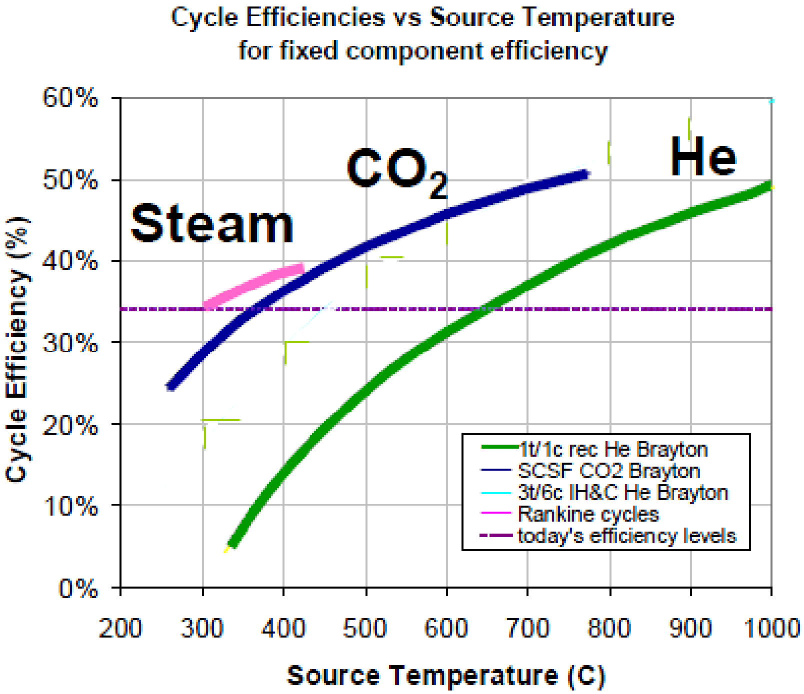
REFPROP (2007)

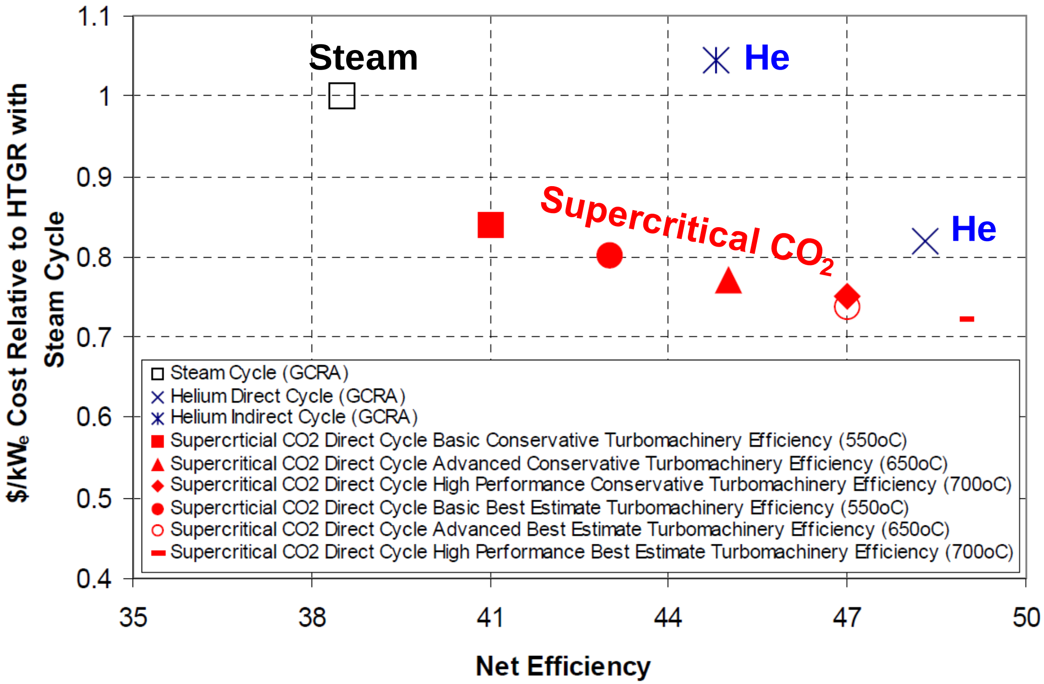
CO_2 Cost Comparison*



*Based on market pricing for laboratory-grade substance

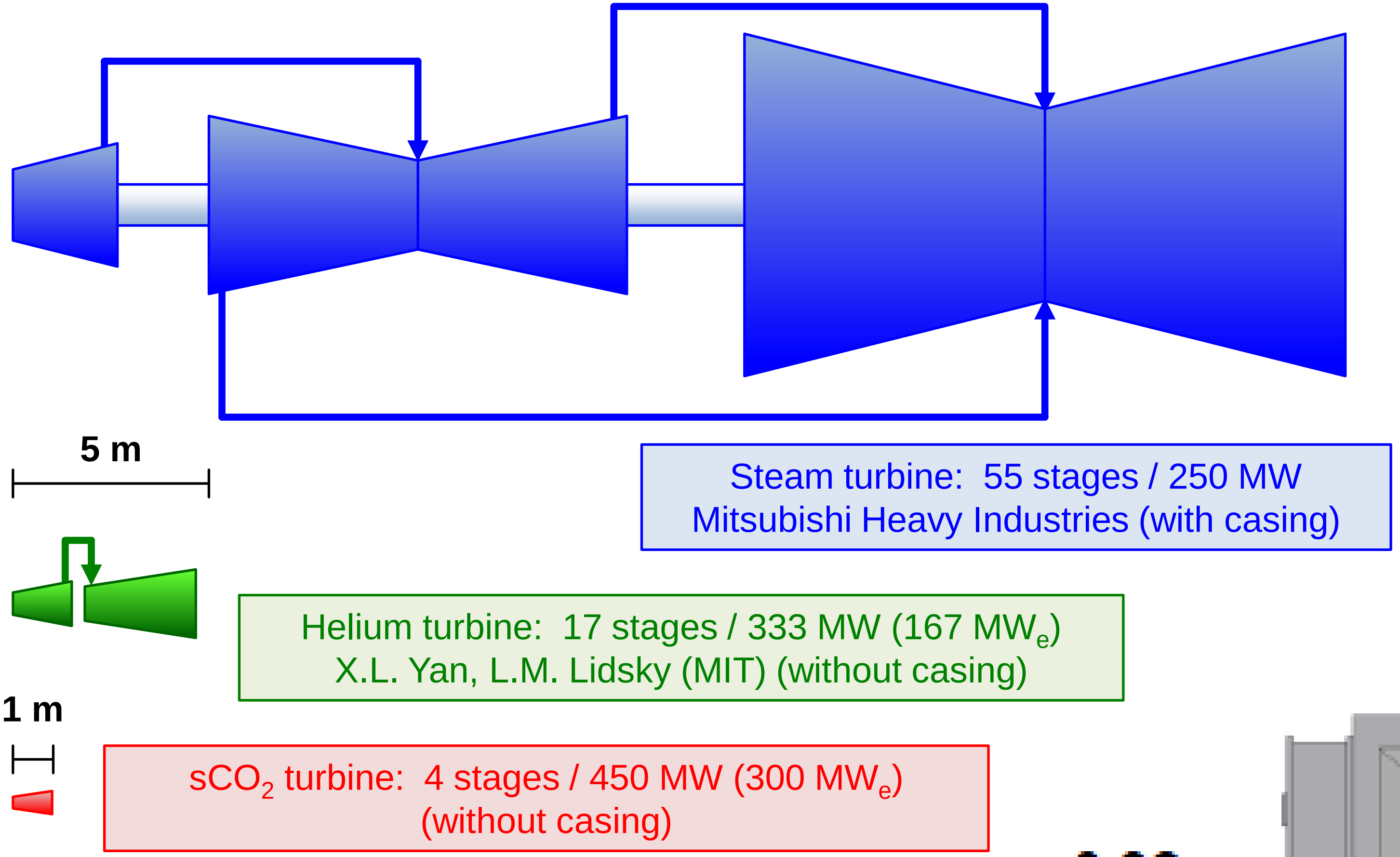
The sCO_2 power cycle can provide efficiencies near a steam cycle for less $/kWh





Source: Wright (2011) and Dostal (2004)

Relative Size of Components



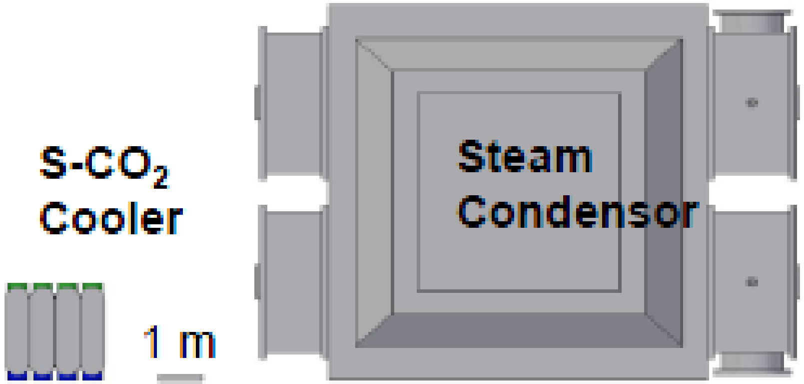
Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries (with casing)

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)

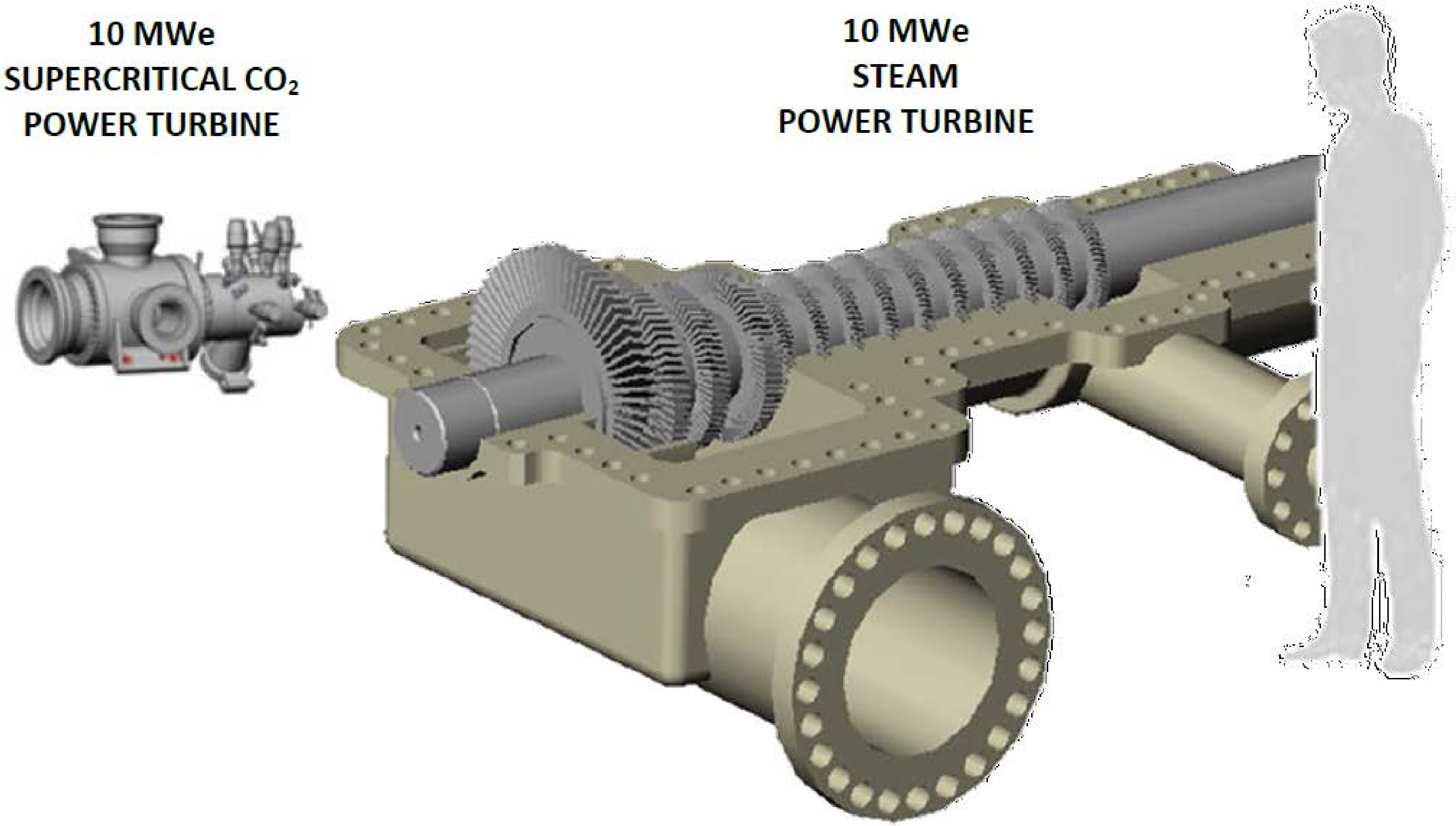
Note: Compressors are comparable in size

Adapted from Dostal (2004)



Source: Wright (2011)

Example: 10 MWe Turbine Comparison



Source: Persichilli et al. (2012)

sCO_2 in Power Cycle Applications

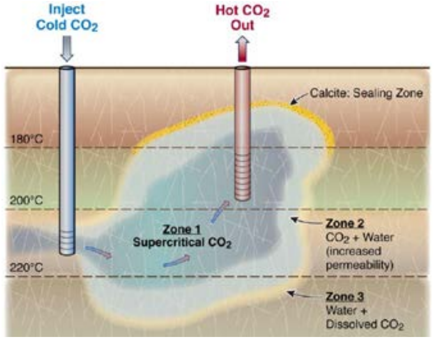
Supercritical CO_2 in Power Cycle Applications


[6-1]

Concentrated Solar Power


[6-2]

Fossil Fuel



[6-3]

Geothermal


[6-4]

Nuclear

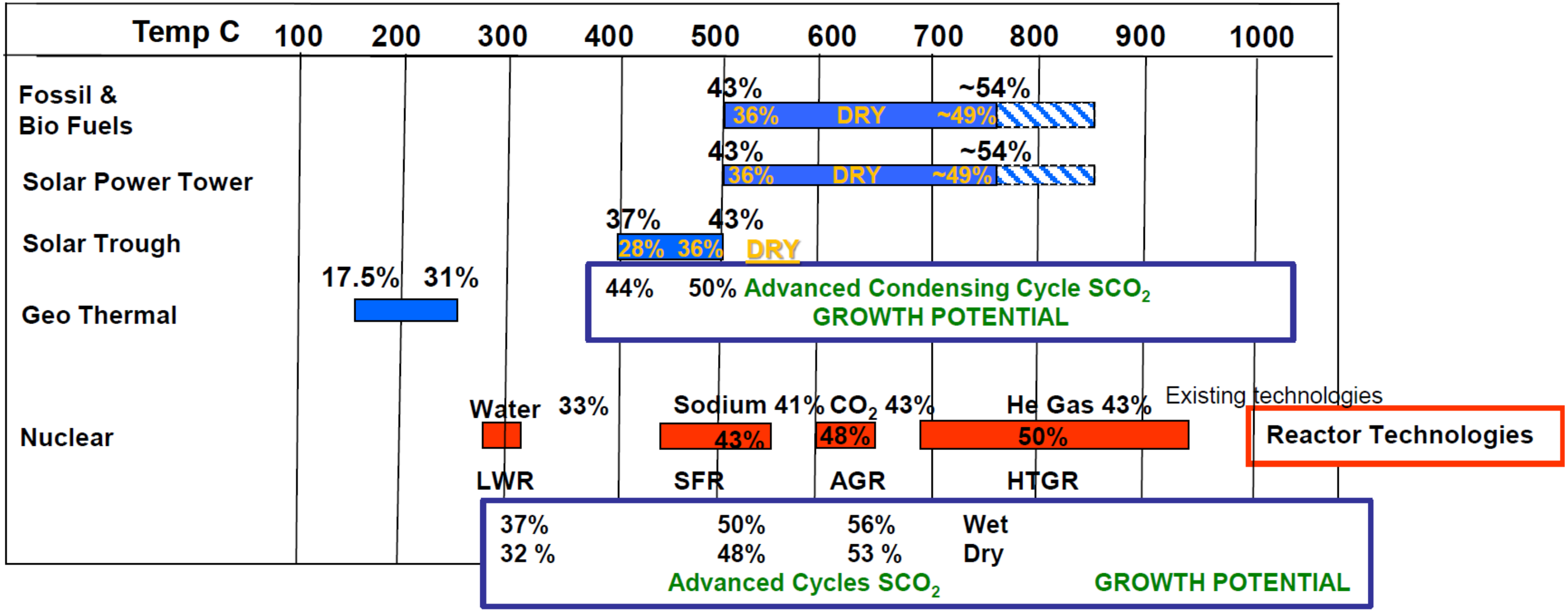

[6-5]

Ship-board Propulsion

“Typical” sCO2 Cycle Conditions

Application	Organization	Motivation	Size [MWe]	Temperature [C]	Pressure [bar]
Nuclear	DOE-NE	Efficiency, Size	300 - 1000	400 - 800	350
Fossil Fuel	DOE-FE	Efficiency, Water Reduction	500 - 1000	550 - 1200	150 - 350
Concentrated Solar Power	DOE-EE	Efficiency, Size, Water Reduction	10 - 100	500 - 800	350
Shipboard Propulsion	DOE-NNSA	Size, Efficiency	10, 100	400 - 800	350
Shipboard House Power	ONR	Size, Efficiency	< 1, 1, 10	230 - 650	150 - 350
Waste Heat Recovery	DOE-EE ONR	Size, Efficiency, Simple Cycles	1, 10, 100	< 230; 230-650	15 - 350
Geothermal	DOE-EERE	Efficiency, Working fluid	1, 10, 50	100 - 300	150

Heat Source Operating Temperature Range & Efficiency



Assumptions (Turbomachinery Eff (MC 85%, RC 87%, T 90%), Wright (2011)

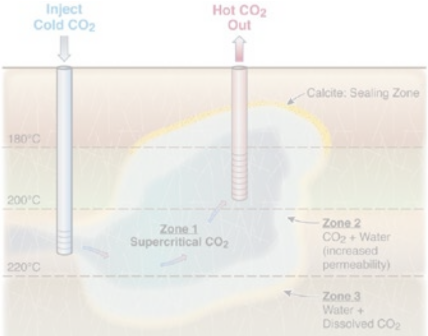
Supercritical CO_2 in Power Cycle Applications

[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

Nuclear

[6-5]

Ship-board Propulsion

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.

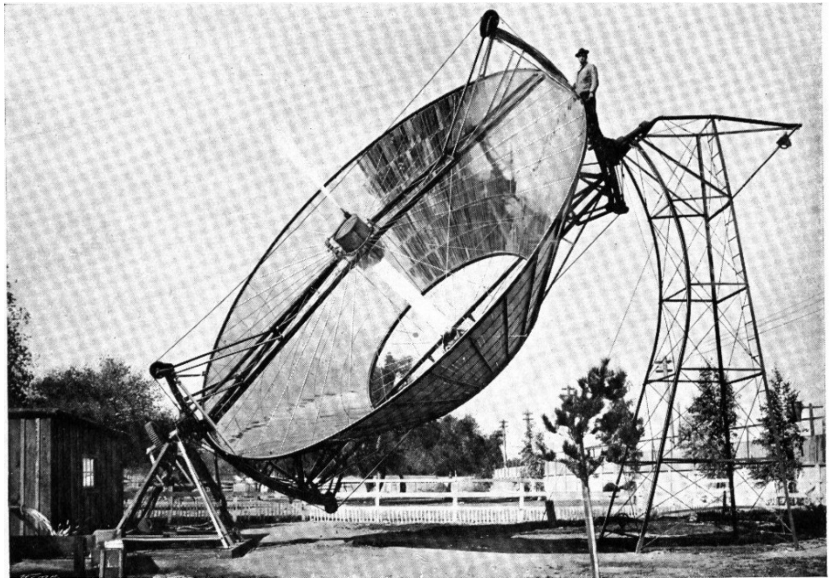


Image source: [6-6]

Image source: [6-7]

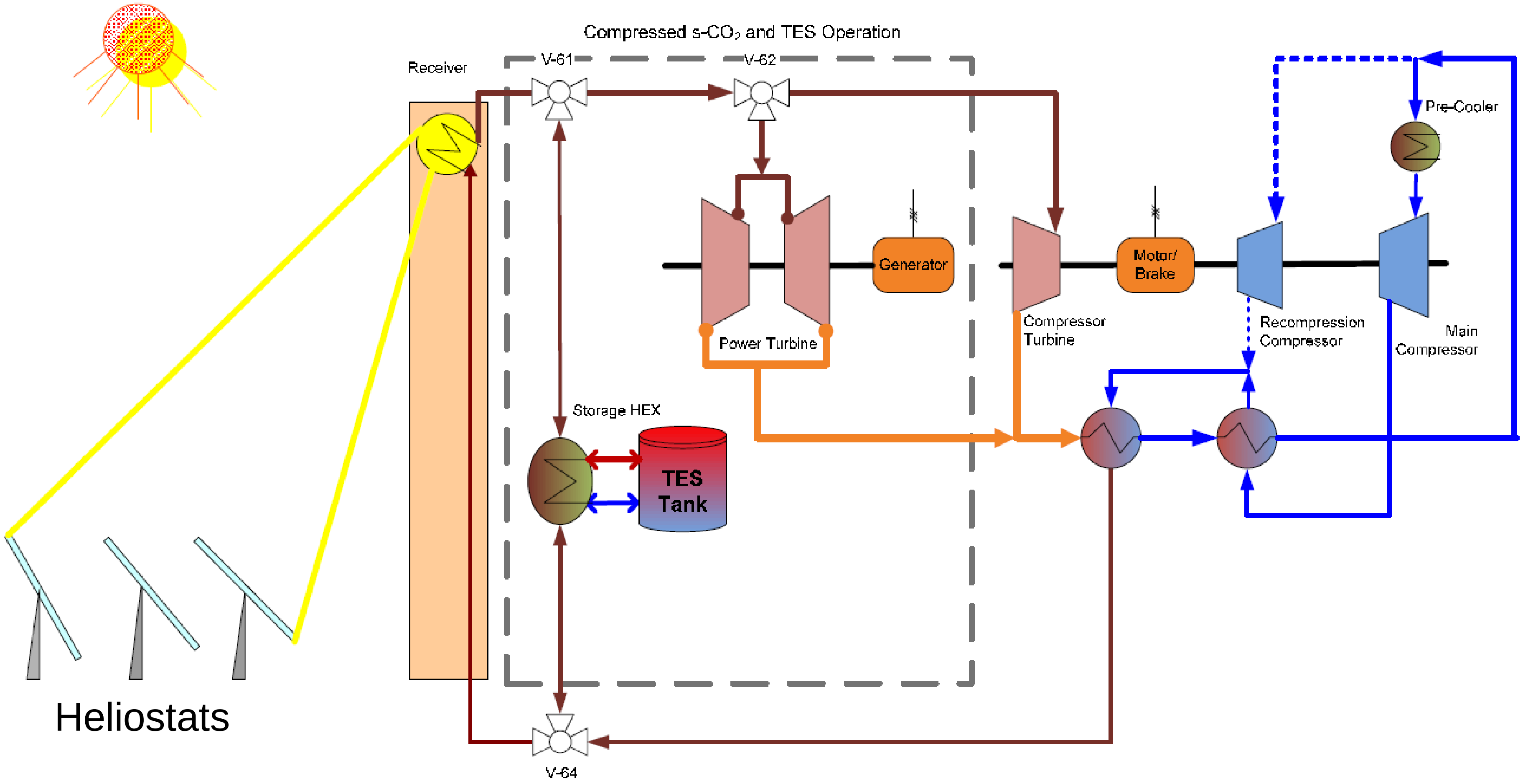
CSP – Improvement Opportunities

- Advanced power cycles
  - Supercritical steam Rankine
  - High temperature air Brayton
  - Supercritical CO_2

- Cooling
  - 650 gal $H_2$0/MWh
  - Dry-cooling technology is needed in most desert venues for CSP
    - 43°C Dry bulb
  - Printed circuit heat exchangers may provide a solution

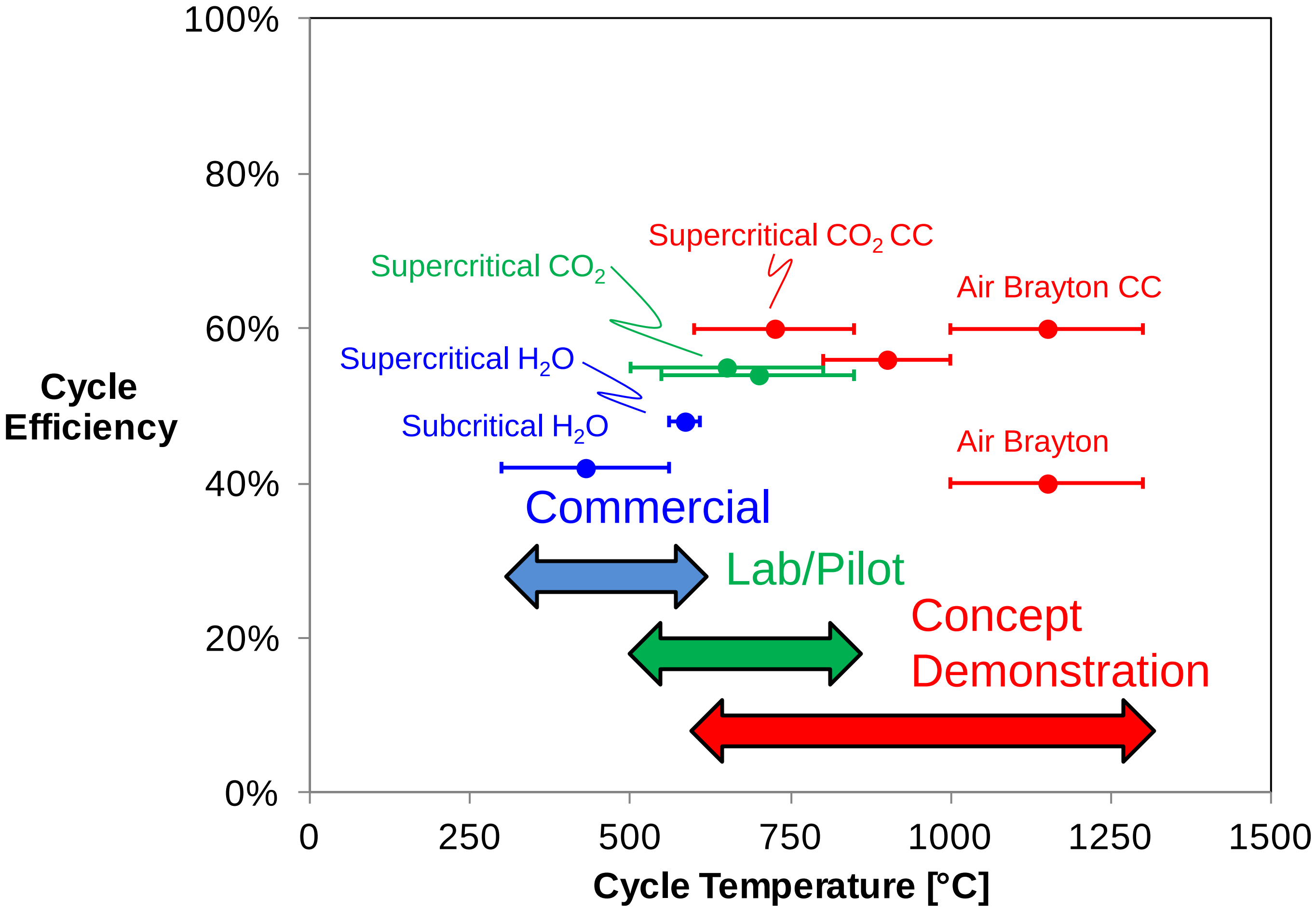
Image source: [6-1]

sCO_2 CSP Process Diagram



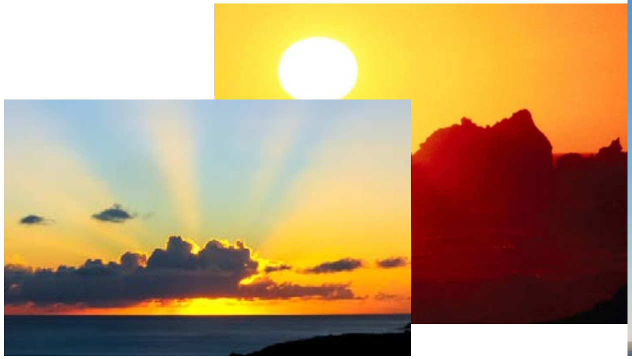
Dual-shaft, tower receiver sCO_2 Brayton Cycle solar thermal power system with thermal energy storage, Zhiwen and Turchi (2011)

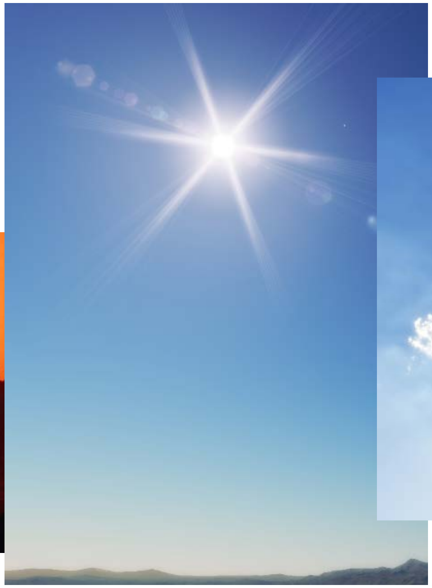
CSP Efficiencies vs. Power Cycle

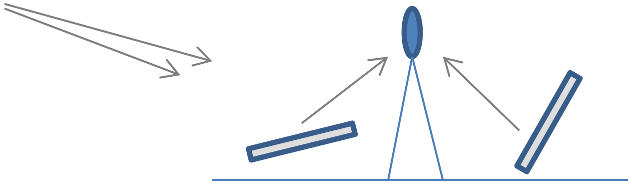


Data from Stekli (2009)

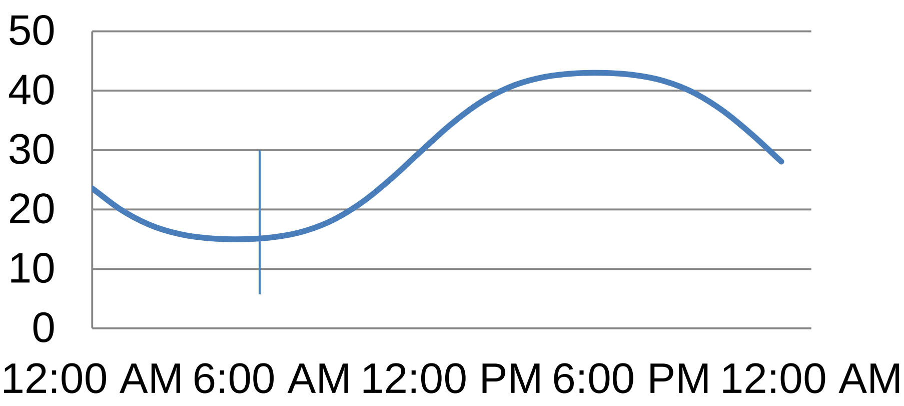
The transient challenges of a concentrated solar power plant are significant





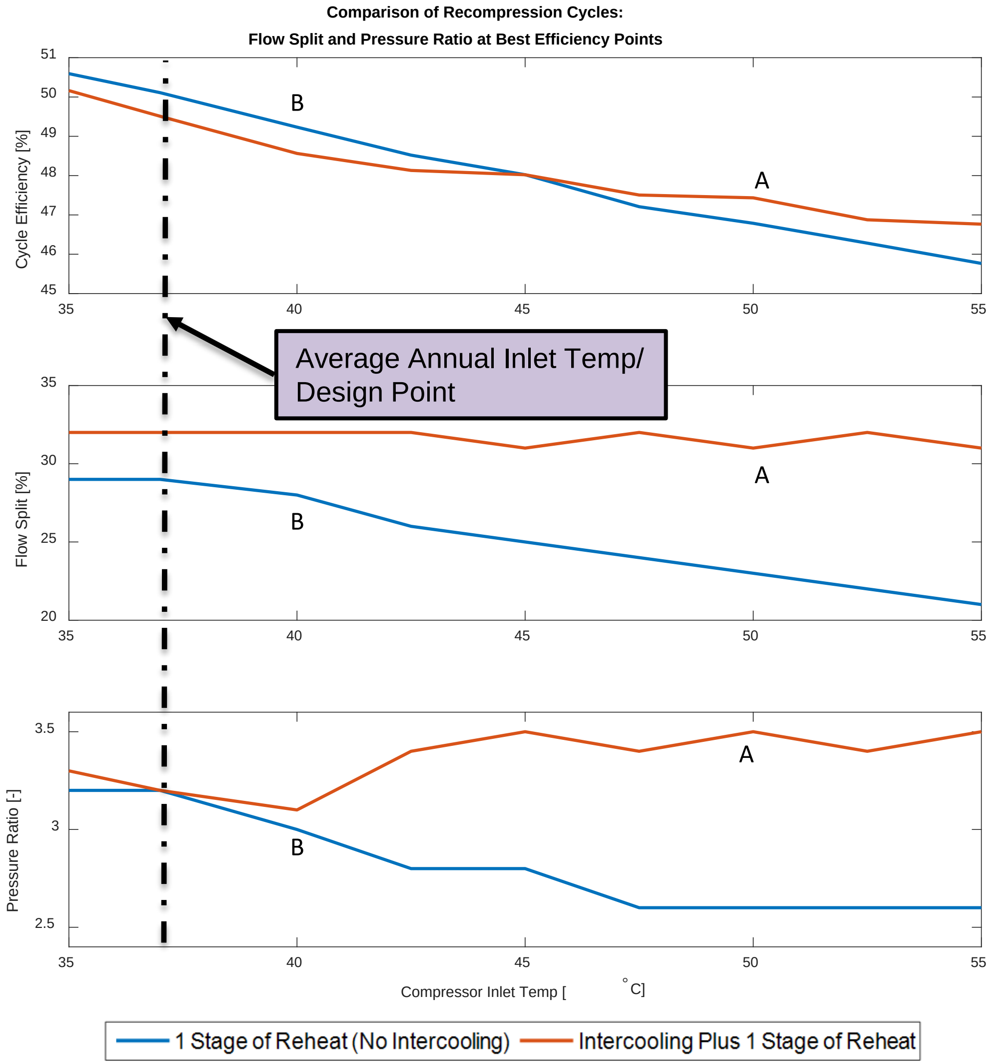


Ambient Temperature °C



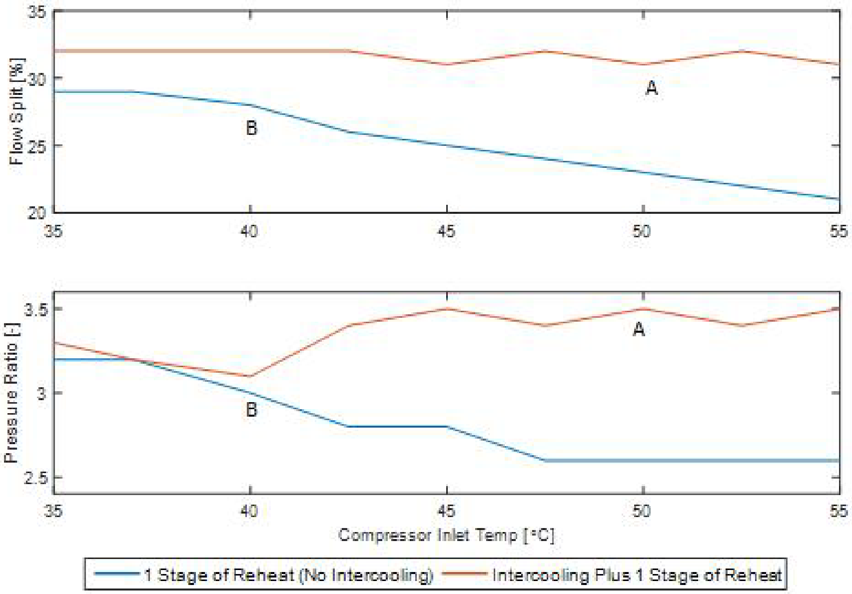
Optimal Cycle Configuration with varying Compressor Inlet Temperature

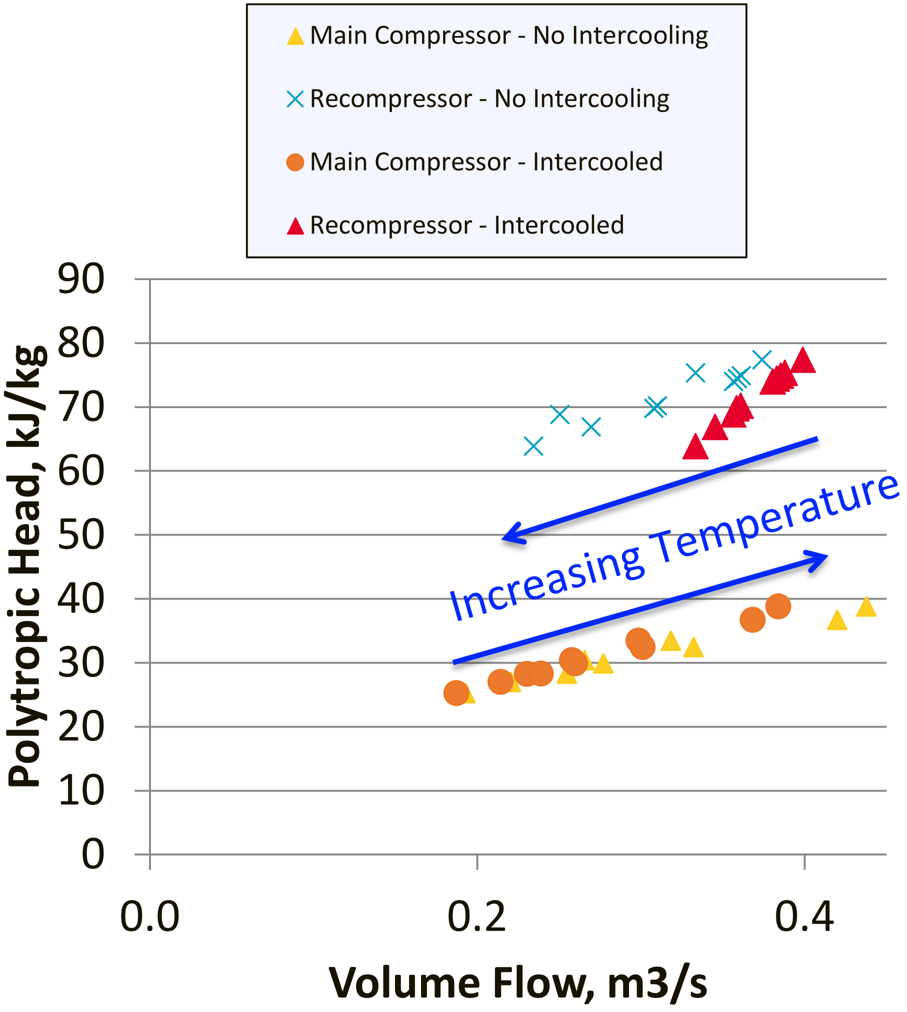
- SAM modeling of typical sites shows an annual average compressor inlet temperature to be 37-38ºC assuming 15ºC approach temperature in the cooler
- Cycle Modeling
  - Optimal flow split
    - 22-33%
    - Heavily dependent on CIT
  - Optimal PR
    - Varies with use of intercooling
  - Intercooled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



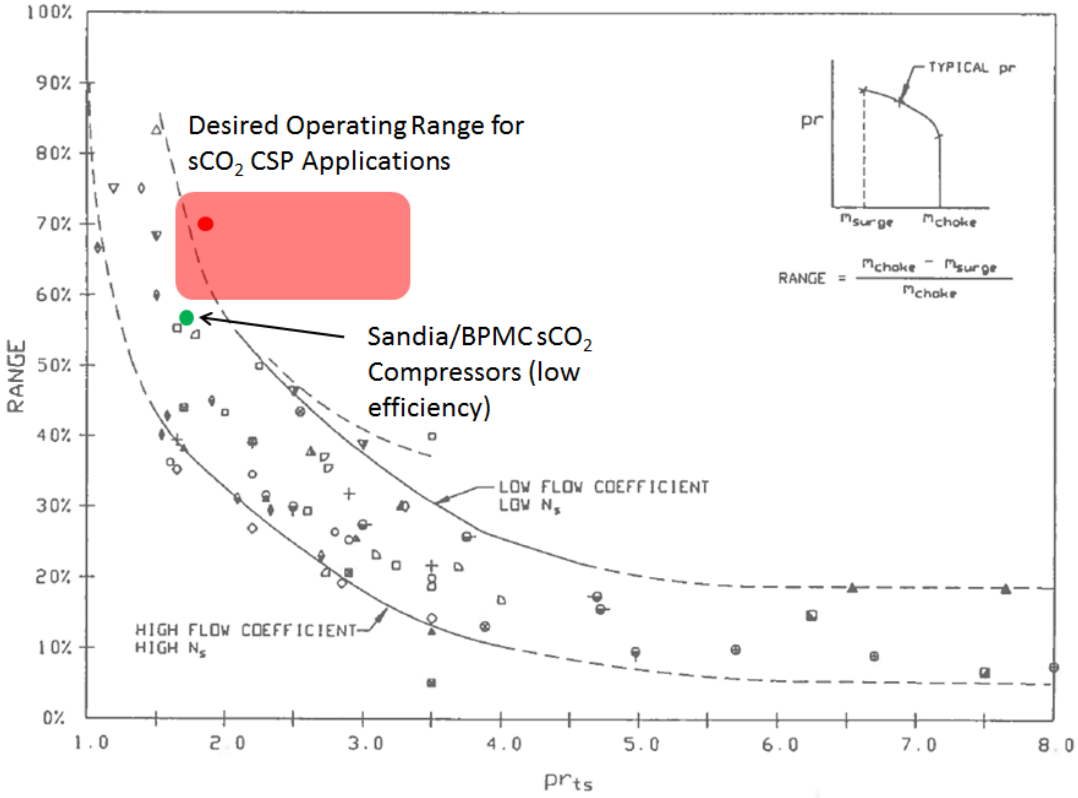
Wide-Range Impeller Requirements

- Range Requirements at Optimal Efficiency Condition (without using range reduction techniques)
  - Compressor > 55%
  - Recompressor > 37%
- Control Strategies
  - Alter flow split and pressure ratio to reduce compressor requirements
  - Control compressor inlet temperature
  - Employ inlet guide vanes





CSP Compressor Inlet Variation and Turbomachinery Performance

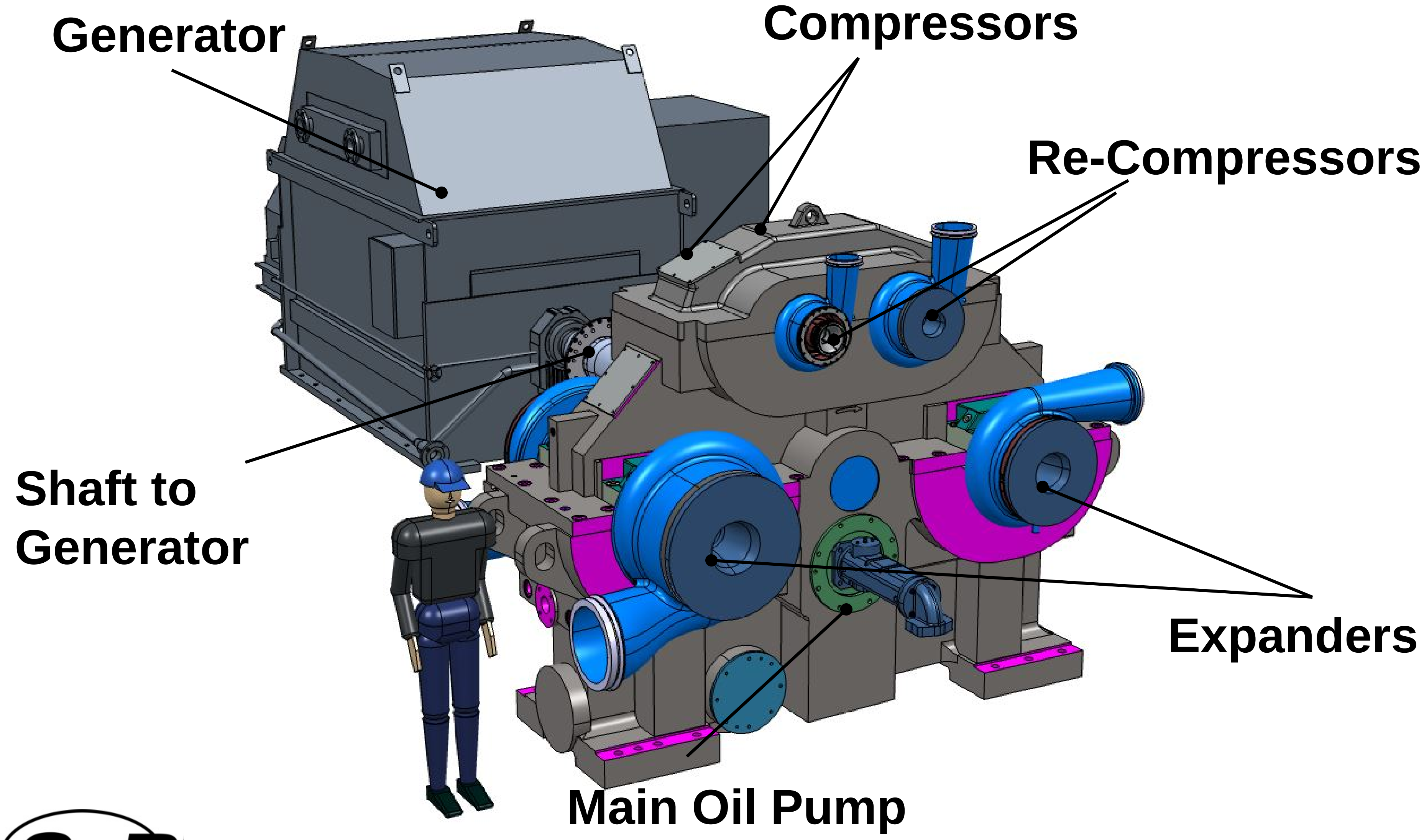


Desired Operating Range for sCO_2 CSP Applications

Sandia/BPMC sCO_2 Compressors (low efficiency)

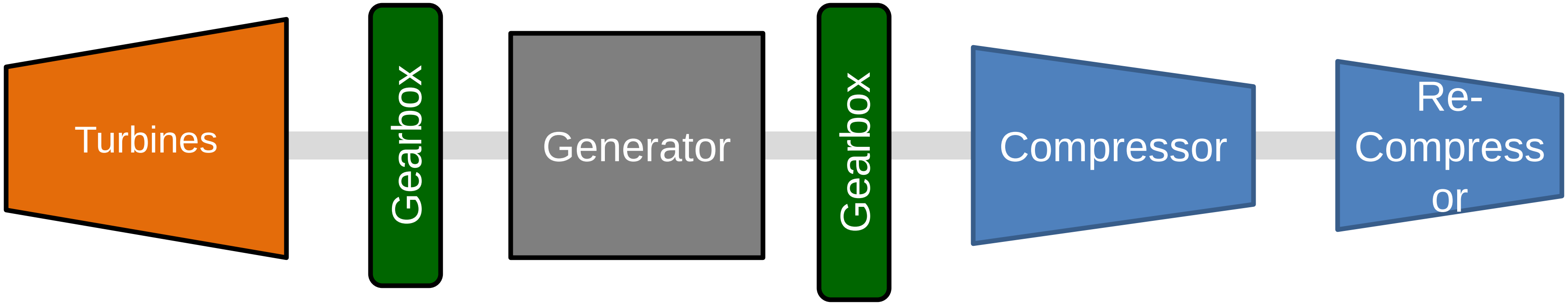
Figure 5: Comparison of Operating Range and Pressure Ratio Requirements [Modified from Japikse[5]]

Conceptual 10 MW_e Integrally Geared Compressor Applied to Recuperated Brayton Cycle



IGC Offers Compact Configuration for this Application

Conventional Turbomachinery Train



Turbines

Gearbox

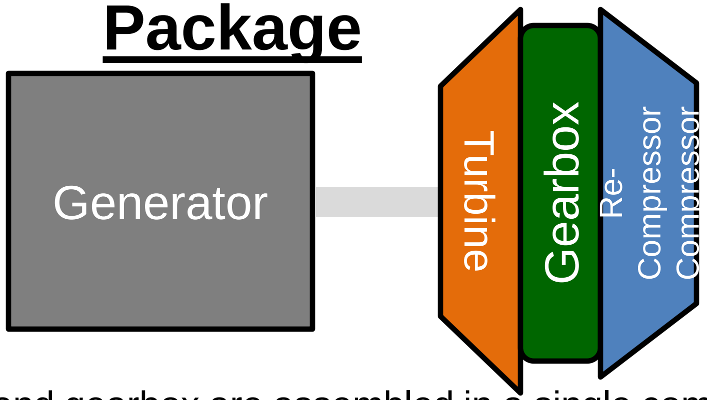
Generator

Gearbox

Compressor

Re-Compressor

Typical IGC Package



Generator

Turbine

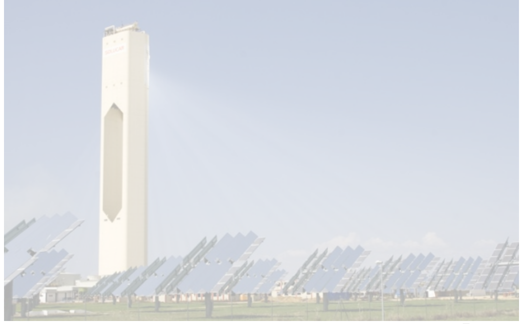
Gearbox

Re-Compressor

Compressor

- An IGC package incorporates all the key elements of a conventional train in a much more compact package
- Compressor, re-compressor, turbine and gearbox are assembled in a single compact core.
- The second gearbox, additional couplings and housings in the conventional train can be eliminated
- Simple IGC package can potentially reduce costs by up to 35%
- Reduced mechanical complexity ➔ improved reliability and reduced maintenance

Supercritical CO_2 in Power Cycle Applications

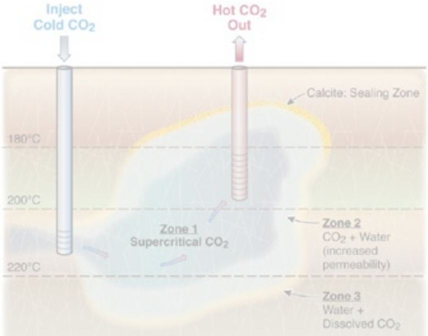


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

Nuclear

[6-5]

Ship-board Propulsion

Rankine Cycle Application: Nuclear Power Generation

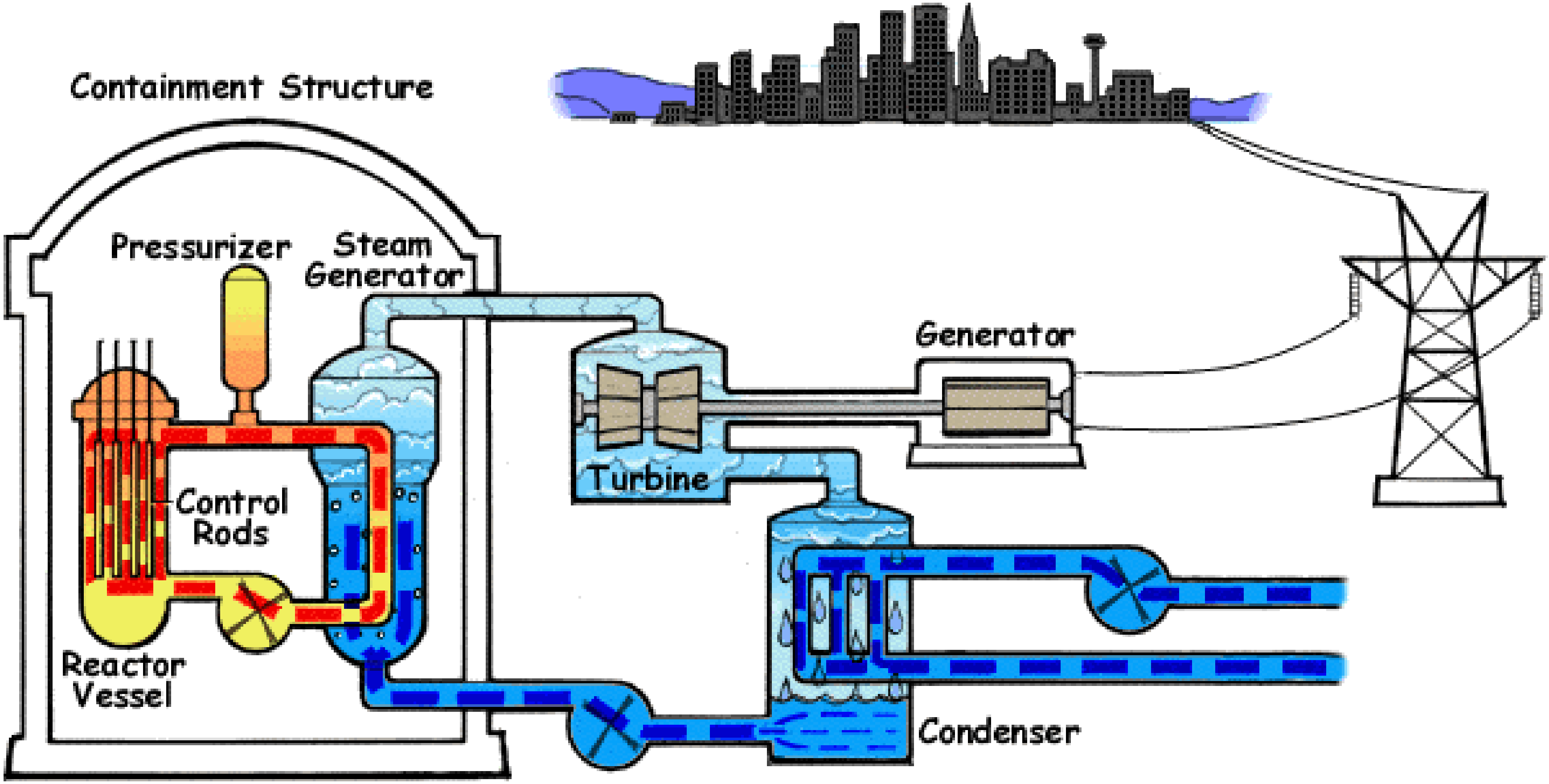


Image source: [6-8]

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

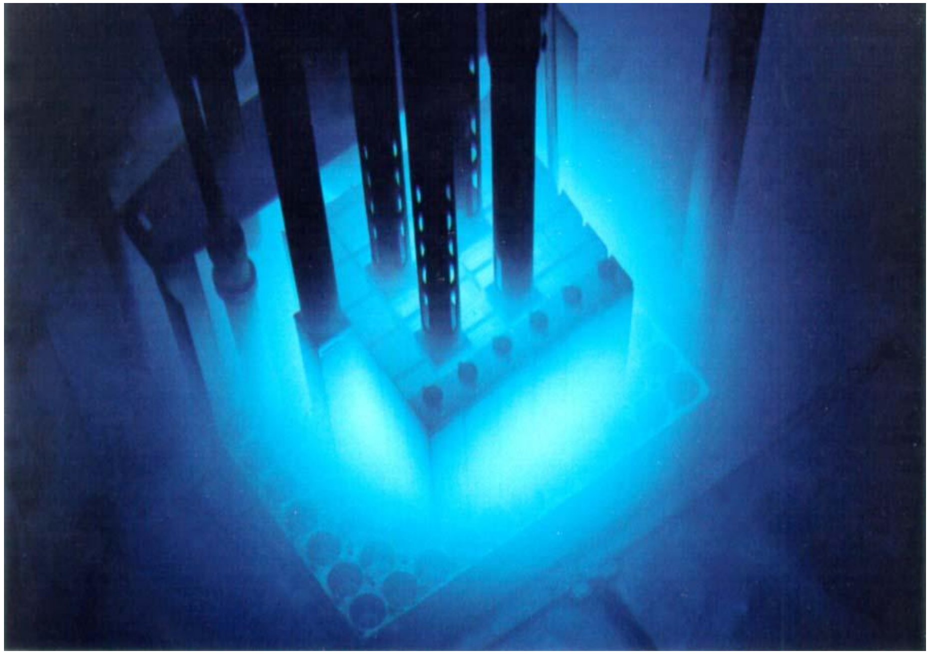
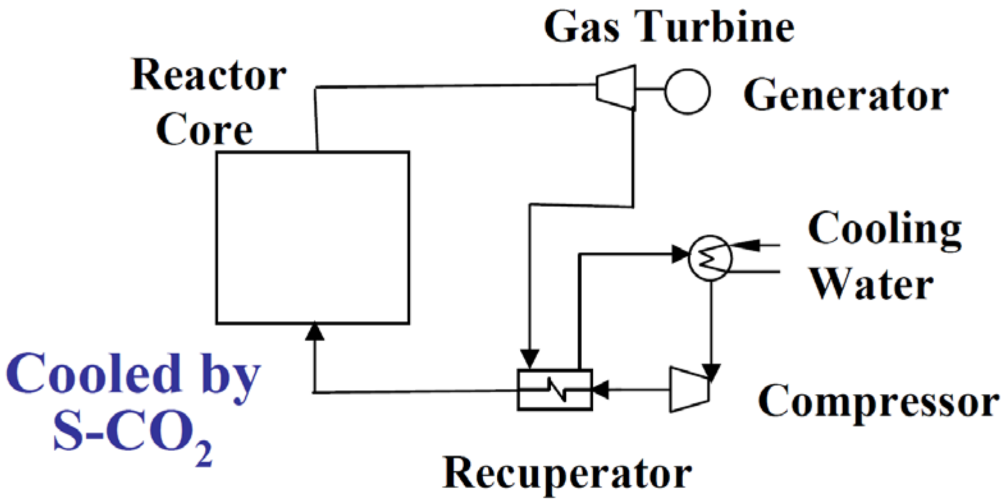


Image source: [6-9]

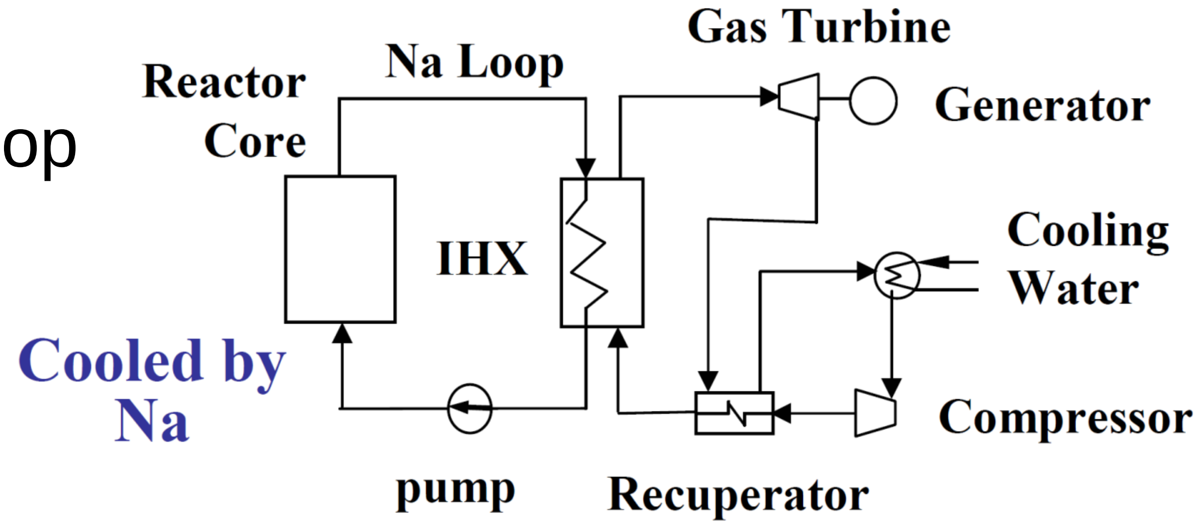
Image source: [6-4]

Proposed Nuclear sCO_2 Cycles

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

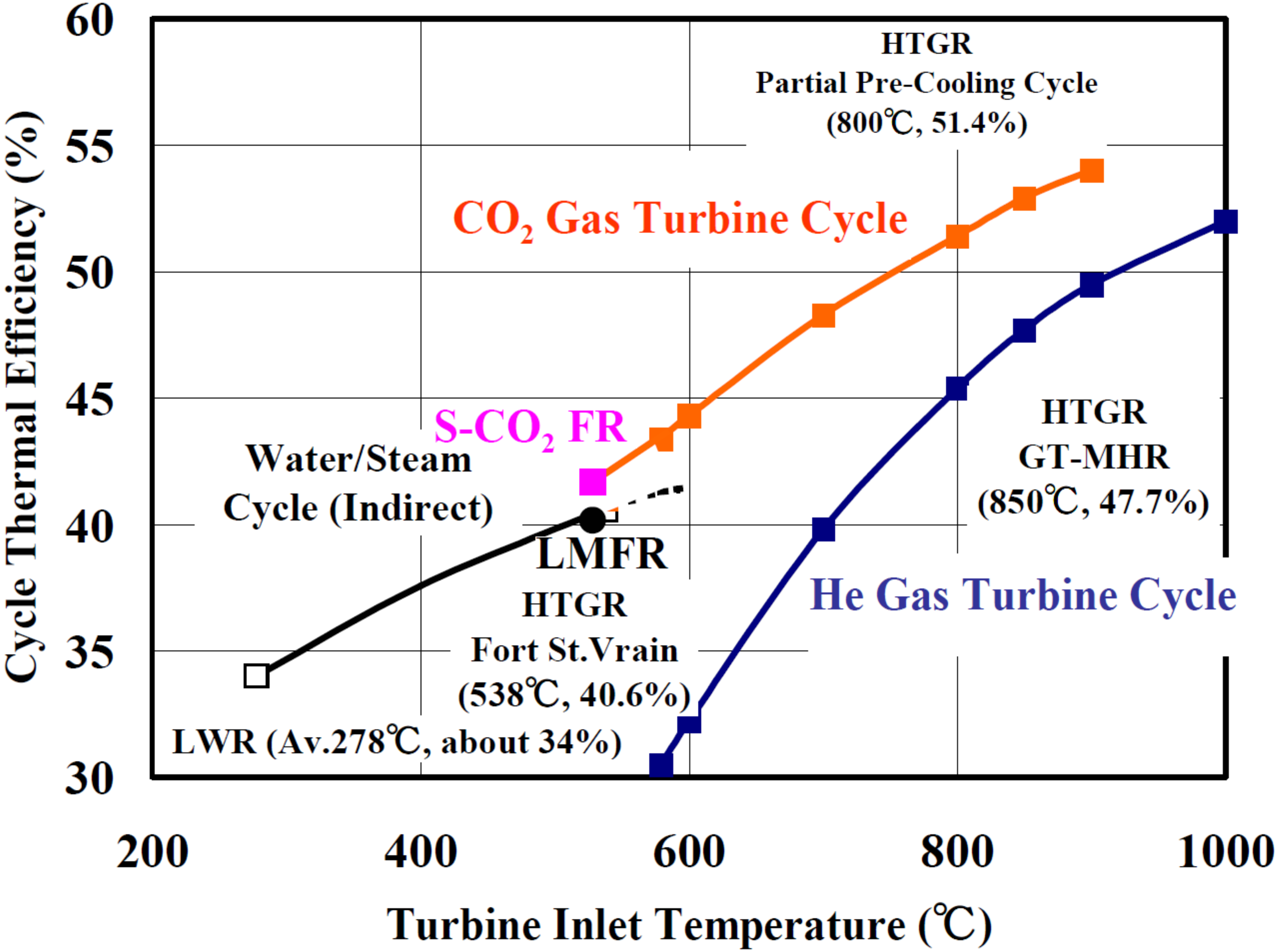


- ❑ Indirect Cycle
  - Primary Na loop
  - Smaller core size



Kato et al. (2007)

Nuclear Plant Efficiency vs. Cycle Prop.

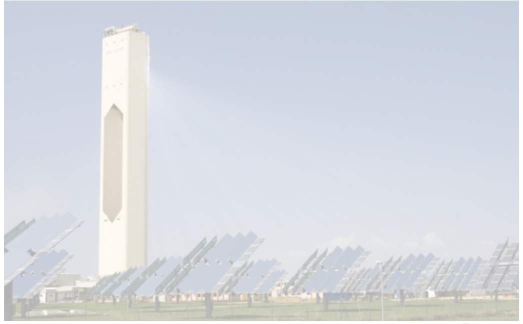


Kato et al. (2007)

Advantages of CO_2 Cycle vs. Helium Cycle in Nuclear Applications

Pro	Con
Smaller turbomachinery than steam or helium	Helium preferred to CO_2 as a reactor coolant for cooling capability and inertness
CO_2 Brayton cycles are more efficient than helium at medium reactor temperatures	CO_2 requires a larger reactor than helium or an indirect cycle
CO_2 is 10× cheaper than Helium	New technology

Supercritical CO_2 in Power Cycle Applications

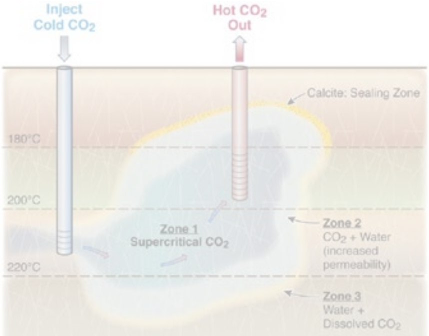


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

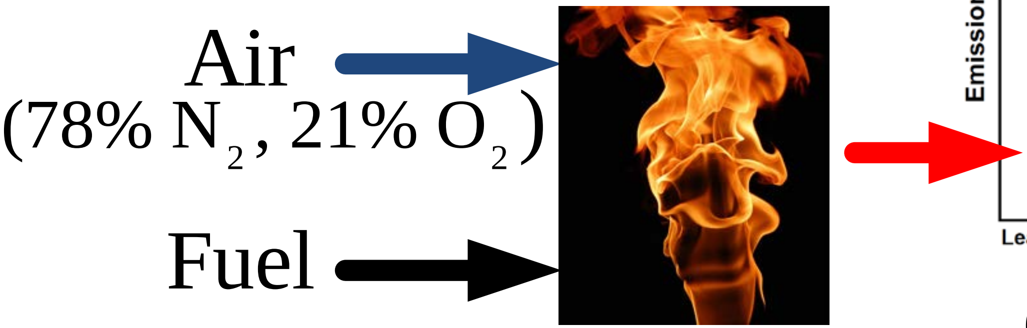
Nuclear

[6-5]

Ship-board Propulsion

Oxy-Fuel Combustion

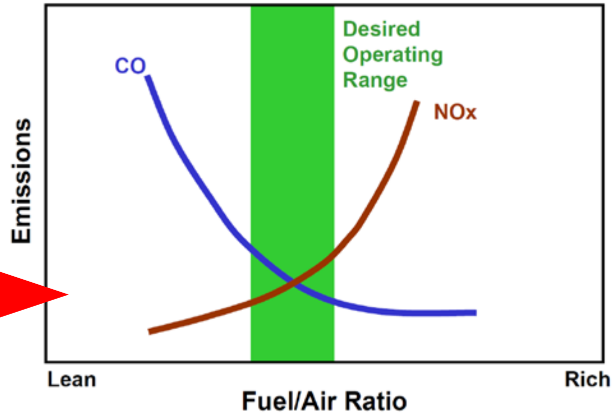
Conventional Combustion



Air

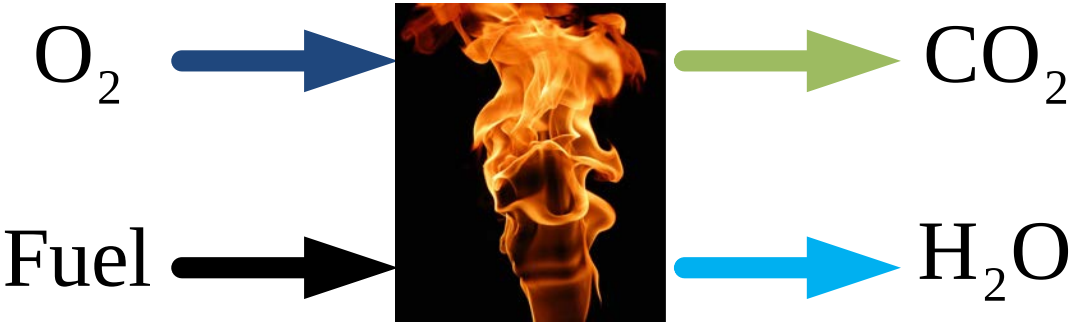
(78% N_2, 21% O_2)

Fuel



(Solar Turbines 2012)

Oxy-Fuel Combustion



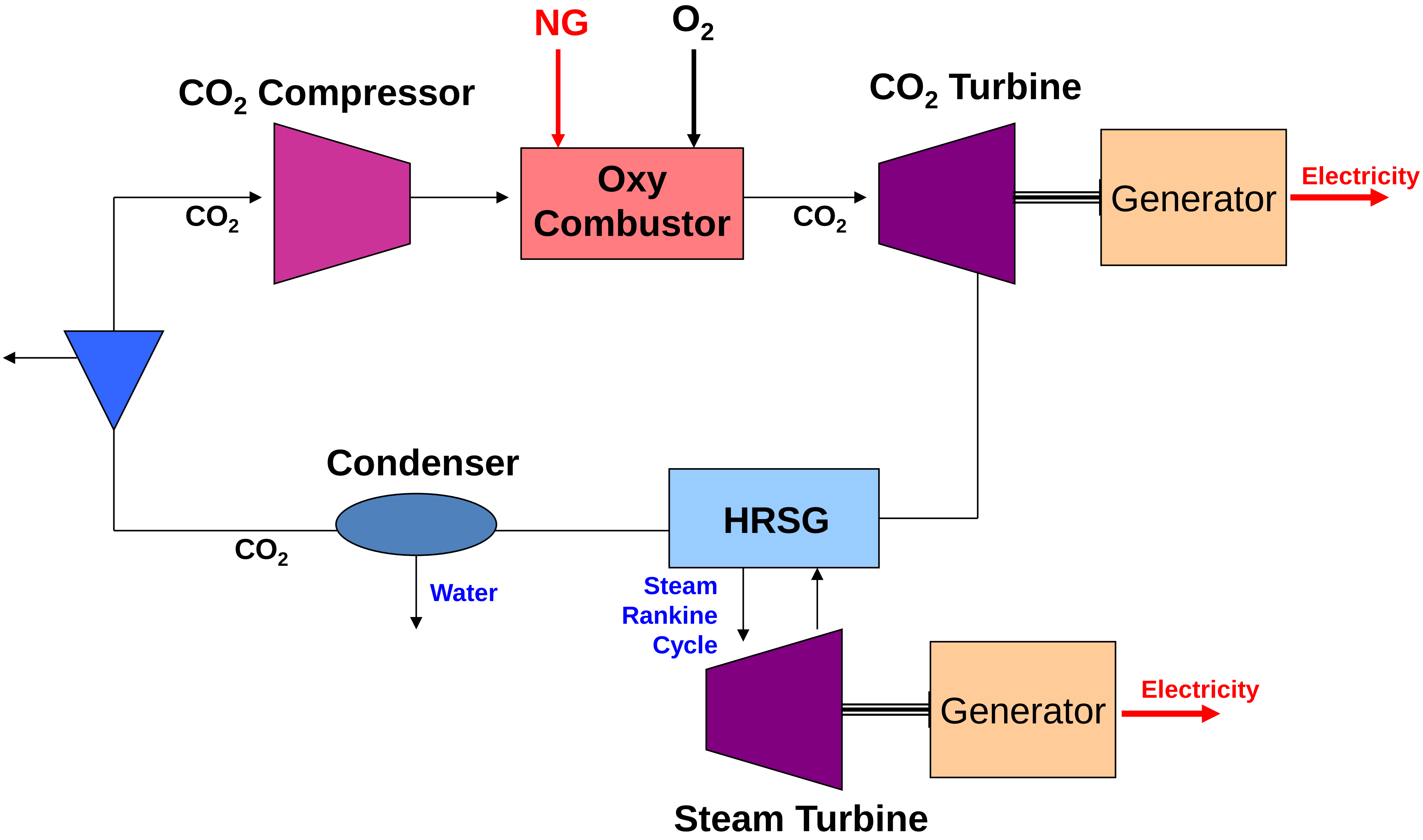
O_2

Fuel

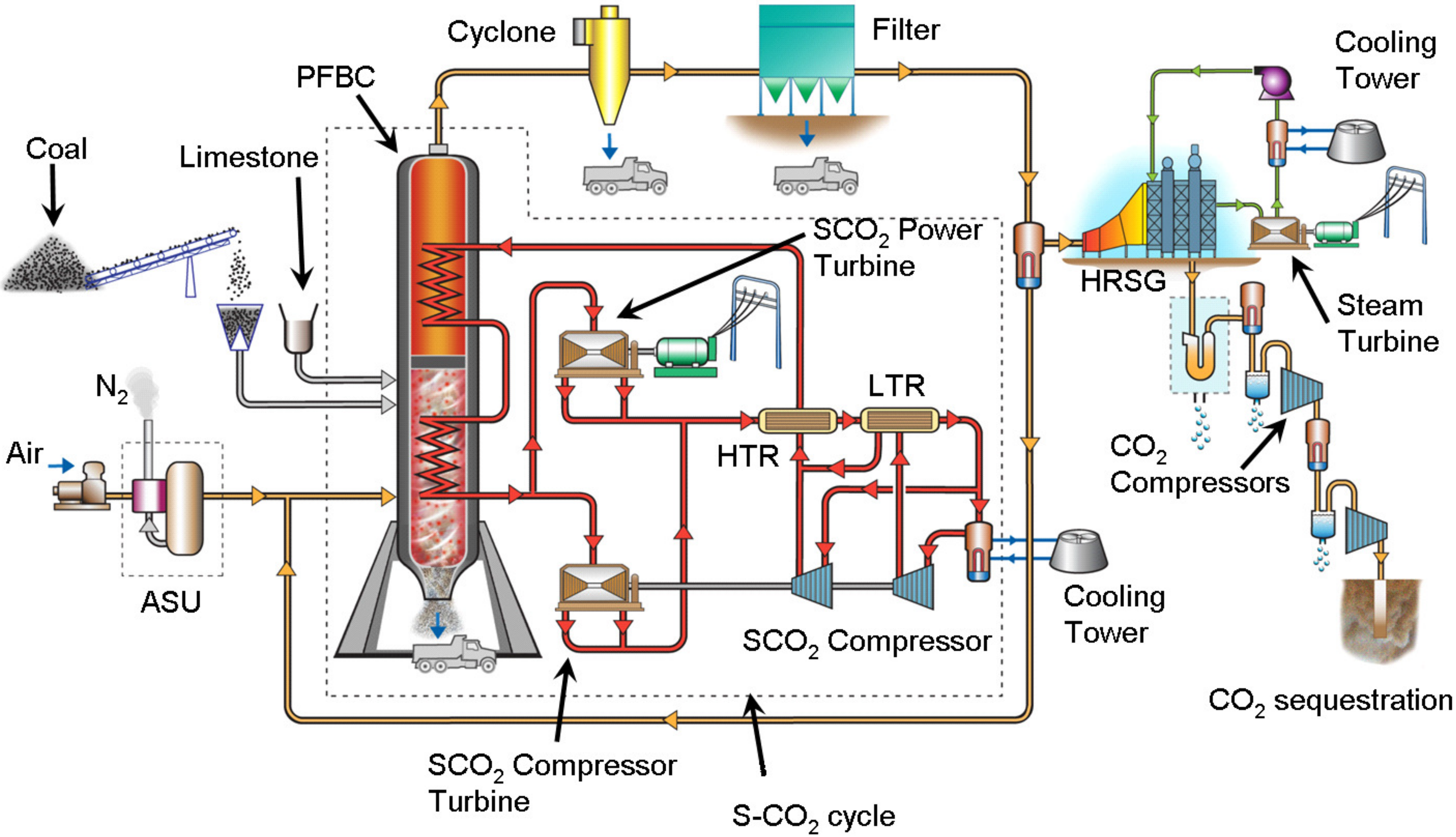
CO_2

H_2O

Direct Oxy-Fuel Combustion

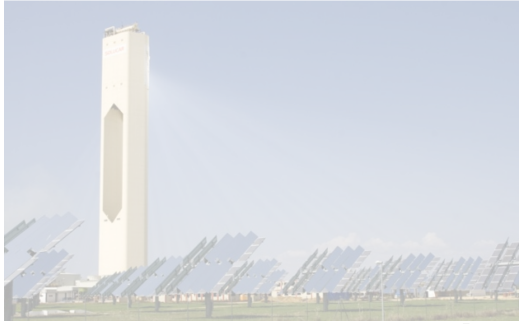


Indirect Oxy-Fuel Combustion



Zero Emission Oxy-Coal Power Plant with Supercritical CO_2 Cycle, Johnson et al. (2012)

Supercritical CO_2 in Power Cycle Applications

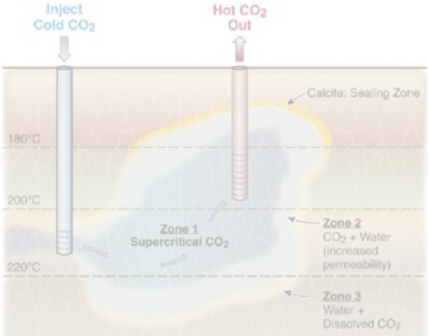


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

Nuclear

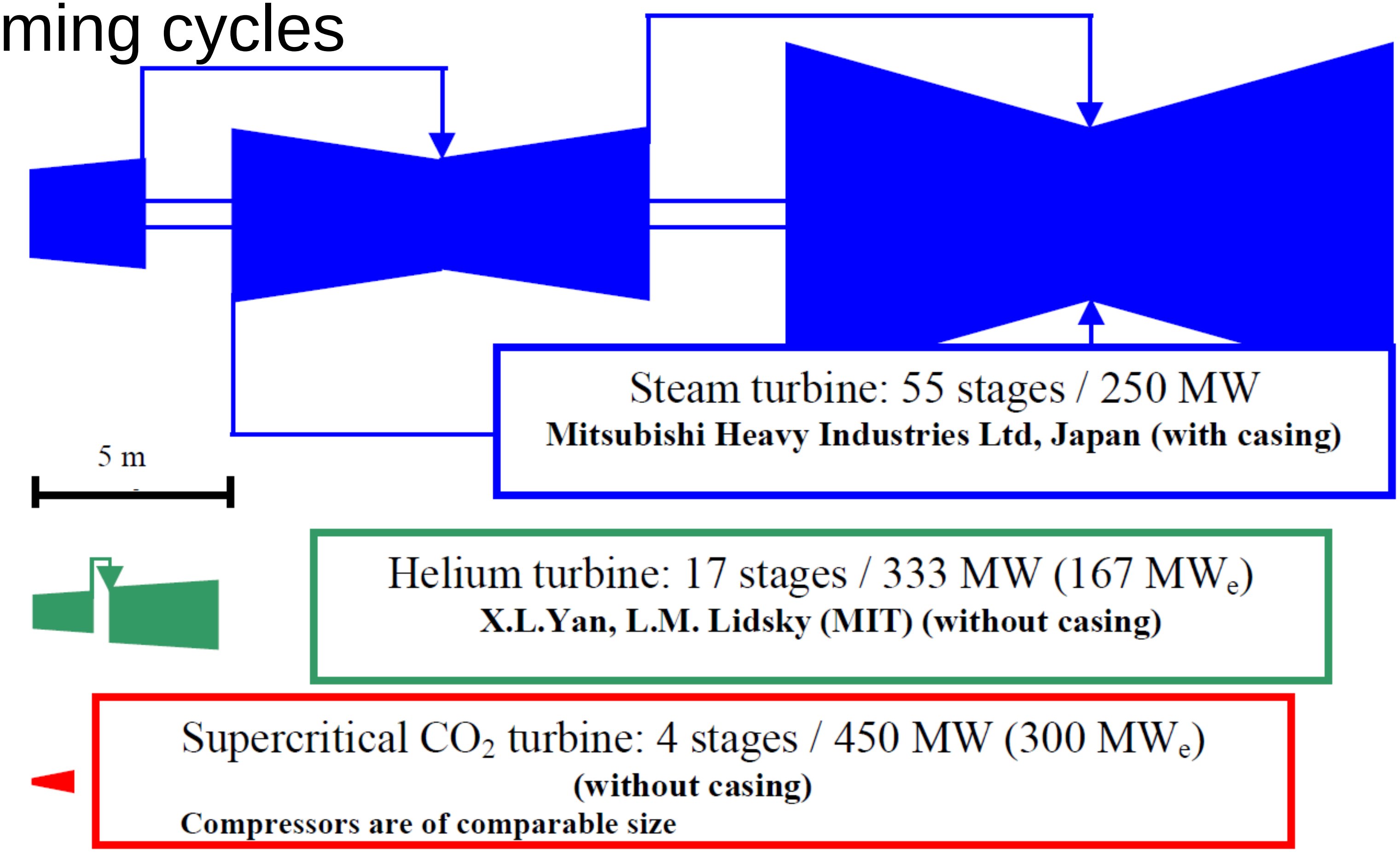
[6-5]

Ship-board Propulsion

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)

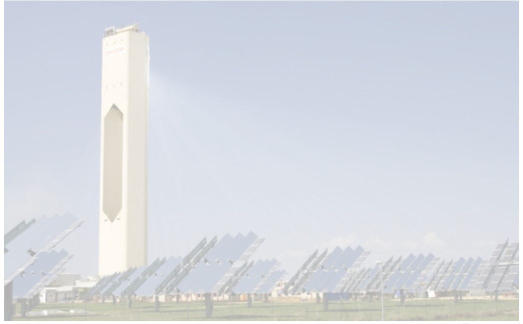
Supercritical CO_2 turbine: 4 stages / 450 MW (300 MW_e)

(without casing)

Compressors are of comparable size

Source: Dostal (2004)

Supercritical CO_2 in Power Cycle Applications

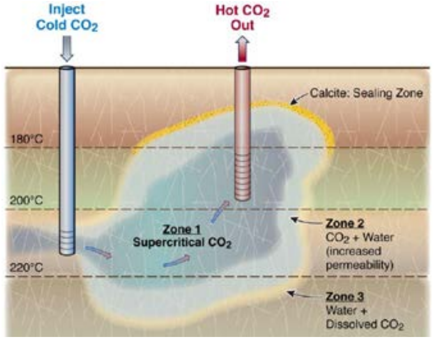

[6-1]

Concentrated Solar Power


[6-2]

Fossil Fuel

[6-3]



Geothermal


[6-4]

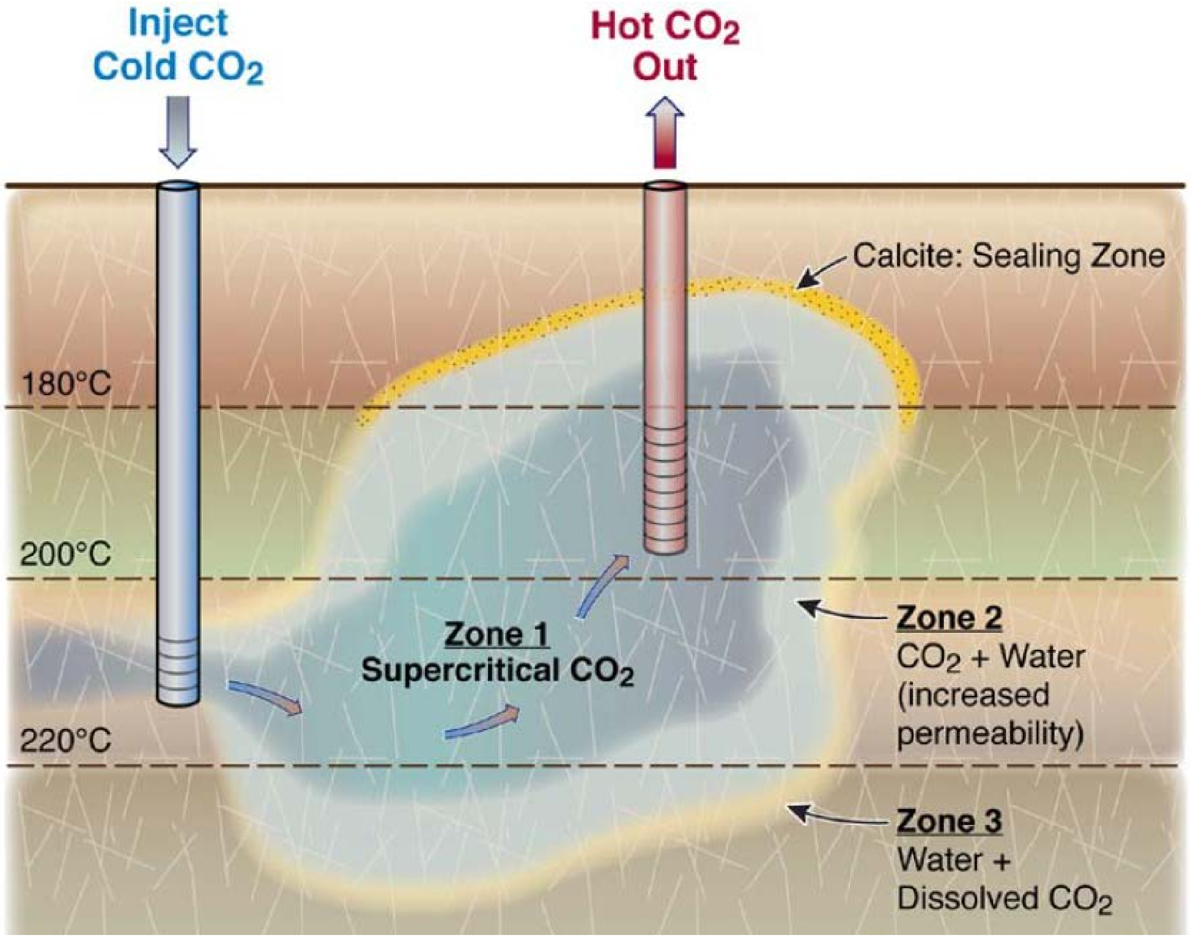
Nuclear


[6-5]

Ship-board Propulsion

Geothermal

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

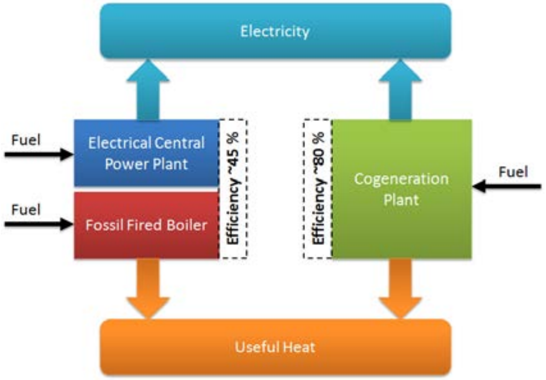


Pruess (May 19, 2010)

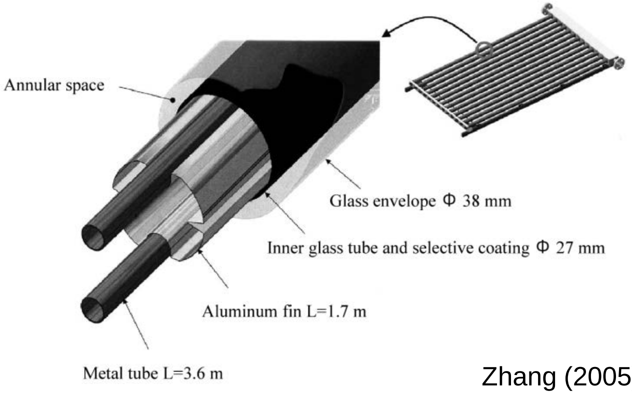
Other sCO_2 Power Cycle Applications

Image source: [6-11]

Waste Heat Recovery



Combined Heat & Power



Zhang (2005)

Non-Concentrated Solar Power

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]

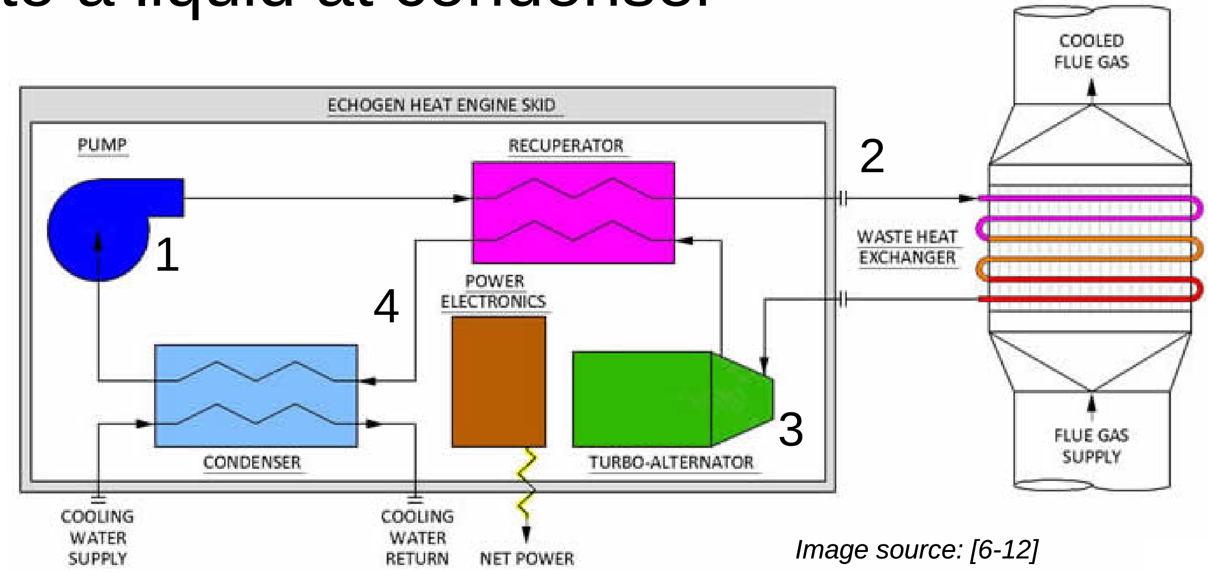
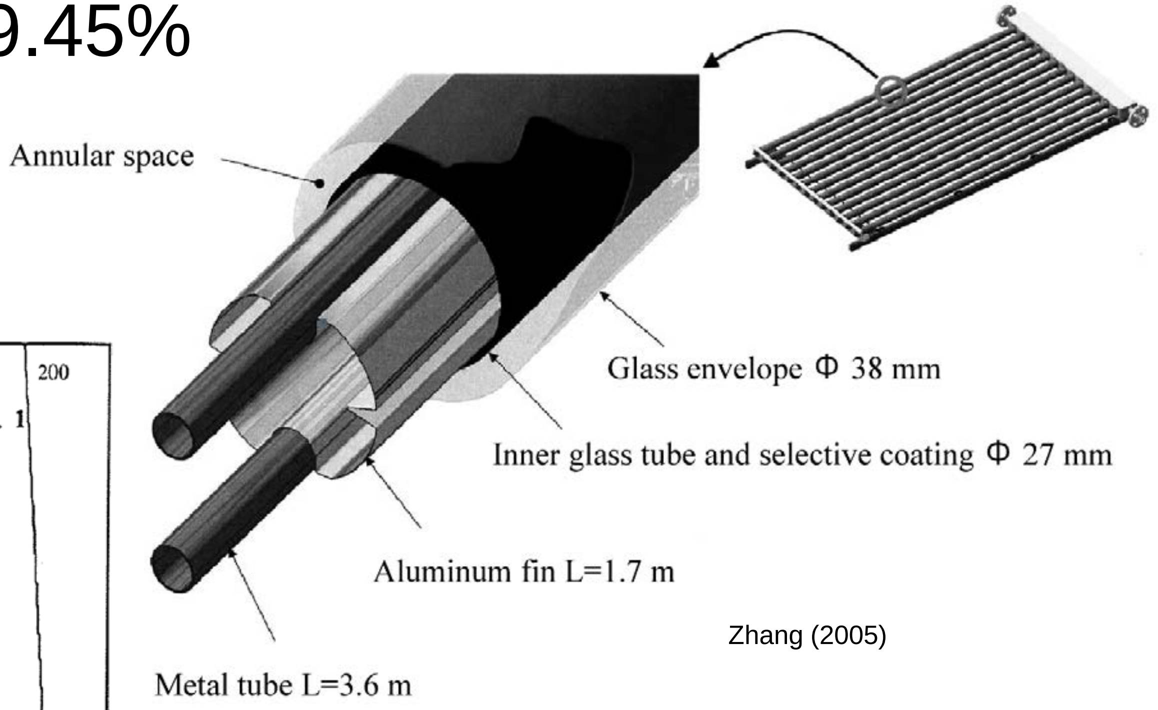


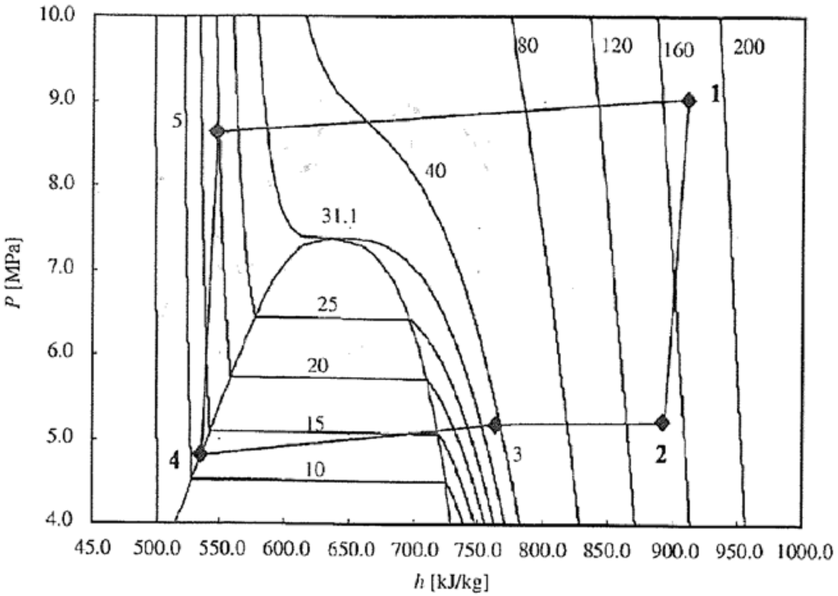
Image source: [6-12]

sCO_2 Rankine Cycle in Non-Concentrated Solar Power

- ❑ NCSP (Trans-critical Rankine) $T_t = 180°C$
  - $\eta_{e,exp} = 8.75\%-9.45\%$
- ❑ Photovoltaic
  - $\eta_{e,exp} = 8.2\%$



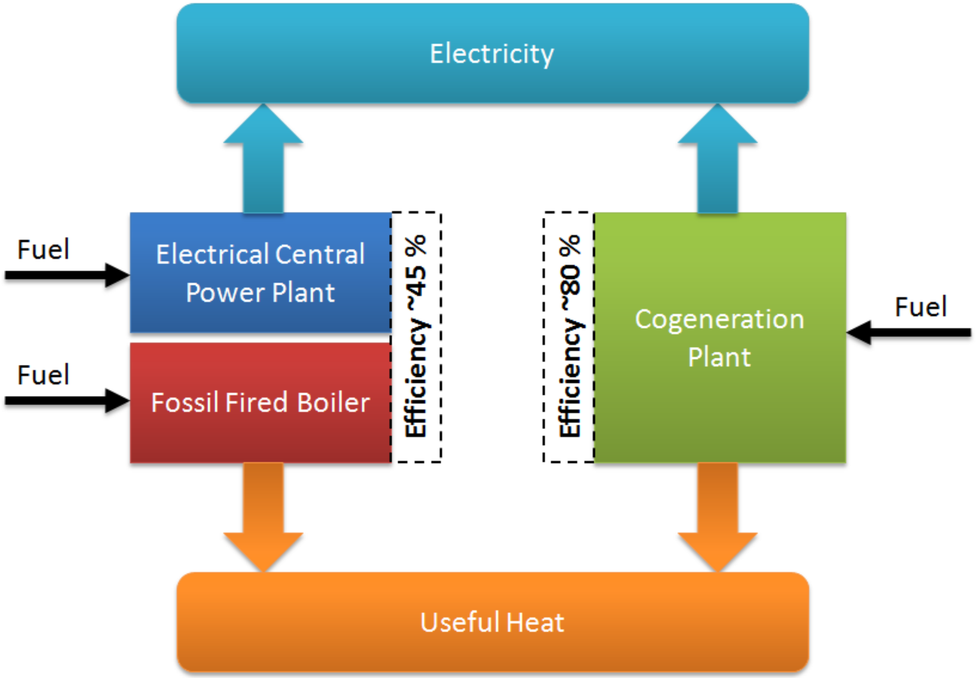
Zhang (2005)



Zhang (2007)

sCO_2 Rankine Cycle in Combined Heat and Power (CHP)

- ❑ Electrical efficiency
  - Higher than ordinary steam CHP
  - Cascaded s-CO2 plant performed best



Moroz (2014)

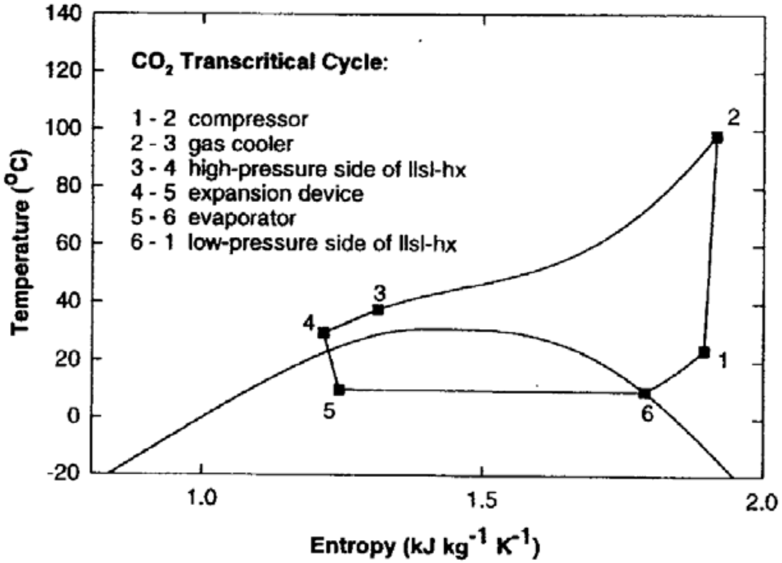
sCO_2 as a Refrigerant

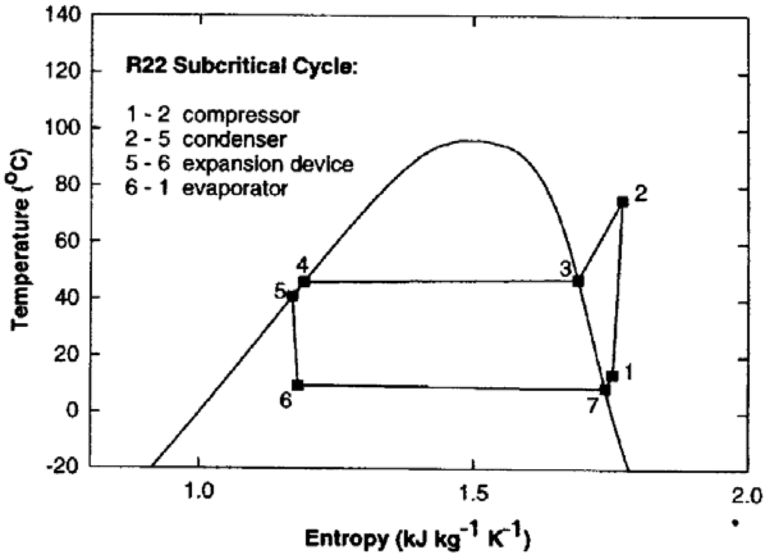
Image source: [6-13]

Image source: [6-14]

sCO_2 vs R-22 in Refrigeration

- Employed MCHEs
- Summary
  - CO_2 COP vs. R-22
    - 42% Lower at 27.8°C
    - 57% Lower at 40.6°C
  - Majority of entropy generation in CO2 cycle was in the expansion device





Brown (2002)

sCO_2 in Heat Pumps

- ❑ sCO_2 replaced as a refrigerant in domestic heat pump hot water heater in Japan.
  - COP = 8, 90°C (194°F)
  - Compared to COP_{typ}=4-5

$$\left(COP = \frac{Q_h + W_e}{W_e} \right)$$

Image source: [6-14]

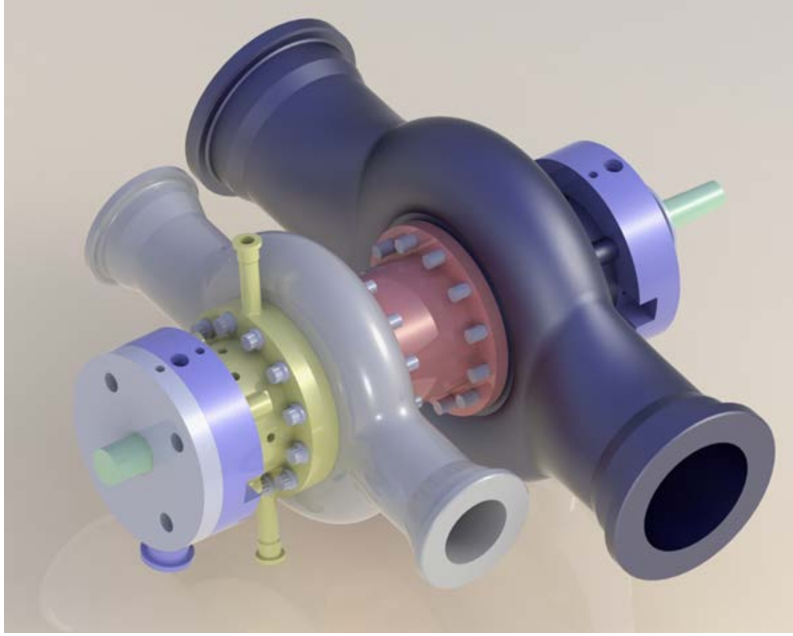
EcoCute Heat Pump (2007)

Supercritical CO_2 Power Cycles Symposium

sCO_2 Power Cycle Research Efforts

Development of a High Efficiency Hot Gas Turbo-expander and Low Cost Heat Exchangers for Optimized CSP SCO$_2$ Operation

J. Jeffrey Moore, Ph.D.
Klaus Brun, Ph.D.
Pablo Bueno, Ph.D.
Stefan Cich
Neal Evans
Kevin Hoopes
Southwest Research Institute
C.J. Kalra, Ph.D.,
Doug Hofer, Ph.D.
Thomas Farineau
General Electric
John Davis
Lalit Chordia
Thar Energy
Brian Morris
Joseph McDonald
Ken Kimball
Bechtel Marine



Taken from SunShot Subprogram Review: Concentrating Solar Power (Sunshot Grand Challenge Summit
Anaheim, CA, May 19-22, 2014)

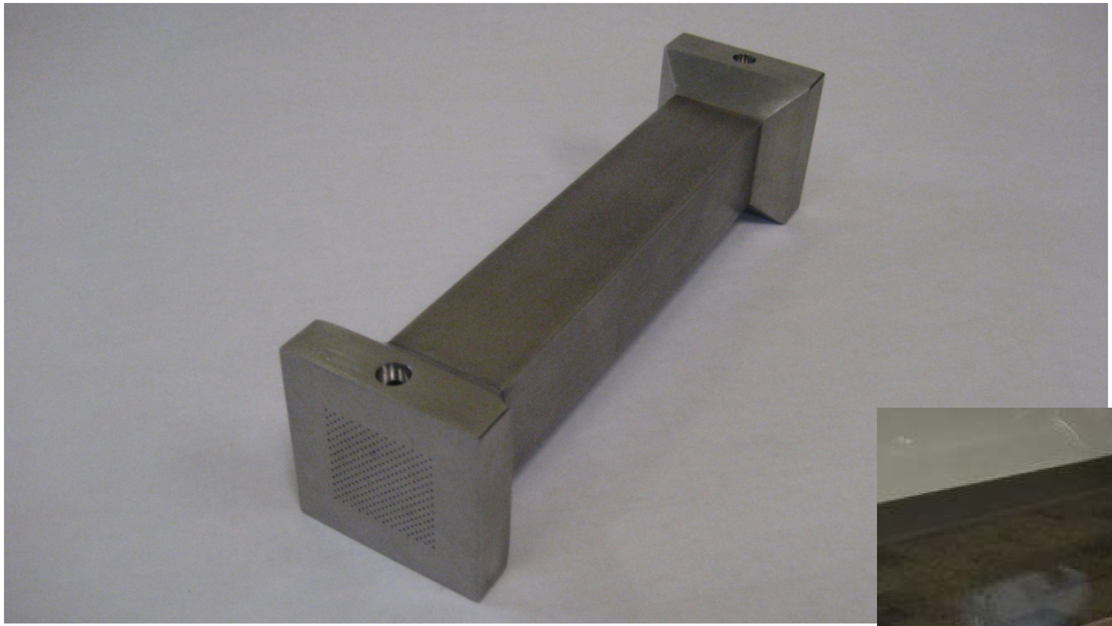
Project Objectives

- To develop a novel, high-efficiency supercritical sCO_2 turbo-expander optimized for the highly transient solar power plant duty cycle profile.
  - This MW-scale design advances the state-of-the-art of sCO_2 turbo-expanders from TRL3 to TRL6.
- To optimize compact heat exchangers for sCO_2 applications to drastically reduce their manufacturing costs.
- The turbo-expander and heat exchanger will be tested in a 1-MWe test loop fabricated to demonstrate component performance and endurance.
- Turbine is designed for 10 MW output in order to achieve industrial scale
- The scalable sCO_2 expander design and improved heat exchanger address and close two critical technology gaps required for an optimized CSP sCO_2 power plant
- Provide a major stepping stone on the pathway to achieving CSP power at $0.06/kW-hr levelized cost of electricity (LCOE), increasing energy conversion efficiency to greater than 50% and reducing total power block cost to below $1,200/kW installed.

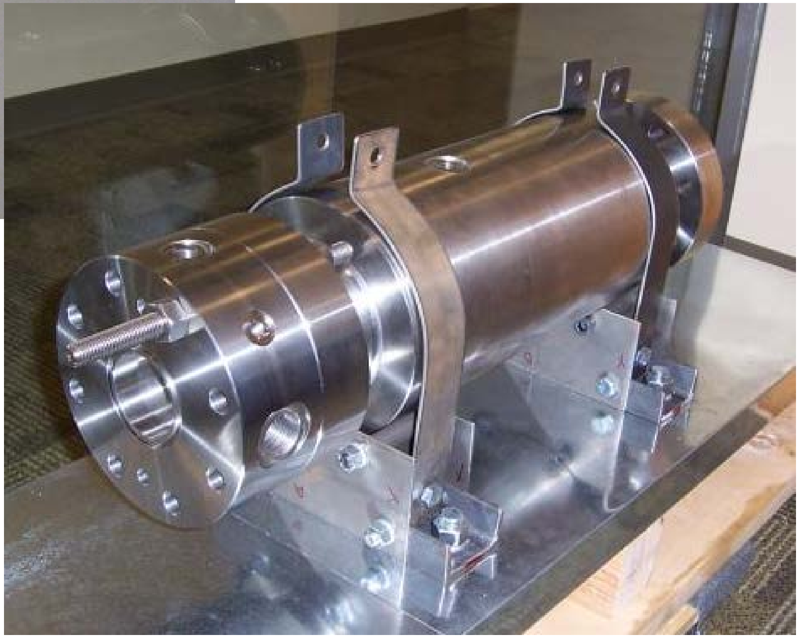
Project Approach

- Work has been divided into three phases that emulate development process from TRL3 to TRL6
- Phase I – Turbomachinery, HX, and flow loop design (17 months)
- Phase II – Component fabrication and test loop commissioning (12 months)
- Phase III – Performance and endurance testing (6 months)

Recuperator Prototypes – 5 and 50 kW



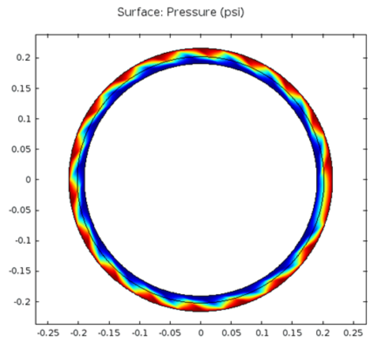
DMLS:
- Expensive and slow to build
- Highly automated
- High pressure drop
- Tested to 5000 psi



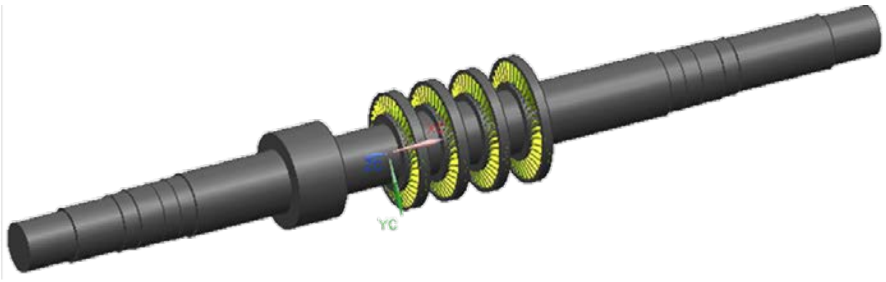
Laser Welded Construction:
- Undergoing flow tests
- Exceeded design predictions for HTC
- Held 2500 psi @ 600° F

TURBOEXPANDER DESIGN

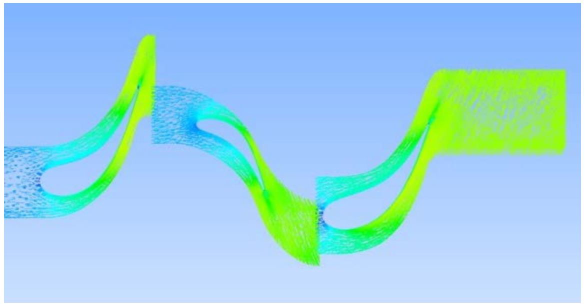
- A novel turboexpander has been designed to meet the requirements of the sCO2 power with these targets:
- ~14MW shaft power
- >700C inlet temp
- >85% aero efficiency



DGS Face Pressure Distribution from CFD

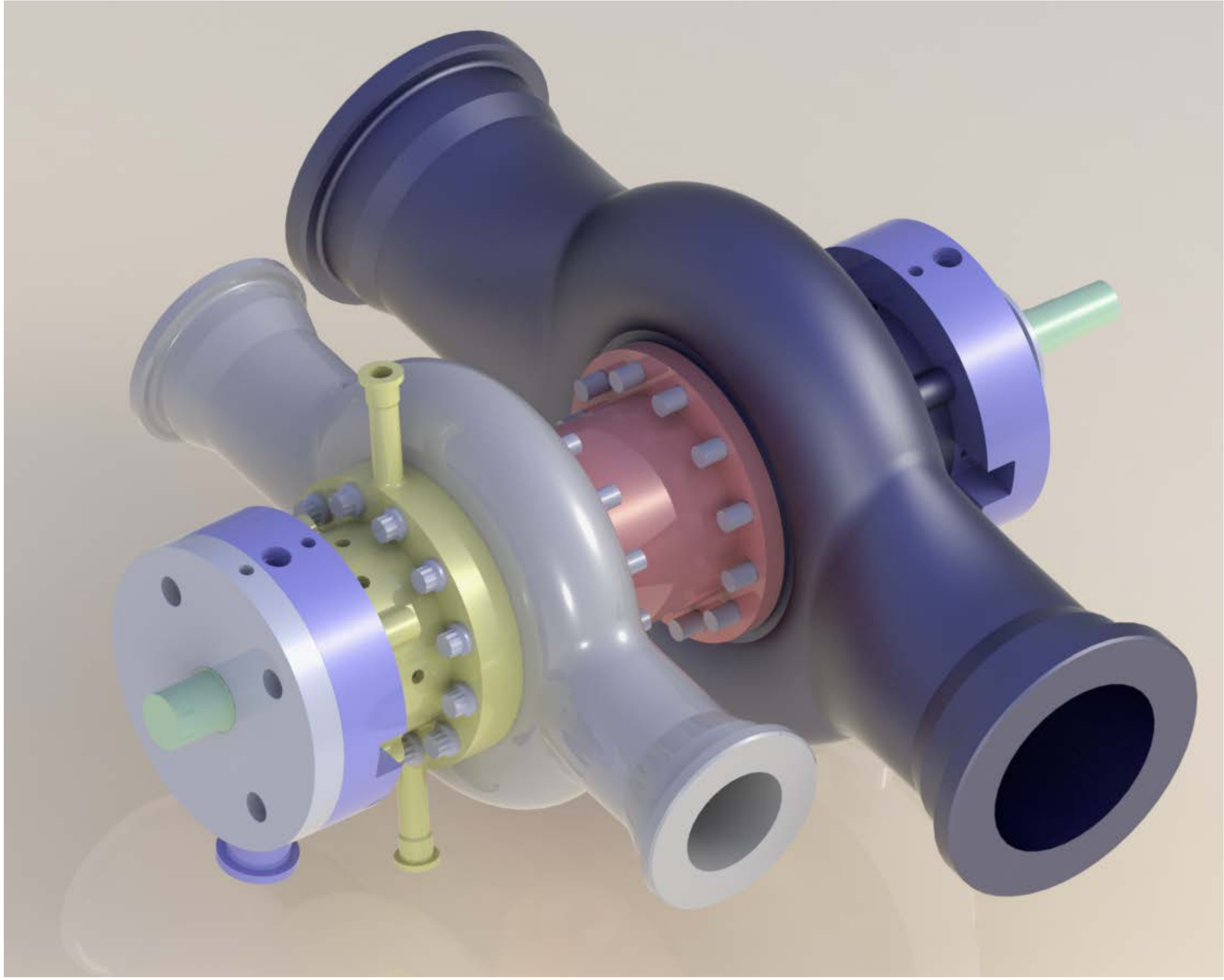


Multi-stage Axial Turbine

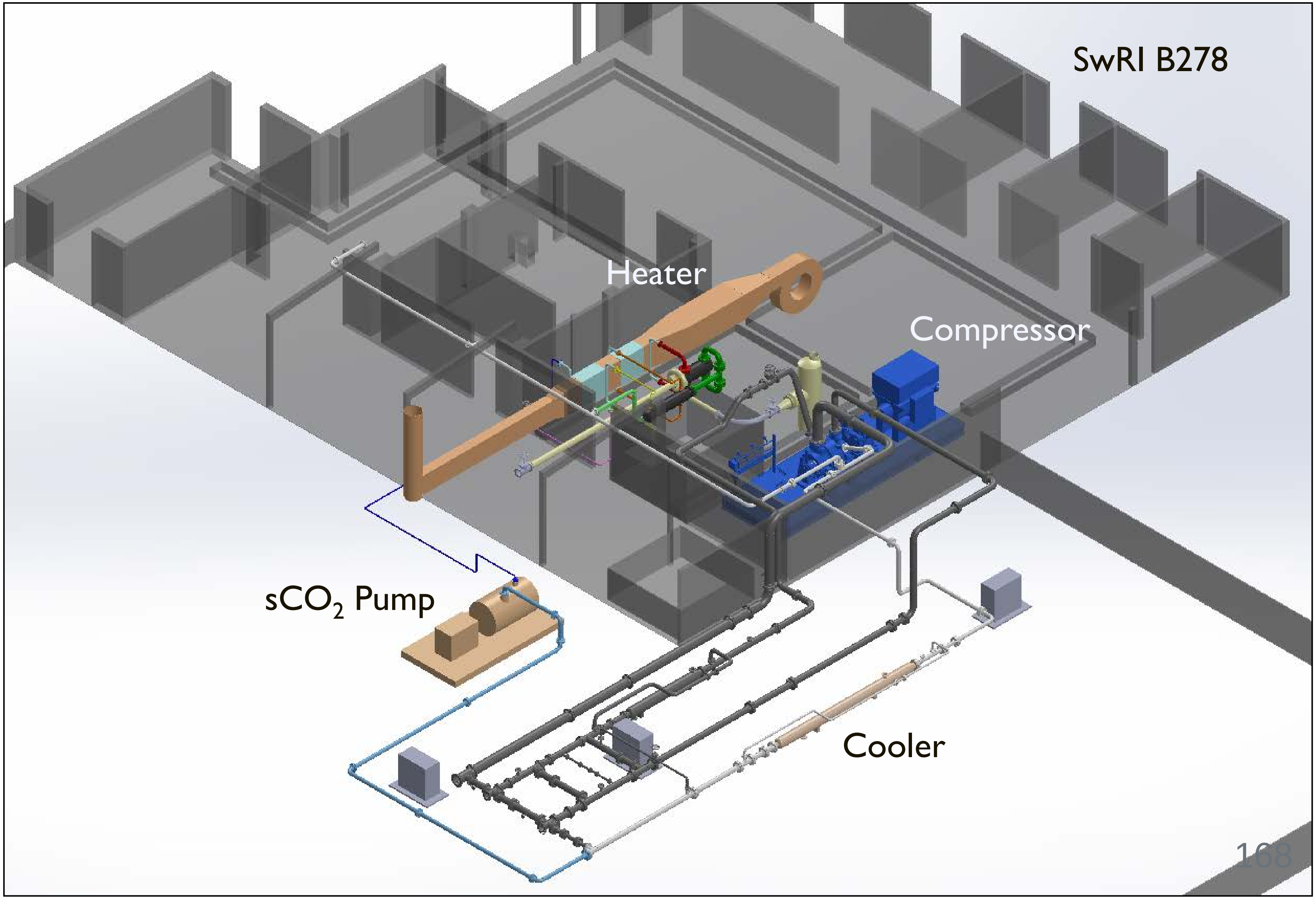


CFD Analysis

10 MW SCO2 Turbine Concept

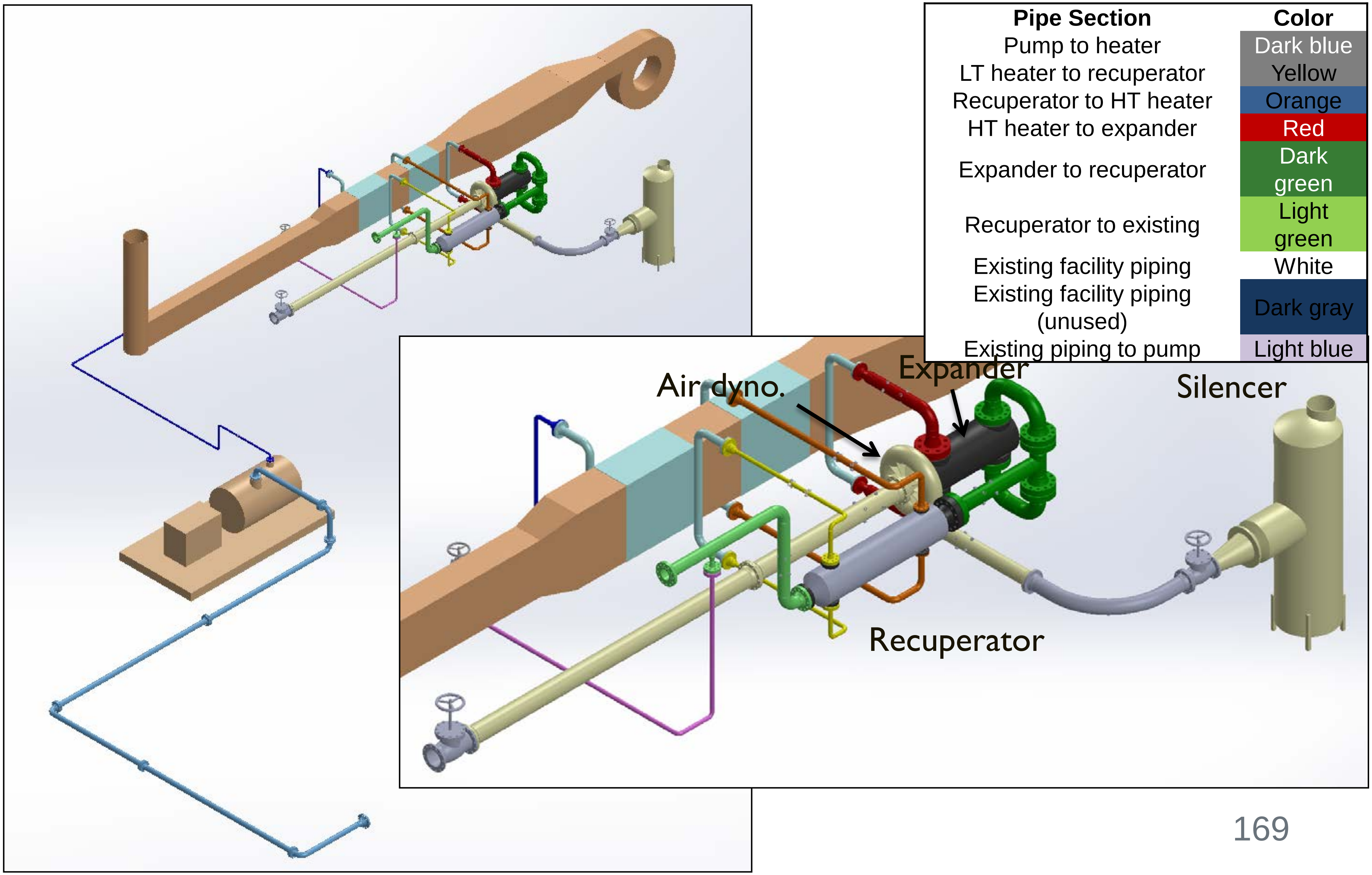


Test Loop Design



Mechanical Test Configuration

Pipe Section	Color
Pump to heater	Dark blue
LT heater to recuperator	Yellow
Recuperator to HT heater	Orange
HT heater to expander	Red
Expander to recuperator	Dark green
Recuperator to existing	Light green
Existing facility piping	White
Existing facility piping (unused)	Dark gray
Existing piping to pump	Light blue



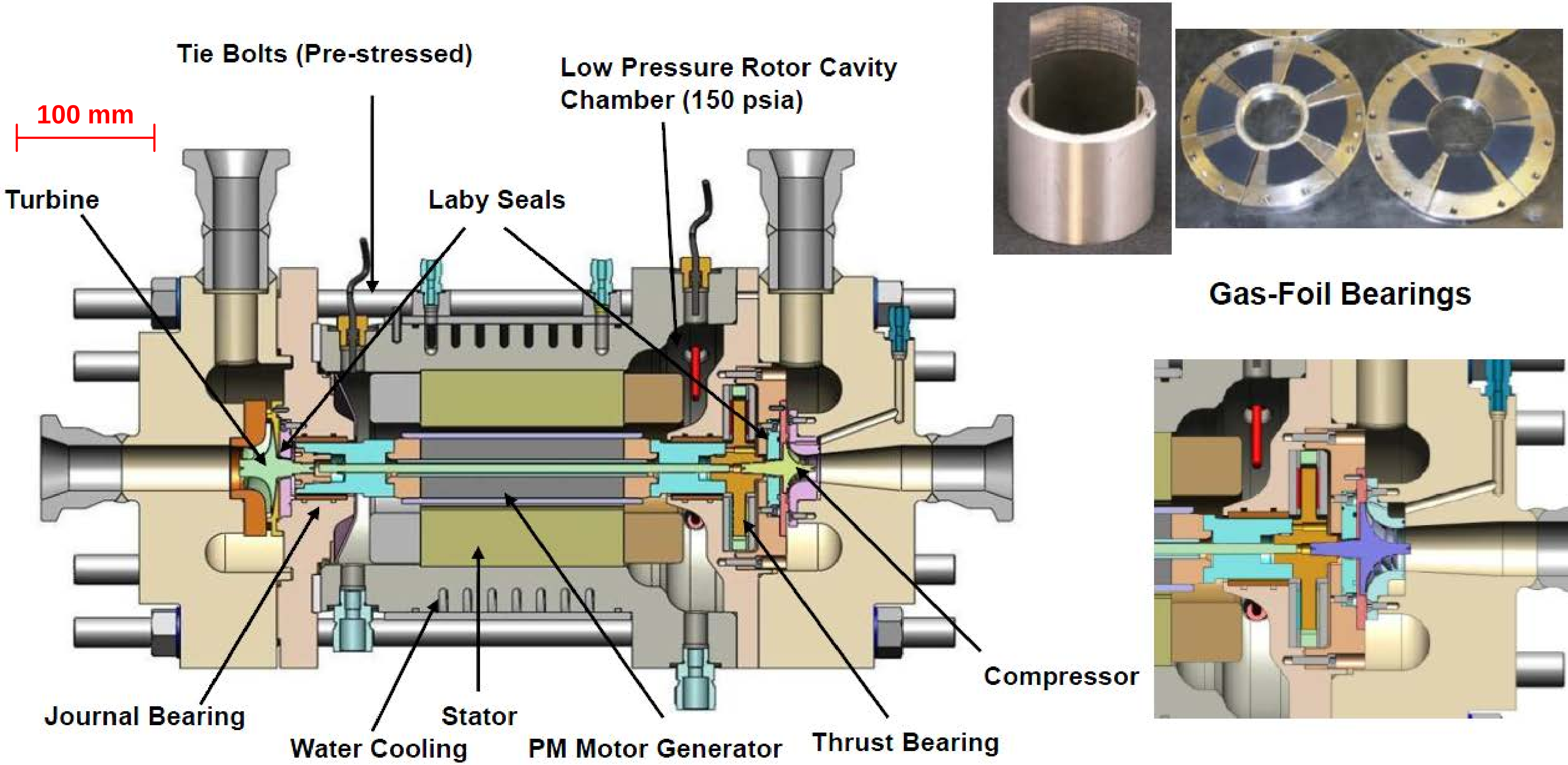
Future Work

- Test heat exchanger prototypes
- Heat exchanger design nearing completion
- Complete Turbomachinery Design
- Procure long lead items for expander and test loop
- Finalize test loop design

DOE sCO_2 Test Program

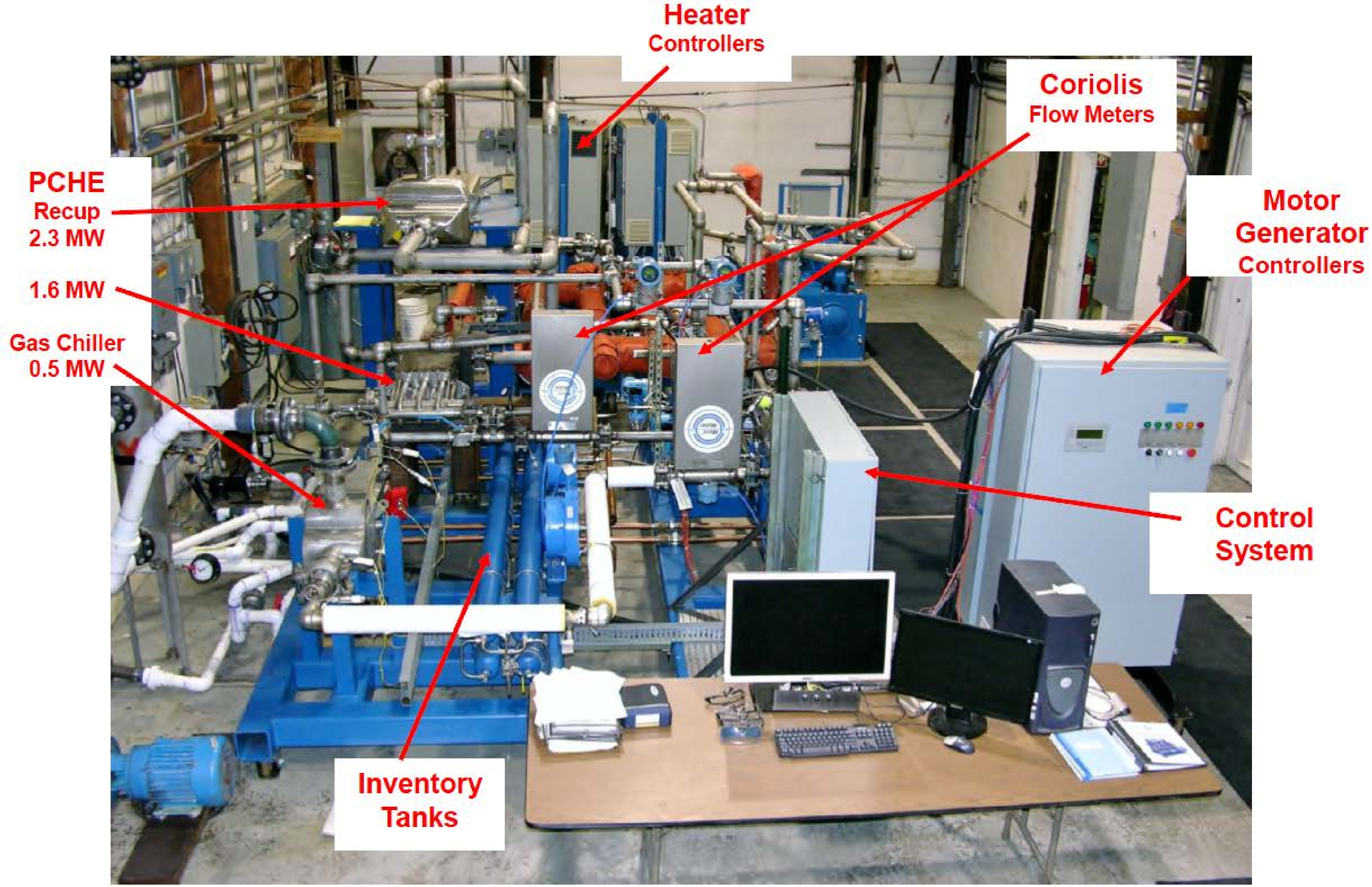
- ☐ Research compression loop
  - Turbomachinery performance
- ☐ Brayton cycle loop
  - Different configurations possible
    - Recuperation, Recompression, Reheat
  - Small-scale proof-of-technology plant
  - Small-scale components
    - Different than hardware for commercial scale

DOE sCO_2 Test Program Turbomachinery



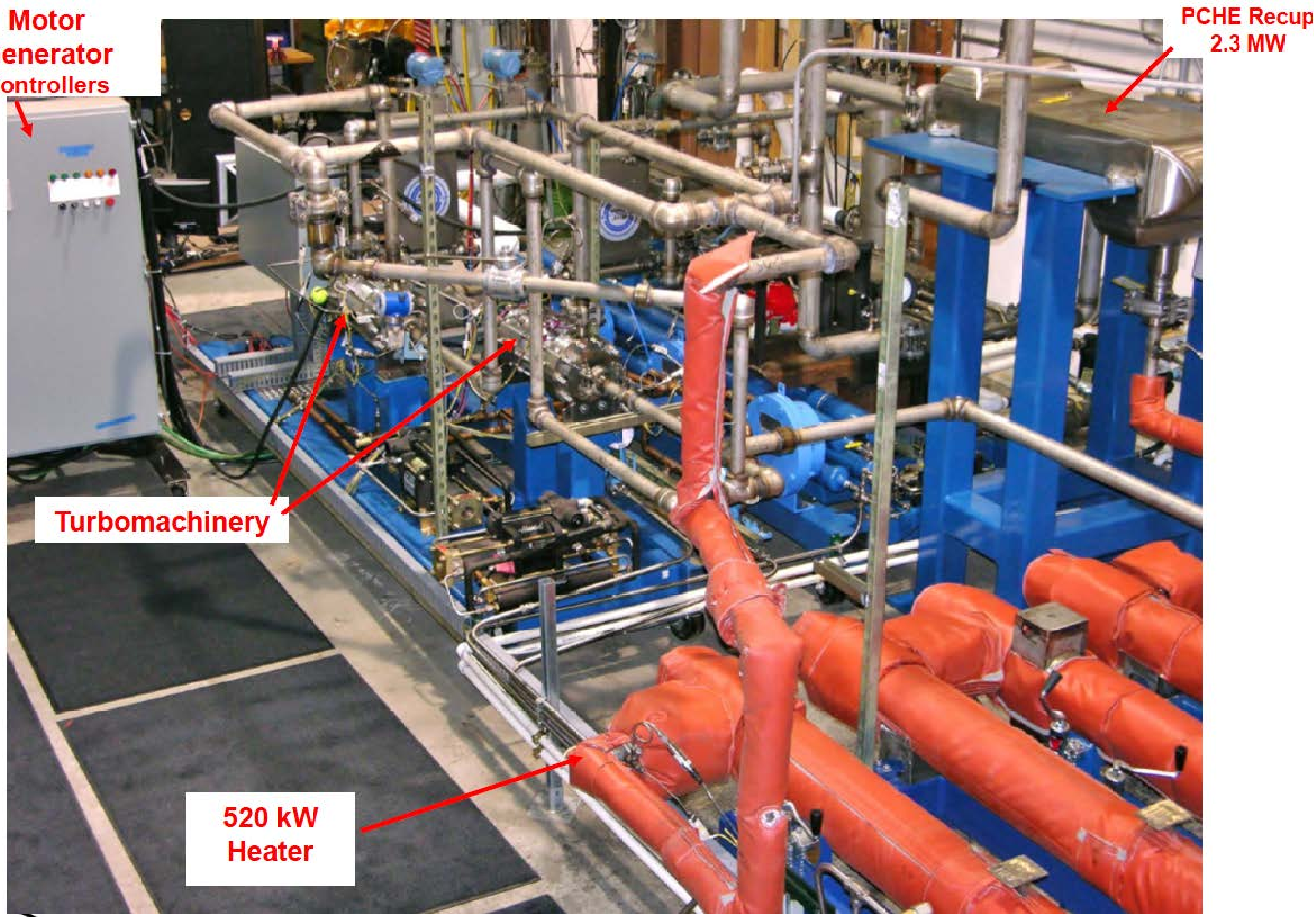
Source: Wright (2011)

sCO$_2$ Brayton Cycle Test Loop



Source: Wright (2011)

sCO_2 Brayton Cycle Test Loop

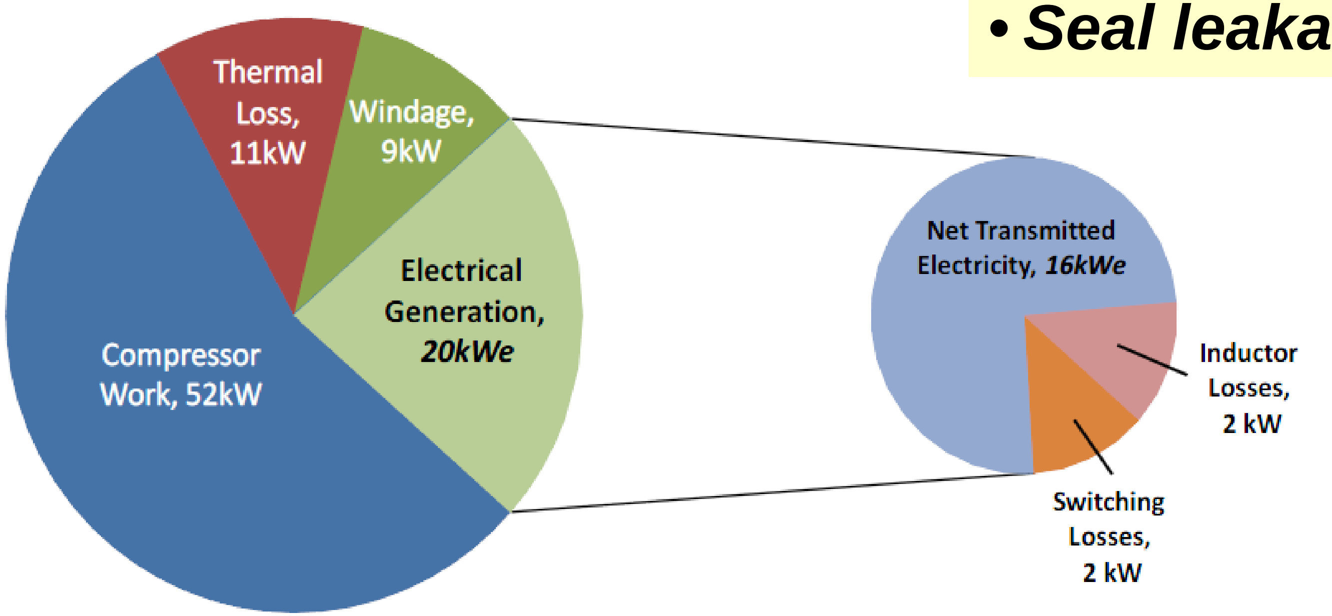


Source: Wright (2011)

sCO_2 Brayton Cycle Performance with Regeneration Config.

Maximum Case:
Total Turbine Work, 92 kW

Improve with larger scale:
- ***Windage losses***
- ***Thermal losses***
- ***Seal leakage***

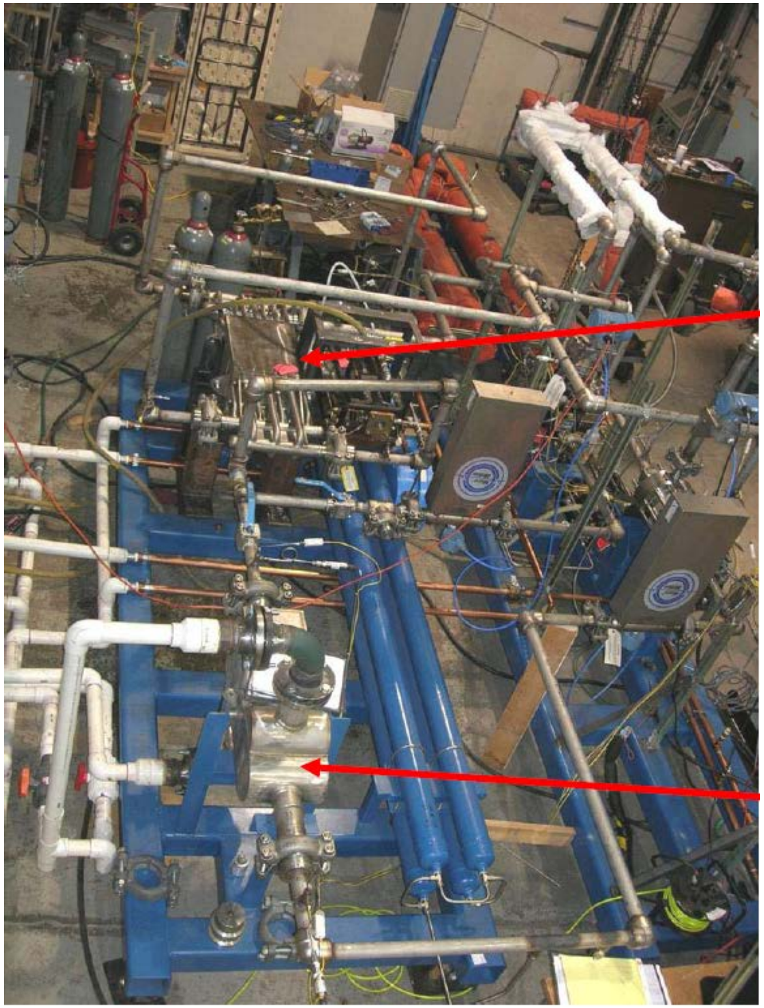


Source: Conboy et al. (2012)

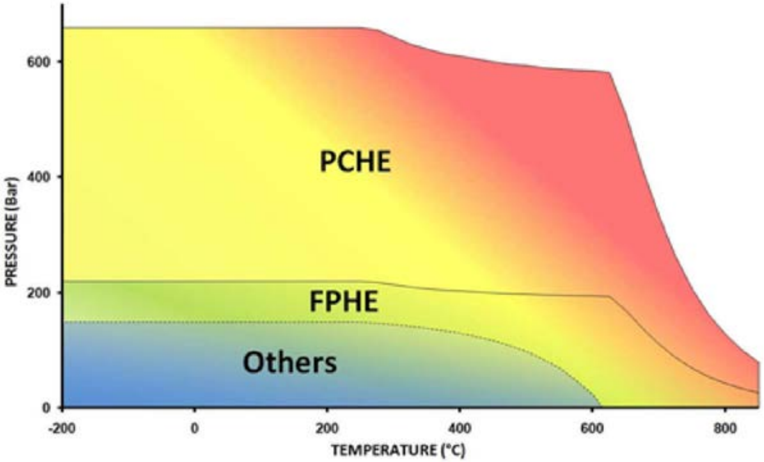
DOE sCO_2 Test Program Summary

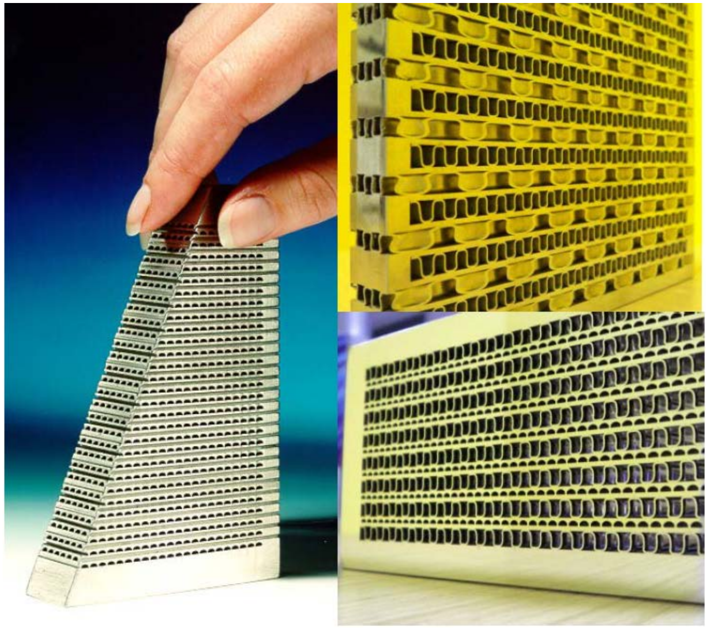
- ☐ Major milestones
  - Test loops operational
  - Demonstrate process stability/control
- ☐ Areas for future development
  - Heat exchanger performance
  - Larger scale test bed
    - Utilize commercial-scale hardware
    - Demonstrate more-realistic (better) performance
  - CO_2 mixtures

Printed Circuit Heat Exchanger (PCHE)



sCO$_2$ test loop used by Sandia/ Barber-Nicholls



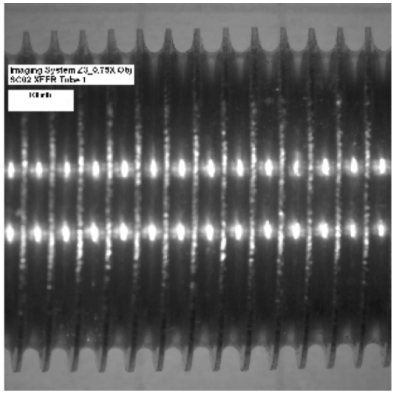


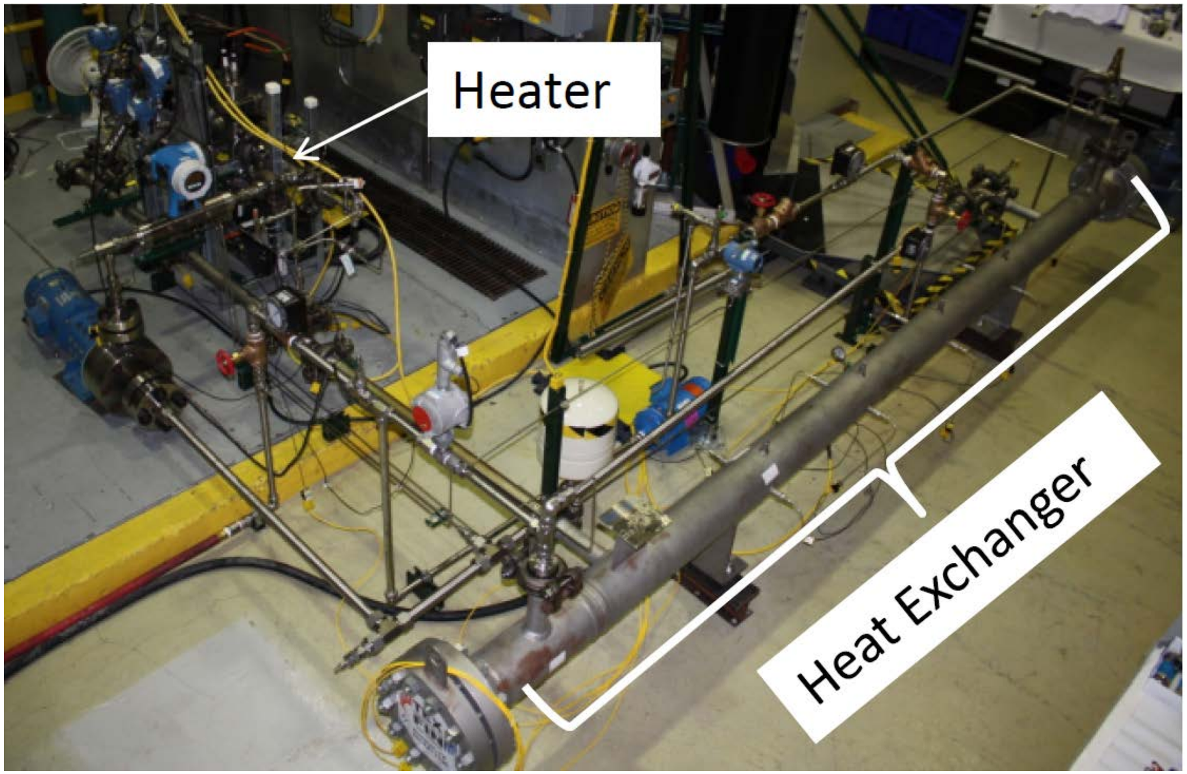
Heatric PCHE

Le Pierres (2011)

Heat Exchanger Testing (Bechtel)

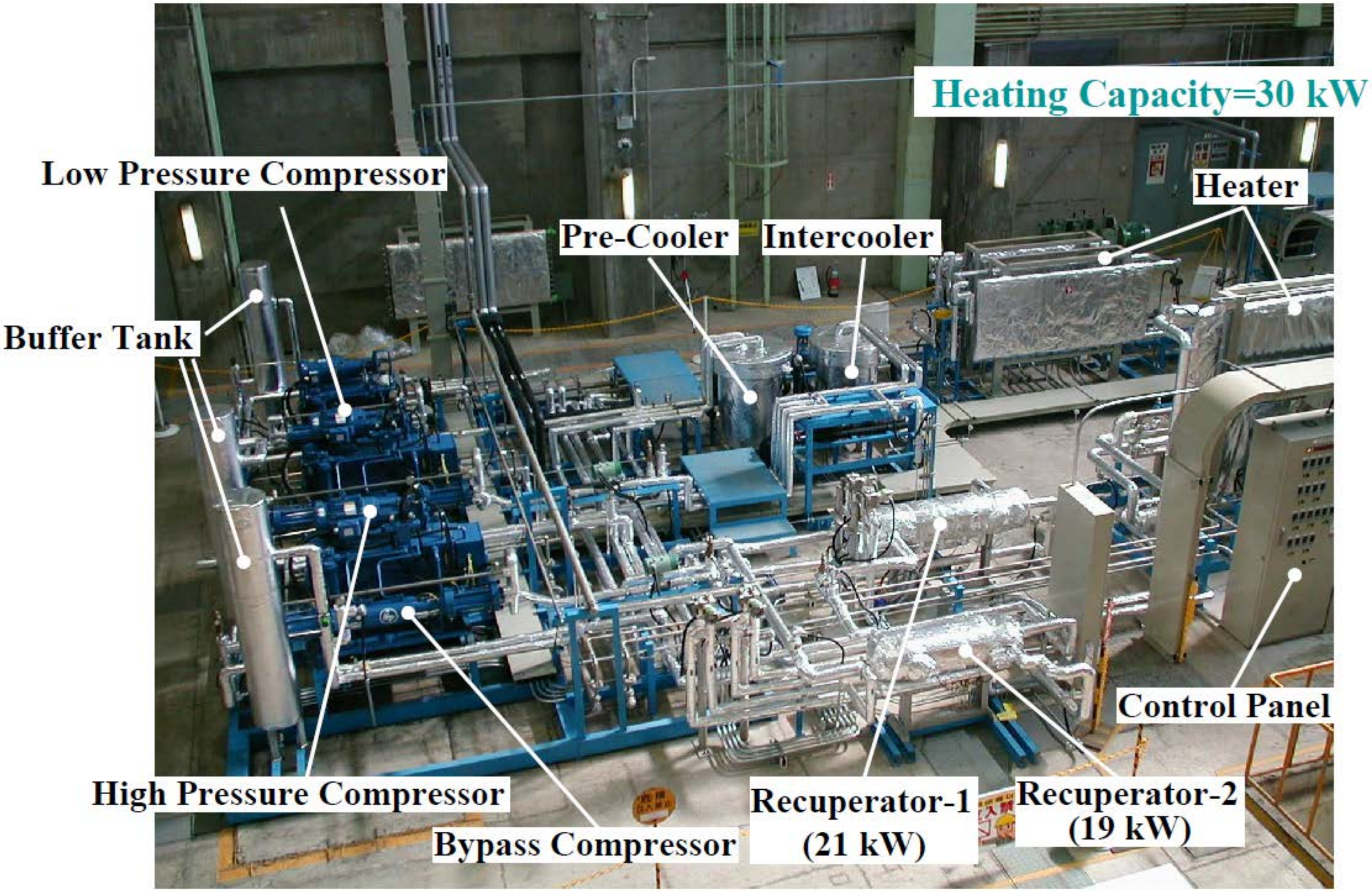
- 150 kW
- 8000 lbm/hr sCO_2
- 2500 psi





Nehrbauer (2011)

Tokyo Institute of Technology (TIT)



Supercritical CO_2 Cycle Mockup Test Loop

- 1. Compressor work reduction around the critical point,
  2. Pressure drop performance of new MCHE

(Kato et al., 2007)

Corrosion Loop at Tokyo Institute of Technology

316 SS, 12% Cr alloy, 200-600°C, 10 Mpa CO_2, Kato et al. (2007)

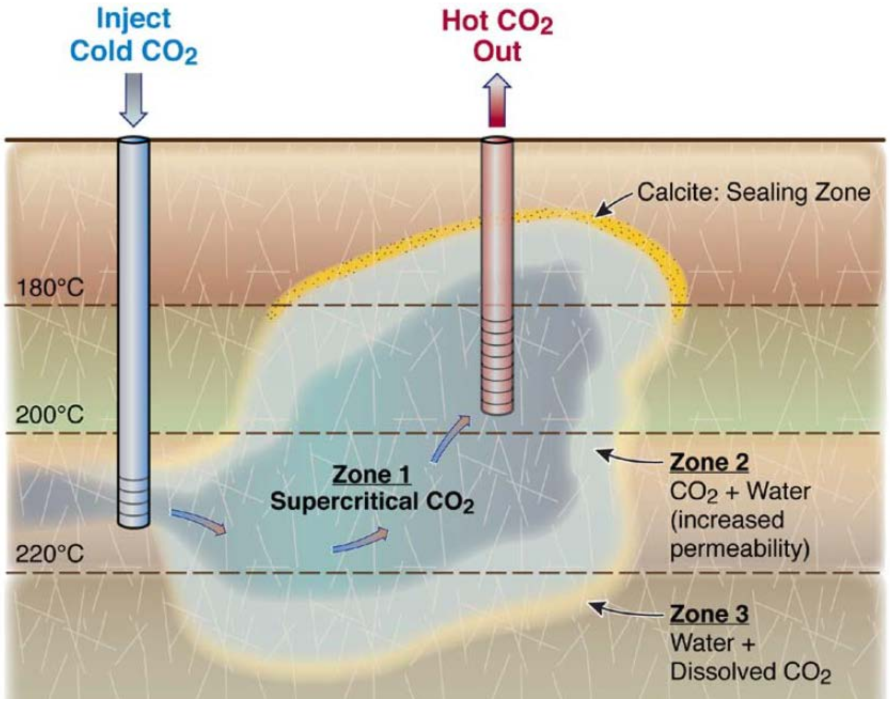
Other sCO_2 Corrosion Test Facilities

Guoping (2009)

- ❑ MIT - 650°C, 22 MPa
  - Steels
- ❑ UW - 650°C, 27 MPa
  - Steels
- ❑ French Alternative Energies and Atomic Energy Commission - 550°C, 25 MPa
  - Steels
- ❑ MDO Labs – 54.4°C, 12.4 MPa
  - Elastomers, engineering plastics, rubbers, etc.

Geothermal Research

- Explore the feasibility of operating enhanced geothermal systems (EGS) with CO_2 as heat transmission fluid
- Collaboration between LBNL (Pruess), UC Berkeley (Glaser), Central Research Institute of the Electric Power Industry, Japan (Kaieda) and Kyoto University (Ueda)
  - UC Berkeley: laboratory testing of CO_2 heat extraction
  - Japan: inject brine-CO_2 mixtures into Ogachi HDR site (T ≈ 210°C, P ≈ 100 bar)
  - LBNL: model reactive chemistry induced by brine-CO_2 injection



Schematic of EGS with sCO_2

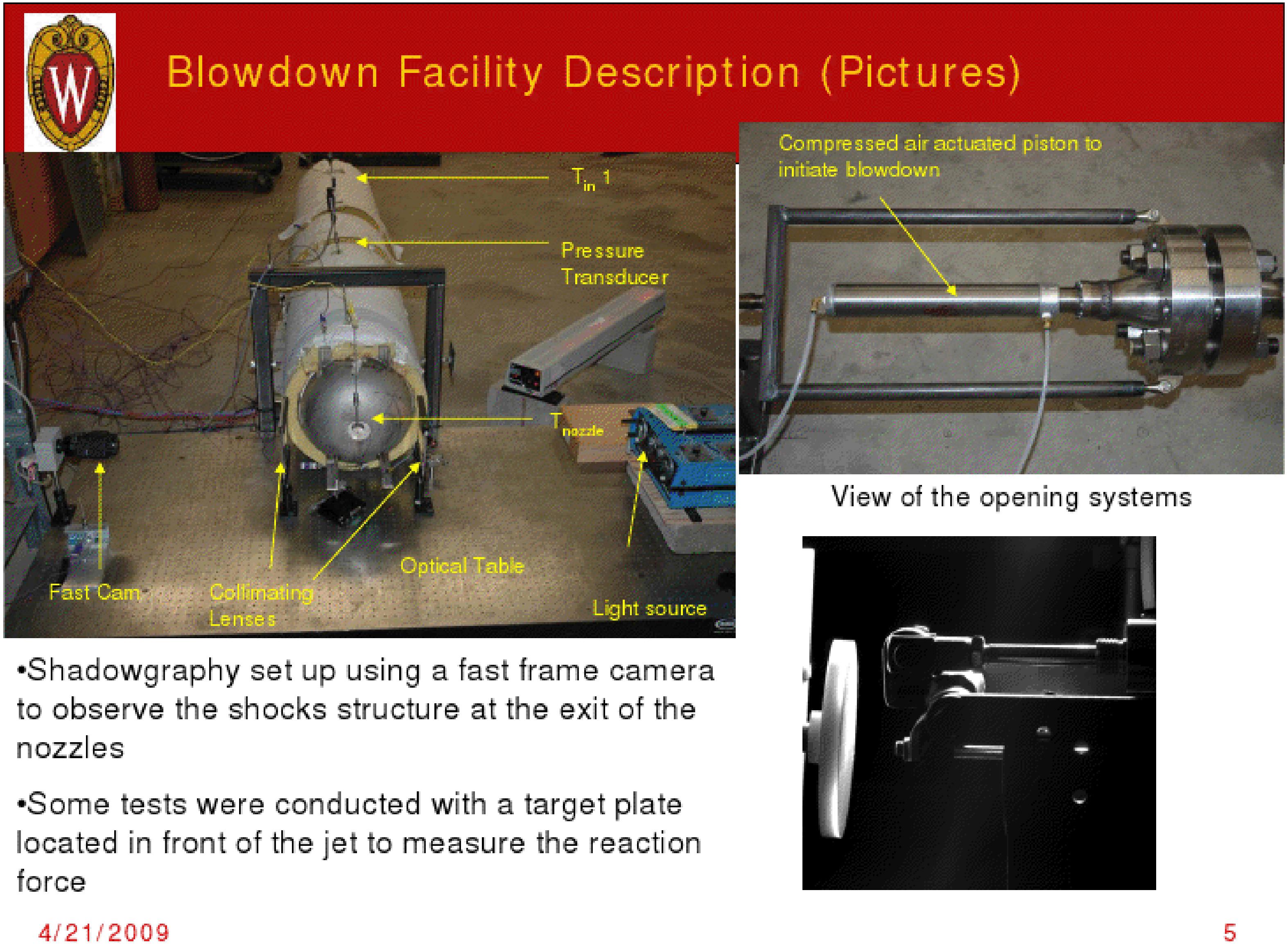
Pruess (May 19, 2010)

- Fructure type geothermal reservior
- Experience and results of circulation tests for the past 20 years or more
- Reservior temperature:more than 200℃

Ogachi, Japan – HDR Site

Pruess (May 18, 2010)

sCO$_2$ Critical Flow (Univ. Wisconsin)



Blowdown Facility Description (Pictures)

View of the opening systems

- Shadowgraphy set up using a fast frame camera to observe the shocks structure at the exit of the nozzles
- Some tests were conducted with a target plate located in front of the jet to measure the reaction force

4/21/2009

5

(Anderson, 2009)

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

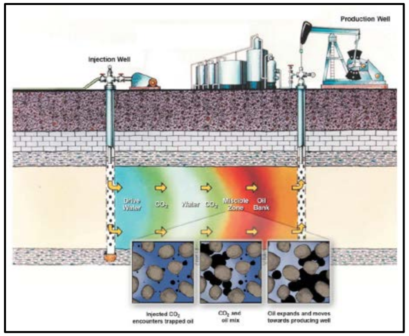
☐Mixture of sCO_2 and other fluids
☐Physical property testing of CO_2 mixtures at extreme conditions with significantly reduced uncertainties (i.e. $\leq$ 1%)

10 MW Scale Pilot Plant

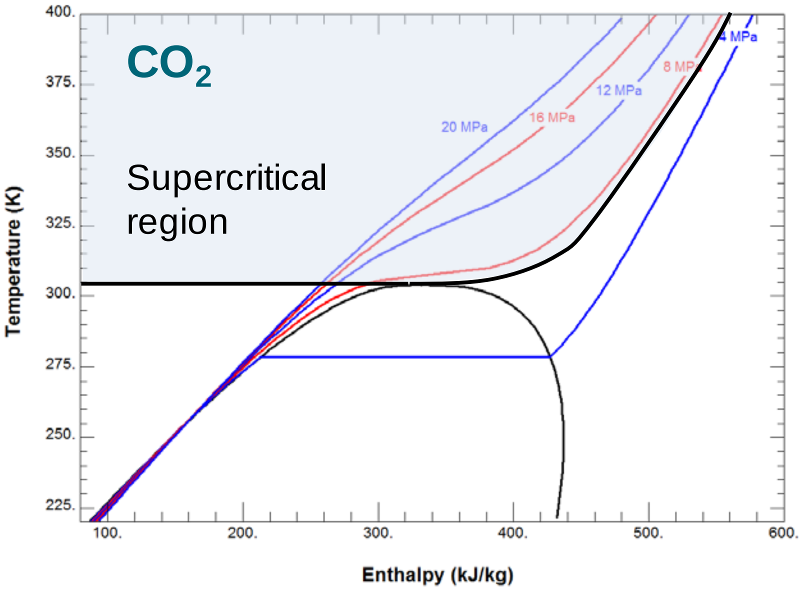
Summary

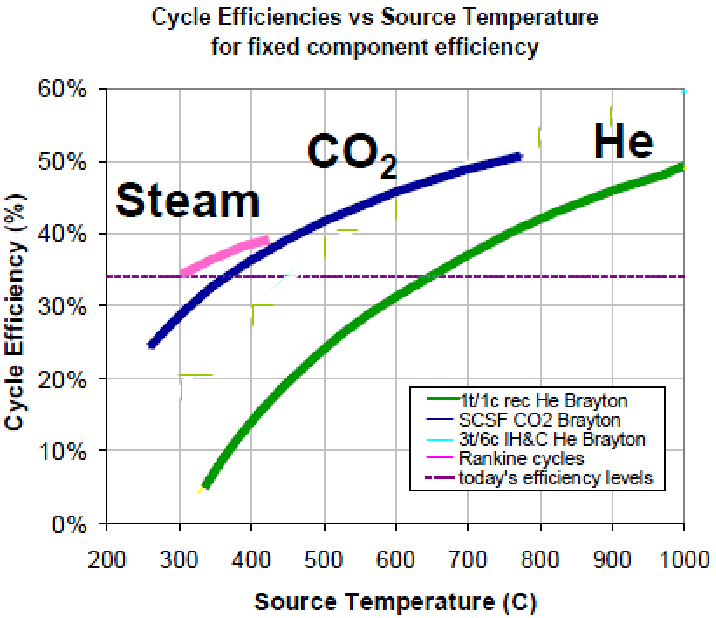
Both supercritical power cycles and the use of sCO_2 are not new concepts

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



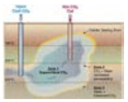

Cycle Efficiencies vs Source Temperature for fixed component efficiency

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

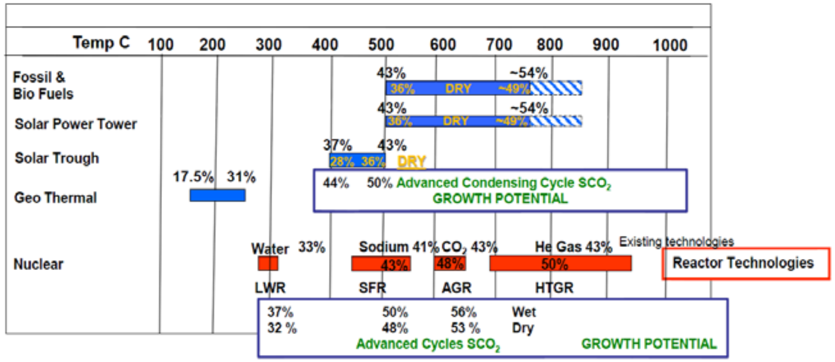

Concentrated Solar Power


Fossil Fuel

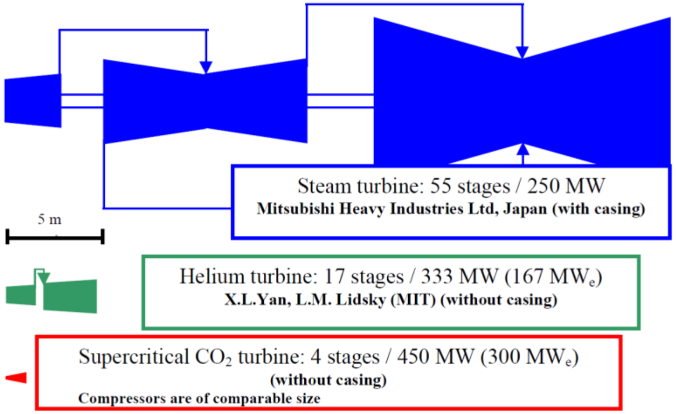

Geothermal


Nuclear


Ship-board Propulsion



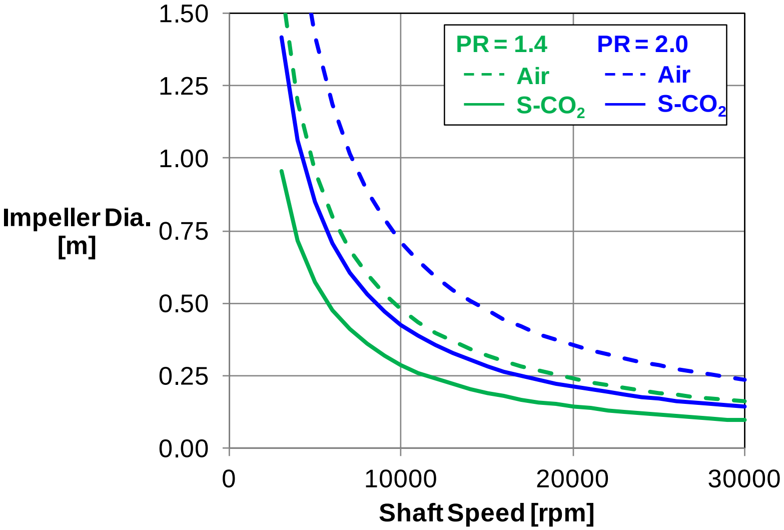
The combination of favorable property variation and high fluid density of sCO_2 allows small footprint of machinery



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?