# Supercritical sCO2 Symposium 2026

- Welcome
- 12:00-6:00 pm – Tutorials:
  - sCO2 Power Cycles Fundamentals Tutorial (SwRI)
  - sCO2 Cycles Tutorial (SwRI/Echogen)
  - sCO2 Oxy-Combustion Tutorial (SwRI/C. S. Mines)
  - sCO2 Turbomachinery Tutorial (SwRI)
  - sCO2 Materials Tutorial (GTI/Carleton/Epri)
  - sCO2 Heat Exchanger Tutorial (SwRI / Heatric/Thar)
- 7 pm - Industry Sponsored Reception – 8 Rivers - Keynote

# Tutorial:
# Fundamentals of Supercritical $CO_2$

Mar 2, 2026

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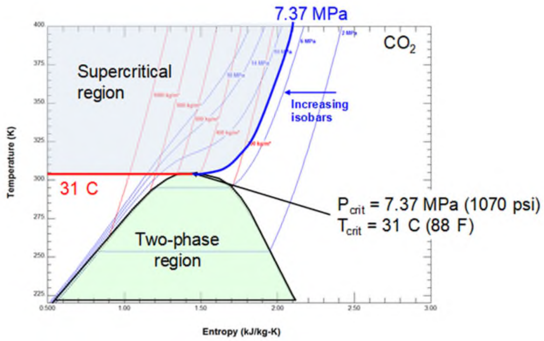
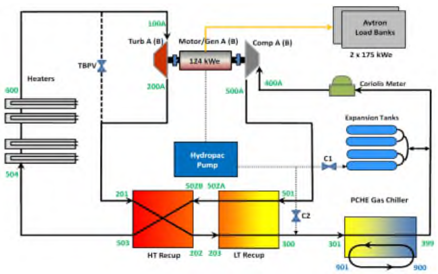
*Southwest Research Institute*

# This tutorial provides an introduction to $sCO_2$ in power cycle applications




**$CO_2$ and supercritical $CO_2$ ($sCO_2$)**



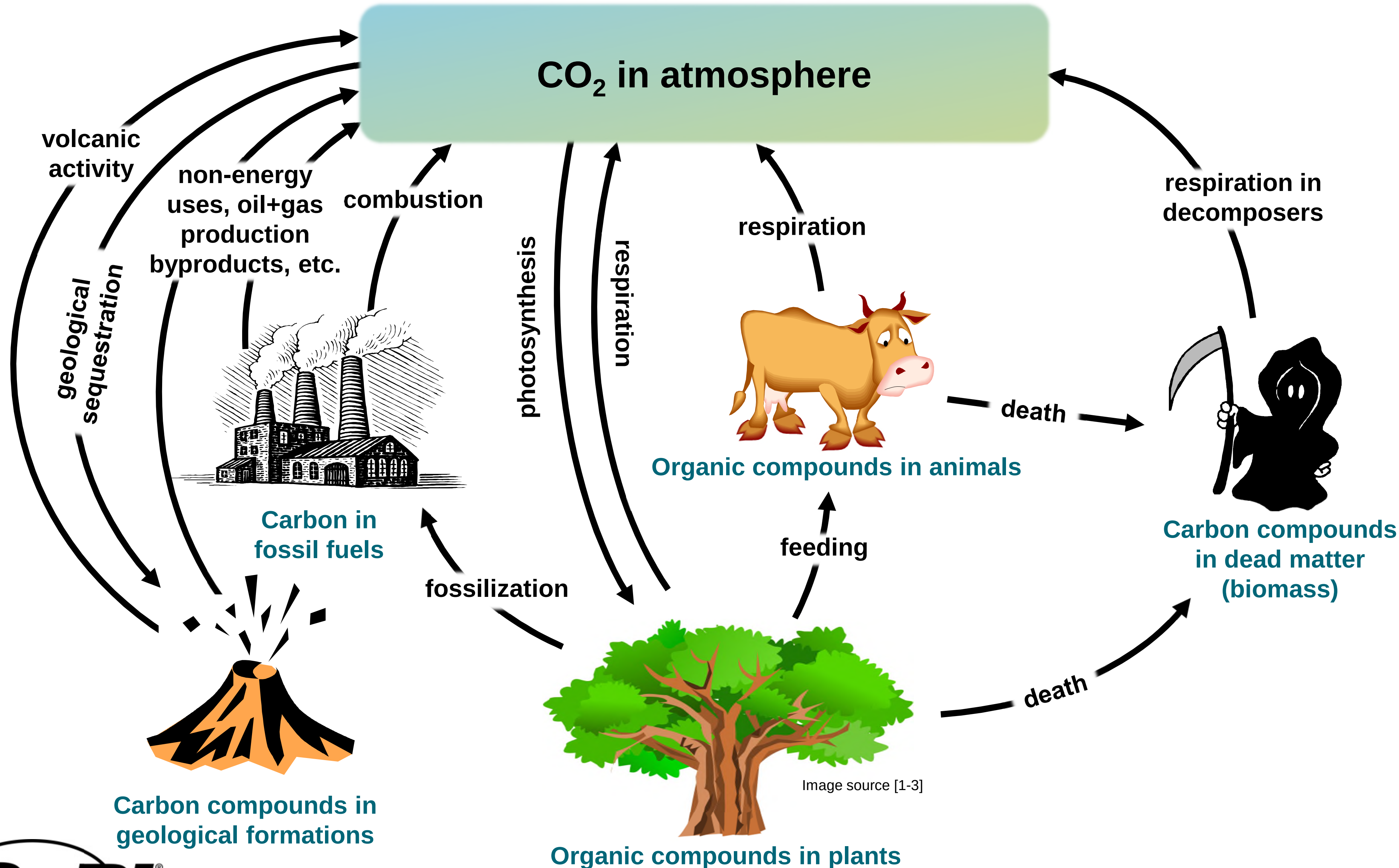

**$sCO_2$ loop hardware & Cycles**


**Power cycle applications**

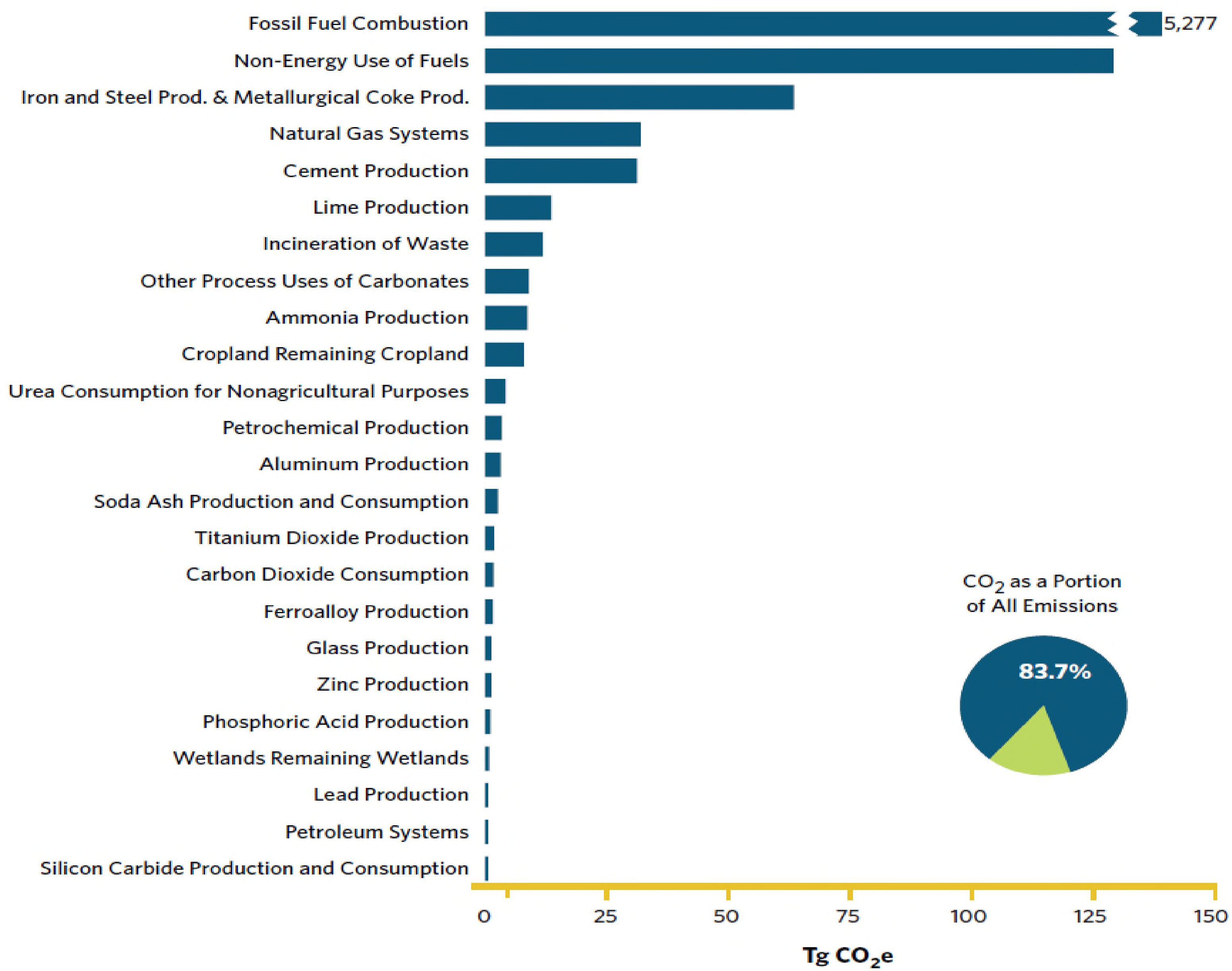
**Research and future trends**

# $CO_2$ General Information

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

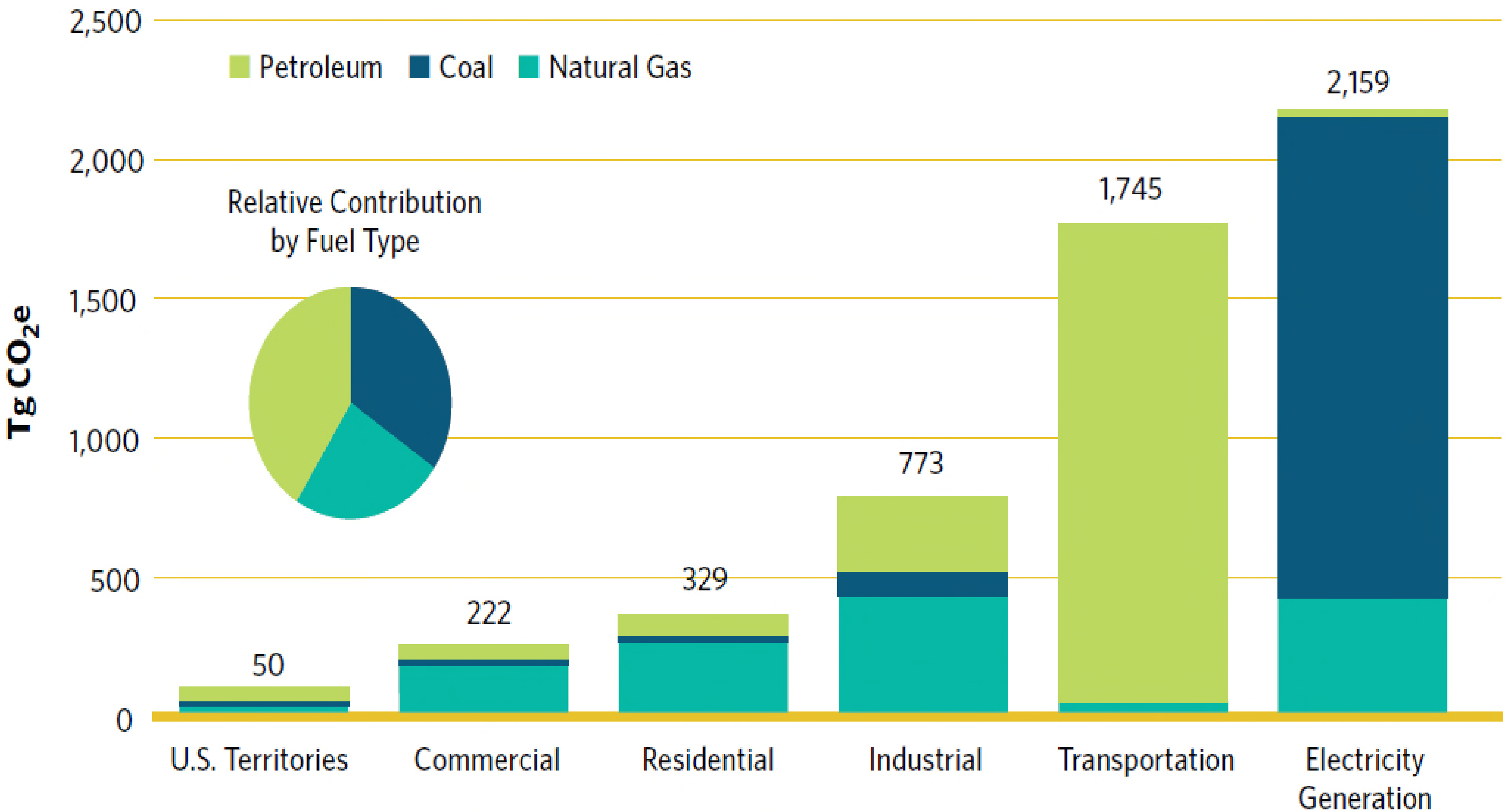


# Fossil fuel combustion is the largest industrial contributor to $CO_2$ production



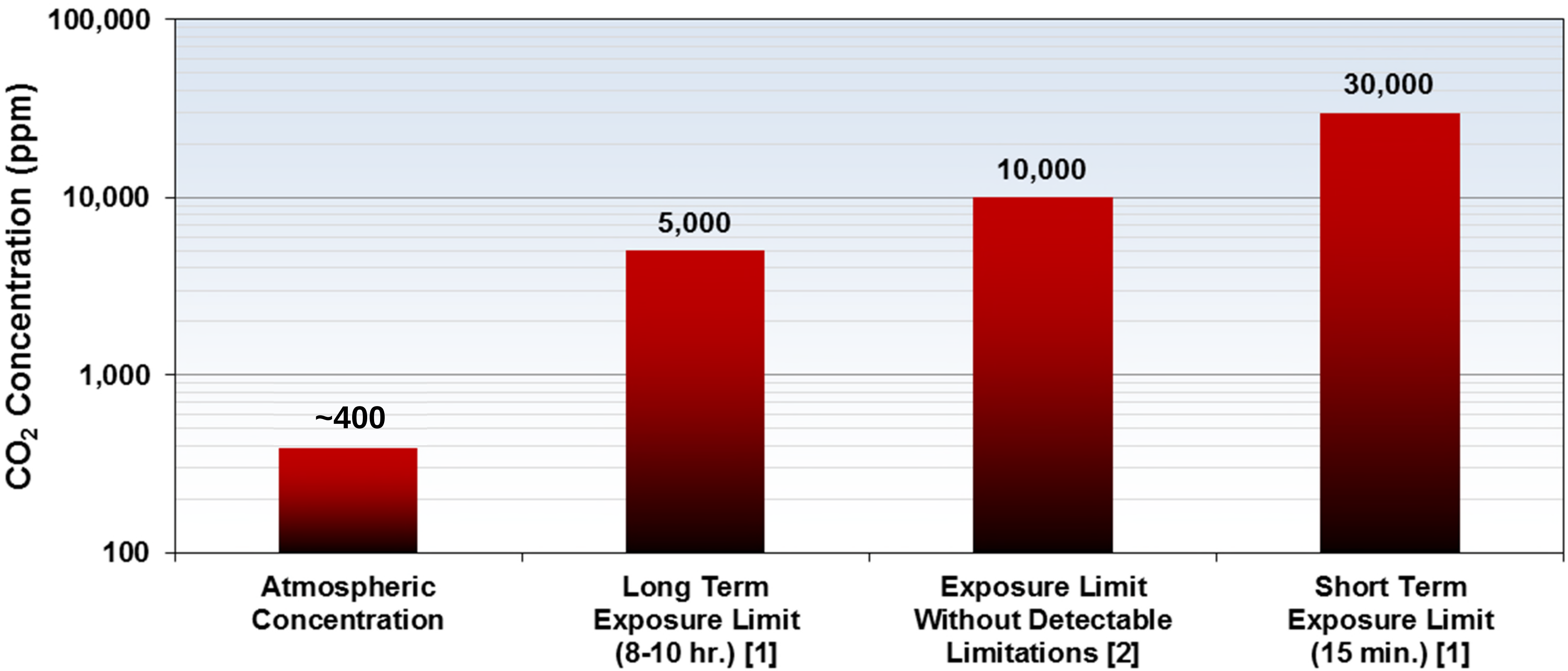

Source: “U.S. Climate Action Report 2014”

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




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

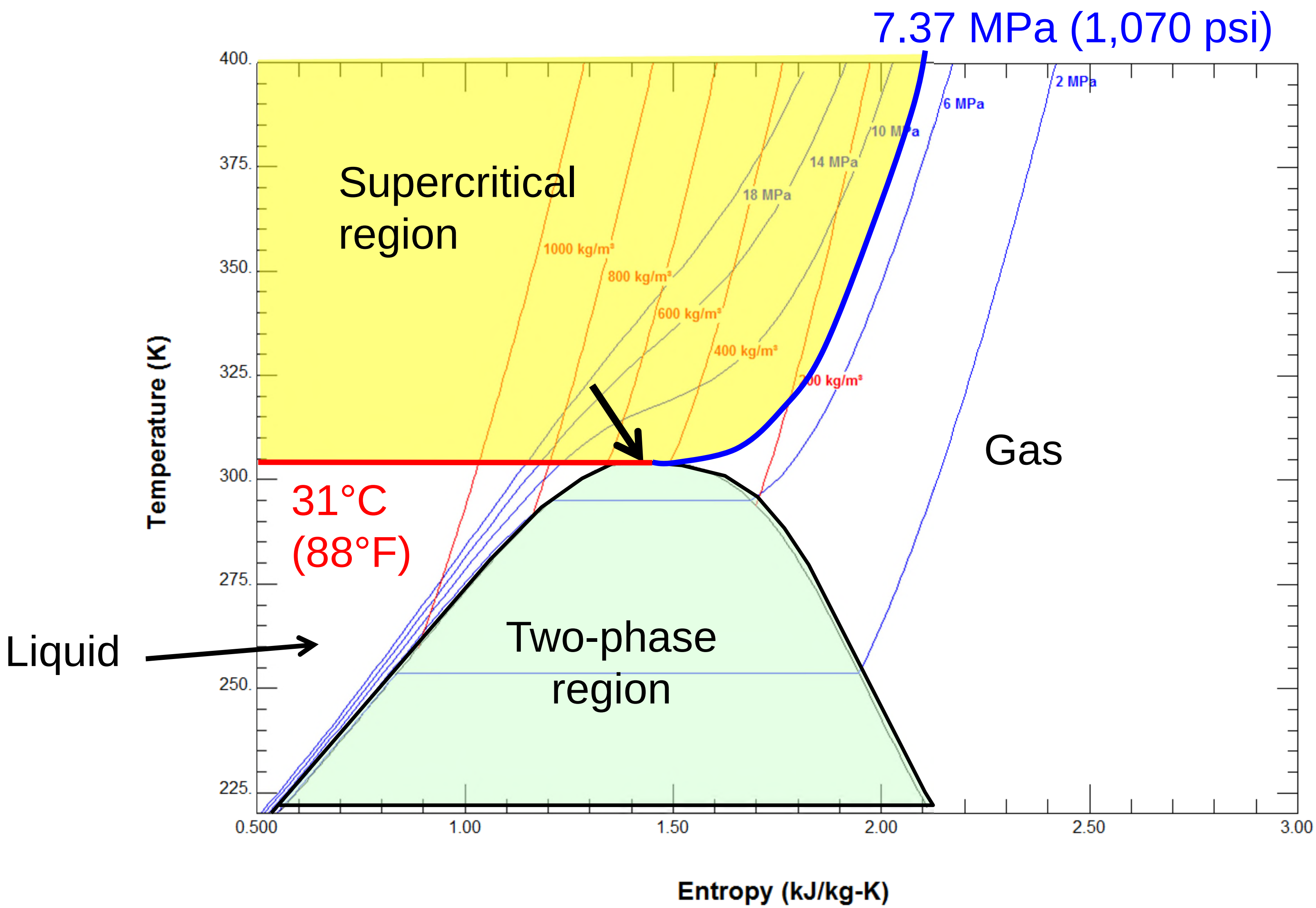
# $CO_2$ has human exposure limits, but is classified at "non-toxic"




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

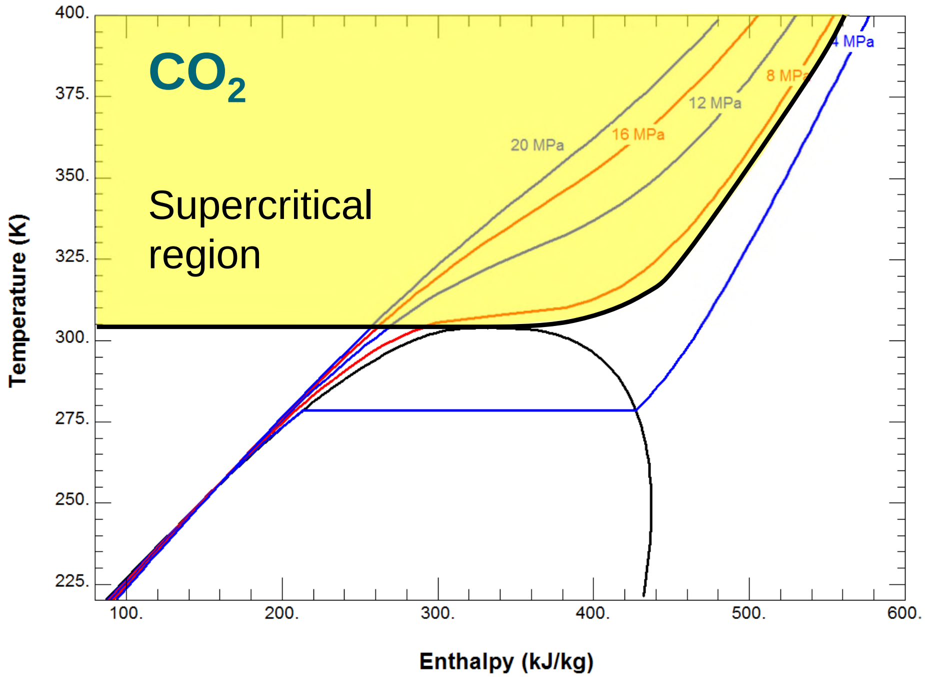
# What is Supercritical $CO_2$?

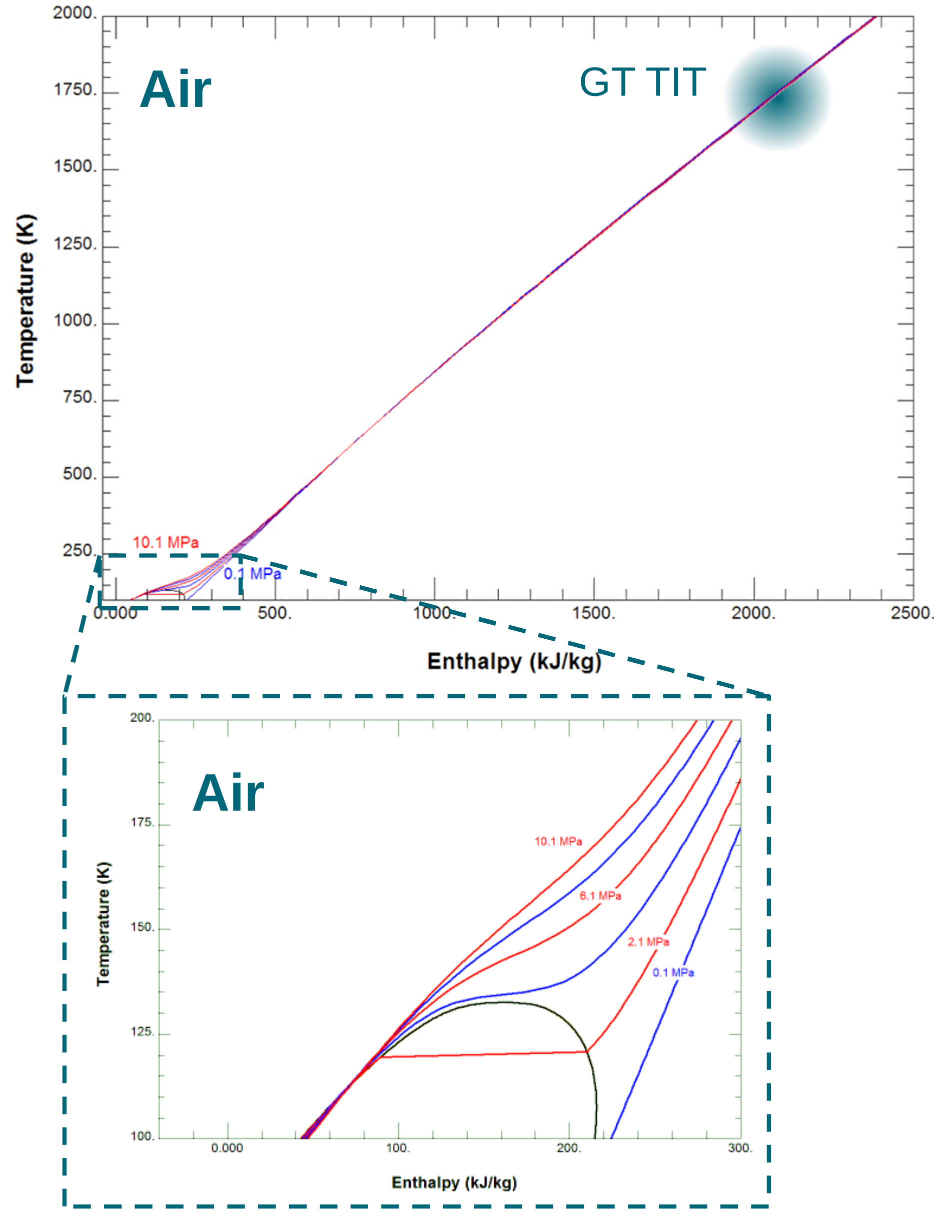
# $CO_2$ is supercritical if the pressure and temperature are greater than the critical values



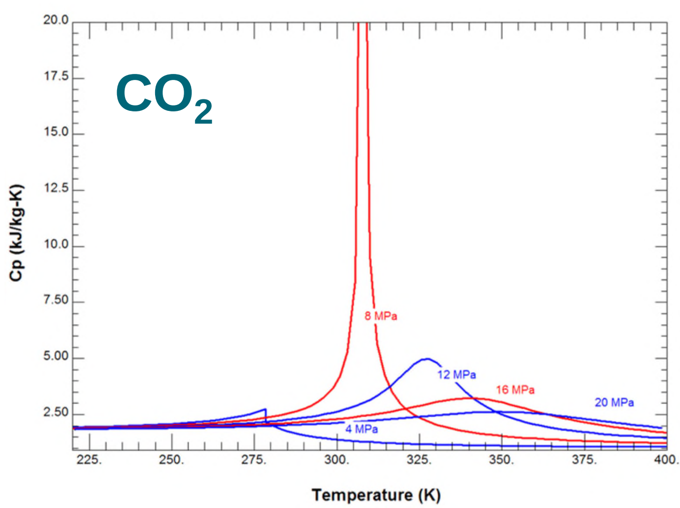

*REFPROP (2007), EOS $CO_2$: Span & Wagner (1996)*

# Fluids operating near their critical point have dramatic changes in enthalpy



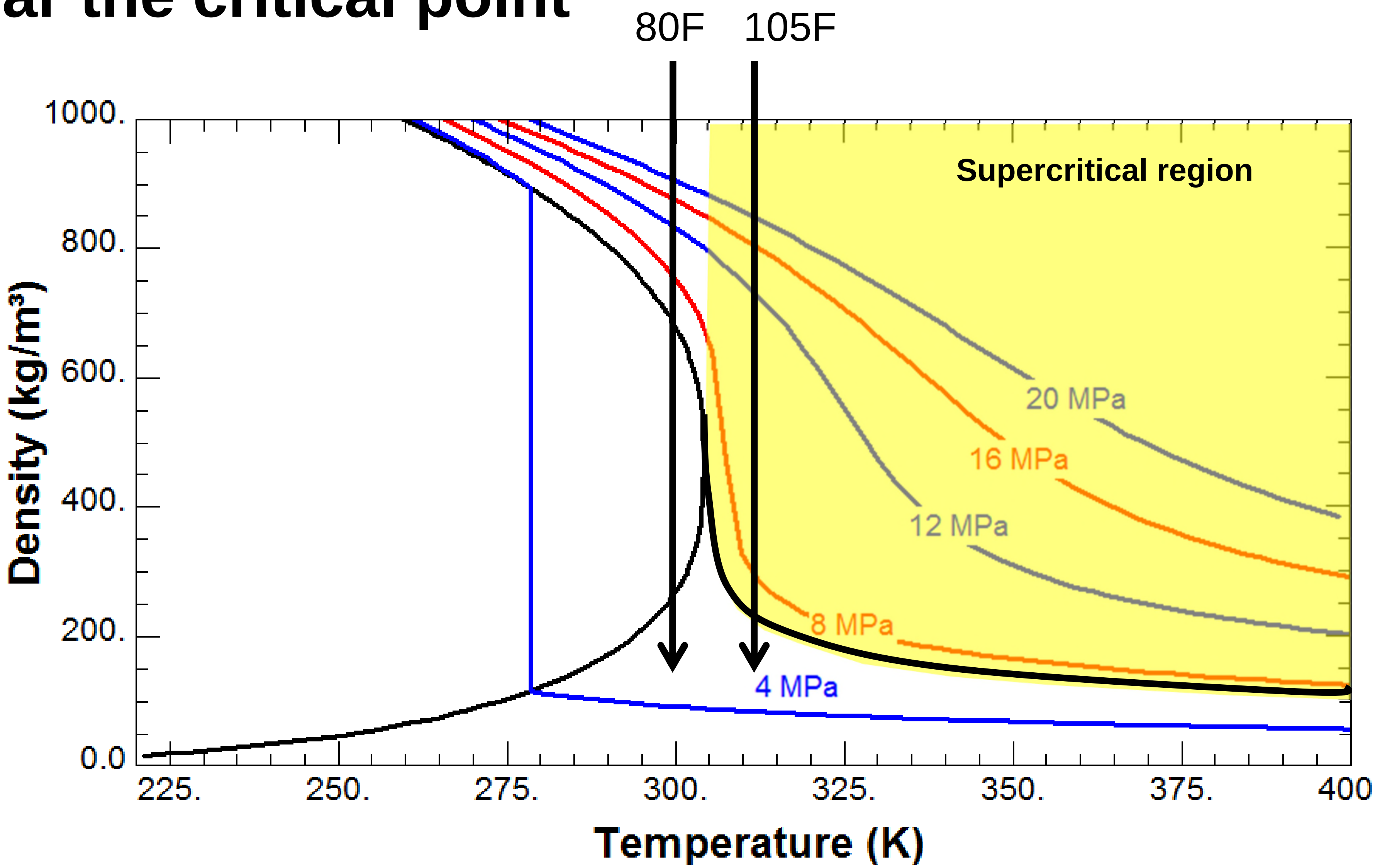




$$C_p = \left.\frac{\partial h}{\partial T}\right)_p$$



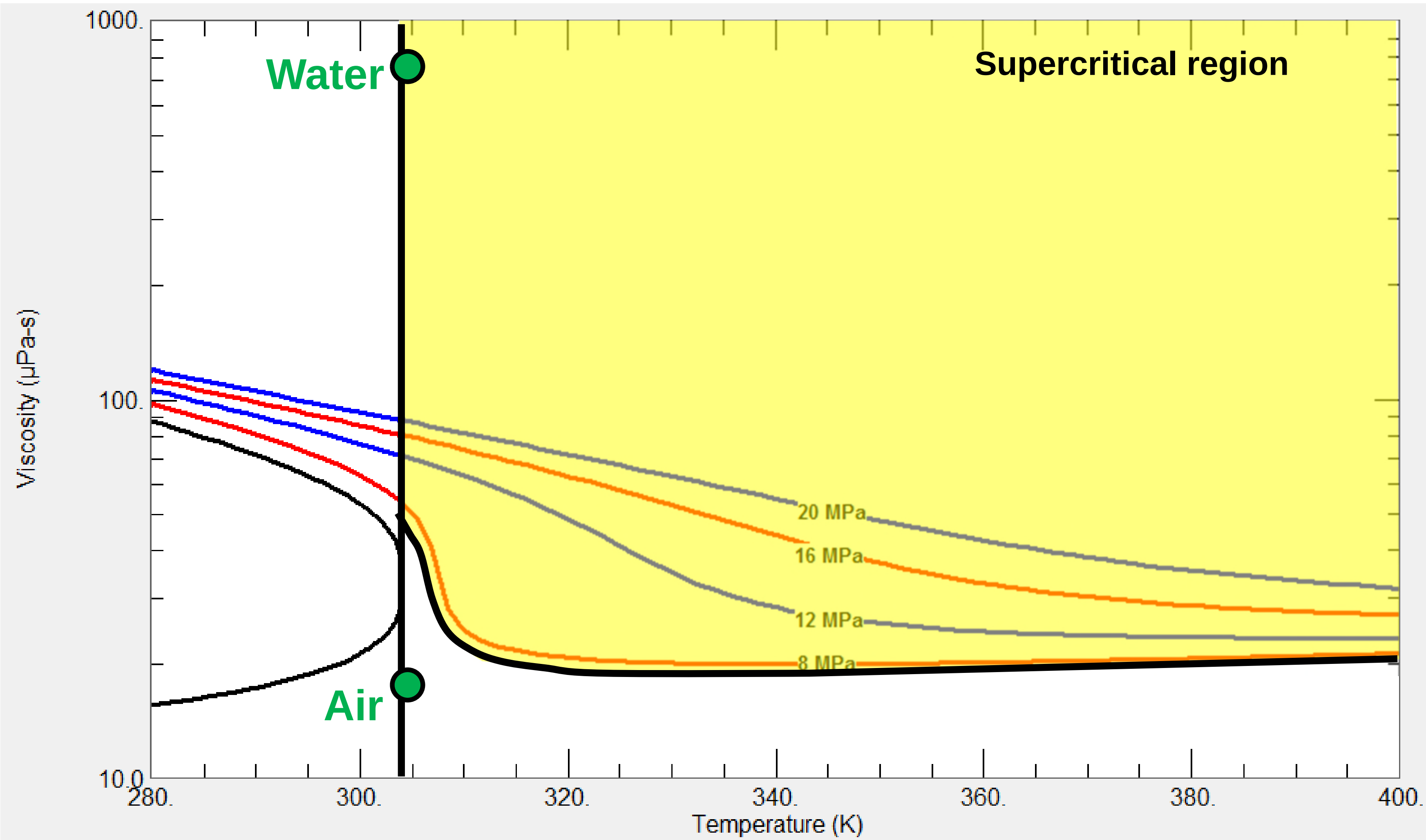

*REFPROP (2007)*

# $CO_2$ density sharply decreases near the critical point




*REFPROP (2007)*

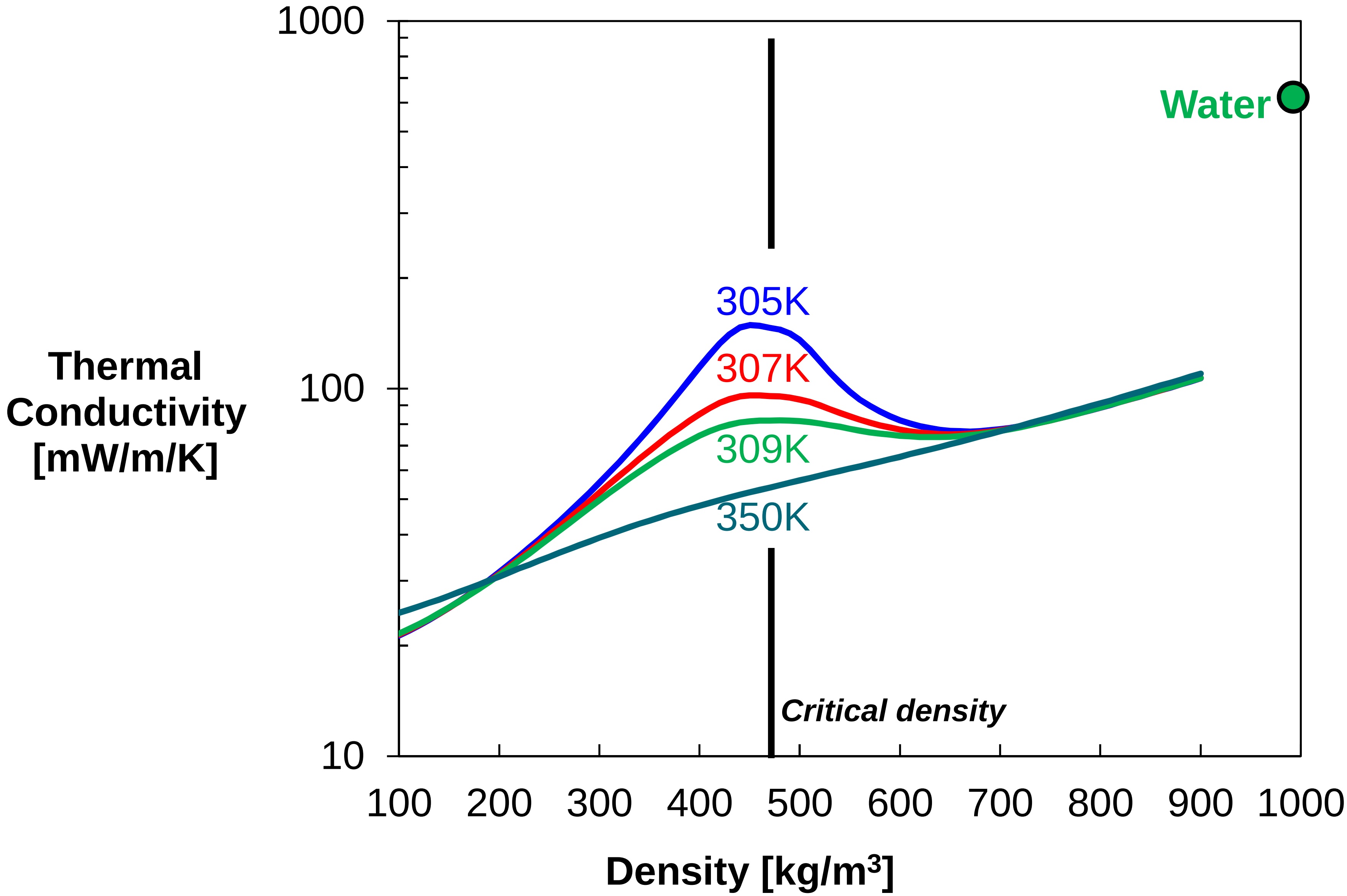
# $CO_2$ viscosity decreases through the critical point




*REFPROP (2007)*

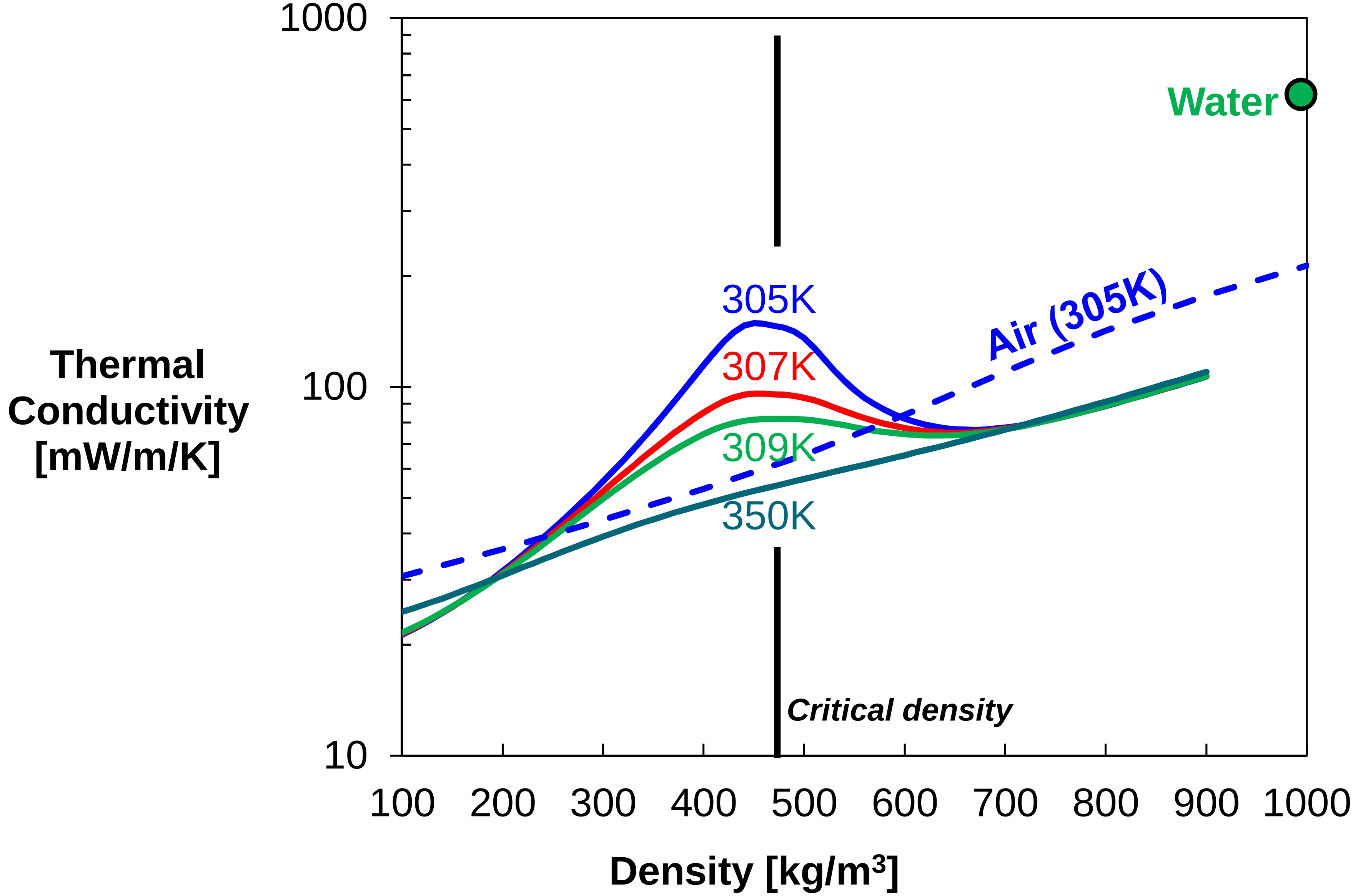
1 µPa-s = $10^{-6}$ kg/m/s

# $CO_2$ thermal conductivity is enhanced near the critical region




*REFPROP (2007)*

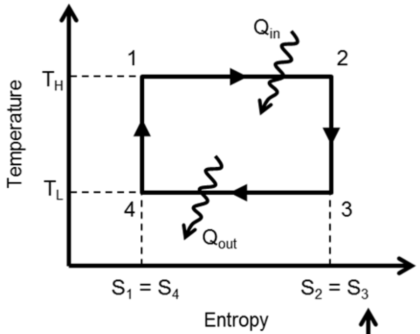
# $CO_2$ thermal conductivity is enhanced near the critical region



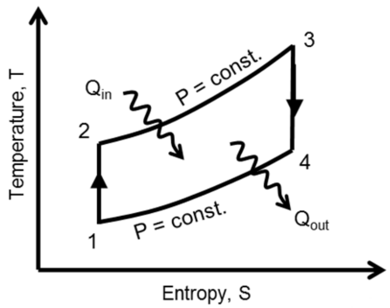

*REFPROP (2007)*

# Power Cycle Basics

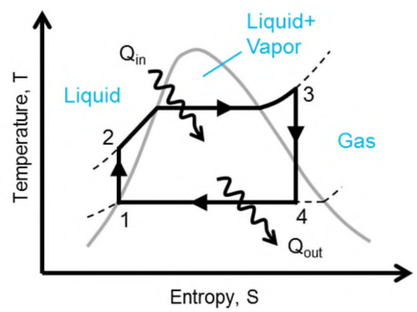
# Power Cycle Basics Overview



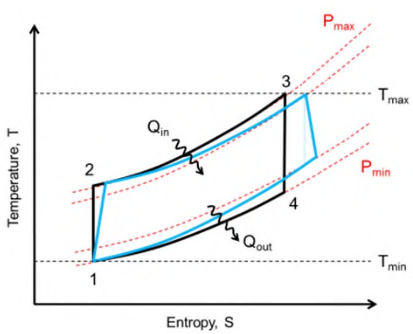

Carnot – “the standard”




Brayton – gas cycle

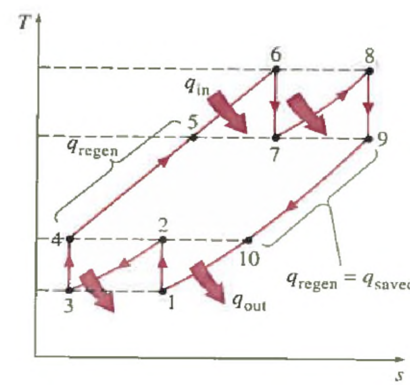



Rankine – vapor cycle




*Ideal vs. actual cycle*

*Cycle variations*



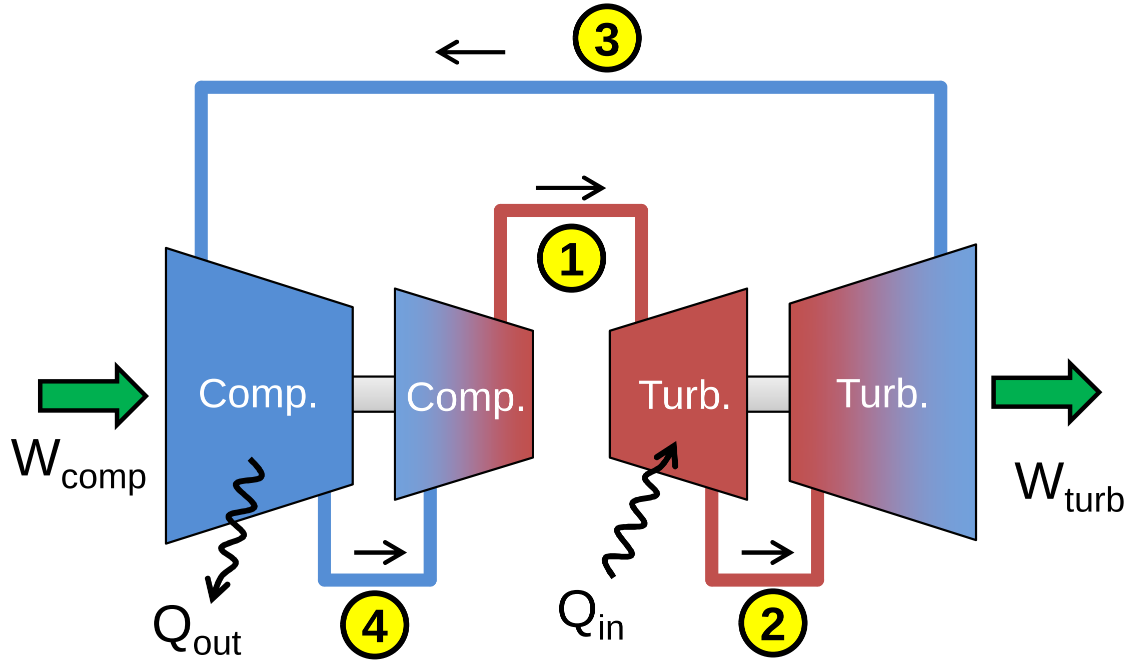
# Carnot Cycle

- Processes
  - (1-2) Isothermal heat addition
  - (2-3) Isentropic expansion
  - (3-4) Isothermal heat rejection
  - (4-1) Isentropic compression
- Not practical to build
- Most efficient heat engine

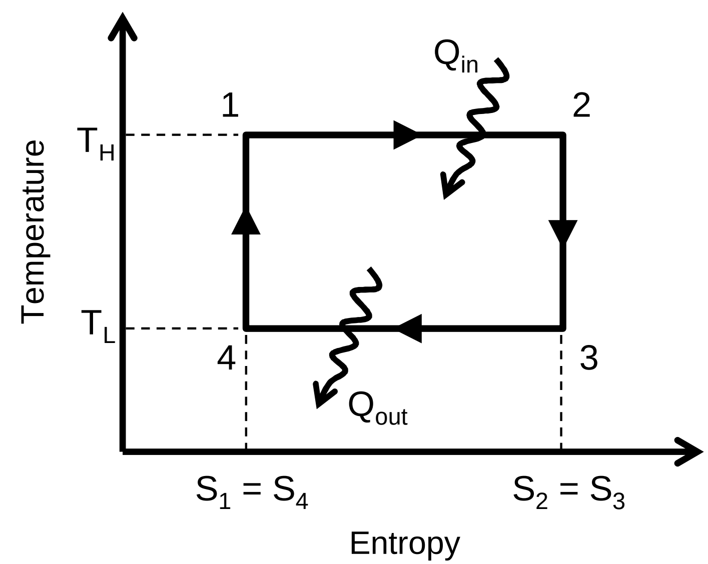
$$\eta_{th,Carnot} = 1 - T_L/T_H$$

↓$T_L$ : Available heat sink?

↑$T_H$ : Available heat source?
Materials?




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

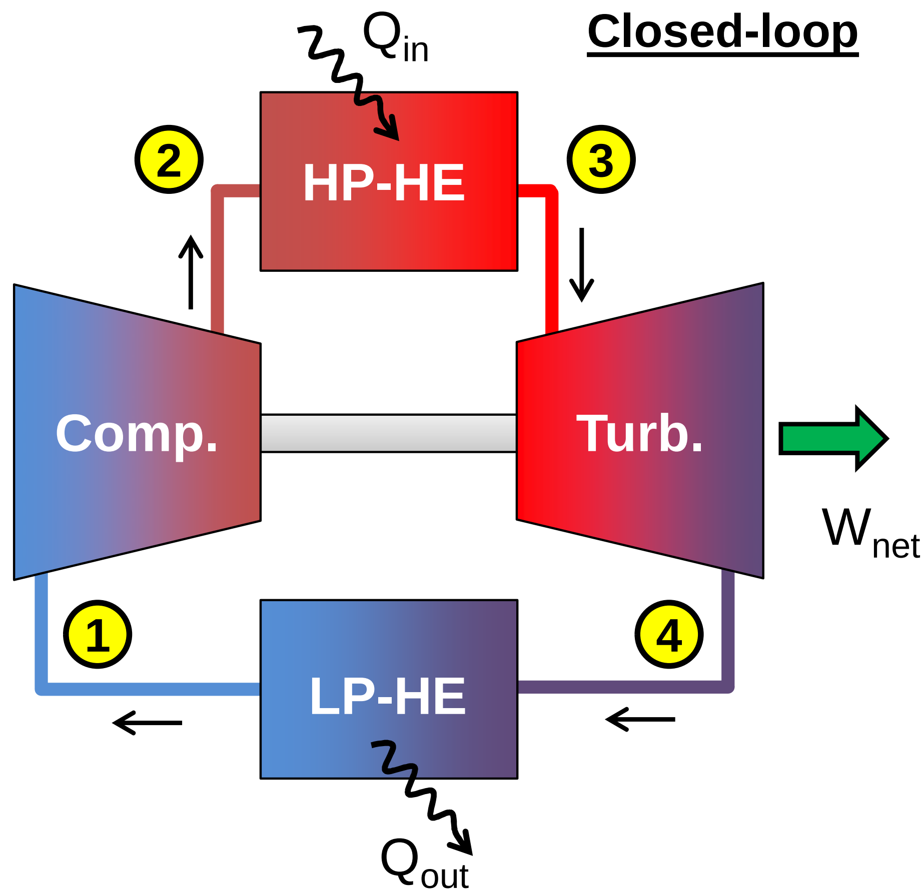


# Brayton Cycle (Ideal)

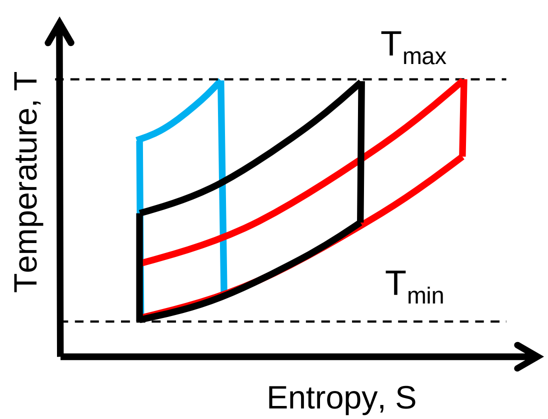
- Processes
  - (1-2) Isentropic compression
  - (2-3) Const. pres. heat addition
  - (3-4) Isentropic expansion
  - (4-1) Const. pres. heat reject.
- Open- or closed-loop

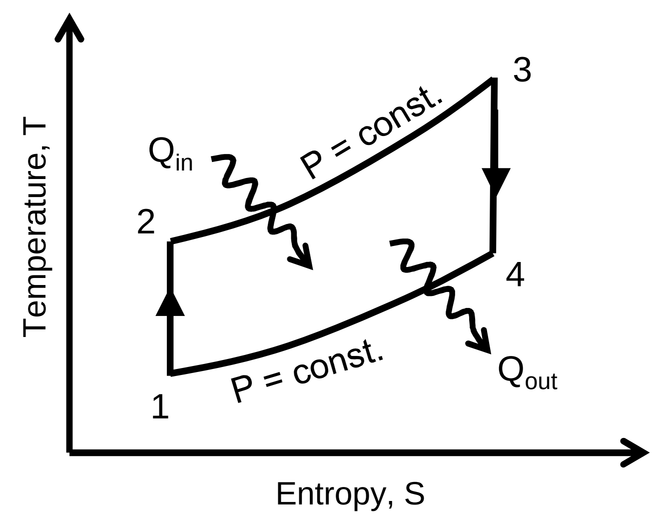
$$\eta_{th,Brayton} = 1 - PR^{(1-k)/k}$$

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



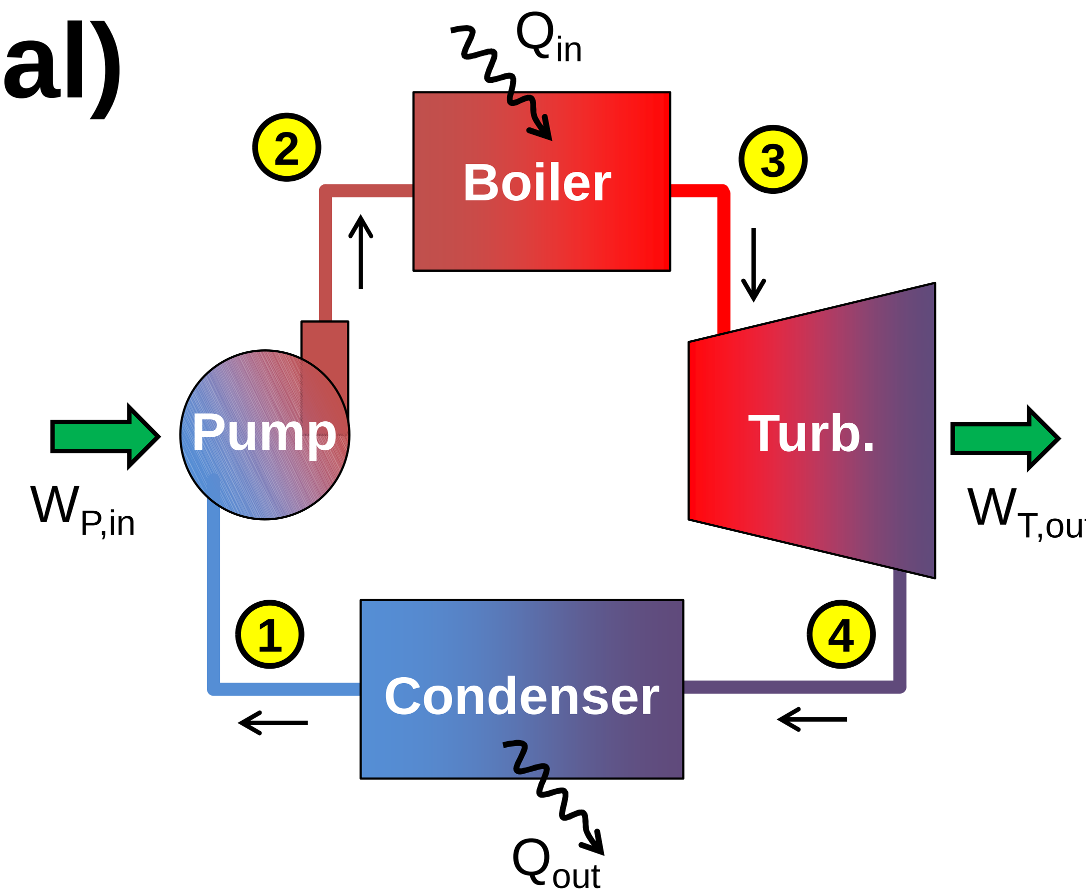

Optimal PR for net work

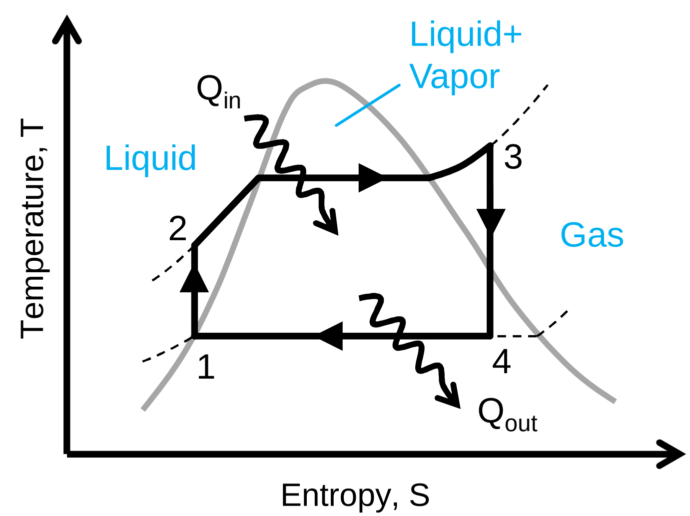


# Rankine Cycle (Ideal)

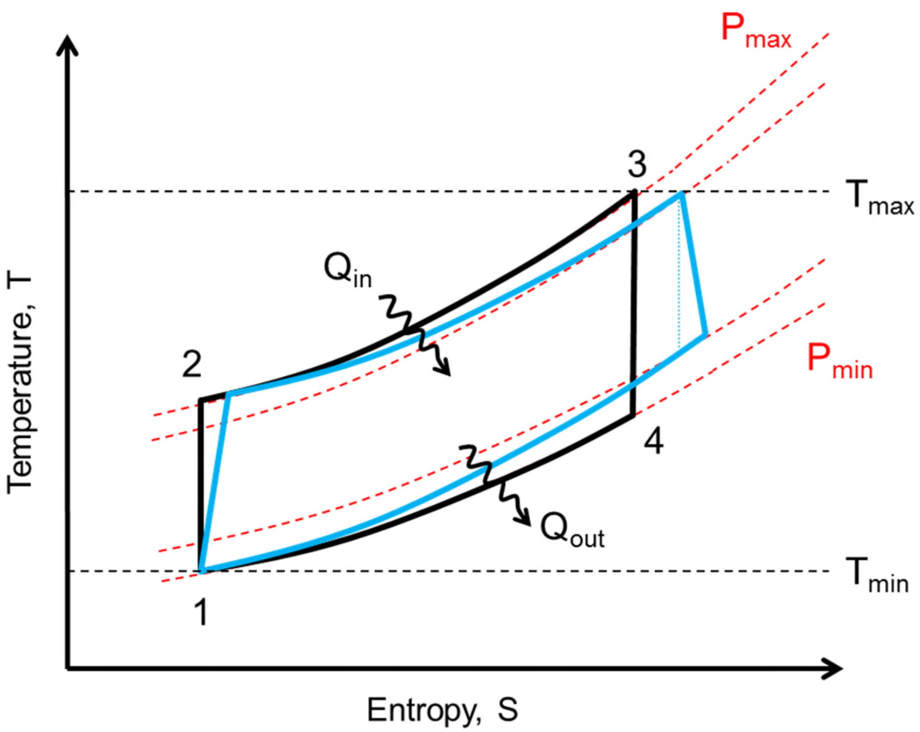
- Processes
  - (1-2) Isentropic compression
  - (2-3) Const. pres. heat addition
  - (3-4) Isentropic expansion
  - (4-1) Const. pres. heat reject.
- Same processes as Brayton; different hardware
- Phase changes
- E.g., steam cycle



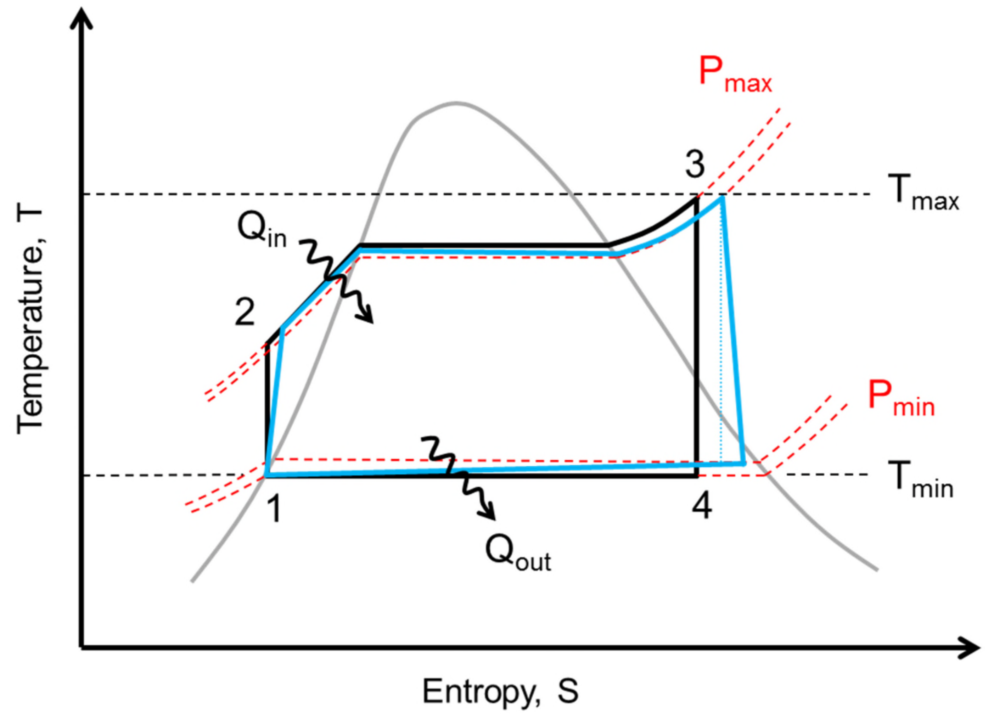



# Ideal vs. Actual Processes

Brayton




Rankine

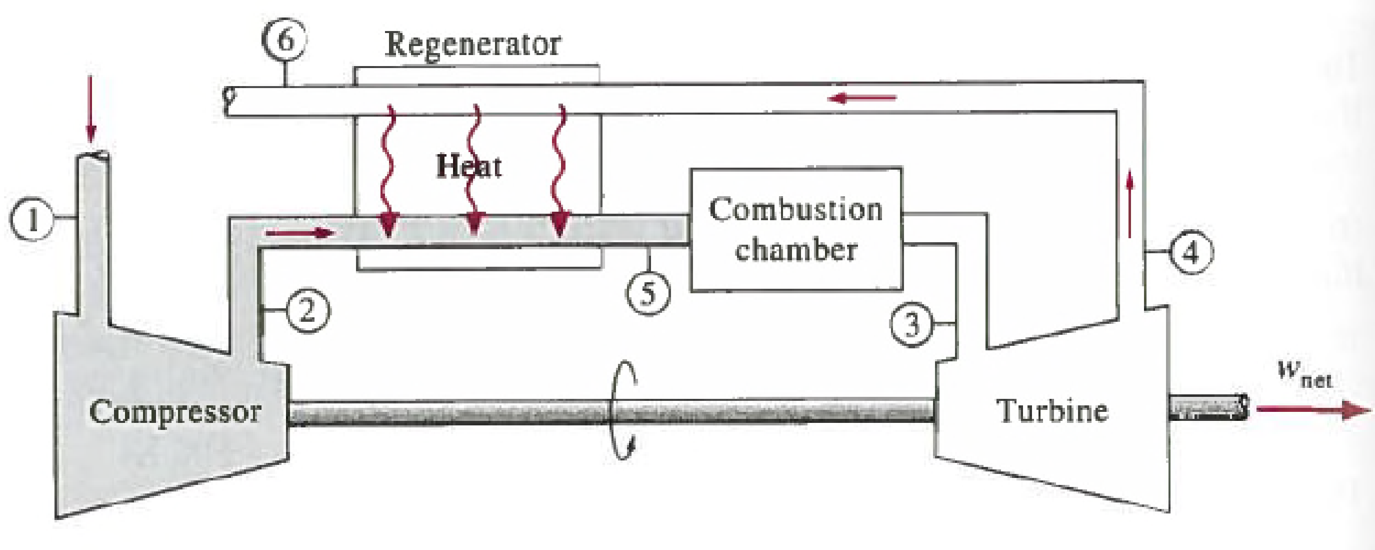



**1-2, 3-4: Irreversibilities**

**2-3, 4-1: Pressure losses**

# Brayton Cycle + Regeneration

**Regenerator = recuperator**




**Effectiveness:**

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

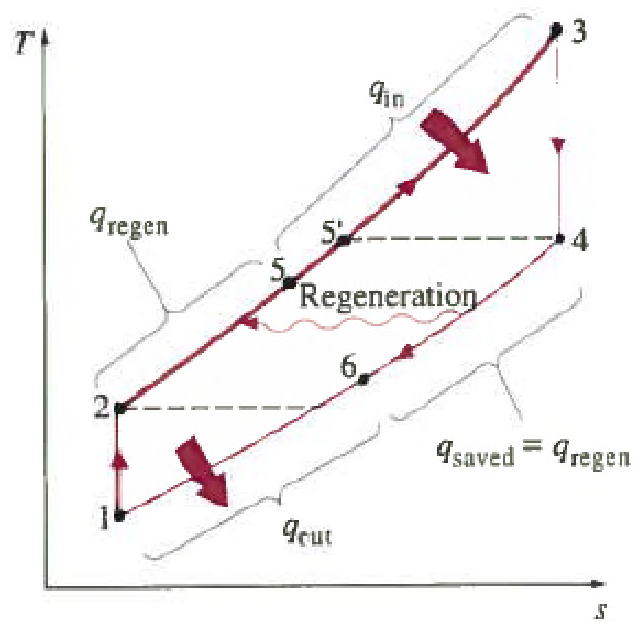



Figure reference: Cengel and Boles (2002)

# Intercooling & Reheating… Two Sides of the Same Coin

Minimize compressor work input

Increase fluid density

Intercooling

Multi-stage intercooling


Maximize turbine work output

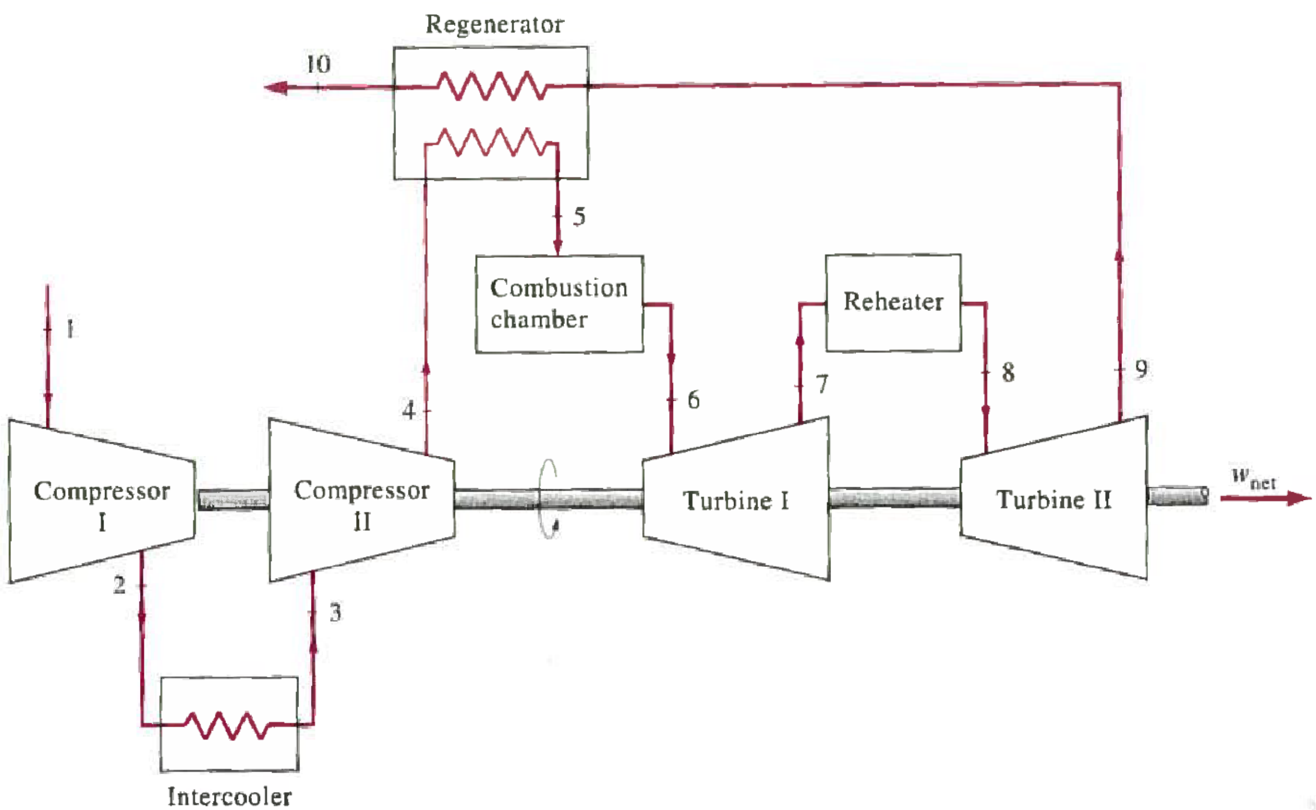
Decrease fluid density

Reheating

Multi-stage reheating

**Approach isothermal conditions**

# Brayton Cycle + Regeneration + Intercooling + Reheating



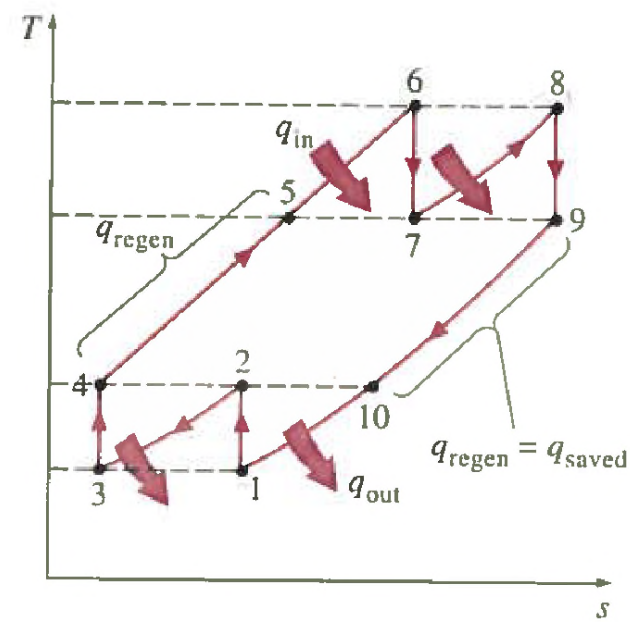




Figure reference: Cengel and Boles (2002)

# Example: Compare Effect of Brayton Variations

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

<u>For real GT</u>

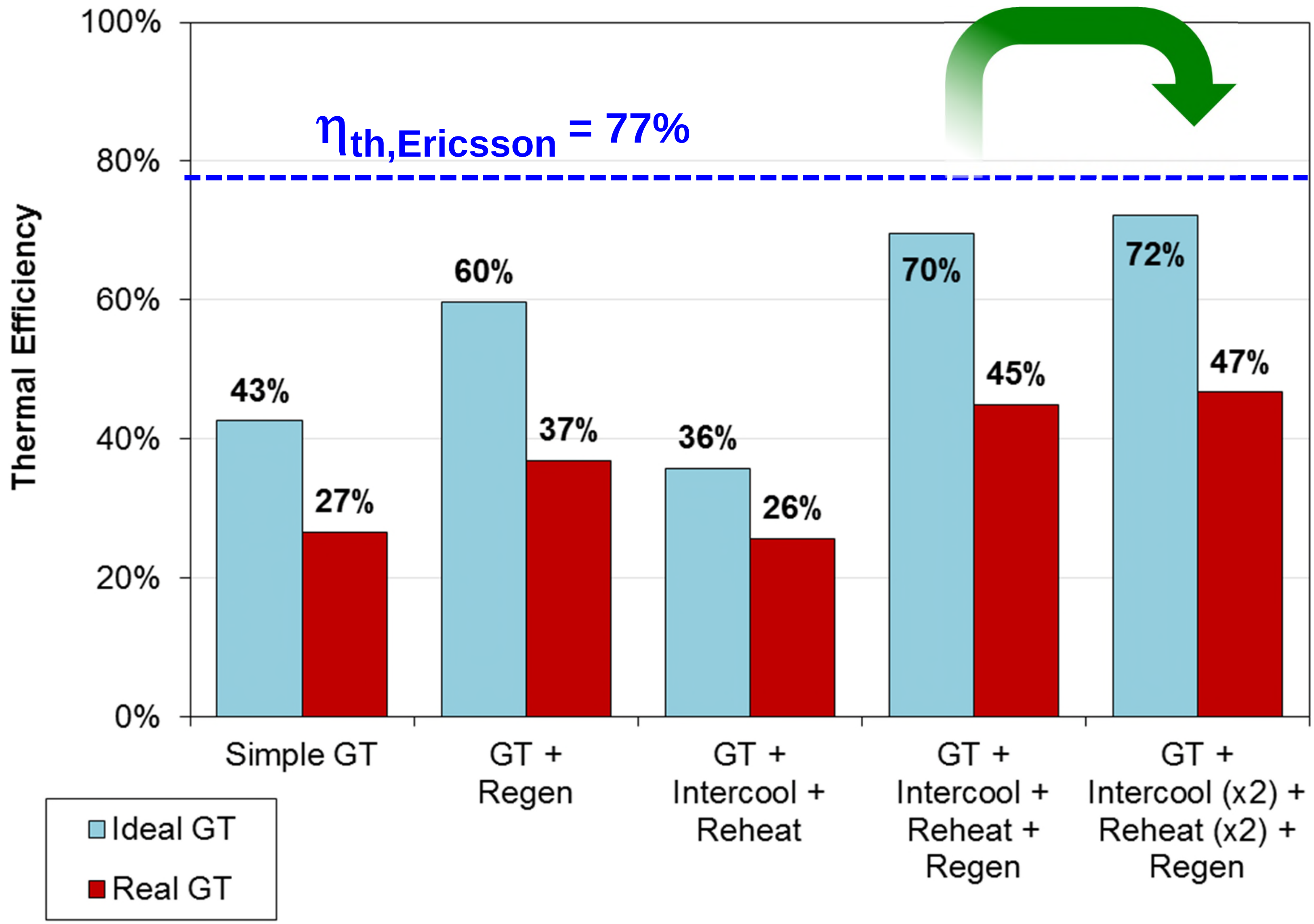
$\eta_{comp}$ = 80%

$\eta_{turb}$ = 85%

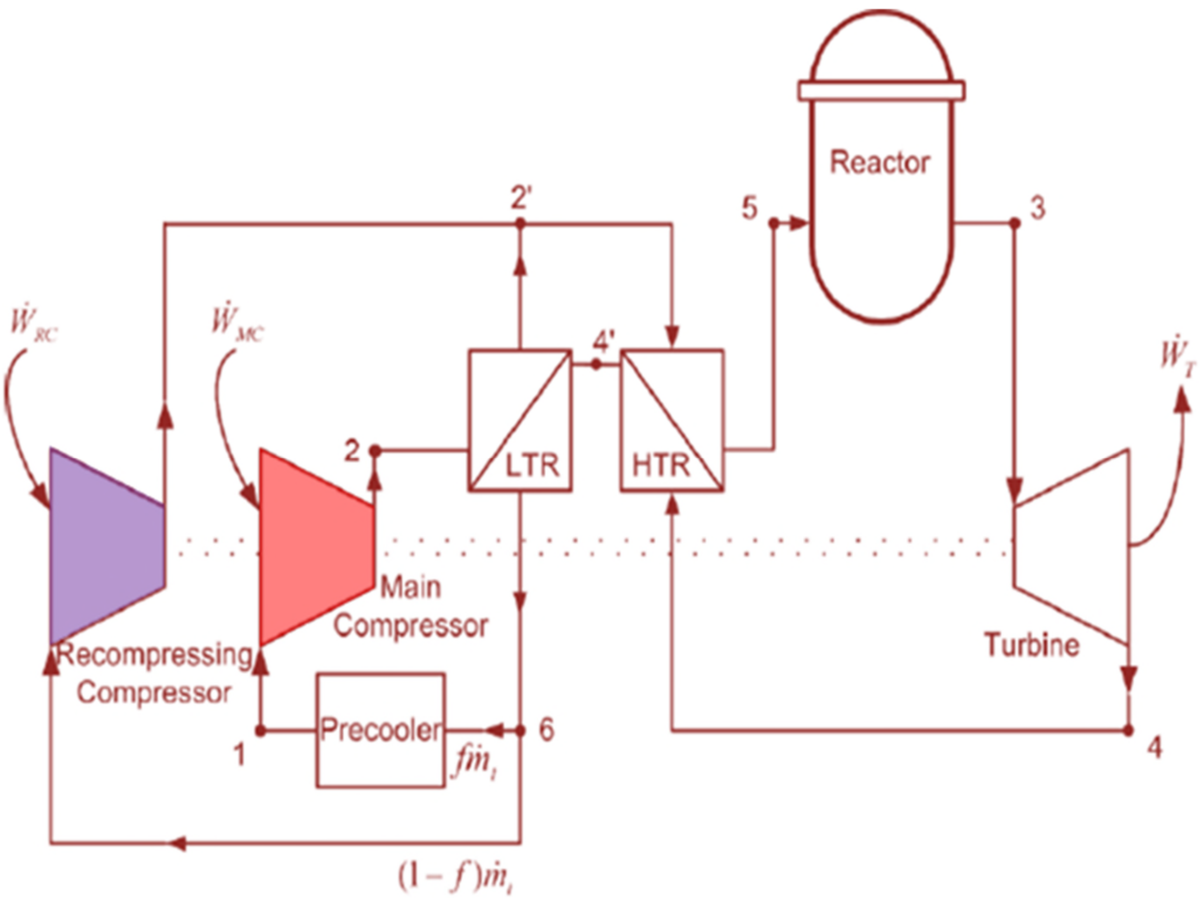
$\varepsilon_{regen}$ = 80%

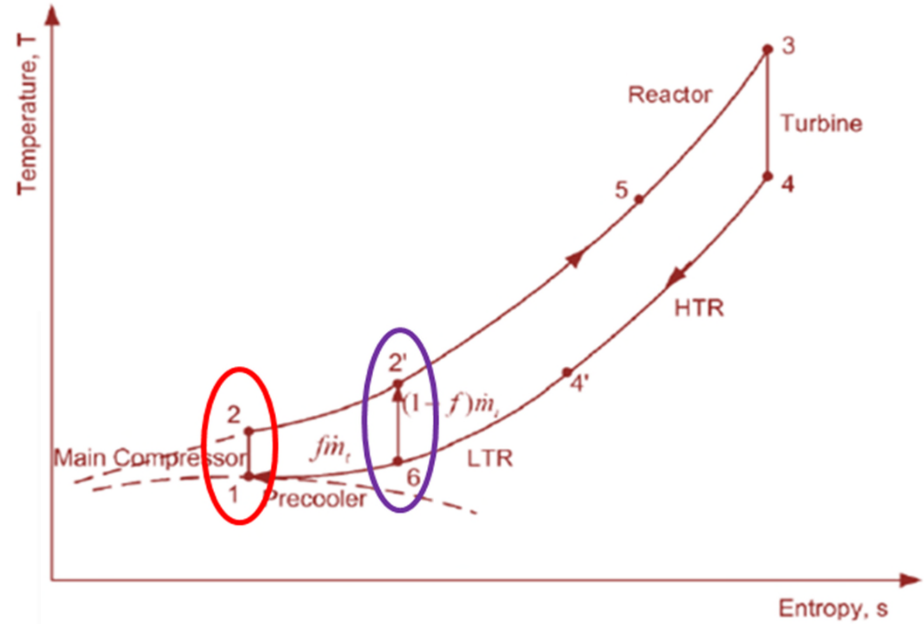
$\Delta P \approx$ negligible

**Cost-benefit analysis…**



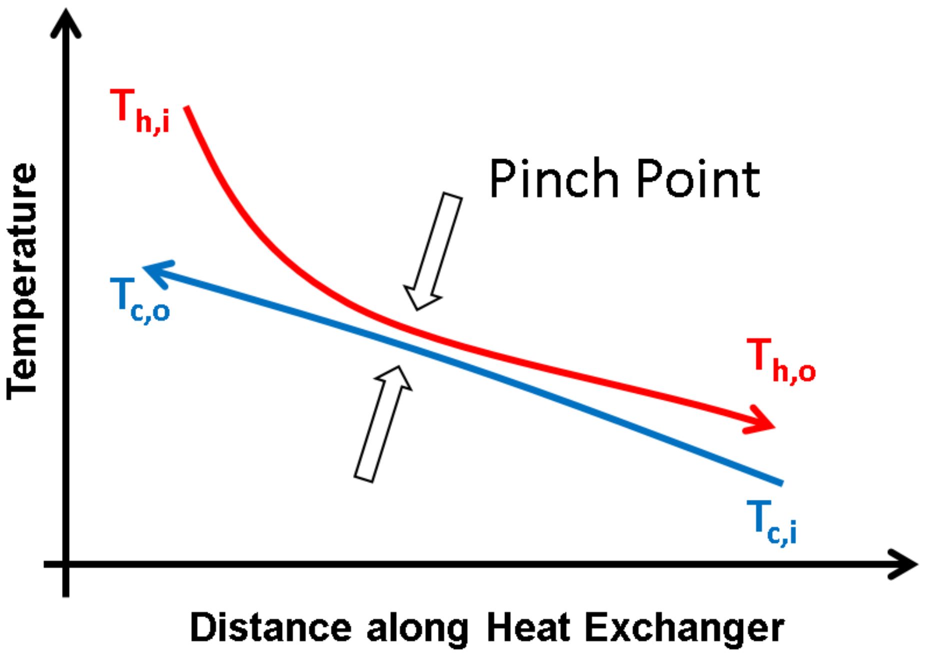
# Recompression in Brayton Cycle

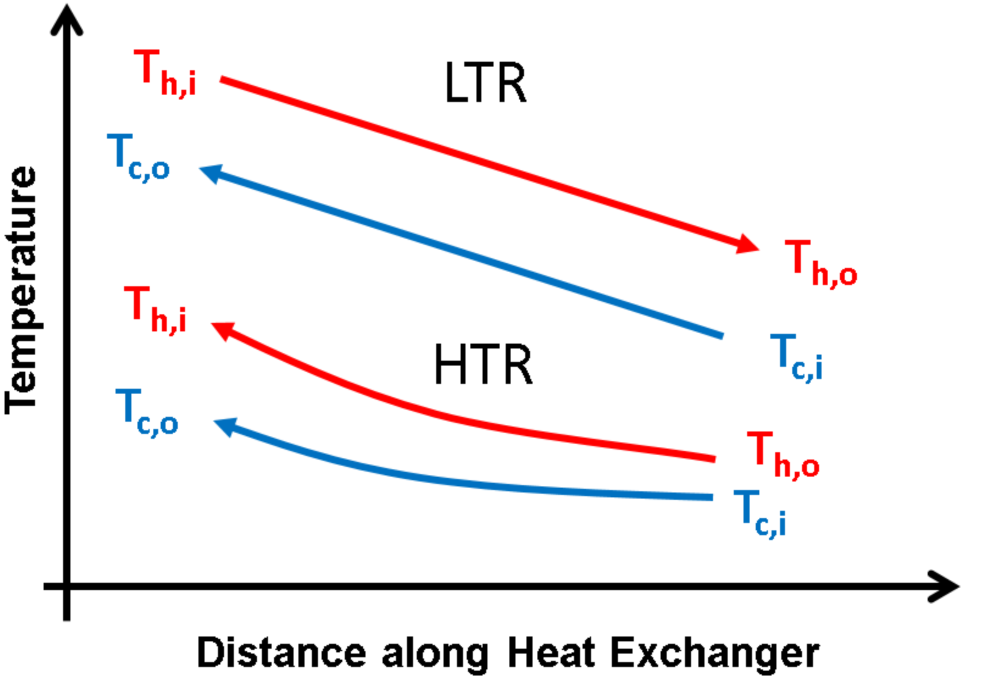


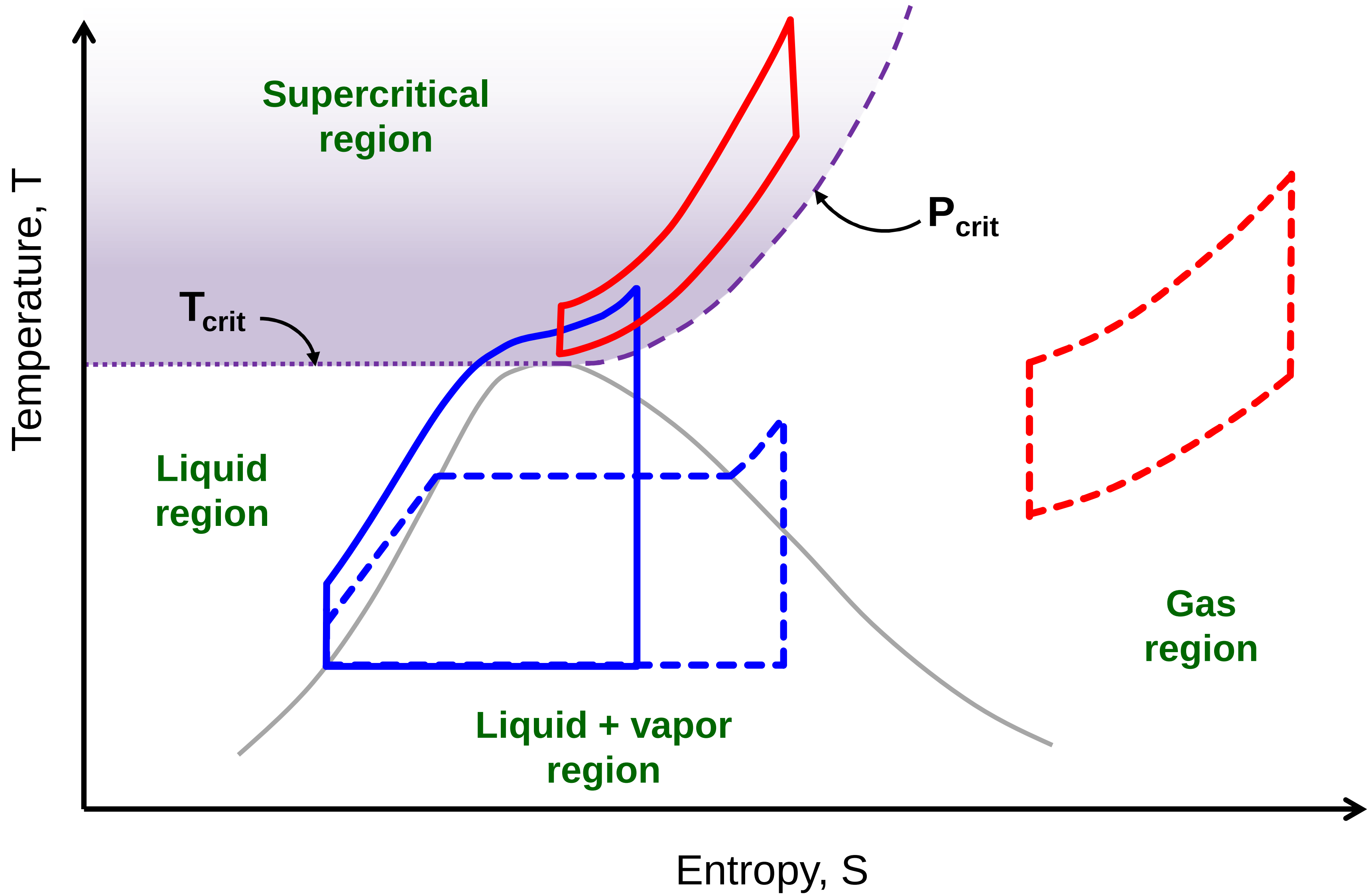

Source: Ludington (2009)

# Split Recuperators can be used to avoid pinch points



# What is a Supercritical Power Cycle?

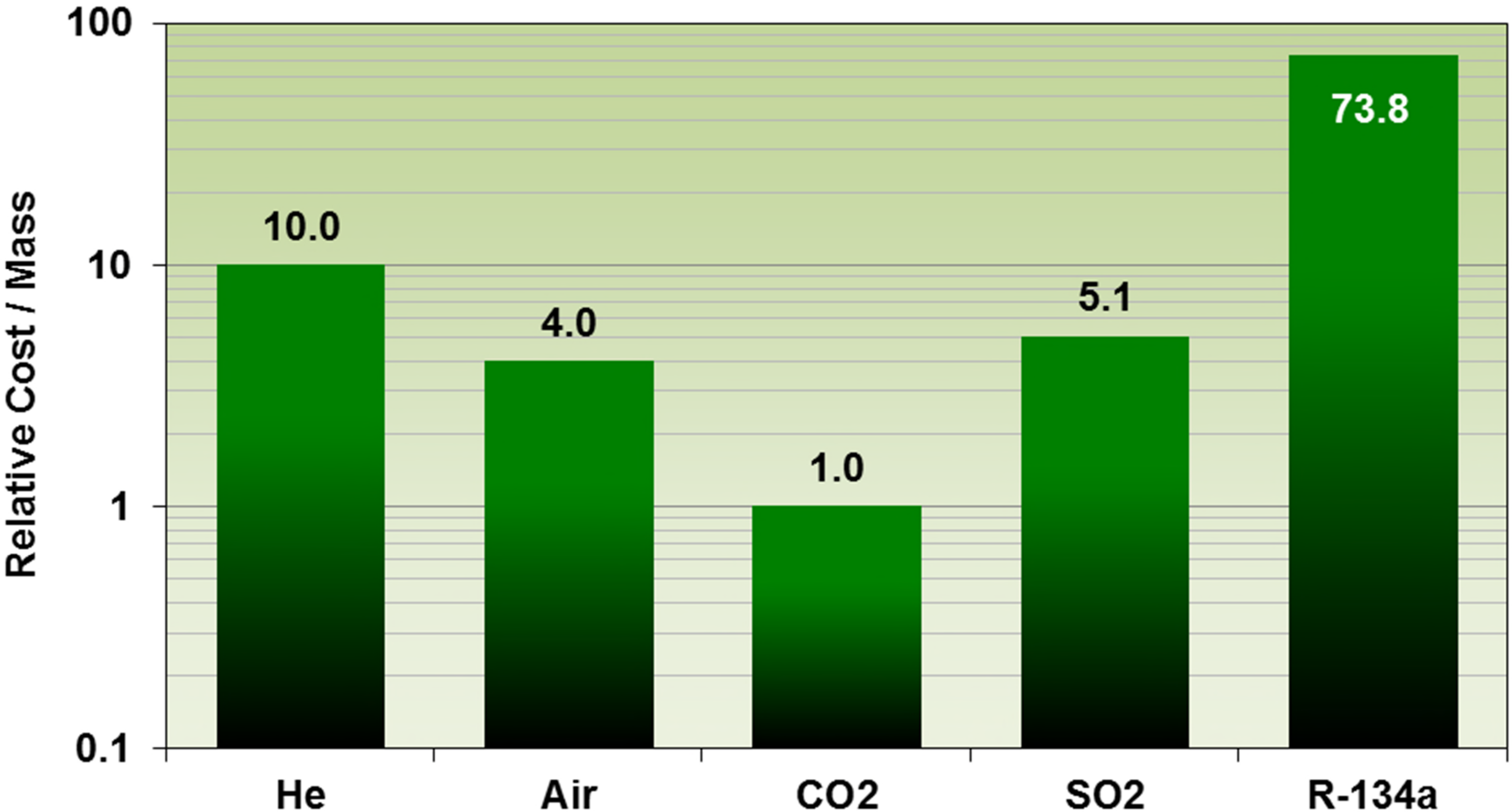


# $sCO_2$ Power Cycles

# Why $sCO_2$ for Power Cycles?

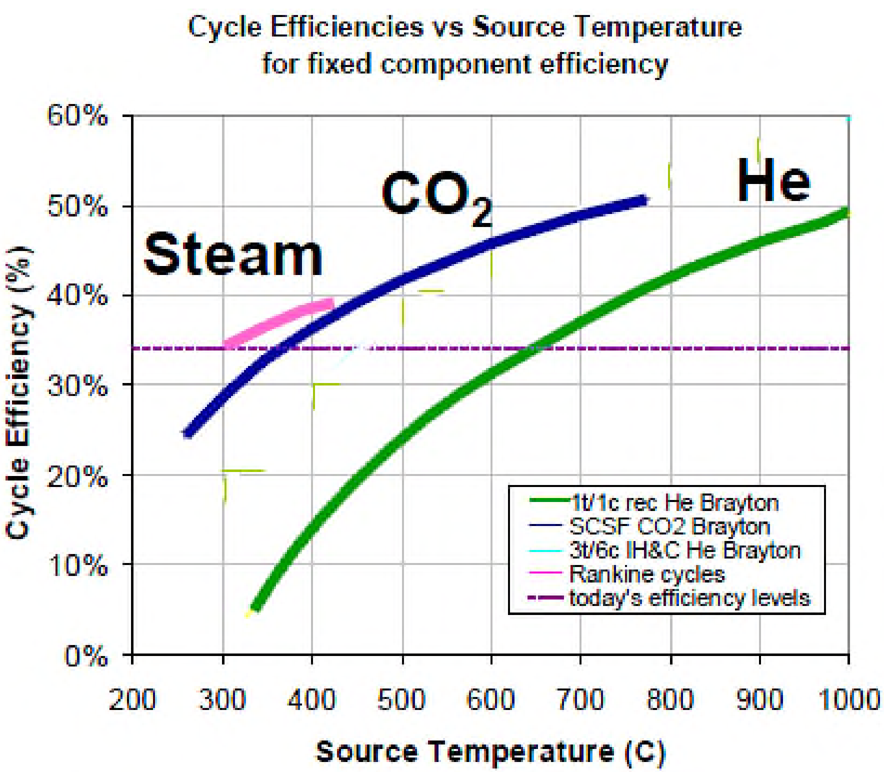
| Property | Effect |
| --- | --- |
| High density, low viscosity, high $C_P$ near C.P. | • Reduced compressor work, increased $W_{net}$<br>• Allow more-compact turbomachinery to achieve same power<br>• Less complex – e.g., fewer compressor and turbine stages, may not need intercooling |
| Near-ambient $T_{crit}$ | • 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 |

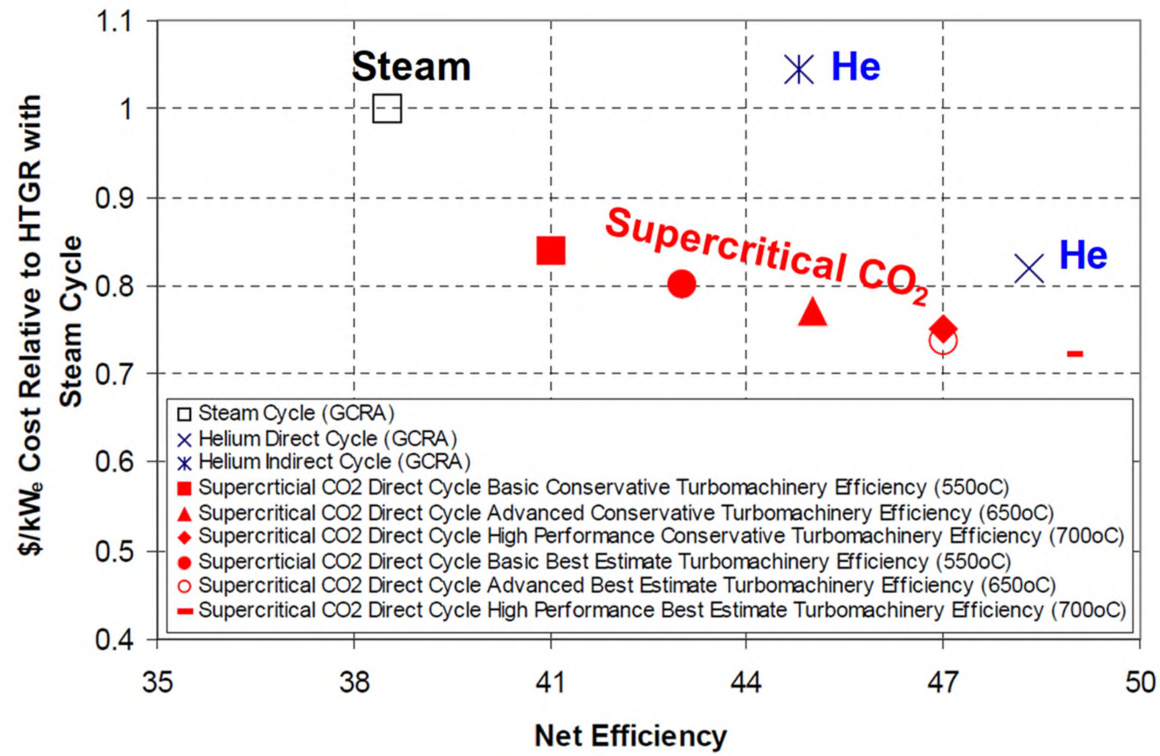
# $CO_2$ Cost Comparison*




*Based on market pricing for laboratory-grade substance

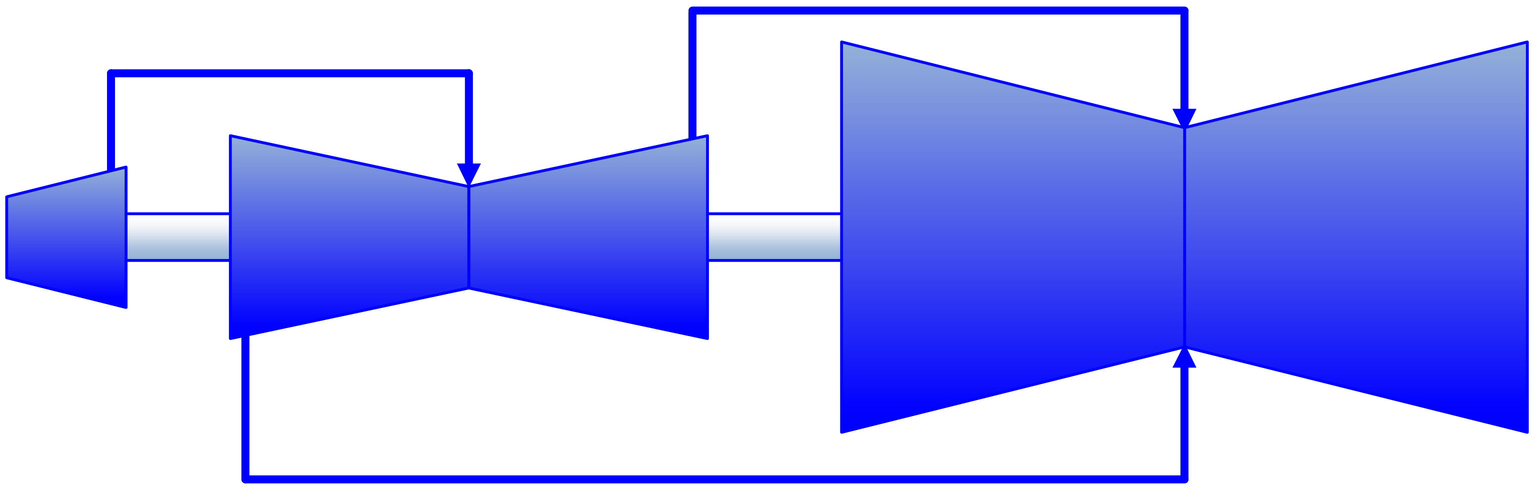
# Calculated $sCO_2$ efficiencies close to a steam cycle for potentially less $/kW

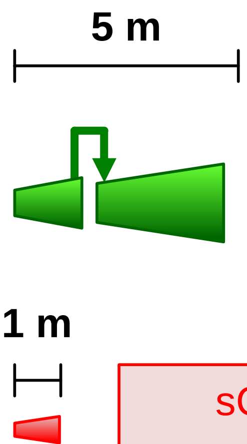



Source: Wright (2011) and Dostal (2004)

# Relative Size of Components





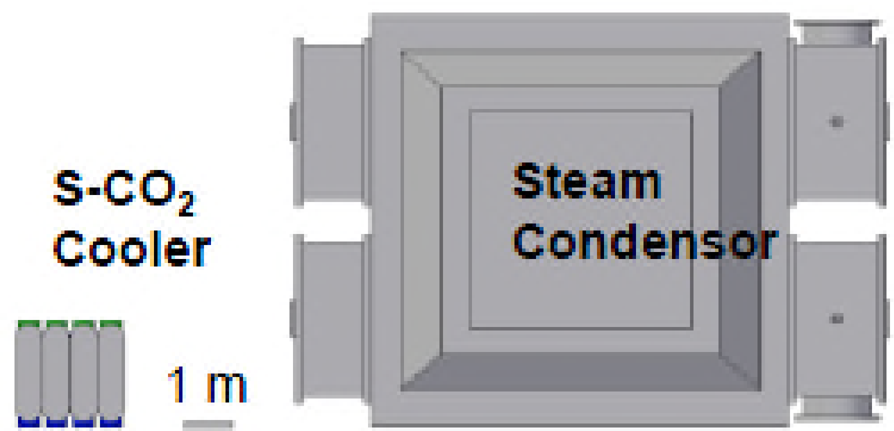

Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries (with casing)

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)

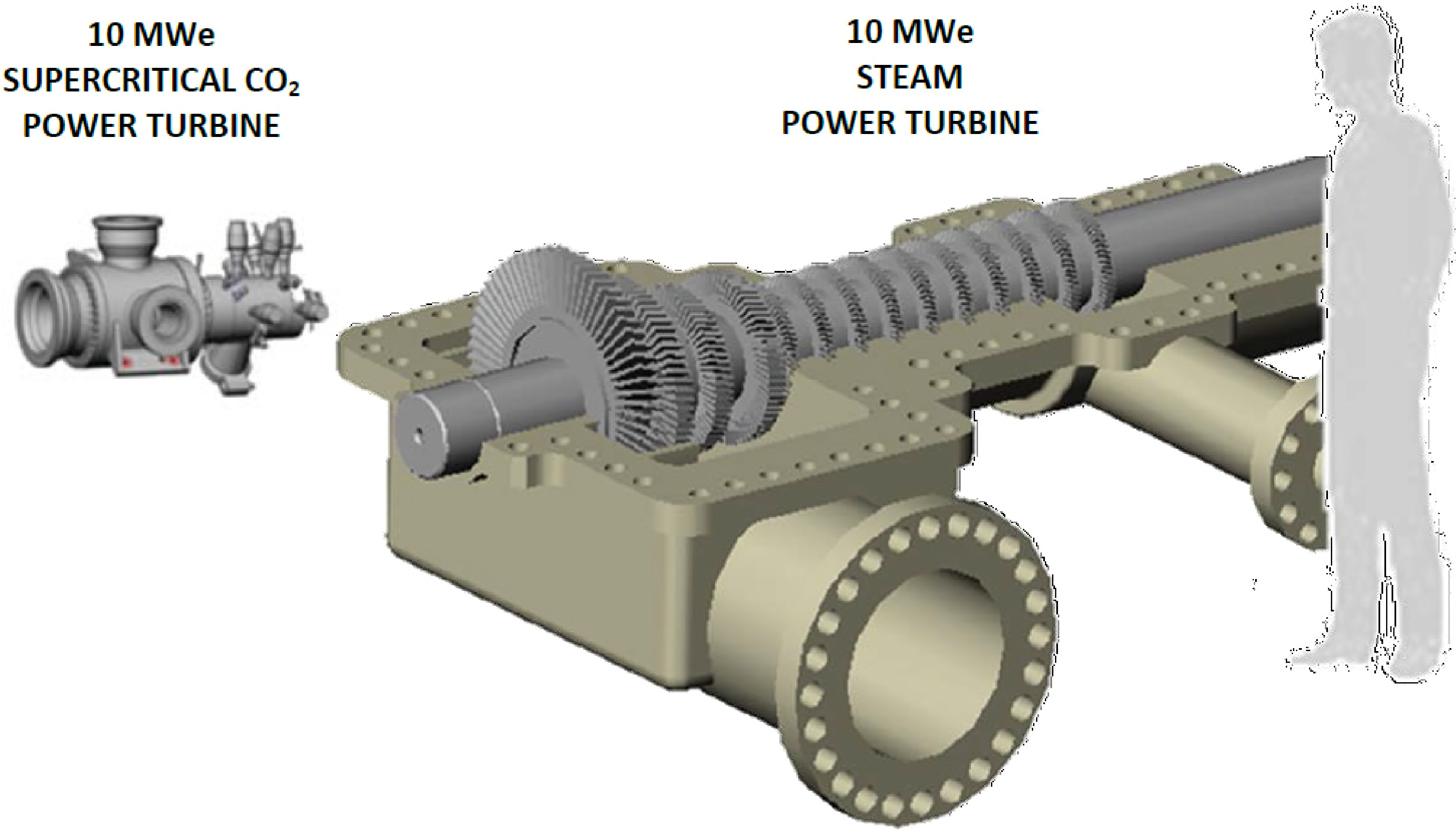
*Note: Compressors are comparable in size*

Adapted from Dostal (2004)



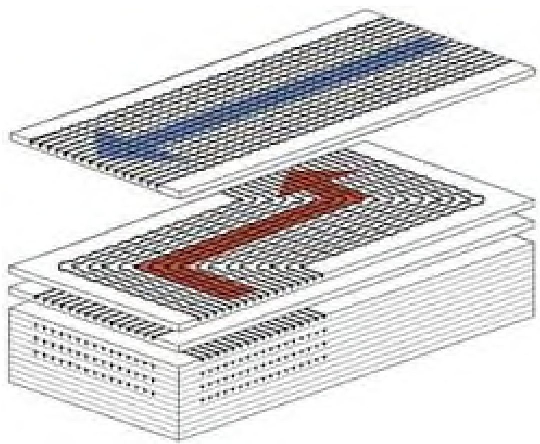

Source: Wright (2011)

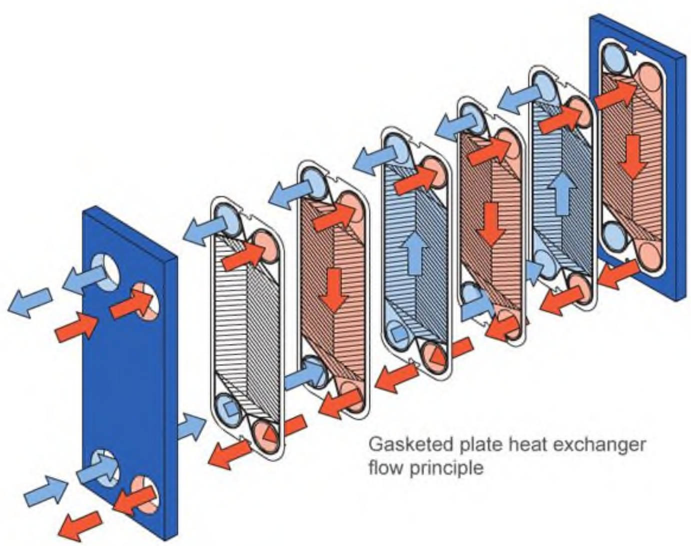
# Example: 10 MWe Turbine Comparison




Source: Persichilli et al. (2012)

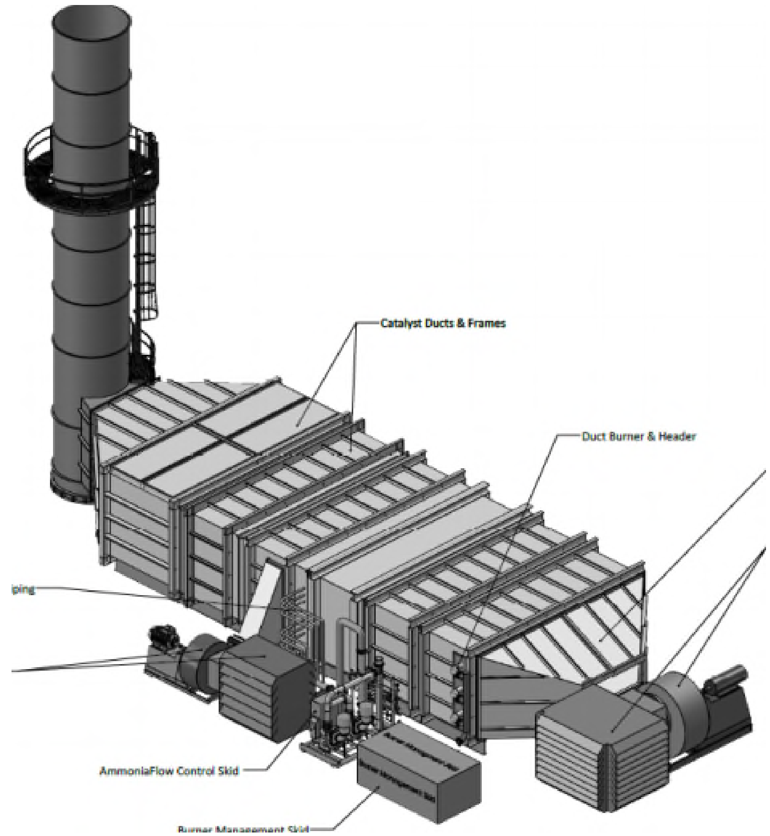
# Heat Exchangers for $sCO_2$: Recuperators






Sources: Top Left: Heatric, Top Right: VPE, Bottom: Alfa Laval

# Heat Exchangers for $sCO_2$: Heaters and Coolers




Sources: Top Left: Southwest Thermal Technology, Right: GTI, Bottom Left: Goodway Technologies

# $sCO_2$ in Power Cycle Applications

# Supercritical $CO_2$ in Power Cycle Applications

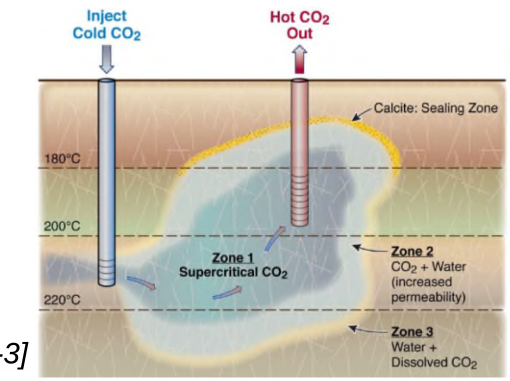
[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel

[6-3]




Geothermal

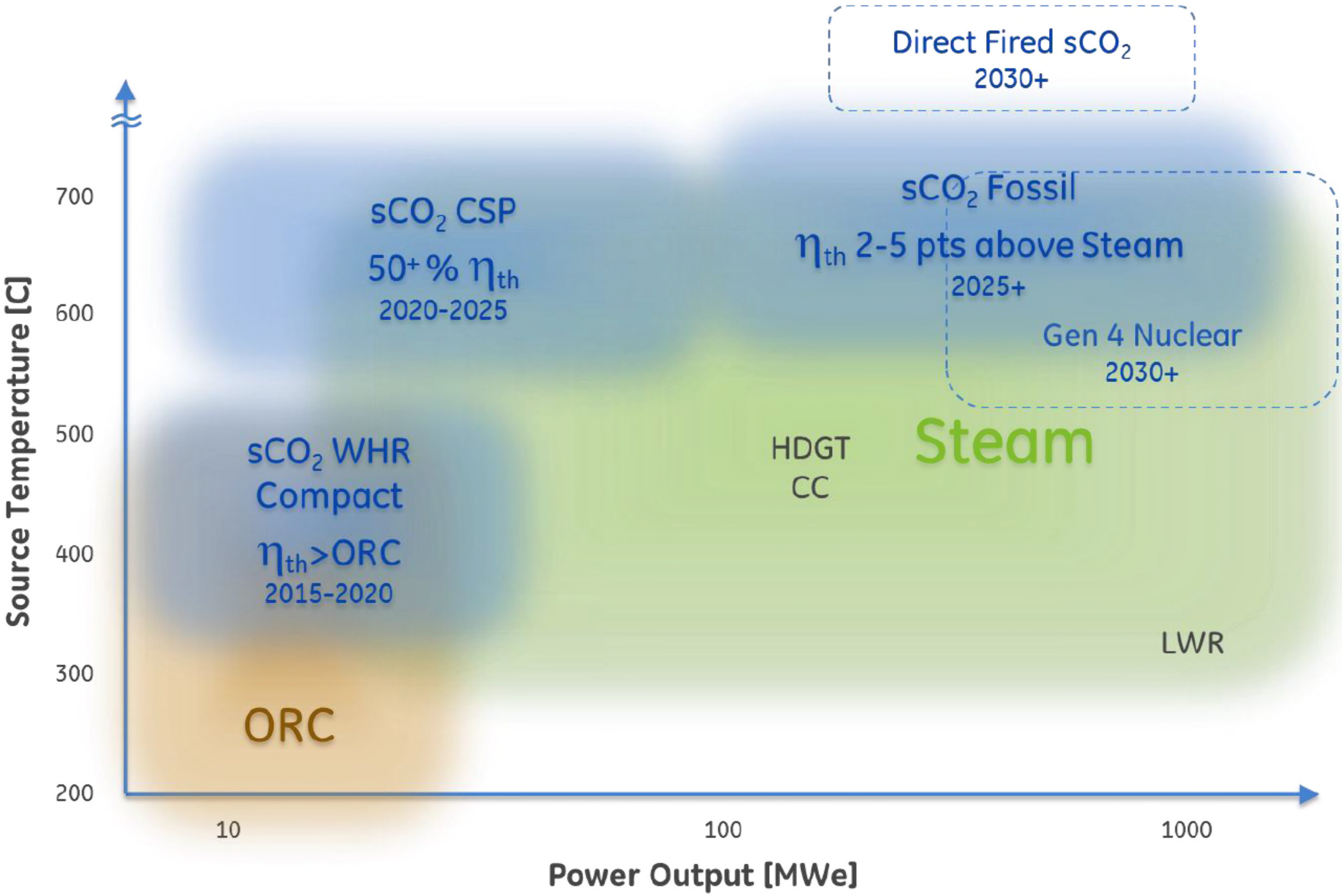
[6-4]

Nuclear

Ship-board Propulsion [6-5]


Waste Heat Recovery [6-11]

# Supercritical $CO_2$ Power Cycle Applications

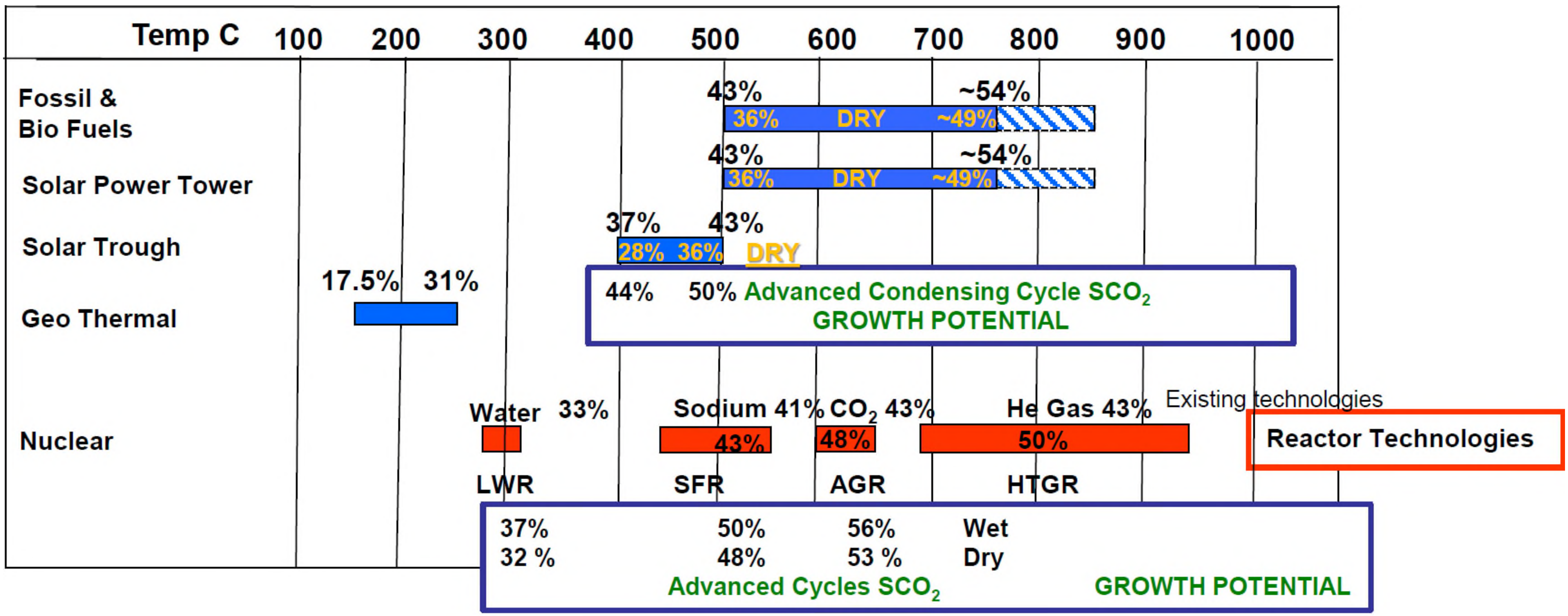



[Bowman 2016]

# "Typical" $sCO_2$ 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)

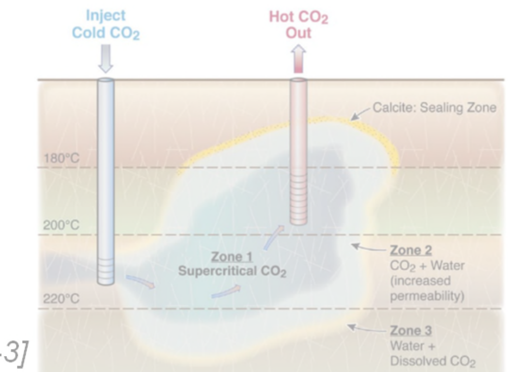
# Supercritical $CO_2$ in Power Cycle Applications


[6-1]

Concentrated Solar Power


[6-2]

Fossil Fuel

[6-3]



Geothermal


[6-4]

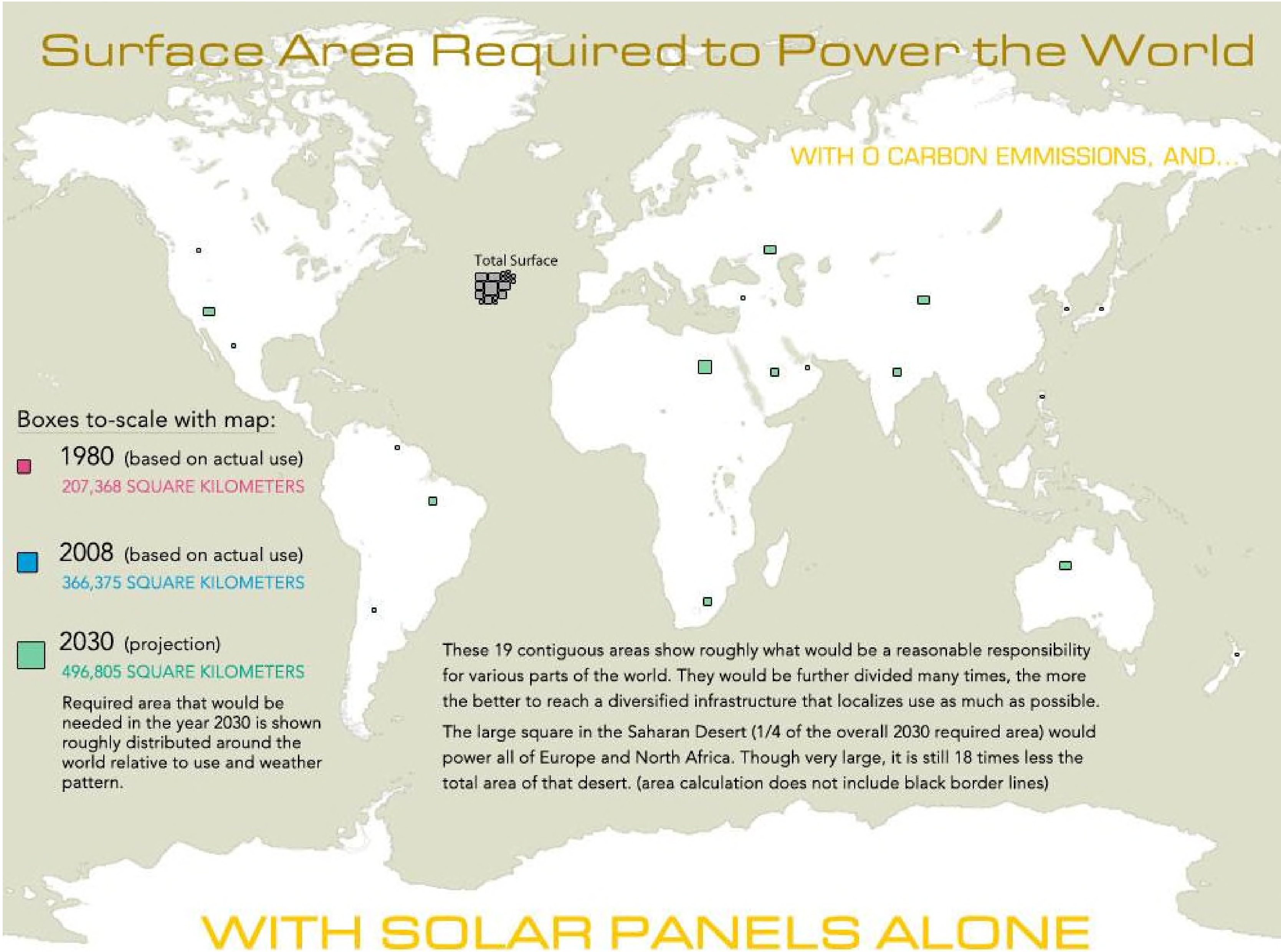
Nuclear


[6-5]

Ship-board Propulsion


Waste Heat Recovery [6-11]

# Why would we use solar power?



# Concentrated Solar Power (CSP)

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

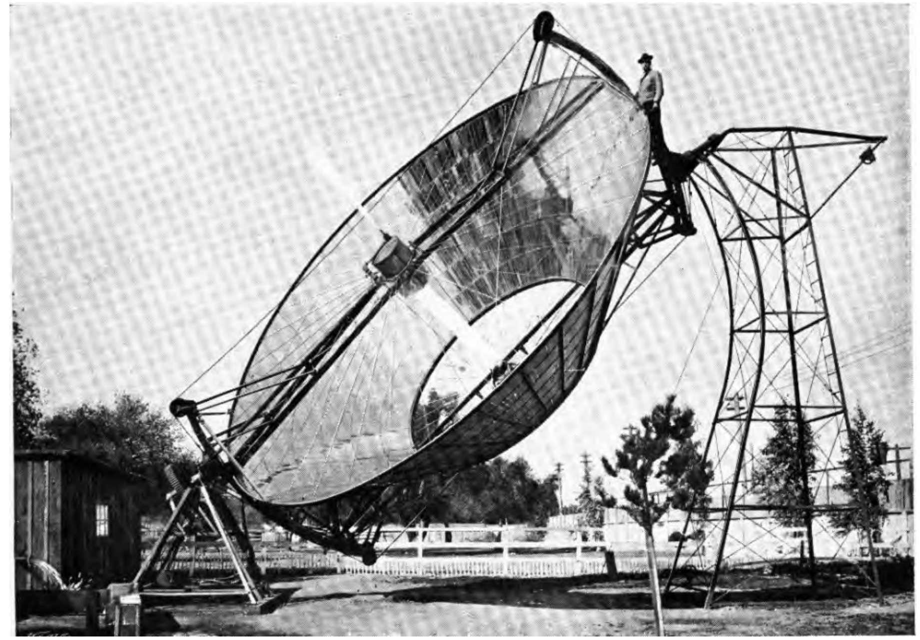
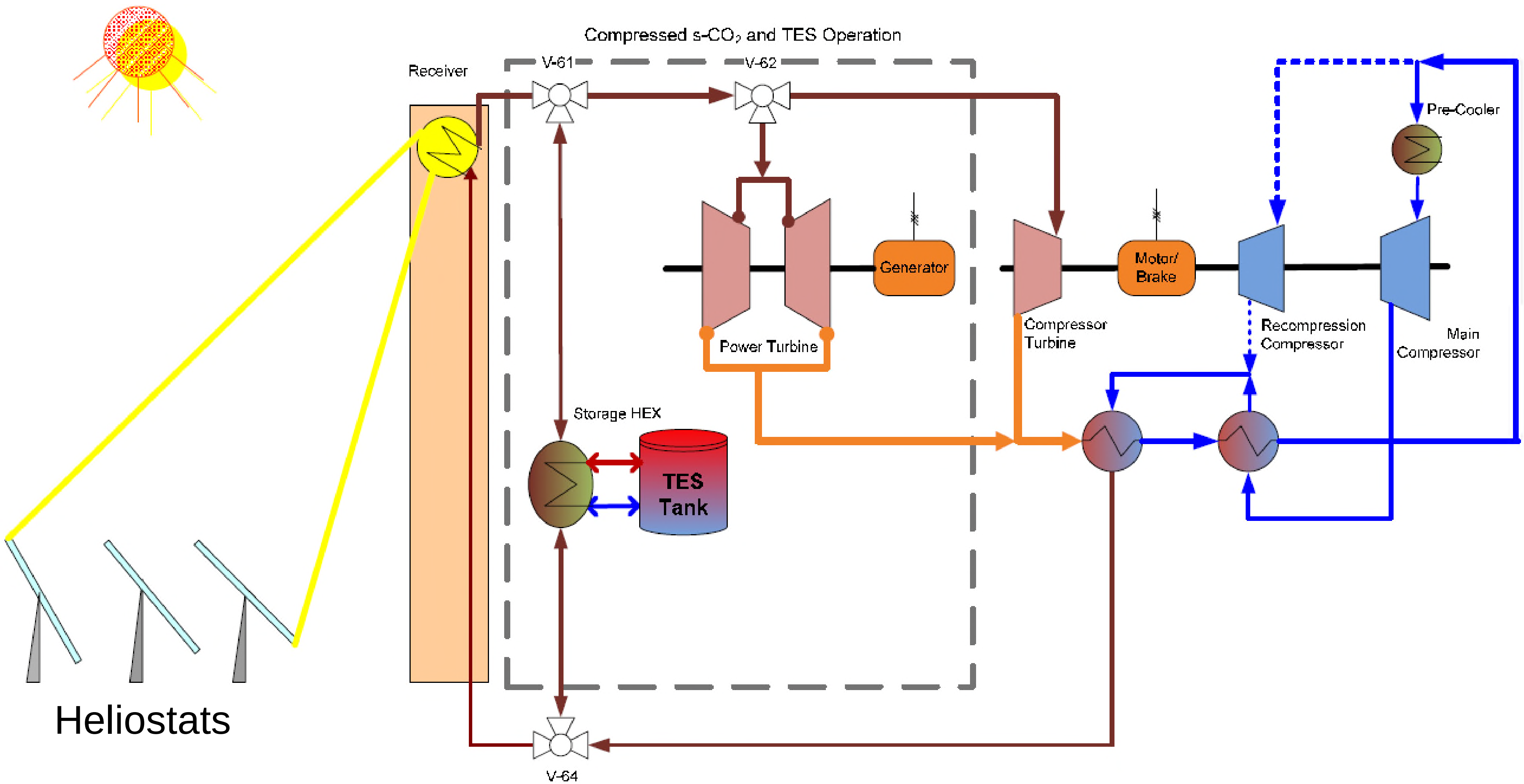


*Image source: [6-6]*

*Image source: [6-7]*

# $sCO_2$ CSP Process Diagram



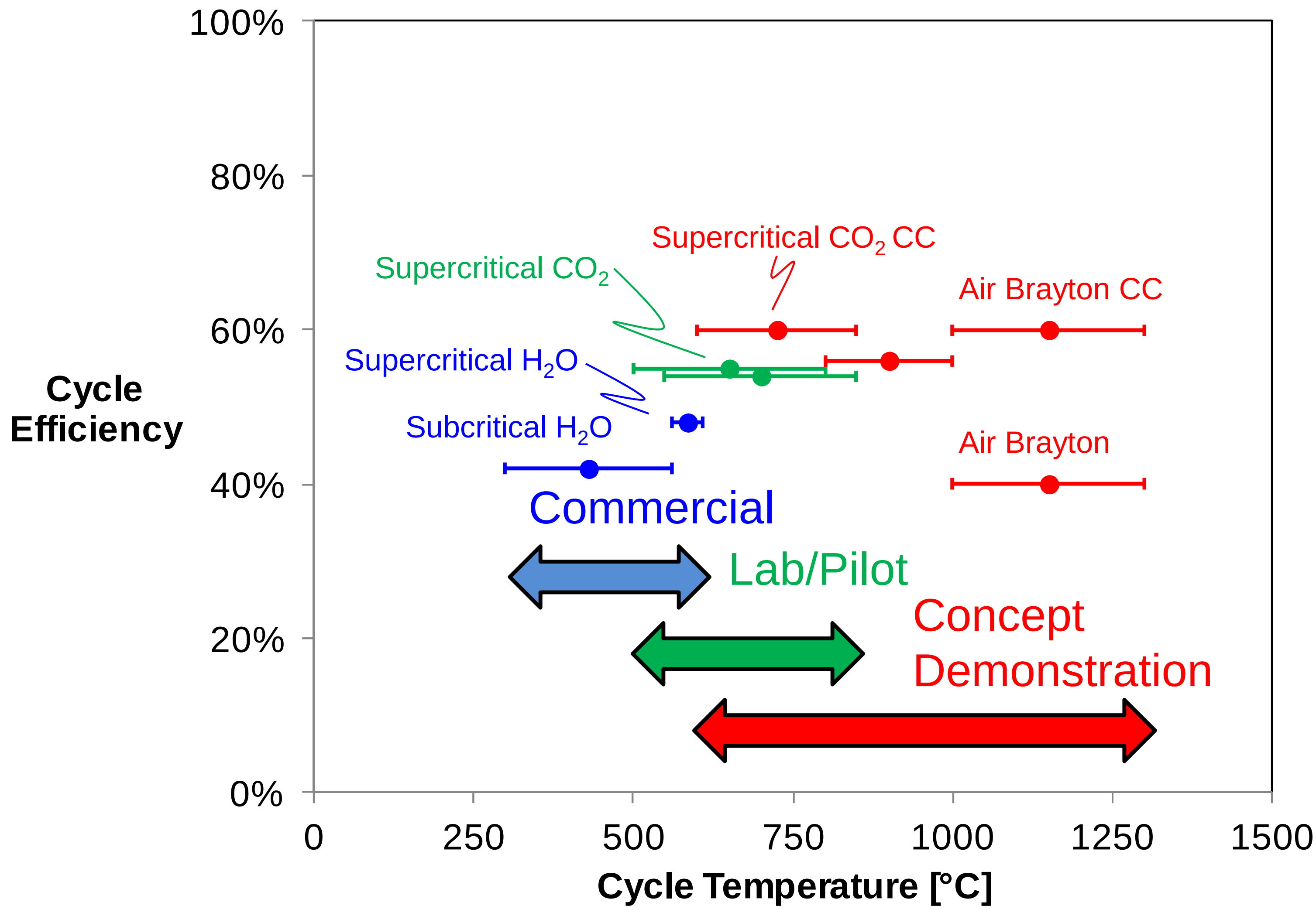

Dual-shaft, tower receiver $sCO_2$ Brayton Cycle solar thermal power system with thermal energy storage, Zhiwen and Turchi (2011)

# CSP – Improvement Opportunities

- Advanced power cycles
  - Supercritical steam Rankine
  - High temperature air Brayton
  - Supercritical $CO_2$
- Cooling
  - 650 gal $H_20$/MWh
  - Dry-cooling technology is needed in most desert venues for CSP
    - 43°C Dry bulb
  - Printed circuit heat exchangers may provide a solution

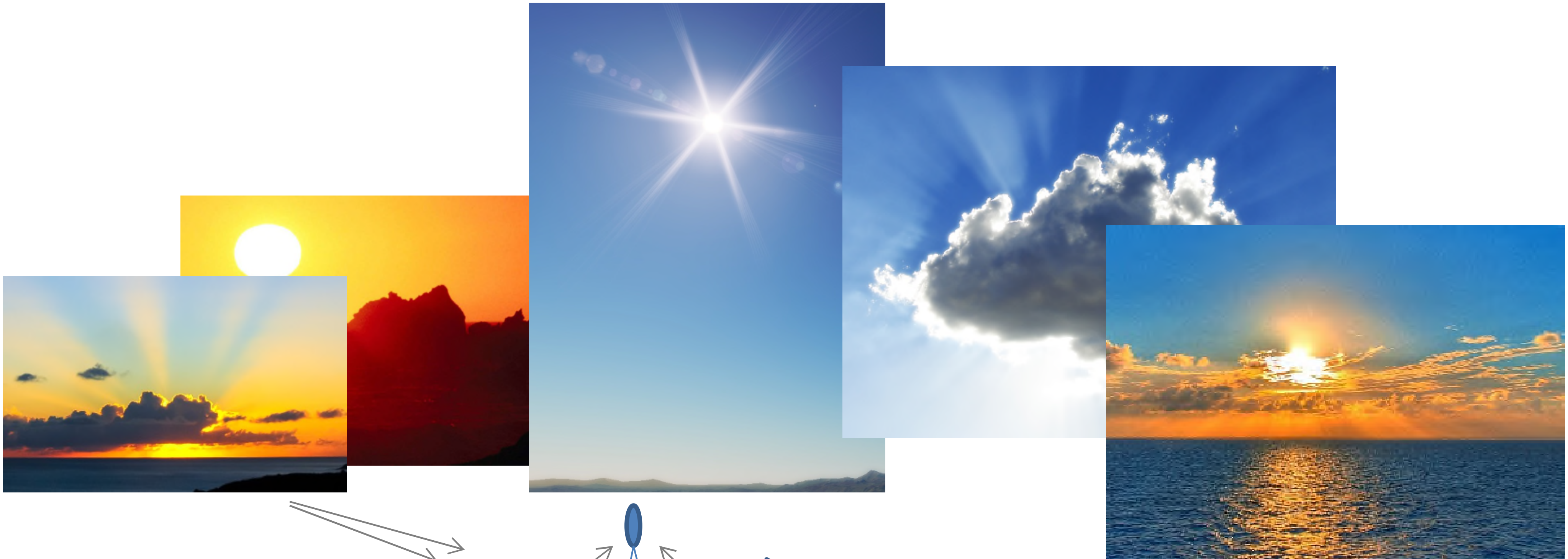

*Image source: [6-1]*

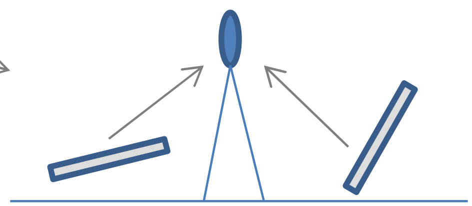
# CSP Efficiencies vs. Power Cycle

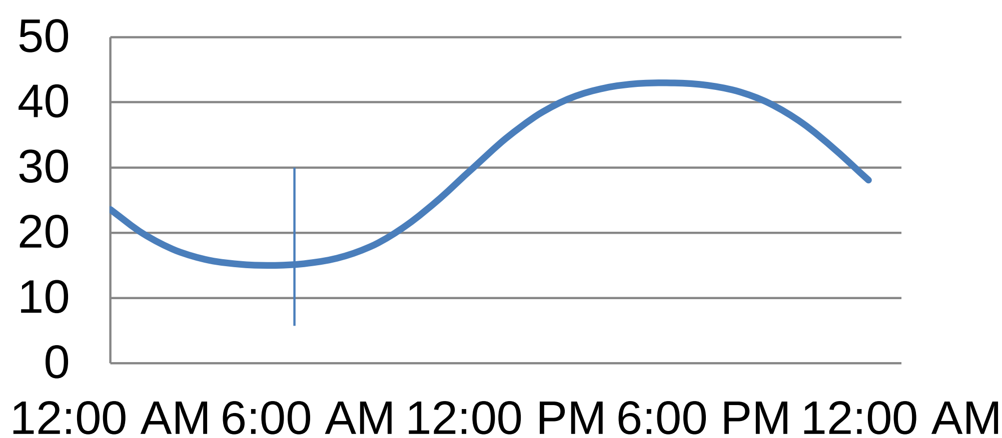



Data from Stekli (2009)

# The transient challenges of a concentrated solar power plant are significant

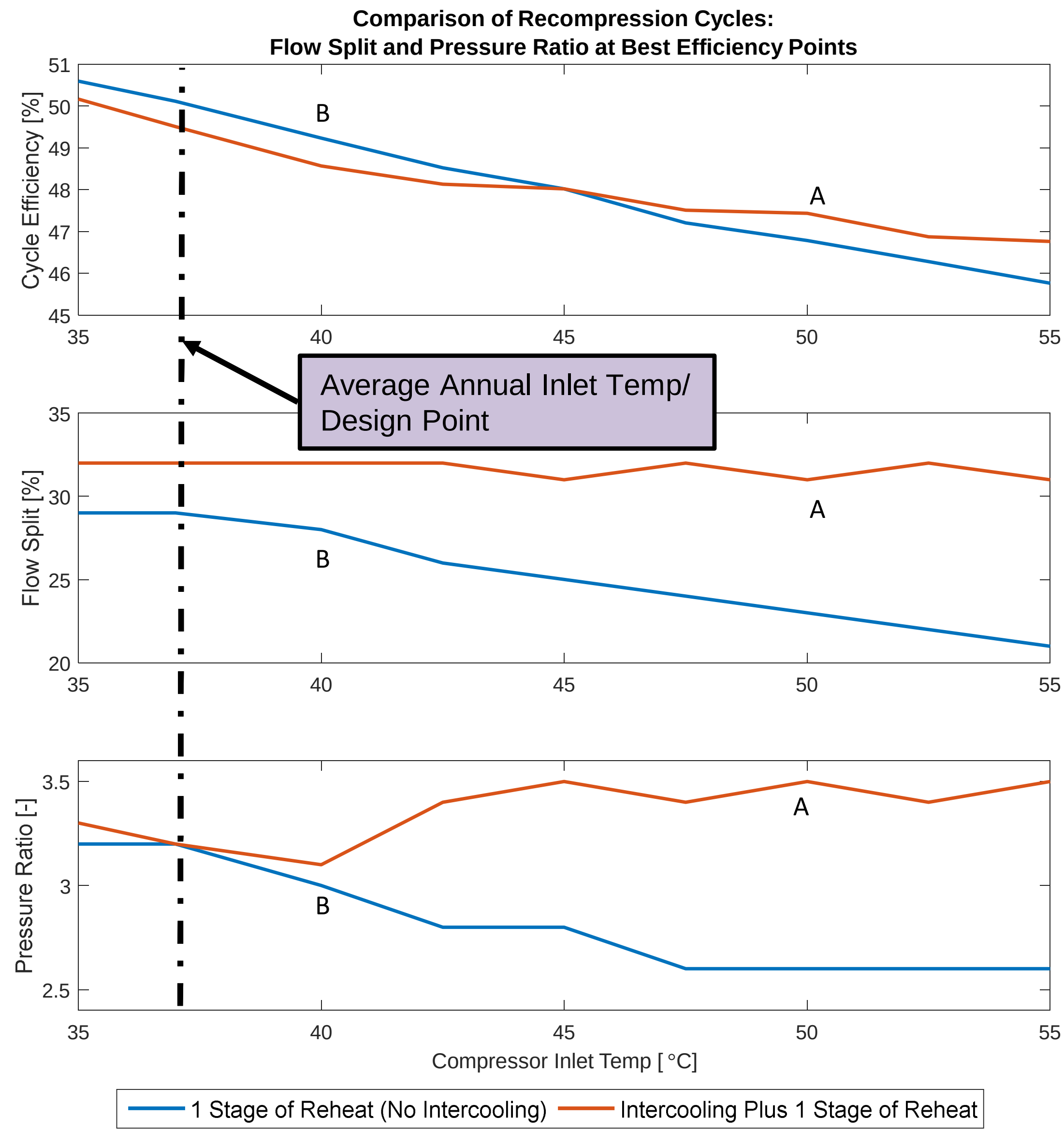






# Optimal Cycle Configuration with varying Compressor Inlet Temperature

- 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



**Need to add Reciever and primary heater and energy storage concerns.**

# CSP Compressor Inlet Variation and Turbomachinery Performance

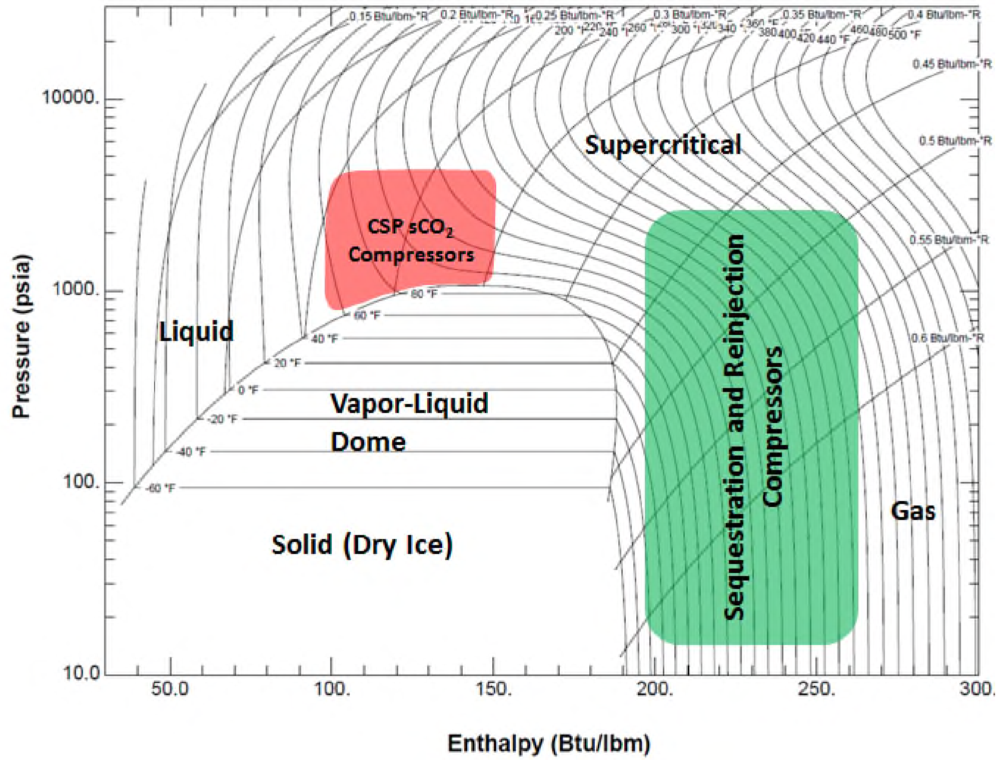



**Table 1: Variation in Compressor Inlet Condition and Typical $sCO_2$ Cycles for CSP**

| Property | Units | Monge 2014[2] | | | Neises 2013[1] | | |
|---|---|---|---|---|---|---|---|
| | | Cold | Design | Hot | Cold | Design | Hot |
| Pressure | MPa | 7.5 | | | 10.05 | | |
| Temperature | °C | 31.5 | 32.6 | 65 | 31.5 | 50 | 65 |
| Density | kg/m3 | 561 | 326 | 165 | 757 | 390 | 268 |
| Speed of Sound | m/s | 177 | 185 | 245 | 368 | 219 | 236 |
| Compressibility | - | 0.23 | 0.40 | 0.71 | 0.23 | 0.42 | 0.59 |

# CSP Compressor Inlet Variation and Turbomachinery Performance

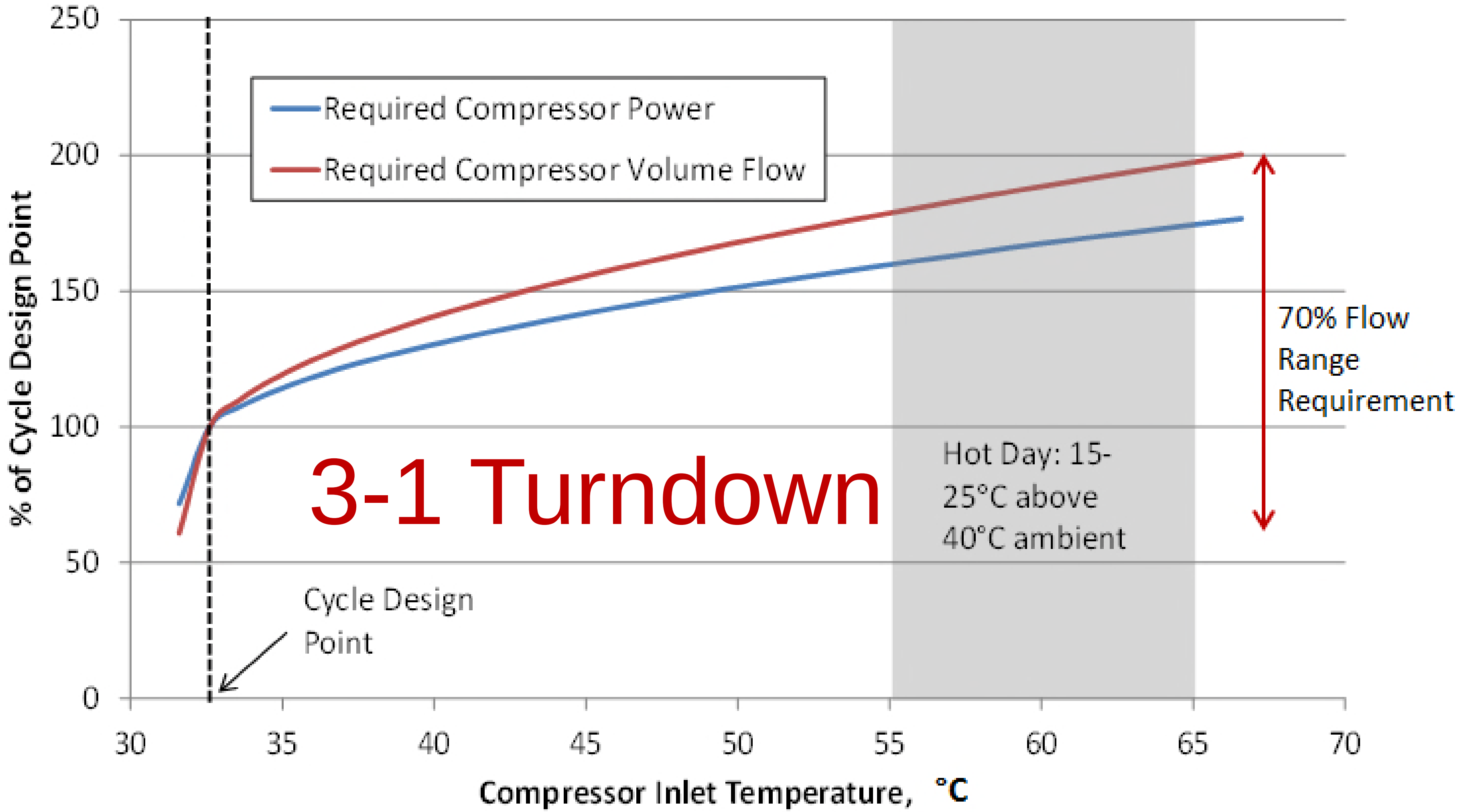



**Figure 3: Compression Power and Inlet Volume Flow Variation over Potential Cycle Temperatures**

# CSP Compressor Inlet Variation and Turbomachinery Performance

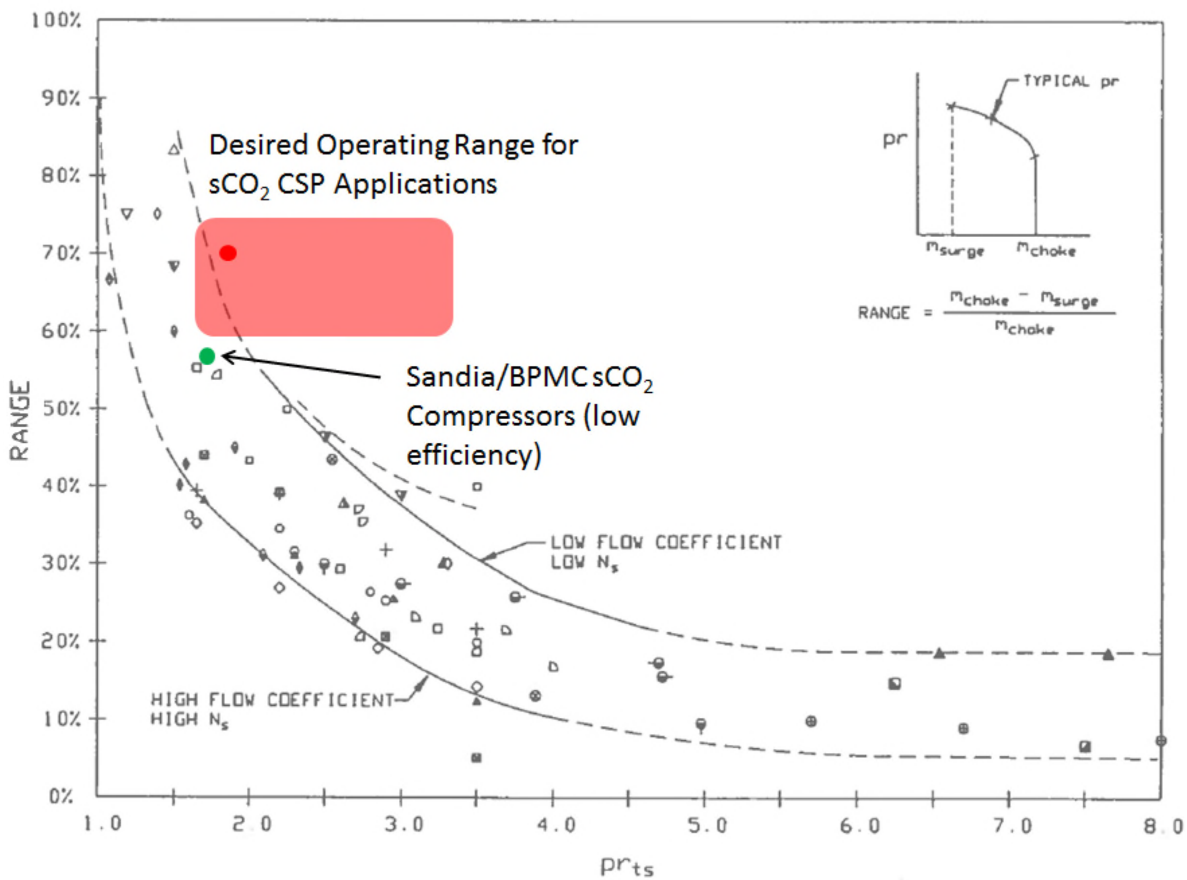
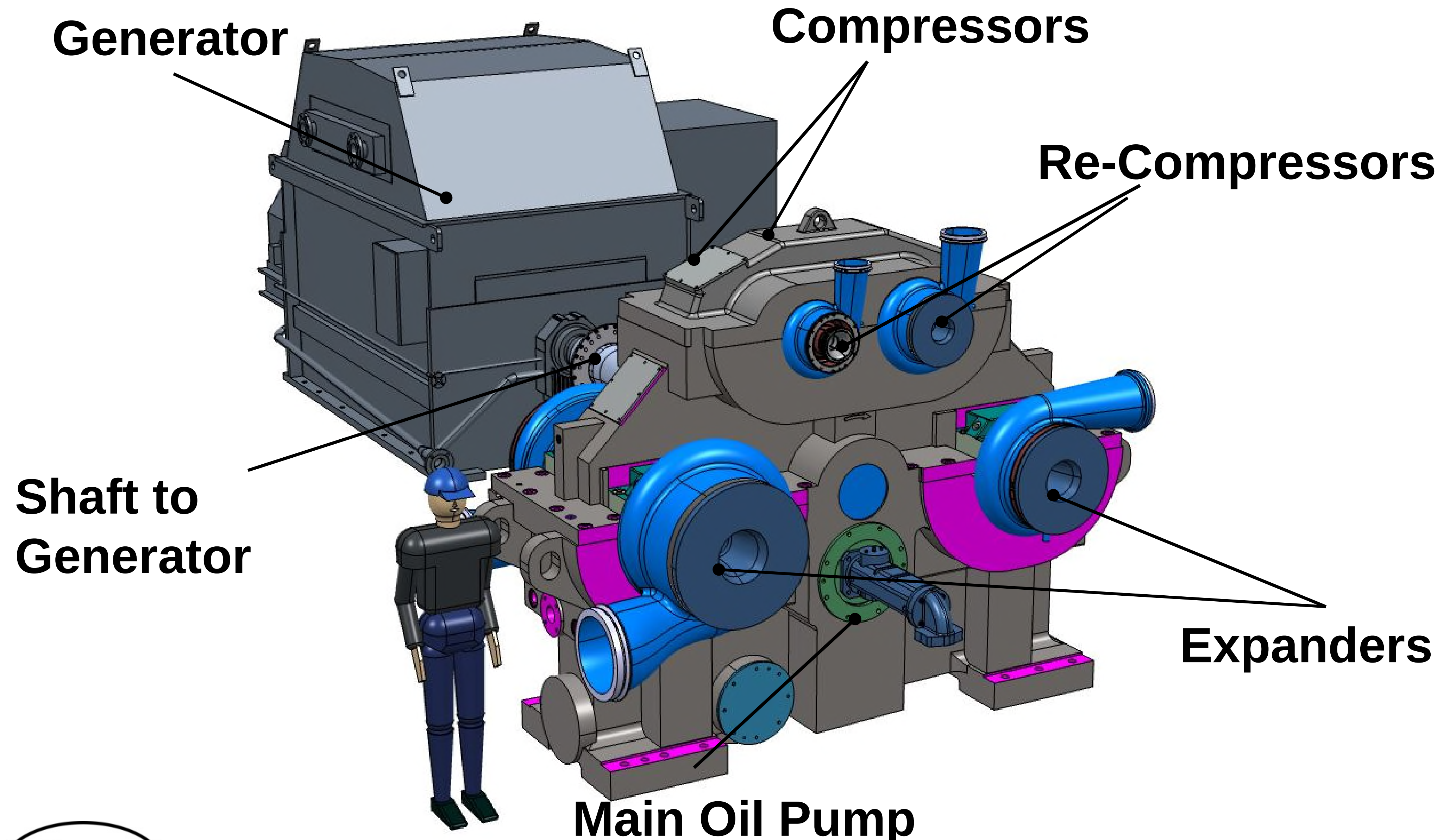



**Figure 5: Comparison of Operating Range and Pressure Ratio Requirements [Modified from Japikse[5]]**

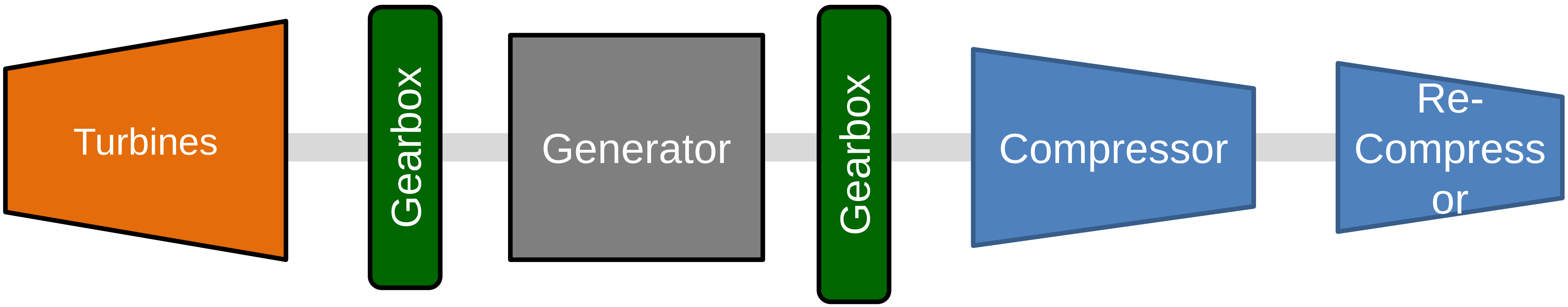
- To manage this challenge, numerous strategies will be required
  - Inventory Control
  - Inlet Guide Vanes
  - Variable Diffuser Vanes
  - Variable Speed Compression
  - Novel Control Features

# Conceptual 10 $MW_e$ Integrally Geared Compressor Applied to Recuperated Brayton Cycle

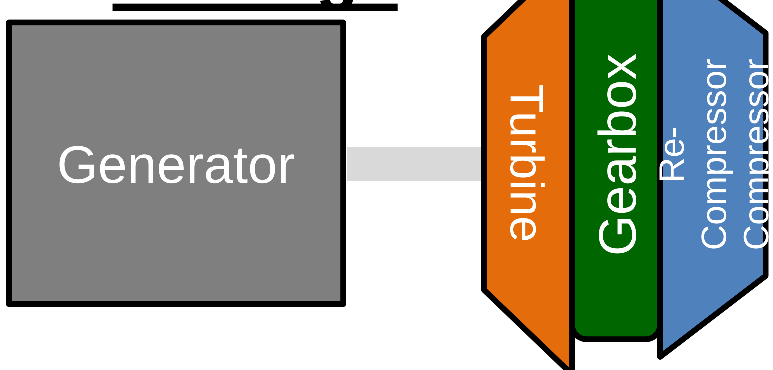


# IGC Offers Compact Configuration for this Application

## Conventional Turbomachinery Train




## Typical IGC Package

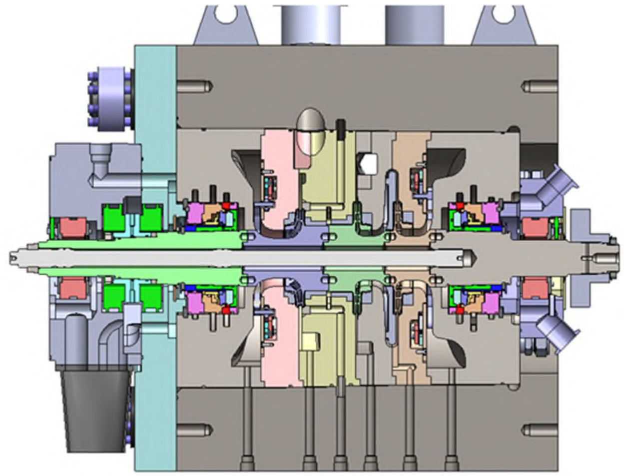


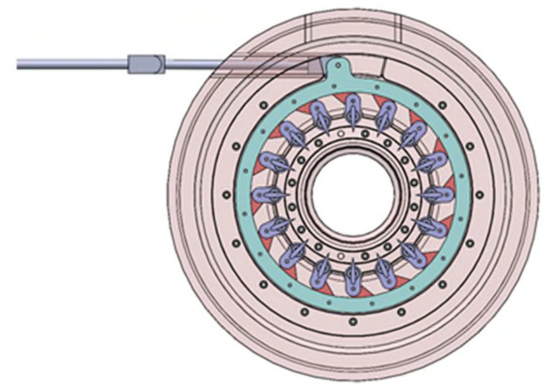

- An IGC package incorporates all the key elements of a conventional train in a much more compact package
- Compressor, re-compressor, turbine and gearbox are assembled in a single compact core.
- The second gearbox, additional couplings and housings in the conventional train can be eliminated
- Simple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

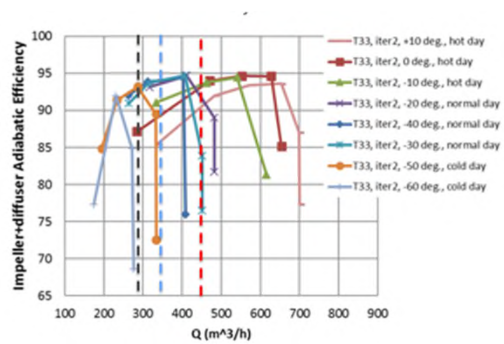
SwRI®

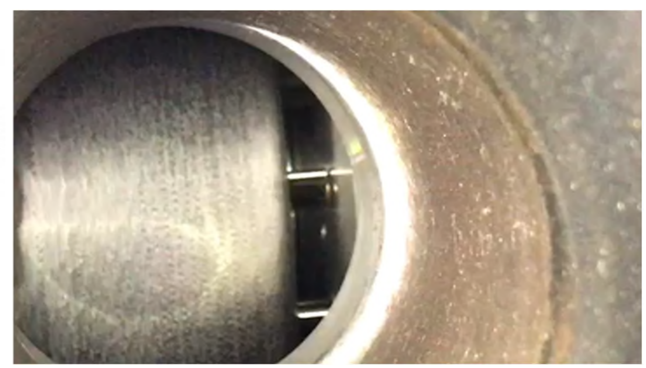
# APOLLO Compressor Development

- ❑ 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



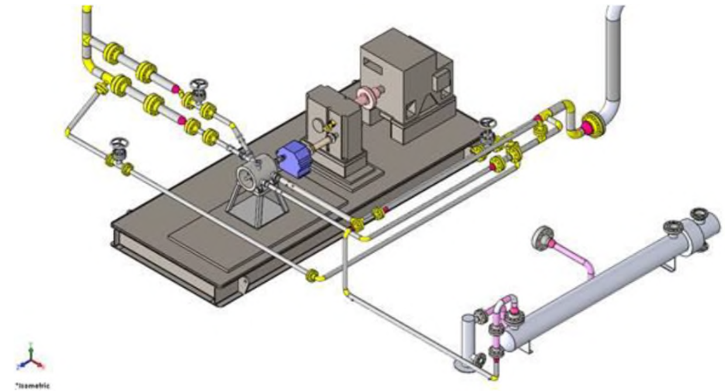




# APOLLO Compressor – Current Status

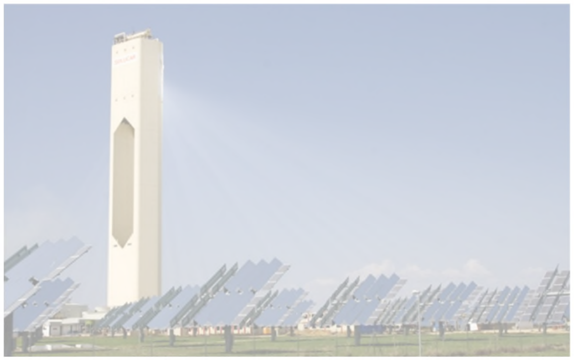
- Installed in test loop at SwRI
  - Full flow, pressure, temperature
- First spin May 2019
- Test program through September 2019
- Test Objectives:
  - Validate rotordynamic, mechanical, and aero performance
  - Various inlet temperatures and IGV settings



# 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



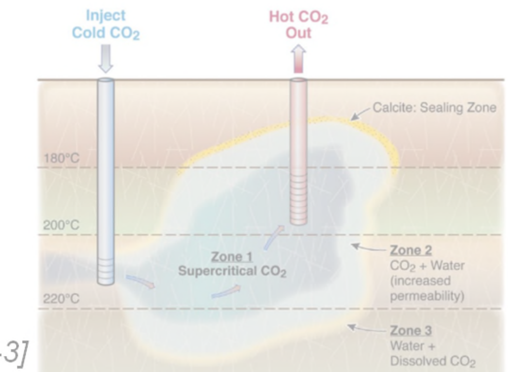
[6-1]

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

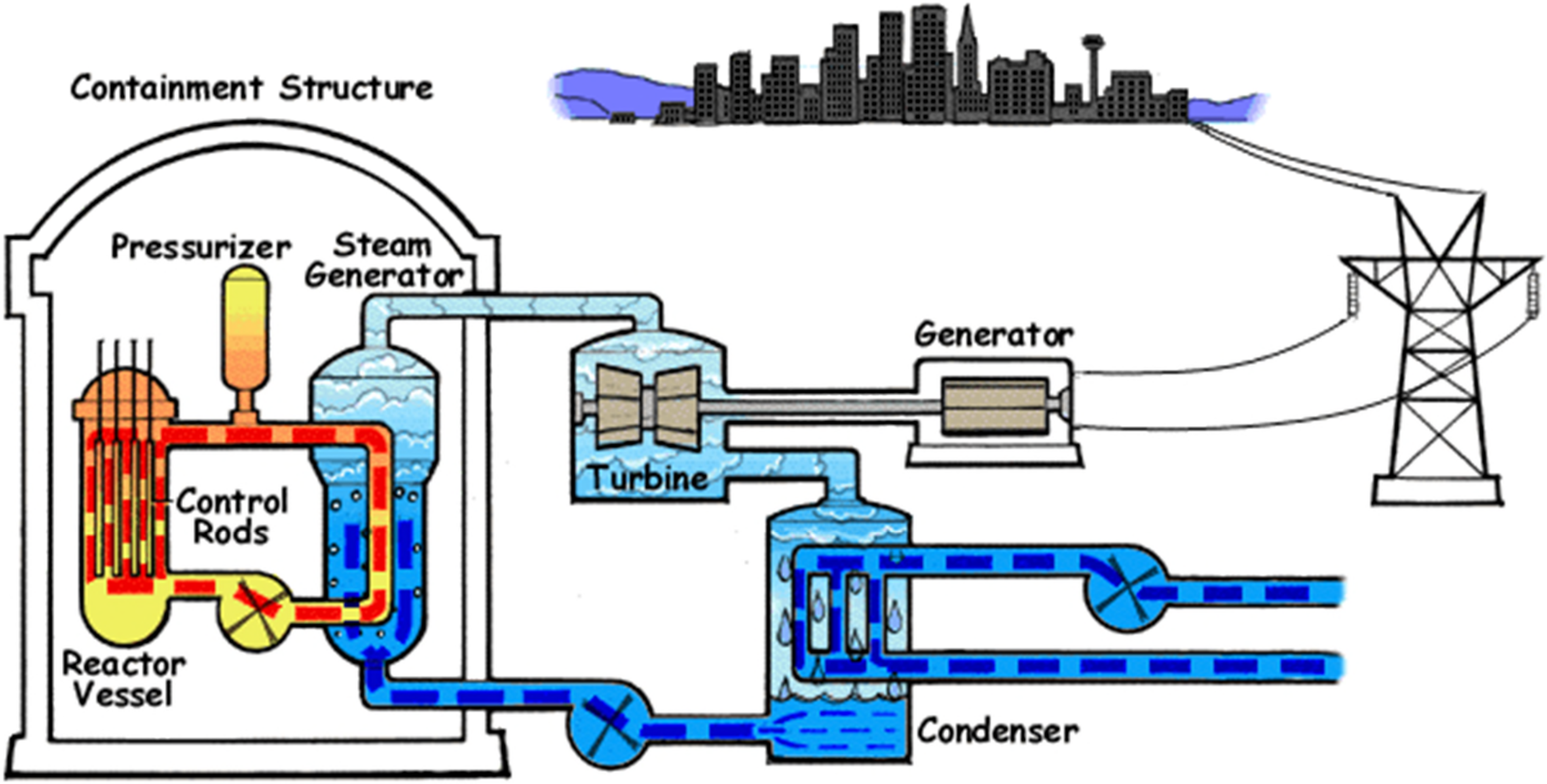



Image source: [6-8]

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

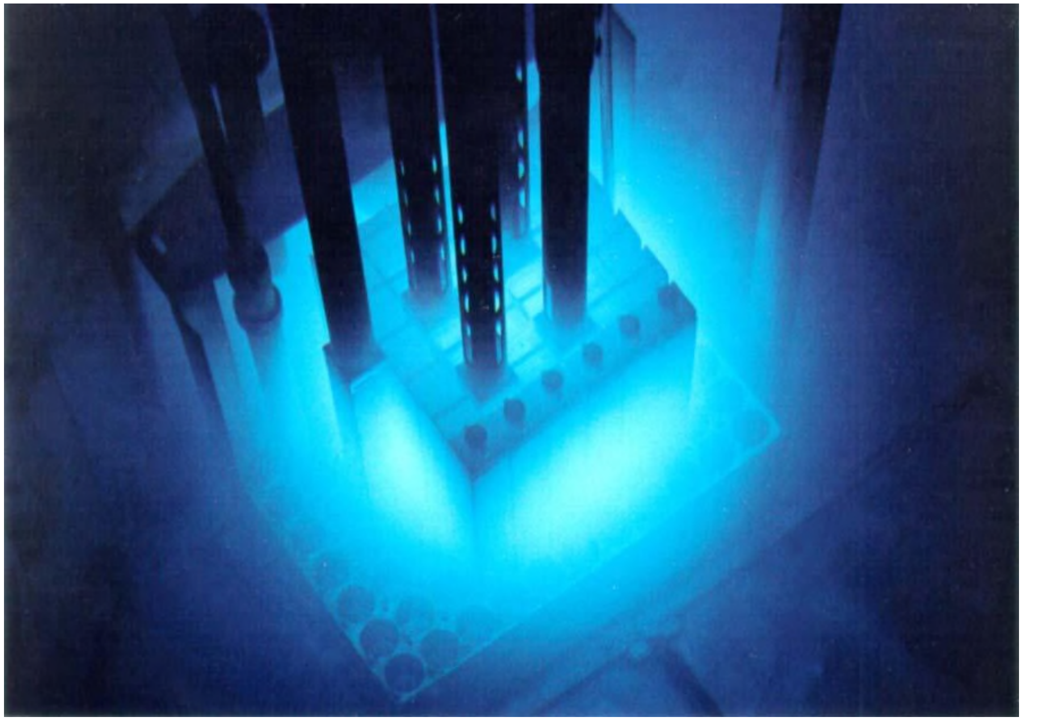
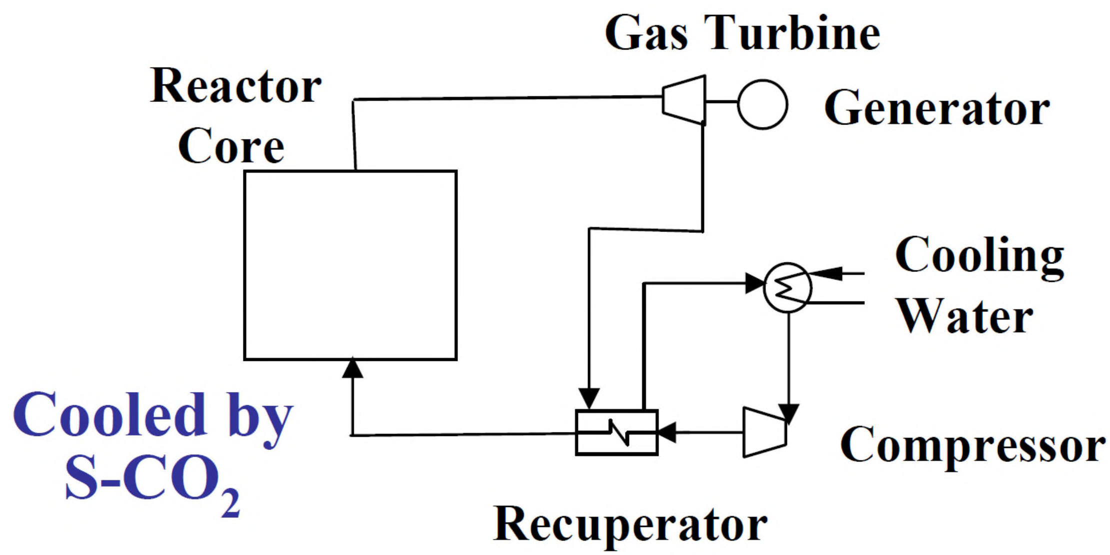


Image source: [6-9]

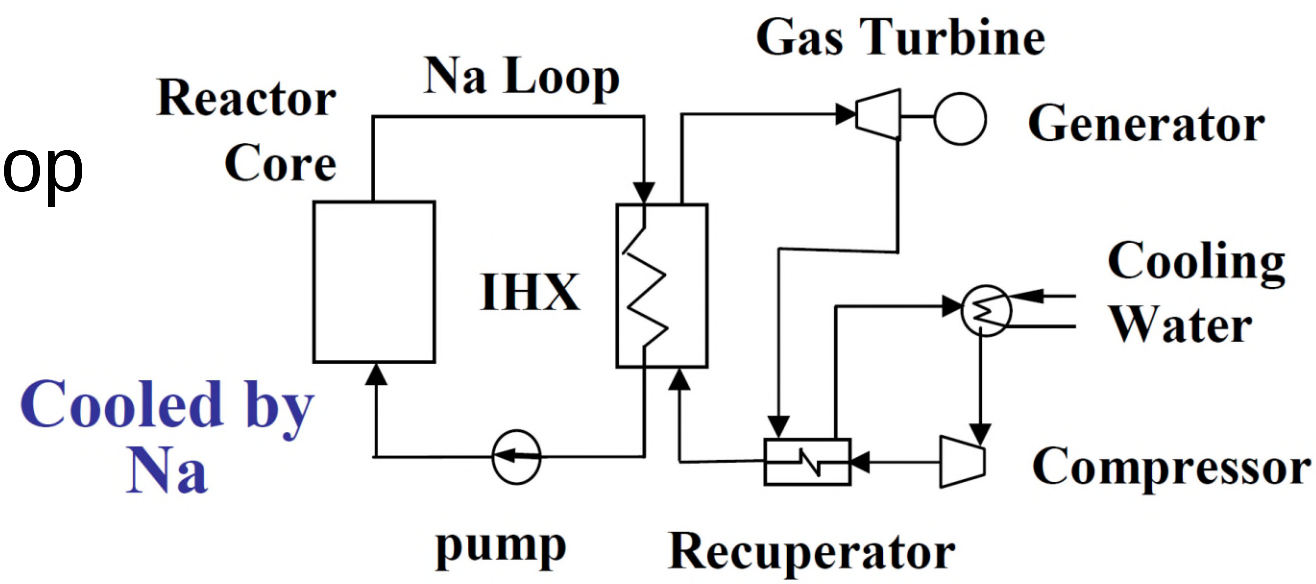
Image source: [6-4]

# 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)

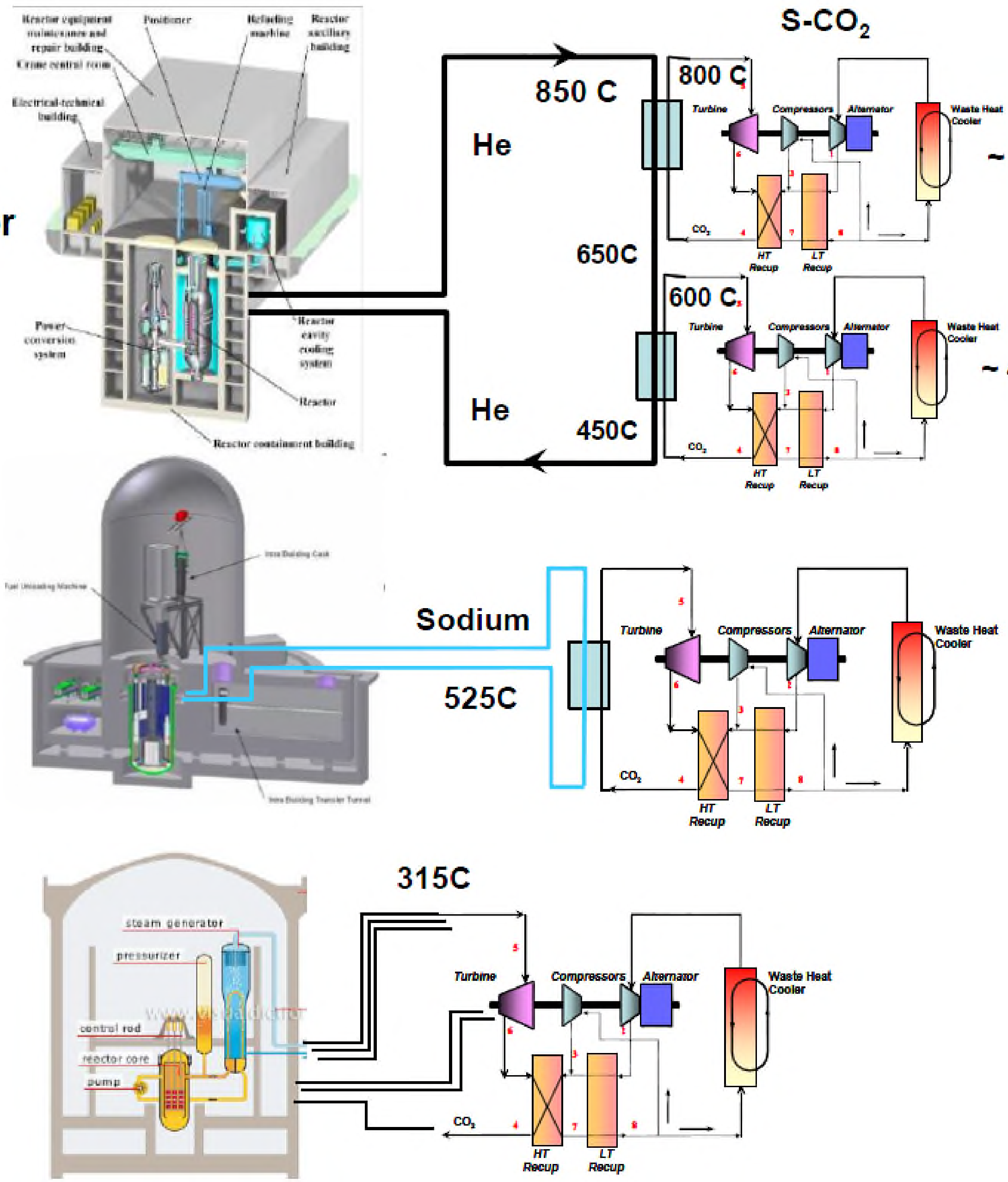
# $sCO_2$ Power Cycle for Nuclear

NGNP
High Temperature
Gas Cooled Reactor
850-900 C

Sodium Cooled
Reactor
500-550 C

LWRs
Pressurized
Water Reactor
330 C

Potential SMR
Applications




*GCRs*

~ 54 %

~ 50 % Efficiency
(S-$CO_2$ Brayton)

~ 46 %

*SFRs*

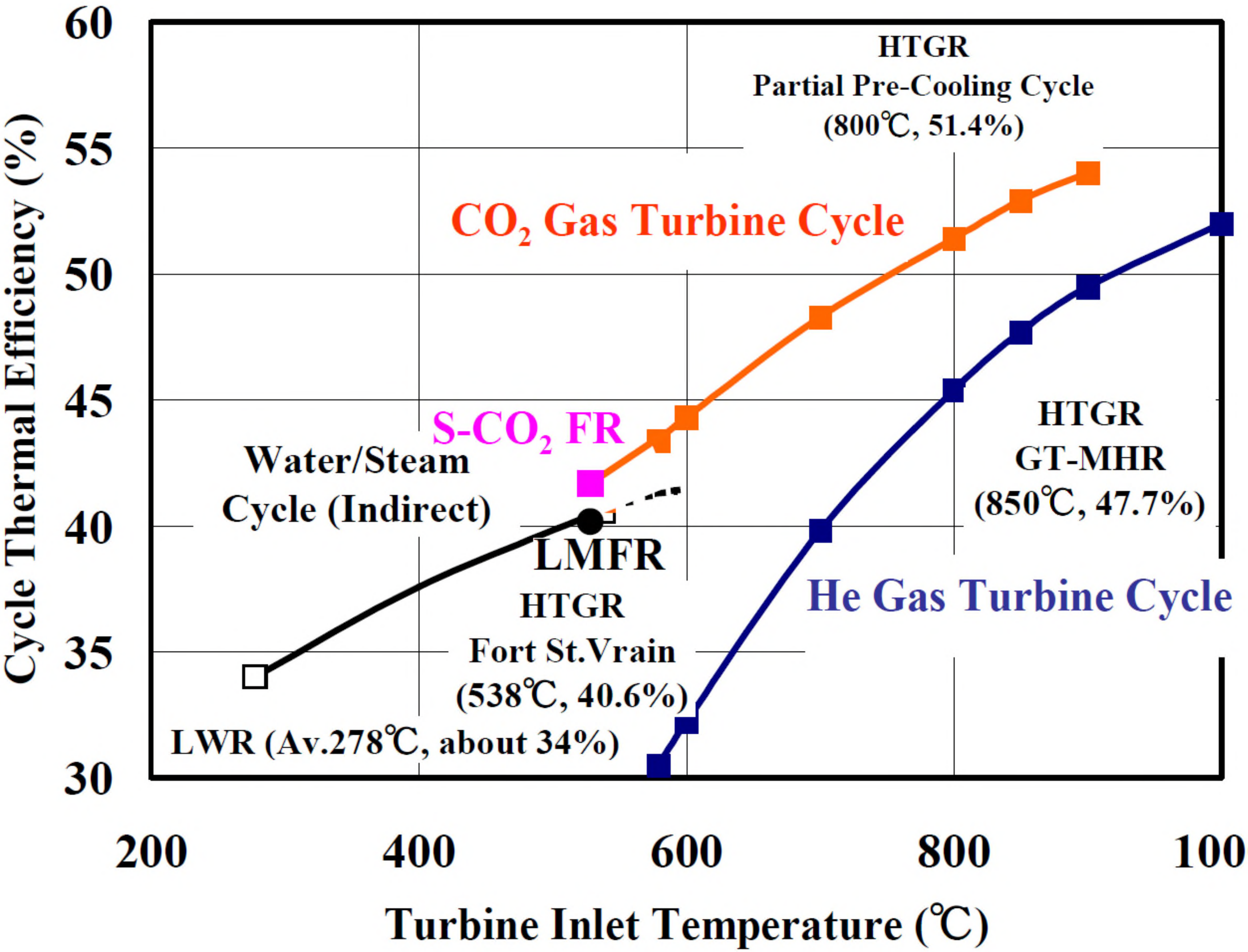
~ 43 % Efficiency
(S-$CO_2$ Brayton)

*LWRs*

~ 40 % Efficiency
(S-$CO_2$ Recup Rankine
Condensing Brayton)

Source: Wright (2011)

# 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 |

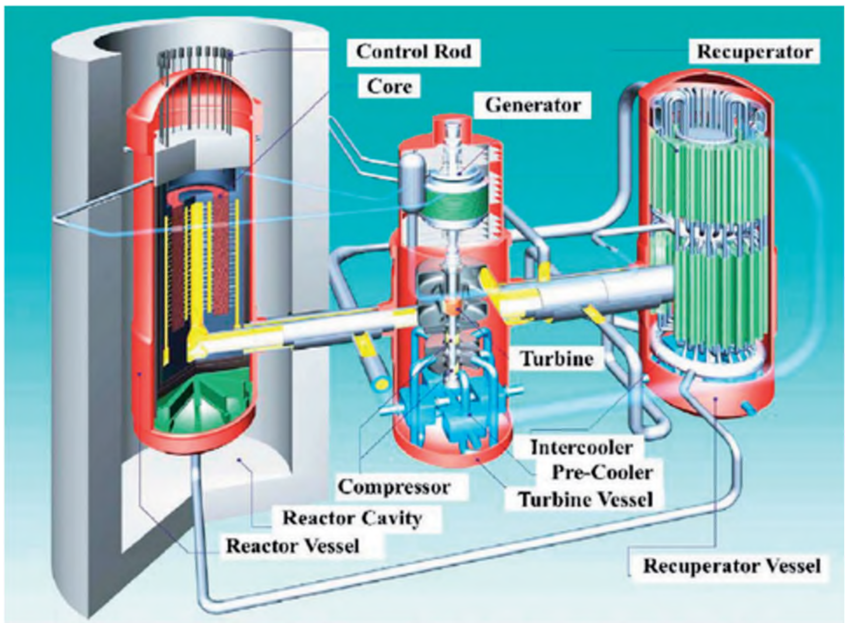
# Modular vs. Consolidated

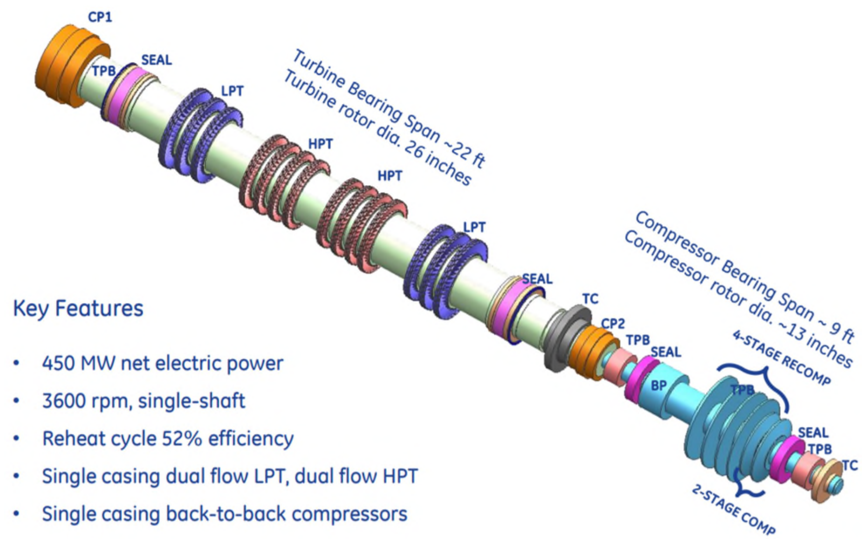
## ❑ 10-20 MW

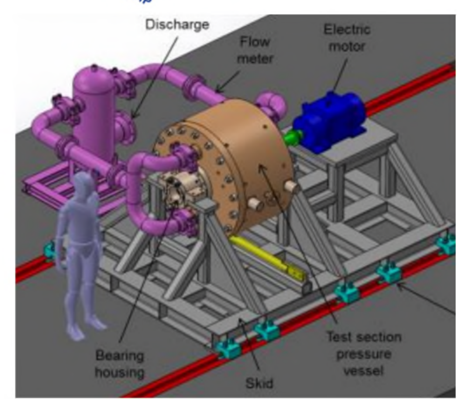
- Multiple High-Speed Trains
- Smaller Capital Investment
- Intrinsically Safe Cooling
- Mass Scale Production
- Smaller Environmental Risk

## ❑ 200 MW-1 GW

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




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

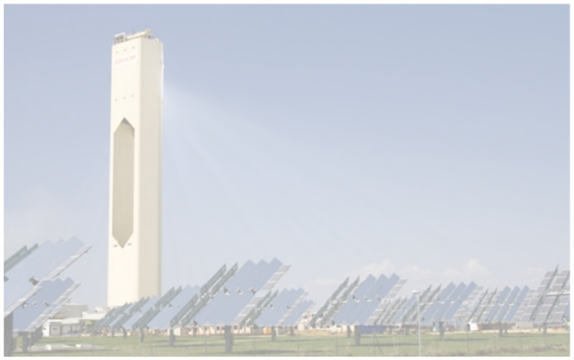
Bidkar et al., sCO2 turbomachinery and Low-Leakage sCO2 End Seals, UTSR (2015)

# What are the key challenges to Nuclear $sCO_2$ cycles

- Aversion to risk likely to push this out past waste heat recovery, solar, Nuclear is a hot topic, and modular 10-30 reactor companies are considering sCO2 cycles.

- ❑ Add slide on nuclear energy potential

# Supercritical $CO_2$ in Power Cycle Applications



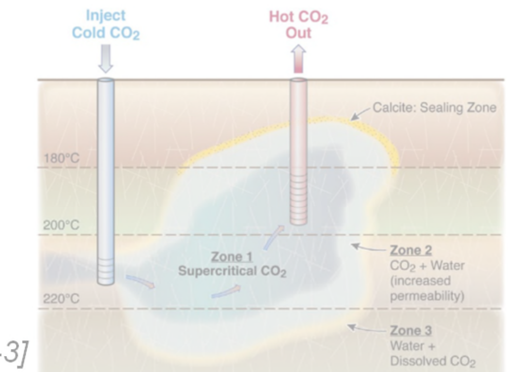
[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel

[6-3]




Geothermal

[6-4]

Nuclear

[6-5]

Ship-board Propulsion

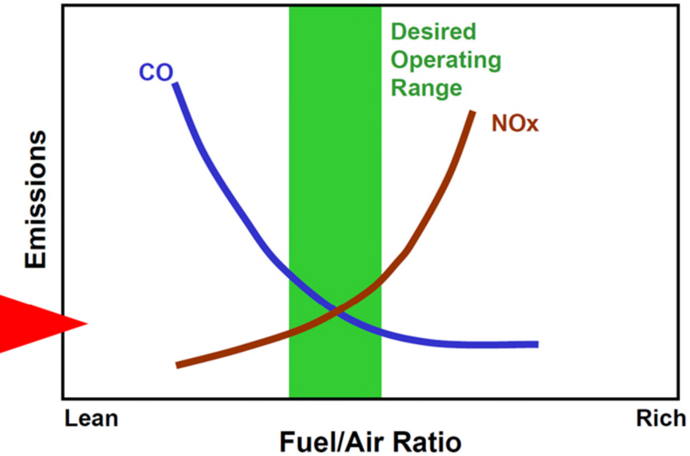

Waste Heat Recovery [6-11]

# Oxy-Fuel Combustion

## Conventional Combustion

Air
(78% $N_2$, 21% $O_2$)

Fuel




(Solar Turbines 2012)

## Oxy-Fuel Combustion

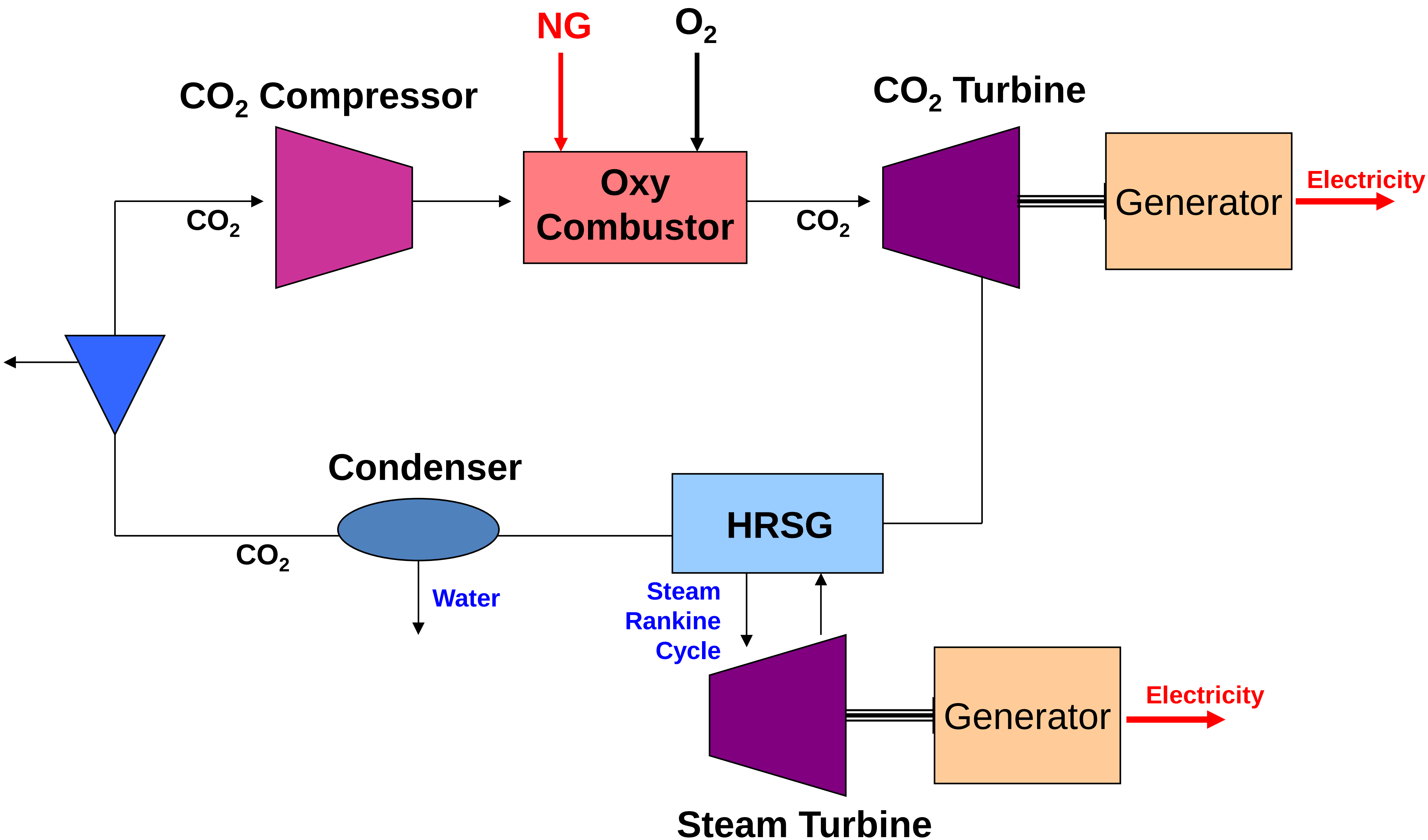
$O_2$

Fuel

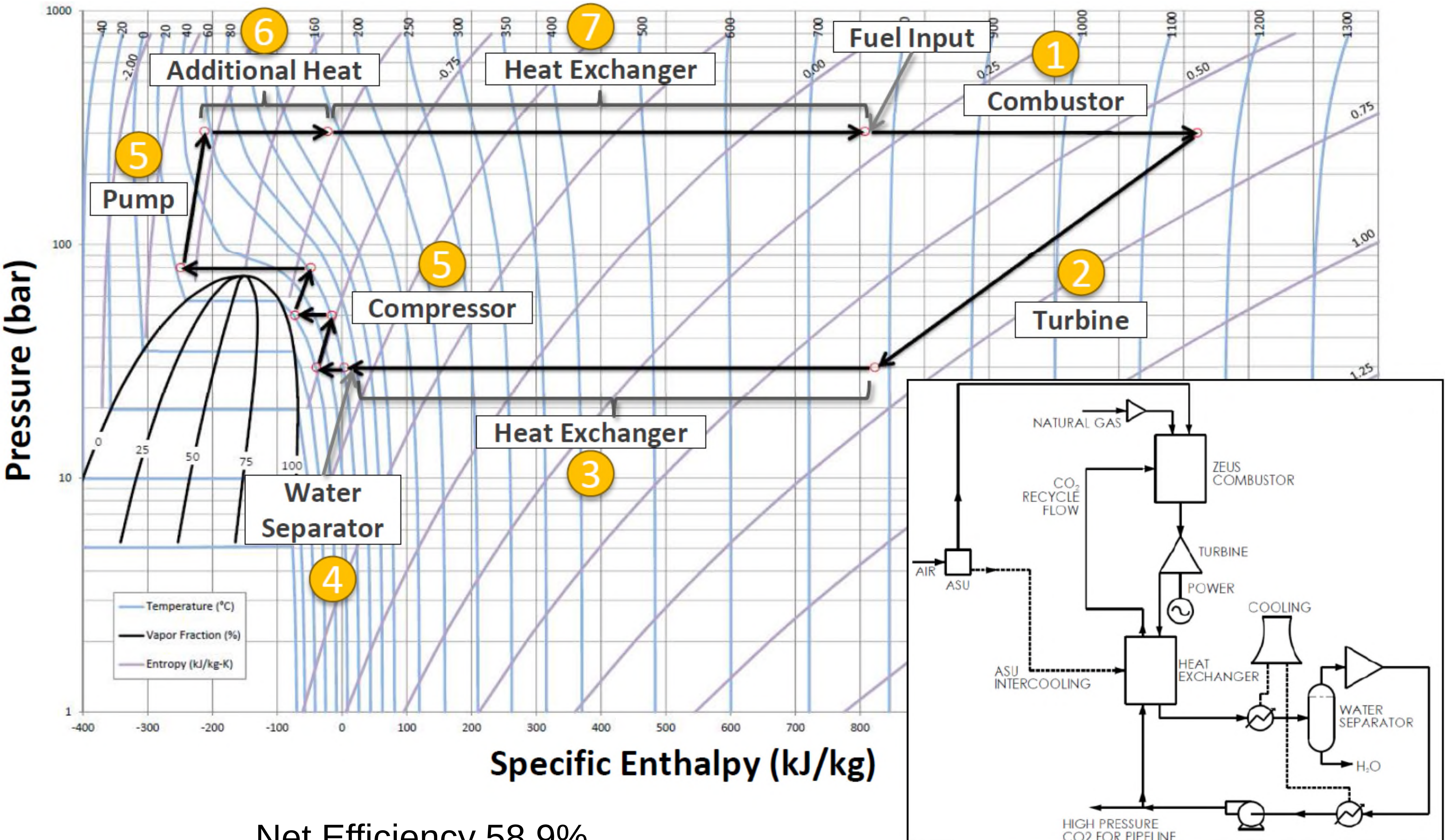
$CO_2$

$H_2O$

# Direct Oxy-Fuel Combustion



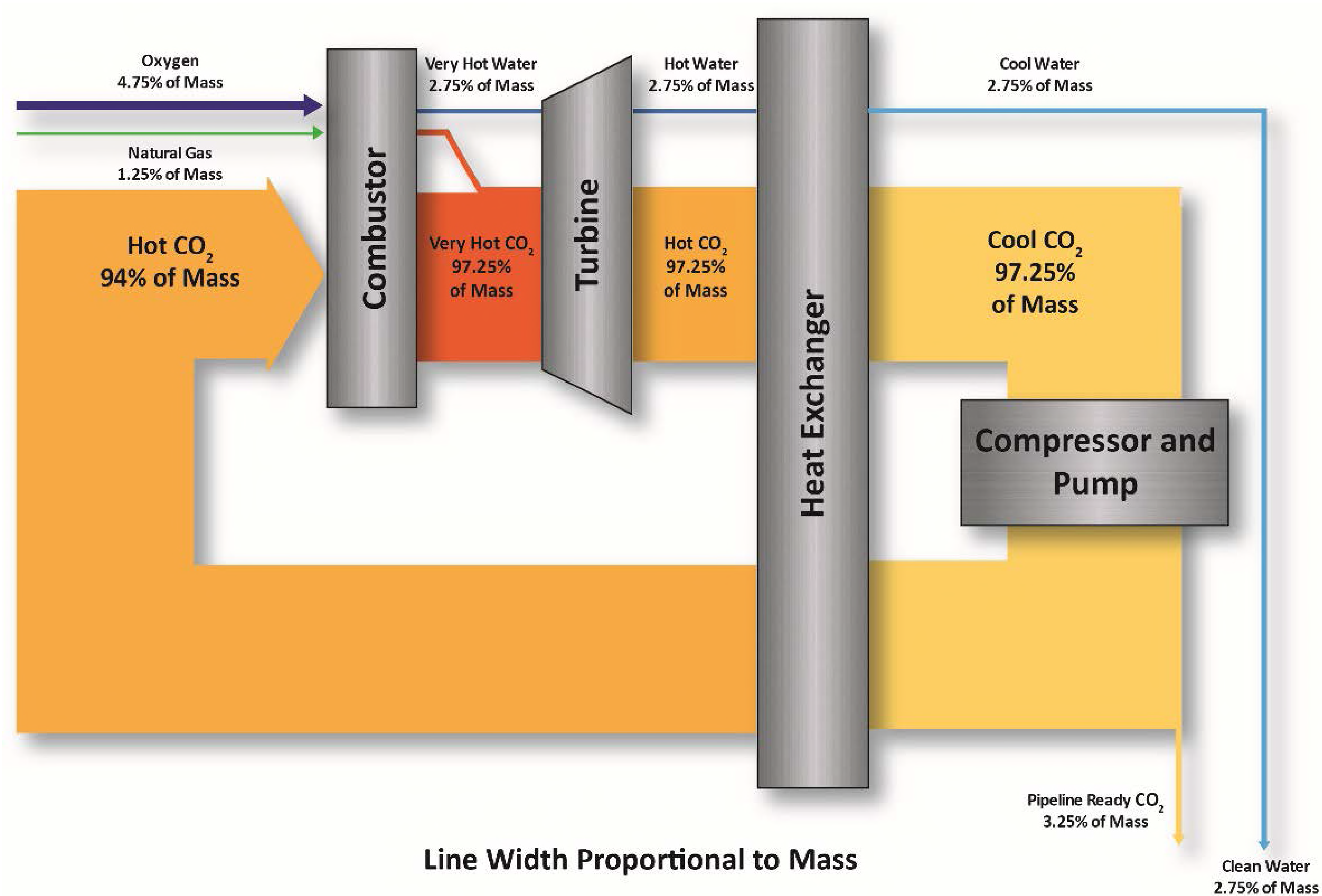
# Allam Cycle (NetPOWER)




Net Efficiency 58.9%

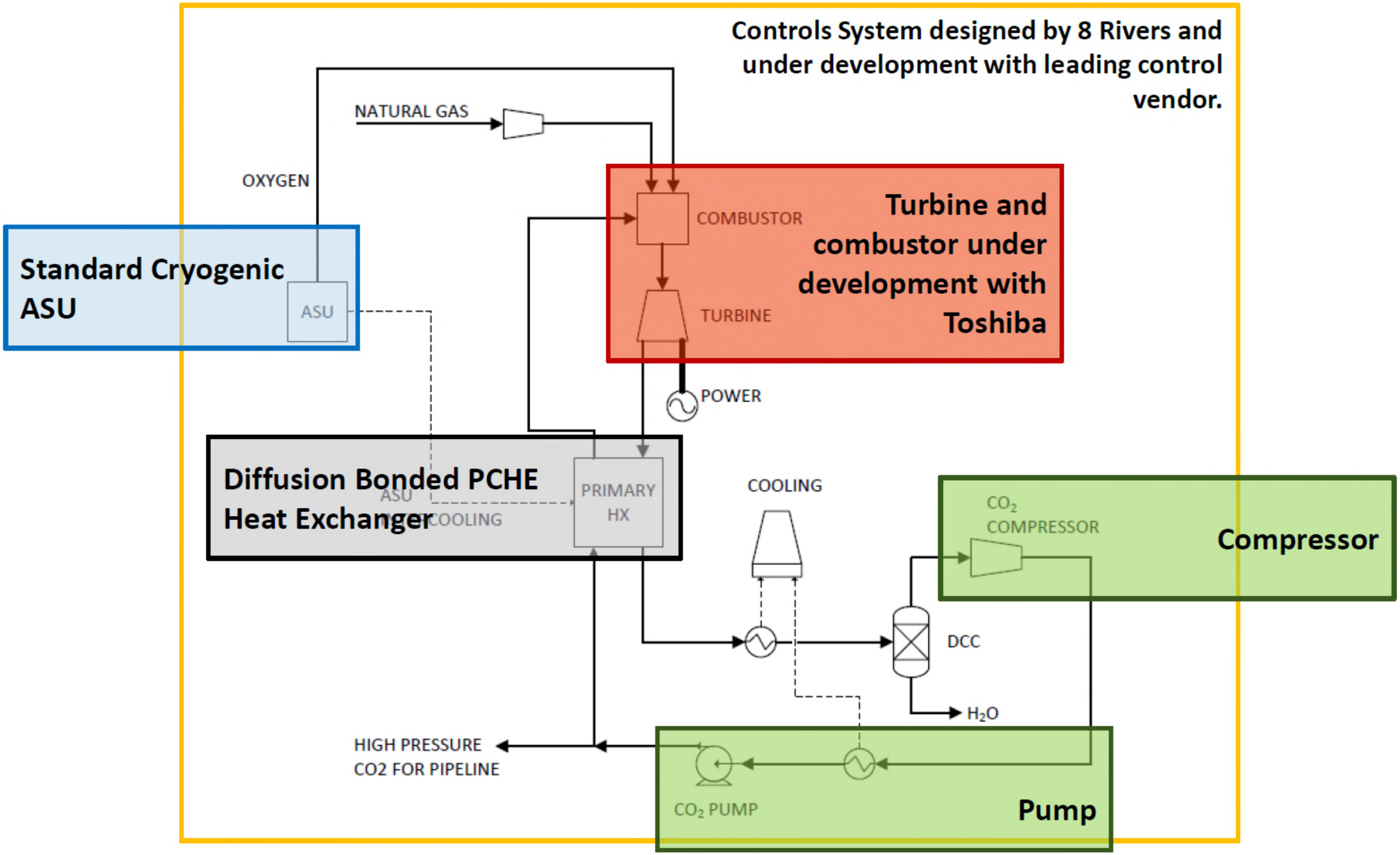
[Fetvedt 2016]

# The Allam Cycle (NetPOWER)




[Fetvedt 2016]

# Component Development

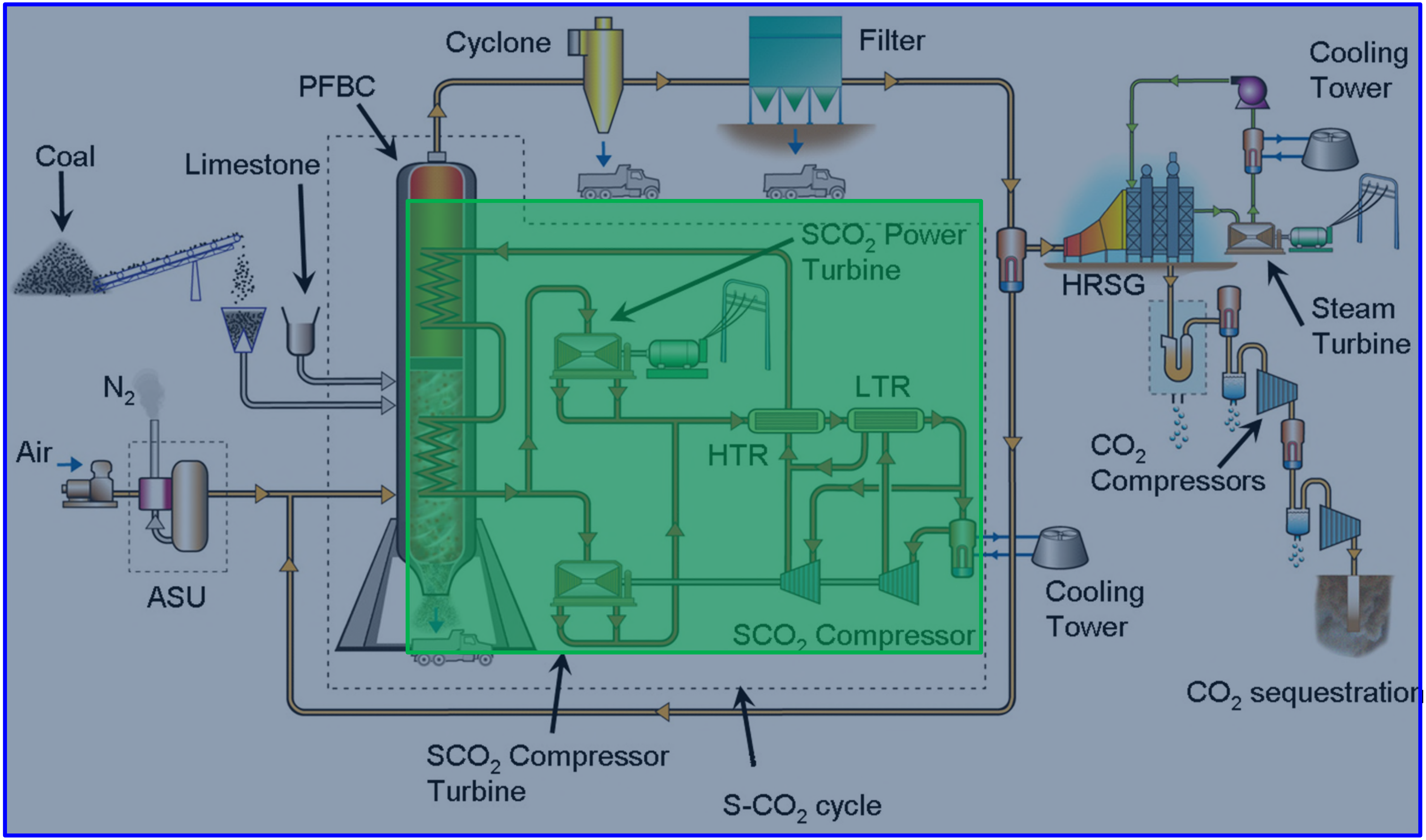



[Fetvedt 2016]


[Fetvedt 2016]

- Add combustion challenges

# Indirect Oxy-Fuel Combustion

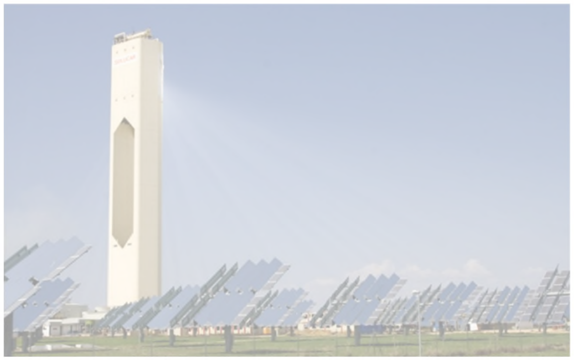



Zero Emission Oxy-Coal Power Plant with Supercritical $CO_2$ Cycle, Johnson et al. (2012)

# What are the key challenges for oxy-fuel $sCO_2$ cycles

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

# Supercritical $CO_2$ in Power Cycle Applications

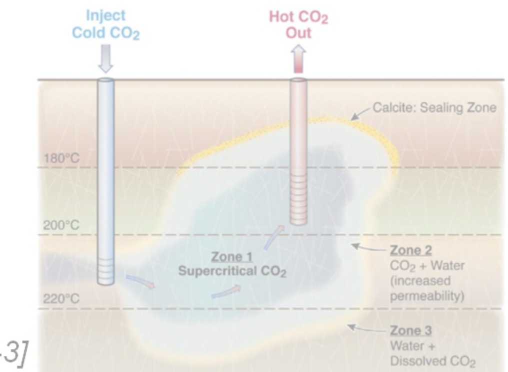


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel




[6-3]

Geothermal

[6-4]

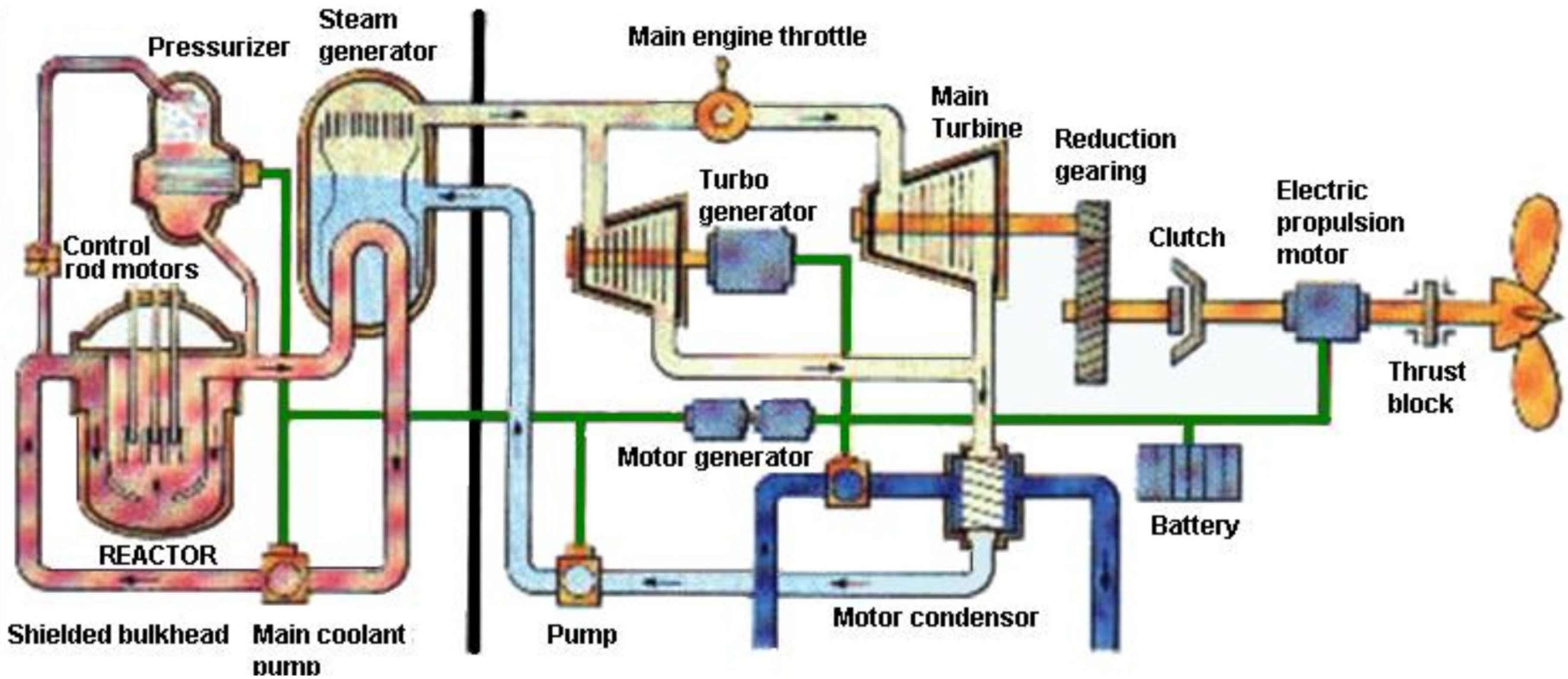
Nuclear

[6-5]

Ship-board Propulsion


Waste Heat Recovery [6-11]

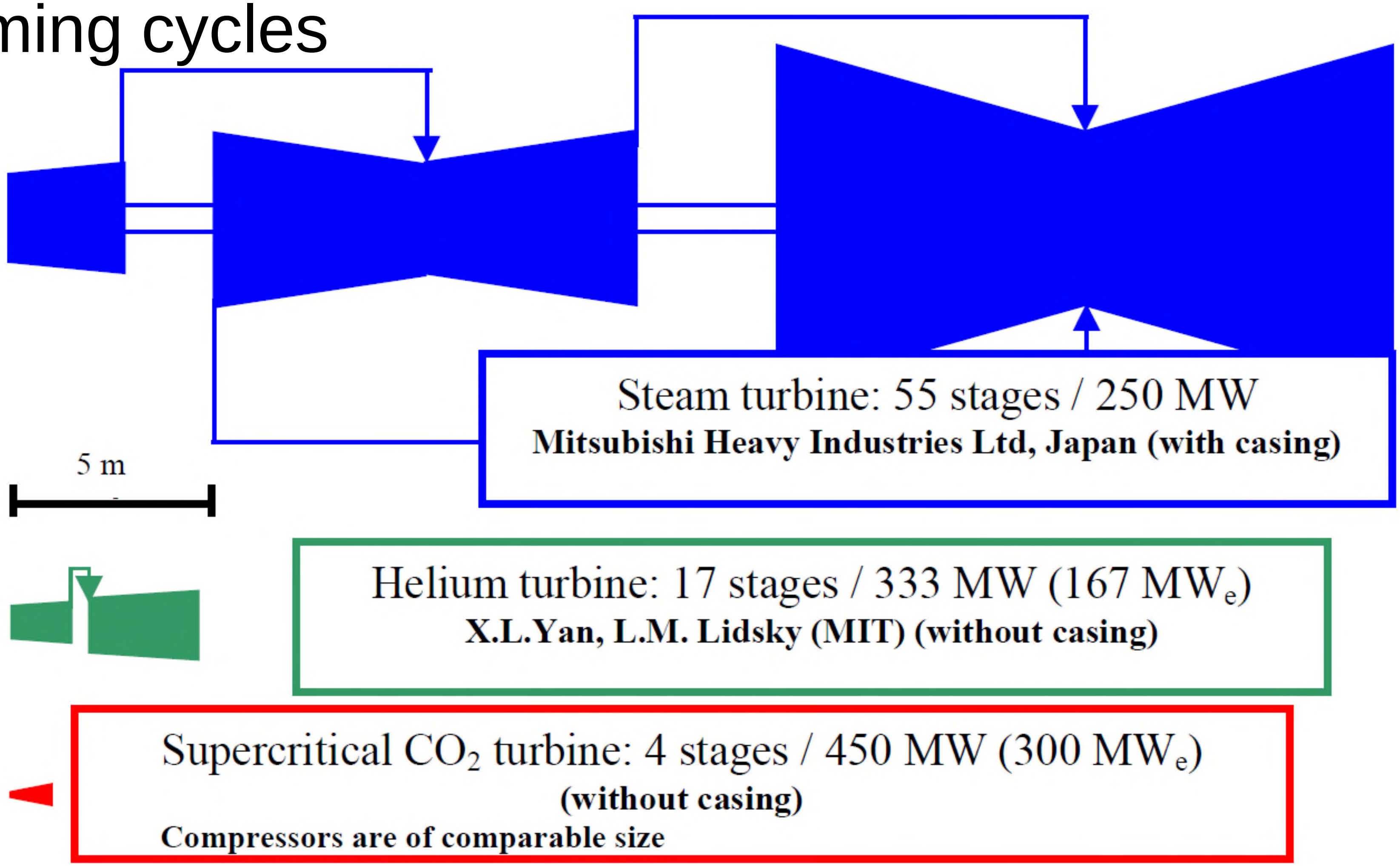
# Pressurized-Water Naval Nuclear Propulsion System



# Ship-board Propulsion

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

*Image source: [6-10]*

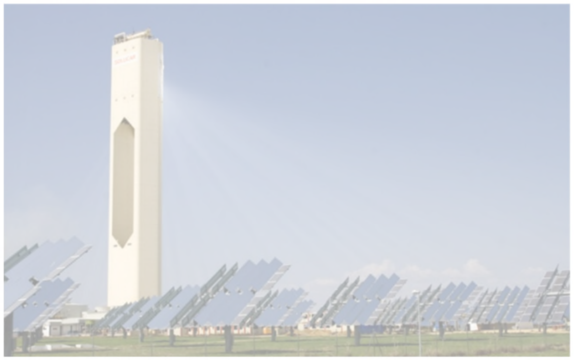



Source: Dostal (2004)

# 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

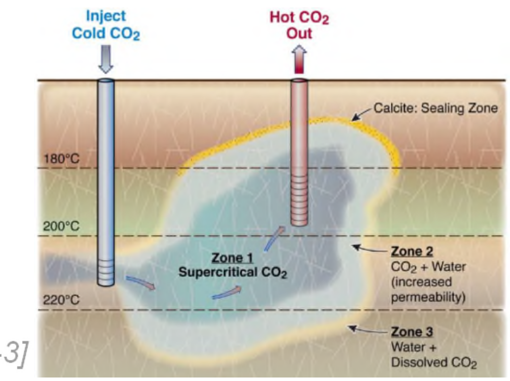


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel




[6-3]

Geothermal

[6-4]

Nuclear

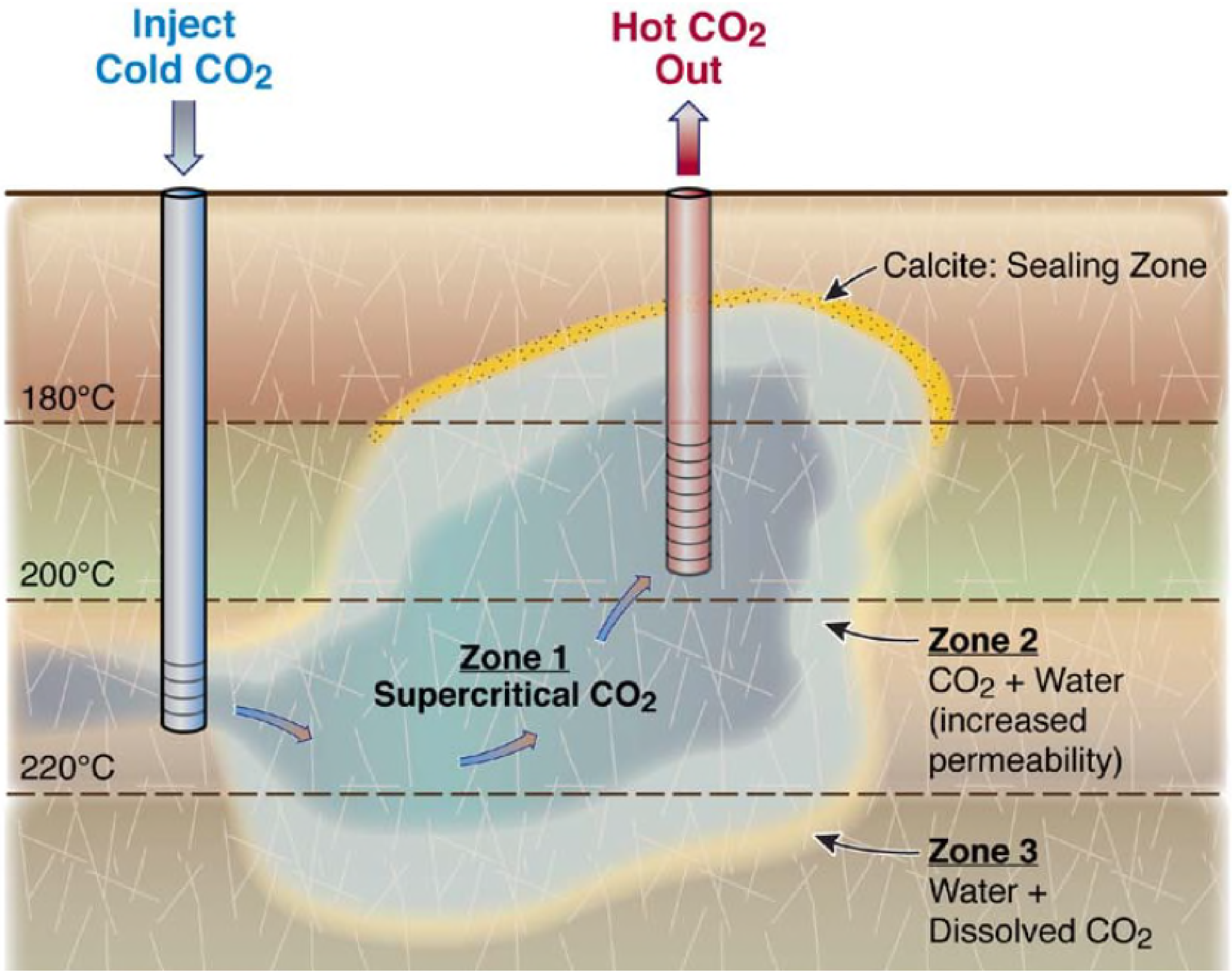
[6-5]

Ship-board Propulsion


Waste Heat Recovery [6-11]

# Geothermal

- ❑ Low Temperature Heat Source
  - $T \approx 210°C$, $P \approx 100$ bar




Pruess (May 19, 2010)

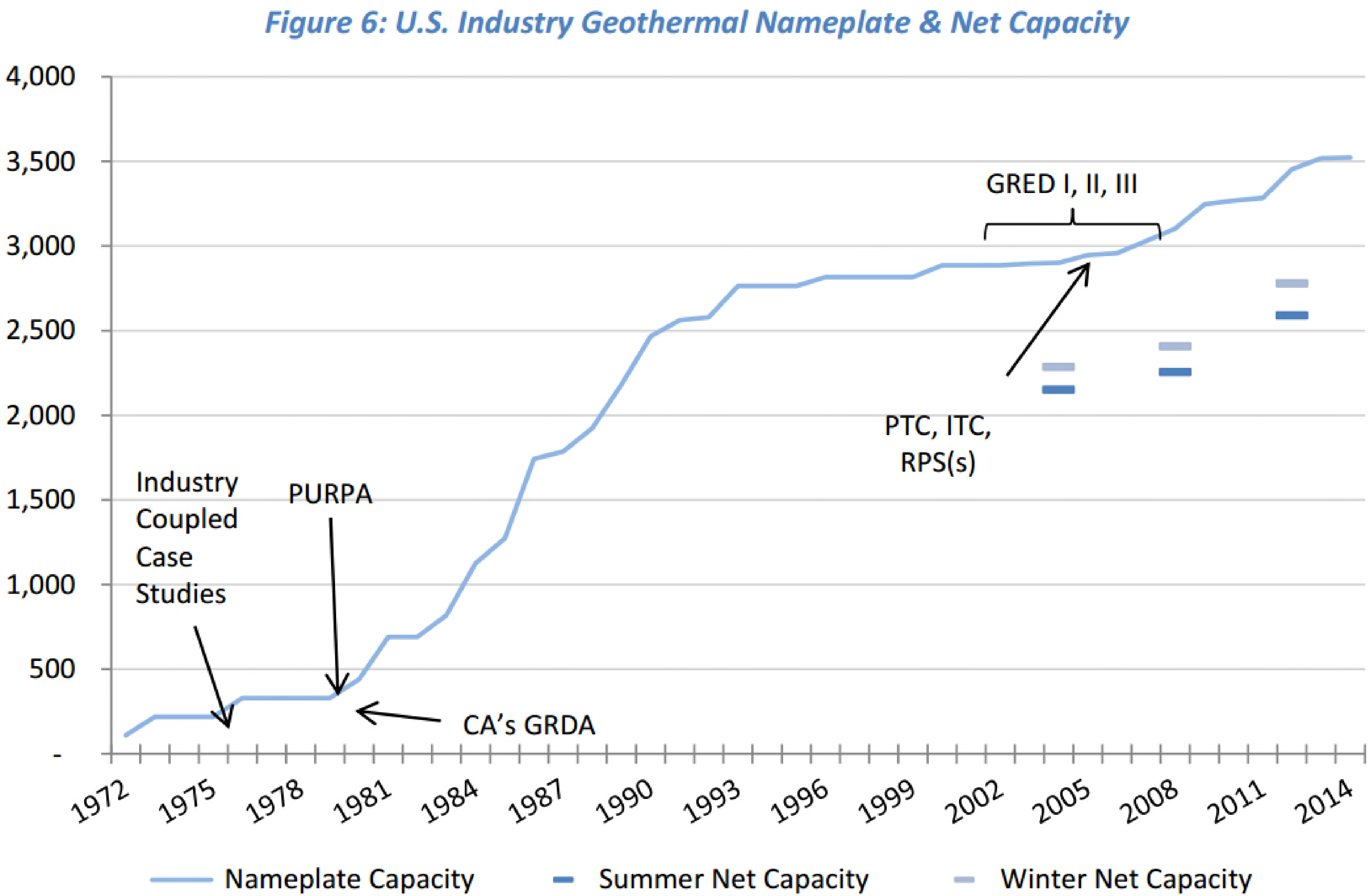
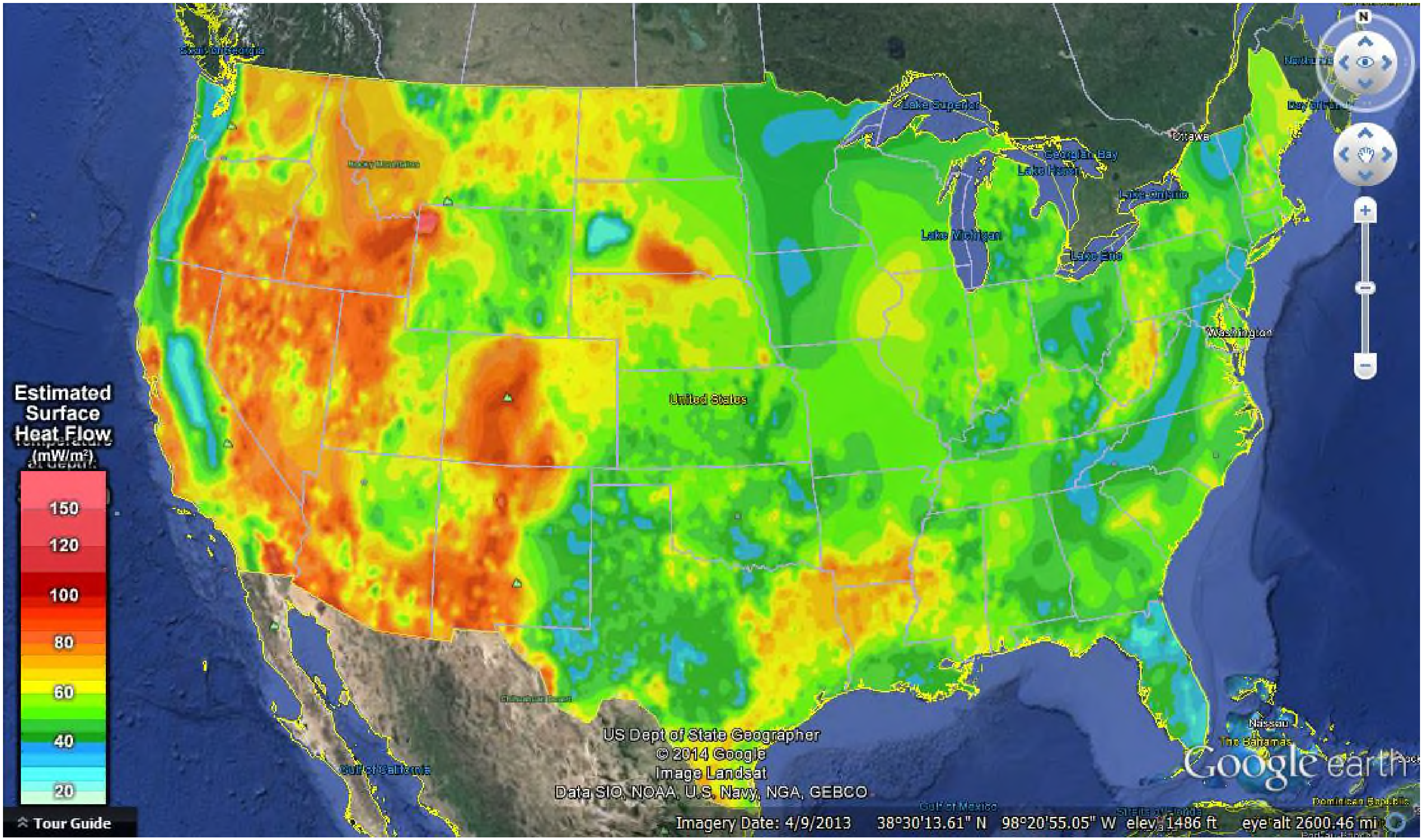


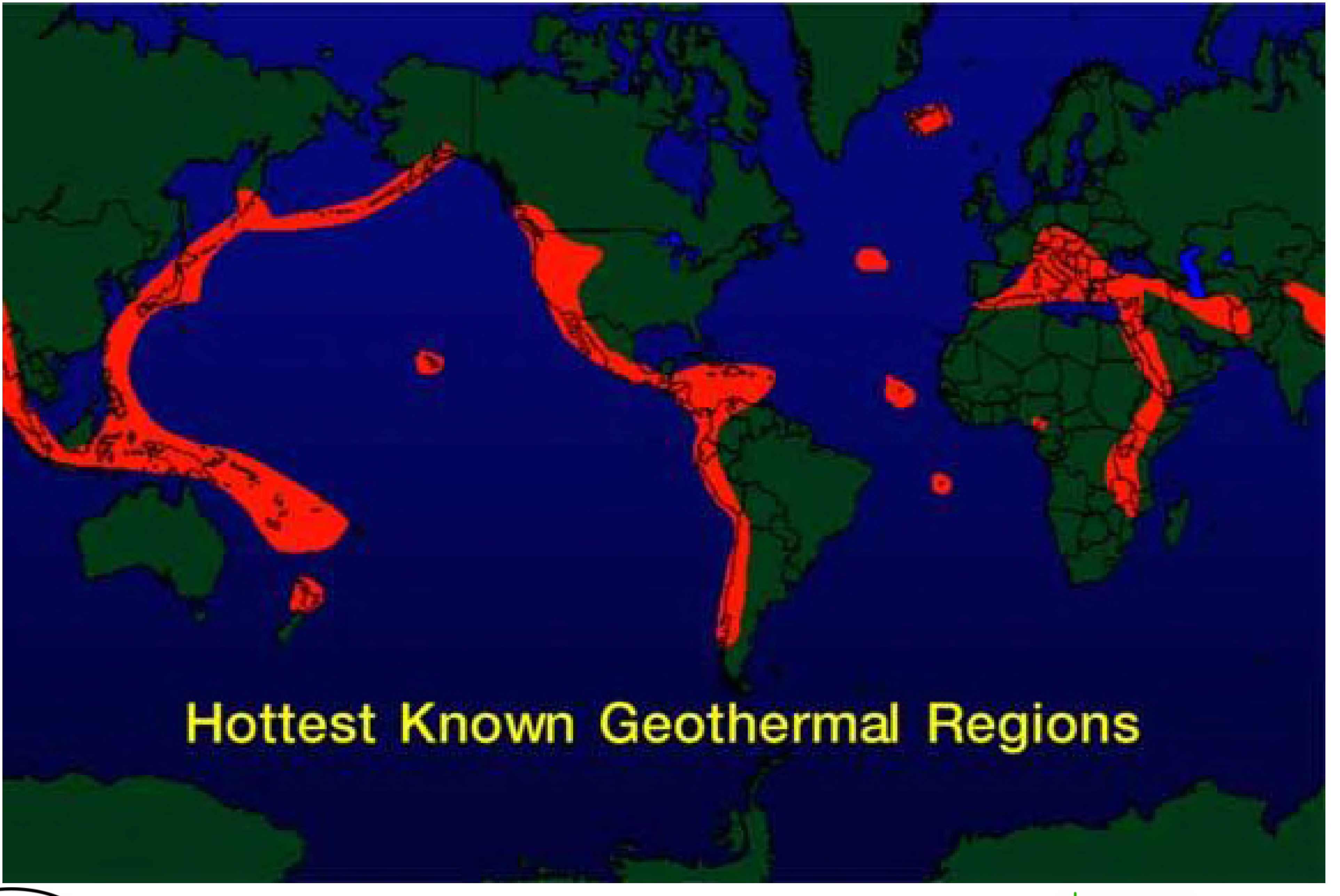
Figure 6: U.S. Industry Geothermal Nameplate & Net Capacity
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
-
GRED I, II, III
PTC, ITC, RPS(s)
Industry Coupled Case Studies
PURPA
CA's GRDA
1972
1975
1978
1981
1984
1987
1990
1993
1996
1999
2002
2005
2008
2011
2014
Nameplate Capacity
Summer Net Capacity
Winter Net Capacity

# US Geothermal Resources




Courtesy: GreenFire Energy [Higgins 2016]

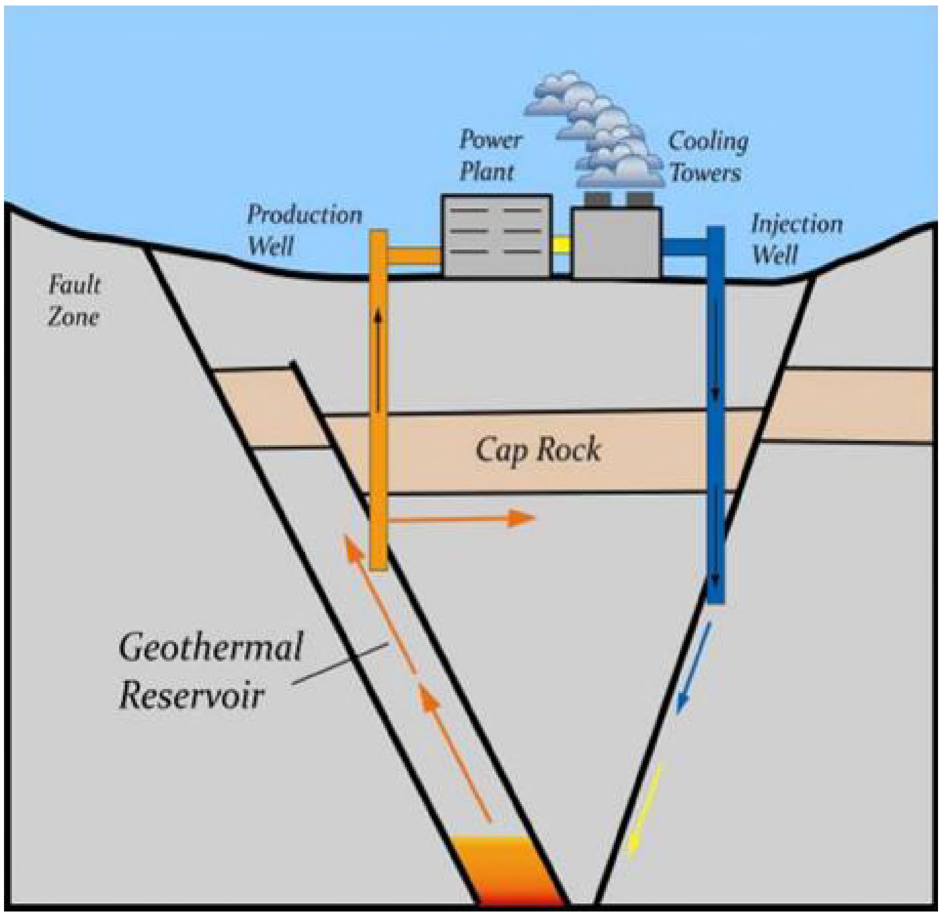
# Global Geothermal Resources



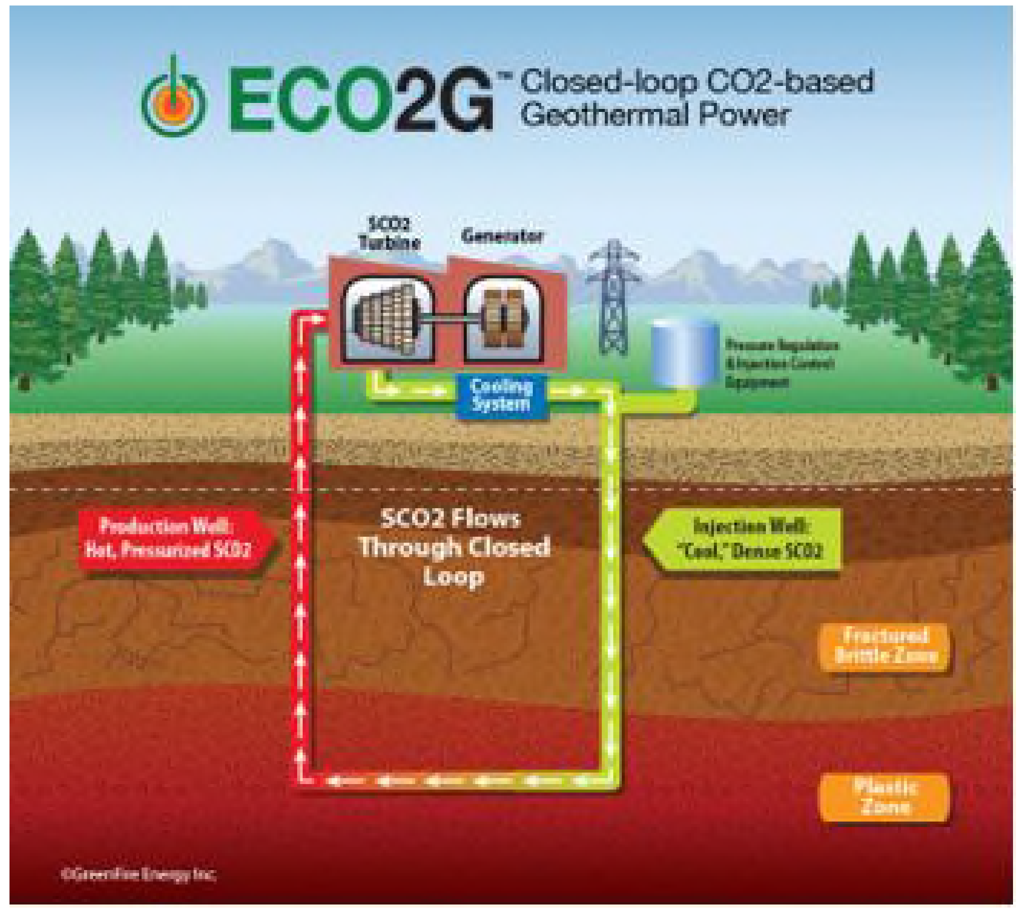

Courtesy: GreenFire Energy [Higgins 2016]

# ECO2G

## Conventional Hydrothermal

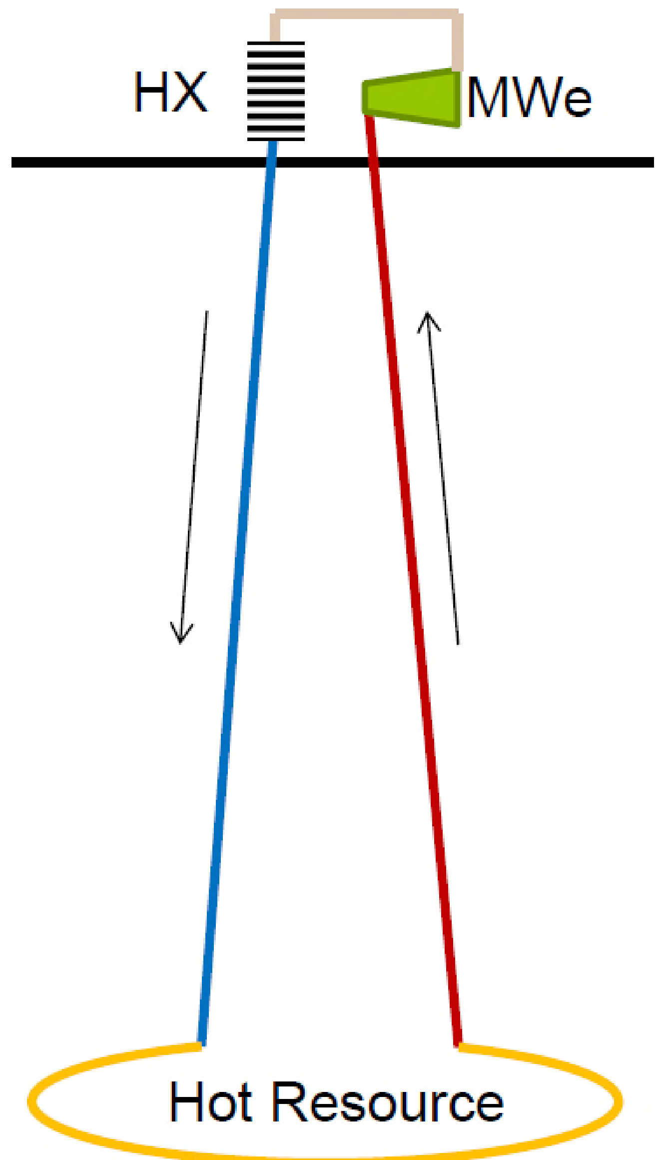



## Closed-Loop Supercritical $CO_2$

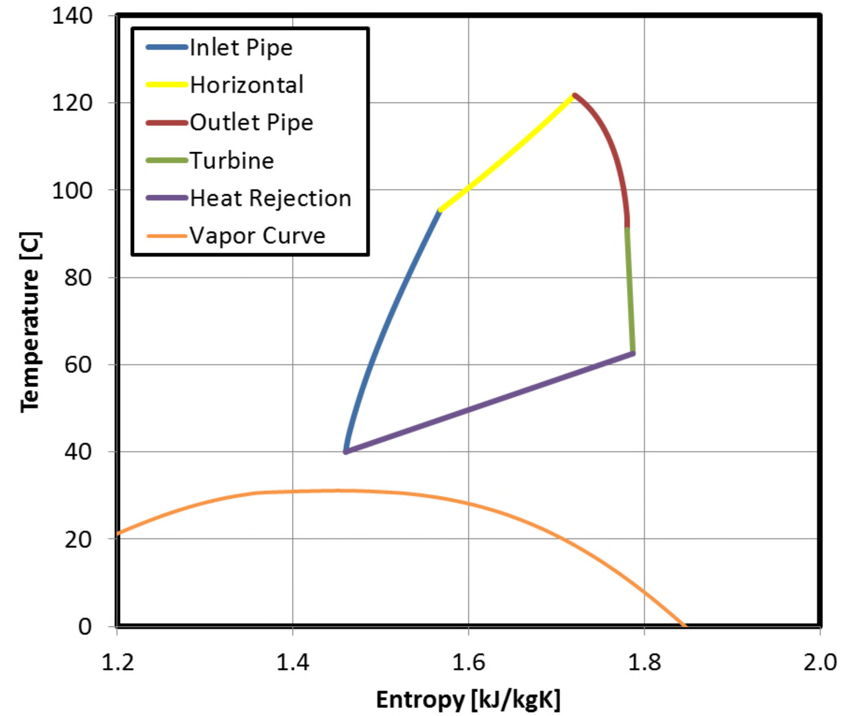



Courtesy: GreenFire Energy [Higgins 2016]

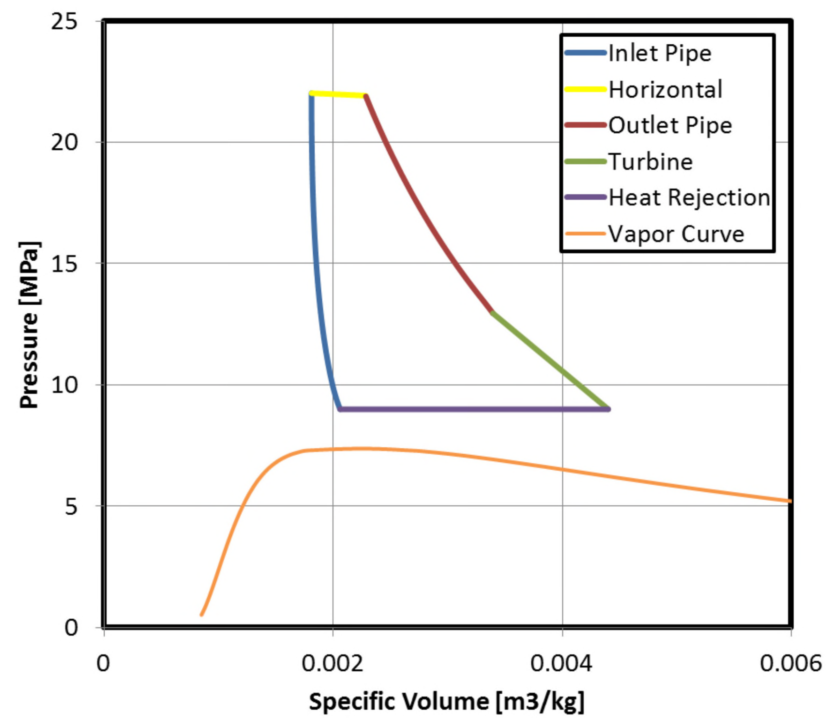
# P-v & T-s Diagram




T-s

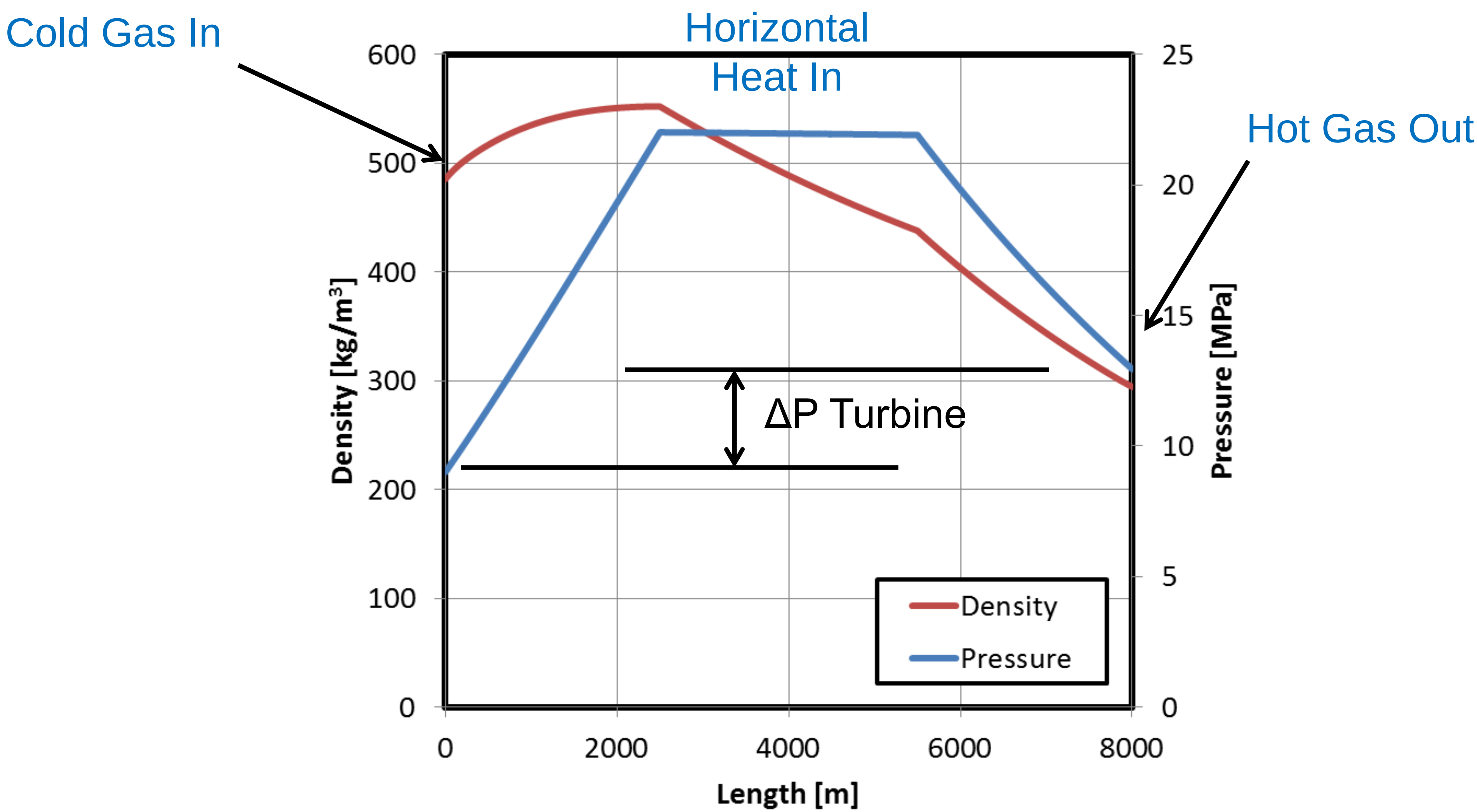



P-v




Courtesy: GreenFire Energy [Higgins 2016]

# How does a Thermosiphon Work




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

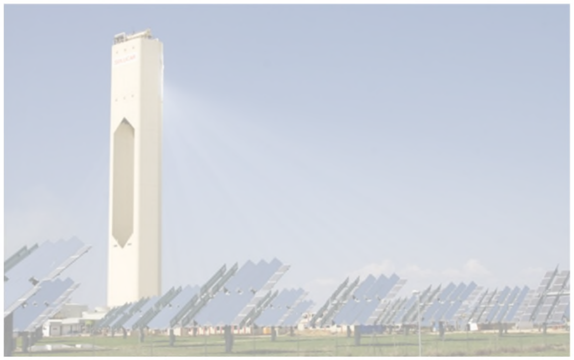
# Benefits of $sCO_2$ Based Geothermal

- 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



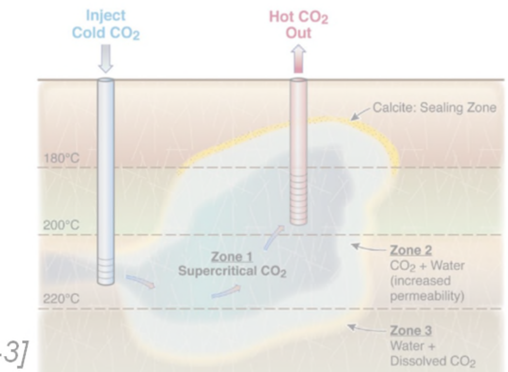
[6-1]

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]*

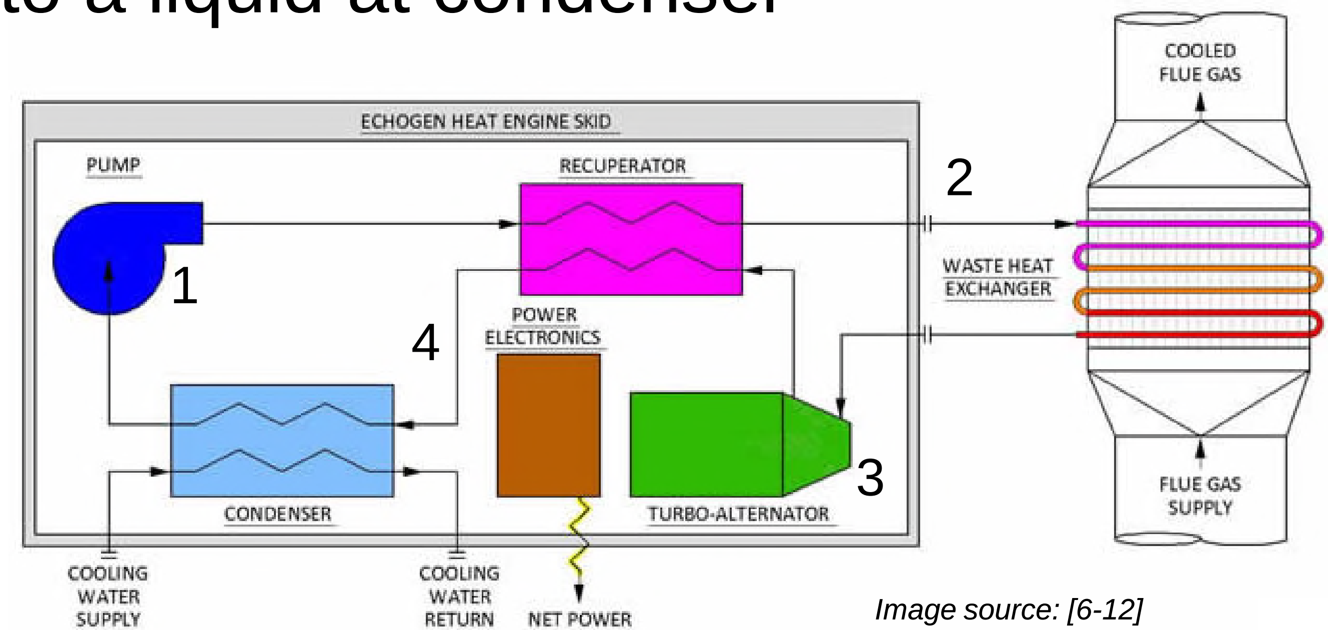



*Image source: [6-12]*

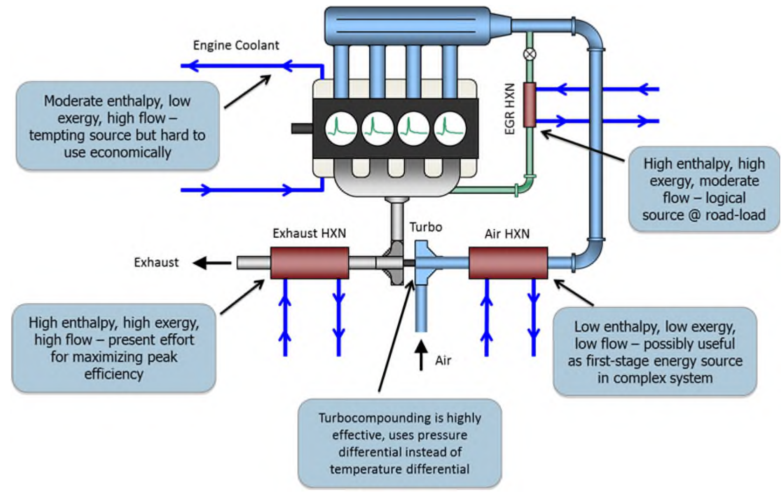
# Sub-1 MWe sCO2 Waste Heat Recovery

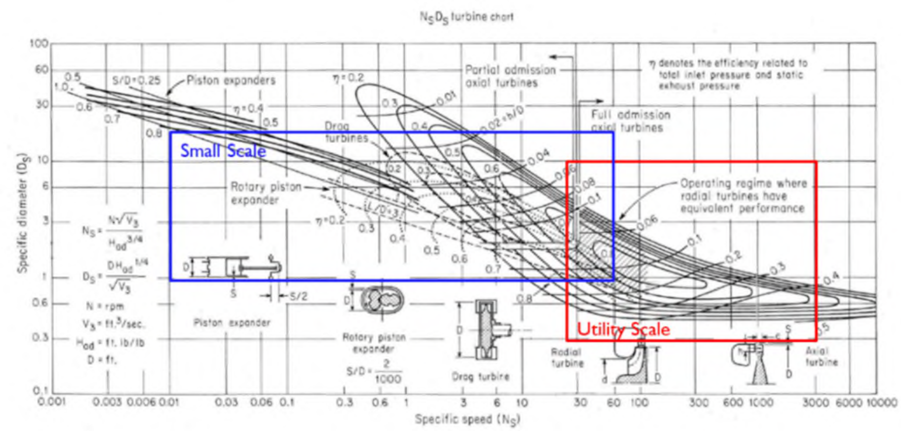
Diesel IC Engine WHR Applications

- 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

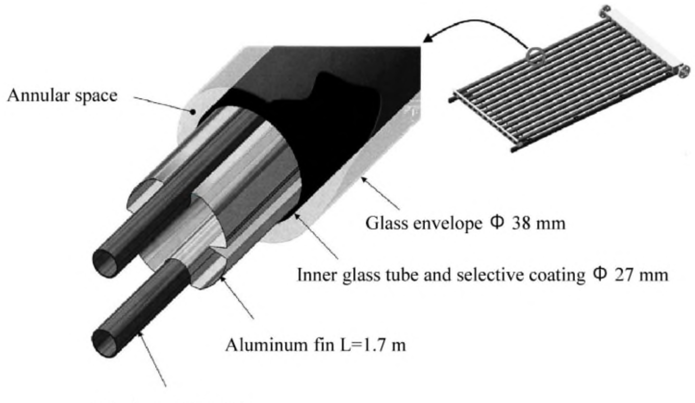


# Key challenges to $sCO_2$ bottoming cycles

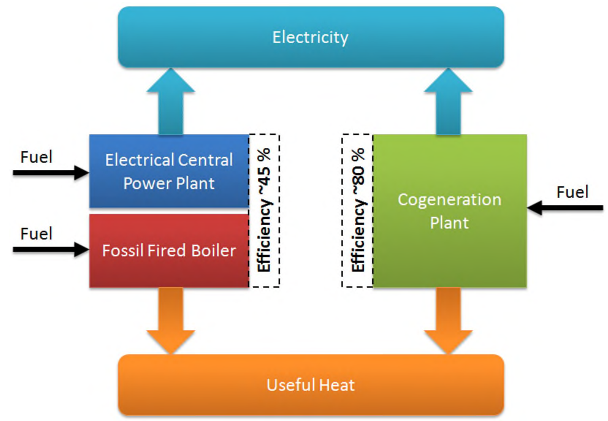
- Efficiencies and costs must compete with with steam/ORC at relevant temperatures
- Unproven technology must move into a field with proven WHR solutions (steam/ORC)
  - Since WHR is not the primary asset in nearly any implementation, shutting down production or heat generation for an unproven benefit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

# Other $sCO_2$ Power Cycle Applications

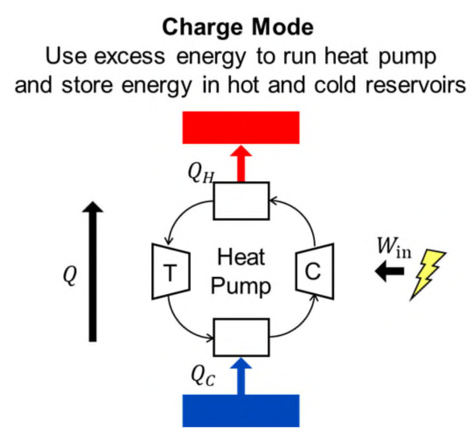



Zhang (2005)

Non-Concentrated Solar Power




Combined Heat & Power




PTES

# sCO2-based Pumped Thermal Energy Storage

PTES Technology Benefits

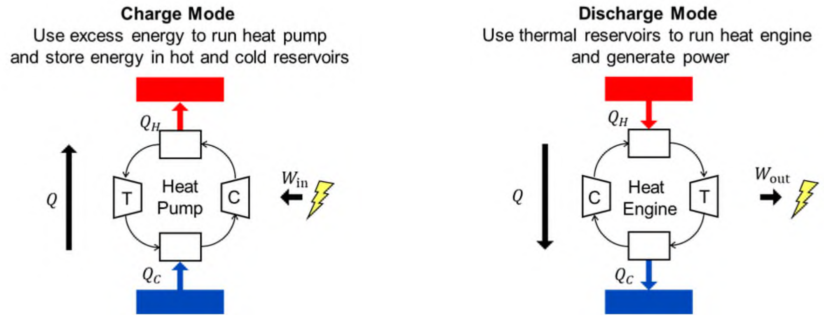
- Up to 50-70% RTE
- No geographical constraints
- Leverages many existing technologies
- Safer than other Thermal ES

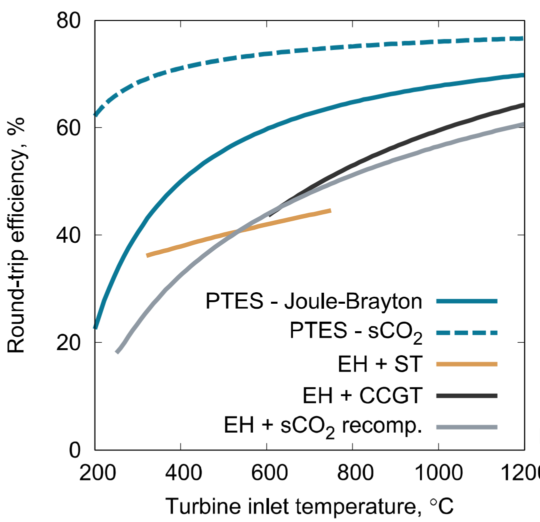
Theoretically, sCO2 PTES has the potential out-perform ideal gas based PTES (in terms of RTE)

- 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

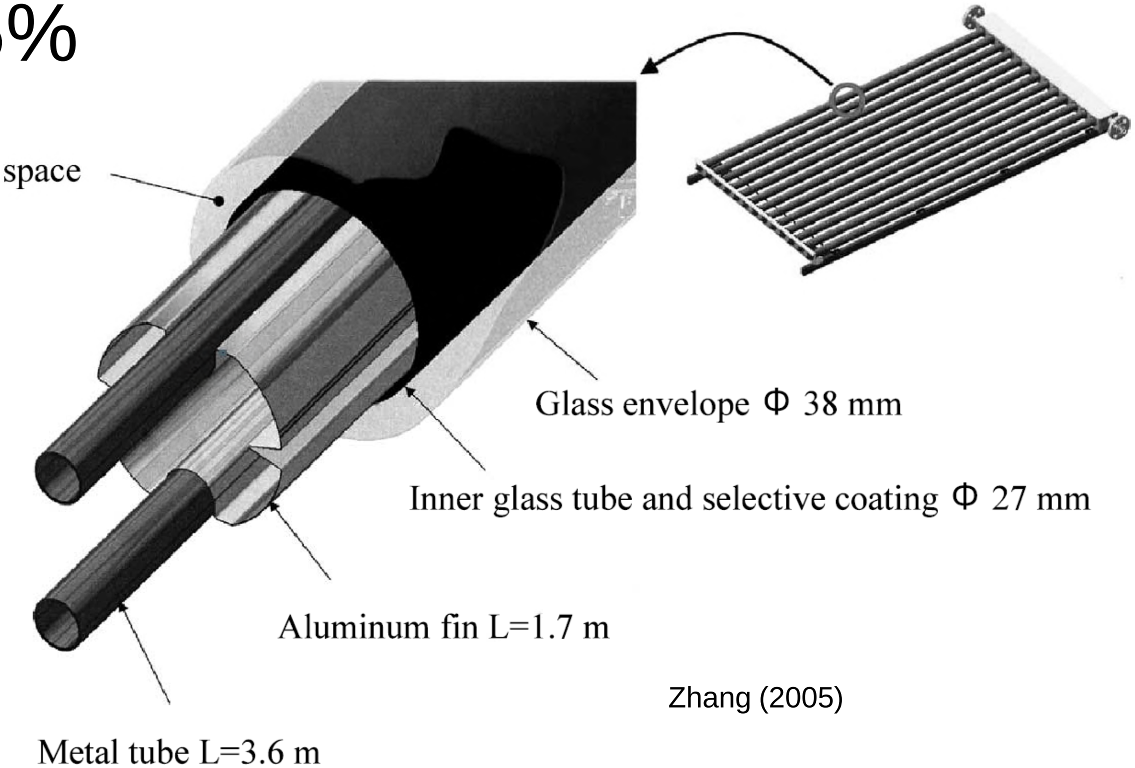


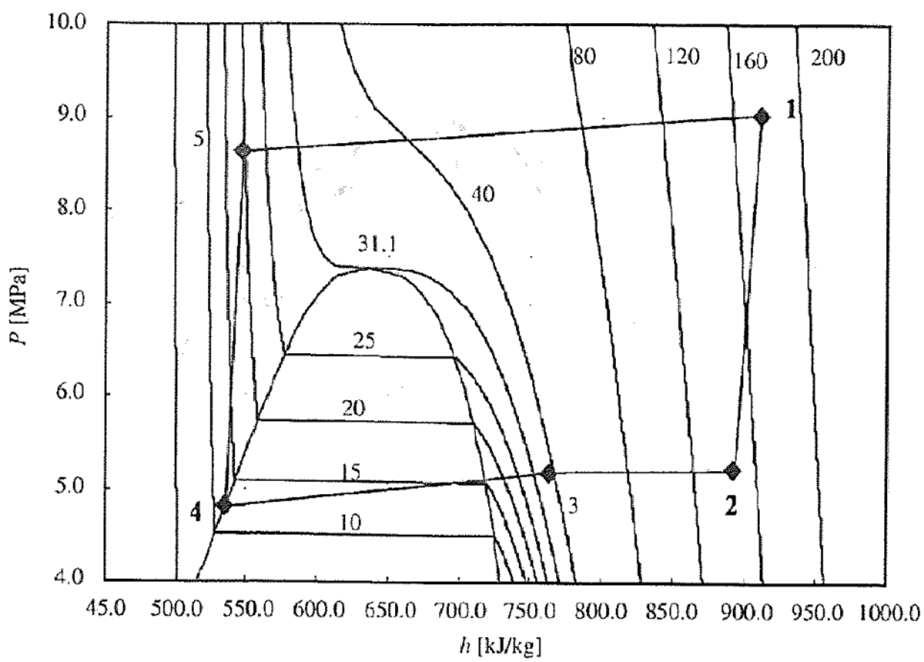

McTigue (2019)

# $sCO_2$ 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%



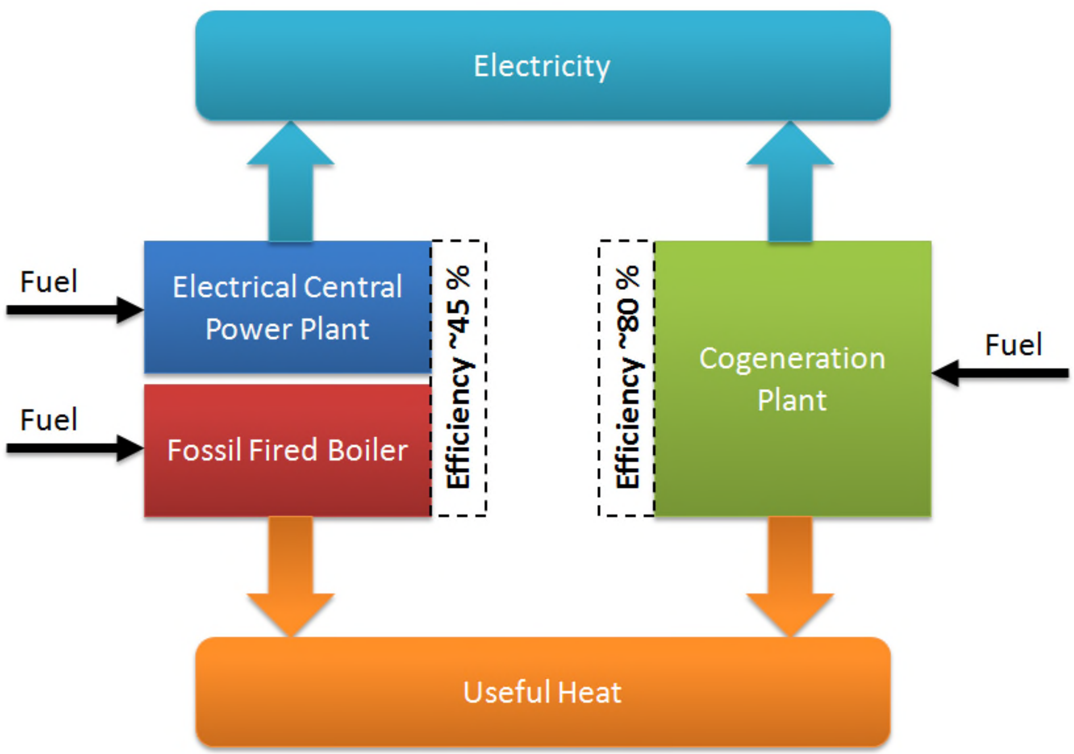

Zhang (2005)




Zhang (2007)

# $sCO_2$ Rankine Cycle in Combined Heat and Power (CHP)

- Electrical efficiency
  - Higher than ordinary steam CHP
  - Cascaded s-$CO_2$ plant performed best




Moroz (2014)

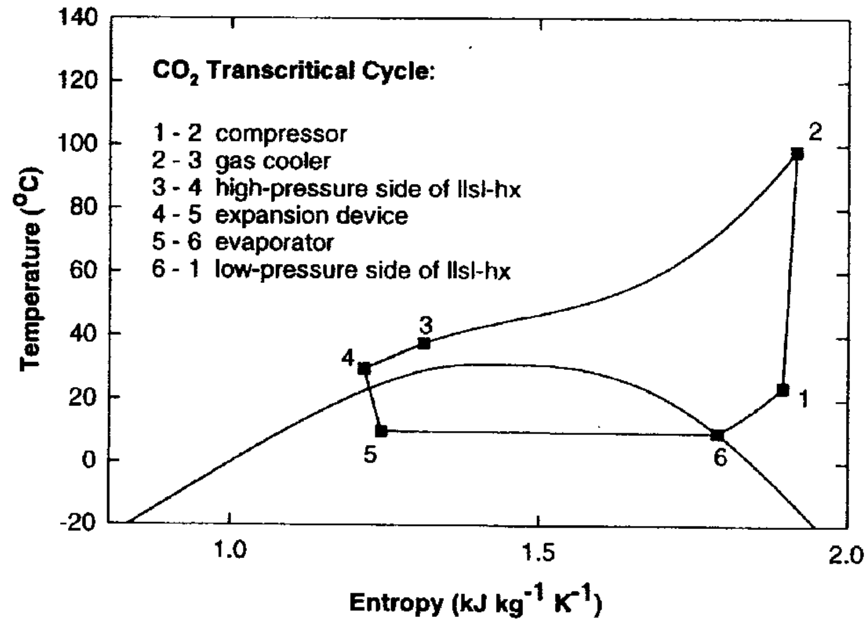
# $sCO_2$ as a Refrigerant

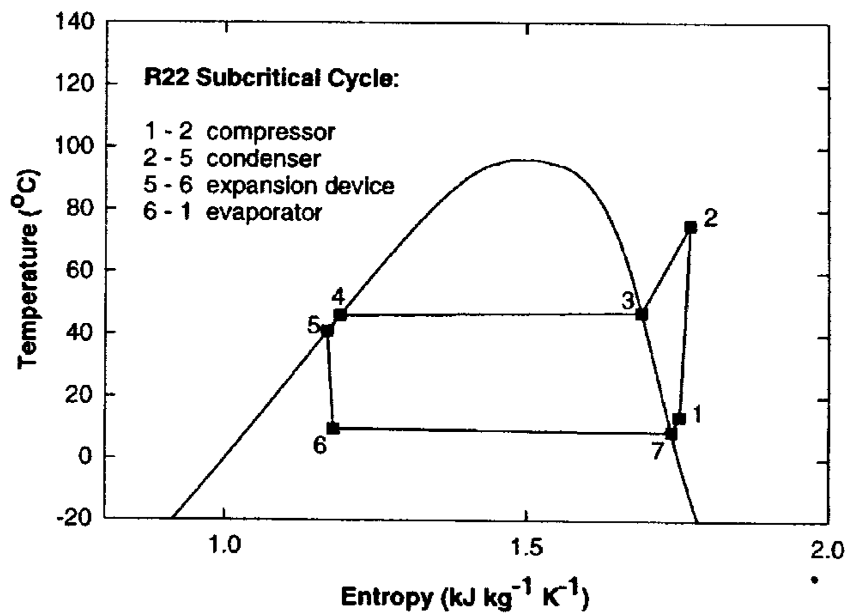
*Image source: [6-13]*

*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 $CO_2$ cycle was in the expansion device




Brown (2002)

SwRI

# $sCO_2$ 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)

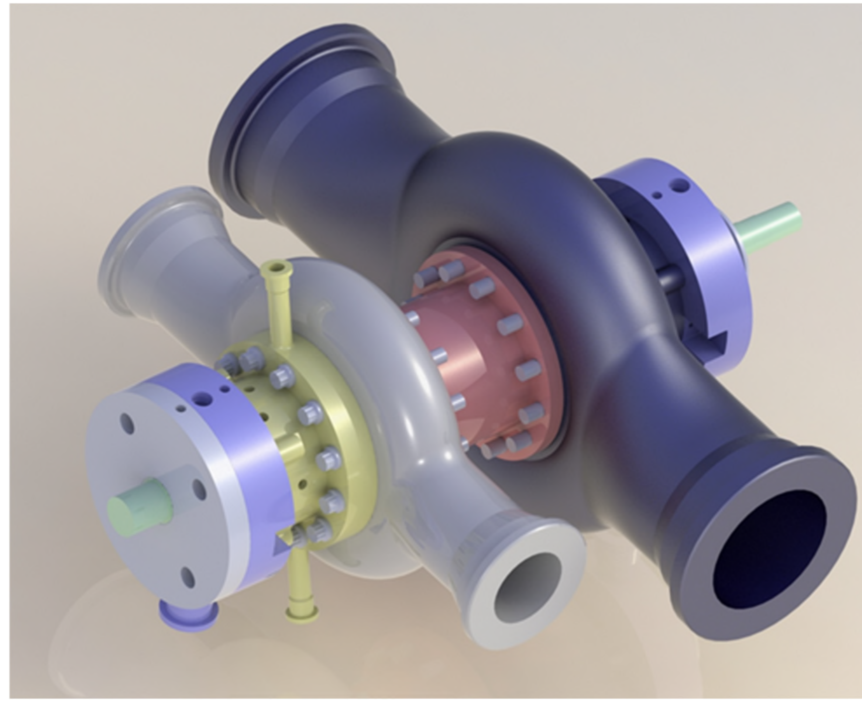
# Supercritical $CO_2$ Power Cycles Symposium

The 7th International Supercritical $CO_2$ Power Cycles Symposium will be held in San Antonio, Texas, March 30 – April 2, 2020

# $sCO_2$ 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**)**

SunShot
U.S. Department of Energy

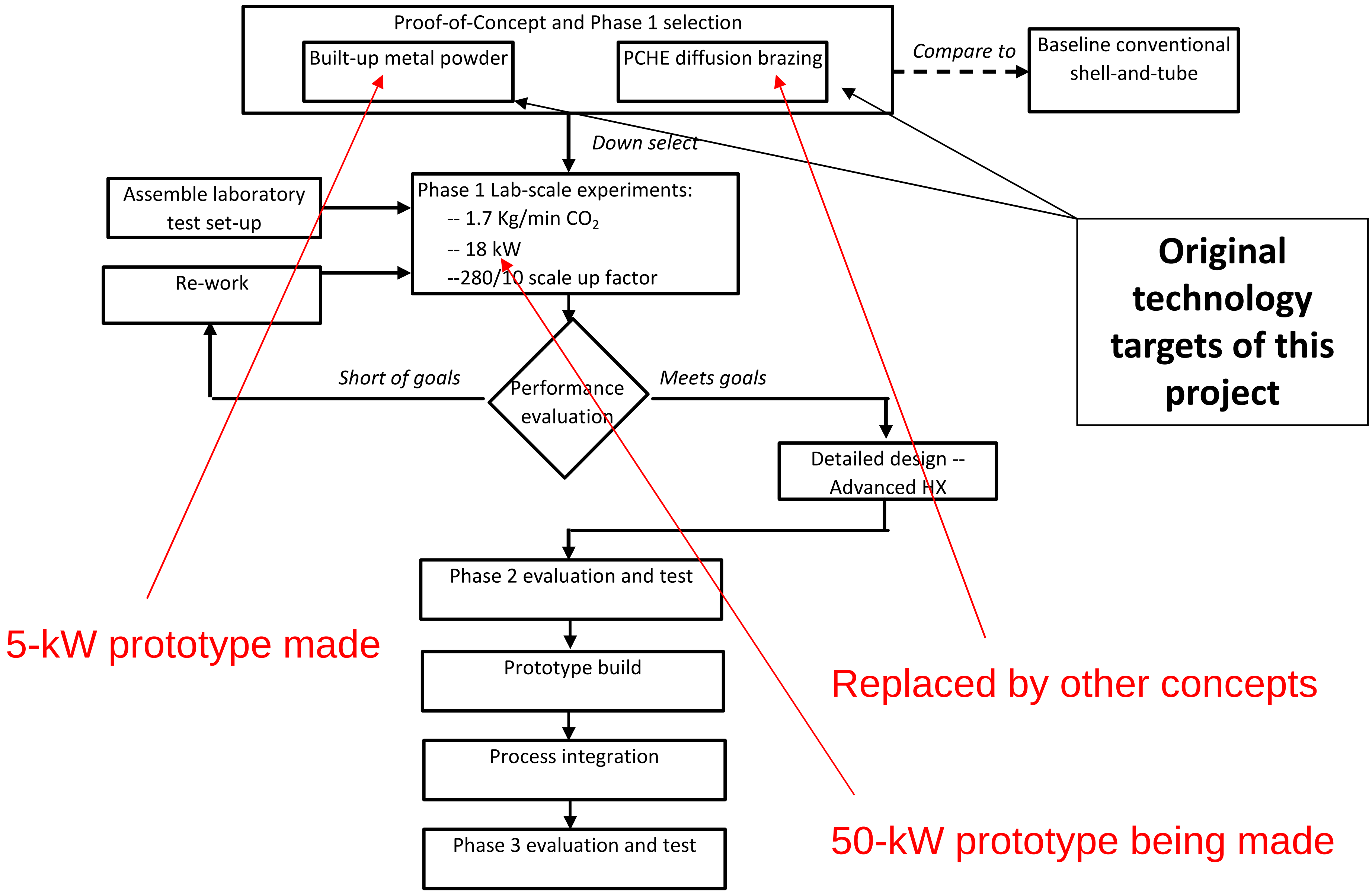
# Project Objectives

- 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)

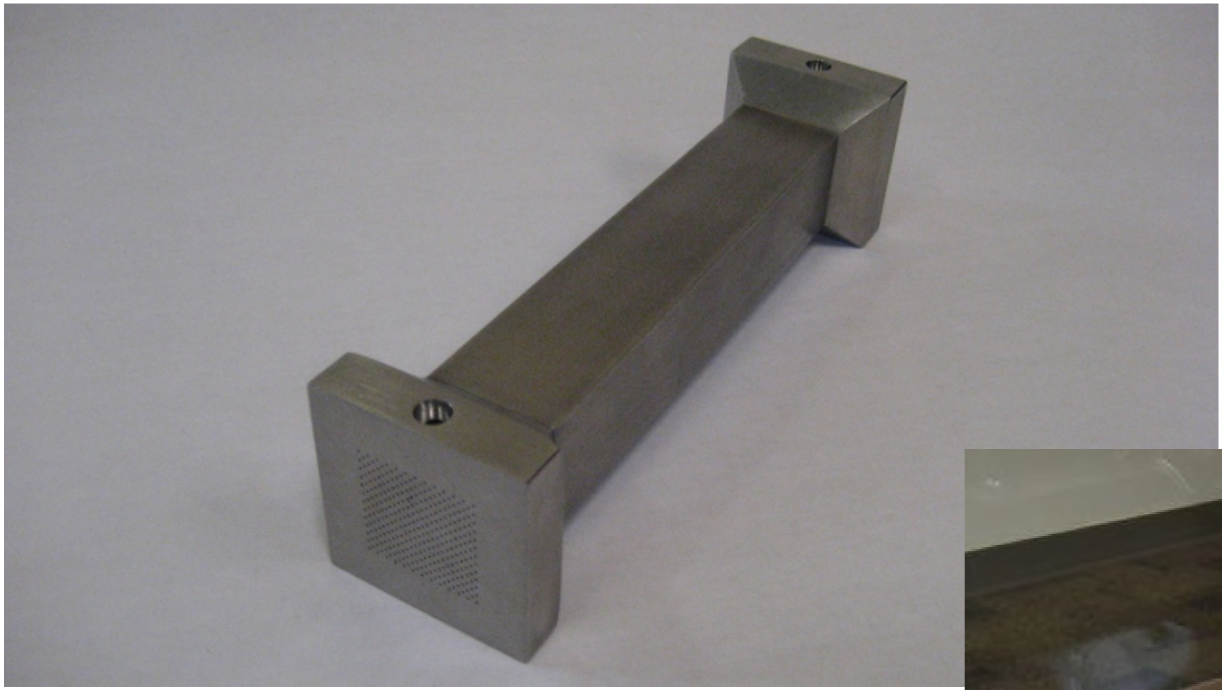
# Heat Exchanger Design Approach



# HEAT EXCHANGER DESIGN

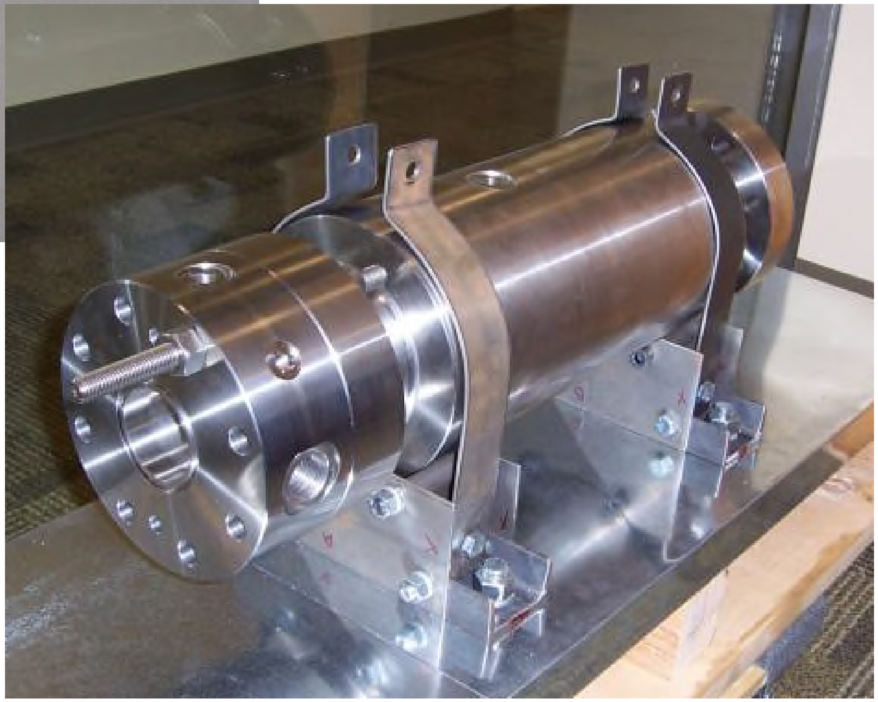
- Two fabrication methods were selected
  - DMLS: automated, works well with high-Ni alloys, expensive, time-consuming
  - Laser welding: can be automated, accurate but requires monitoring and hand work to be reliable.
- Prototypes of both methods were tested at KAPL.
  - The DMLS prototype held pressure up to 5,000 psi.
  - It showed high heat transfer capability but very high pressure drop.
  - The laser-welded prototype held 2,500 psi at 600 °F
  - Testing showed heat transfer capability that is as good or better than design.
- Corrosion damage during fabrication needed to be repaired using a brazing operation that may become the preferred forming process
- Detailed design of the 5 MWt was accomplished.

# Recuperator Prototypes – 5 and 50 kW



DMLS:

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



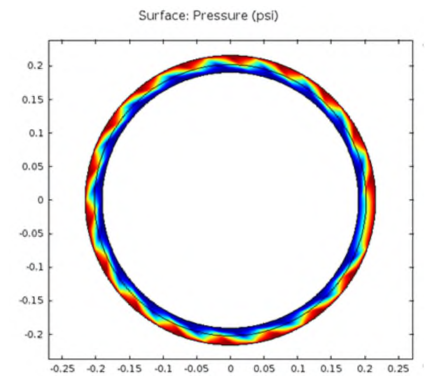
Laser Welded Construction:

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

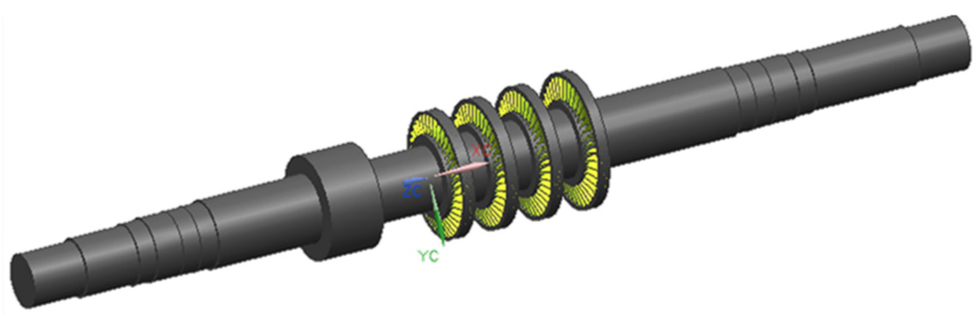
# TURBOEXPANDER DESIGN

- A novel turboexpander has been designed to meet the requirements of the $sCO_2$ power with these targets:
- ~14MW shaft power
- >700C inlet temp
- >85% aero efficiency

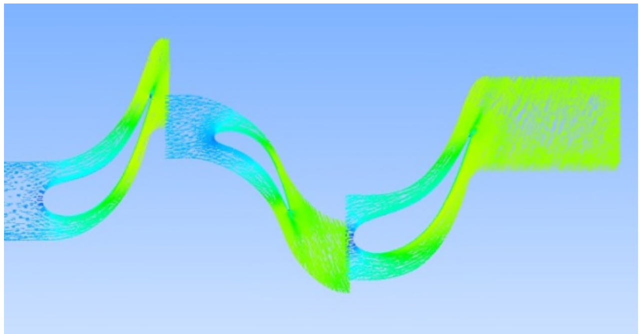
DGS Face Pressure Distribution from CFD



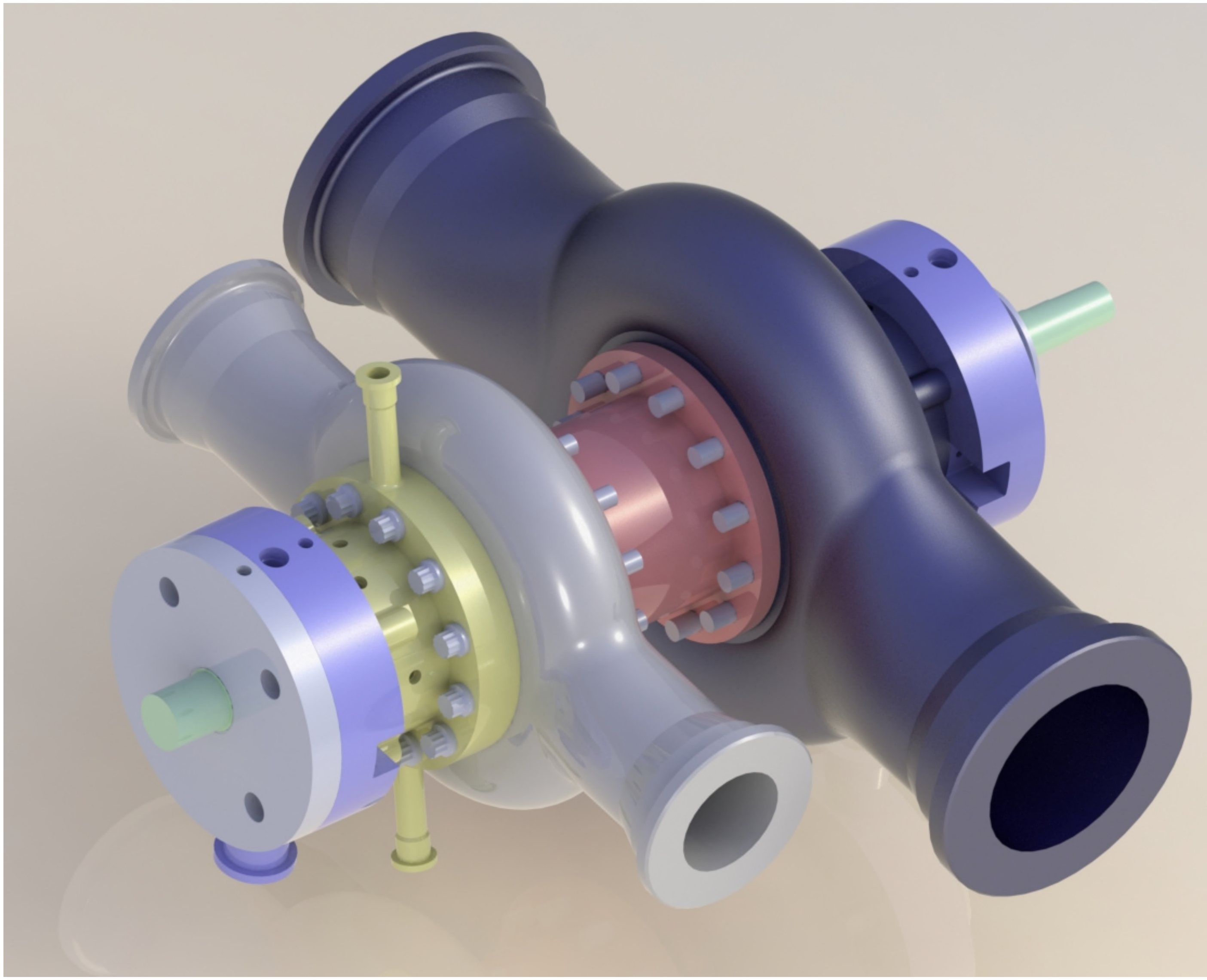

Multi-stage Axial Turbine



CFD Analysis



# 10 MW $sCO_2$ Turbine Concept



# Test Loop Layout and Integration

- The test loop layout has been designed with the intent of minimizing thermal stress, and maximizing use of existing infrastructure
- Loop piping and components will make use of the recently completed Turbomachinery Research Facility at SwRI
- The test loop is designed around the main and supporting components: expander, heater, pump, compressor, cooler, and dyno
  - Custom engineered air dynamometer will absorb the ~600kW produced by the expander during testing

# 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

# SunShot Project Overview

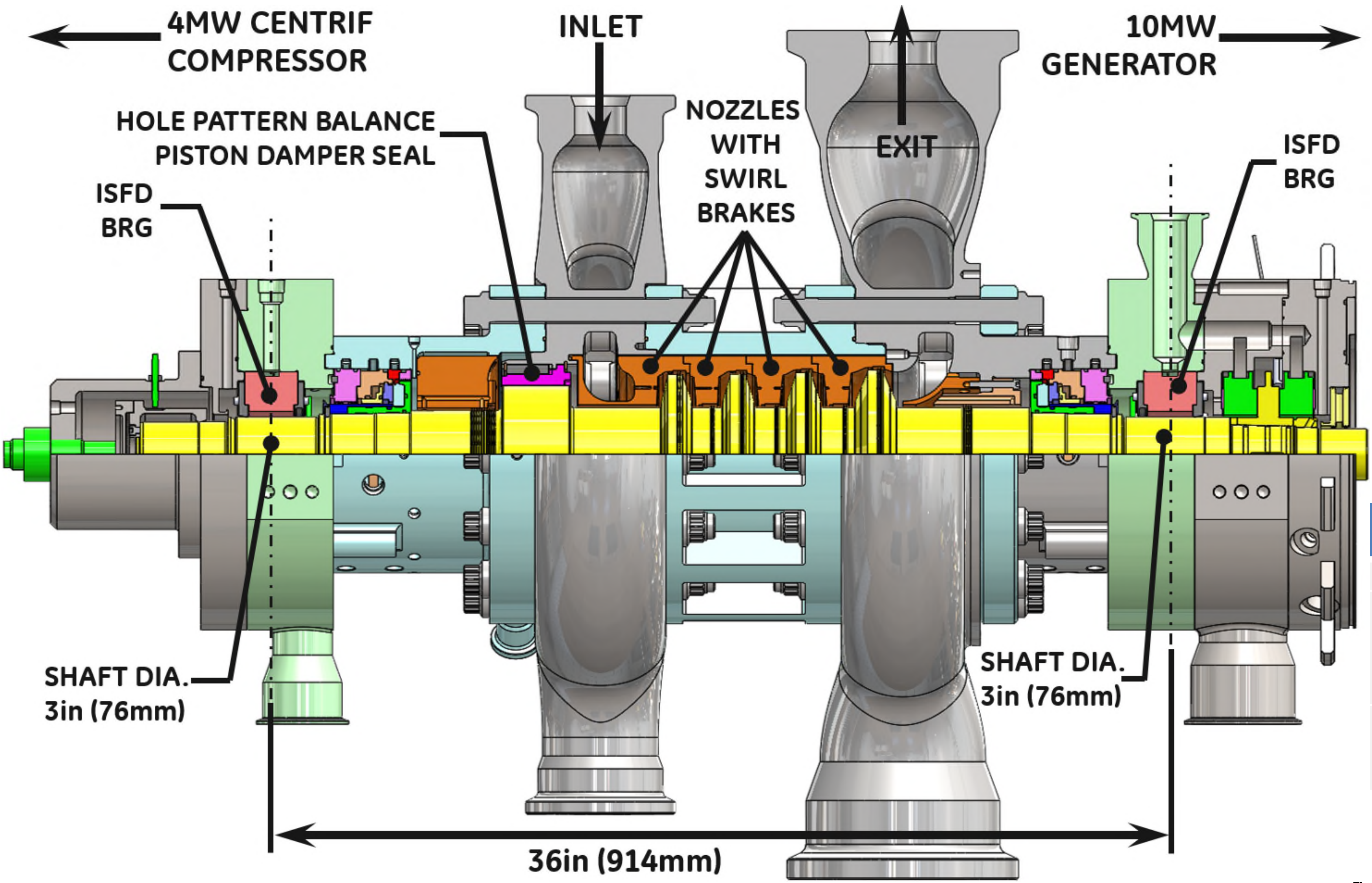
- Develop a novel, high-efficiency $sCO_2$ hot-gas turbo-expander optimized for the highly transient solar power plant duty cycle profile
  - Advances the state-of-the-art from Technology Readiness Level (TRL) 3 to TRL 6
- Develop novel recuperator technology for $sCO_2$ applications to reduce manufacturing costs
- Develop a 1-MWe $sCO_2$ test loop
- Technology development helping to achieve CSP at $0.06/kW-hr levelized cost of electricity, increasing energy conversion efficiency to greater than 50%, and reducing total power block cost to below $1200/kW installed

| Total Project Cost | $9.8M |
|---|---|
| Department of Energy | 70% |
| General Electric | 10% |
| Thar Energy | 8% |
| EPRI | 4% |
| Naval Nuclear Lab | 4% |
| Saudi Aramco | 3% |
| SwRI | 1% |

# Project Approach

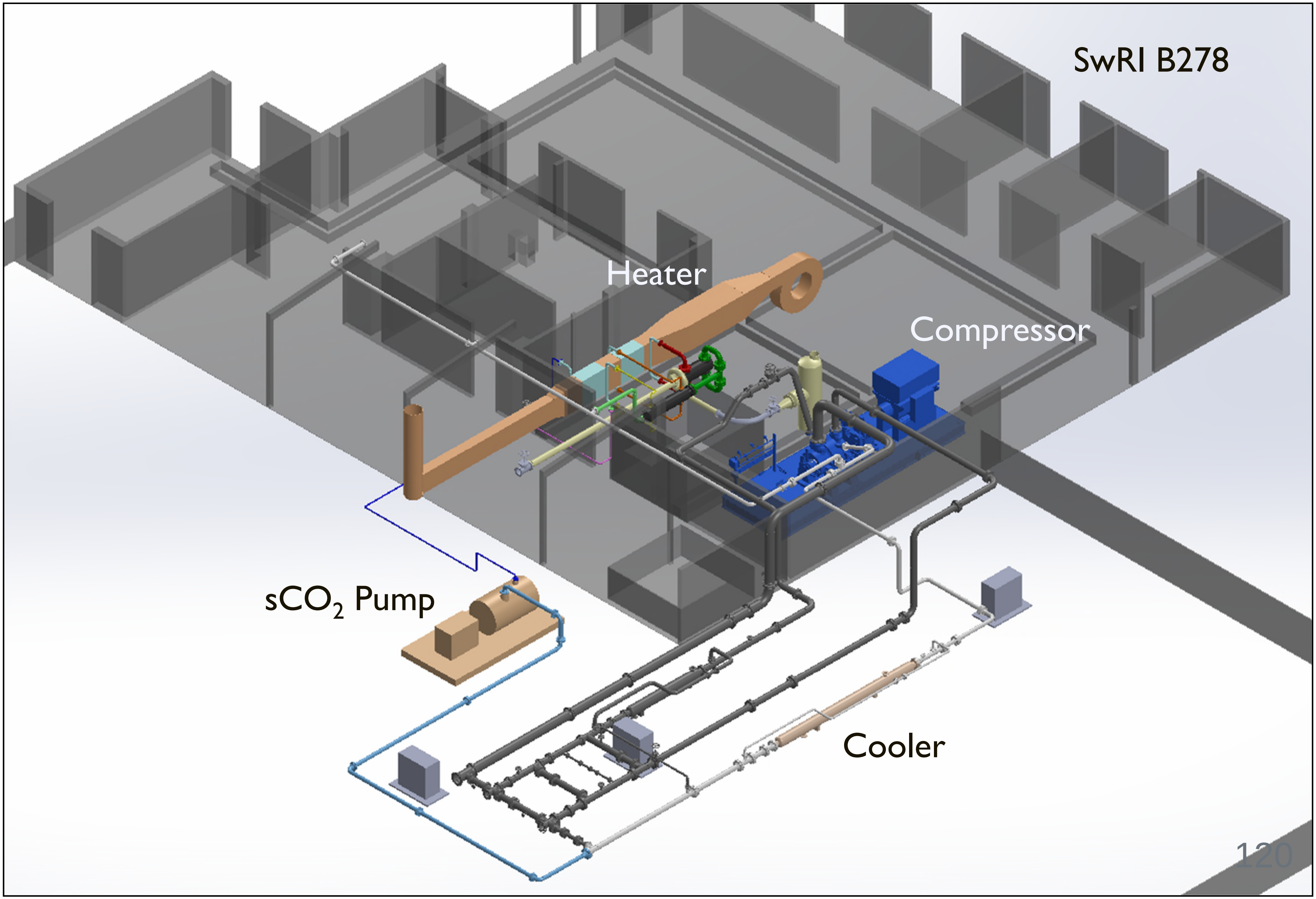
- Work has been divided into three phases that emulate development process from TRL3 to TRL6
- Phase I – Turbomachinery, HX, and flow loop design (17 months)
- Phase II – Component fabrication and test loop commissioning (12 months)
- Phase III – Performance and endurance testing (6 months)

# SunShot Project Details



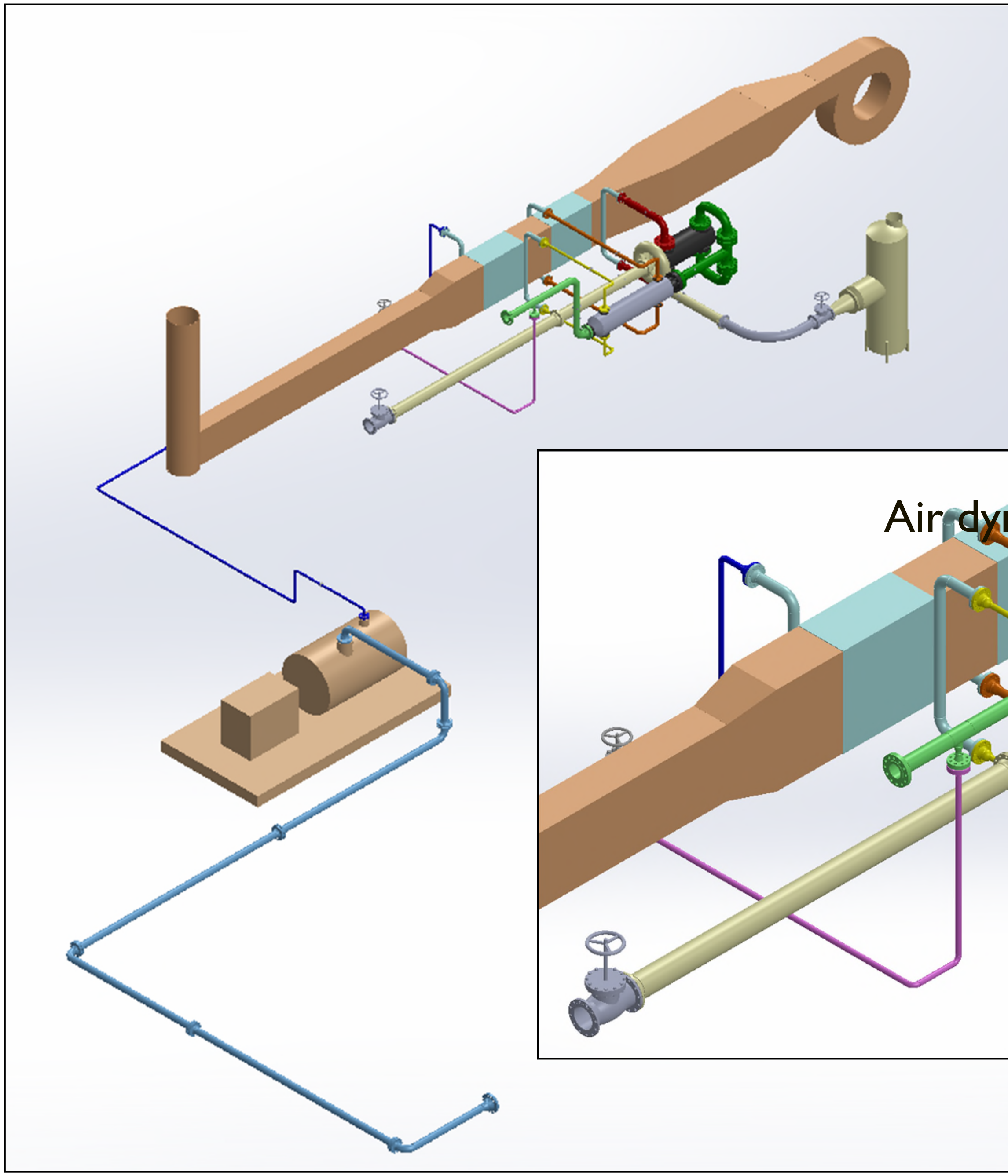

| Flow, kg/s |
|---|
| 9.91 |
| 8.41 |
| 9.91 |

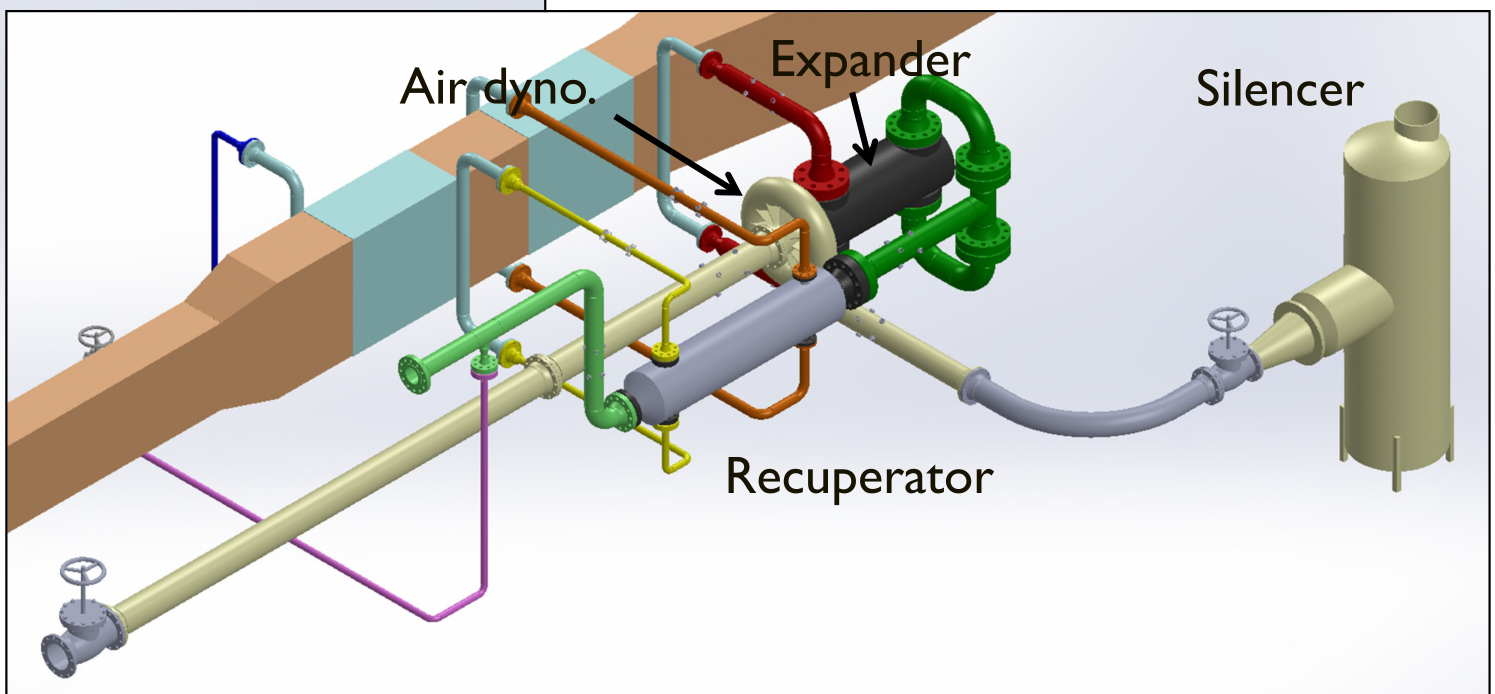
# Test Loop Design



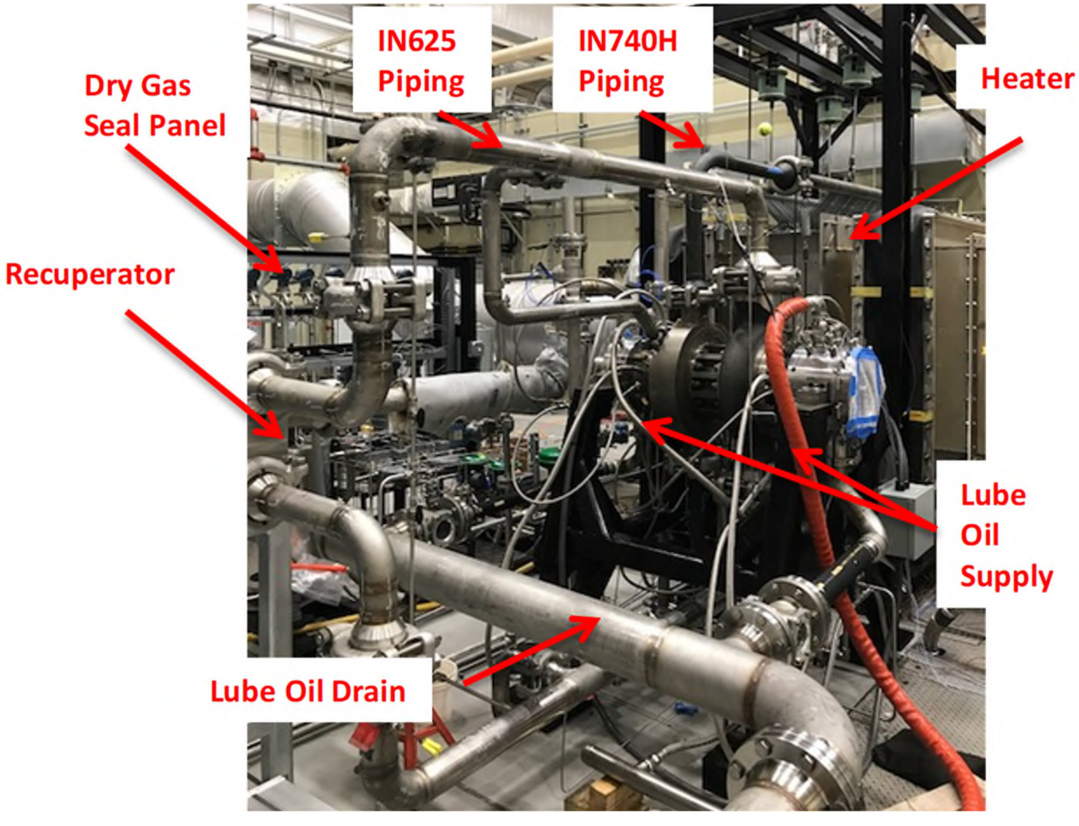
# Mechanical Test Configuration

| 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 |



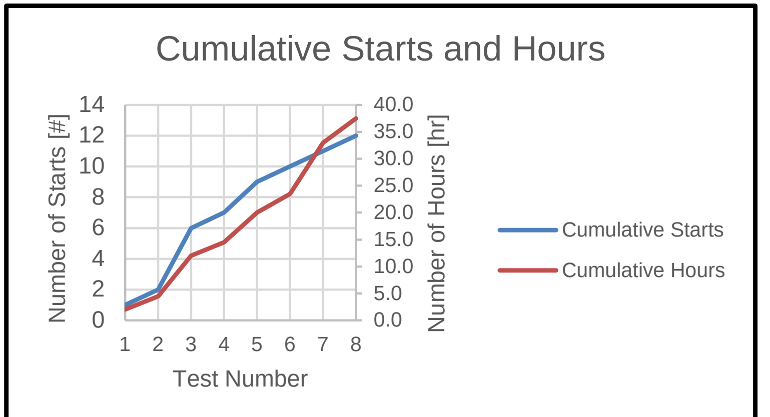


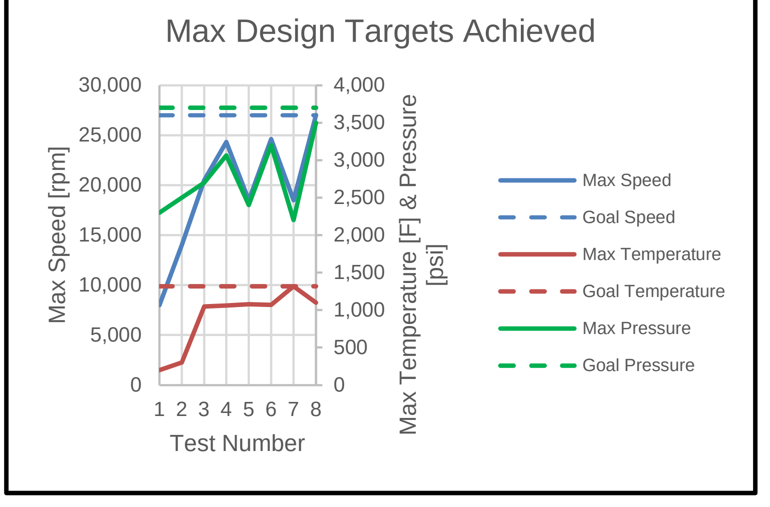
# SunShot Test Loop Components



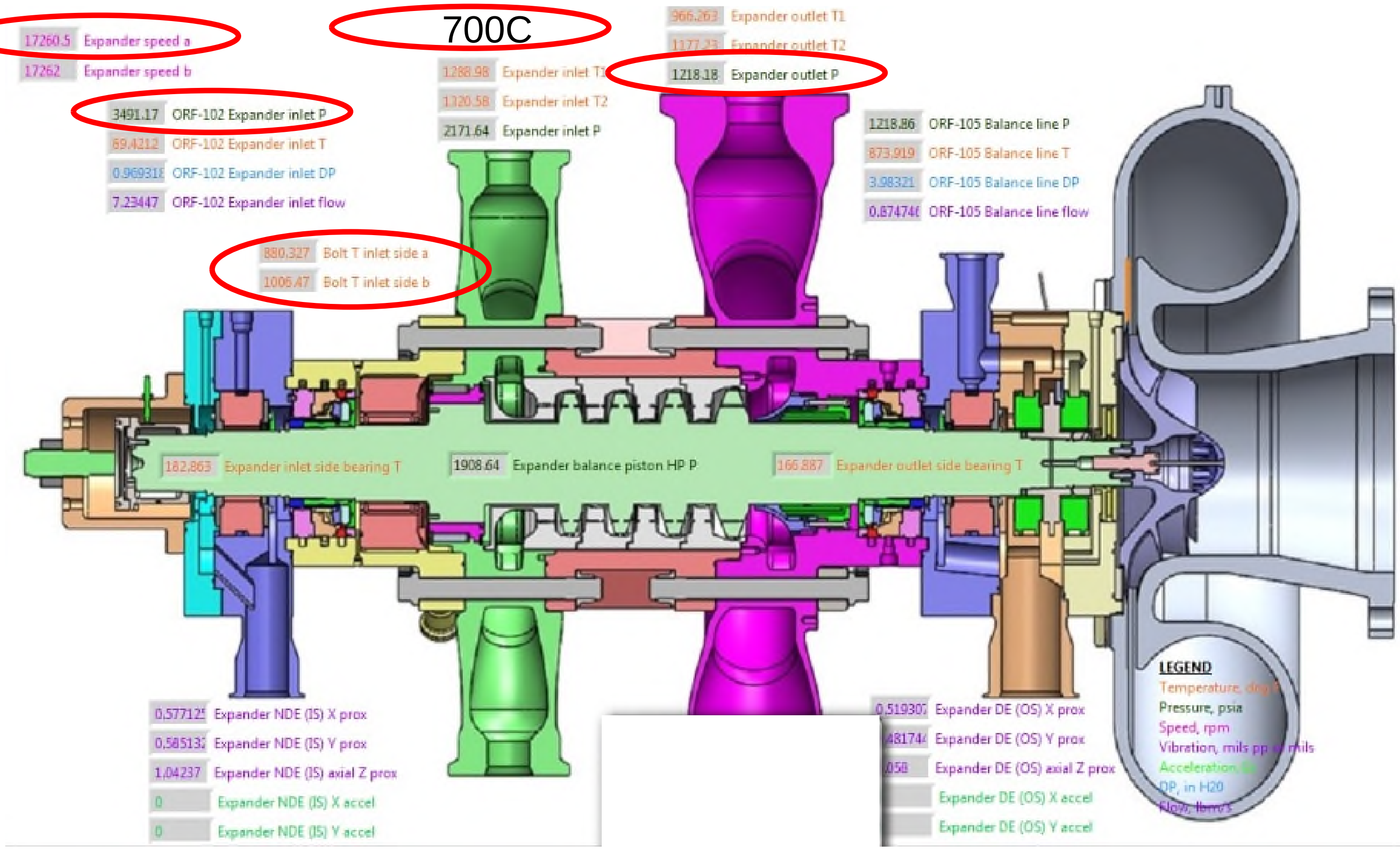
# SunShot Project Achieved Target Conditions

- Sunshot
  - 27,000 rpm; 1,320F; 3,500 psi
  - 12 total turbine starts with 3 controlled shutdowns and 9 observed trips
  - 37.5 hours of turbine operation
- FOCUS
  - Tested both thermals seals to similar operating conditions
  - 1020F; 21,000 rpm
  - Matched similar dry gas seal flows
  - Obtained thermal seal and case temperatures

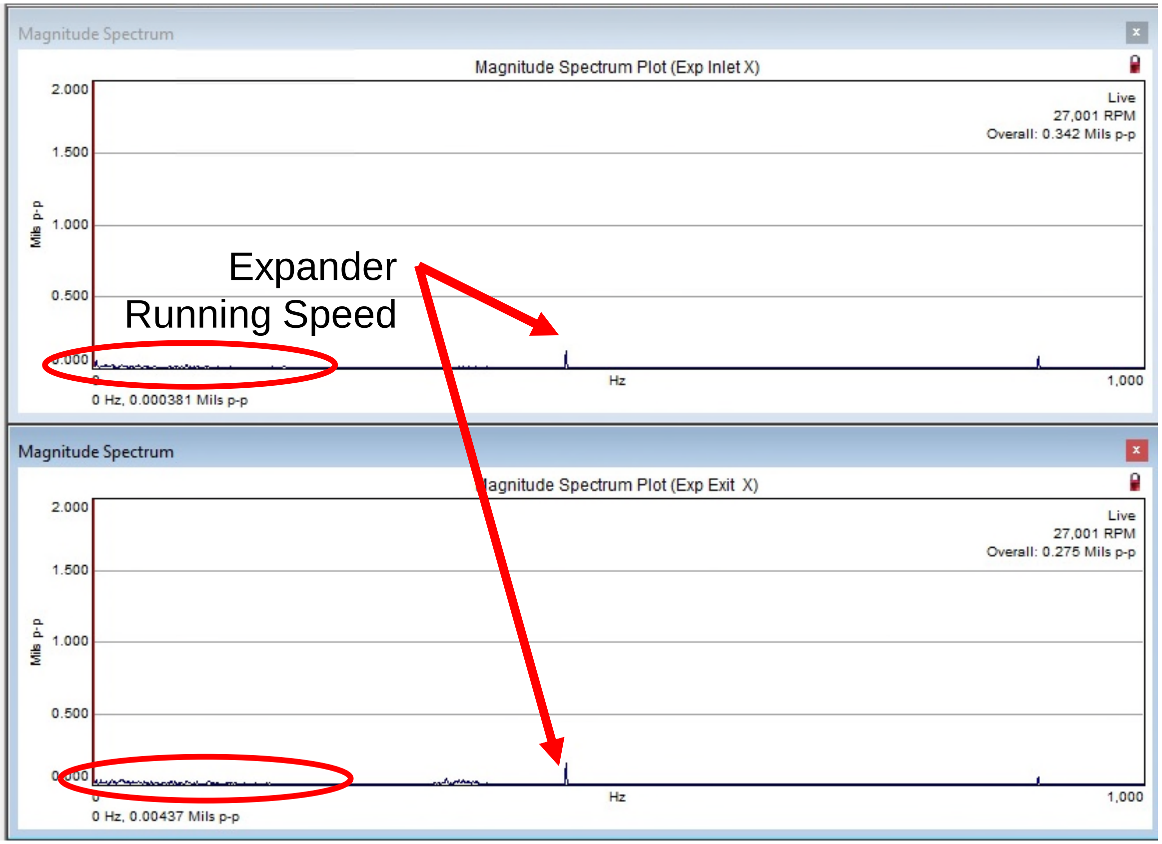


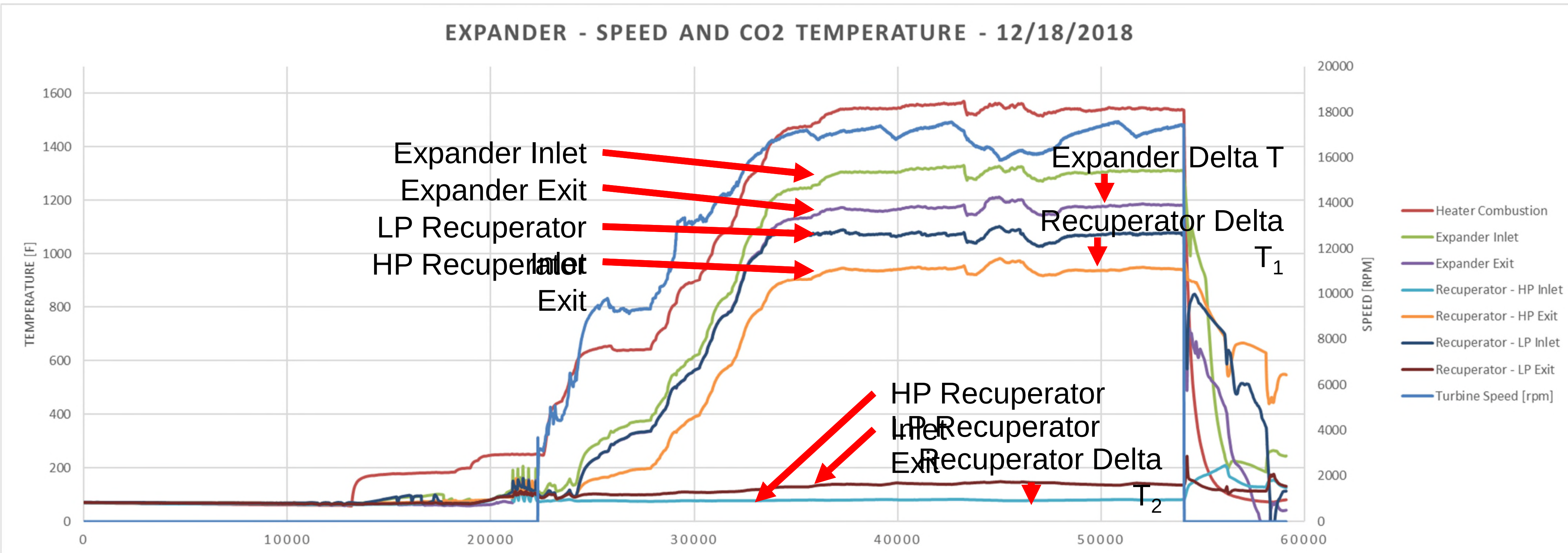
# Test Results – 700C+



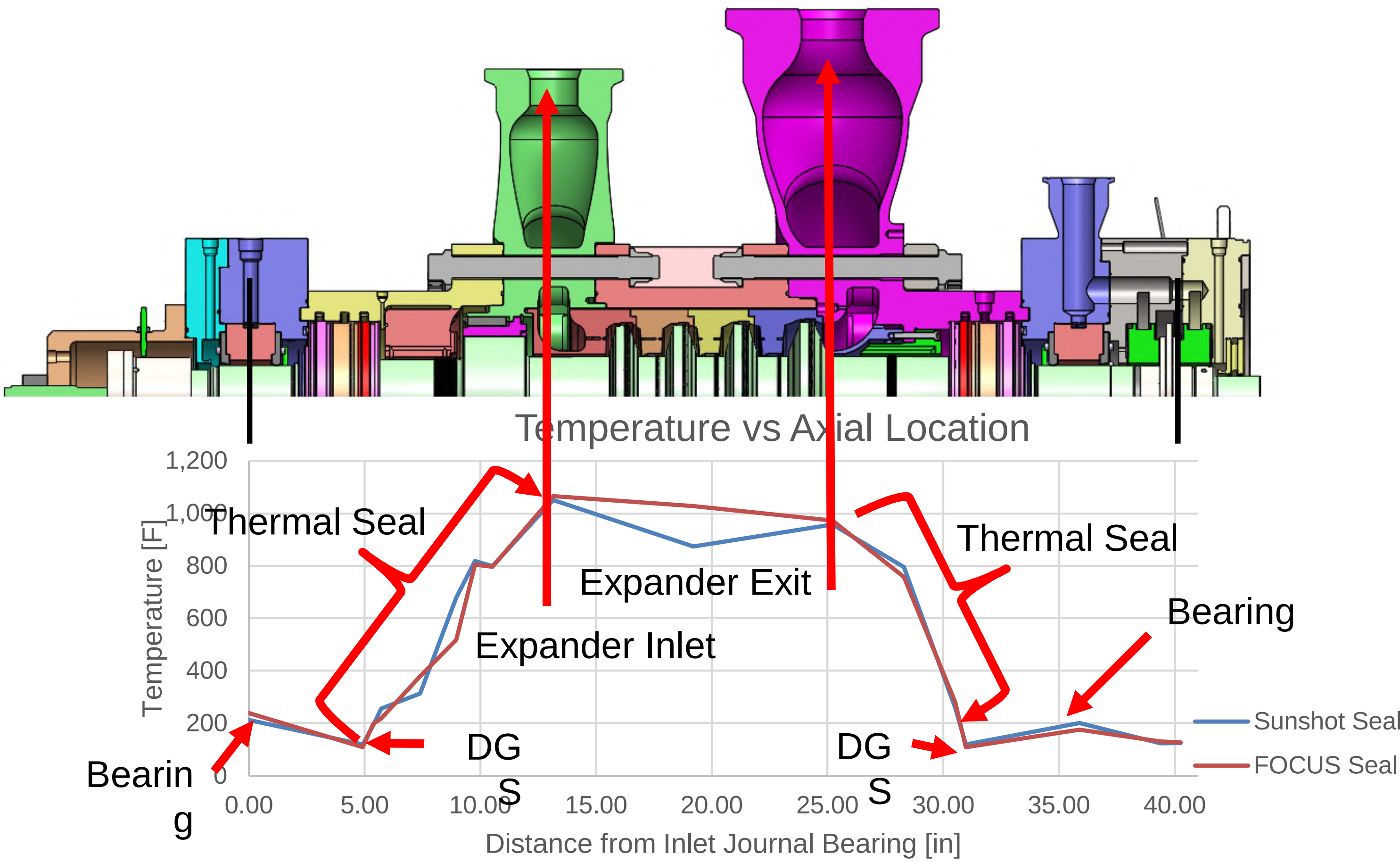
# Turbine Vibration Spectra at 27,000 rpm was Healthy



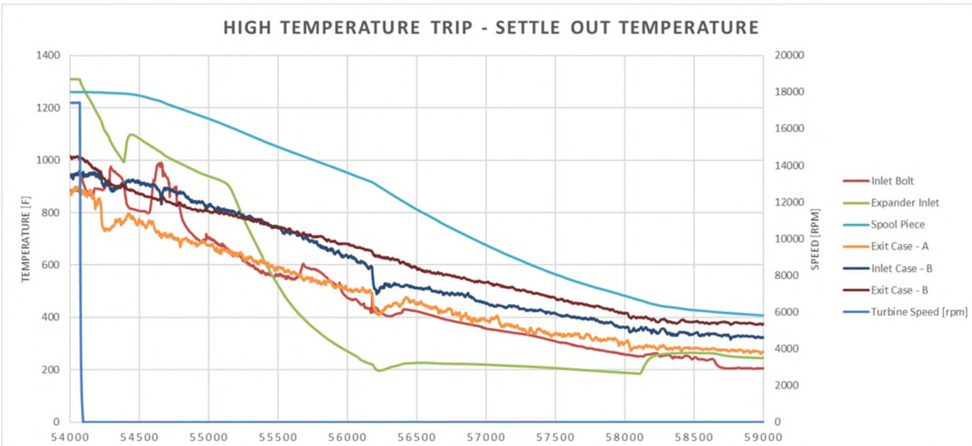
# Loop Temperatures

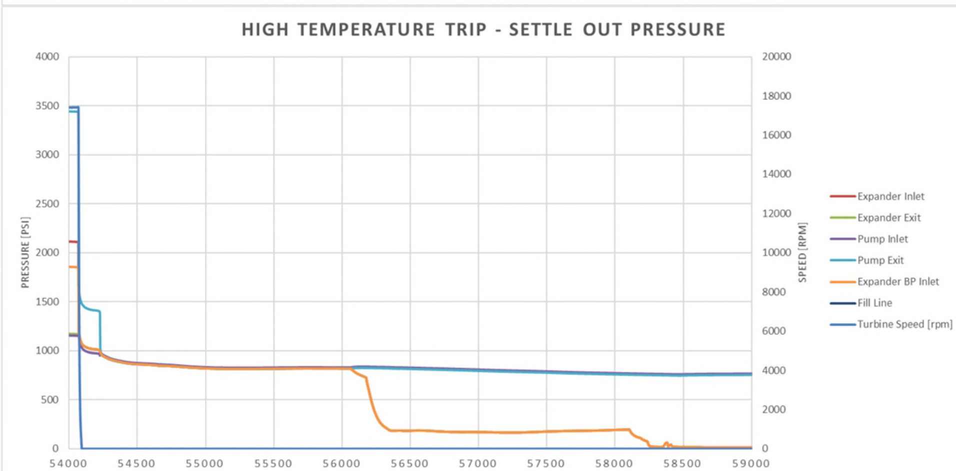


# Thermal Seal Performance Matched Expectations



# Test Loop Transients Performed




- Two maximum condition trips
  - Highest temperature trip after 1,320F was reached
  - Highest pressure trip after 27,000 rpm was reached
- High temperature trip
  - Settle pressure is reached in less than 10 seconds
- Turbine case cooled down at a similar rate with or without dry gas seal flow

SwRI®

# SunShot Project Summary

- ❑ Turbine performance met all mechanical and performance objectives
  - Achieved design temperature of 715C, design speed of 27000 rpm, and near design pressure of 3600 psi.
  - Thermal seal maintained acceptable dry gas seal operating temperature with near linear profile.
  - Vibration well less than 0.5 mils with no signs of instability
  - Low critical speed response (good bearing damping and balance)
  - Good thrust balanced and low thrust bearing temperature
  - Many shutdown transients tolerated
  - Modified dry gas seal met requirements
  - Modified dry gas seal panel maintained warm seal gas preventing dry ice formation
- ❑ Test loop performed well meeting project objectives
- ❑ Highest temperature $SCO_2$ turbine in the world

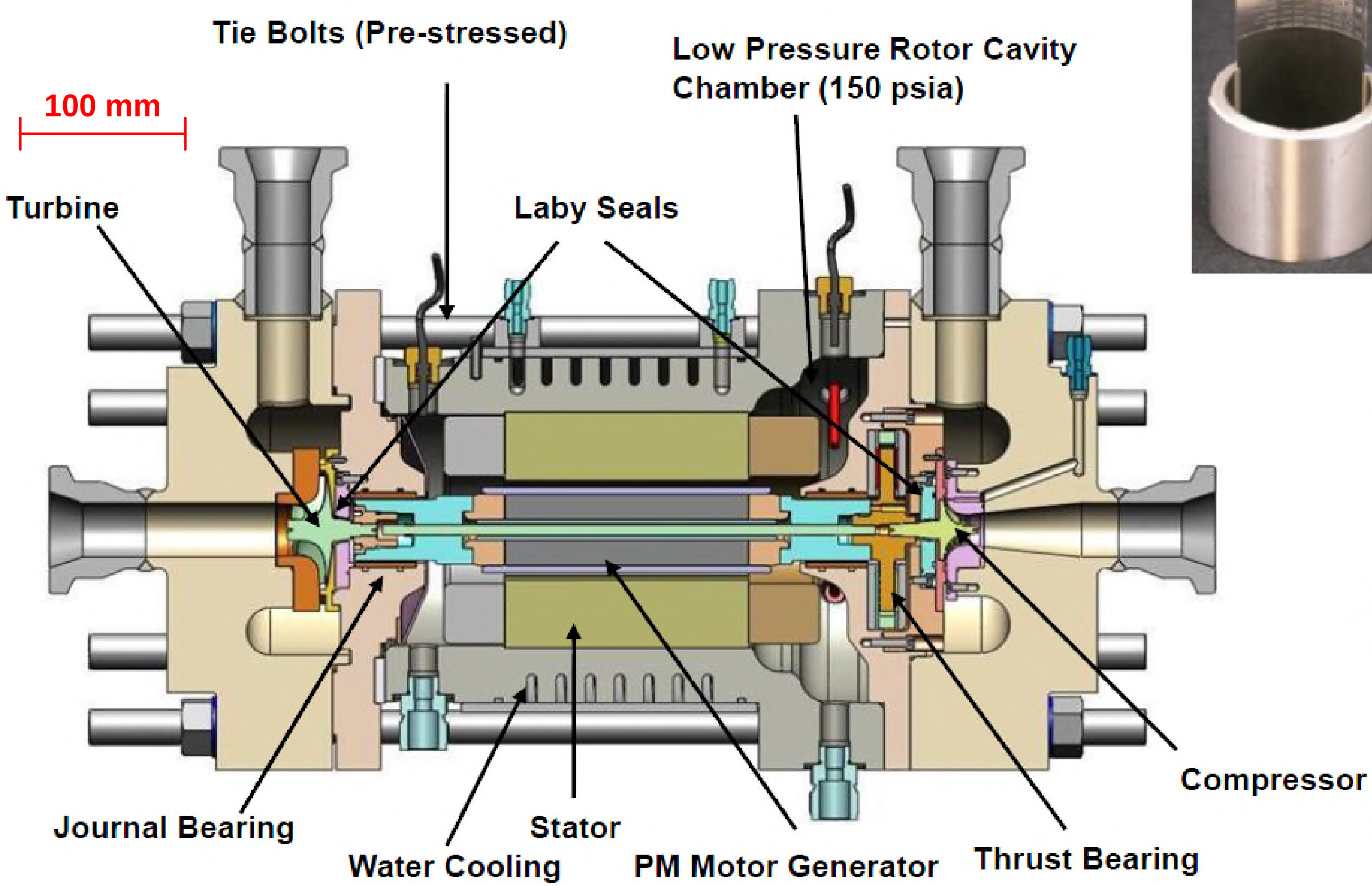


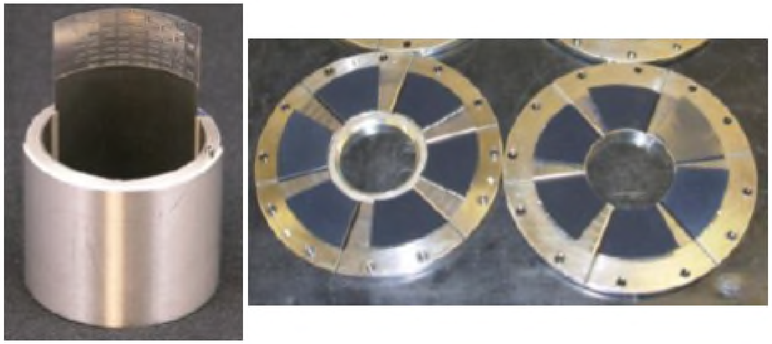
SwRI

# DOE $sCO_2$ Test Program

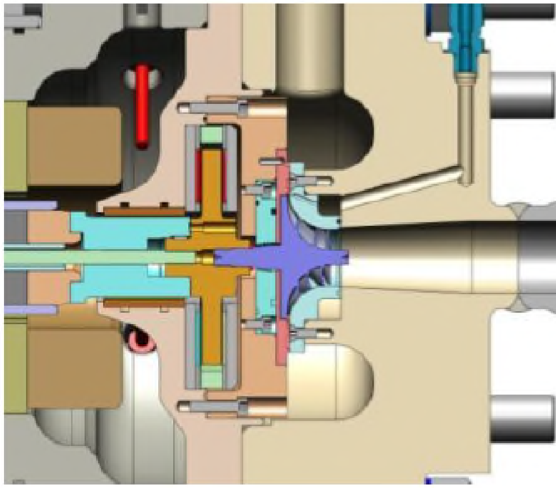
- Research compression loop
  - Turbomachinery performance
- Brayton cycle loop
  - Different configurations possible
    - Recuperation, Recompression, Reheat
  - Small-scale proof-of-technology plant
  - Small-scale components
    - Different than hardware for commercial scale

# DOE $sCO_2$ Test Program Turbomachinery



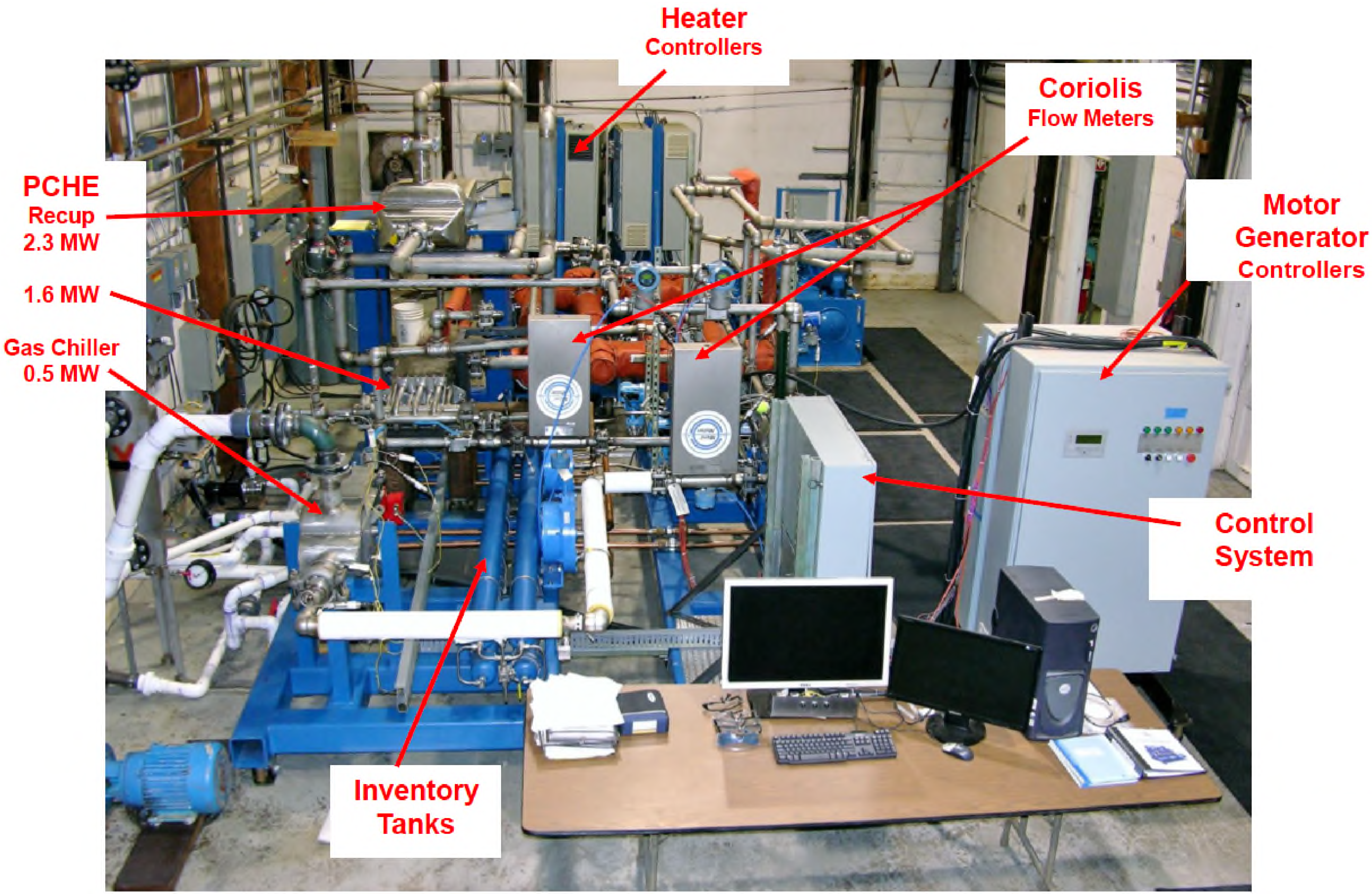



Gas-Foil Bearings



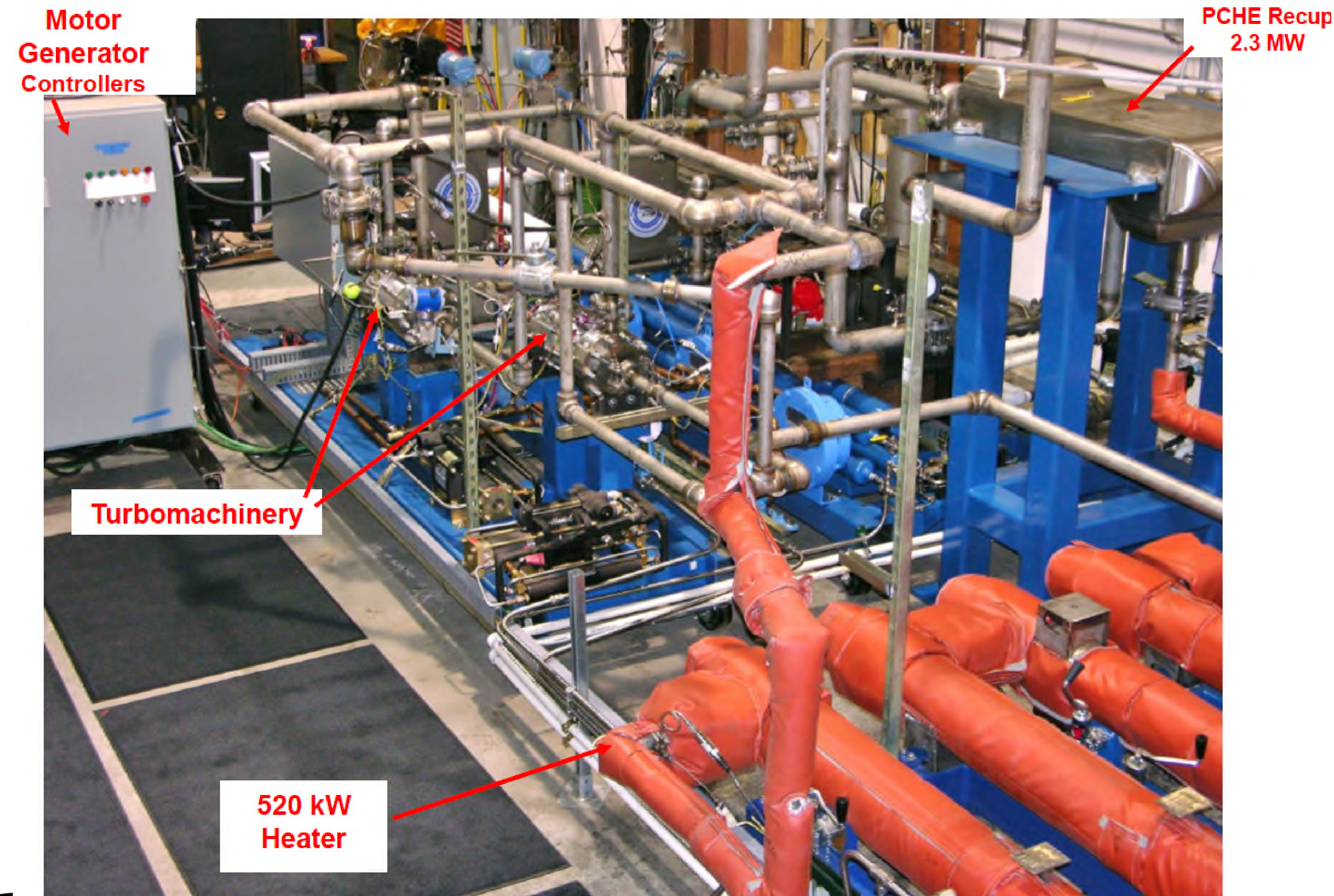
Source: Wright (2011)

# $sCO_2$ Brayton Cycle Test Loop



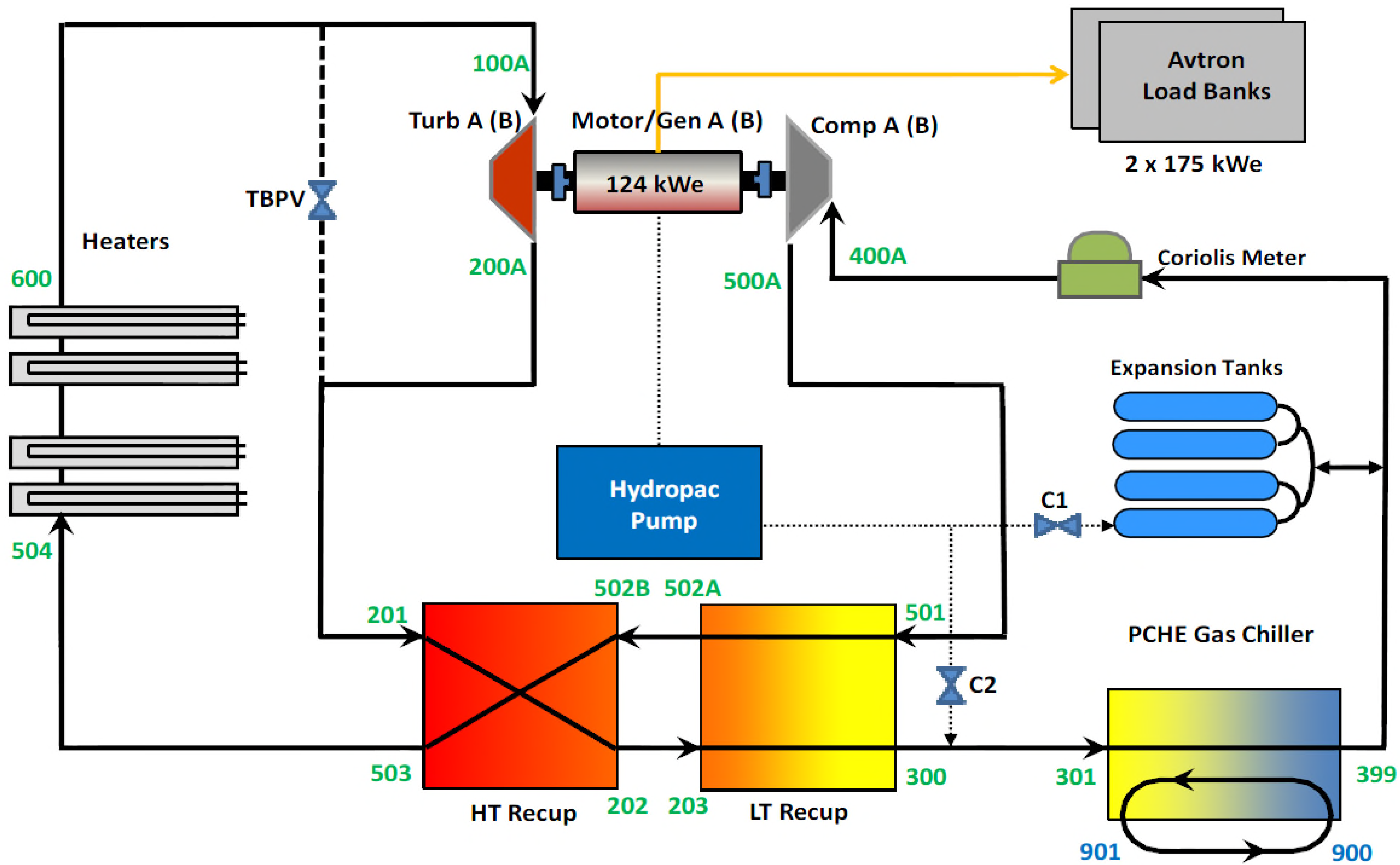

Source: Wright (2011)

# $sCO_2$ Brayton Cycle Test Loop



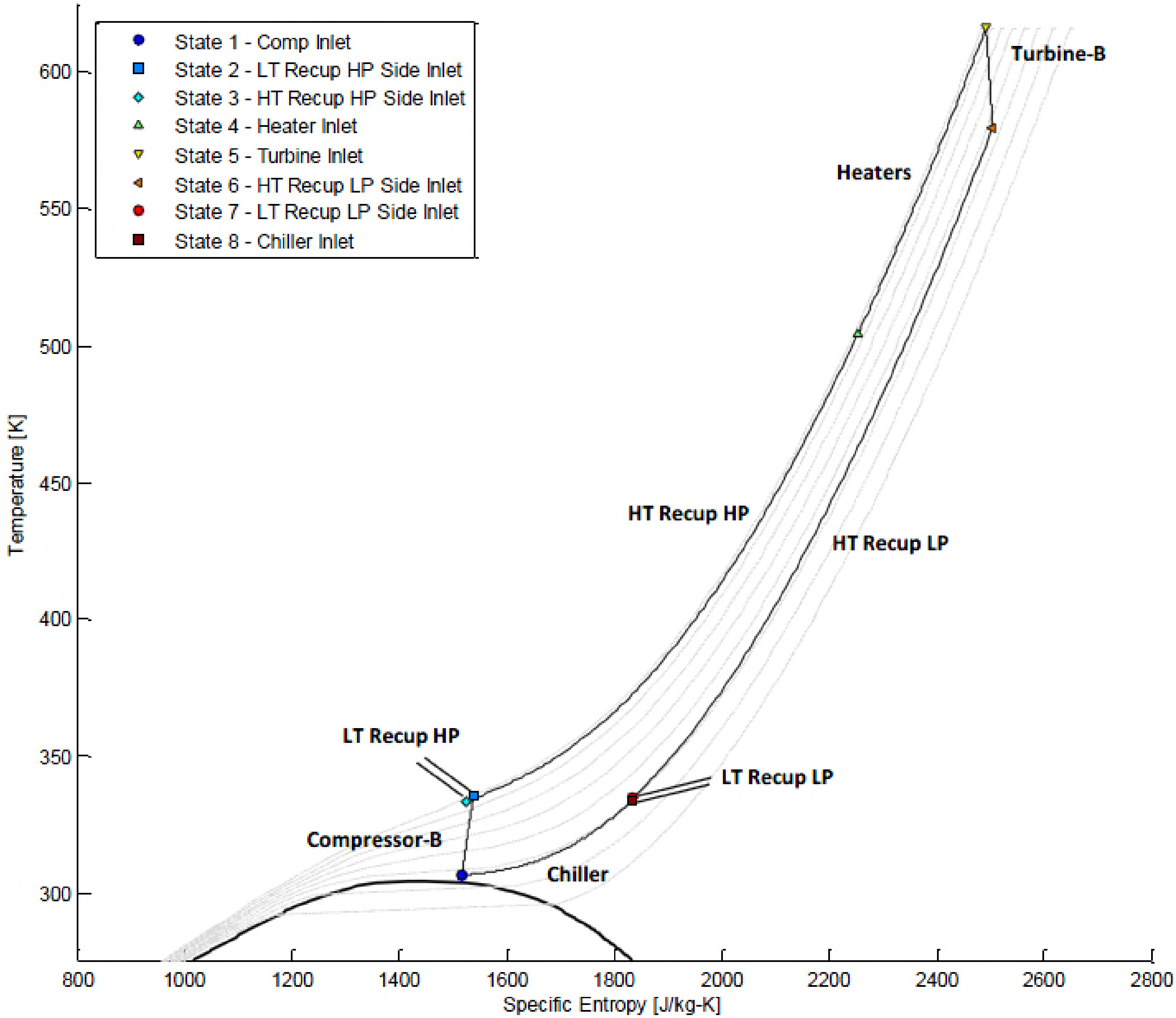

Source: Wright (2011)

# $sCO_2$ Brayton Cycle with Regeneration



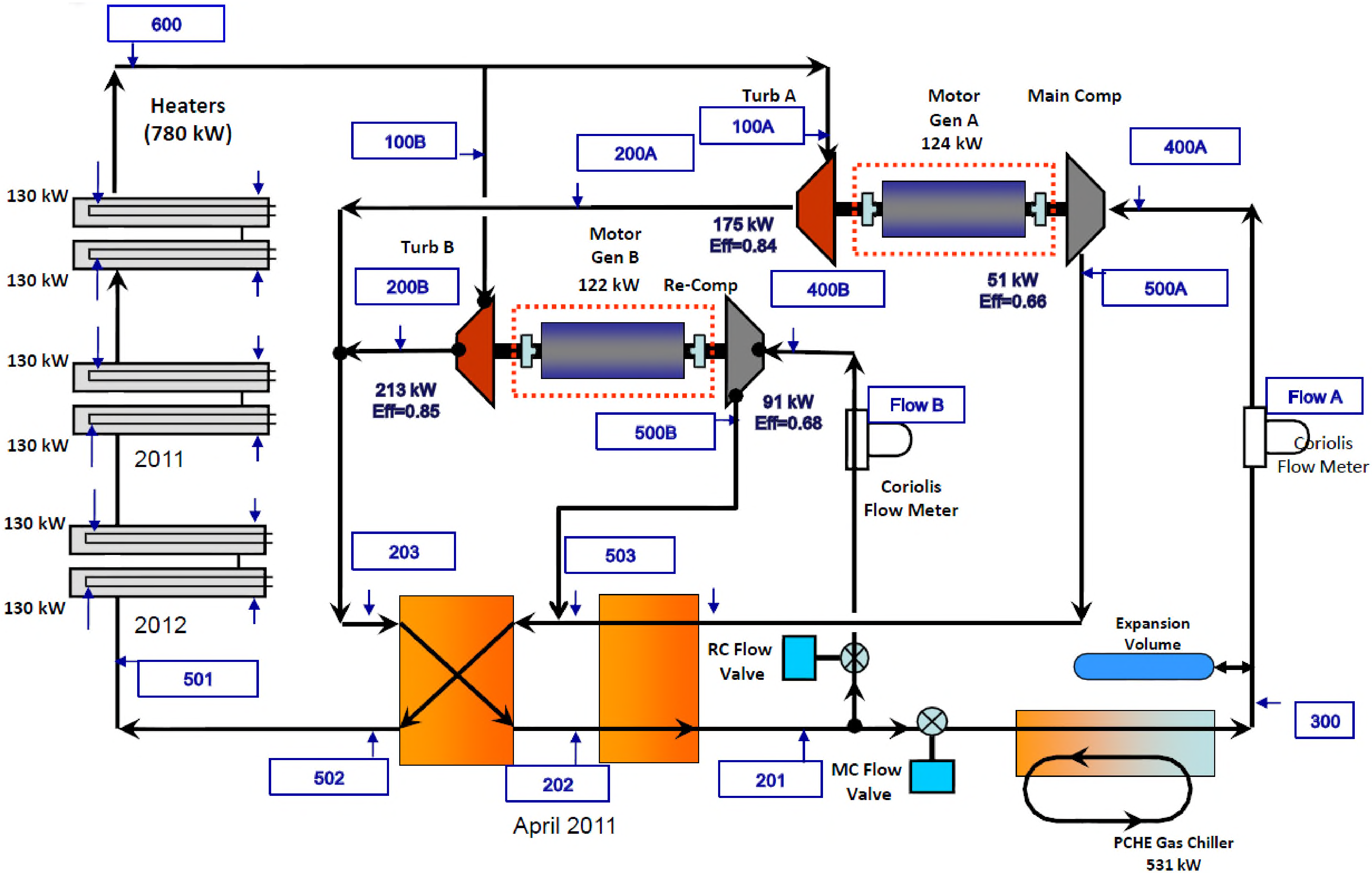

Source: Conboy et al. (2012)

# $sCO_2$ Brayton Cycle with Regeneration




Source: Conboy et al. (2012)

# $sCO_2$ Brayton Cycle with Regen. + Recomp.

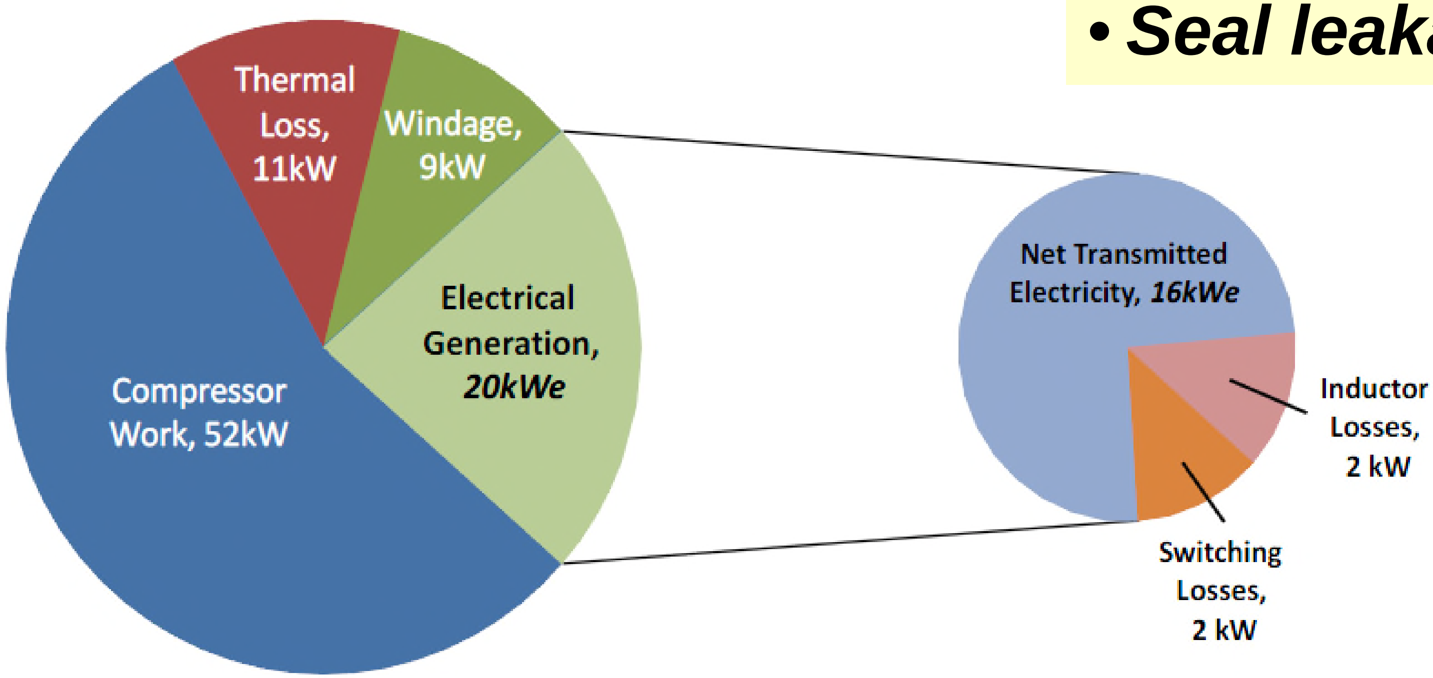



Source: Wright (2011)

# $sCO_2$ Brayton Cycle Performance with Regeneration Config.

**Maximum Case:**
**Total Turbine Work, 92 kW**

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

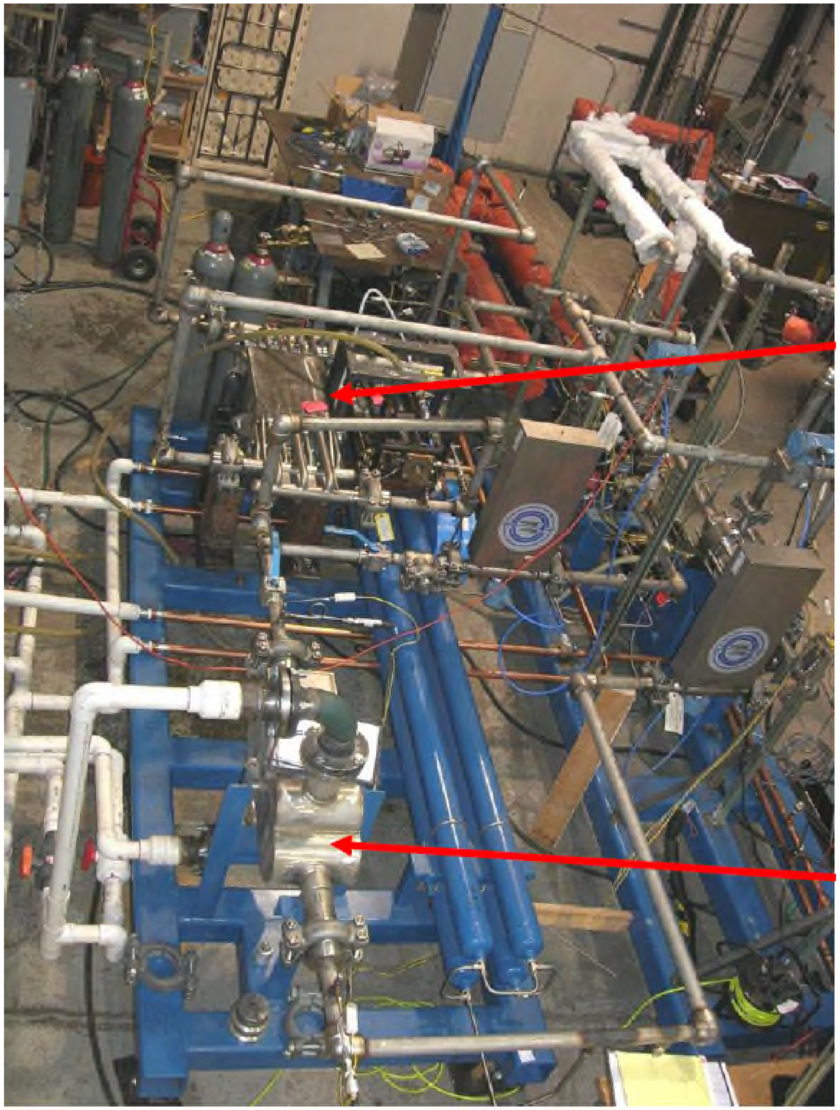



Source: Conboy et al. (2012)

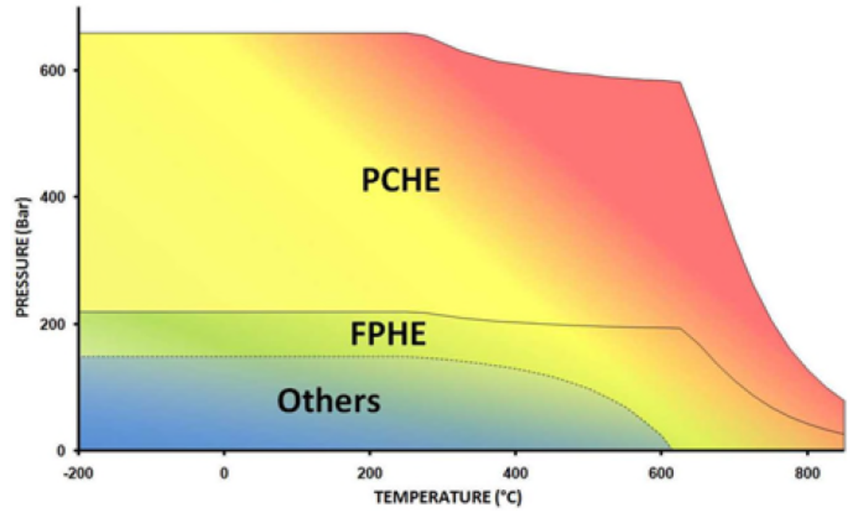
# DOE $sCO_2$ Test Program Summary

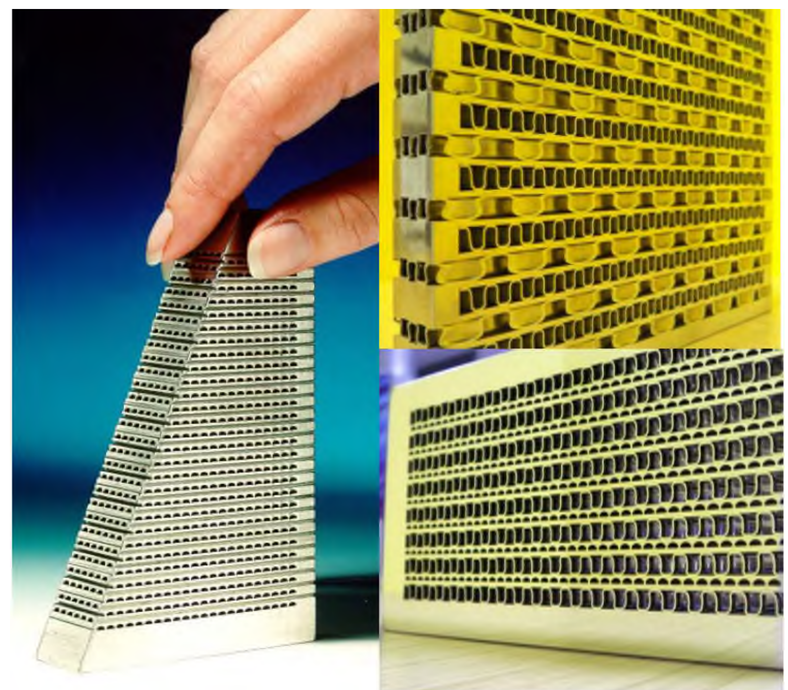
- Major milestones
  - Test loops operational
  - Demonstrate process stability/control
- Areas for future development
  - Heat exchanger performance
  - Larger scale test bed
    - Utilize commercial-scale hardware
    - Demonstrate more-realistic (better) performance
  - $CO_2$ mixtures

# Printed Circuit Heat Exchanger (PCHE)



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



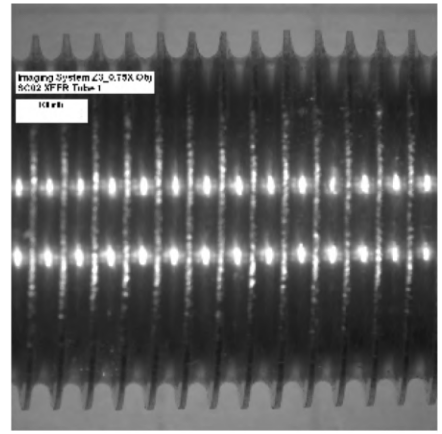



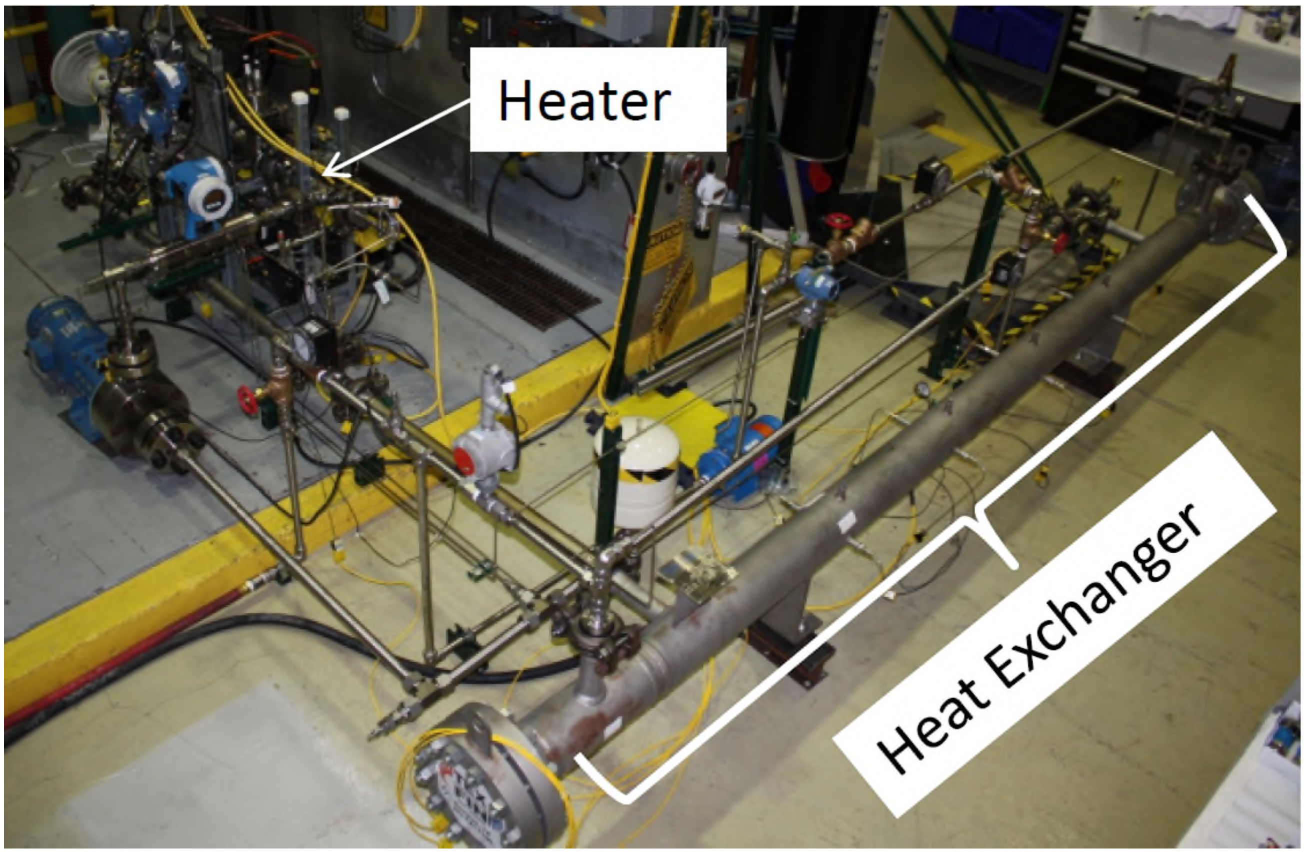
Heatric PCHE

Le Pierres (2011)

# Heat Exchanger Testing (Bechtel)

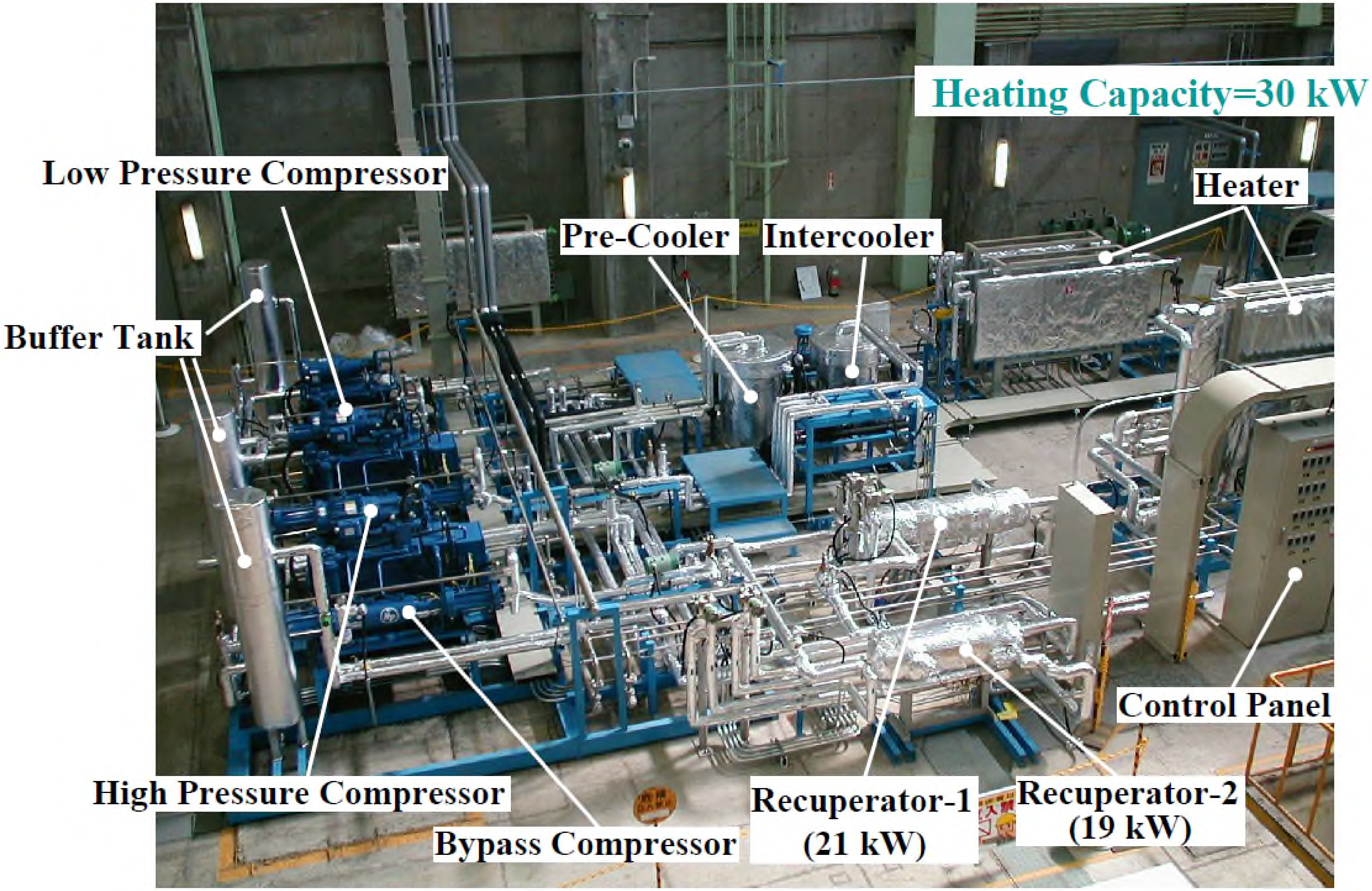
- 150 kW
- 8000 lbm/hr $sCO_2$
- 2500 psi






Nehrbauer (2011)

# Tokyo Institute of Technology (TIT)

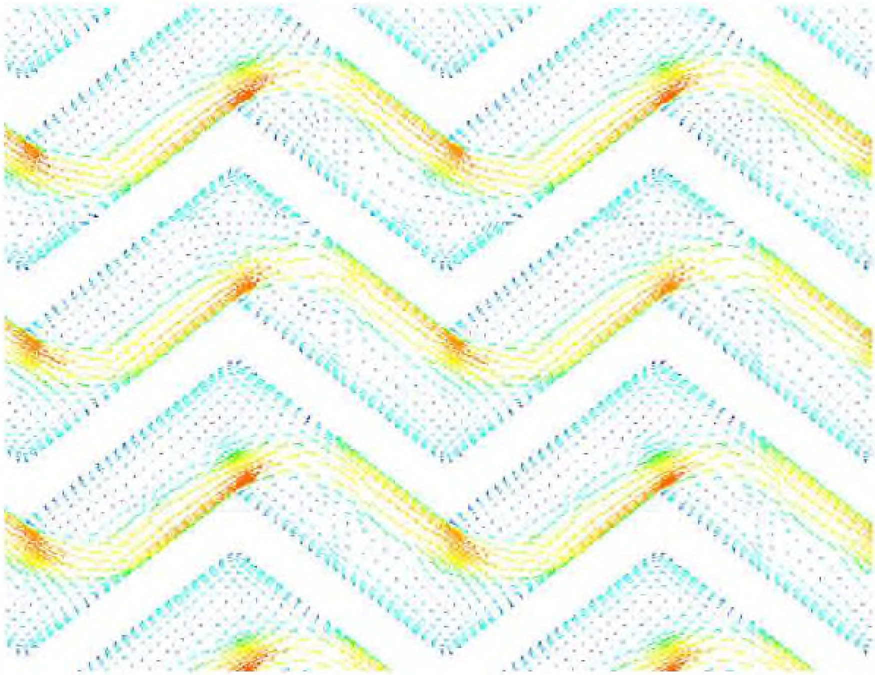



**Supercritical $CO_2$ Cycle Mockup Test Loop**

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

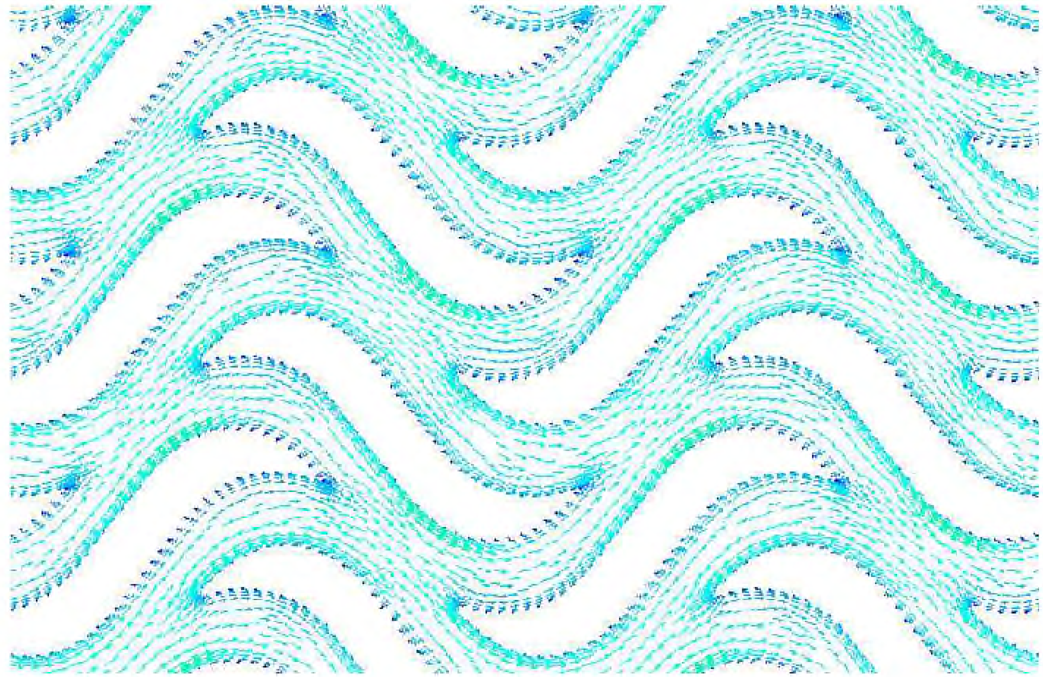
(Kato et al., 2007)

# TIT, New Micro-Channel Heat Exchanger



**Zigzag Model**

- Localized velocity profile
- Eddies around the corners



**"S" Shape Fin model**

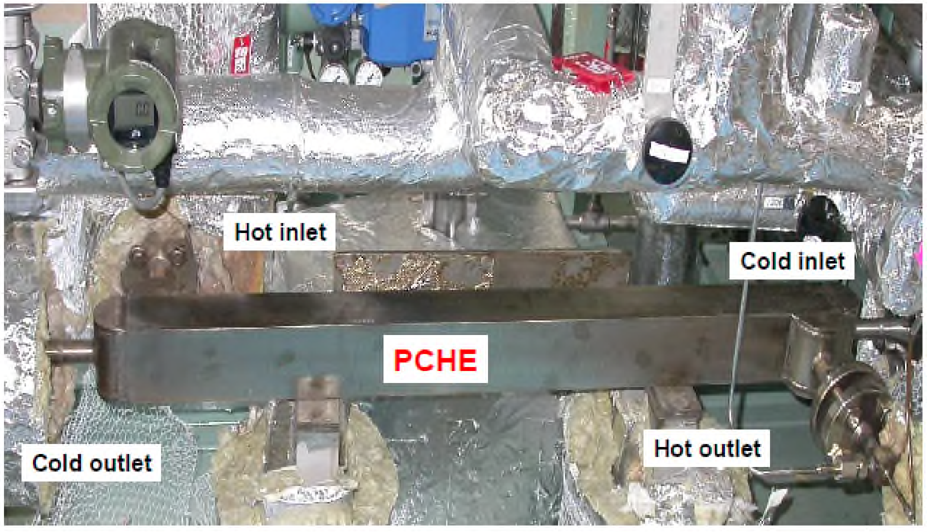
- Uniform velocity profile
- No eddies

(Kato et al., 2007)

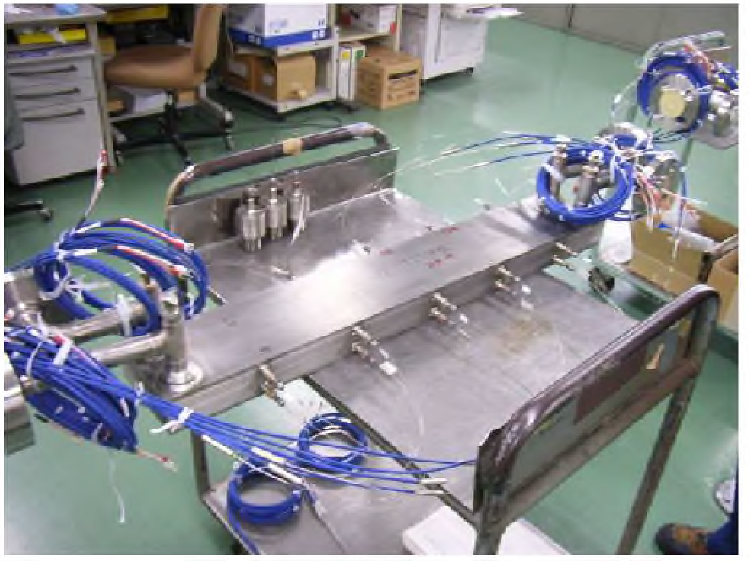
# TIT, Heat Exchanger Testing

(Kato et al., 2007)

3kW



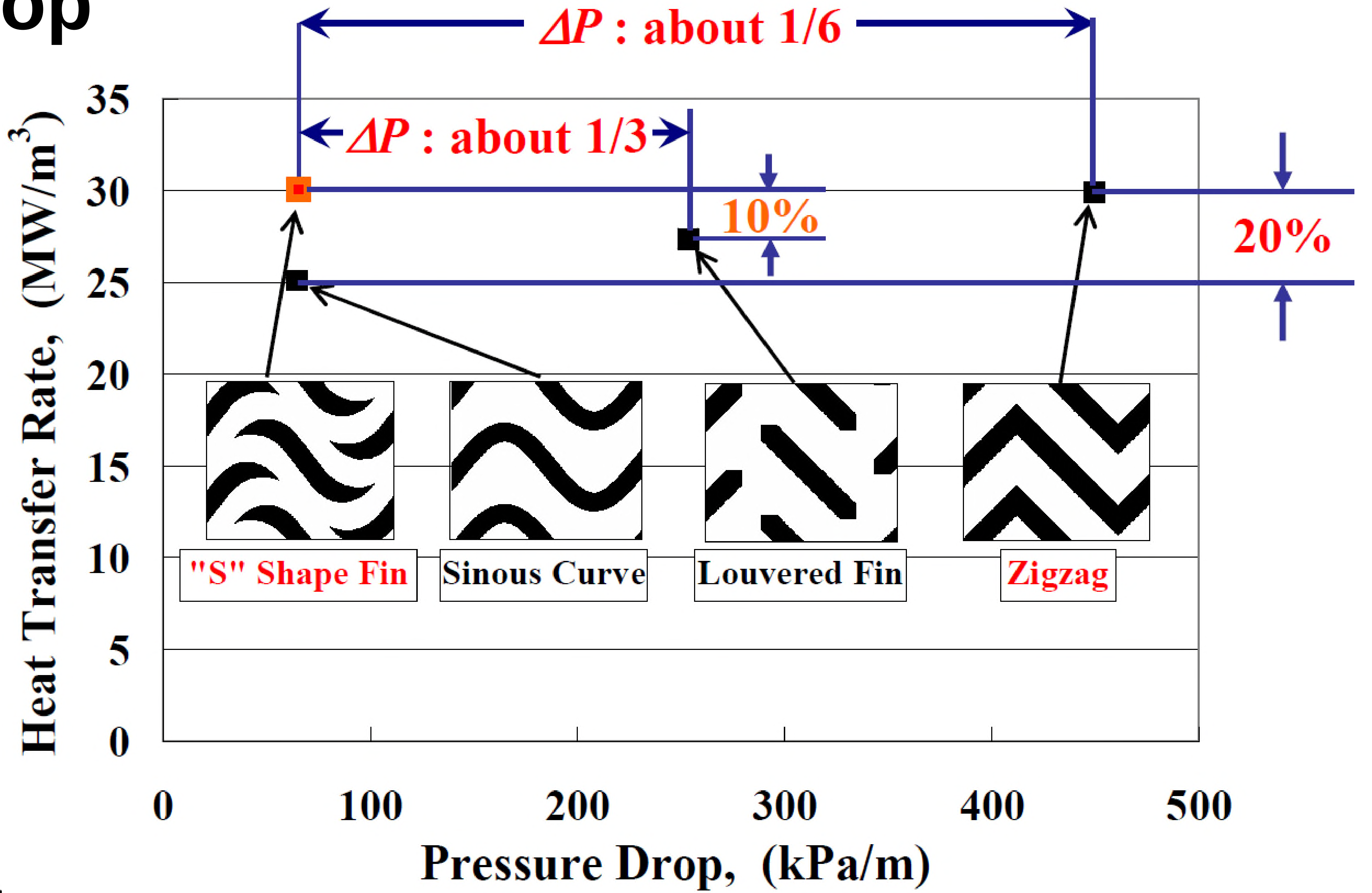

19,21 kW



TokyoTech,
(S-Shaped Fins)

HEATRIC
(Zigzag Fins)

# TIT, Heat Transfer Rate vs. Pressure Drop




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

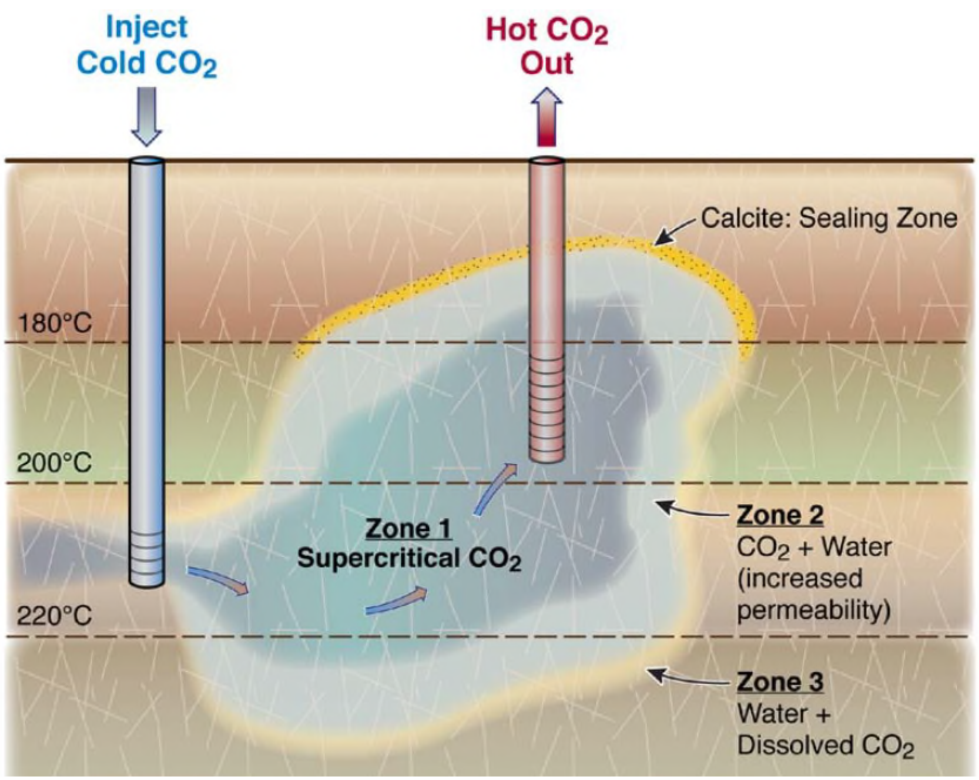
- MIT - 650°C, 22 MPa
  - Steels
- UW - 650°C, 27 MPa
  - Steels

Guoping (2009)

- 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.

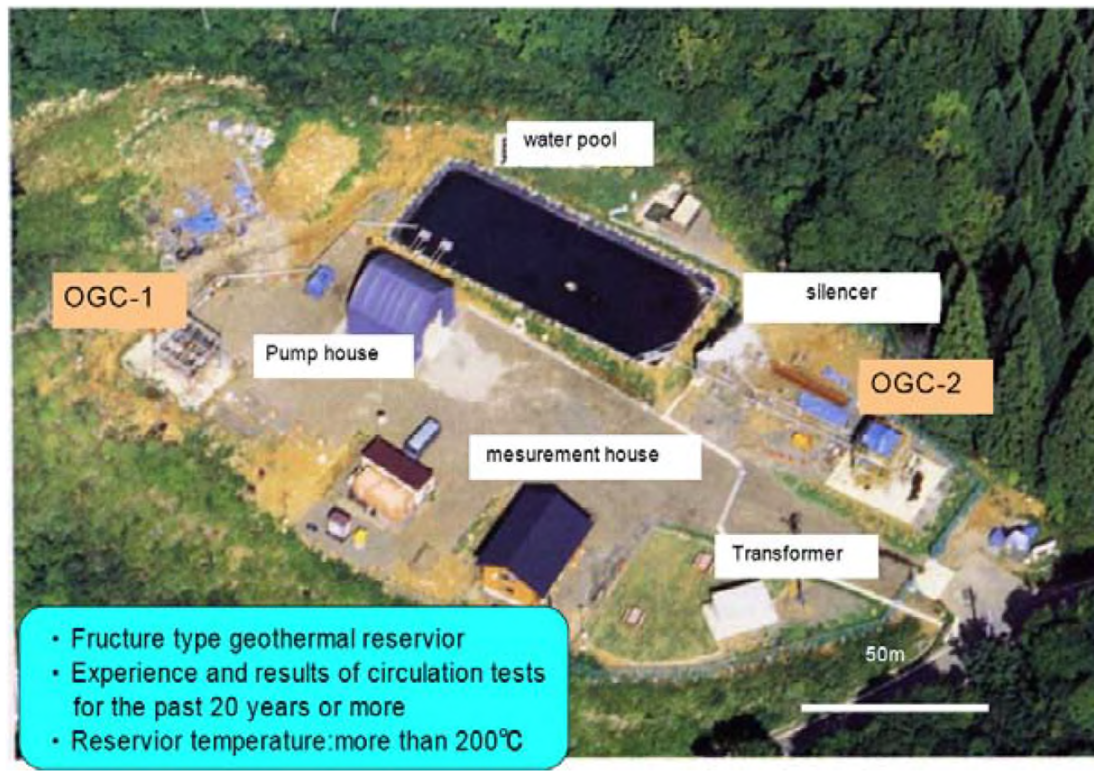
# Geothermal Research

- ❑ 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 $sCO_2$

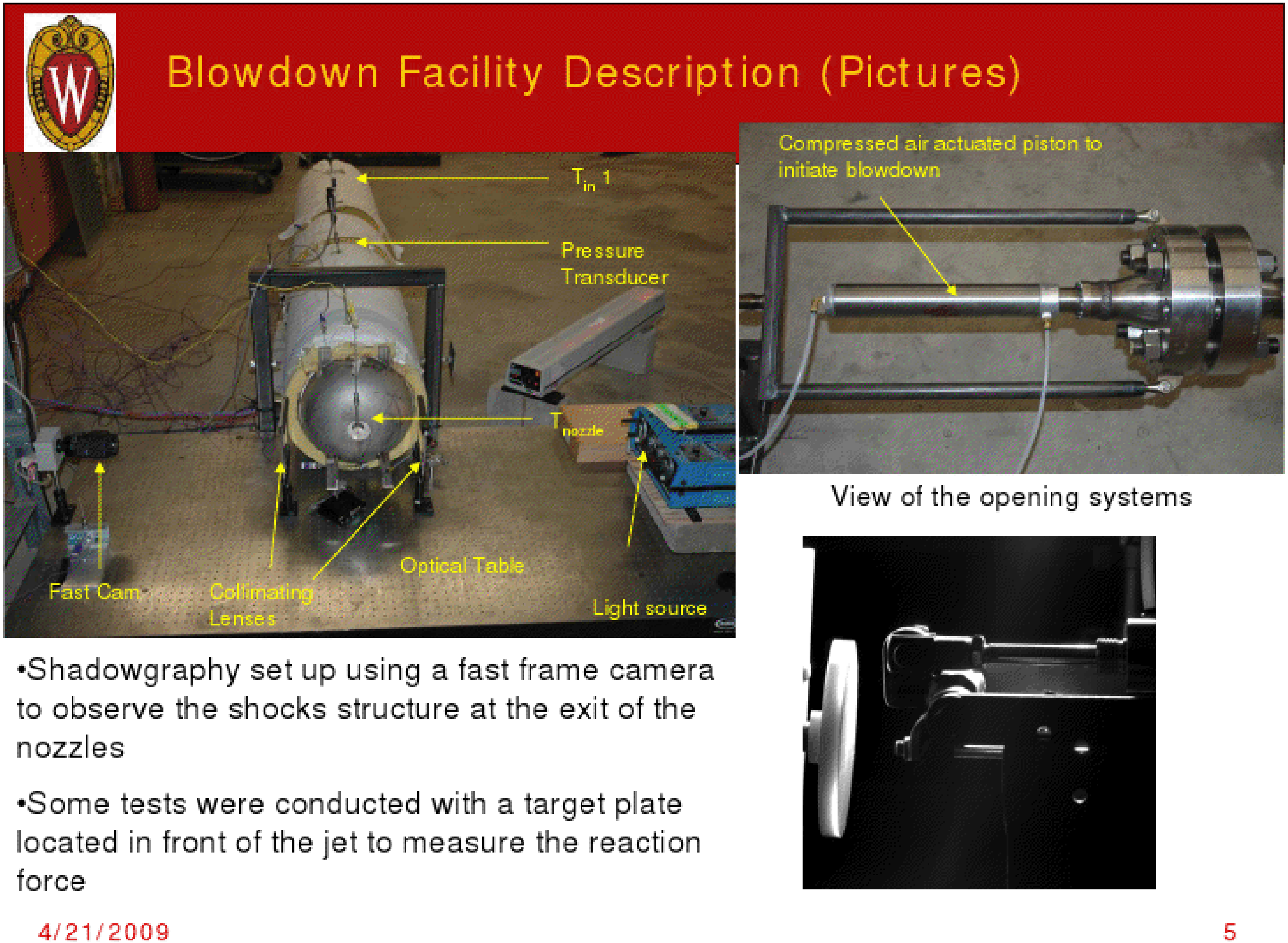
Pruess (May 19, 2010)




Ogachi, Japan – HDR Site

Pruess (May 18, 2010)

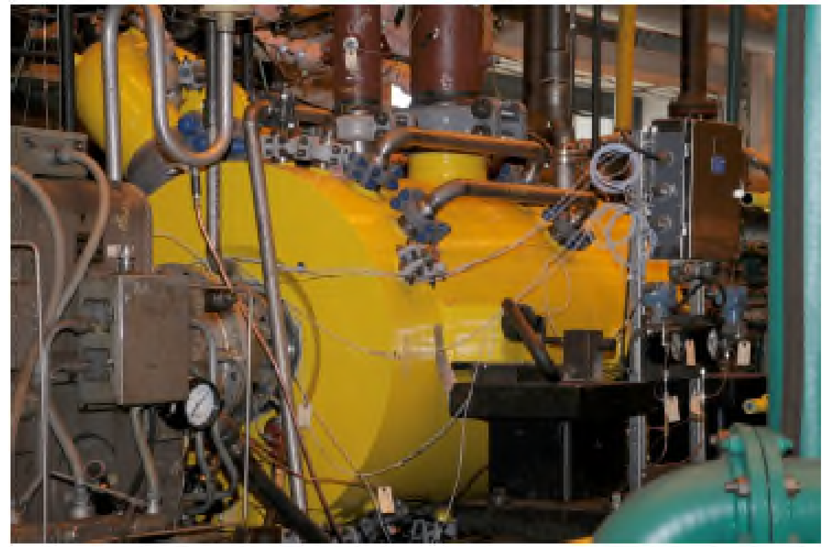
# $sCO_2$ Critical Flow (Univ. Wisconsin)




(Anderson, 2009)

# $sCO_2$ High Pressure Compression (Dresser-Rand)


Tupi - I



Tupi - III

(GT2012-70137)

# 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%)

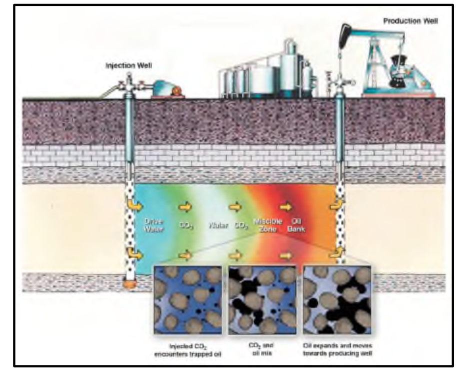
# 10 MW Scale Pilot Plant

SwRI®

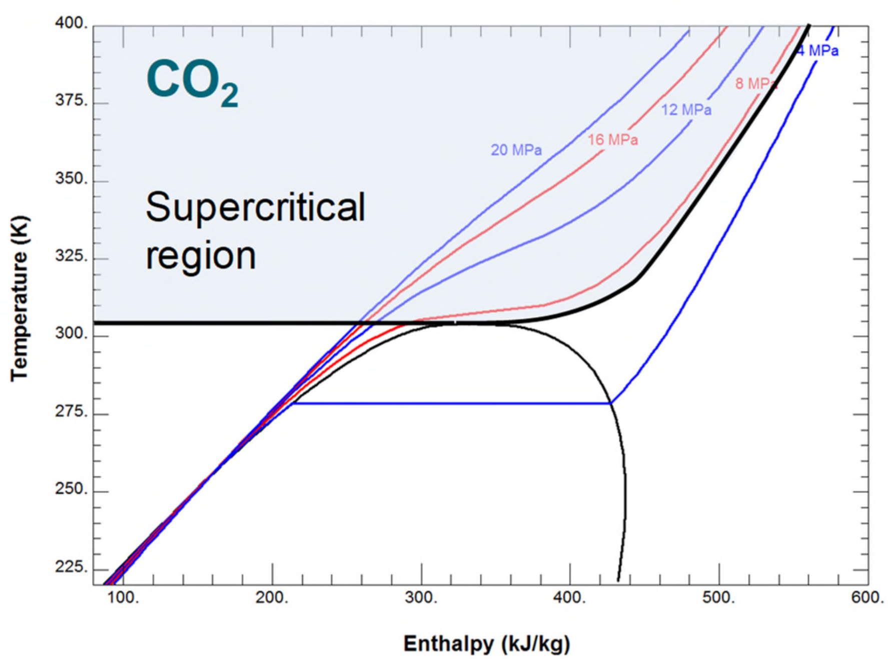
# Summary

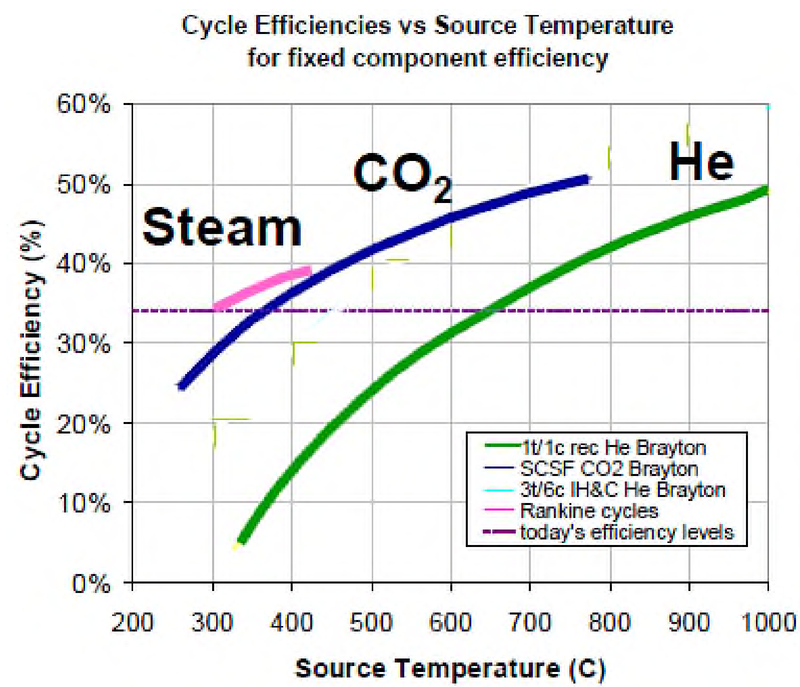
# Both supercritical power cycles and the use of $sCO_2$ are not new concepts

**$sCO_2$ is used in a variety of industries as a solvent**



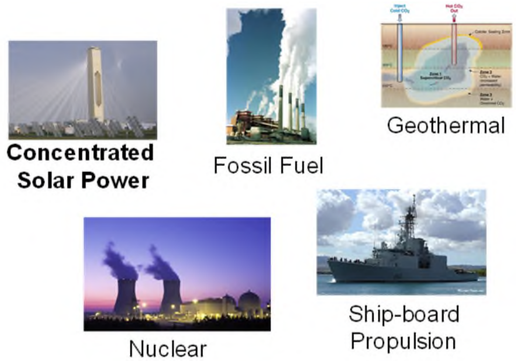

**$sCO_2$ is desirable for power cycles because of its near-critical fluid properties**

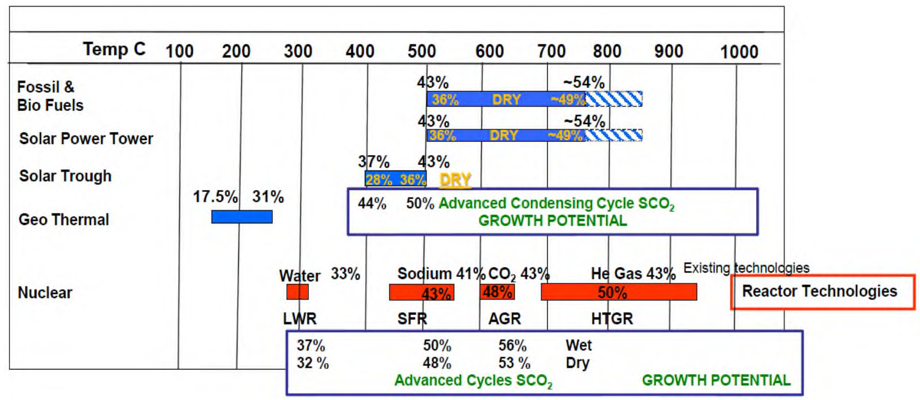


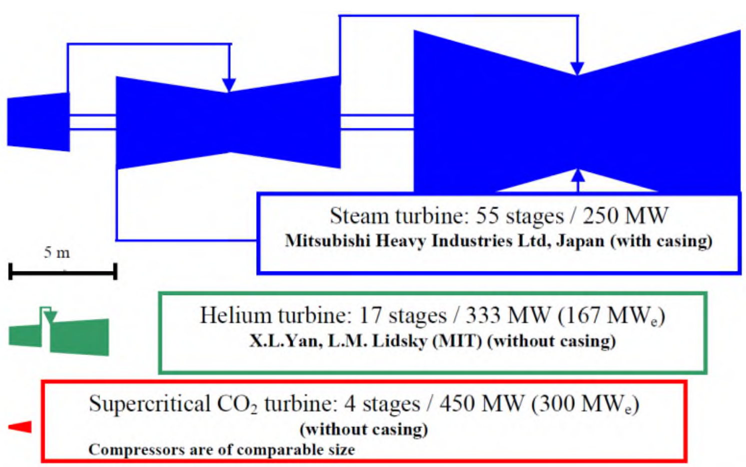
# $sCO_2$ power cycles can be applied to many heat sources and have a small footprint

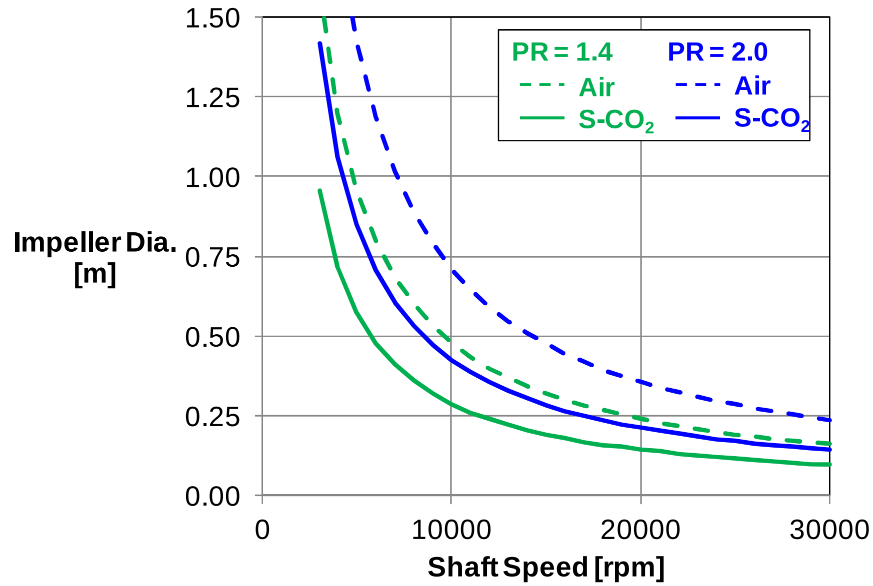
**The near ambient critical temperature of $CO_2$ allows it to be matched with a variety of thermal heat sources**




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



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

**International $sCO_2$ power cycle research is ongoing**

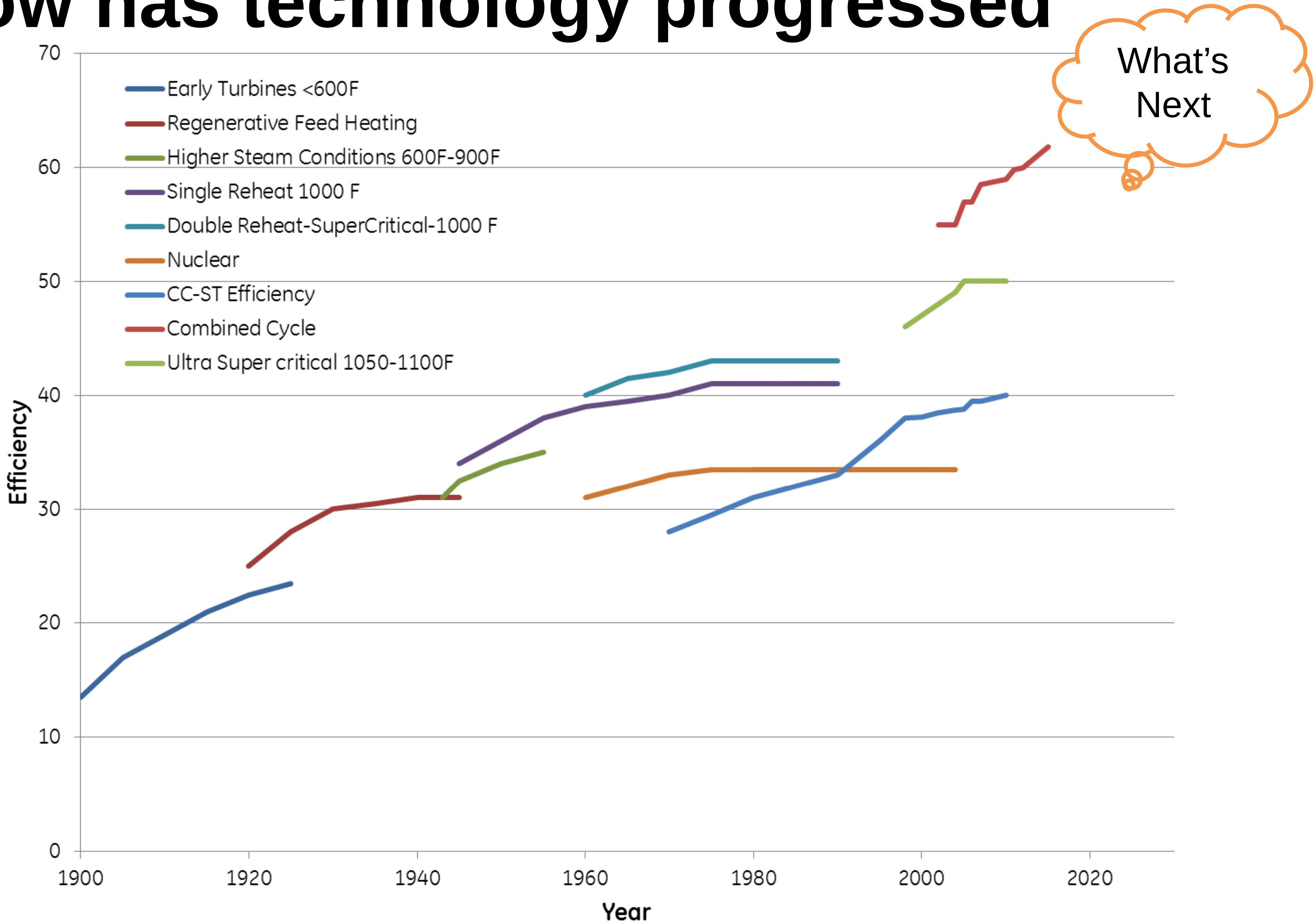
- Power production test loops
- Machinery component test loops
- Materials corrosion test facilities
- Fluid property testing

**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




[Bowman 2016]

# $sCO_2$ Announcements

| Turbo Expo 2015 | Time | Room |
|---|---|---|
| **Tutorial**: Cycle Analysis | Mon 8:00-10:00 | 511F |
| **Tutorial**: Fundamentals | Mon 2:30-5:30 | 510C |
| **Panel**: $CO_2$ Power Cycle R&D | Tues 2:30-5:30 | 516B |
| **Tutorial**: Turbomachinery | Wed 2:30-5:30 | 516B |
| **Tutorial**: Heat Exchangers | Thurs 2:30-5:30 | 510B |
| **Tutorial:** Materials | Fri 2:30-5:30 | 512CG |

**Supercritical $CO_2$ Power Cycles Symposium**

**March 29 – 31, 2016**
**San Antonio, TX**

**Abstracts Due July 31, 2015**