ASME Turbo Expo 2014
Düsseldorf Germany, June 16-21, 2014

Fundamentals of Supercritical CO_2

Presentation by:

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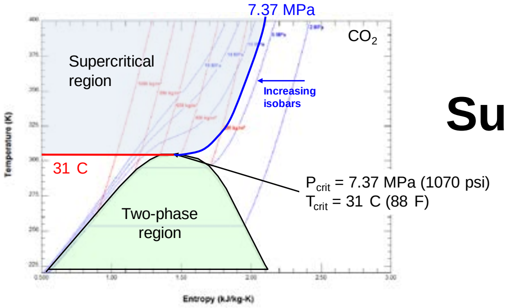
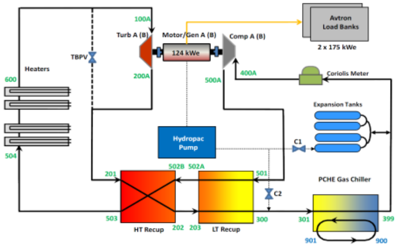
June 16, 2014

This tutorial provides an introduction to S-CO_2 in power cycle applications



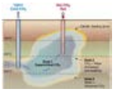
Supercritical CO_2 (S-CO_2)



S-CO_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

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

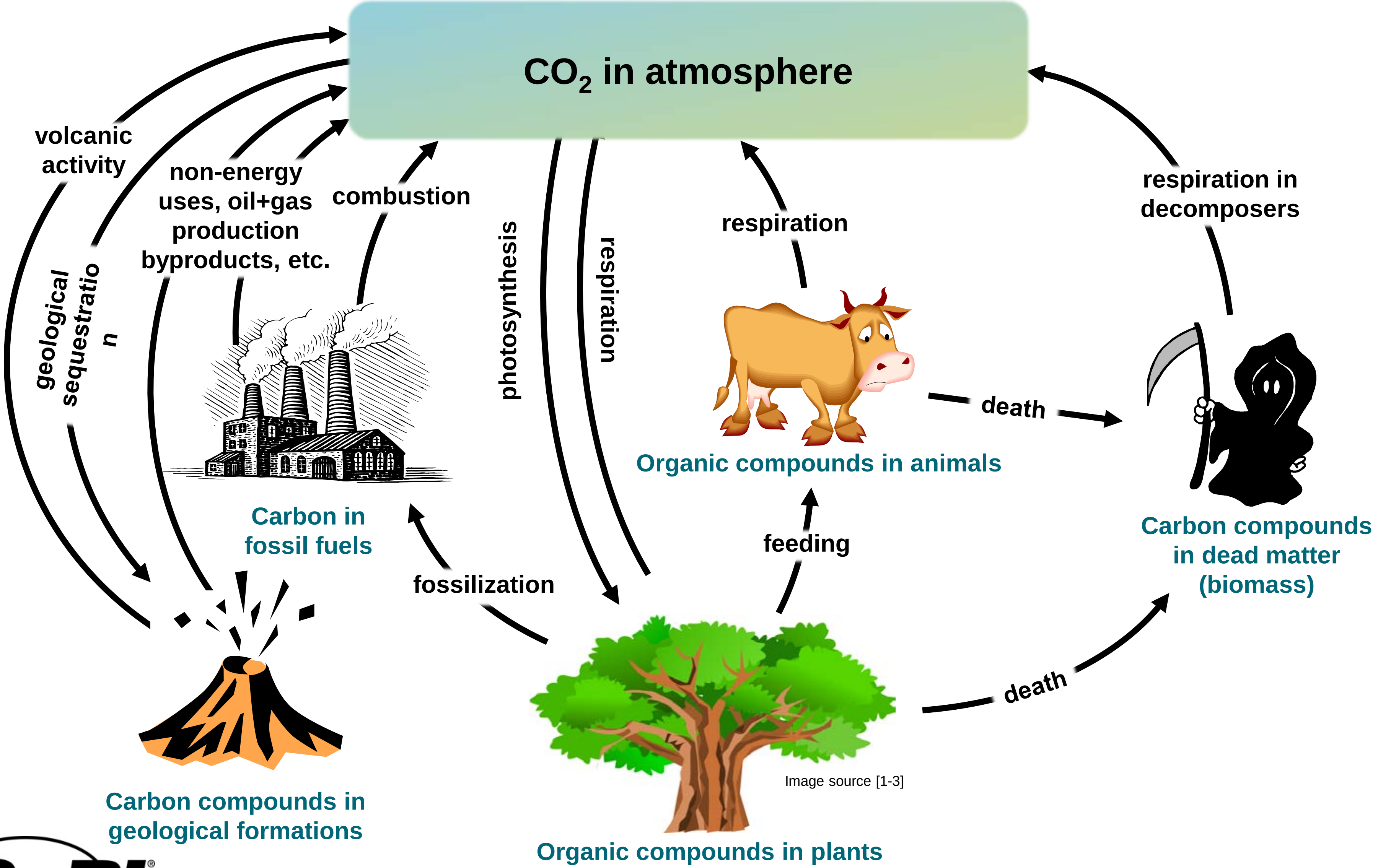


Image source [1-3]

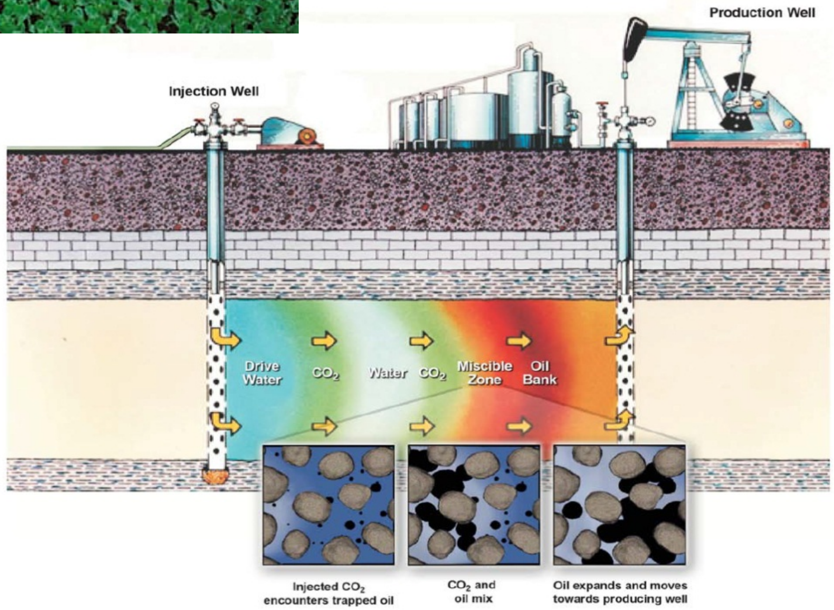
CO_2 has many industrial applications

Food & beverage

Agriculture

Welding (shield gas)

Oil & gas production (more info with S-CO_2)



Fire extin-guishers

Various image sources [1-4]

What is Supercritical CO_2?

The fluid critical point was discovered by Cagniard de la Tour using a pressure cooker

“Steam digester”
Invented by Denis Papin

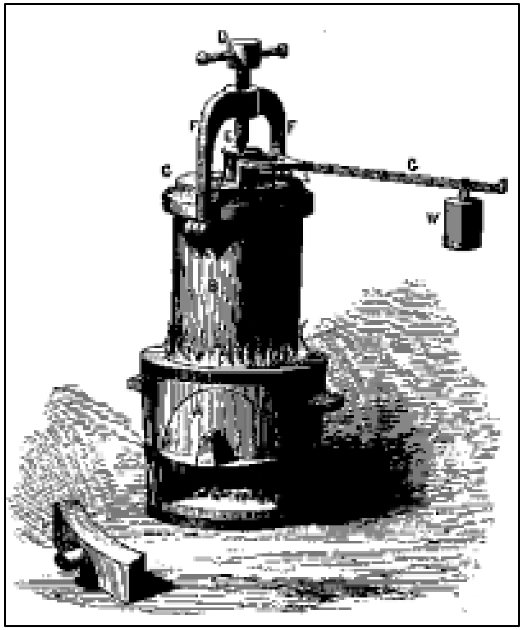


Image Source: [2-1]

Cagniard de la Tour (1777-1859)

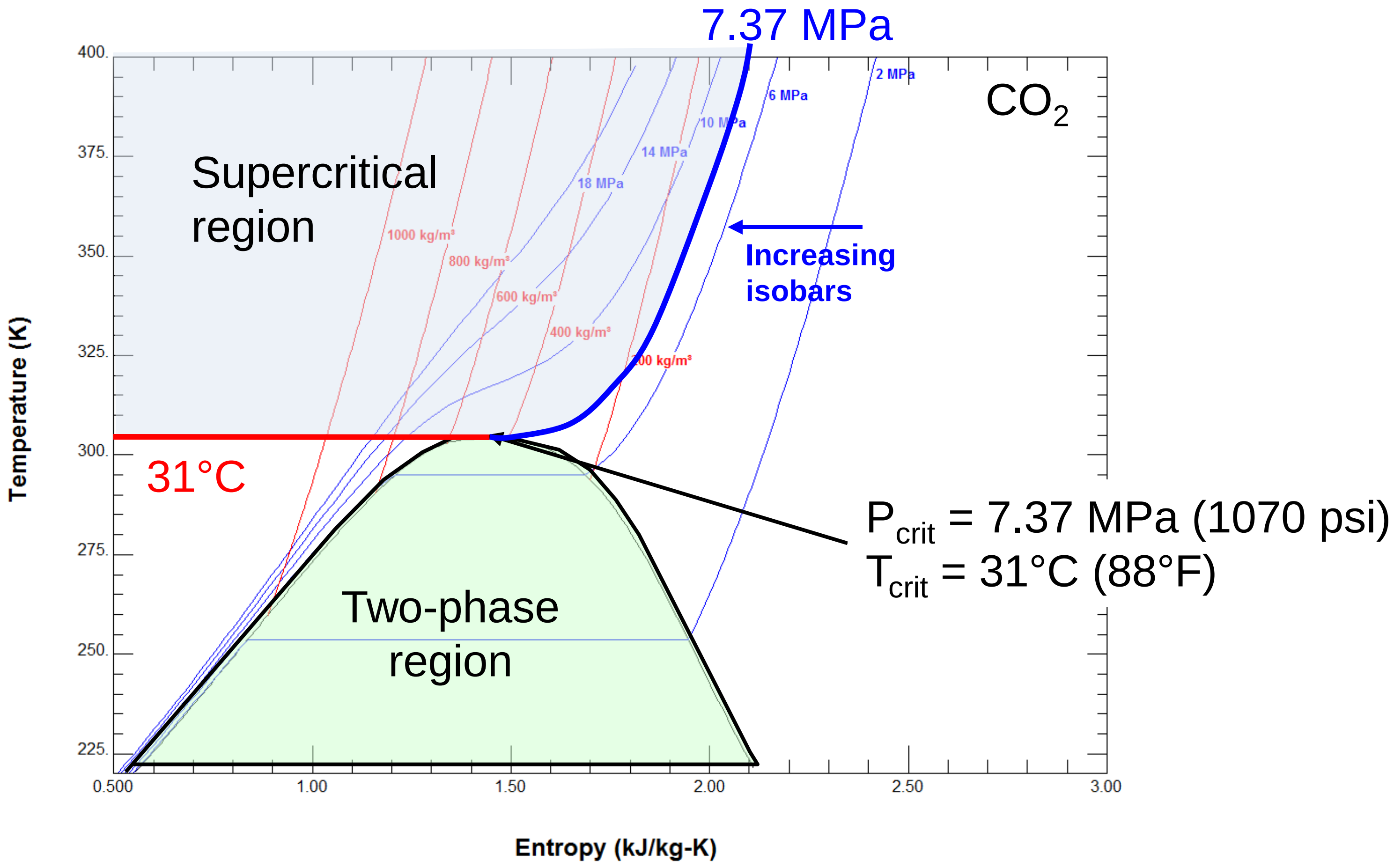
- Placed a flint ball in the digester filled with liquid such that rolling the digester produced a splashing sound
- The splashing sound stopped after heating much higher than the liquid boiling temperature
- Experiments with a sealed glass tube at constant pressure allowed observation of phase transformation
- Measured the critical temperature of alcohol, ether, and water

Berche et al. (2009)

Video of Supercritical CO_2

Image source: [2-2]

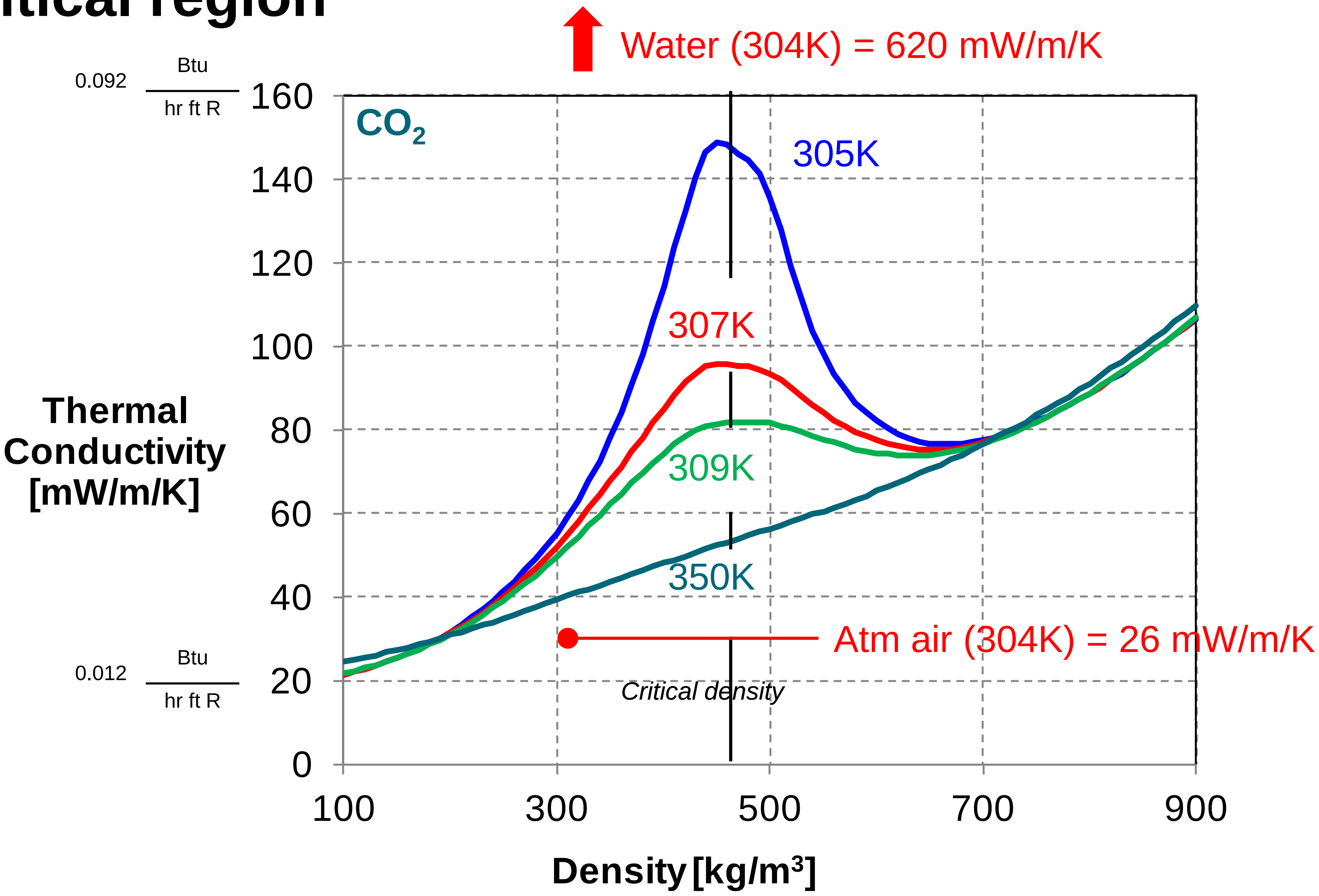
A fluid is supercritical if the pressure and temperature are greater than the critical values



P_{crit} = 7.37 MPa (1070 psi)
T_{crit} = 31°C (88°F)

REFPROP (2007), EOS CO$_2$: Span & Wagner (1996)

Fluid thermal conductivity is enhanced near the critical region

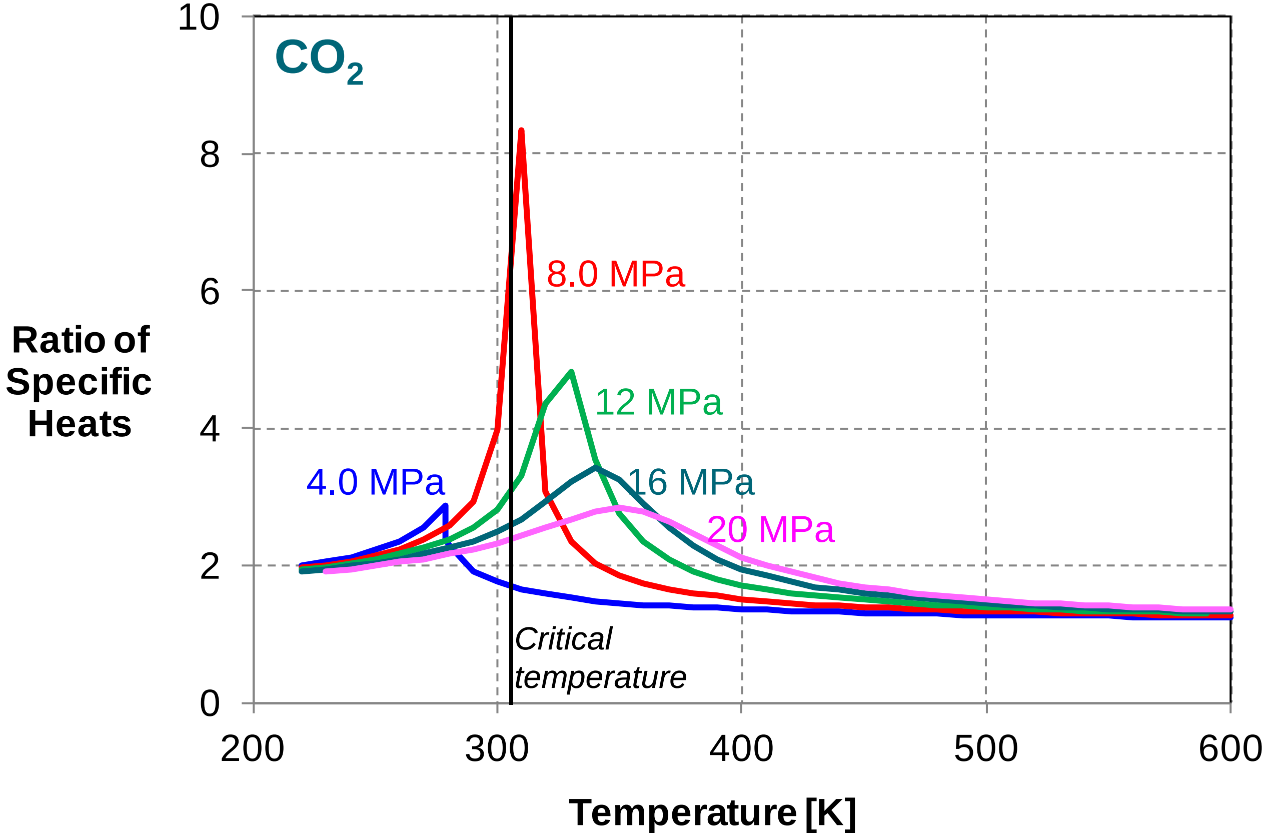


Water (304K) = 620 mW/m/K

Atm air (304K) = 26 mW/m/K

REFPROP (2007)

The ratio of specific heats peaks near the critical region



Air = 1.4

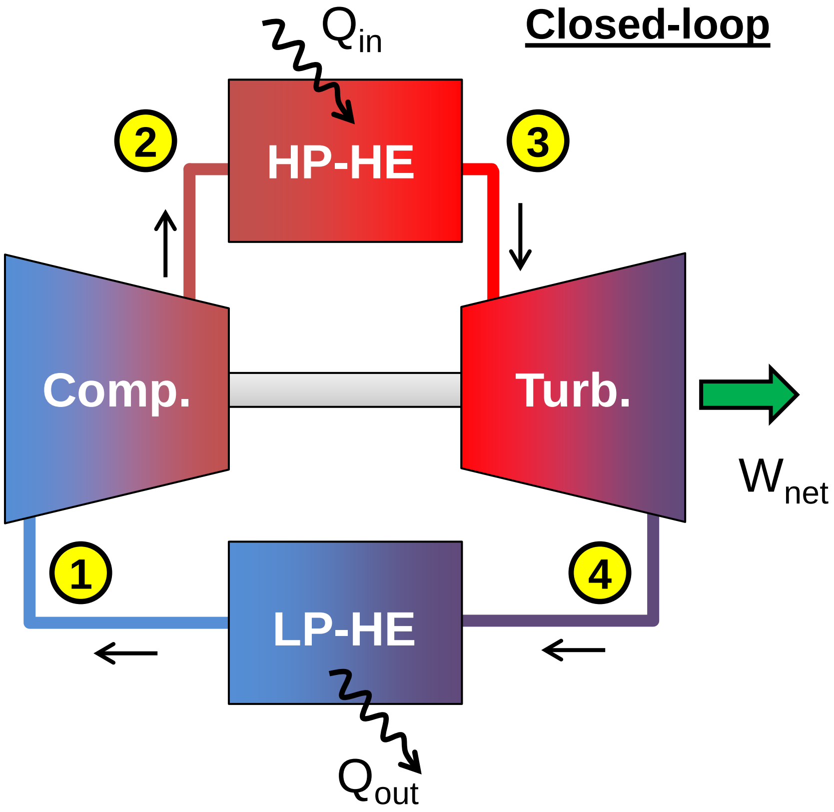
REFPROP (2007)

Power Cycle Basics

Power Cycle Basics Overview

- Carnot – “the standard”
- **Brayton – gas cycle**
- **Rankine – vapor cycle**
- Ideal vs. Actual
- Variations

Brayton Cycle (Ideal)

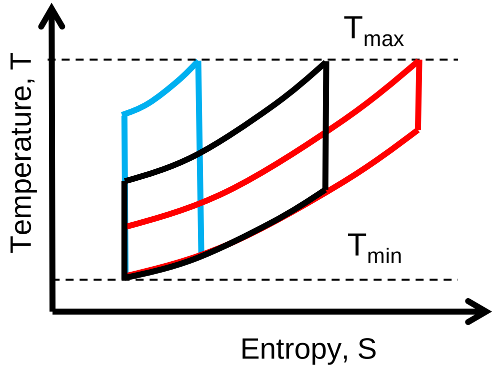


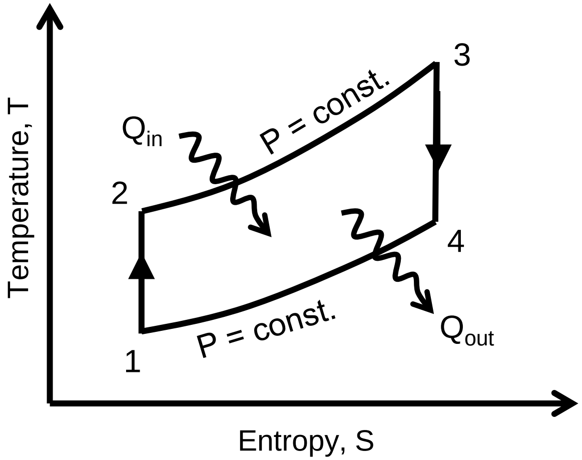
- ❑ Processes
  - (1-2) Isentropic compression
  - (2-3) Const. pres. heat addition
  - (3-4) Isentropic expansion
  - (4-1) Const. pres. heat reject.
- ❑ Open- or closed-loop

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

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

Optimal PR
for net work

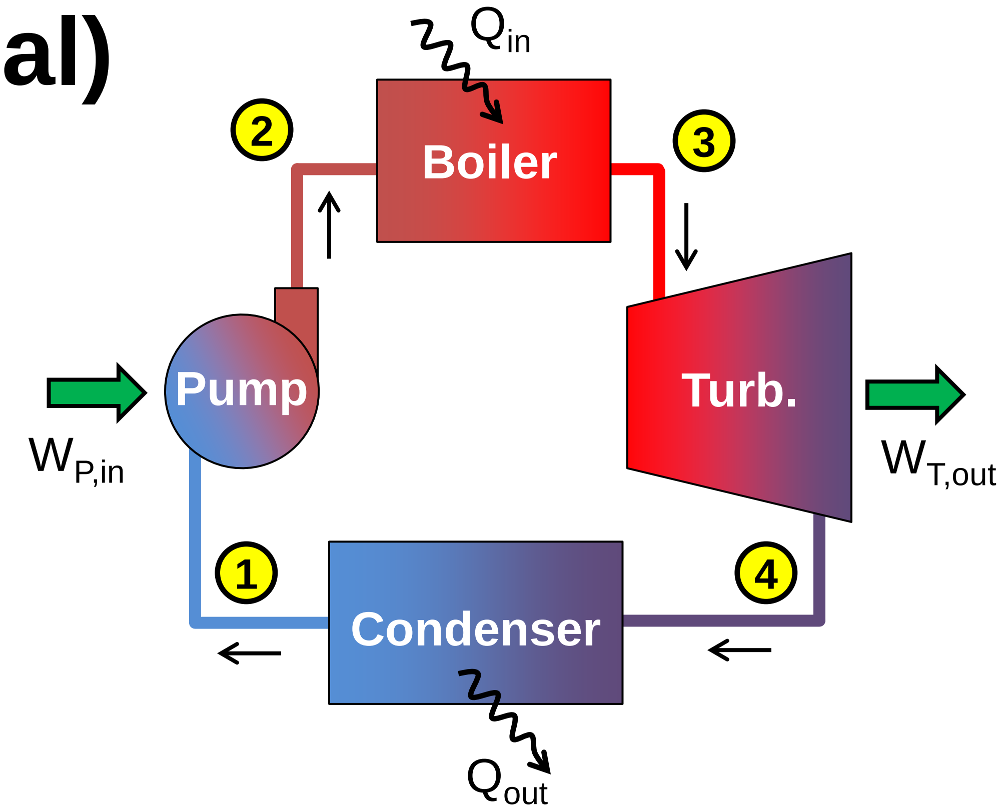


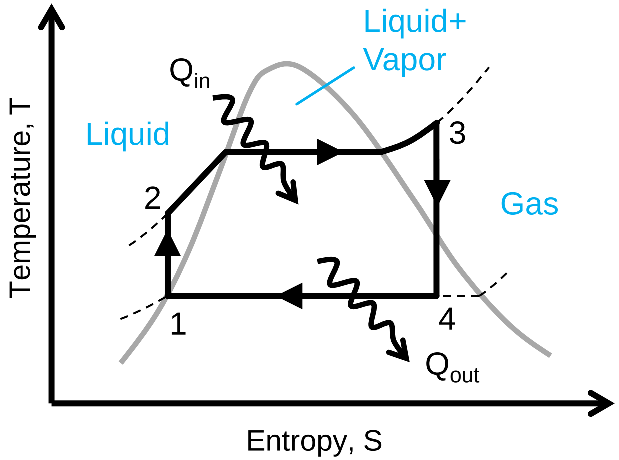


Rankine Cycle (Ideal)

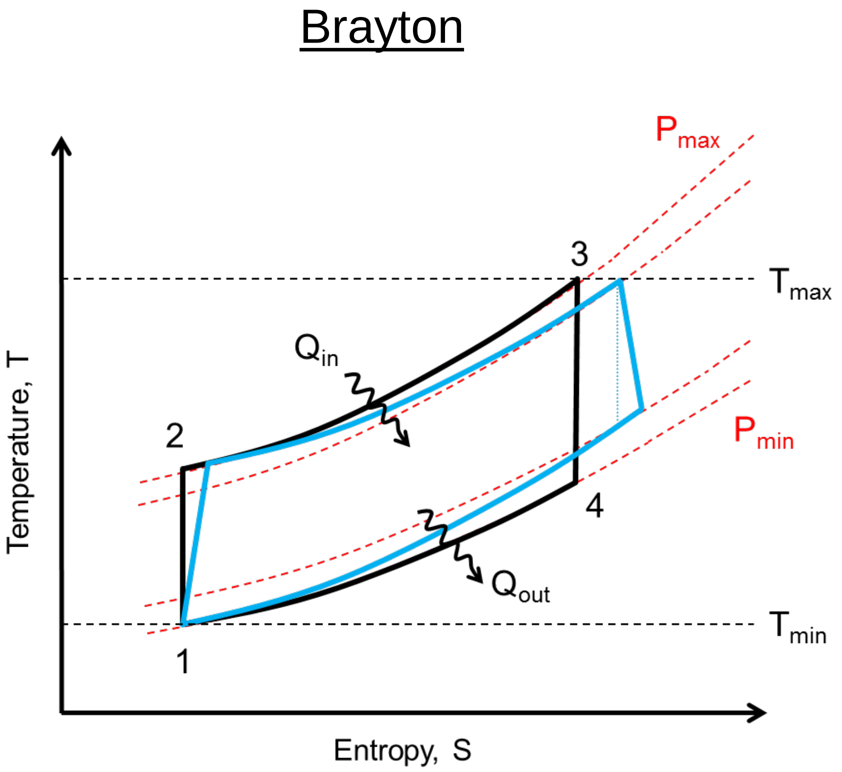
- ☐ Processes
  - (1-2) Isentropic compression
  - (2-3) Const. pres. heat addition
  - (3-4) Isentropic expansion
  - (4-1) Const. pres. heat reject.
- ☐ Same processes as Brayton; different hardware
- ☐ Phase changes
- ☐ E.g., steam cycle

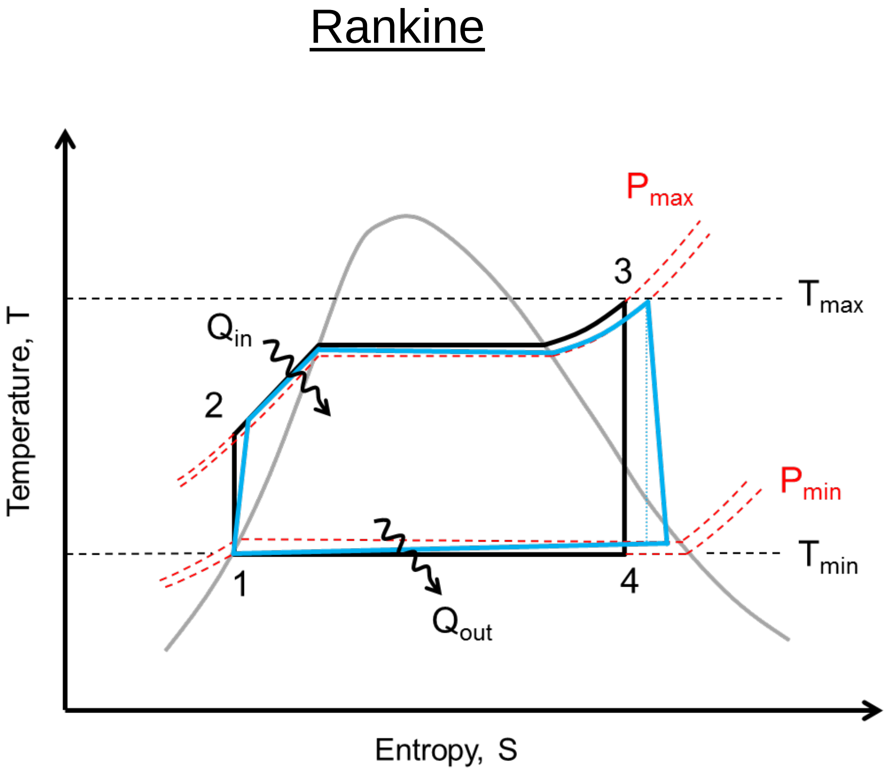
$$\eta_{th} = 1 - Q_{in}/Q_{out}$$





Ideal vs. Actual Processes





1-2, 3-4: Irreversibilities

2-3, 4-1: Pressure losses

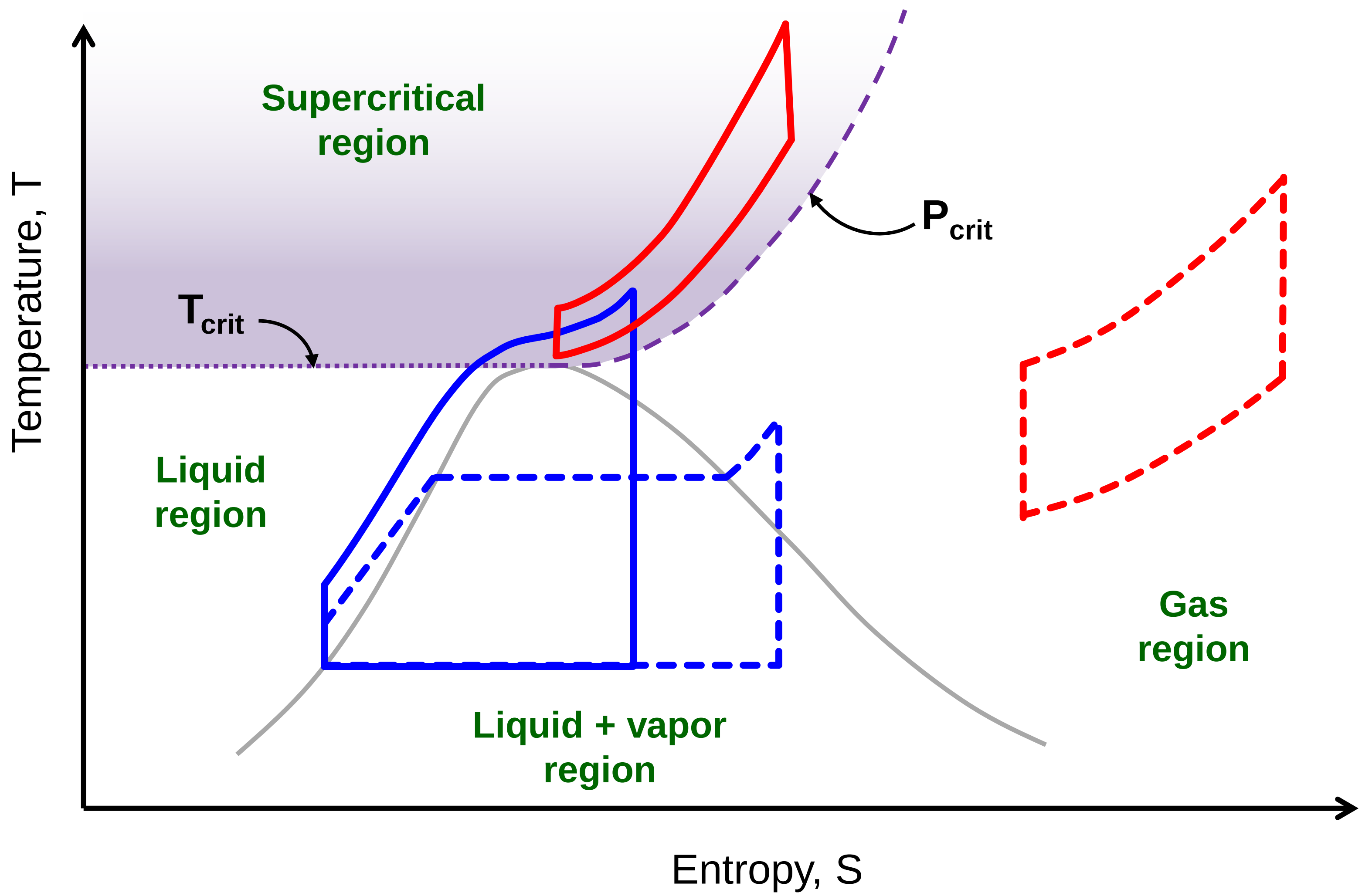
Power Cycle Variations

- ❑ Regeneration
- ❑ Intercooling
- ❑ Reheating
- ❑ Recompression

⋮

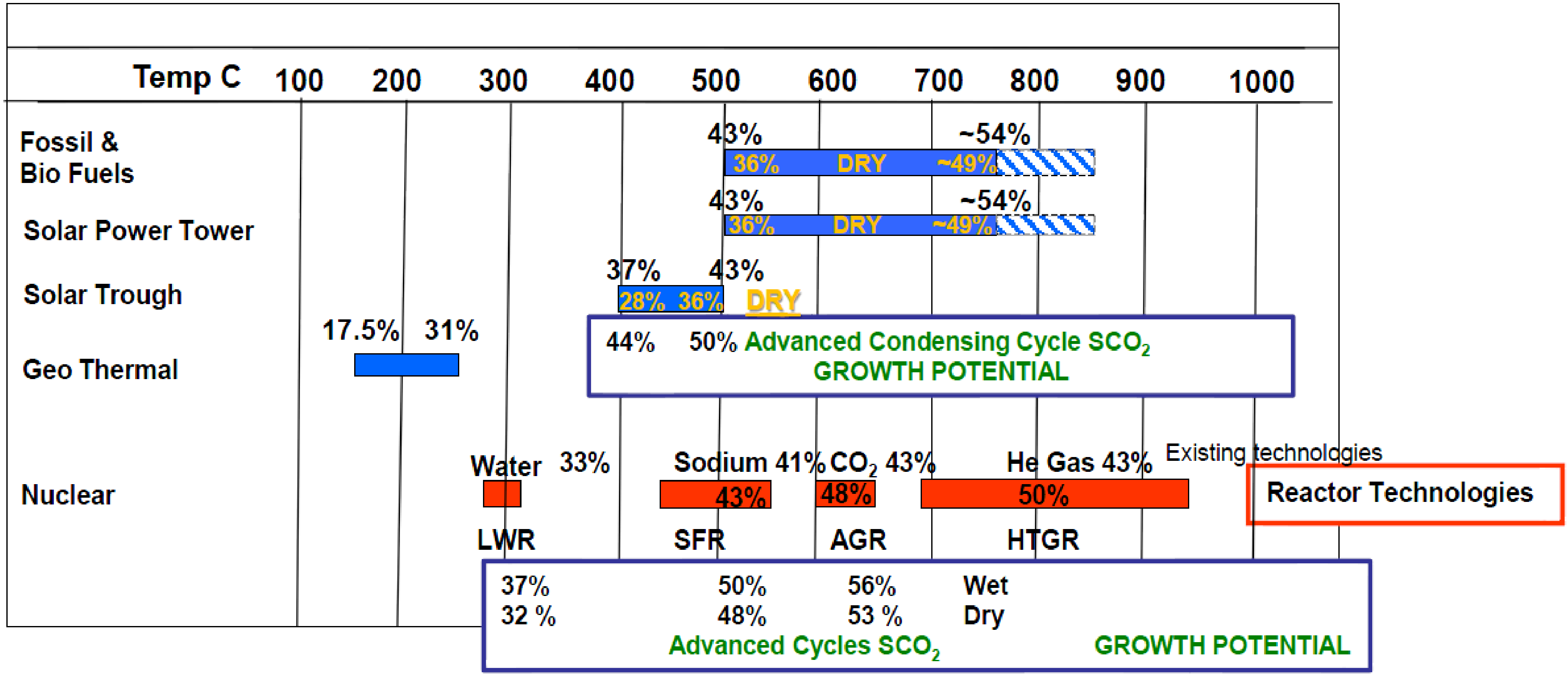
- ❑ What is supercritical power cycle?

What is a Supercritical Power Cycle?



S-CO_2 in Power Cycle Applications

Heat Source Operating Temperature Ranges & Efficiencies with S-CO_2



Assumptions (Turbomachinery Eff (85%/87%/90% : MC/RC/T), 5 K Approach T, 5% dp/p losses, Hotel Losses Not In Included, Dry Cooling at 120 F)

Source: Wright (2011)

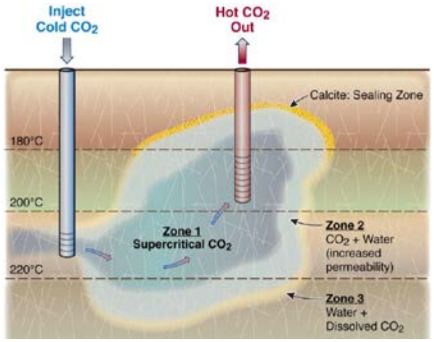
Supercritical CO_2 in Power Cycle Applications

[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

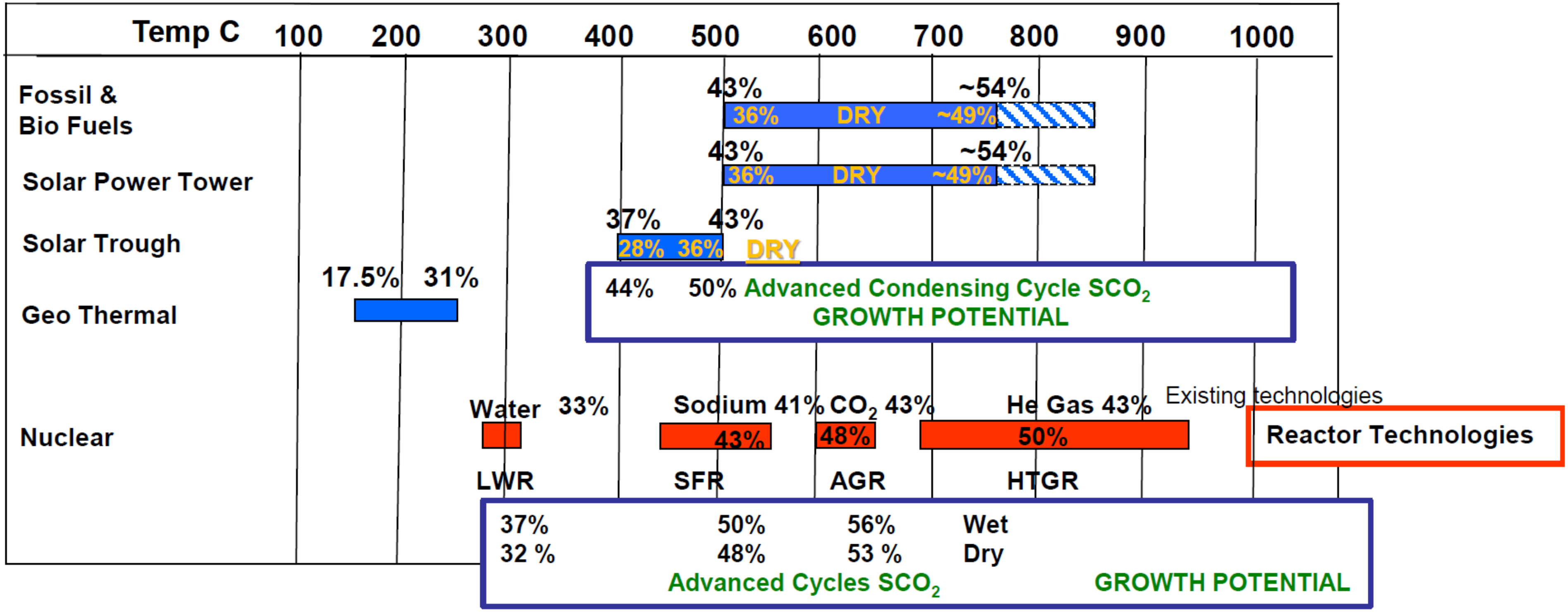
[6-4]

Nuclear

[6-5]

Ship-board Propulsion

Heat Source Operating Temperature Range & Efficiency



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

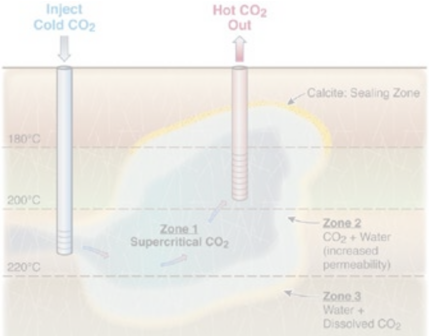
Supercritical CO_2 in Power Cycle Applications

[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

Nuclear

[6-5]

Ship-board Propulsion

S-CO$_2$: Solar Power Requirements (Sunshot Program)

- ☐ Effective Dry Cooling
- ☐ Thermal Energy Storage
- ☐ Affordable $.06/kWh
- ☐ Component Size

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.
- ❑ Currently
  - 5GW Worldwide
  - 1.8GW US

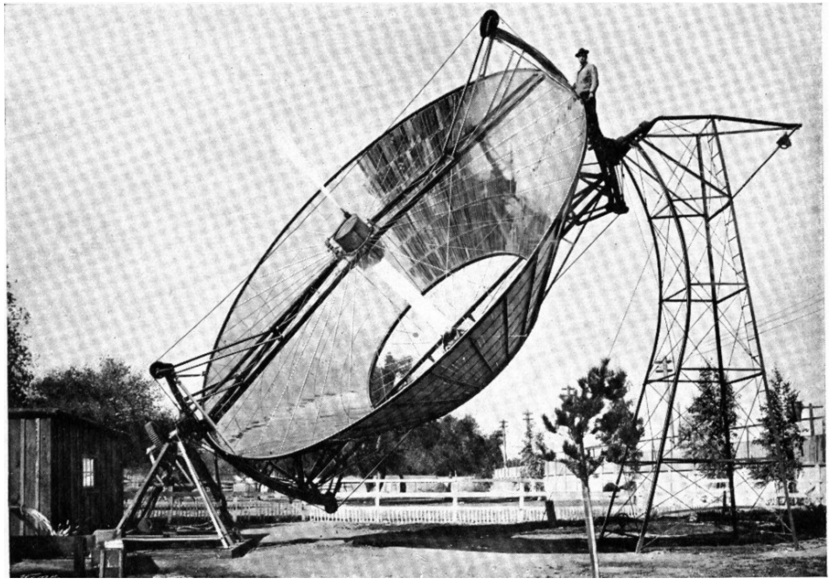


Image source: [6-6]

Image source: [6-7]

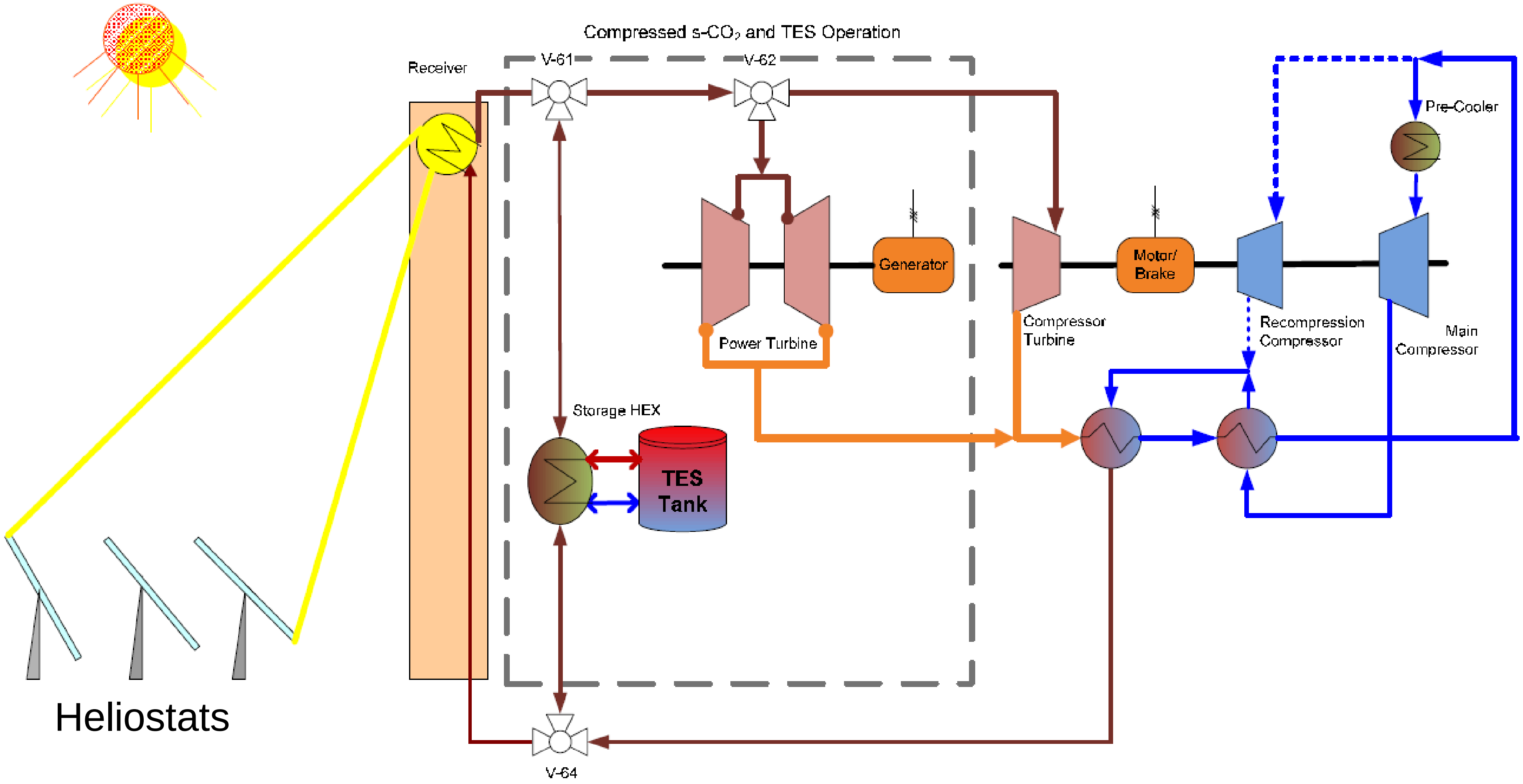
CSP – Improvement Opportunities

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

- Cooling
  - 650 gal H_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

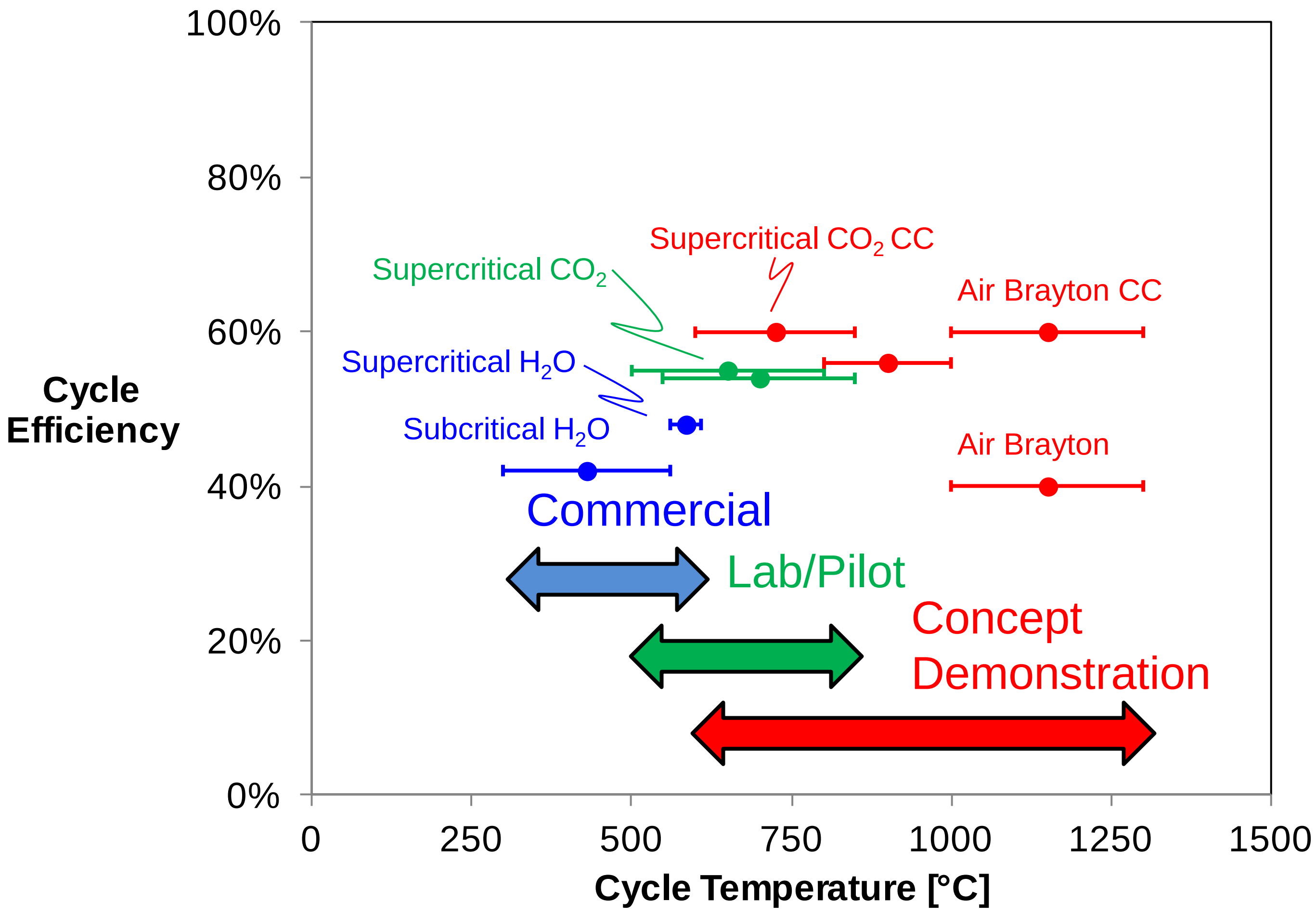
Image source: [6-1]

S-CO$_2$ CSP Process Diagram



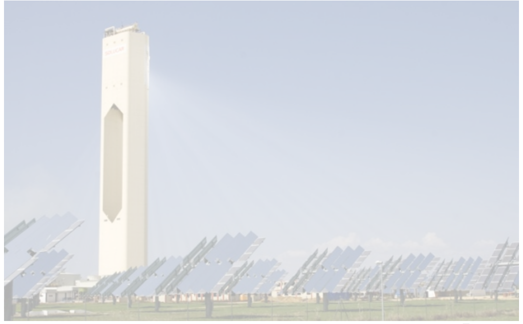
Dual-shaft, tower receiver S-CO$_2$ Brayton Cycle solar thermal power system with thermal energy storage, Zhiwen and Turchi (2011)

CSP Efficiencies vs. Power Cycle



Data from Stekli (2009)

Supercritical CO_2 in Power Cycle Applications

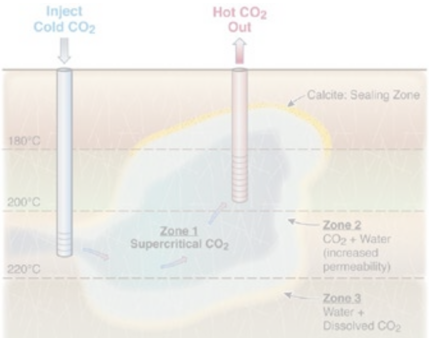


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

Nuclear

[6-5]

Ship-board Propulsion

S-CO_2: Nuclear Requirements

- ❑ Moderate temperature Reactors
- ❑ Affordability (less expensive reactors)
- ❑ Safe and Reliable

Rankine Cycle Application: Nuclear Power Generation

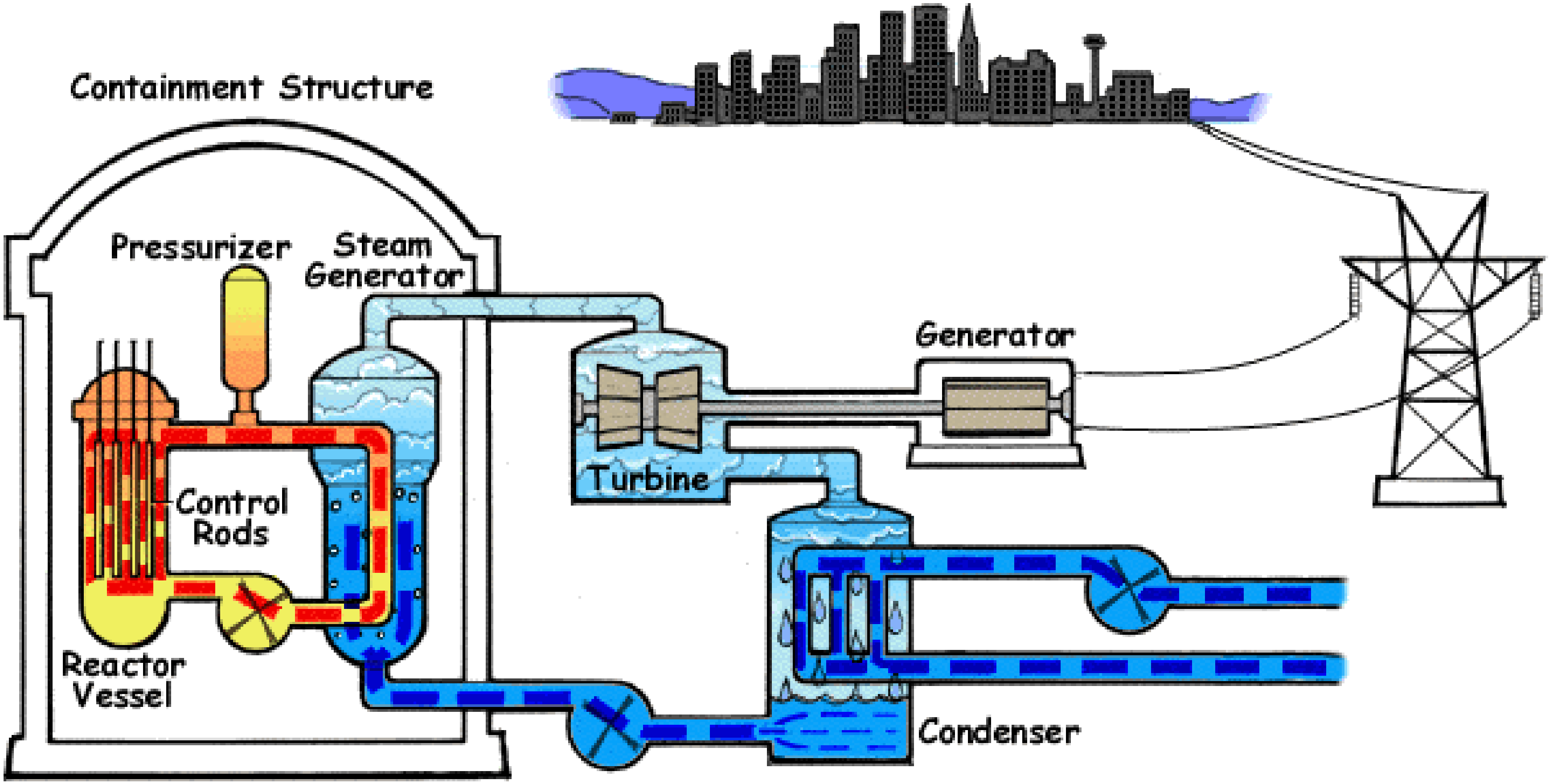


Image source: [6-8]

S-CO_2 for Nuclear Applications (550°C-700°C, 34 MPa)

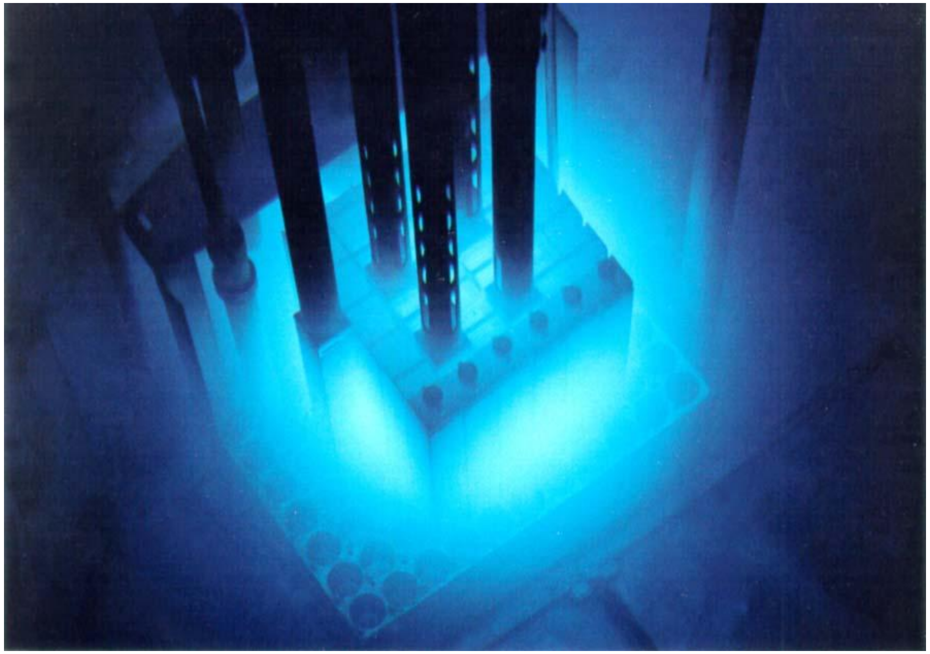
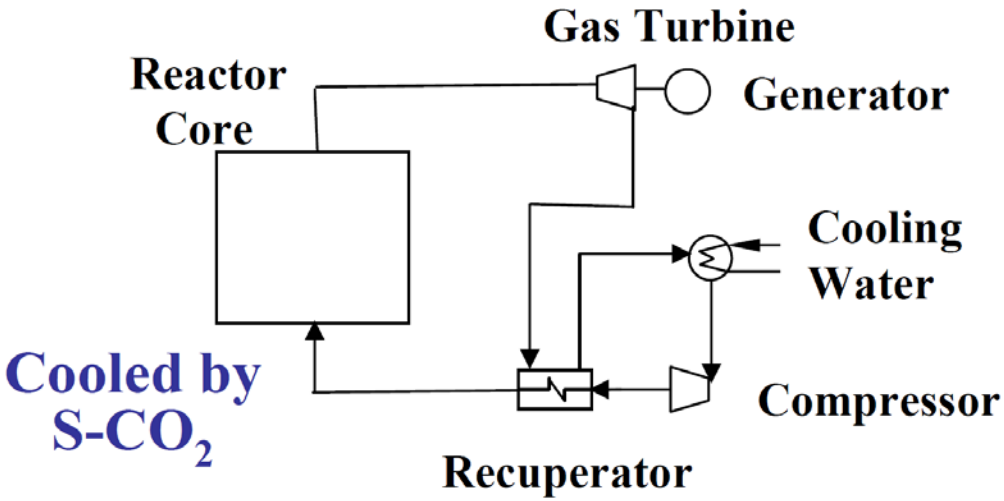


Image source: [6-9]

Image source: [6-4]

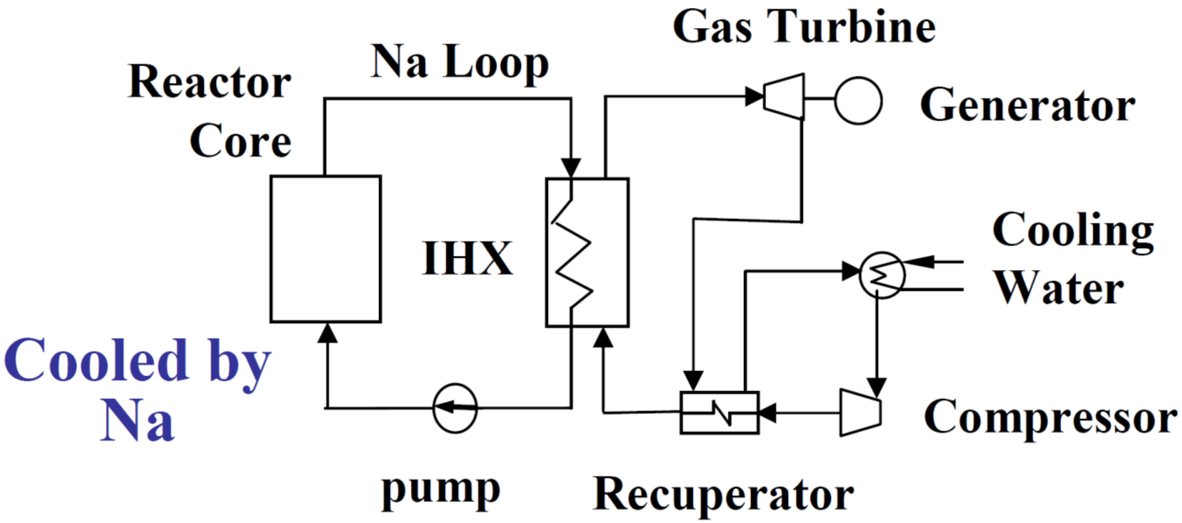
Proposed Nuclear S-CO_2 Cycles

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



Cooled by S-CO_2

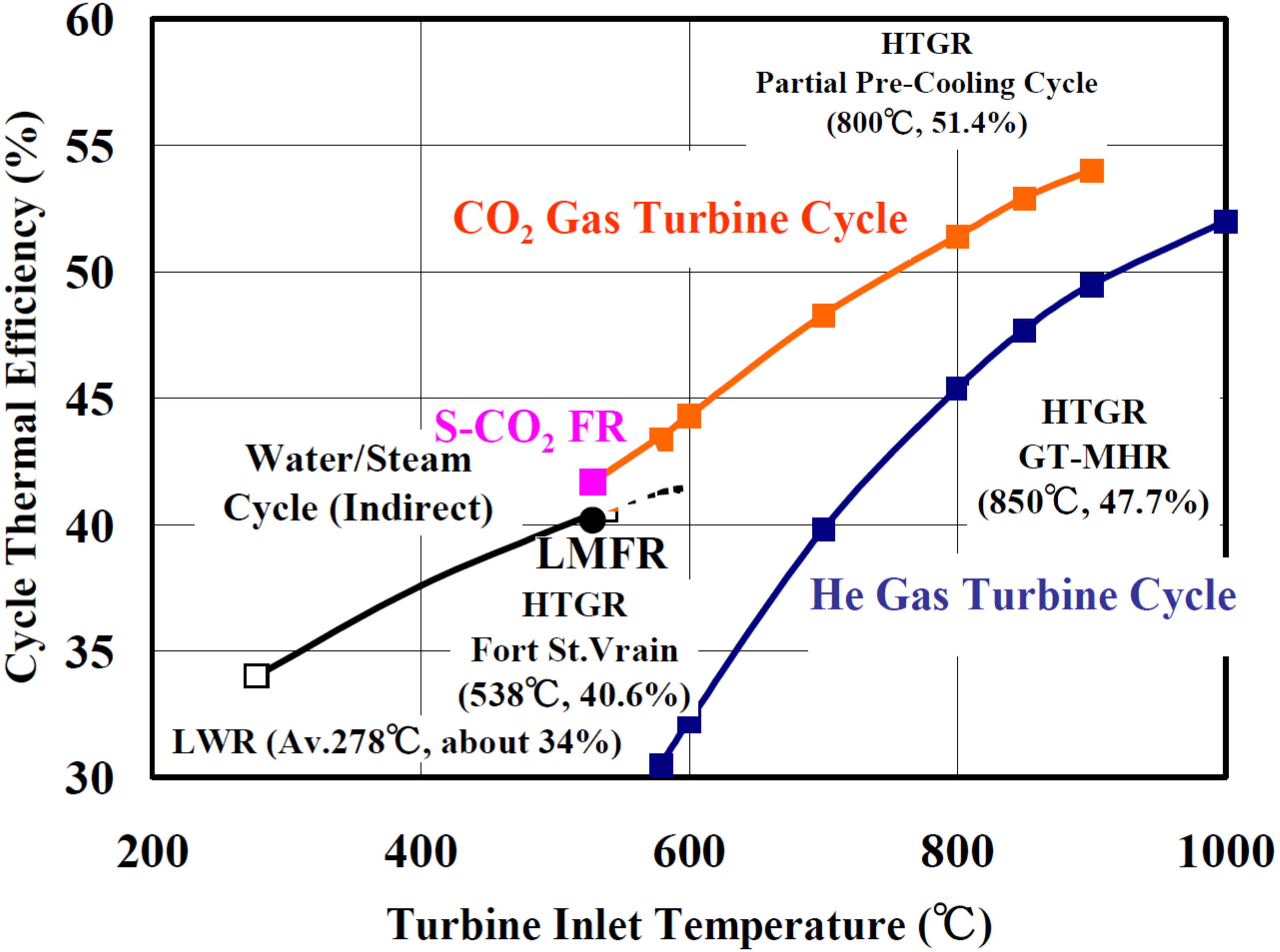
- ☐ Indirect Cycle
  - No secondary Na Loops
  - Smaller core size



Cooled by Na

Kato et al. (2007)

Nuclear Plant Efficiency vs. Cycle Prop.

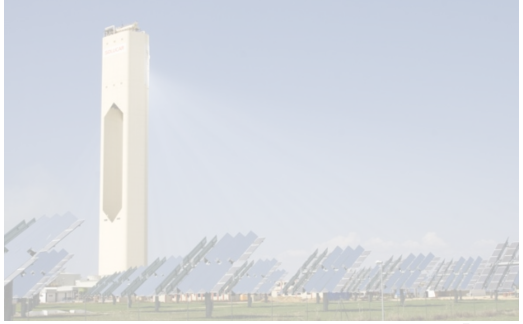


Kato et al. (2007)

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

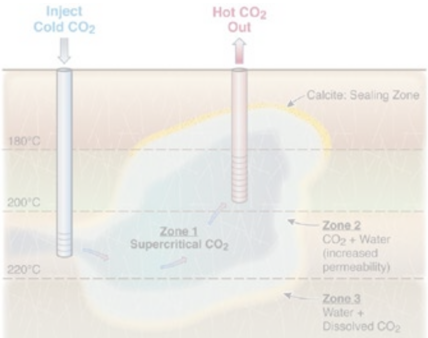


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

Nuclear

[6-5]

Ship-board Propulsion

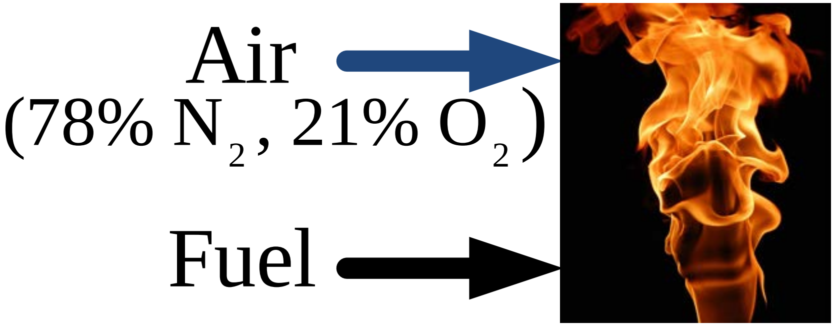
S-CO_2: Fossil Fuel Needs

❑ Emission Reduction (Sequestration)

❑ Affordability

Oxy-Fuel Combustion

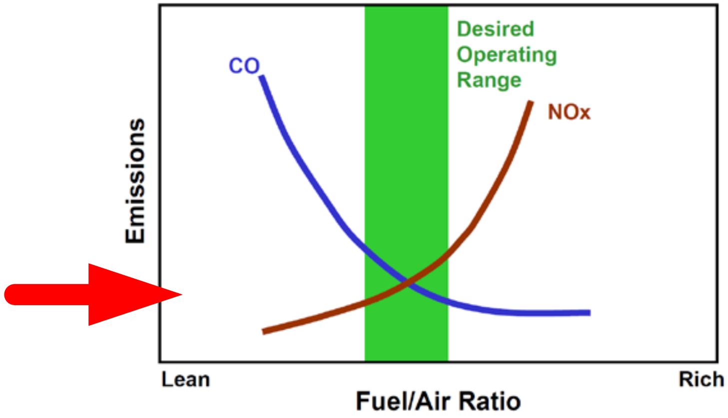
Conventional Combustion



Air

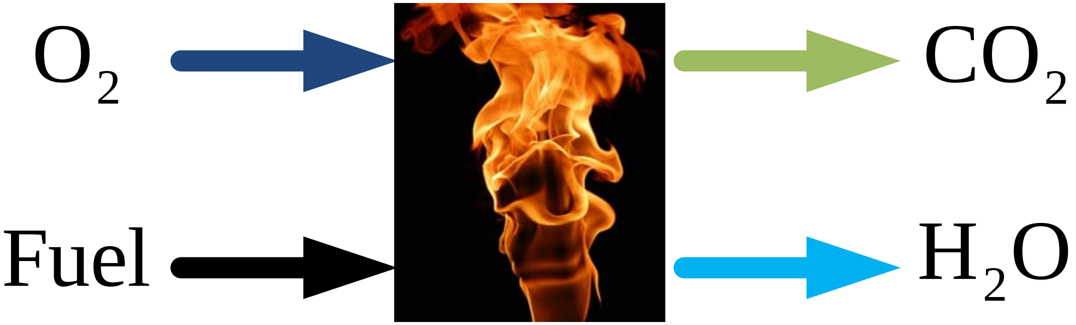
(78% N_2, 21% O_2)

Fuel



(Solar Turbines 2012)

Oxy-Fuel Combustion



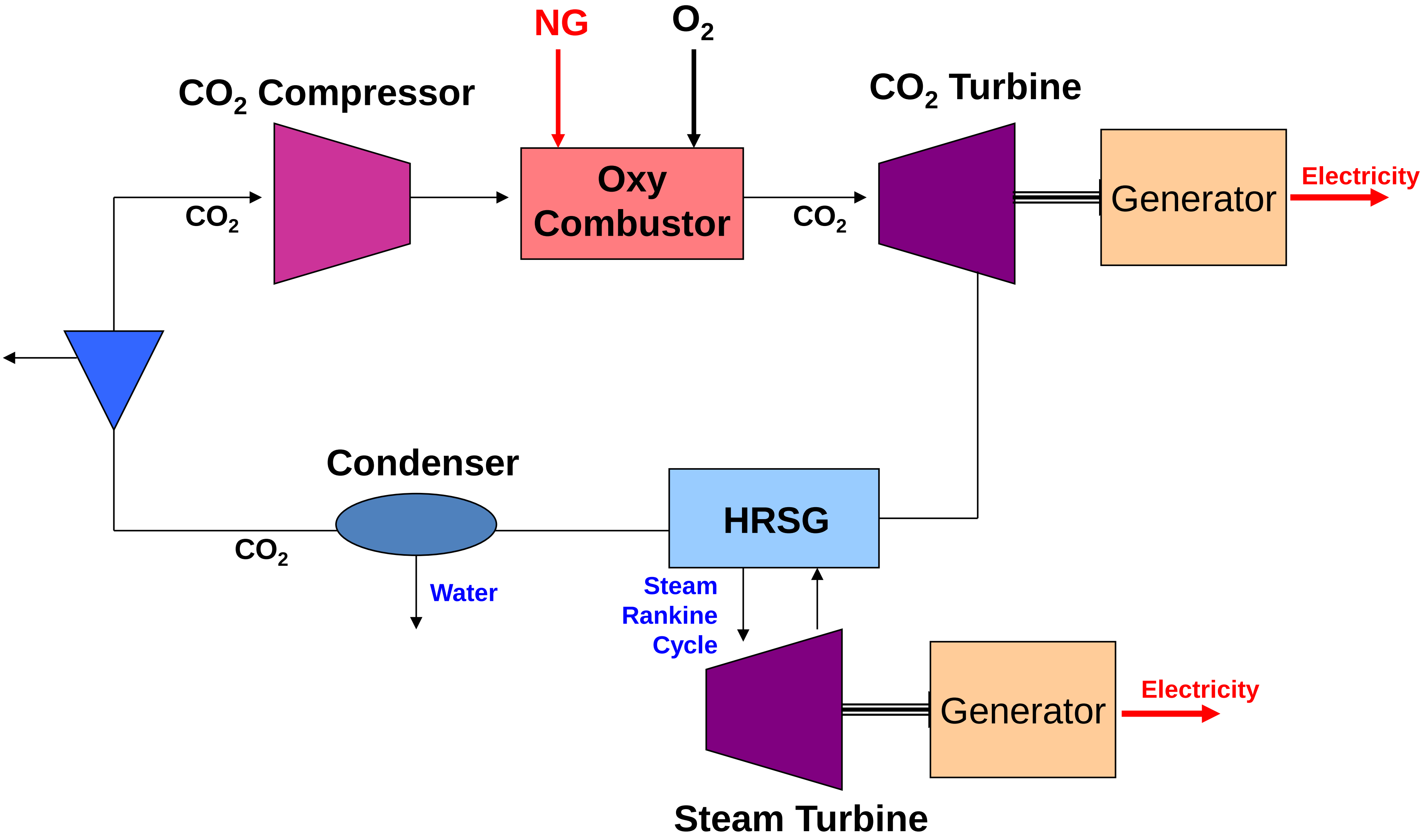
O_2

Fuel

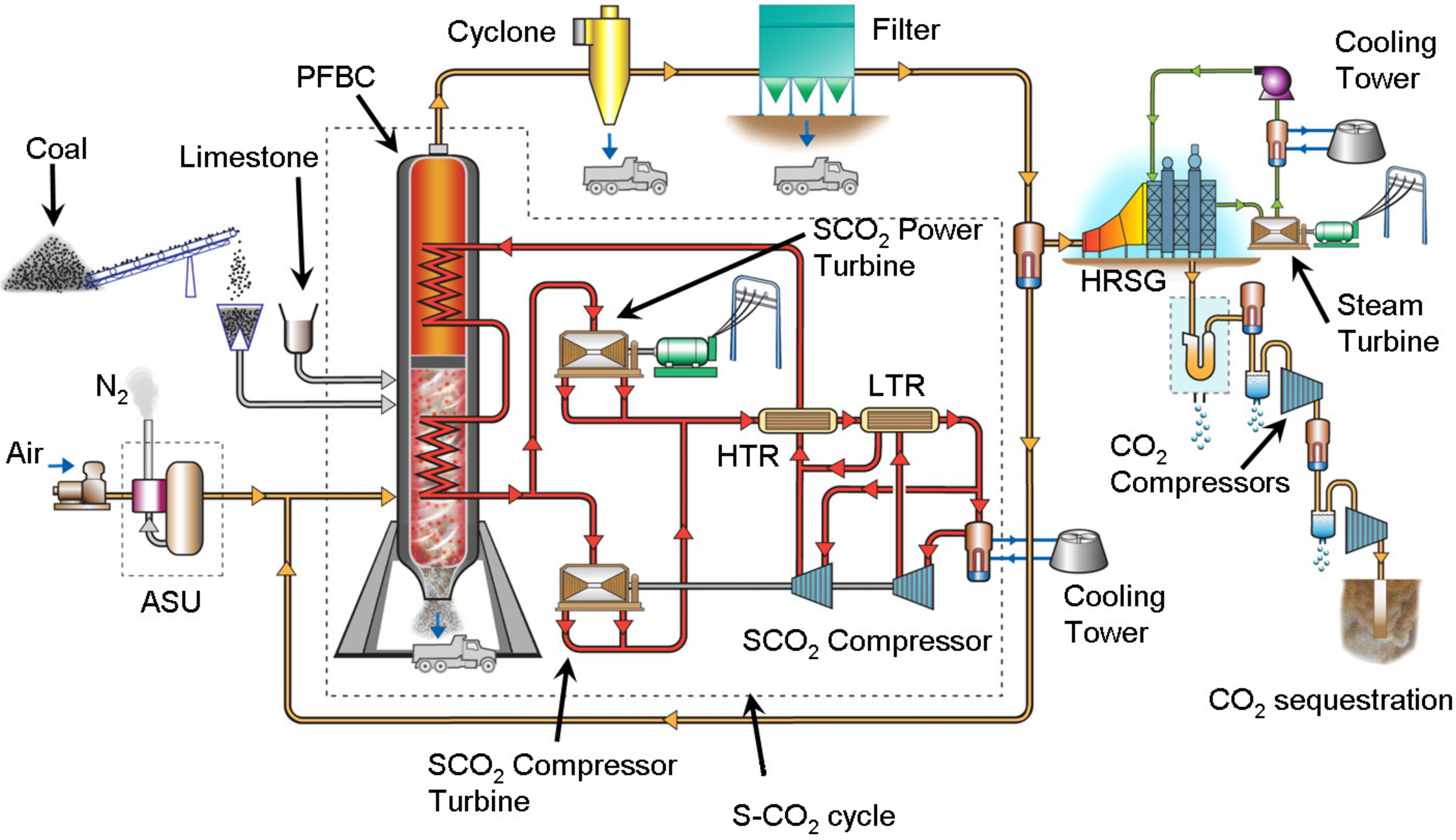
CO_2

H_2O

Direct Oxy-Fuel Combustion

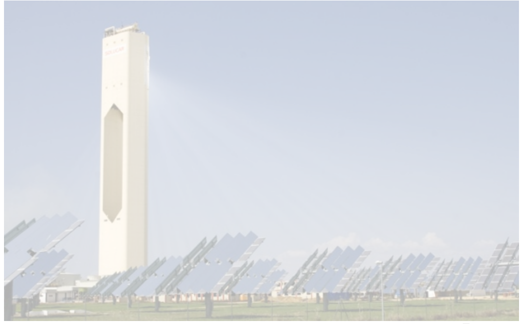


Indirect Oxy-Fuel Combustion



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

Supercritical CO_2 in Power Cycle Applications

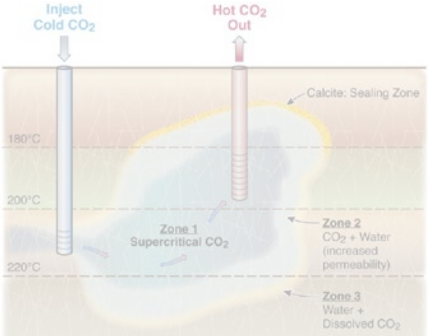


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

Nuclear

[6-5]

Ship-board Propulsion

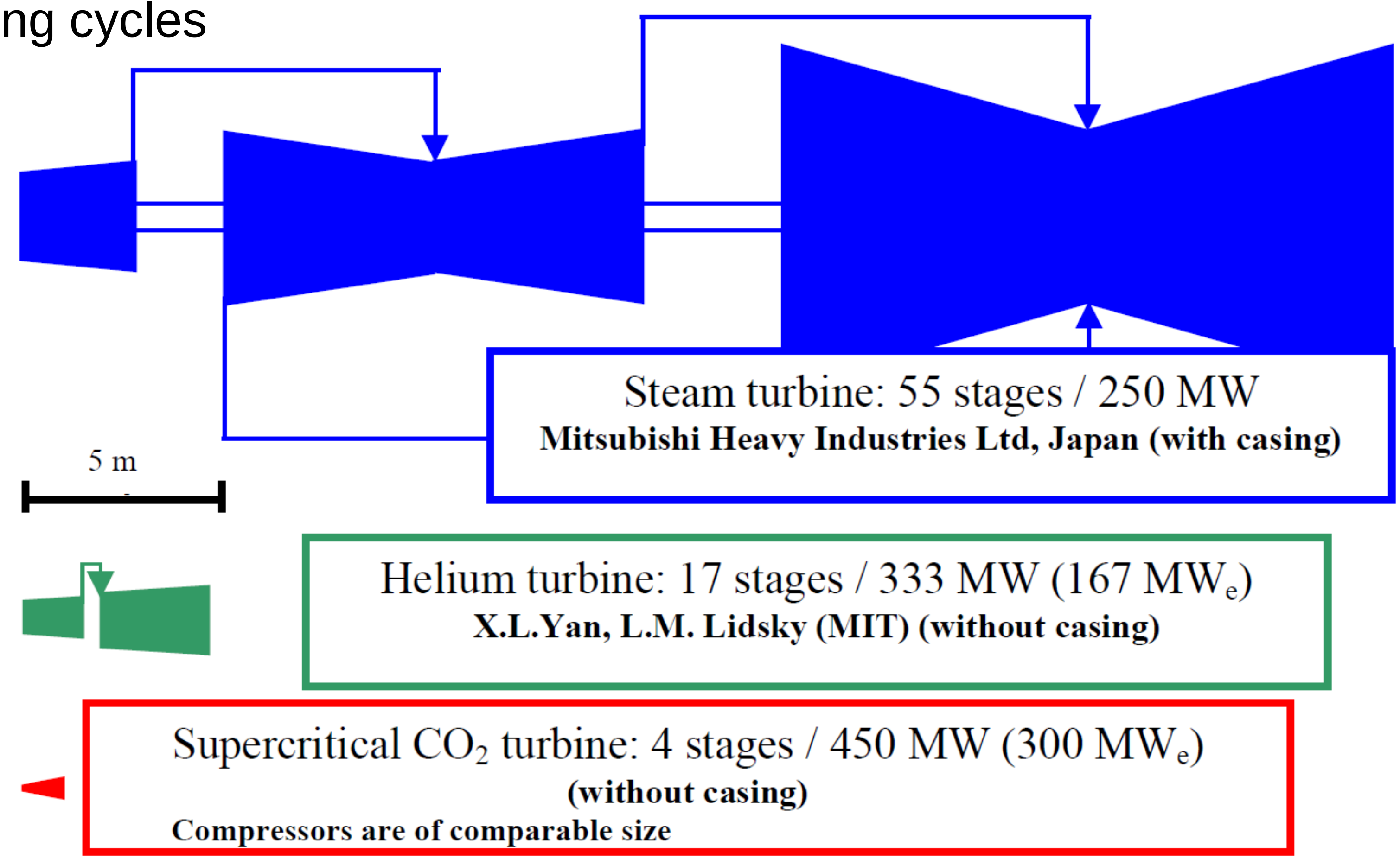
S-CO_2: Ship-board Propulsion

- ☐ Size
- ☐ Weight
- ☐ Efficiency
- ☐ Speed

Ship-board Propulsion

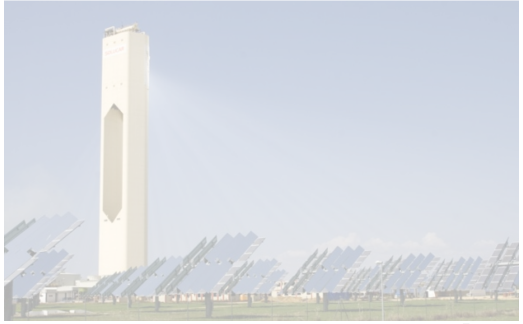
- ☐ Nuclear S-CO_2 cycles?
- ☐ No implementations yet
- ☐ Improved power to weight
- ☐ Rapid startup
- ☐ Bottoming cycles

Image source: [6-10]



Source: Dostal (2004)

Supercritical CO_2 in Power Cycle Applications

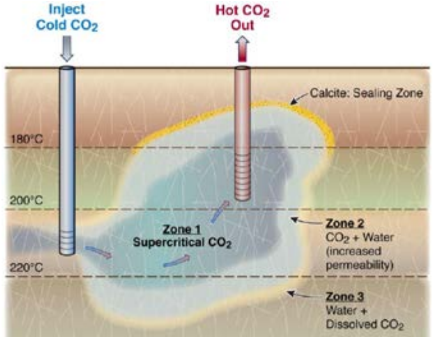


[6-1]

Concentrated Solar Power

[6-2]

Fossil Fuel



[6-3]

Geothermal

[6-4]

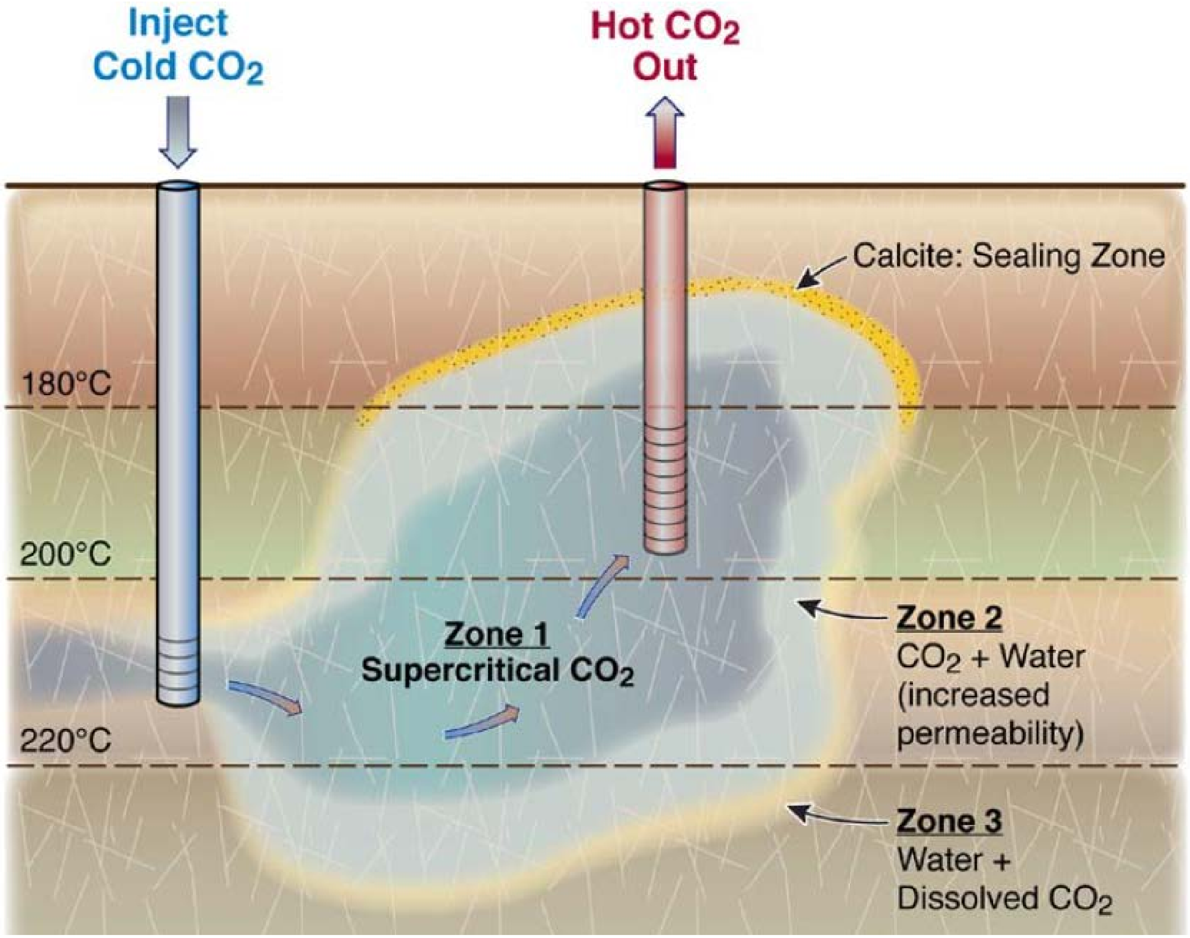
Nuclear

[6-5]

Ship-board Propulsion

Geothermal

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

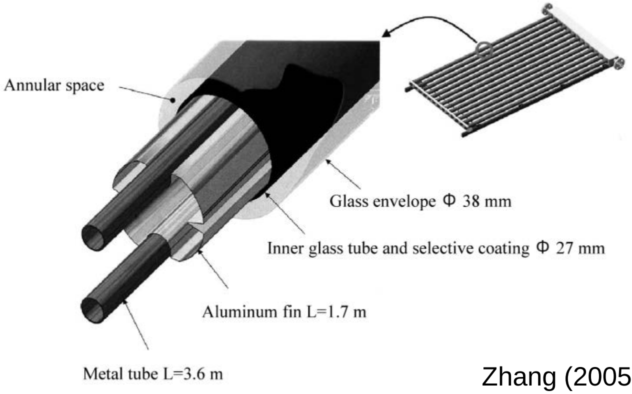


Pruess (May 19, 2010)

Other S-CO_2 Power Cycle Applications

Image source: [6-11]

Waste Heat
Recovery



Zhang (2005)

Non-Concentrated
Solar Power

Waste Heat Recovery (Bottoming)

- Rankine Cycle Description
  1. Liquid CO_2 is pumped to supercritical pressure
  2. S-CO2 accepts waste heat at recuperator and waste heat exchanger
  3. High energy S-CO_2 is expanded at turbo-alternator producing power
  4. Expanded S-CO_2 is cooled at recuperator and condensed to a liquid at condenser

Image source: [6-11]

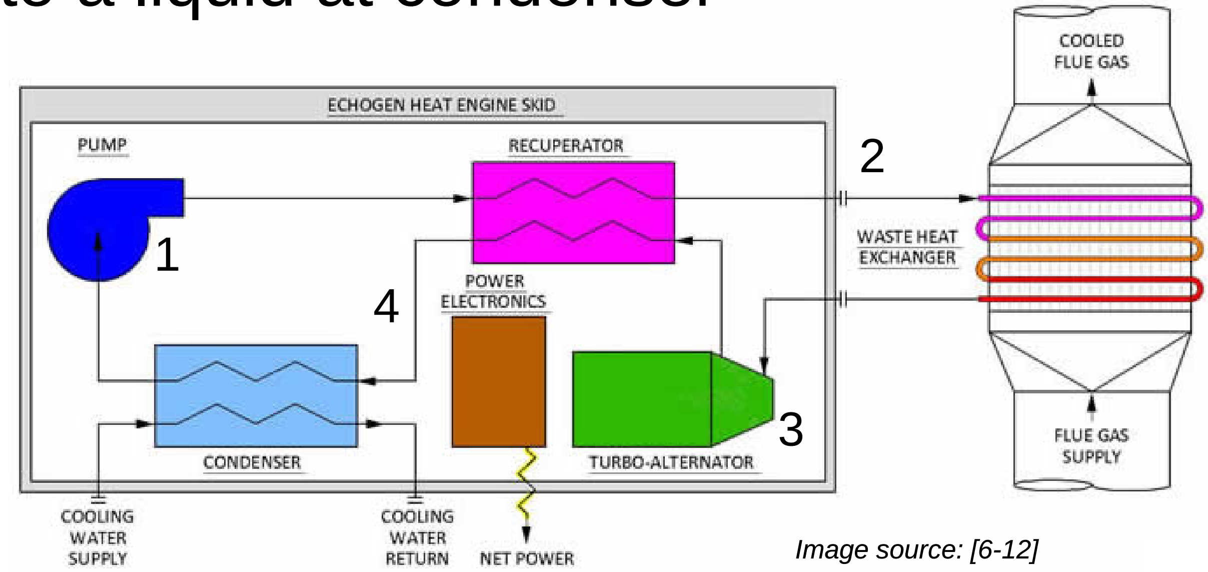
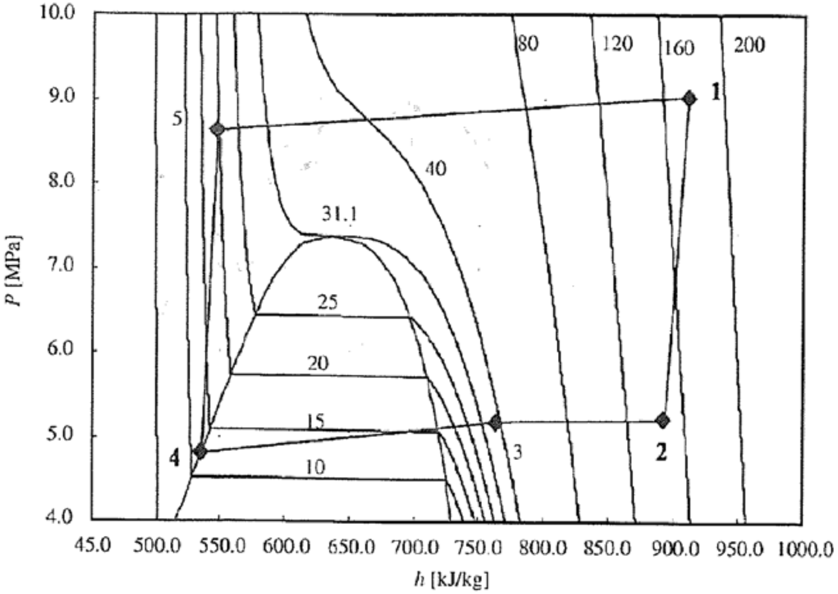


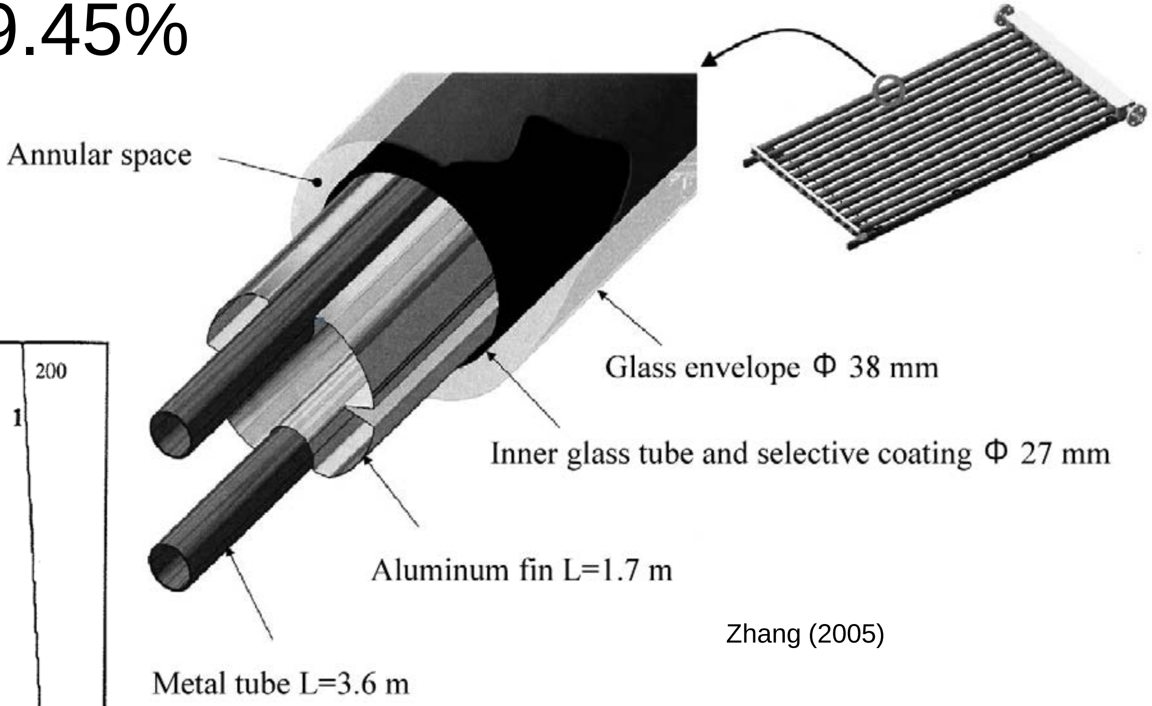
Image source: [6-12]

S-CO$_2$ 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 (2007)



Zhang (2005)

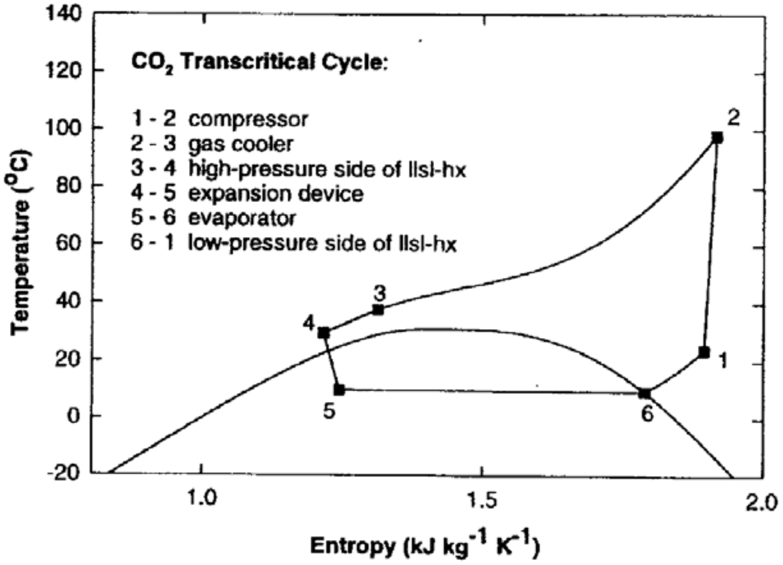
S-CO_2 as a Refrigerant

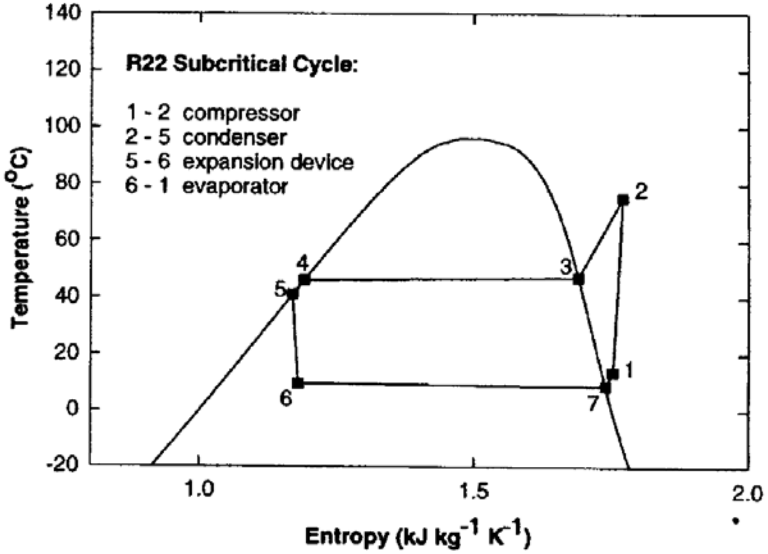
Image source: [6-13]

Image source: [6-14]

S-CO_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)

S-CO_2 in Heat Pumps

- ❑ S-CO_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)

$S\text{-}CO_2$ Power Cycle

Research Efforts

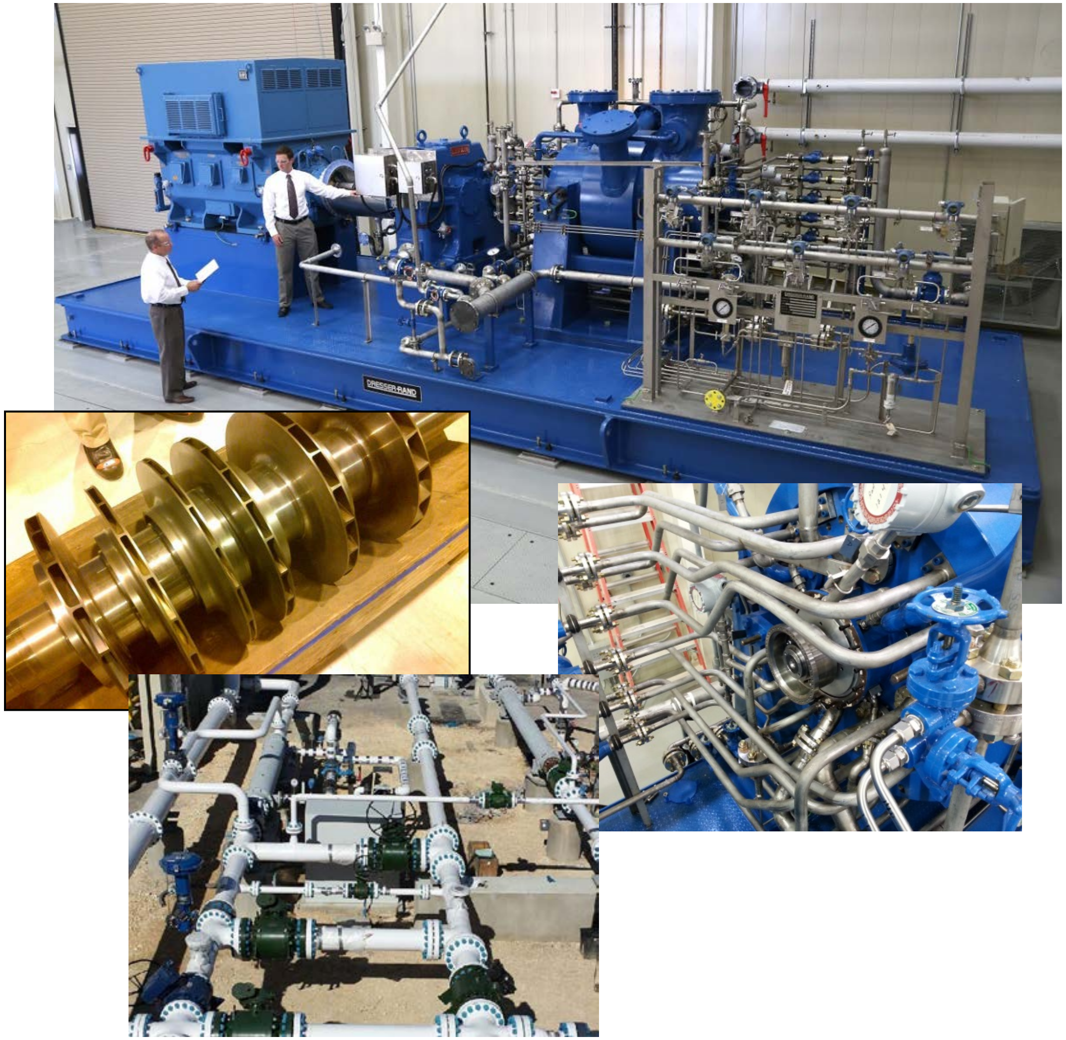
SwRI Machinery Program Projects Supporting sCO2 Power Cycle and Component Development

Machinery Program
sCO2 Related Projects

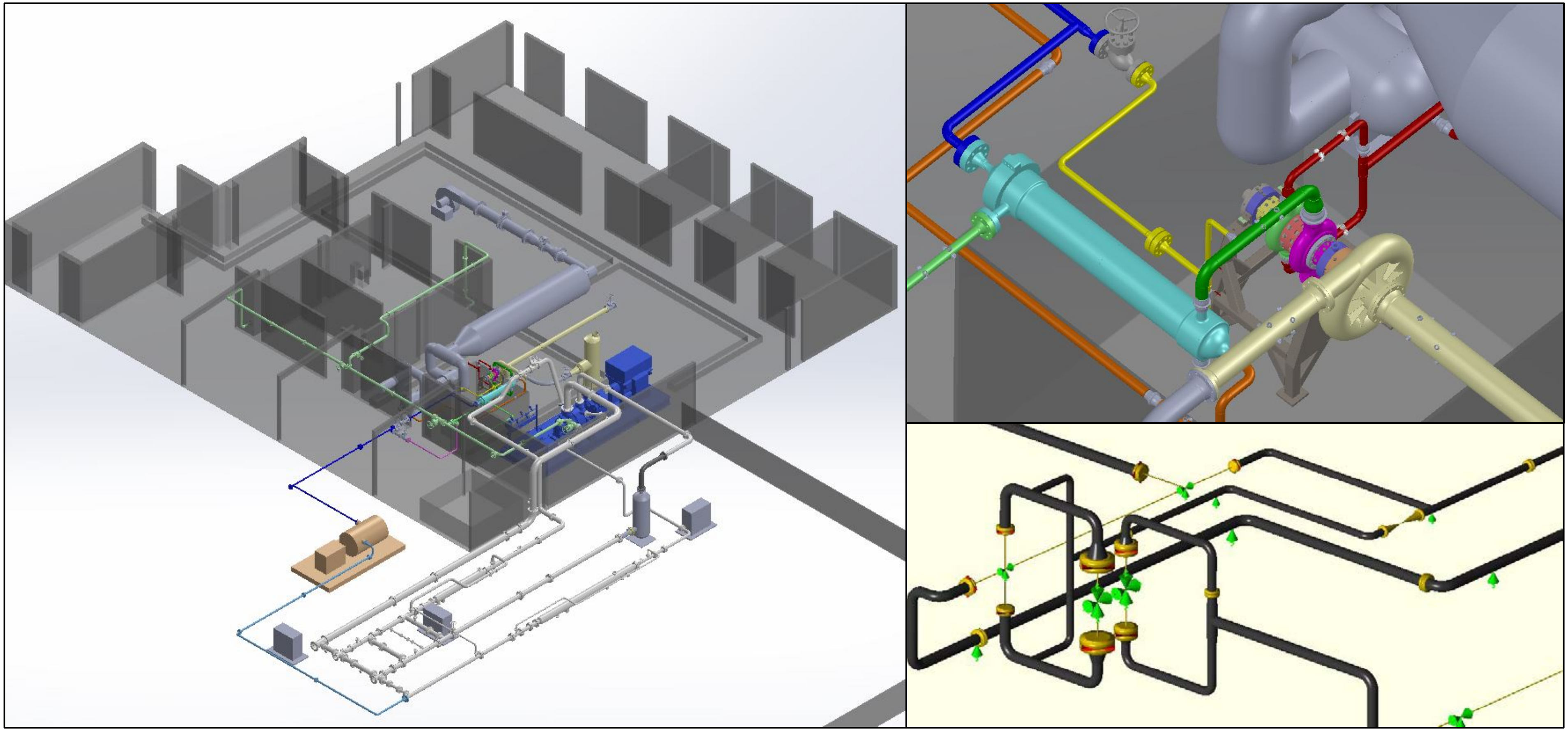
- ☐ CO2 Pipeline Pulsation Analysis and Mitigation
- ☐ Novel Concepts for the Compression of Large Volumes of CO2 (FC26-05NT42650)
- ☐ Development of a High Efficiency Hot Gas Turbo-Expander and Low Cost Heat Exchangers for Optimized CSP Supercritical CO2 Operation (DE-EE0005805)
- ☐ Novel Supercritical Carbon Dioxide Power Cycle Utilizing Pressurized Oxy-combustion In Conjunction With Cryogenic Compression (DE-FE0009395)
- ☐ Electrothermal Energy Storage with A Multiphase Transcritical CO2 cycle (DE-AR0000467)
- ☐ Physics-Based Reliability Models for Supercritical CO2 Turbomachinery Components (DE-FOA-0000861, PREDICTS)
- ☐ Utility-Scale sCO2 Turbomachinery and Seal Test Rig Development (DE-FOA-0001107)
- ☐ High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion (DE-FE0024041)
- ☐ High Temperature, High Pressure Compact Heat Exchanger Development (DE-FOA-0001095)
- ☐ Development of a Thin Film Primary Surface Heat Exchanger for Advanced Power Cycles (DE-FOA-0001095)
- ☐ High-Pressure Gas Property Measurements

DOE CO_2 Compression Project
Development of Isothermal Compression

- Pilot-scale demonstration of an internally cooled compressor design
- Isothermal compressor and liquefaction / CO_2 pump equipment design
- Thermodynamic analysis of CO_2 separation, compression, and transport
- CO_2 liquefaction loop for proof of concept demonstration



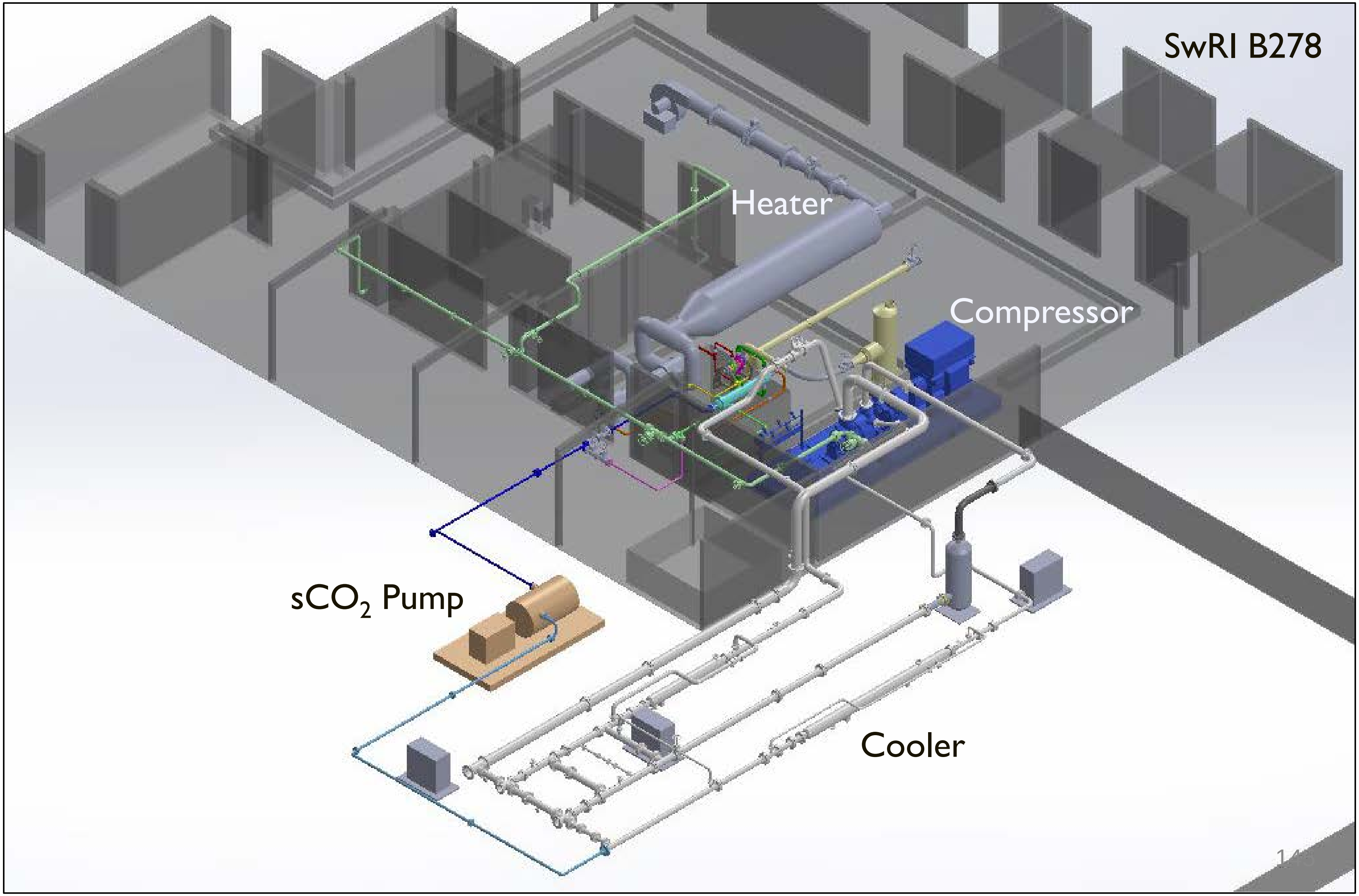
sCO_2 Expander Test Loop Development



Objectives & progress

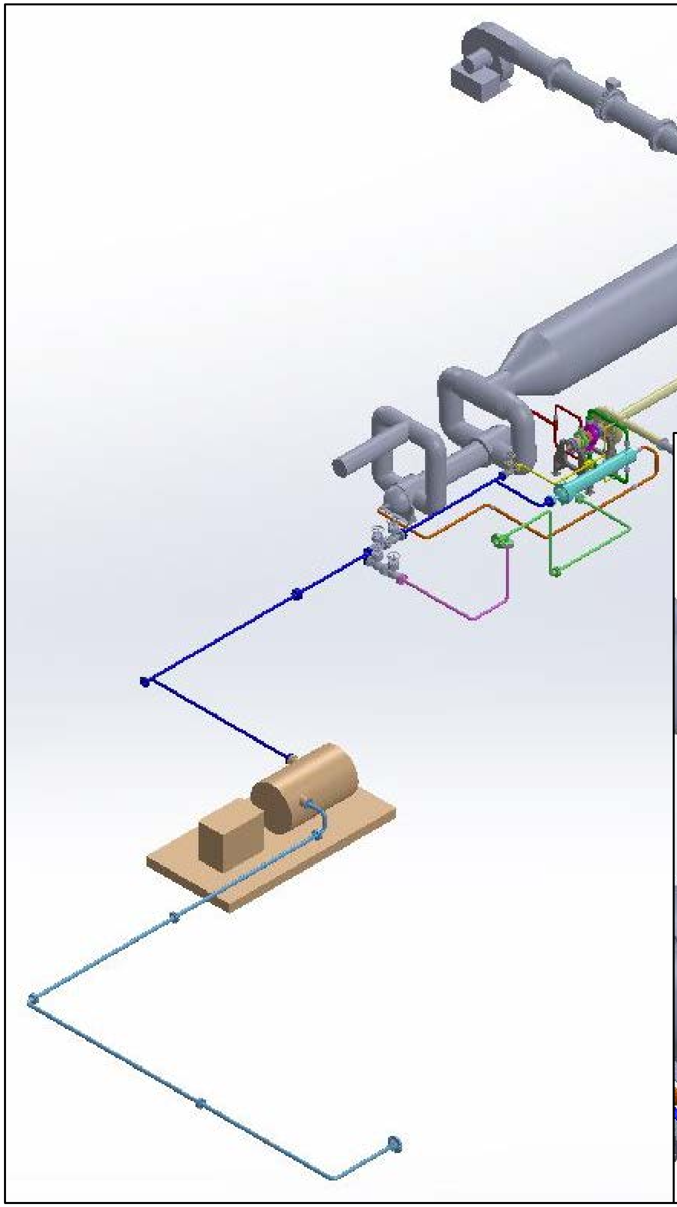
- **Scope:** Mechanical design of the 1 MW turbine, primary objective of mechanical integrity and safety while performance is a secondary objective.
- Final mechanical design review of 1 MW turbine to be tested under the SunShot program recently completed
- <u>Pending approval to advance to phase 2 fabrication</u>

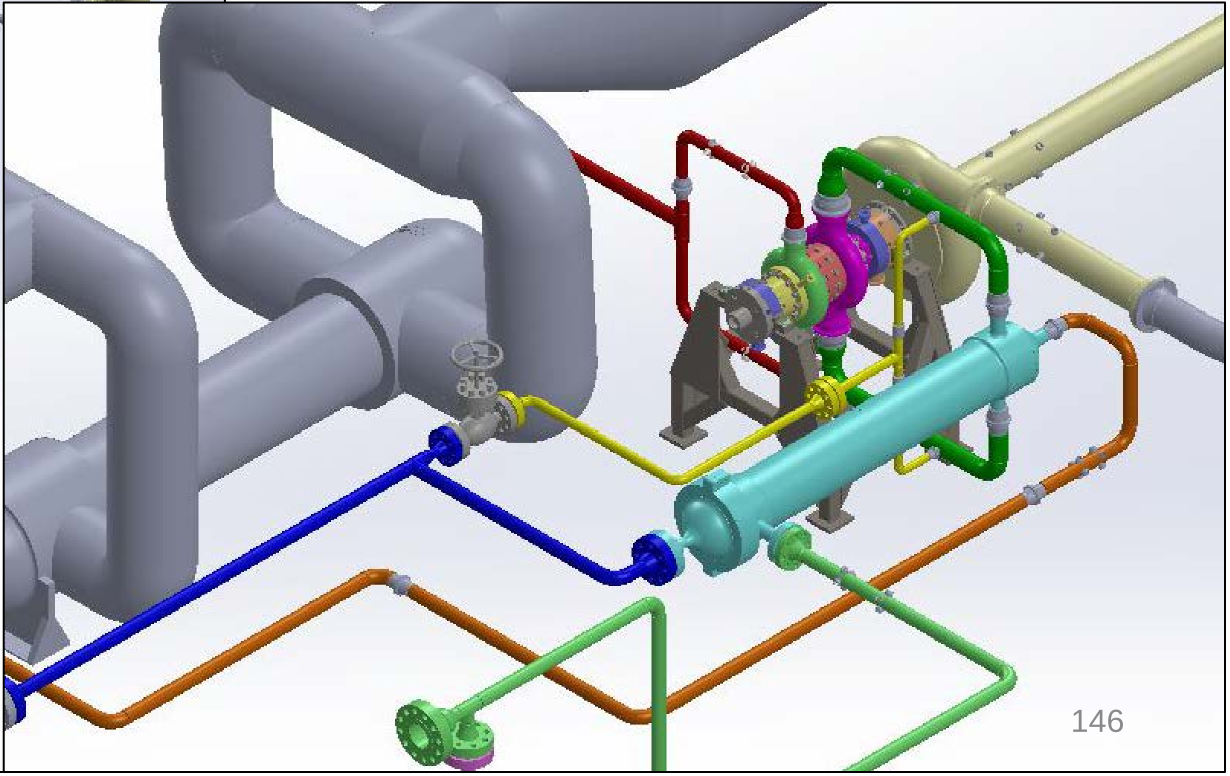
Test Configuration



Test Configuration

Pipe Section	Color
Pump to heater	Dark blue
Mixing line	Yellow
Recuperator to heater	Orange
HT heater to expander	Red
Expander to recuperator	Dark green
Recuperator to existing	Light green
Existing piping to pump	Light blue

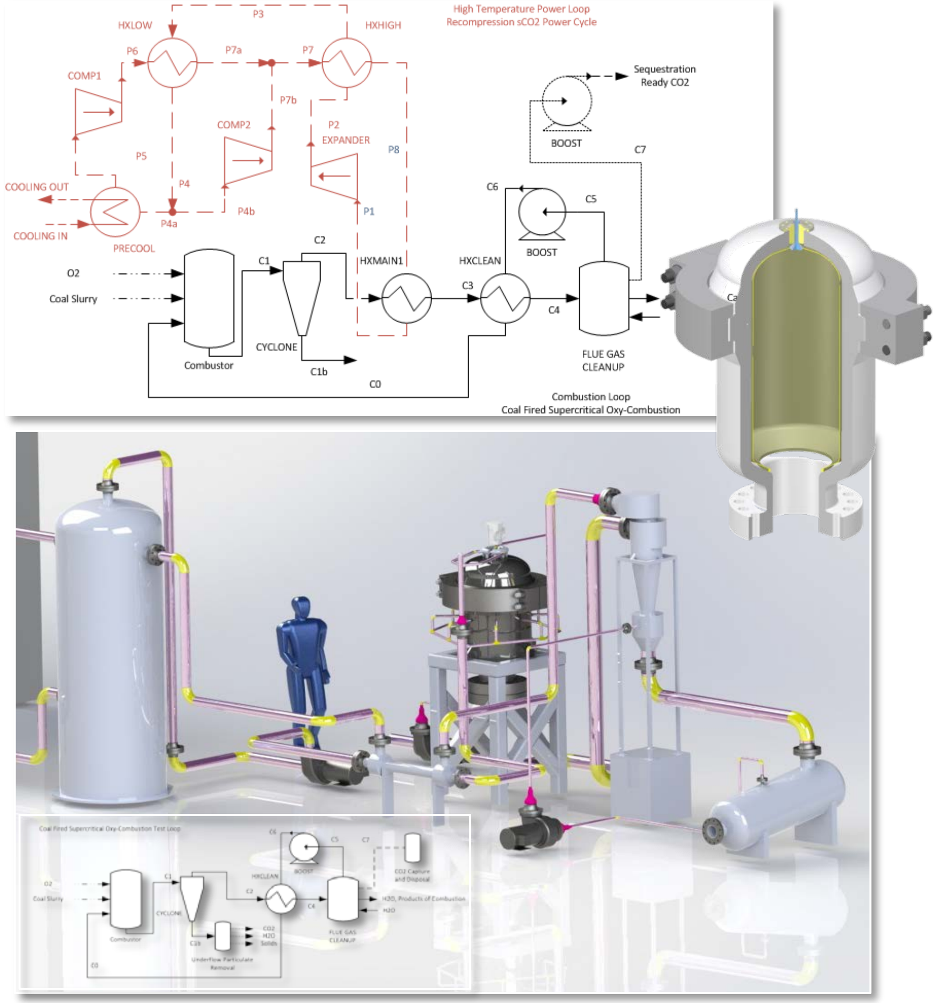




Development of a Supercritical Oxy-combustion Power Cycle with 99% Carbon Capture

Southwest Research Institute® and Thar Energy L.L.C.

- Engineering development, technology assessment, and economic analysis used to evaluate technical risk and cost of a novel supercritical oxy-combustion power cycle
- Optimized cycle couples a coal-fired supercritical oxy-combustor with a supercritical CO_2 power cycle to achieve *40% efficiency at low firing temperature, 650 C*
  - Cycle is limited by TRL of critical components
- COE $121/MWe with 99% carbon capture
  - 49% increase over Supercritical Steam Without Carbon Capture ($81/MWe), *exceeding the 35% target*
  - 21% reduction in cost as compared to Supercritical Steam with 90% Carbon Capture ($137/MWe).
- Phase 1 completed in September 2013, Extended to March 2014 to cover closeout
- Budget $1.25 million
- Ready to demonstrate supercritical oxy-combustor and critical low TRL technologies

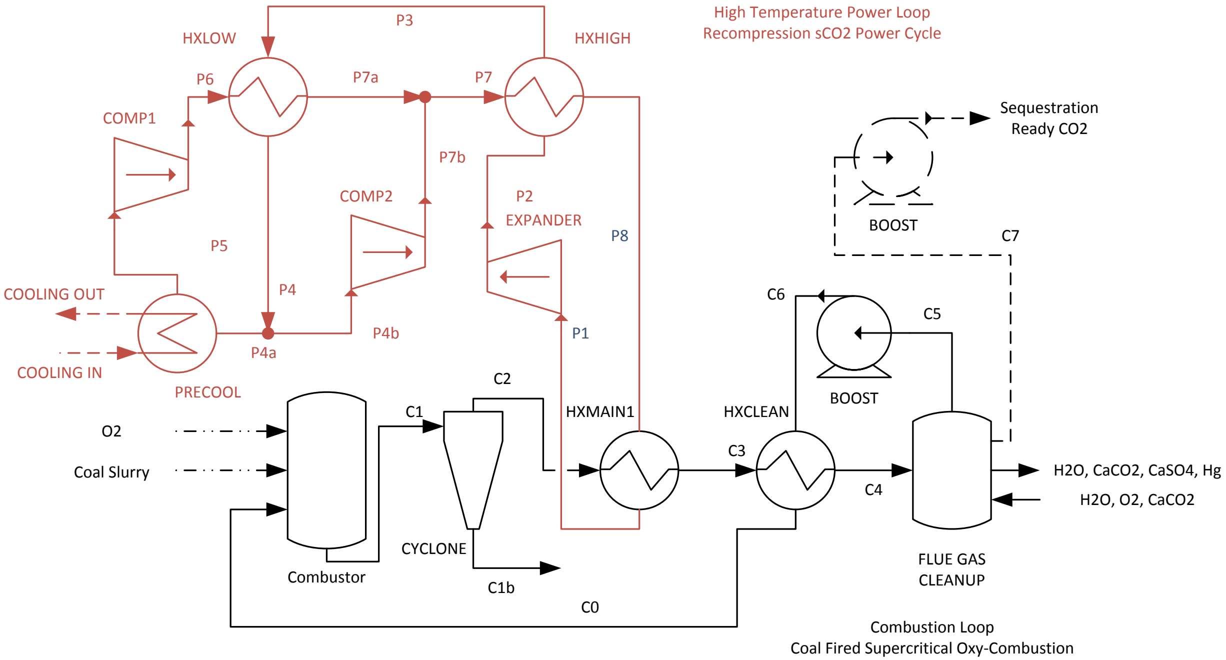


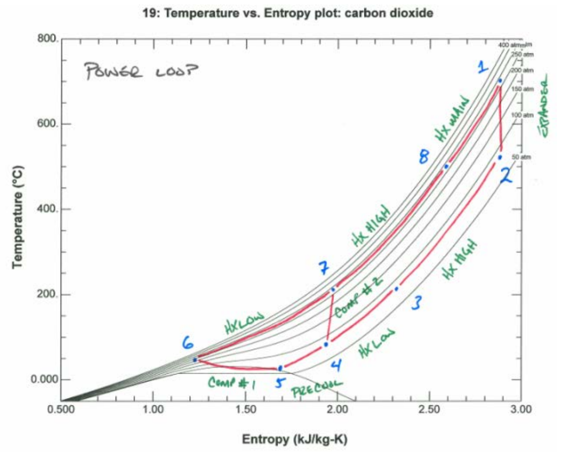
Supported by DOE Project DE-FE0009395

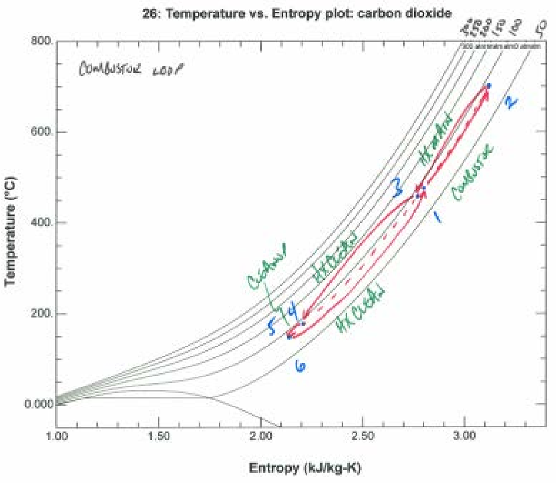
Project Scope

- ❑ Evaluate a novel supercritical oxy-combustion power cycle for meeting the DOE goals of:
  - Over 90% CO2 removal for less than 35% increase in cost of electricity (COE) when compared to a Supercritical Pulverized Coal Plant without CO_2 capture
- ❑ Cycle evaluation based on:
  - Cycle and economic modeling to qualify cost and cycle performance
  - Technology gap assessment to identify critical low TRL components and technologies
  - Bench scale testing to back up cycle models and evaluate state of low TRL technologies
- ❑ Propose development path to address low TRL components

Final Supercritical Oxy-combustion Cycle Configuration







	Power Block	Thermal Loop	Overall
Efficiency [%]	48 Thermal	78.9 HHV / 81.8 LVH	37.9 HHV / 39.3 LHV
CO2 Flow [kg/s]	4887	4930 Recycle	
P high / P low [atm]	290 / 82	100 / 93	
T high / T low [C]	650 / 20	653 / 78	

Combustion Loop TRL

Component/Sub-system	Technology Type	Operating Conditions				Assumed or Specified Performance Characteristics	Assumptions Regarding Anticipated Application Issues	Technology Readiness
		Inlet		Outlet				
		Temperature [C]	Pressure [atm]	Temperature [C]	Pressure [atm]			
Combustion Loop								
Coal Pulverizer	Generic	25	1	25	1	< 9 kw-h/ton		TRL 9
Slury Pump	Generic	25	1	30	92.25	60% Efficiency		TRL 9
Supercritical oxy-combustor	**New vertical flow swirl combustor**	**450**	**95**	**93**	**92.25**	**98+% combustion efficiency**	**Combustor to be demonstrated in Phase 2**	**TRL 6 at the completion of Phase 2 demonstration**
Dry pulverized coal feed	**Supercritical CO2 slurry**	**25**	**1**	**<450**	**110**	**Minimal added water content**		**TRL 2**
Dry pulverized coal feed	**Posimetric Pump**	**25**	**1**	**<450**	**110**	**Dry feed**	**Demonstrated systems can not achieve pressure ratio**	**TRL 4**
Removal of solid products of combustion	**Lock-hopper**	**703**	**92**	**80**	**1**	**Fluid and thermal losses, impact on efficiency unknown**		**TRL 4**
Cyclone Separator	Generic	703	93	703	91	98% Removal 3 atm dP	Materials considerations and thermal insulation for hot gas cleanup	TRL 9
Recouperator (HXMAIN)	Compact micro-channel heat exchanger	703	91	460	88	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1
Pre-heater (HXCLEAN)	Compact micro-channel heat exchanger	460	88	162	85	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1
Sulfur Cleanup	Under evaluation for hot, high pressure cleanup	162	85	?	?	Under Evaluation to identify technologies compatible with loop conditions	High efficiency requirements drive the need for hot, high pressure cleanup	TRL 5 - 9 depending on cleanup conditions
Water Removal	Under evaluation for hot, high pressure cleanup	162	85	?	?	Under Evaluation to identify technologies compatible with loop conditions	High efficiency requirements drive the need for hot, high pressure cleanup	TRL 5 - 9 depending on cleanup conditions
Boost Pump	Generic	150	80	95			Seals and materials for supercirtical CO2	TRL 9
Air Separation Unit	Cryogenic	30	1	450	93	140 kWh/t for 95% O2 based on literature		TRL 9

Note 1: TRL 7 at the completion of a compantion DOE SunShot Project in 2016 (DE-EE0005804)

Note 2: TRL 7 at the completion of a compantion DOE SunShot Project in 2013 (FC26-05NT42650)

Note 3: Materials and manufacturing assumptions for cost and performance

Note 4: Turbomachinery layout and design is being adressed in other DOE sponsored programs (DE-EE0005804)

Power Loop TRL

Component/Sub-system	Technology Type	Operating Conditions				Assumed or Specified Performance Characteristics	Assumptions Regarding Anticipated Application Issues	Technology Readiness
		Inlet		Outlet				
		Temperature [C]	Pressure [atm]	Temperature [C]	Pressure [atm]			
Power Loop	Supercritical CO2 Recompression Cycle							TRL 7, See Note 1
sCO2 Turbo-expander		650	290	509	86	90+% efficiency	See Note 4	TRL 7, See Note 1
Recouperator (HXHIGH)	Compact micro-channel heat exchanger	509	86	213	84	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1
Recouperator (HXLOW)	Compact micro-channel heat exchanger	213	84	70	83	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1
sCO2 Pump/Compressor		70	83	190	290	05+% efficiency	See Note 4	TRL 7, See Note 2
sCO2 Pump/Compressor		25	82	60	290	05+% efficiency	See Note 4	TRL 7, See Note 2
Pre-cooler	Compact micro-channel heat exchanger	70	83	25	82	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1

Note 1: TRL 7 at the completion of a compantion DOE SunShot Project in 2016 (DE-EE0005804)

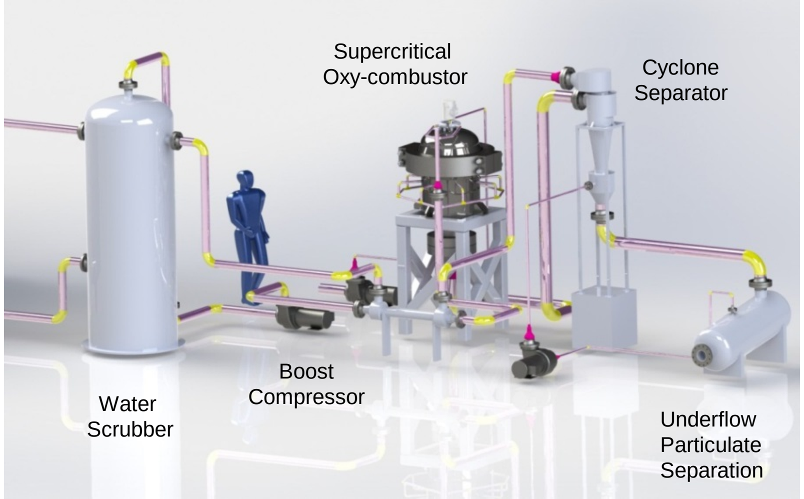
Note 2: TRL 7 at the completion of a compantion DOE SunShot Project in 2013 (FC26-05NT42650)

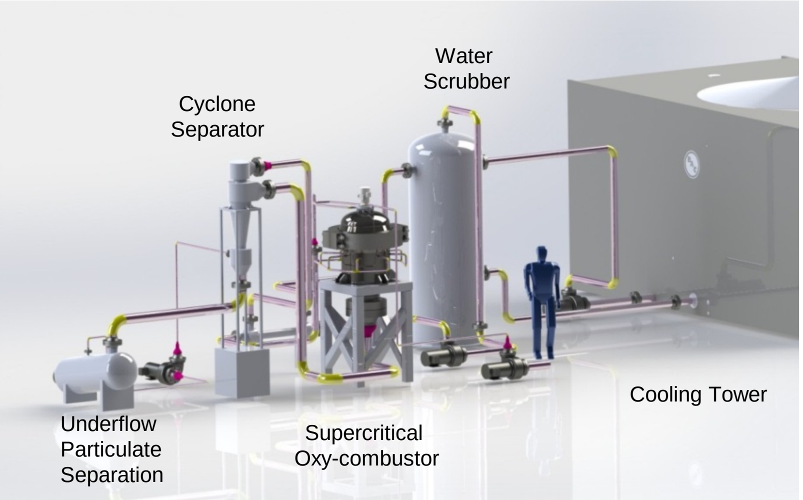
Note 3: Materials and manufacturing assumptions for cost and performance

Note 4: Turbomachinery layout and design is being adressed in other DOE sponsored programs (DE-EE0005804)

Technology Development: Proposed follow on

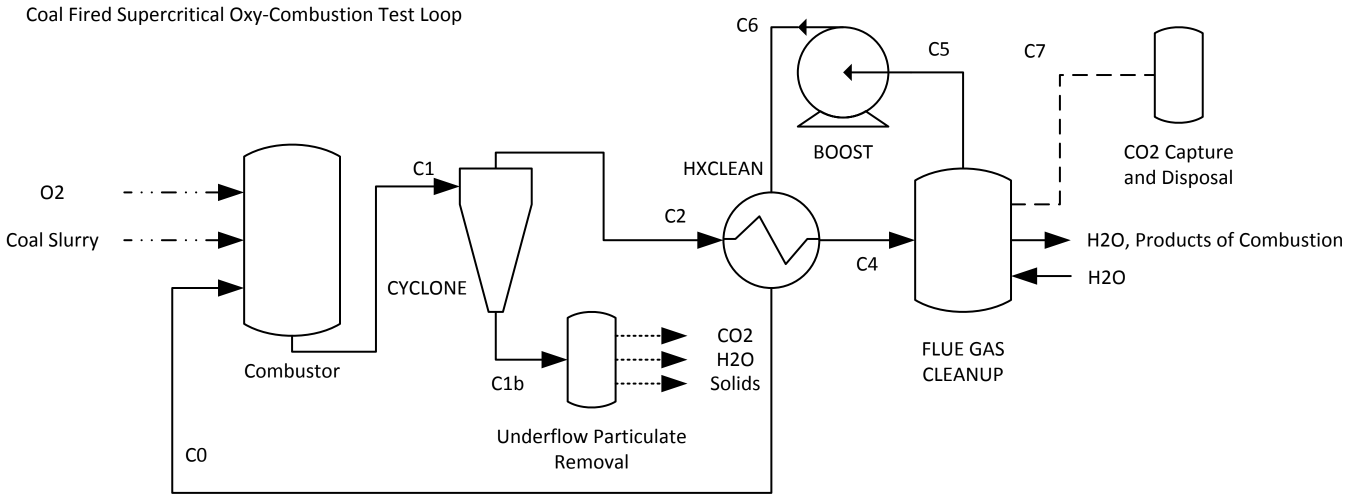
- ❑ 1 MWth Supercritical Oxy-combustor Demonstration
- ❑ Test bed for technology development
  - Supercritical oxy-combustor
  - Particulate cleaning of the compact microchannel heat exchanger
  - Solids injection at pressure
  - Solids removal at pressure
- ❑ Advance technologies from TRL 2, *Technology Concept*, to TRL 6, *Pilot Scale System Demonstrated in a Relevant Environment*
- ❑ Operate with coal water slurry, plan for dry feed or sCO2 slurry extension





Oxy-Combustion Test Loop

- Major components
  - Charge Compressor or Pressurized CO2 Feed
  - Combustor
    - Oxygen feed
    - Coal slurry feed
  - Cyclone separator
    - Solids removal and handling
  - Recuperater
  - Water scrubber and cleanup
    - Liquid removal and handling
    - CO2 removal and handling
  - Cooling Tower
  - Boost Compressor
- Operating Conditions
  - 450 – 650 C (800 – 1200 F)
  - 102 atm (1500 psi)
- Flow Rates: 1 MWth
  - 3.4 kg/s Hot side flow rate
  - 3.2 kg/s CO2 recycle
  - 0.05 kg/s Coal feed
  - 0.08 kg/s O2 Feed
  - 4.25 kg/s H2O Recycle



Analysis of the Recuperated Cryogenic Pressurized Oxy-Combustion Cycle (CPOC)

Aaron McClung, Ph.D.
Sr. Research Engineer
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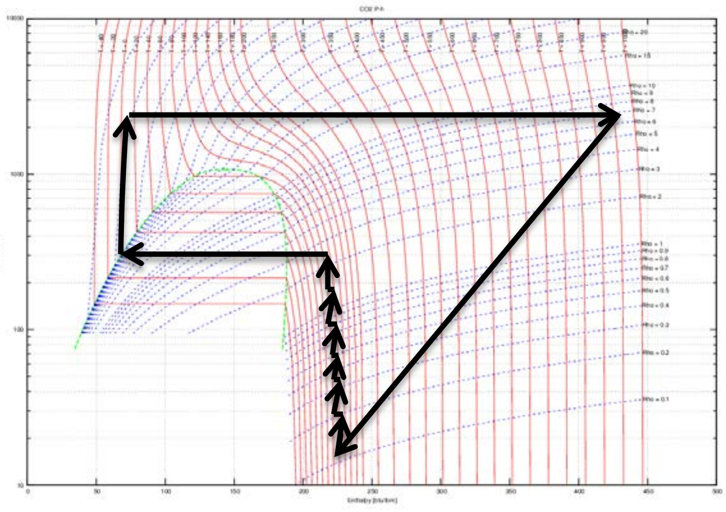
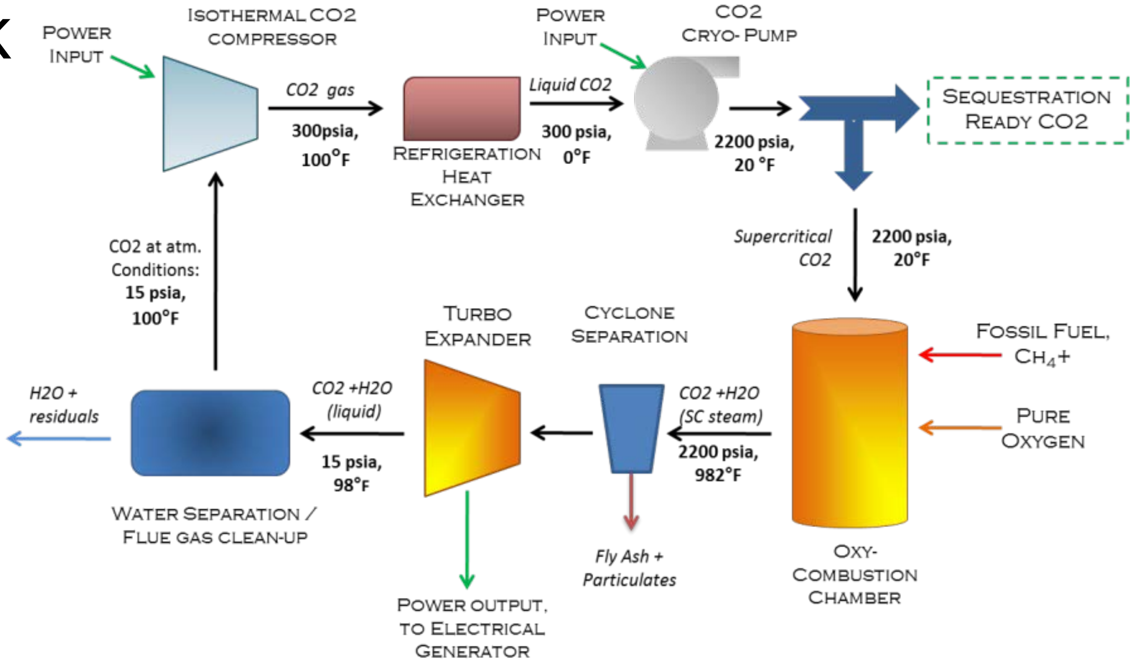
210-522-2677

Initial Cycle: Cryogenic Pressurized Oxy-combustion (CPOC)

- ☐ Transcritical cycle (gas, liquid, and supercritical states)
- ☐ Leverage iso-thermal compression to minimize compression work





POWER INPUT

ISOTHERMAL CO2 COMPRESSOR

CO2 gas

300psia, 100°F

REFRIGERATION HEAT EXCHANGER

Liquid CO2

300 psia, 0°F

POWER INPUT

CO2 CRYO- PUMP

2200 psia, 20 °F

SEQUESTRATION READY CO2

Supercritical CO2

2200 psia, 20°F

CO2 at atm. Conditions: **15 psia, 100°F**

FOSSIL FUEL, CH_4+

PURE OXYGEN

OXY-COMBUSTION CHAMBER

CYCLONE SEPARATION

CO2 +H2O (SC steam)

2200 psia, 982°F

Fly Ash + Particulates

TURBO EXPANDER

POWER OUTPUT, TO ELECTRICAL GENERATOR

CO2 +H2O (liquid)

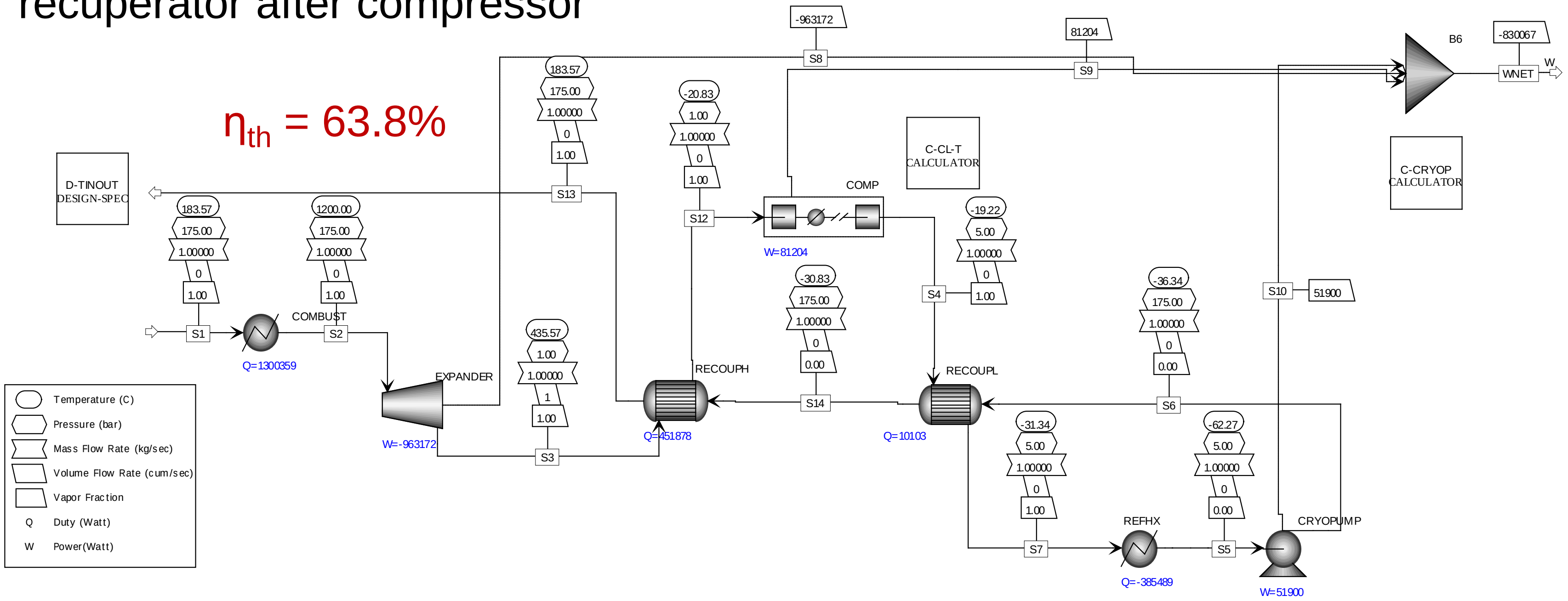
15 psia, 98°F

WATER SEPARATION / FLUE GAS CLEAN-UP

H2O + residuals

Recuperated CPOC

Add high temperature recuperator after expander, low temperature recuperator after compressor



$\eta_{th} = 63.8\%$

High temperature recuperator

- Hot stream: Turbine outlet
- Cold stream: Low temperature recuperator
- Assume 10 C pinch point

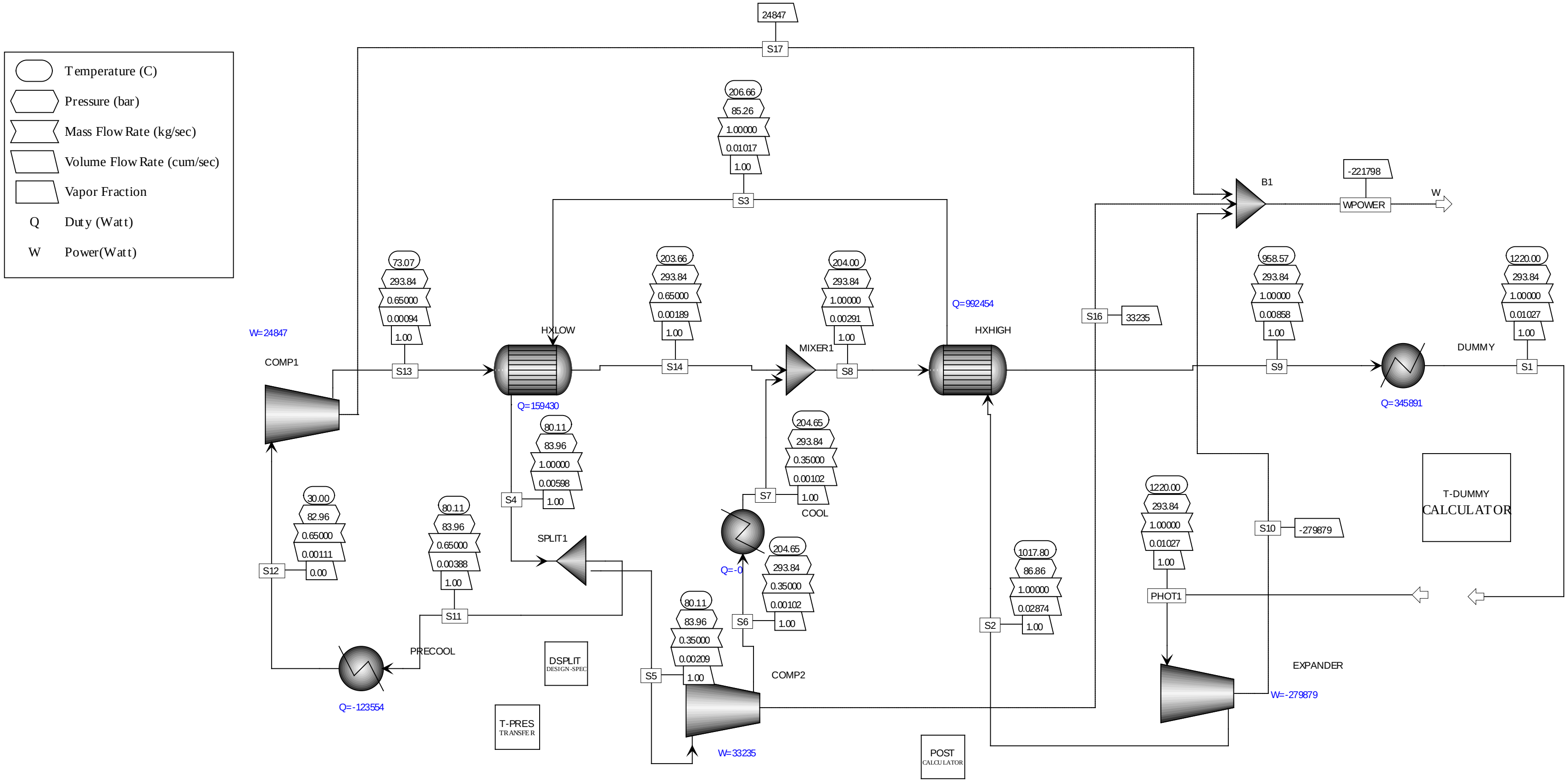
Low temperature recuperator

- Hot stream: Iso-thermal compressor outlet
- Cold stream: Dense phase pump
- Assume 5 C pinch point

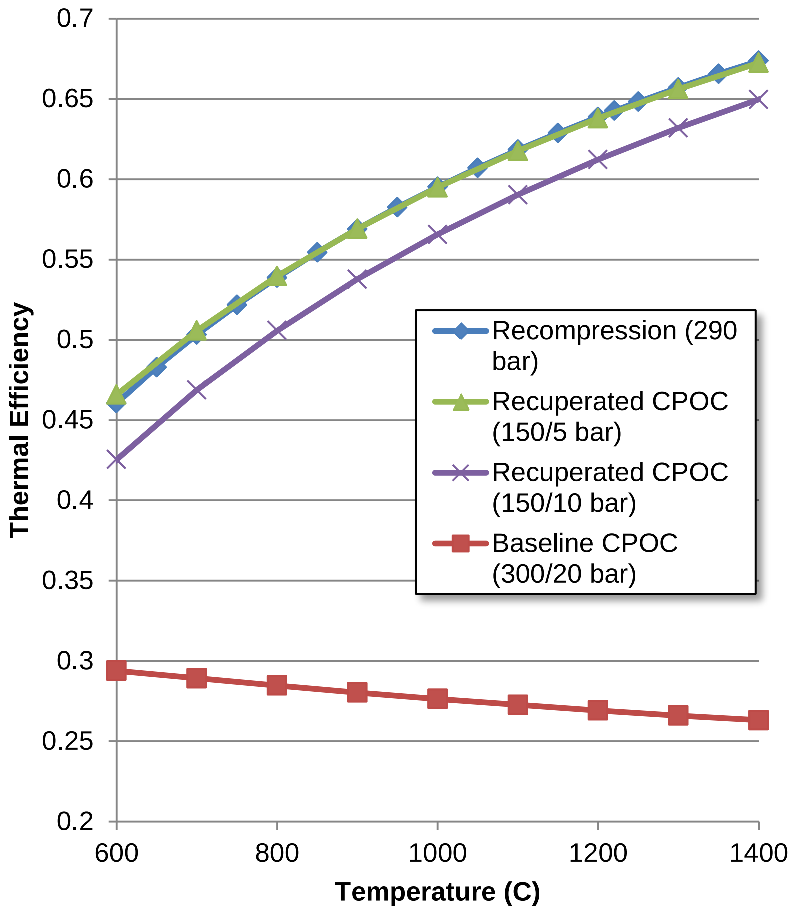
Performance tweaks

- Iso-thermal compressor
  - Reduce pressure ratio (Increases refrigeration requirements)
  - Assume 20% of adiabatic temperature rise
- Turbine inlet pressure between 145 and 175 bar
- Assume 5C of sub-cooling for refrigeration

Baseline Recompression Cycle



Efficiency Comparison



Recuperated CPOC performs on par with the recompression cycle, has larger thermal input window, higher power density, and requires less recuperation

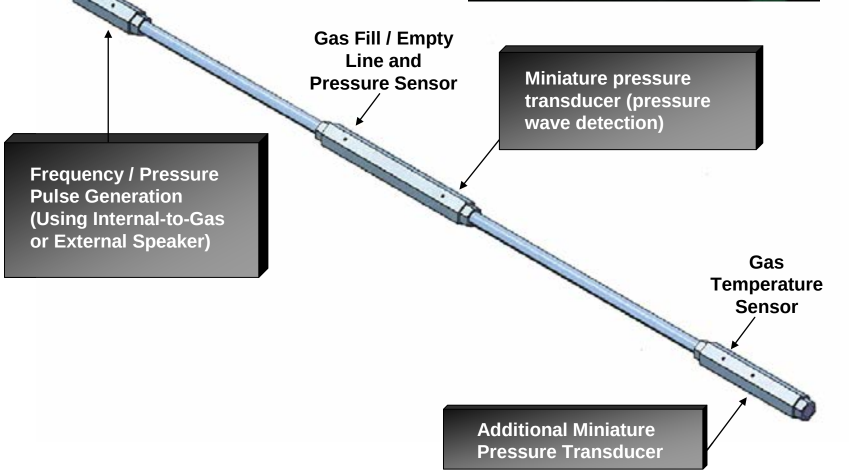
	CPOC	Recompression
Efficiency	63.85%	64.00%
Turbine Inlet Temp (C)	1200	1200
Turbine Inlet Pressure (bar)	150	290
Turbine Outlet Pressure (bar)	1	100
Mass flow (kg/s)	1.00	1.00
W net (MW)	0.830	0.221
Q in (MW)	1.300	0.345
HX high (MW)	0.451	0.992
HX low (MW)	0.010	0.154
Total Recuperation (MW)	0.461	1.146

Scaled to 550 MWe plant, parasitic losses neglected

	CPOC	Recompression
Mass flow (kg/s)	662.65	2,488.69
W net (MW)	550.00	550.00
Q in (MW)	861.45	858.60
HX high (MW)	298.86	2,468.78
HX low (MW)	6.63	383.26
Total Recuperation (MW)	305.48	2,852.04

FUNDAMENTAL GAS PROPERTY TESTING

- Fundamental gas property tests for high H_2S and CO2 content mixtures, falling outside of typical EOS model limits: speed of sound, specific heat, and density up to 15,000 psi, 400°F.
- Adapted high pressure autoclaves / adiabatic calorimeters for specific heat determination.
- Specialized test methods for speed of sound using high pressure fixture design developed by SwRI.
- Gas sampling and species determination near critical point.
- Controlled long-term tests using for H_2S / CO_2 / water mixtures to characterize gas-liquid behavior.



Gas Fill / Empty Line and Pressure Sensor

Miniature pressure transducer (pressure wave detection)

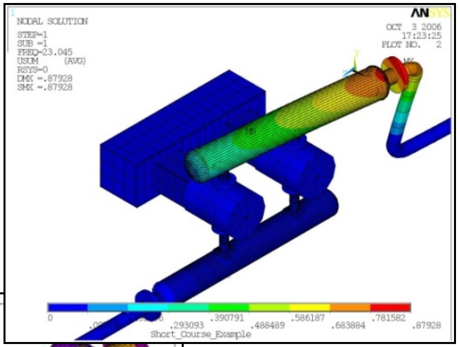
Frequency / Pressure Pulse Generation (Using Internal-to-Gas or External Speaker)

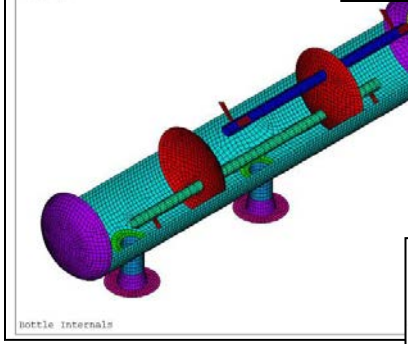
Gas Temperature Sensor

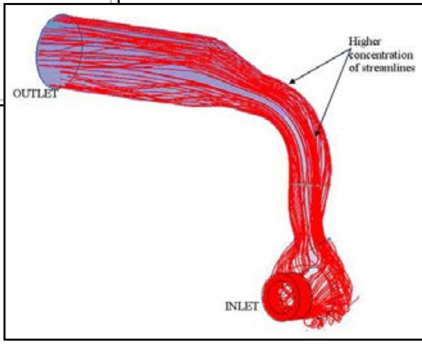
Additional Miniature Pressure Transducer

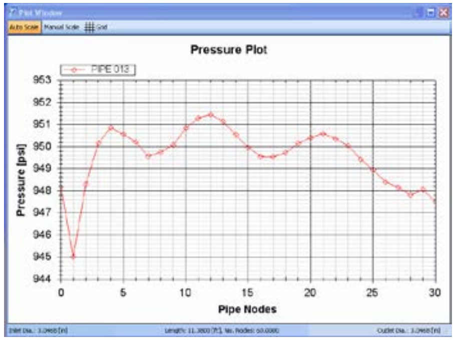
COMPRESSOR STATION DESIGN

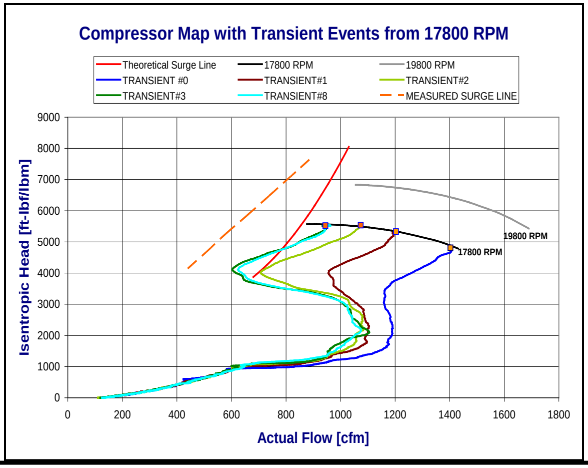
- ❑ API 618 Standard Analyses: Pulsation, Mechanical and Thermal Analysis of Reciprocating Compressor Systems
- ❑ 1-D / 3-D Pulsation Analysis
- ❑ Simulation of piping components for design review: Regulators, check valves, process valves, heat exchanger components
- ❑ Larger pipeline system modeling and simulation: Pump / compressor optimization, Leak detection, MAOP Limit analysis
- ❑ Transient surge / Surge control
- ❑ Blow-down station analysis and Acoustic-Induced Vibration









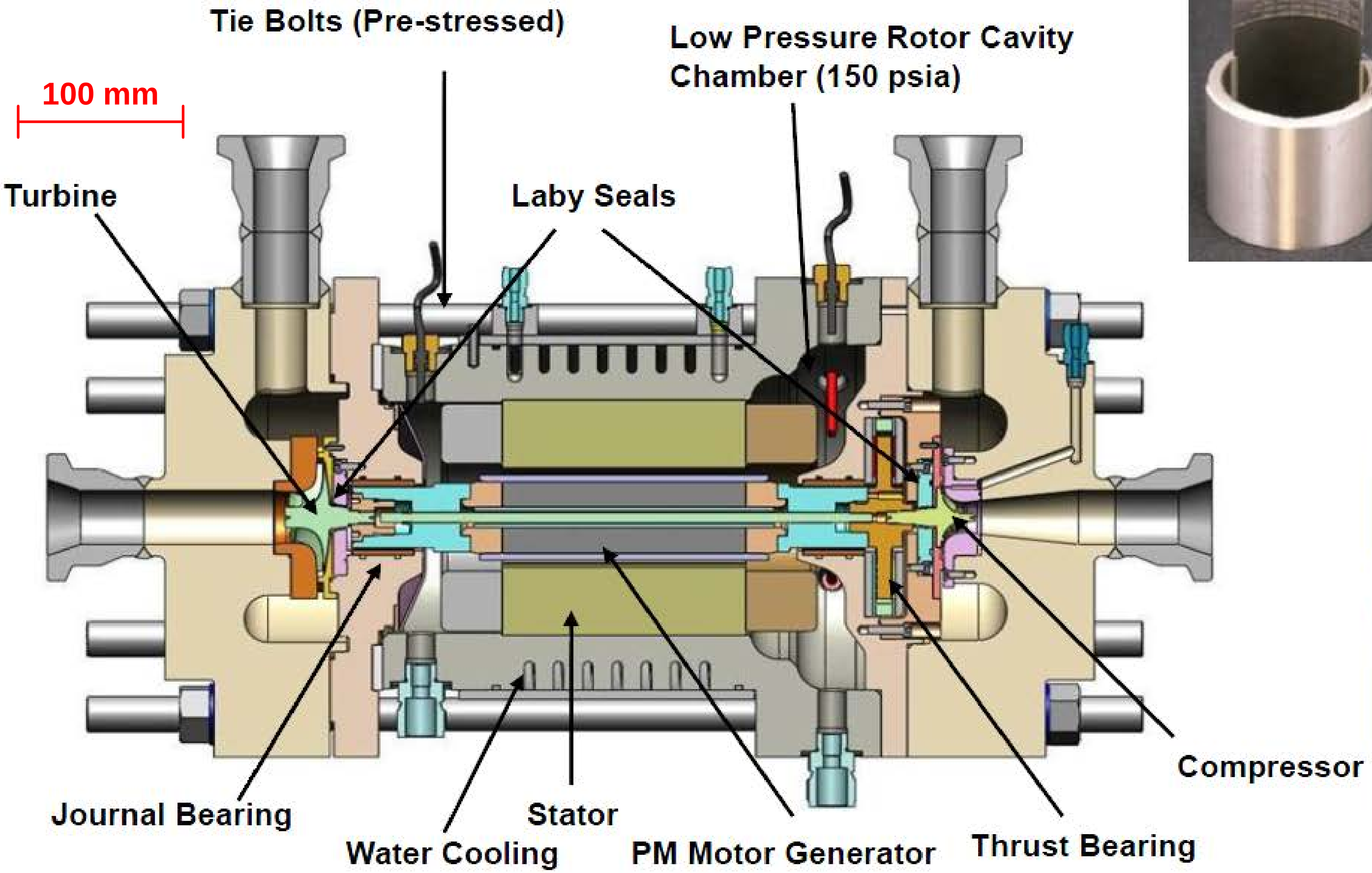


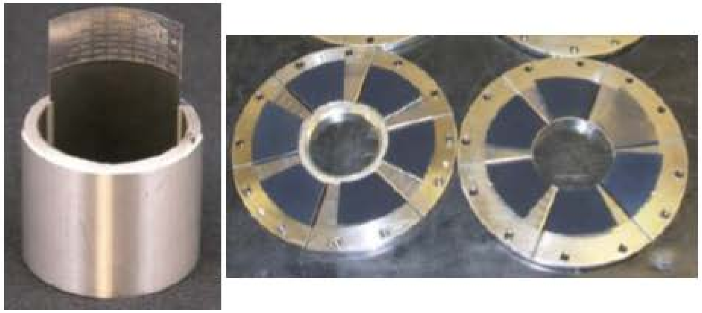
DOE S-CO_2 Test Program

- ❑ 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

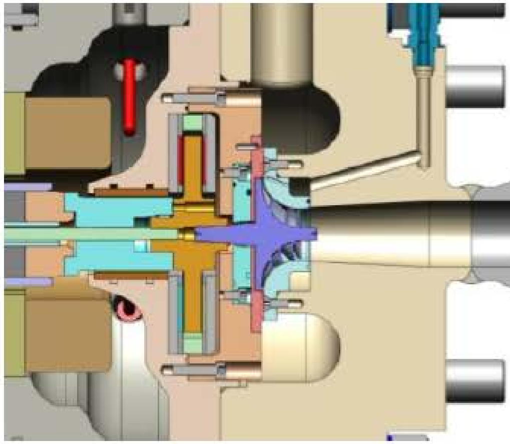
Barber Stockwell, Sandia National Laboratories,

DOE S-CO_2 Test Program Turbomachinery



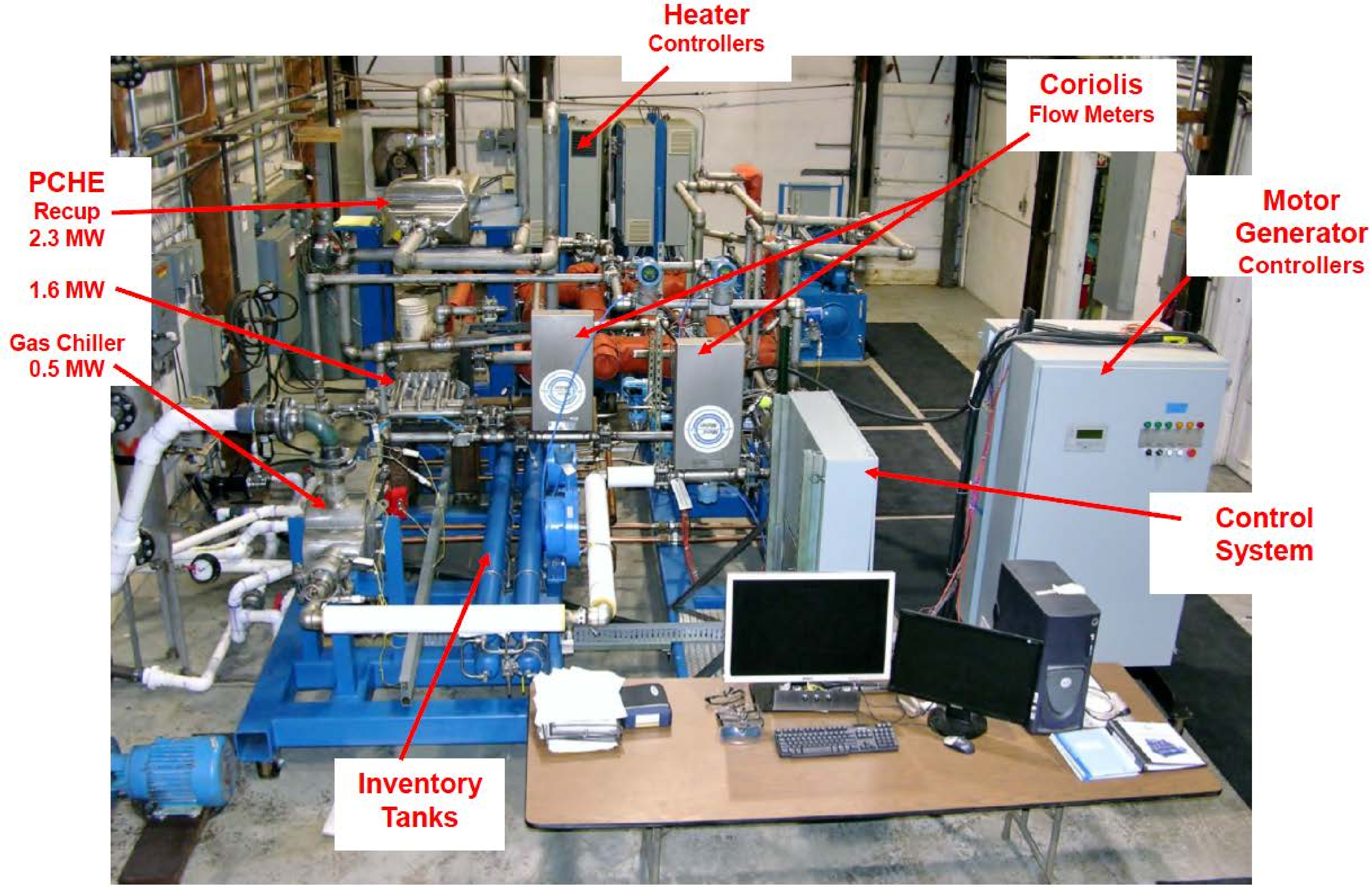


Gas-Foil Bearings



Source: Wright (2011)

S-CO_2 Brayton Cycle Test Loop



Heater Controllers

Coriolis Flow Meters

PCHE Recup 2.3 MW

1.6 MW

Gas Chiller 0.5 MW

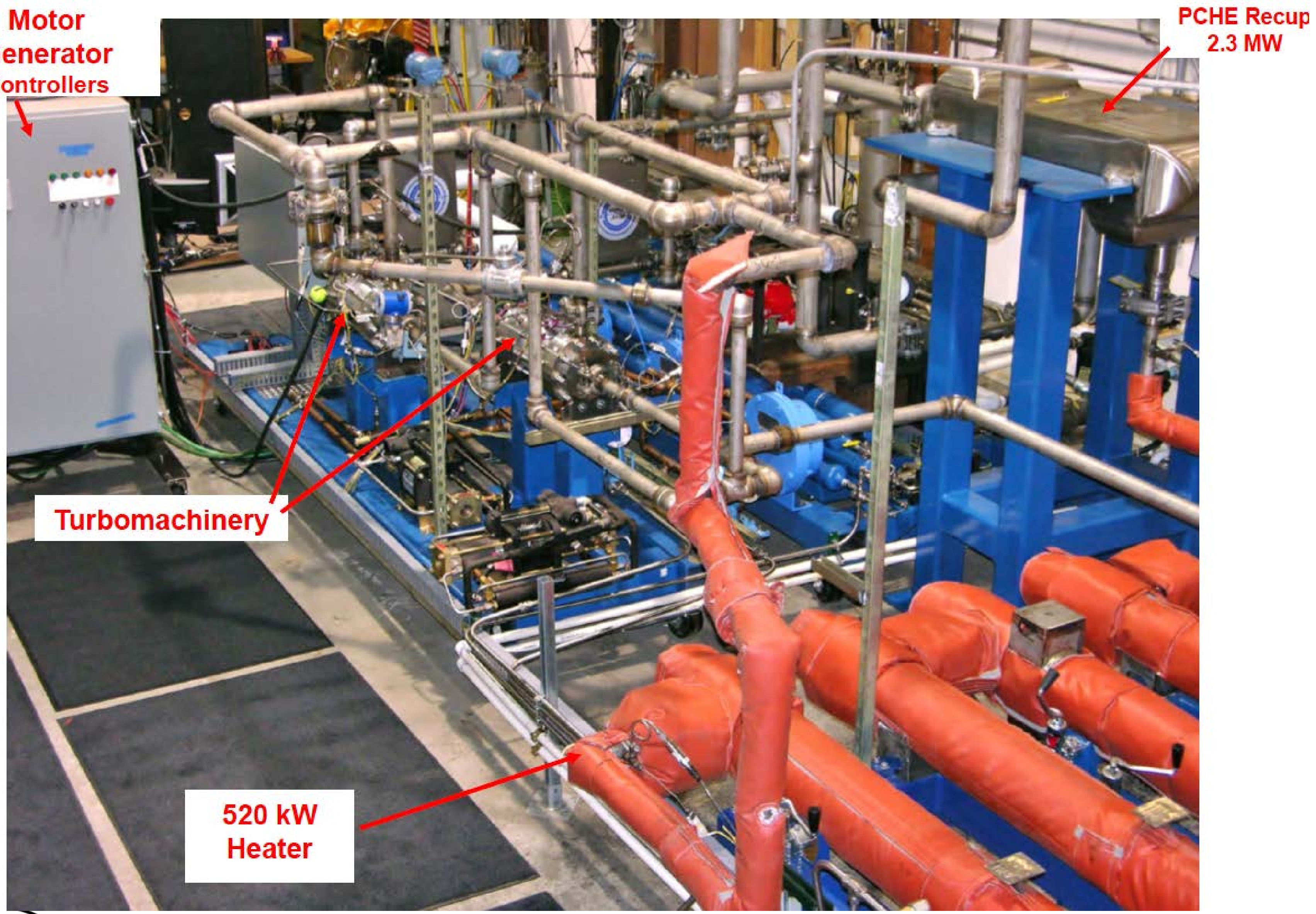
Motor Generator Controllers

Control System

Inventory Tanks

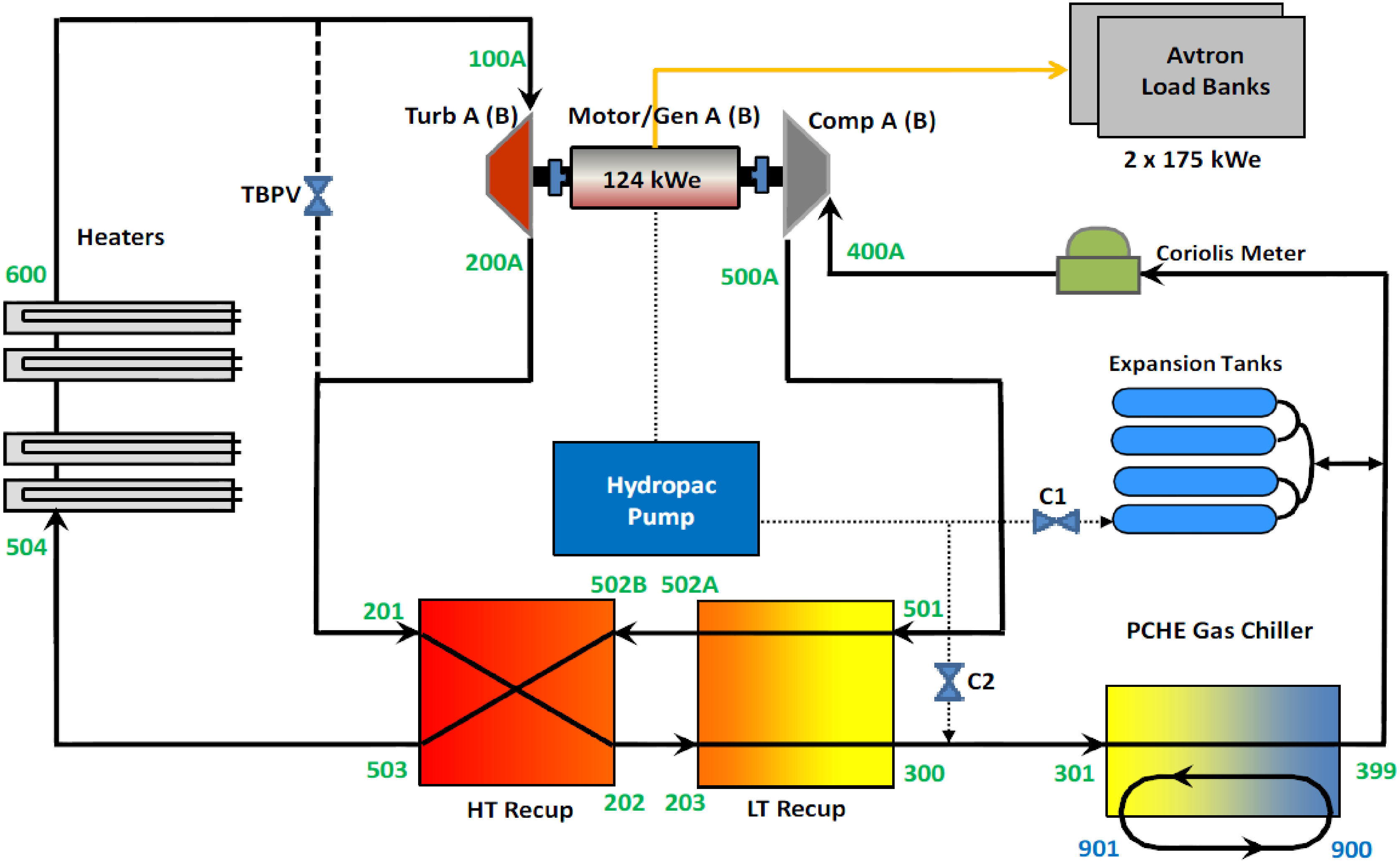
Source: Wright (2011)

S-CO_2 Brayton Cycle Test Loop



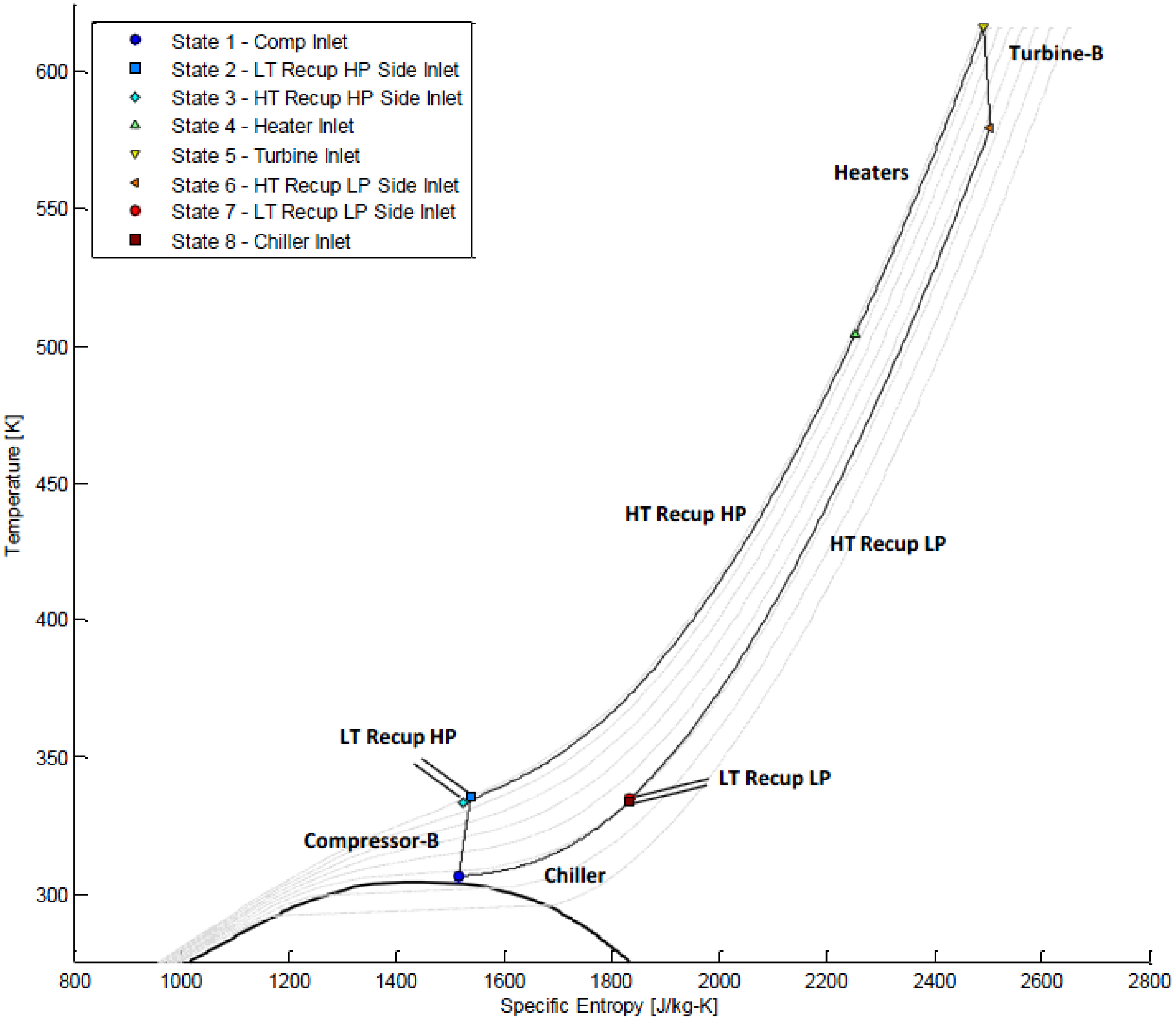
Source: Wright (2011)

S-CO$_2$ Brayton Cycle with Regeneration



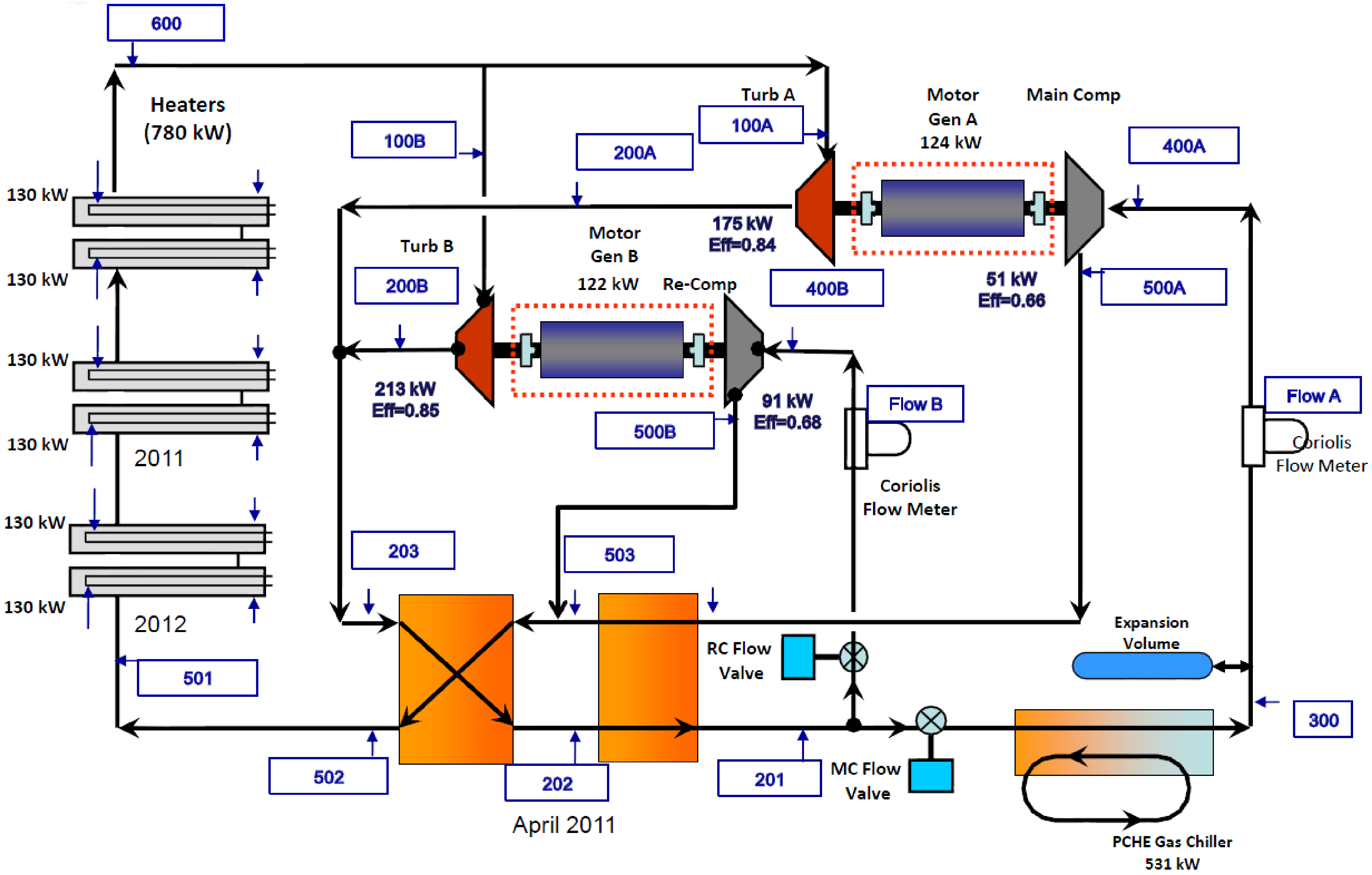
Source: Conboy et al. (2012)

S-CO_2 Brayton Cycle with Regeneration



Source: Conboy et al. (2012)

S-CO$_2$ Brayton Cycle with Regen. + Recomp.

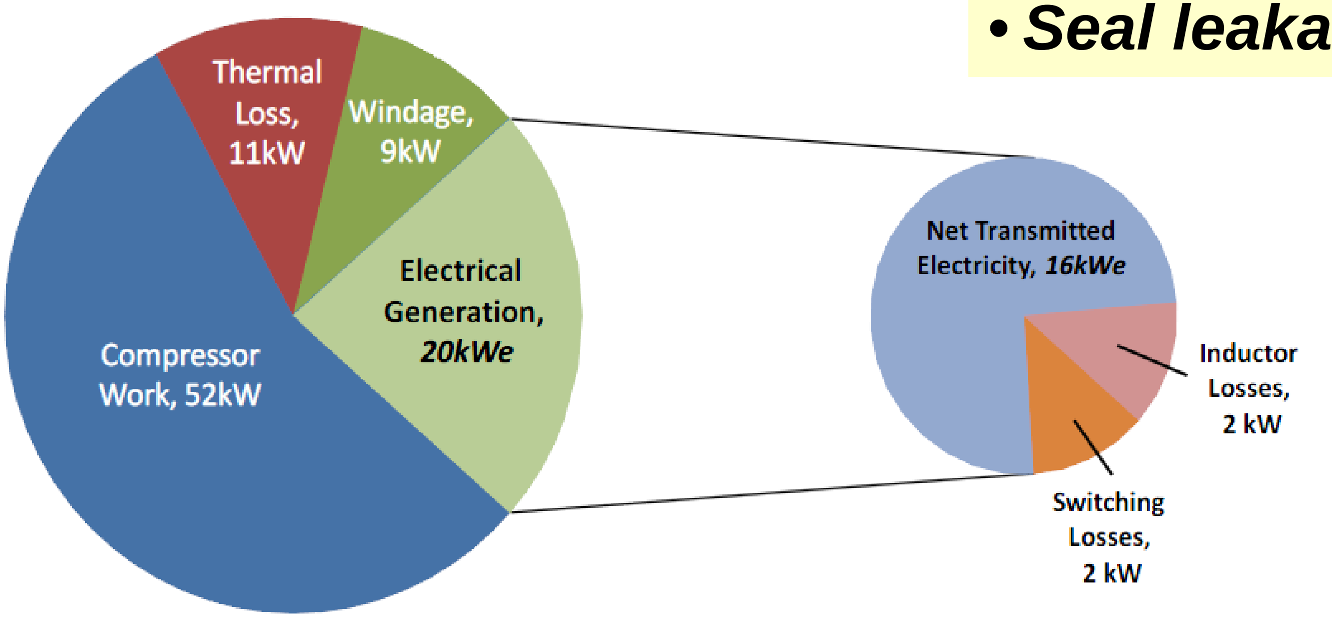


Source: Wright (2011)

S-CO$_2$ Brayton Cycle Performance with Regeneration Config.

Maximum Case:
Total Turbine Work, 92 kW

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

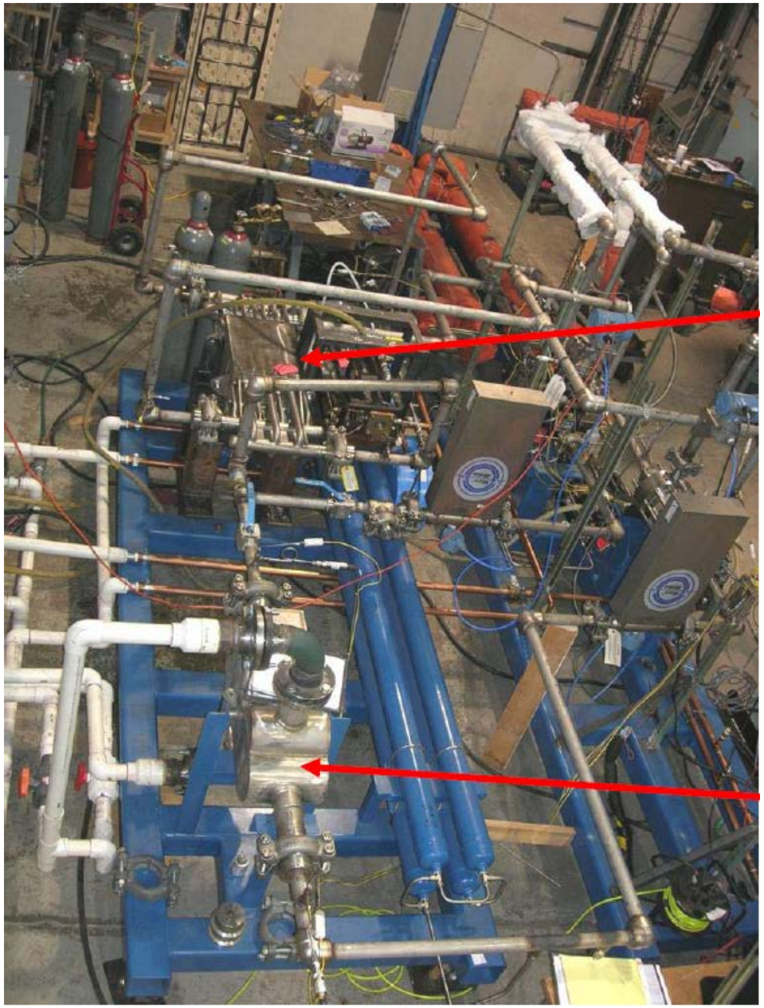


Source: Conboy et al. (2012)

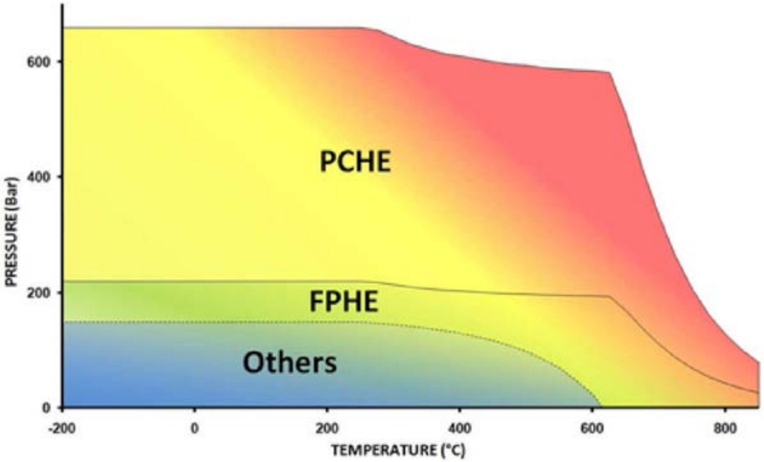
DOE S-CO_2 Test Program Summary

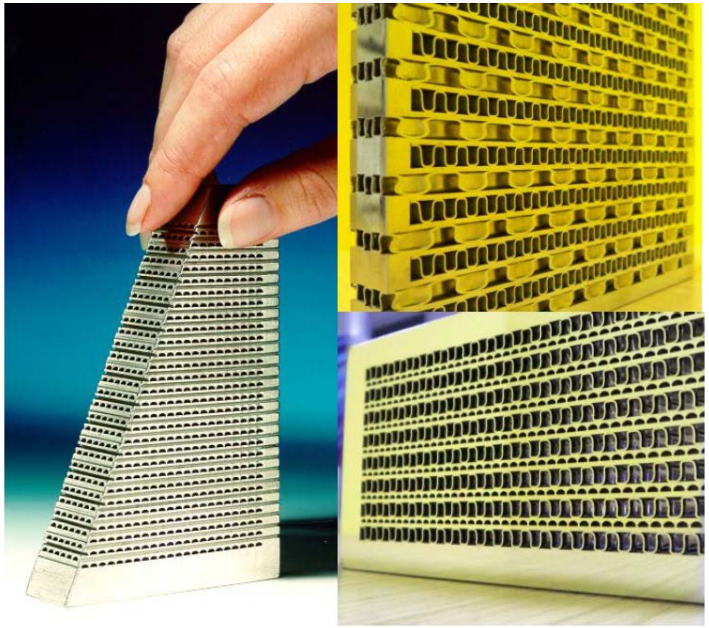
- ☐ Major milestones
  - Test loops operational
  - Demonstrate process stability/control
- ☐ Areas for future development
  - Heat exchanger performance
  - Larger scale test bed
    - Utilize commercial-scale hardware
    - Demonstrate more-realistic (better) performance
  - CO_2 mixtures

Printed Circuit Heat Exchanger (PCHE)



S-CO_2 test loop used by Sandia/ Barber-Nicholls



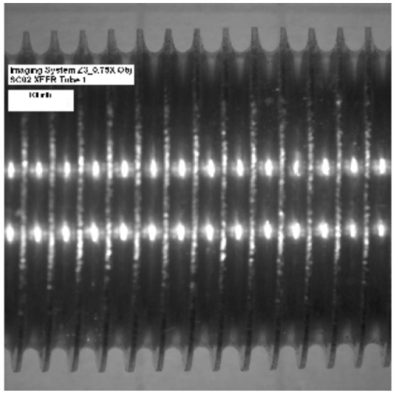


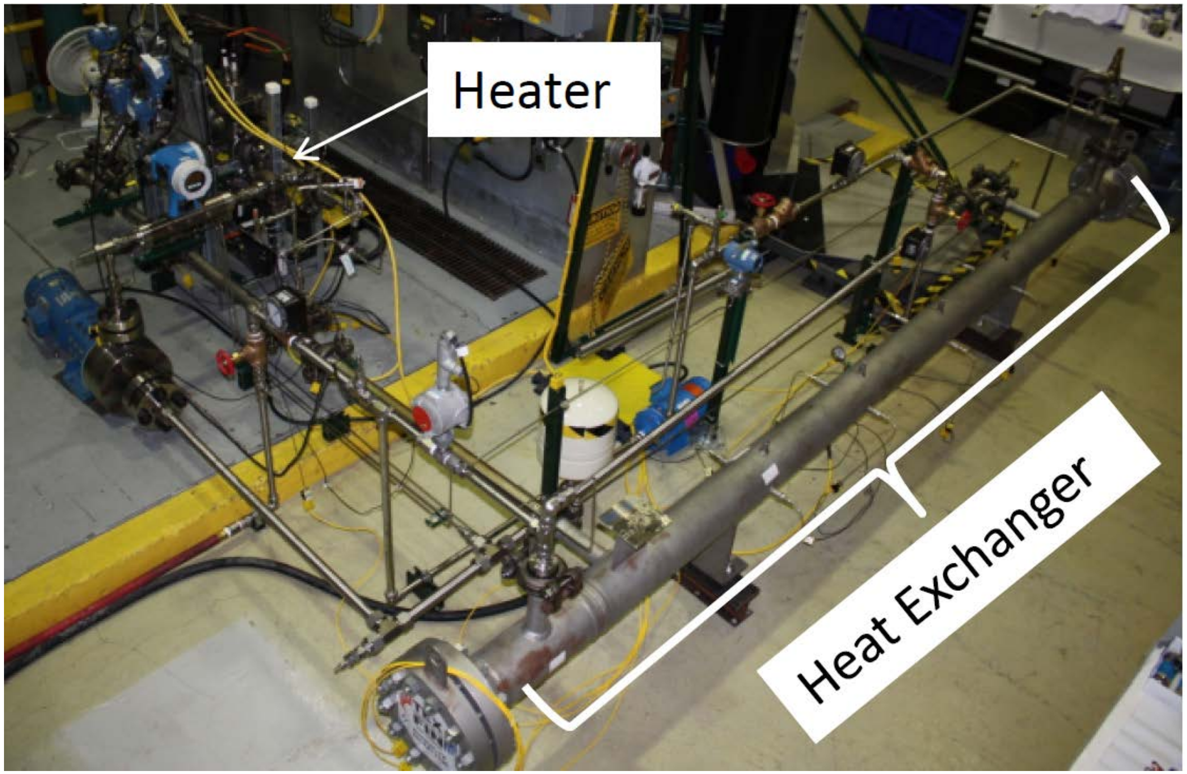
Heatric PCHE

Le Pierres (2011)

Heat Exchanger Testing (Bechtel)

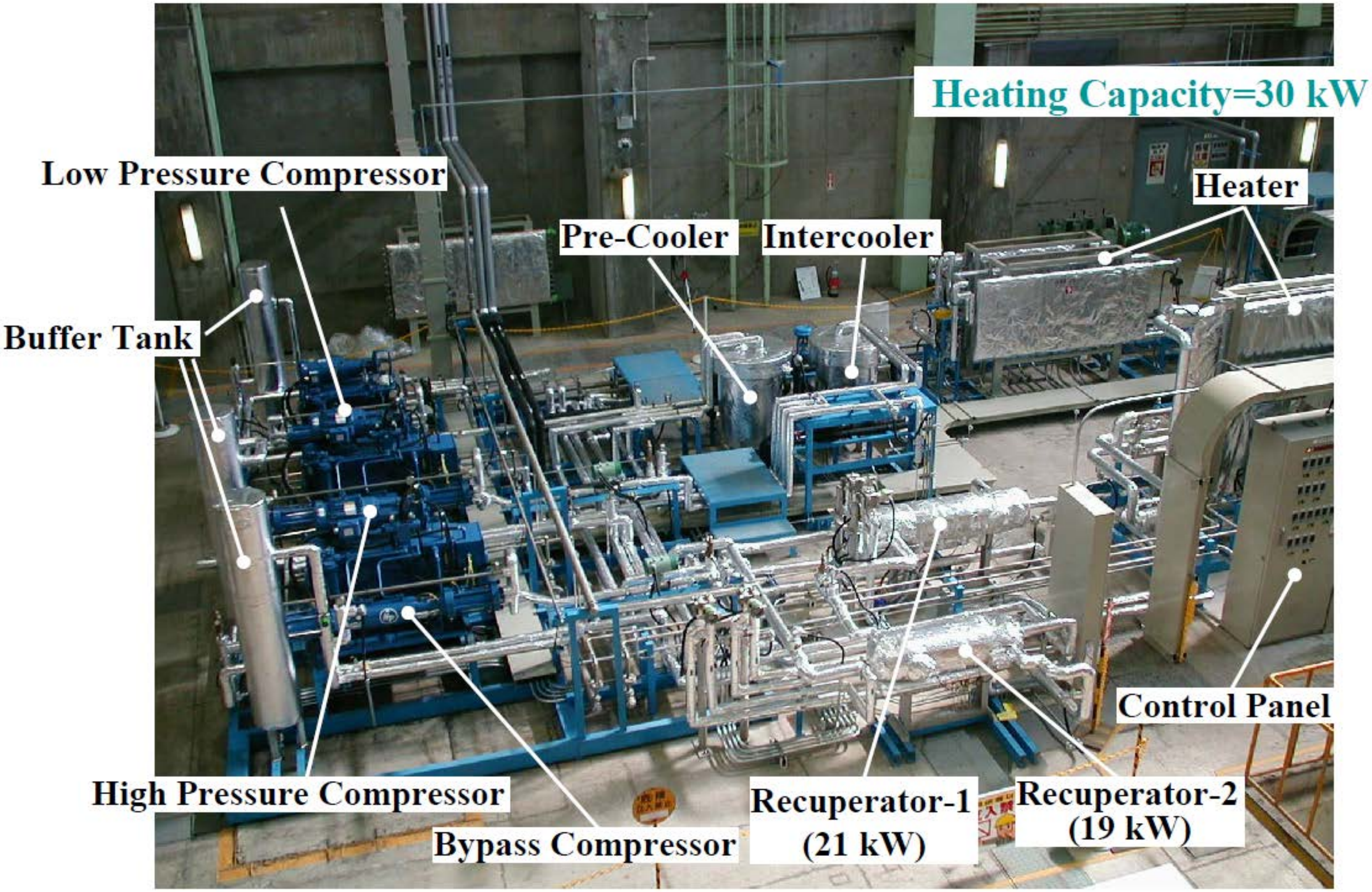
- ☐ 150 kW
- ☐ 8000 lbm/hr S-CO_2
- ☐ 2500 psi





Nehrbauer (2011)

Tokyo Institute of Technology (TIT)

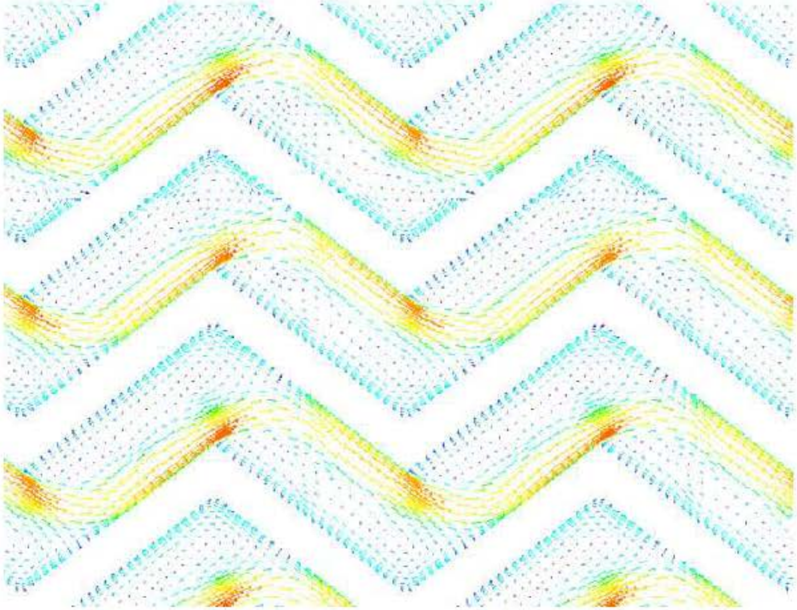


Supercritical CO_2 Cycle Mockup Test Loop

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

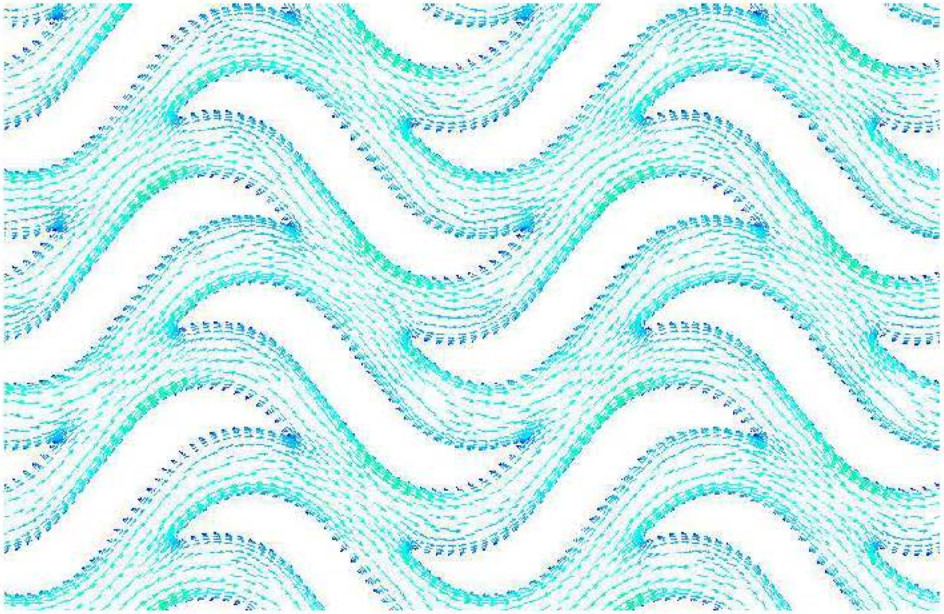
(Kato et al., 2007)

TIT, New Micro-Channel Heat Exchanger



Zigzag Model

- Localized velocity profile
- Eddies around the corners



“S” Shape Fin model

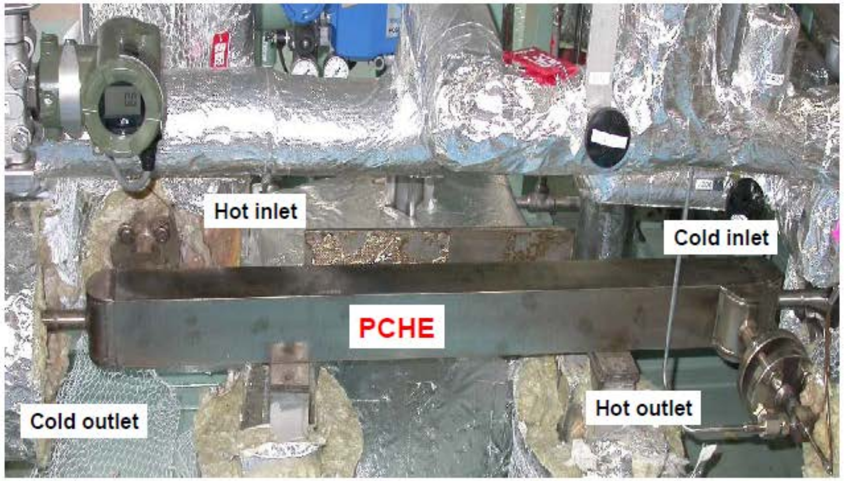
- Uniform velocity profile
- No eddies

(Kato et al., 2007)

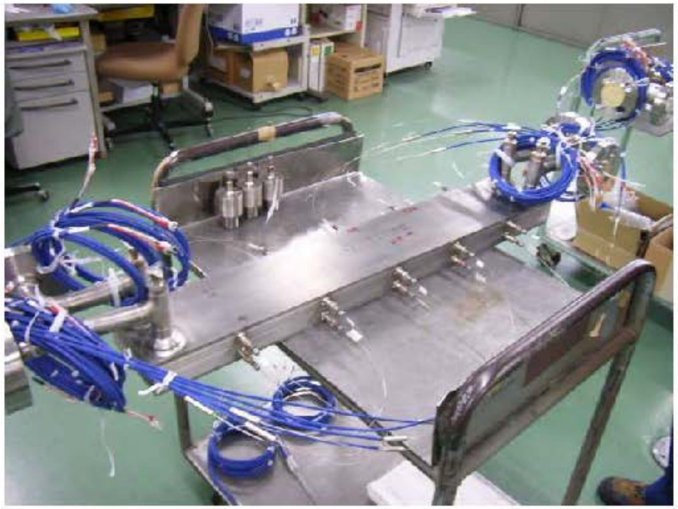
TIT, Heat Exchanger Testing

(Kato et al., 2007)

3kW



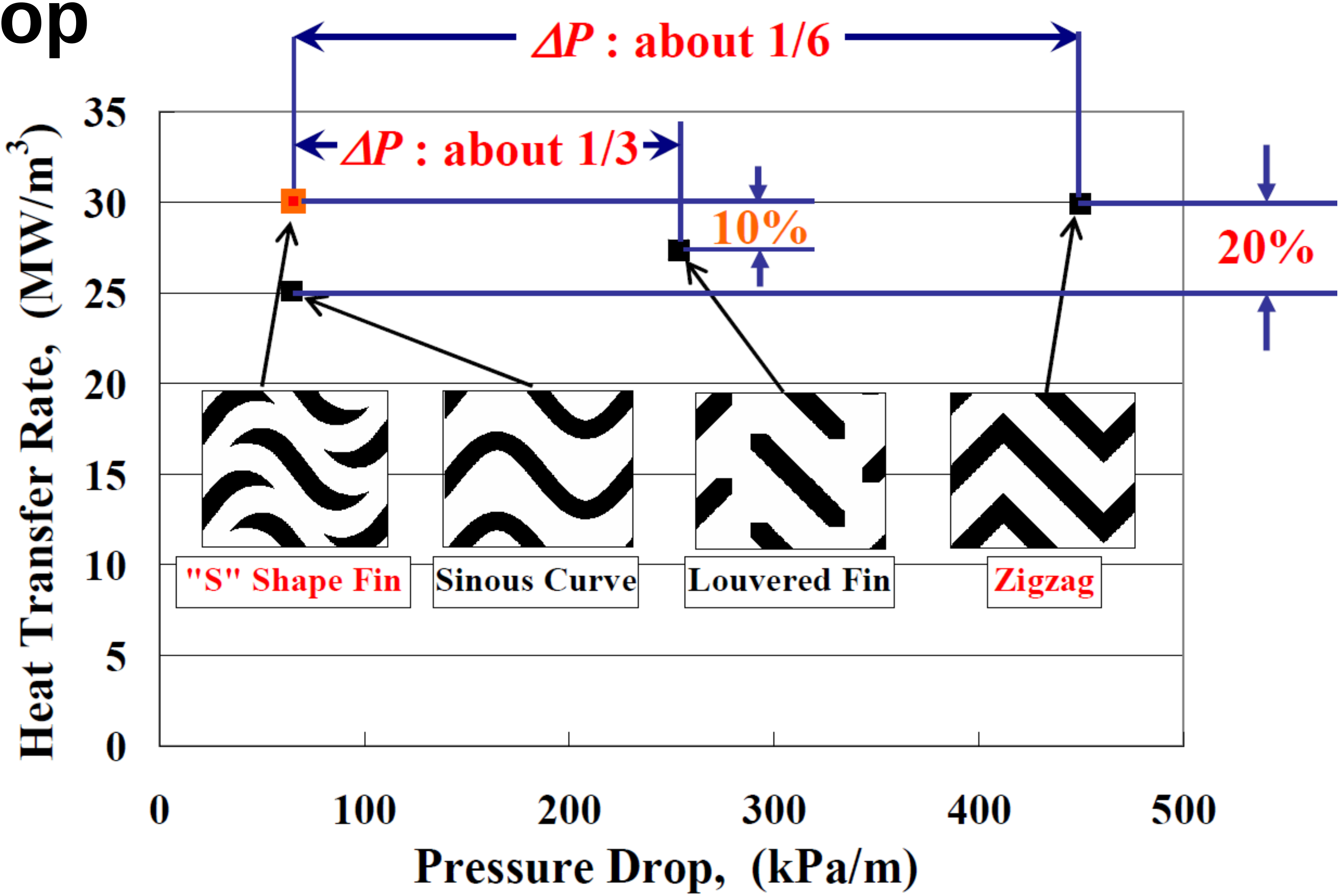
19,21 kW



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)

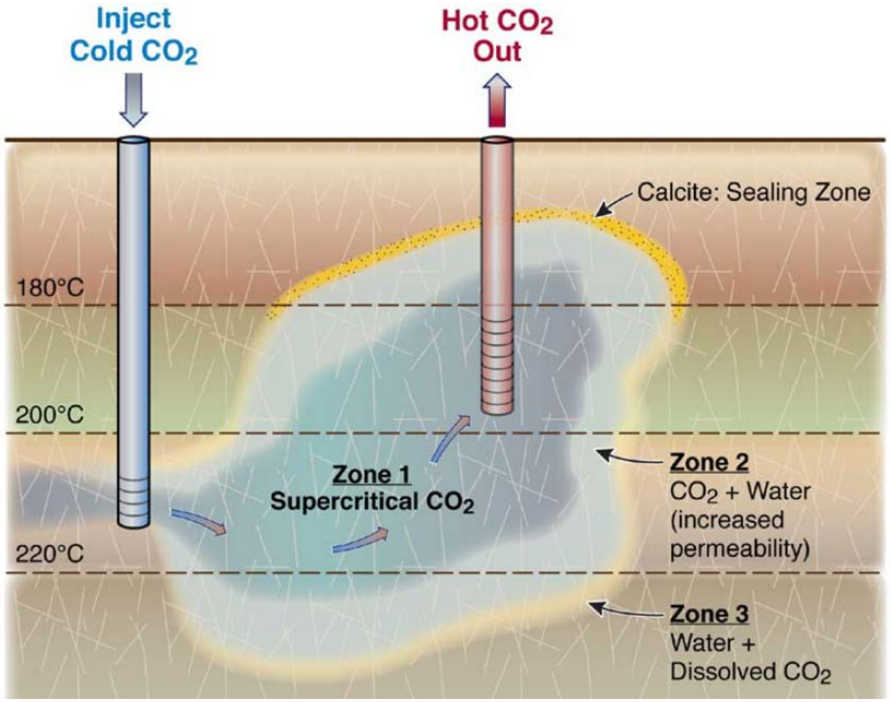
Other S-CO_2 Corrosion Test Facilities

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 S-CO_2

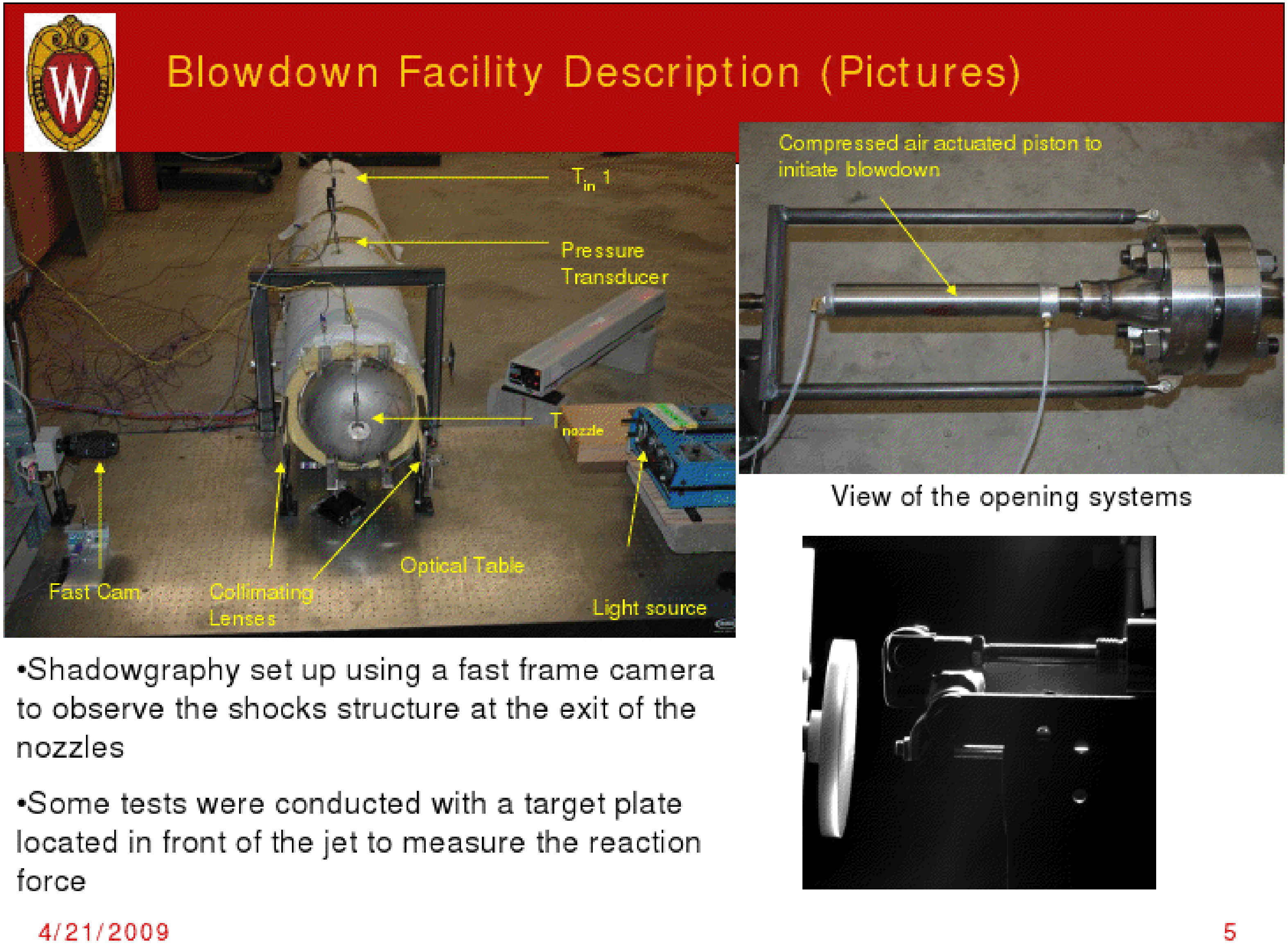
Pruess (May 19, 2010)

- 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)

S-CO$_2$ 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

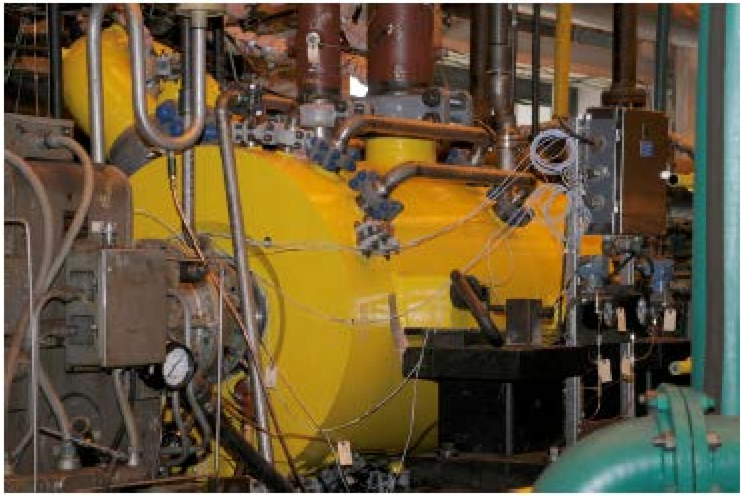
4/21/2009

5

(Anderson, 2009)

S-CO$_2$ High Pressure Compression (Dresser-Rand)

Tupi - I



Tupi - III

(GT2012-70137)

Future Trends for
S-CO_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 S-CO_2

Pulsation analysis

- ❑Development of transient pipe flow analysis models for S-CO_2

Future trends and research needs

Control System and Simulation

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

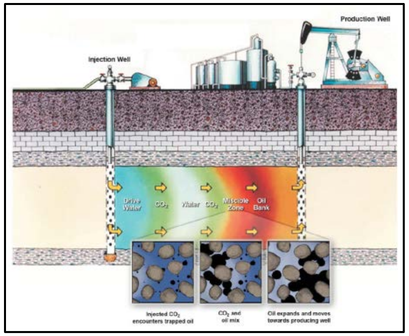
Fluid properties

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

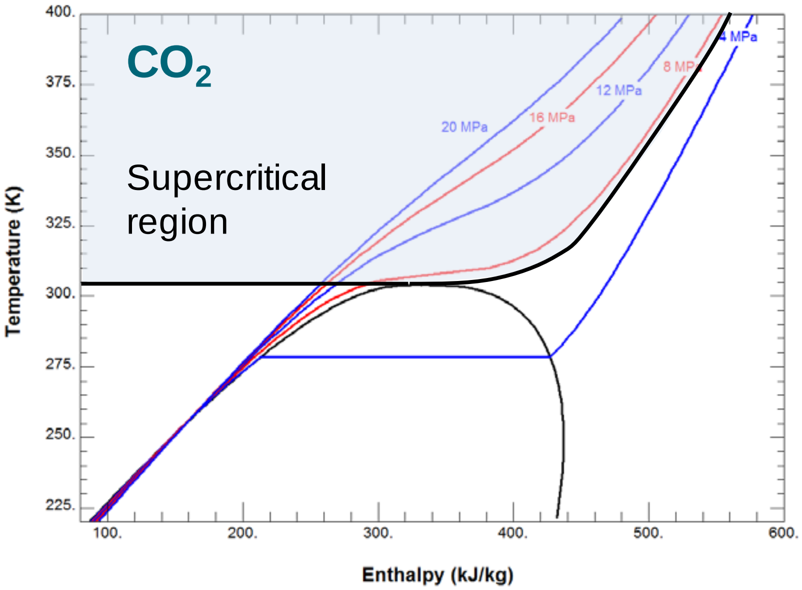
Summary

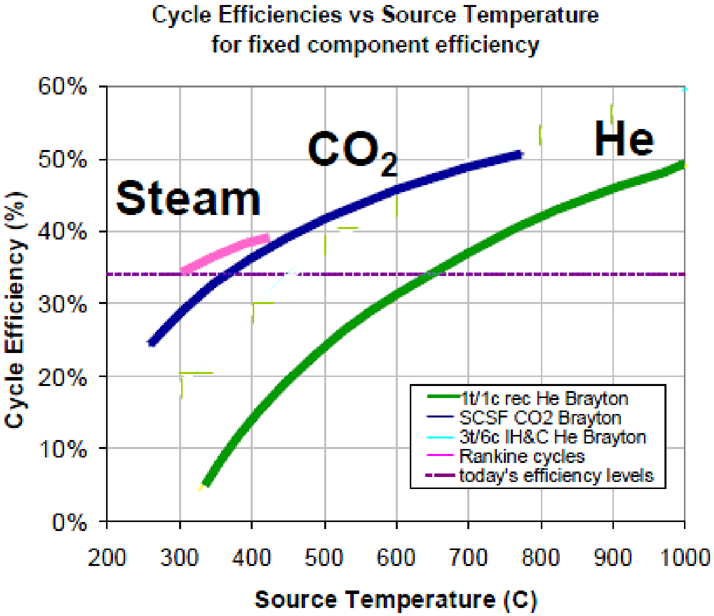
Both supercritical power cycles and the use of S-CO_2 are not new concepts

S-CO_2 is used in a variety of industries as a solvent



S-CO_2 is desirable for power cycles because of its near-critical fluid properties



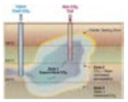


S-CO_2 power cycles can be applied to many heat sources and have a small footprint

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

Concentrated Solar Power

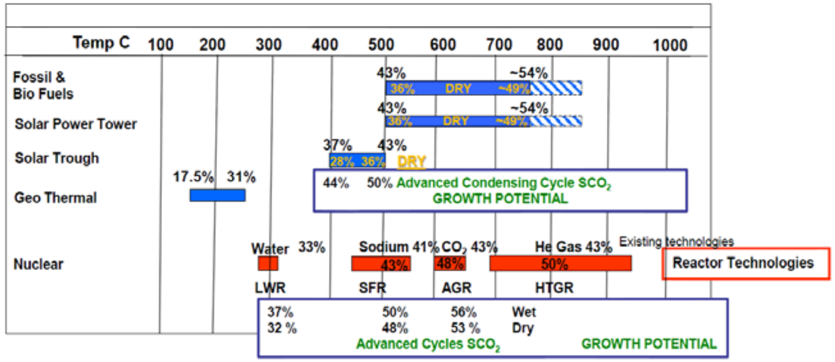
Fossil Fuel



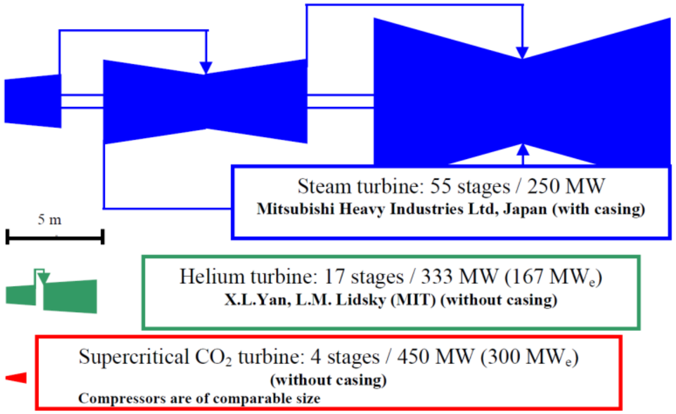
Geothermal

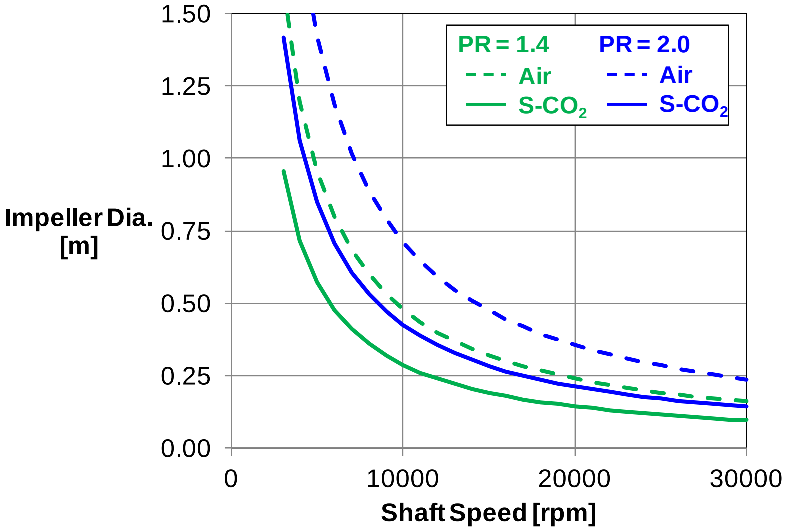
Nuclear

Ship-board Propulsion



The combination of favorable property variation and high fluid density of S-CO_2 allows small footprint of machinery





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

International S-CO_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 S-CO_2 power cycle applications

- Intermediate scale (10MW) demonstration
- Materials testing at high temperature, pressure and stress
- Property testing with S-CO_2 mixtures
- Rotordynamics with S-CO_2
- S-CO_2 heat transfer and heat exchangers
- More detailed dynamic simulation and control systems

Questions?