Abstract

The recent interest to use supercritical CO$_2$ (sCO$_2$) in power cycle applications over the past decade has resulted in a large amount of literature that focuses on specific areas related to sCO$_2$ power cycles in great detail. Such focus areas are demonstration test facilities, heat exchangers, turbomachinery, materials, and fluid properties of CO$_2$ and CO$_2$ mixtures, to name a few. As work related to sCO$_2$ power cycles continues, more technical depth will be emphasized in each focus area, whereas those unfamiliar with the topic are left to undertake the large task of understanding fundamentals on their own.

The following content provides an introductory tutorial on sCO$_2$ used in power cycle applications, aimed at those who are unfamiliar or only somewhat familiar to the topic. The tutorial includes a brief review of CO$_2$ and its current industrial uses, a primer on thermodynamic power cycles, an overview of supercritical CO$_2$ power cycle applications and machinery design considerations, and a summary of some of the current research and future trends.

The views and opinions expressed in this document are those of the authors and do not necessarily reflect the official policy or position of Southwest Research Institute.
This tutorial provides an introduction to sCO₂ in power cycle applications.

CO₂ and supercritical CO₂ (sCO₂)

sCO₂ loop hardware

Power cycle applications

Research and future trends
CO$_2$ General Information
CO$_2$ is a gas at atmospheric conditions with a concentration of $\approx 400$ ppm
There are both industrial and natural contributors and consumers of CO$_2$ in our atmosphere.
Fossil fuel combustion is the largest industrial contributor to CO₂ production

Source: “U.S. Climate Action Report 2014”
Transportation (petroleum) and electricity generation (coal) majority contributors of CO₂

Source: “U.S. Climate Action Report 2014”
CO₂ has human exposure limits, but is classified at “non-toxic”

Notes:
[1] Reference safety standards: OSHA, ACGIH, NIOSH (USA)
What is Supercritical CO$_2$?
\( \text{CO}_2 \) is supercritical if the pressure and temperature are greater than the critical values.

**Supercritical region**

7.37 MPa (1,070 psi)

31°C (88°F)

**Two-phase region**

**Gas**

**Liquid**

**REFPROP (2007), EOS CO\textsubscript{2}: Span & Wagner (1996)**
Fluids operating near their critical point have dramatic changes in enthalpy.

\[ C_p = \frac{\partial h}{\partial T} \]

**CO₂**

Supercritical region

**Air**

GT TIT

REFPROP (2007)
CO₂ density sharply decreases near the critical point.
CO₂ viscosity decreases through the critical point.
CO$_2$ thermal conductivity is enhanced near the critical region.
CO₂ thermal conductivity is enhanced near the critical region.
Power Cycle Basics
Power Cycle Basics Overview

Carnot – “the standard”

Brayton – gas cycle

Rankine – vapor cycle

Ideal vs. actual cycle

Cycle variations
Carnot Cycle

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

- Not practical to build
- Most efficient heat engine

\[ \eta_{th,\text{Carnot}} = 1 - \frac{T_L}{T_H} \]

↓T_L : Available heat sink?

↑T_H : Available heat source? Materials?
Brayton Cycle (Ideal)

- Processes
  1. Isentropic compression (1-2)
  2. Constant pressure heat addition (2-3)
  3. Isentropic expansion (3-4)
  4. Constant pressure heat rejection (4-1)

- Open- or closed-loop

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

\[ \uparrow PR, \uparrow k : \uparrow \eta_{th} \]

Optimal PR for net work

\[ \text{Closed-loop} \]
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

Temperature, T

Entropy, S

1-2, 3-4: Irreversibilities

Rankine

Temperature, T

Entropy, S

2-3, 4-1: Pressure losses
Power Cycle Variations

- Regeneration
- Intercooling
- Reheating
- Recompression

What is supercritical power cycle?
Brayton Cycle + Regeneration

Regenerator = recuperator

Effectiveness:
\[ \varepsilon = \frac{h_5 - h_2}{h_4 - h_2} \]

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
Multi-Stage Intercooling & Reheating

Approximates Ericsson cycle

\[ \eta_{th, Ericsson} = \eta_{th, Carnot} \]

Figure reference: Cengel and Boles (2002)
Brayton Cycle + Regeneration + Intercooling + Reheating

Figure reference: Cengel and Boles (2002)
Recompression in Brayton Cycle

Source: Ludington (2009)
What is a Supercritical Power Cycle?

![Diagram showing the Supercritical region, Liquid region, Liquid + vapor region, and Gas region on a T-S diagram.]

- **Supercritical region**
- **Liquid region**
- **Liquid + vapor region**
- **Gas region**

Temperature, $T$

Entropy, $S$

$T_{crit}$

$P_{crit}$
sCO\textsubscript{2} Power Cycles
## Why sCO$_2$ for Power Cycles?

<table>
<thead>
<tr>
<th>Property</th>
<th>Effect</th>
</tr>
</thead>
</table>
| High density, low viscosity, high CP near C.P. | • Reduced compressor work, increased $W_{\text{net}}$  
• Allow more-compact turbomachinery to achieve same power  
• Less complex – e.g., fewer compressor and turbine stages, may not need intercooling |
| Near-ambient $T_{\text{crit}}$   | • 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 |
CO₂ Cost Comparison*

*Based on market pricing for laboratory-grade substance
Calculated sCO$_2$ efficiencies close to a steam cycle for potentially less $/kW$

Relative Size of Components

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

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

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

Note: Compressors are comparable in size

Adapted from Dostal (2004)

Source: Wright (2011)
Example: 10 MWe Turbine Comparison

10 MWe SUPERCRITICAL CO₂ POWER TURBINE

10 MWe STEAM POWER TURBINE

Source: Persichilli et al. (2012)
sCO$_2$ in Power Cycle Applications
Supercritical CO₂ in Power Cycle Applications

Concentrated Solar Power

Fossil Fuel

Ship-board Propulsion

Nuclear

Geothermal

Waste Heat Recovery
Supercritical CO2 Power Cycle Applications

- **sCO2 CSP**
  - 50+ % $\eta_{th}$
  - 2020-2025

- **sCO2 WHR Compact**
  - $\eta_{th}$ > ORC
  - 2015-2020

- **ORC**

- **Direct Fired sCO2**
  - 2030+

- **sCO2 Fossil**
  - $\eta_{th}$ 2-5 pts above Steam
  - 2025+

- **Gen 4 Nuclear**
  - 2030+

- **Steam**

- **HDGT CC**

- **LWR**

[Bowman 2016]

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# Heat Source Operating Temperature Range & Efficiency

<table>
<thead>
<tr>
<th>Temp C</th>
<th>100</th>
<th>200</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
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</thead>
<tbody>
<tr>
<td>Fossil &amp; Bio Fuels</td>
<td></td>
<td></td>
<td></td>
<td>43%</td>
<td>36%</td>
<td>DRY</td>
<td>~54%</td>
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<tr>
<td>Solar Power Tower</td>
<td></td>
<td></td>
<td></td>
<td>37%</td>
<td>43%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Solar Trough</td>
<td></td>
<td>17.5%</td>
<td>31%</td>
<td></td>
<td></td>
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<tr>
<td>Geo Thermal</td>
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<tr>
<td>Nuclear</td>
<td>Water</td>
<td>33%</td>
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<tr>
<td>LWR</td>
<td>Sodium 41%</td>
<td>CO₂ 43%</td>
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<td></td>
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<tr>
<td>SFR</td>
<td>He Gas 43%</td>
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<tr>
<td>AGR</td>
<td>48%</td>
<td>50%</td>
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<tr>
<td>HTGR</td>
<td>53%</td>
<td>Wet Dry</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37%</td>
<td>32%</td>
<td>Advanced Cycles CO₂</td>
<td>Growth Potential</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

Assumptions (Turbomachinery Eff (MC 85%, RC 87%, T 90%), Wright (2011)
Supercritical CO$_2$ in Power Cycle Applications

1. Concentrated Solar Power
2. Fossil Fuel
3. Geothermal
4. Nuclear
5. Ship-board Propulsion
6. Waste Heat Recovery
Why would we use solar power?

Surface Area Required to Power the World

Boxes to-scale with map:
- 1980 (based on actual use)
  207,368 SQUARE KILOMETERS
- 2008 (based on actual use)
  366,375 SQUARE KILOMETERS
- 2030 (projection)
  496,805 SQUARE KILOMETERS

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

The large square in the Saharan Desert (1/4 of the overall 2030 required area) would power all of Europe and North Africa. Though very large, it is still 18 times less the total area of that desert. (area calculation does not include black border lines)
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.
sCO$_2$ CSP Process Diagram

Dual-shaft, tower receiver sCO$_2$ Brayton Cycle solar thermal power system with thermal energy storage, Zhiwen and Turchi (2011)
The transient challenges of a concentrated solar power plant are significant.
Optimal Cycle Configuration with varying Compressor Inlet Temperature

- SAM modeling of typical sites shows an annual average compressor inlet temperature to be 37-38°C assuming 15°C approach temperature in the cooler

- Cycle Modeling
  - Optimal flow split
    - 22-33%
    - Heavily dependent on CIT
  - Optimal PR
    - Varies with use of intercooling
  - Intercooled cycles are more efficient on hot days, and less efficient on cool days
CSP Compressor Inlet Variation and Turbomachinery Performance

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

Figure 5: Comparison of Operating Range and Pressure Ratio Requirements [Modified from Japikse\textsuperscript{[5]}]
Conceptual 10 MW_e Integrally Geared Compressor Applied to Recuperated Brayton Cycle

Generator

Compressors

Re-Compressors

Shaft to Generator

Expanders

Main Oil Pump
What are the key challenges to CSP sCO2 cycles

- Variable inlet temperature creates numerous cycle challenges
  - Dry cooling mandatory
  - Compressor operation near the critical point requires careful cycle control (not yet demonstrated)
- Heat addition to the sCO2 while incorporating thermal energy storage is challenging
- Turbine inlet temperatures approaching 750° with very high cycle efficiency requirements expected.
Supercritical CO₂ in Power Cycle Applications

Concentrated Solar Power

Fossil Fuel

Geothermal

Nuclear

Ship-board Propulsion

Waste Heat Recovery
Rankine Cycle Application: Nuclear Power Generation

Image source: [6-8]
sCO$_2$ for Nuclear Applications
(550°C-700°C, 34 MPa)
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)
## Advantages of CO₂ Cycle vs. Helium Cycle in Nuclear Applications

<table>
<thead>
<tr>
<th>Pro</th>
<th>Con</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smaller turbomachinery than steam or helium</td>
<td>Helium preferred to CO₂ as a reactor coolant for cooling capability and inertness</td>
</tr>
<tr>
<td>CO₂ Brayton cycles are more efficient than helium at medium reactor temperatures</td>
<td>CO₂ requires a larger reactor than helium or an indirect cycle</td>
</tr>
<tr>
<td>CO₂ is 10× cheaper than Helium</td>
<td>New technology</td>
</tr>
</tbody>
</table>
Supercritical CO₂ in Power Cycle Applications

Concentrated Solar Power

Fossil Fuel

Geothermal

Nuclear

Ship-board Propulsion

Waste Heat Recovery
Oxy-Fuel Combustion

Conventional Combustion

Air
(78% N₂, 21% O₂)

Fuel

(Solar Turbines 2012)

Oxy-Fuel Combustion

O₂

Fuel

CO₂

H₂O

Desired Operating Range

Lean Fuel/Air Ratio

Rich

Emissions

CO

NOₓ
Direct Oxy-Fuel Combustion

CO₂ Compressor → Oxy Combustor → CO₂ Turbine → Generator

NG → O₂

Condenser

CO₂ → Water

HRSG

Steam Rankine Cycle

Steam Turbine

Generator

Electricity
Allam Cycle (NetPOWER)

Net Efficiency 58.9%

© Southwest Research Institute 2012
The Allam Cycle (NetPOWER)

Oxygen 4.75% of Mass
Natural Gas 1.25% of Mass

Hot CO$_2$ 94% of Mass

Very Hot Water 2.75% of Mass
Hot Water 2.75% of Mass

Cool Water 2.75% of Mass

Compressor and Pump

Pipeline Ready CO$_2$ 3.25% of Mass

Clean Water 2.75% of Mass

Line Width Proportional to Mass
Component Development

Controls System designed by 8 Rivers and under development with leading control vendor.

Turbine and combustor under development with Toshiba
Indirect Oxy-Fuel Combustion

Zero Emission Oxy-Coal Power Plant with Supercritical CO₂ Cycle, Johnson et al. (2012)
What are the key challenges for oxy-fuel sCO2 cycles

- Very high combuster and expander temperatures (1200°C)
  - Film cooling mandatory
  - Containment challenges
  - Sealing challenges
- Unproven combustion dynamics
- Complex auxiliary hardware
Supercritical CO$_2$ in Power Cycle Applications

- Concentrated Solar Power
- Fossil Fuel
- Geothermal
- Nuclear
- Ship-board Propulsion
- Waste Heat Recovery
Ship-board Propulsion

- Nuclear sCO\textsubscript{2} cycles?
- Improved power to weight
- Rapid startup
- Bottoming cycles

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

Helium turbine: 17 stages / 333 MW (167 MW\textsubscript{e})
X.L. Yan, L.M. Lidsky (MIT) (without casing)

Supercritical CO\textsubscript{2} turbine: 4 stages / 450 MW (300 MW\textsubscript{e})
(without casing)
Compressors are of comparable size

Source: Dostal (2004)
Key challenges to sCO2 nautical applications

- Weight
- Startup transient response times
- Impulse load robustness
- Containment (ships do get hit)
Supercritical CO\textsubscript{2} in Power Cycle Applications

Concentrated Solar Power

Fossil Fuel

Geothermal

Nuclear

Ship-board Propulsion

Waste Heat Recovery
Geothermal

- Low Temperature Heat Source
  - $T \approx 210^\circ C$, $P \approx 100$ bar
US Geothermal Resources

[Map showing estimated surface heat flow in the United States with color coding for different values.]

Courtesy: Higgins 2016

© Southwest Research Institute 2012
Global Geothermal Resources

Hottest Known Geothermal Regions

Courtesy: [Higgins 2016]
ECO2G

Conventional Hydrothermal

Closed-Loop Supercritical CO$_2$

Courtesy: [Higgins 2016]
P-v & T-s Diagram

P-v

T-s

© Southwest Research Institute 2012

Courtesy: [Higgins 2016]
How does a Thermosiphon Work

Cold Gas In

Horizontal Heat In

ΔP Turbine

Hot Gas Out

Pressure [MPa]

Density [kg/m³]

Length [m]

Density
Pressure

© Southwest Research Institute 2012

Courtesy: [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 s-CO2 Based Geothermal

- Highly Compressible
  - Produces a strong thermosiphon
- Inexpensive
- High-Efficiency, Small Turbines
- No Process Water
- Outperforms Hydrothermal
  - Steam (flash tank) and binary (ORC) cycles
- Environmentally Friendly
  - Relatively Inert
  - No Process Water
  - Zero Emissions
  - Small Footprint
Challenges to sCO2 geothermal

- Drilling technology is very expensive and (probably) not a sure thing.
Supercritical CO\textsubscript{2} in Power Cycle Applications

Concentrated Solar Power

Fossil Fuel

Geothermal

Nuclear

Ship-board Propulsion

Waste Heat Recovery
Waste Heat Recovery (Bottoming)

- **Rankine Cycle Description**
  1. Liquid CO\textsubscript{2} is pumped to supercritical pressure
  2. sCO\textsubscript{2} accepts waste heat at recuperator and waste heat exchanger
  3. High energy sCO\textsubscript{2} is expanded at turbo-alternator producing power
  4. Expanded sCO\textsubscript{2} is cooled at recuperator and condensed to a liquid at condenser

*Image source: [6-11]*

*Image source: [6-12]*
Key challenges to sCO2 bottoming cycles

- Efficiencies and costs must compete with steam/ORC at relevant temperatures
- Unproven technology must move into a field with proven WHR solutions (steam/ORC)
  - Since WHR is not the primary asset in nearly any implementation, shutting down production or heat generation for an unproven benefit is challenging.
Other $\text{sCO}_2$ Power Cycle Applications

Non-Concentrated Solar Power

Combined Heat & Power

Zhang (2005)
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 (2007)
sCO₂ Rankine Cycle in Combined Heat and Power (CHP)

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

Moroz (2014)
sCO\textsubscript{2} as a Refrigerant

Image source: [6-13]

Image source: [6-14]
sCO₂ vs R-22 in Refrigeration

- Employed MCHEs
- Summary
  - CO₂ 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
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

\[
\text{COP} = \frac{Q_h + W_e}{W_e}
\]

Image source: [6-14]

EcoCute Heat Pump (2007)
Supercritical CO$_2$ Power Cycles Symposium
sCO$_2$ Power Cycle

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

J. Jeffrey Moore, Ph.D.
Klaus Brun, Ph.D.
Pablo Bueno, Ph.D.
Stefan Cich
Neal Evans
Kevin Hoopes

Southwest Research Institute
C.J. Kalra, Ph.D.,
Doug Hofer, Ph.D.
Thomas Farineau

General Electric
John Davis
Lalit Chordia

Thar Energy
Brian Morris
Joseph McDonald
Ken Kimball

Bechtel Marine

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

- To develop a novel, high-efficiency supercritical sCO\textsubscript{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\textsubscript{2} turbo-expanders from TRL3 to TRL6.
- To optimize compact heat exchangers for sCO\textsubscript{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\textsubscript{2} expander design and improved heat exchanger address and close two critical technology gaps required for an optimized CSP sCO\textsubscript{2} power plant.
- Provide a major stepping stone on the pathway to achieving CSP power at $0.06/kW-hr levelized cost of electricity (LCOE), increasing energy conversion efficiency to greater than 50% and reducing total power block cost to below $1,200/kW installed.
Project Approach

- Work has been divided into three phases that emulate development process from TRL3 to TRL6

- Phase I – Turbomachinery, HX, and flow loop design (17 months)

- Phase II – Component fabrication and test loop commissioning (12 months)

- Phase III – Performance and endurance testing (6 months)
Recuperator Prototypes – 5 and 50 kW

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

Laser Welded Construction:
• Undergoing flow tests
• Exceeded design predictions for HTC
• Held 2500 psi @ 600°F
A novel turboexpander has been designed to meet the requirements of the sCO2 power with these targets:

- ~14MW shaft power
- >700C inlet temp
- >85% aero efficiency
10 MW SCO2 Turbine Concept
Test Loop Design
Mechanical Test Configuration

Pipe Section
- Pump to heater
- LT heater to recuperator
- Recuperator to HT heater
- HT heater to expander
- Expander to recuperator
- Recuperator to existing
- Existing facility piping
- Existing facility piping (unused)
- Existing piping to pump

Color
- Dark blue
- Yellow
- Orange
- Red
- Dark green
- Light green
- White
- Dark gray
- Light blue
DOE sCO₂ 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 sCO₂ Test Program
Turbomachinery

Tie Bolts (Pre-stressed)
Low Pressure Rotor Cavity Chamber (150 psia)

Turbine
Laby Seals
Water Cooling
Stator
PM Motor Generator
Thrust Bearing

Journal Bearing

Gas-Foil Bearings

Source: Wright (2011)
sCO$_2$ Brayton Cycle Test Loop

Source: Wright (2011)
sCO₂ Brayton Cycle Test Loop

Motor
Generator
Controllers

Turbomachinery

520 kW Heater

PCHE Recup
2.3 MW

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)

sCO₂ 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 CO₂ Cycle Mockup Test Loop

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

(Kato et al., 2007)
Corrosion Loop at Tokyo Institute of Technology

316 SS, 12% Cr alloy, 200-600°C, 10 Mpa CO₂, Kato et al. (2007)
Other sCO$_2$ Corrosion Test Facilities

- 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.

Guoping (2009)
Geothermal Research

- Explore the feasibility of operating enhanced geothermal systems (EGS) with CO₂ 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 CO₂ heat extraction
  - Japan: inject brine-CO₂ mixtures into Ogachi HDR site (T ≈ 210°C, P ≈ 100 bar)
  - LBNL: model reactive chemistry induced by brine-CO₂ injection
sCO₂ Critical Flow (Univ. Wisconsin)

 Blowdown Facility Description (Pictures)

- 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

Compressed air actuated piston to initiate blowdown

View of the opening systems

(Anderson, 2009)
Future Trends for sCO$_2$ Power Cycles
Future trends and research needs

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

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

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

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

Pulsation analysis
- Development of transient pipe flow analysis models for sCO₂
Future trends and research needs

Control System and Simulation
- Detailed models of turbo machinery
- Improved transient analysis – surge, shutdown events

Fluid properties
- Mixture of sCO₂ and other fluids
- Physical property testing of CO₂ mixtures at extreme conditions with significantly reduced uncertainties (i.e. < 1%)

10 MW Scale Pilot Plant
Summary
Both supercritical power cycles and the use of sCO$_2$ are not new concepts.

sCO$_2$ is used in a variety of industries as a solvent.

sCO$_2$ is desirable for power cycles because of its near-critical fluid properties.
sCO$_2$ power cycles can be applied to many heat sources and have a small footprint.

The near ambient critical temperature of CO$_2$ allows it to be matched with a variety of thermal heat sources:

- Concentrated Solar Power
- Fossil Fuel
- Geothermal
- Nuclear
- Ship-board Propulsion
- Solar Power Tower
- Solar Trough
- Geo Thermal
- Fossil & Bio Fuels
- Advanced Condensing Cycle SCO$_2$

The combination of favorable property variation and high fluid density of sCO$_2$ allows small footprint of machinery.

![Diagram showing comparisons of various power cycles](image)

- Steam turbine: 55 stages / 250 MW
- Mitsubishi Heavy Industries Ltd, Japan (with casing)
- Helium turbine: 17 stages / 333 MW (167 MW$_e$)
  X.L. Yan, L.M. Lidsky (MIT) (without casing)
- Supercritical CO$_2$ turbine: 4 stages / 450 MW (300 MW$_e$)
  (without casing)

![Graph showing impeller diameter vs. shaft speed](image)

- PR = 1.4
- PR = 2.0

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222
The near future goal is to improve understanding and develop commercial-scale power

International sCO₂ power cycle research is ongoing

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

More research is needed sCO₂ power cycle applications

- Intermediate scale (10MW) demonstration
- Materials testing at high temperature, pressure and stress
- Property testing with sCO₂ mixtures
- Rotordynamics with sCO₂
- sCO₂ heat transfer and heat exchangers
- More detailed dynamic simulation and control systems

Questions?
How has technology progressed

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What's Next

[Bowman 2016]