SUPERCritical CO₂ Power Cycle Development Summary at Sandia National Laboratories

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Advanced Nuclear Technology
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Goals of Presentation

• *What is a Supercritical CO₂ Brayton Cycle?*
• Economic and Environmental Benefits of S-CO₂ Power Systems
  – Economic and Environmental
  – All Heat Sources
• Scaling Study Results (10 MWe)
  – 10 MWe Development and Demonstration Program Status of Development Effort
  – Commercial and Government
• DOE Gen-IV S-CO₂ Research Program
• Summary and Conclusions
What is a Supercritical CO$_2$ Brayton Cycle? How does it work?

**Liquid like Densities with CO$_2$**

Very Small Systems,

High Efficiency due to Low Pumping Power

High Efficiency at Lower Temp
(Due to Non-Ideal Gas Props)

Non-Ideal Gas Means Higher Efficiency at Moderate Temperature

Cycle Efficiencies vs Source Temperature
for fixed component efficiency

Critical Point

88 F / 31 C
1070 psia / 7.3 MPa

Reacts Heat Above Critical Point
High Efficiency Non-Ideal Gas
Sufficiently High for Dry Cooling

Critical Point

31 C (88 F)

Critical Point

1070 psia / 7.3 MPa

Steam Turbine (250 MWe)

S-CO$_2$ (300 MWe)

He Turbine (300 MWe)

Steam Condensor

S-CO$_2$ Cooler

Steam Condensor

He Turbine

S-CO$_2$ (300 MWe)

Steam Turbine (250 MWe)

High Density Means Very Small Power Conversion System

Today's efficiency levels
Supercritical CO₂ Cycle Applicable to Most Thermal Heat Sources

Solar

Military Fix Base & Marine

ARRA Geothermal

Waste Heat Bottoming Cycle to a Gas Turbine

SNL Solar Tower

Nuclear (Gas, Sodium, Water)

SNL has Funding or Research Agreements with most Agencies Representing these Heat Sources

DOE-NE Gen IV

Carbon Capture & Sequestration CCS Fossil

Energy Storage & Heat Transport & CCHE

Clean Coal & Natural Gas Power Systems
Key Features to a Supercritical Brayton Cycle

- Peak Turbine Inlet Temp is well matched to a Variety of Heat Sources (Nuclear, Solar, Gas, Coal, Syn-Gas, Geo)
- Efficient ~43% - 50% for 10 - 300 MWₑ Systems
  - 1000 F (810 K) ~ 538 C Efficiency = 43%
  - 1292 F (1565 K) ~ 700 C Efficiency = 50%
- Standard Materials (Stainless Steels and Inconels)
- High Power Density for Conversion System
  - ~30 X smaller than Steam or 6 X for Helium or Air
  - Transportability (Unique or Enabling Capability)
  - HX’s Use Advanced Printed Circuit Board Heat Exchanger (PCHE) Technology
- Modular Capability at ~10-20 MWe
  - Factory Manufacturable (10 MW ~ 2.5m x 8m)
- Advanced Systems (Increase Eff 5-8% points) & Dry

GenIV S-CO₂ Brayton Cycle

Turbine Building

Steam

S-CO₂

Good Efficiency at Low Operating Temps
Standard Materials, Small Size
Modular & Transportable
AFFORDABLE and FABRICABLE

Modular & Self Contained Power Conversion Systems
~ 1.5 m x 8 m
Heat Source Operating Temperature Range & \( \text{SCO}_2 \) Power Conversion Efficiency for Various Heat Sources

<table>
<thead>
<tr>
<th>Heat Source</th>
<th>Operating Temperature Range</th>
<th>Power Conversion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil &amp; Bio Fuels</td>
<td>100 → 1000°C</td>
<td>43%</td>
</tr>
<tr>
<td>Solar Power Tower</td>
<td>100 → 1000°C</td>
<td>43%</td>
</tr>
<tr>
<td>Solar Trough</td>
<td>100 → 1000°C</td>
<td>43%</td>
</tr>
<tr>
<td>Geo Thermal</td>
<td>100 → 1000°C</td>
<td>43%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>100 → 1000°C</td>
<td>43%</td>
</tr>
</tbody>
</table>

Optimum Design Requires Different Approaches for Each Heat Source

Supercritical Fluid Technology has Untapped Growth Potential

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)
S-CO$_2$ Power Cycle Economic and Environmental Benefits

- DOE has invested 5 years and ~ $10-11$ M on Proof-of-Principle S-CO$_2$ Power Systems

- The Potential Economic and Environmental Benefits of S-CO$_2$ Power Systems are Large
  - Useful with All Heat Sources
  - Wide number of Applications (Bottoming Cycles, Solar, Waste Heate, Marine, Nuclear..)
  - Economic Benefits Mean 100’s of Billions of Dollars
  - Environmental Benefits are also Large
    - Increased Efficiency
    - Significant Efficiency improvements for Carbon Capture and Sequestration with Advanced Coal Combustion
    - Dry Cooling is possible for all heat sources

- Development is Still Needed (especially at larger scales)
  - Heat Source and Power Cycle are Linked (Cycle/Design Research)
  - Heat Exchanger Development is Needed
    - Micro-Channel Design Costs, Nuclear Certification, Packaging, Failure Modes, Cost Reductions
  - Commercial Engineering and Demonstration is Needed using Industrial Hardware (~10 MW$_e$)
Potential Markets

- Pulverized Coal Steam Plant Replacement Efficiency upgrade Efficiency to >50%
  - X100’s of plants refurbished
- PC with CCS Demo System
- Solar Power Towers
  - Renewable Portfolio Standard
  - 6 Plants planned (50-100 MW_e each)
- Solar Troughs (Needs cycle optimized for 400 C)
- Integrated Bio-Fuel/SCO_2 Plant (Carbon Reduction Requirements)
- Military Applications (Fixed Base and Marine)
- Commercial Marine (Gas Fired Turbines)
- Geo-Thermal Wells
- Waste Heat Applications
  - Gas Turbine Bottoming Cycle
  - Supercritical Water Oxidation
- Nuclear Reactors
  - (LWR, SFR, GCR, Molten Salt Reactors)
Scaling Study
### Scaling Rules and Ranges of Application for Key Brayton Cycle Turbomachinery Components

<table>
<thead>
<tr>
<th>TM Feature</th>
<th>Power (MWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td><strong>TM Speed/Size</strong></td>
<td></td>
</tr>
<tr>
<td>75,000 / 5 cm</td>
<td></td>
</tr>
<tr>
<td>30,000 / 14 cm</td>
<td></td>
</tr>
<tr>
<td>10,000 / 40cm</td>
<td></td>
</tr>
<tr>
<td>3600 / 1.2 m</td>
<td></td>
</tr>
<tr>
<td><strong>Turbine type</strong></td>
<td></td>
</tr>
<tr>
<td>Single stage</td>
<td></td>
</tr>
<tr>
<td>Radial multi stage</td>
<td></td>
</tr>
<tr>
<td>Axial multi stage</td>
<td></td>
</tr>
<tr>
<td><strong>Bearings</strong></td>
<td></td>
</tr>
<tr>
<td>Gas Foil</td>
<td></td>
</tr>
<tr>
<td>Hydrodynamic oil</td>
<td></td>
</tr>
<tr>
<td>Magnetic</td>
<td></td>
</tr>
<tr>
<td>Hydrostatic</td>
<td></td>
</tr>
<tr>
<td><strong>Seals</strong></td>
<td></td>
</tr>
<tr>
<td>Adv labyrinth</td>
<td></td>
</tr>
<tr>
<td>Dry lift off</td>
<td></td>
</tr>
<tr>
<td><strong>Freq/alternator</strong></td>
<td></td>
</tr>
<tr>
<td>Permanent Magnet</td>
<td></td>
</tr>
<tr>
<td>Wound, Synchronous</td>
<td></td>
</tr>
<tr>
<td>Gearbox, Synchronous</td>
<td></td>
</tr>
<tr>
<td><strong>Shaft Configuration</strong></td>
<td></td>
</tr>
<tr>
<td>Dual/Multiple</td>
<td></td>
</tr>
<tr>
<td>Single Shaft</td>
<td></td>
</tr>
</tbody>
</table>

**High Technology**  
High $$/kWe ← Commercial Technology  
Lower $$/kWe  

- 10 MWe allows use of Commercial Technologies
Approximate Shaft Speed and Turbine Wheel Diameter

**Shaft Speed versus Elect. Power**

- **1 stage rpm**
- **2 stage rpm**
- **3 stage rpm**

**Turbine Diameter versus Elect. Power**

- **1 stage Turb OD**
- **2 stage Turb OD**
- **3 stage Turb OD**

Shaft Speed (rpm): 15 krpm, 35 krpm

Turbine OD (m): 0.25 m ~ 10”
Printed Circuit Heat Exchanger Scaling Rules

<table>
<thead>
<tr>
<th>Actual</th>
<th>Specific Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>kW</td>
</tr>
<tr>
<td>60000</td>
<td>510</td>
</tr>
<tr>
<td>106000</td>
<td>1600</td>
</tr>
<tr>
<td>210000</td>
<td>2300</td>
</tr>
<tr>
<td>Average</td>
<td></td>
</tr>
</tbody>
</table>

= $ 600/kWe

Need 50% reduction (Materials, Scale, & Advanced Manuf.) to reach 200$/ kWe
Concentrated Solar Applications

Small or Big?
1-10 MWe or 100 MWe

Modular s-CO2 receiver / power block in each tower...

or centralized s-CO2 power block with salt receivers?

Advanced S-CO₂ Power System
Reheat and Inter-Cooling   TIT=700°C

S-CO₂ Recompression Brayton Cycle
(with Reheat and IC)

Efficiency or Split Flow Fraction

Compressor Inlet T
DOE Supercritical CO$_2$ Program
Description
• DOE Gen-IV S-CO\textsubscript{2} Research Program
  • Testing
    – Brayton and Compression Loop Descriptions
    – Compressor Performance Mapping
    – \textbf{Power Generation in Simple Heated Brayton Cycle}
    – Mixtures
    – Condensation Cycles
    – Thrust Bearing Heating
    – Sealing Technology
  • Modeling
  • Ability of Sandia S-CO\textsubscript{2} Brayton Loop to Reproduce Other Cycles
  • \textbf{Summary and Conclusions}
Key Technology
Turbo- Alternator Compressor Design
Permanent Magnet Generator with Gas Foil Bearings
~24” Long by 12” diameter

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

Turbine
Laby Seals

Journal Bearing
Stator

Water Cooling
PM Motor Generator
Thrust Bearing

Compressor

Gas-Foil Bearings

125 kWe at 75,000 rpm
GenIV-Supercritical CO$_2$ Brayton Cycle Loop

Motor
Generator
Controllers

PCHE Recup
2.3 MW

Turbomachinery

520 kW
Heater
Power Generation in Upgraded S-CO2 Simple Heated Recuperated Brayton Loop

![Graph showing TAC A Speed and Power over time](image)

- **Startup Transient Complete**
- **Breakeven**
- **Electrical Power Generated 15 kWe**

**Axes:**
- **Time [s]**: 0 to 7000
- **TAC A Speed [rpm]**: 0 to 6 x 10^4
- **Power [W]**: -1.5 to 1.5 x 10^4

**Lines:**
- **RPM A**
- **SetRPM1**
- **Power A**
Loss Measurements
C-2 Compressor T-2 Turbine

Fraction of Turbine Power Used or Lost

Fraction Elect. Loss

- Compressor
- Total Elect.
- Windage
- Thermal

Heat Loss

Windage Loss
S-CO$_2$: Summary and Conclusions

Potential for S-CO$_2$ Power Conversion Systems to Improve Economics and Environmental Issues on a Large Scale

1) *Dry Cooling*
2) *CCS*
3) *Improved Efficiency*

For All Types of Heat Sources
Sandia Research Program Summary

• Sandia/DOE have two operating S-CO$_2$ test loops
  – Research Compression Loop
  – Reconfigurable Brayton Loop

• Measured Main Compressor Flow Maps
  – Overall Good Agreement with Mean-Line Predictions of the Performance Maps
  – Over a wide range of operating Temperature, pressure, and density

• Using Brayton loop Configuration available in FY2010
  • Heater power was limited to 520/390 kW
  • Produced Power in simple heated recuperated Brayton loops (Main TAC and Re-Comp TAC)
  • Cold Startup, Breakeven, Power Production (6% efficiency and 20 kWe), Power/RPM Operation Maps

• Condensation in Tube and Shell and PCHE heat exchangers
  – Improved Efficiency

• Test (critical point) were performed with mixtures of CO$_2$, CO$_2$-Neon, CO$_2$ SF$_6$, CO$_2$-Butane
  – Can Increase or decrease T$_{crit}$
  – Improved Efficiency (especially for low temperature applications)

• Thrust Gas Foil Bearing Tests and Modeling
  – Goal : higher thrust load capability and lower frictional power

• Natural Circulation
  – S-CO$_2$ Gas Fast Reactor
  – C3D CFD Model development

• Collaborations with Industry + Larger Scale System Development
Path Forward

Path Forward

• Continue Testing of Proof-of-Principle Small Loop
• Work/Collaborate with industry to develop S-CO₂ System for any heat source at the 10 MWₑ sized system
• Propose for First Nuclear Applications
  – Use with LWRs
  – Wet and Dry Cooling
  – 37% and 30% Efficiencies
  – Develop S-CO₂ Systems for Nuclear Technology

Begin Seeking Gov. Funded 10 MWₑ S-CO₂ power system development to support FE, EERE, NE, others

• Useful for all heat sources (Nuclear, Solar, Fossil, Geothermal)
• Numerous early non-nuclear Products (Marine, Fossil, Solar, Geo, Waste Heat, Heat Storage and Transport)
• Improved the economic and environmental benefits for all systems
• Dry Cooling is Possible
  – Required for some heat sources
  – Power Cycle modifications are required