DOE Generation IV Energy Conversion

Supercritical CO2 Cycle Development

Paul Pickard (SNL)
Technical Director – Gen IV Energy Conversion

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# Generation IV Energy Conversion

- **Electrical generation** - *Gen IV Energy Conversion Program*
- **Hydrogen production** - *Nuclear Hydrogen Initiative (NHI)*

<table>
<thead>
<tr>
<th>Temp C</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
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</table>

- **Sulfur Cycles**
- **Alt Cycles**
- **High Temp Elect**
- **He Brayton**
- **S-CO2 Brayton**
- **Rankine**

**Gen IV Reactor Output Temperature Ranges**

**Hydrogen Production Methods**

**Electrical Conversion Technologies**
Gen IV Energy Conversion Objectives: Optimize performance and cost effectiveness of Gen IV reactors

Brayton Cycle Options for Gen IV Reactors

- 1t/1c rec He Brayton
- SCSF CO2 Brayton
- 3t/6c IH&C He Brayton

Source Temperature (°C)

Cycle Efficiency (%) vs Source Temperature

- Rankine Bottoming Cycle
- Interstage Heated, Cooled - He Cycle
- Recuperated He Cycle

Figure 11: T-s plot for simple Brayton cycle using Helium flow at 6.9 and 23 MPa with SC steam bottoming cycle with mass flow ratio of 1.241 water/helium (eff=48%)

Figure 13: T-s diagram for split flow recuperated Brayton cycle using CO2 between 7.5 and 22.5 MPa with 29% of the flow diverted by the intermediate compressor (eff=49%)
FY07 Gen IV Power Conversion

S-CO2 - intermediate temperature reactors (500-700 C)
- High efficiencies in intermediate temperature ranges
- Relatively compact, little additional complexity
- Potential for reduced capital costs
- Key issues – compression near critical point, control strategy for split flow

FY07 Task Areas
1. S-CO2 system design (MIT)
2. S-CO2 control analysis (ANL, MIT)
3. PCHE heat transfer experiments (ANL)
4. S-CO2 materials testing (MIT, LANL)
5. Initiate construction of small scale S-CO2 compression exps and (~ MW) class split flow Brayton cycle system (SNL, Industry)
Supercritical CO2 Cycle Activities
Power Conversion System Studies (MIT)

- FY06 studies developed layouts for PCS ratings ranging from 20 to 1200MWe
- “3rd generation” concepts evolved from earlier MIT studies, addressed impact of ductwork pressure drop on thermodynamic efficiency;
- Radial compressors used for main compressor (1 stage ~0.85) and recompressor (3 stages ~0.89)
- Modular approach to extend power range
- Reference version - 300MWe two-train recuperator configuration using parallel clusters of commercial HEATRIC™ PCHE
- FY07 activities at MIT focus on control simulations

Net efficiency = 0.47 @650 C versus 0.45 for 2nd generation PCS
S-CO2 Controls – Model Development, Simulation (ANL, MIT)

- **S-CO2 control strategy Options**

- Earlier tasks refined analysis tools at MIT and ANL
- GASS-PASS/CO2 (MIT, ANL) – fast running, adaptable code now operational – including radial compressor models
- ANL Plant Dynamics Code – incorporated radial compressor models – simulated control options for LFR/S-CO2
- FY07 studies use updated models to simulate range of control strategies for S-CO2 cycle
Closed Brayton Cycle Testing

CBC operational data for model comparisons
- Transient, steady state operations
- Working fluids -- N2, He, Ar, CO2, mixtures
- Operational data for -- Inventory, temperature changes, startup, shutdown, power changes

<table>
<thead>
<tr>
<th>SNL CBC Testing For Gen IV</th>
<th>Pure Gases</th>
<th>Gas Mixtures</th>
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<td>3/16/2005</td>
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<tr>
<td></td>
<td>3/16/2006</td>
<td>3/16/2005</td>
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<tr>
<td>Gas Type</td>
<td>N2 Ar CO2 He</td>
<td>90N2-10Ar 90Ar-10He 80Ar-20He 70N2-30He</td>
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<tr>
<td>Description</td>
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<tr>
<td>Cp J/kg*K</td>
<td>1026</td>
<td>518</td>
</tr>
<tr>
<td>k(300K) mW/m*K</td>
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<tr>
<td>k(1000K) mW/m*K</td>
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<td>42</td>
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<tr>
<td>Ro (J/kg*K)</td>
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<td>MW (gm/mole)</td>
<td>28</td>
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<td>Flow and RPM Op-Curves</td>
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<td>Operating Pwr Curve</td>
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<td>Operating Pressure Ratio</td>
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<td>RPM Step Decrease (5000 rpm)</td>
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<td>Mix</td>
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<tr>
<td>RPM Step Increase (1000 rpm)</td>
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<td>Shutdown</td>
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<td>MW Increase</td>
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<tr>
<td>MW Decrease</td>
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</table>
Comparison of Measurements and Predictions

SNL 30 kWe CBC Measurements

Dynamic Model Predictions

- Power
- Rpm and flow
- Temperatures
- Pressure

Temperatures | Pressures | Power | Custom Graph | Load Data File
---|---|---|---|---

Gas Coolant Temps (K)

Heater Power (%)

Startup Inventory Reductions

TIT Increase 650 K, 700 K, 750 K

RPM Increase Shutdown

10 kPa Argon Fill

10 kPa Bleed

100% N₂

10 kPa Argon Fill

dP =10 kPa

dP =10 kPa

5 Steps

Power (kW)

Heater Power (%)

Gas Coolant Temps (K)

RPM/5000

Power (kW)

Startup Inventory Reductions

TIT Increase 650 K, 700 K, 750 K

RPM Increase Shutdown

10 kPa Argon Fill

10 kPa Bleed

100% N₂

10 kPa Argon Fill

dP =10 kPa

5 Steps
**S-CO2 PCHE Heat Transfer Testing Facility -- ANL**

- Initial configuration - CO$_2$-to-water heat exchange tests
- 17.5 KW heat duty PCHE represents section of cooler for S-CO$_2$ Brayton cycle
- FY07 upgrade to CO$_2$ to CO$_2$ configuration (started in FY06). (low temperature recuperator).

- Conducted initial series of CO2-to-water steady state under prototypical conditions.
- Determined average heat transfer coefficients on the water and CO2 sides. Compared ANL PCHE modeling with test data
- Good agreement is obtained for the heat exchange rate, Q, or CO2 and H2O outlet temperatures. CO2 side pressure drop is overpredicted
Small Scale S-CO2 Cycle Demonstration Loop

- Next stage of S-CO2 development – construct small scale S-CO2 power conversion system to demonstrate key technology issues
- Phased approach – key technical issues first -- and budget constraints
- First stage – experiments to address compression near critical point
- Progress to split flow recuperated Brayton cycle demo
- Contracts (FY06) solicited TM Industry input on small scale test loop to test key technical features (BNI, P&W-Rocketdyne)

Primary FY06 SOW Tasks
- Review key technical issues for full scale system
- Examine approach for S-CO2 compression tests
- Phased approach to develop full cycle, preliminary cost and schedule
Key Technology for S-CO₂ Development
SNL LDRD -- S-CO₂ other working fluids

S-CO₂ Main Compressor Test
Electric Motor Driven Option

Phase 1-LS: Turbo Assisted Main Compressor Study SC-CO₂ Flow Compression (3 kg/s)

Major Technology Issues
Gas Liftoff Seals
Efficiency of Compression
Thermal Input Control
Bearings and Thrust Loads
Off-Normal behavior (wet)

Turbo Assisted Motor/Compressor
Reduces motor power requirements
Allow modification – wheels, housings could be replaced with different designs.
Gen IV S-CO2
(1 MW_th => 300 kW_e with Split Flow)

Phase 1 - Split flow (Main and Recompressor) Study

No Heater
~ 40 kW Motor
Consumes Electricity

Phase 2 - Non-recuperated Brayton split flow

Phase 3 – Recuperated split flow S-CO2 cycle

~1 MW Heater & ~40 kW Motor/Alternator + 300 kW Dynometer or 300 kW Alt. is an Option
Produces Electricity

Phase 1

Up to 1 MW Heater
~ 40 kW Alternator Pwr
Produces Electricity

Phase 2

Phase 3

~1 MW Heater and ~40 kW Motor/Alternator + 300 kW Dynometer or 300 kW Alternator is an Option
Produces Electricity
Gen IV Energy Conversion
FY07 S-CO2  Summary

Develop experimental capability to address key technical issues
– Main compressor operation,
– System control strategies
– Heat transfer experiments

Approach: phased design, construction
– Address main compressor exps first
– Split flow compression as first stage of small scale system
– Optimize construction sequence to provide early results and leverage previous phase

Planning Schedule for Gen IV scope
– Gen IV funding - ~ 4 year schedule
– Other SC fluids work on supercritical compression studies
– GNEP – other program involvement
Gen IV Energy Conversion
S-CO2 cycle phases, proposed schedule

<table>
<thead>
<tr>
<th>Dev Phase</th>
<th>Adv Cycle Eval.</th>
<th>Key Technology Exps</th>
<th>Pilot Scale Demo</th>
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<tbody>
<tr>
<td>S-CO2 Cycle Development</td>
<td>S-CO2 Design / Eval</td>
<td>Main Comp, PCHE Exps</td>
<td>Sustainable System Selection</td>
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<tr>
<td>Components</td>
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<td>MW S-CO2 split flow devel.</td>
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<tr>
<td>Small Scale</td>
<td>Split flow comp exps</td>
<td>Non-recup: Brayton</td>
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<tr>
<td>Pilot Scale</td>
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<td>Recup Brayton</td>
<td>Pilot Scale S-CO2 system design and technology demonstration</td>
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</table>
Extra VGs
SNL LDRD Single Shaft SC-CO₂ opt for SC-Xe
Lab-Scale 120 kWth Heater Power: 7 kWe SC-CO₂: 33 kWe SC-Xe

SC-CO₂ Comp. LDRD

Phase 1-LS: Turbo Assisted Main Compressor Study SC-CO₂ Flow Compression (3 kg/s)

Phase 2-LS: Un-Recup. Brayton Cycle SC-CO₂ & SC-Xe Compression Higher TIT various RPMs SC-CO₂ and SC-Xe


120 kW Lab-Scale Heater ~ 20 kW Motor Pwr CO₂ ~ 10 kW Alternator Pwr Xe Consumes & Produces Electricity

120 kW Lab-Scale Heater ~ 30 kW Motor Consumes Electricity

~120 kW Heater & ~40 kW Motor/Alternator + 300 kW Dynometer
300 kW Alt. is an Option Produces Limited Electricity 7-32 kWe (CO₂/Xe)
Small Scale S-CO2 Demo Unit
Conceptual Approach

Phase 1 - Main compressor and/or Recompressor with/without split flow

Phase 2 – Non-recuperated Brayton Split flow

Phase 3 – Split Flow S-CO2 Brayton

No Heater & ~40 kWe Motor

Up to 1 MW Heater & ~40 kWe Motor/Alternator

Producer Limited Electricity
Gen IV Energy Conversion

S-CO2 Interactions

- CO2 reaction with Na at higher temperatures
- Japanese observed slow reactions below ~ 550 C, increasing reaction rates above 550 C
- Korean data (CO2 bubbled into Na Column) suggest some reaction below ~ 550 C

- Expected interaction mode in PCHE – small cracks – form oxides or carbonates – could lead to plugging if not removed, E release not primary concern.
- Does not appear to be major issue for current Na outlet temperatures – but need to confirm
- Significantly less of a concern than water – Na reaction
- ABR program – constructing a small facility to investigate plugging issue (ANL)
- ABR will investigate Na CO2 interactions,
- Gen IV focus on cycle development

### Sodium-CO2 reaction (Japanese results)

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Na Temp. (°C)</th>
<th>X Ray Diffraction 1)</th>
<th>Gas Chromatography 2)</th>
<th>Carbon Analysis</th>
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<tr>
<td></td>
<td>Na</td>
<td>Na₂O</td>
<td>Na₂CO₃</td>
<td>CO</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
<td>+ + +</td>
<td>+</td>
<td>Not detected</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>+ + +</td>
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<td>Not detected</td>
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<tr>
<td>3</td>
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<td>+ + +</td>
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<tr>
<td>4</td>
<td>550</td>
<td>+ + +</td>
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<td>8</td>
<td>600</td>
<td>+ +</td>
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<td>+</td>
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<tr>
<td>9</td>
<td>615</td>
<td>+</td>
<td>Not detected</td>
<td>+ + +</td>
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<td>+ +</td>
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<tr>
<td>11</td>
<td>650</td>
<td>Not detected</td>
<td>Not detected</td>
<td>+ + +</td>
</tr>
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1) +++: Large amount, +: Small amount.
2) Taken sample from the exhaust gas.
ANL S-CO2 Heat Transfer Loop

CO$_2$ / H$_2$O Heat Exchanger

CO$_2$ / CO2 Heat Exchanger Design
Gen IV Energy Conversion Objectives: Optimize performance and cost effectiveness of Gen IV reactors

Brayton Cycle Options for Gen IV Reactors

Split Flow S-CO2 Brayton Cycle

Rankine Bottoming Cycle

Multi Reheat - Interstage cooled Brayton Cycle