Integrally-Geared sCO$_2$ Power Systems

Design, Test, and Commercialization of an Integrally-Geared sCO$_2$ Power System

February 22, 2022

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Hanwha Galleria Timeworld
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Apollo Development / Test Phase
Technology Progression Lead to Closed Loop sCO₂ Power System

CLOSED MASTER IMPELLER
- Entry into O&G applications
- Entry into higher-pressure applications

RANGE EXTENSION
- Passive technology
- Competitive advantage
- Reduced risk of surge damage.

ADDITIONAL MANUFACTURING
- Improved Reliability
- Improved design flexibility
- General trend of other manufacturers

HIGH TEMPERATURE CASINGS
- Unique Expander abilities
- High Reliability

HIGH TEMPERATURE EXPANDER
- Solution minimizes Inconel,
- Reduced cost,
- Creep life testing,
- Ensure wide product range

HIGH PRESSURE CASINGS
- Extended product range for O&G
- Increased reliability

THRUST COLLAR DESIGN TOOL
- Texas A&M
- Improved reliability
- SOA analytics

2016

2018

2019

2019

2020

2021

2021 Present

2022-2024

SMW sCO₂ Power Systems

- Limited market competition,
- Small foot print,
- Rapid skid deployment – foot print and skid confirmation to occur 2021

RECOMPRESSION PILOT SITE
- Allows long term validation,
- Provides site specific references,
- Establish cost savings opportunity

RECUPERATED PILOT SITE
- VHR
- Power Generation
- Min CAPEX

U.S. DOE Apollo

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Product Approach: Leverage Commercial Grade Components for Maximum Reliability

Our design approach to the *Integrally Geared sCO₂ Power System* is built largely on existing industrial grade equipment.

**Tilting Pad Journal Bearings**
- Conventional – 5 Pad TPJB Oil lubricated configuration.
- Excellent bearing stiffness and damping.

**Thrust Management System**
- Bull Gear – Fixed geometry thrust collar
- Thrust collars pass thrust from high-speed pinion to Bull gear

**Lubrication System**
- Oil lubrication system allows direct start-stop without need

**Variable Inlet Guide Vane**
- Controls the flow to the main compressor and the recompressor.

**Dry Gas Seal Rack**
- Dry gas seals and dry gas seal rack are common in O&G industry.

**Generator**
- Low-Speed generator is industry standard and highest reliability.

**Southwest Research Institute and Hanwha Power Systems** partnered to develop an sCO₂ Power System based on an integrally geared turbomachinery concept.

- Project successfully completed three funding phases.
- 10MW electrical (size basis)
- System built and tested:
  - Full size main compressor,
  - Full size expander 1st stage,
  - Full mechanical system
  - Sealing system,
  - Lubrication system,
  - 1+ MW testing loop infrastructure
IG Arrangement Offer Tremendous Cycle and Product Flexibility

Turbomachinery
(Expansion Only)

Turbomachinery
(Compression Only)

Turbomachinery
(Expansion and Compression)

Recompression Cycle

Ability to offer variability allows commercial advantages: adjusting cycle and configuration to meet customer needs
Validate of Integrated Turbomachinery Components Achieved

- Reliability elements of the sCO2 power system have been identified related to conventional IG turbomachines.
- Reliability factors were verified by design/interpretation/component tests and MRT, and Apollo integrated test.

### sCO2 Power System

<table>
<thead>
<tr>
<th>Prior Experience</th>
<th>sCO2 Testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>Air, N2, CH4, sCO2</td>
</tr>
<tr>
<td>Operating Conditions</td>
<td>T: ~288℃, P: ~75bar</td>
</tr>
</tbody>
</table>

1) DGS: Dry Gas Seal

### Reliability Factor

- sCO2 gas properties
- Real gas properties integrated and verified through test
- Commercial supplied with HPS peripheral cooling
- Loads and Speeds with experience limits
- Extensive validation and over-speed testing
- Thermal management of casing demonstrated
- Casing pressure containment within ASME BPVC

### Solution

### Integrated Verification

DOE Testing Program Validates Critical CO2 Characteristics
Wide Range Technology Improves Reliability and Operational Range

- Casing treatment designed based on extensive computational fluid dynamics (CFD) analysis
- Analysis based on real gas properties since the compressor operates near the critical point
- Incorporating a casing treatment was found to extend the operating range significantly (from 43% to 74%)

• Improved Reliability (Passive)
• Reduced Dynamic Stress
• Increased Operating Range

Scaled Test Results

Traditional Design

Wide Range Technology
Apollo IG sCO2 Test Facility at Southwest Research Institute

- Highest power test loop currently available for proof of concept testing
Sustained Operation at Expander Inlet Conditions (720 °C and 260 bar)

OEM: Hanwha Power Systems

Tested: Southwest Research Institute

DOE Program Achievements:
- Highest inlet expander temperature for CO₂
- Lowest leakage IG CO₂ compressor
- Widest range sCO₂ compressor
- Highest efficiency sCO₂ compressor stages

Maximize Reliability in Operation

EERE APOLLO program (EE0007114)
- to convert sunlight to power at a 700 °C inlet temperature
- η=50%

• Design Conditions
  - CIT: 37 °C (95-120 °F)
  - TIT: 700 °C (1300 °F)
  - TIP: 275 bar (4000 psi)
  - Mass Flow: 50-70 kg/s
  - Nominal Power: 10 MW
Post-Apollo Testing
Test data shows variation in compressor efficiency near the critical points.
Performance variation may be due to the development of liquid regions where local static temperature and pressure are suppressed due to high passage velocity.
Off-design cycle modeling can be updated to give an improved estimate of power production.
Expander Thermal Management Approach Validated at 720°C

- Thermal gradients in the expander measured with embedded thermocouples and visualized with a thermal imaging camera
- Results confirmed performance expected based on analytic simulations

Patented Thermal Management System
- Apollo test proved thermal-mechanical integrity
- Leakage controlled dry gas seals
- Low-Loss thrust collar management system
- Titling pad journal bearings (Robust rotor-bearing system)

Expander Casing Thermal Analysis
Demonstrated machinery endurance is critical:
✓ Customer confidence
✓ Allows ability for OEM to more readily offer warranties, guaranties, etc.

HPS sCO₂ Power System passed Endurance Test:
✓ Full scale,
✓ Full-speed,
✓ Full pressure,
✓ Full temperature, and
✓ Full success on endurance test.

- 12 hr continuous operation test passed
- Total operational time > 100 hrs.
- Peak operating Temperature > 705 C

Test Data: 11.94 hrs at average P= 247.27 bar
Average T= 606.8 C
Commercial Phase
Business Growth for Condition Based Health Monitoring with Partnerships

- Leverage Existing Inventory stocking and service capabilities in U.S.
- Real-time monitoring of the operation status of multiple sites through the web environment at our central monitoring center
- Real-time storage and management of operating data of the sCO₂ power system on a remote server

24/7 sCO₂ Power Plant Performance & Status

- Operational information
- Consumable parts are replaced
- Regular/predictive preventive maintenance

Internet

Cloud Server

Repair Center (BGA)
Houston, TX

Monitoring Center (PSM)
West Palm Beach
**5MW Size can be Modular and is Highly Similar to Existing Product Portfolio**

- HPS’s sCO2 Power System applies the same structure and operation method as IG-Type turbo equipment
- More than 6,000 HPS references are held for IG-Type turbo equipment (field operation reliability has been proven)

<table>
<thead>
<tr>
<th>Package</th>
<th>IG Gas Compressor-Expander</th>
<th>IG sCO2 Power System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td></td>
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<tr>
<td>Inter-stage Cooler</td>
<td></td>
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<tr>
<td>Cooler</td>
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<tr>
<td>Motor</td>
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<tr>
<th>Machinery</th>
<th>COMP 1 STG</th>
<th>COMP 2 STG</th>
<th>COMP 3 STG</th>
<th>EXP STG</th>
</tr>
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<tbody>
<tr>
<td>Bull Gear</td>
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<tr>
<td>Pinion Gear</td>
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<tr>
<td>Bearing</td>
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<tr>
<td>Gas &amp; Oil Seal</td>
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<tr>
<td>Impeller</td>
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<tr>
<td>Generator</td>
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<tr>
<td>Recuperator</td>
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5MW Recompression Product: sCO\textsubscript{2} Power Systems

- Recompression Cycle Allows High Efficiency, Modular, Compact Design
  - 5 MWe, 600 °C Expander Inlet Temperature,
  - Recompression Brayton Cycle – chosen for optimal efficiency
  - Modular: (1) Turbomachinery Skid, (2) Inventory Control, (3) Generator
  - Integrated: lubrication system, dry gas sealing, recuperator, piping, etc.

- Target Deployment - Early 2024
  - Field test allows full validation of integrated system
  - sCO\textsubscript{2} Power System allows compact cluster of reflector mirrors
5.5MW Recuperated sCO₂ Power System for Gas Turbine Heat Recovery

Split Recuperated Brayton Cycle
- Air-Cooled (no water needs)
- 5.5 MW electric
- Optimized for CAPEX/OPEX/Heat Recovery

Service and Maintenance
- 24/7 Remote monitoring for control and health management

Build-Own-Operate Model
- Design Point:
- Technical Features:
  - Wide Range Technology™
  - Dry gas seals
  - Titling pad journal bearings
  - Thrust collars

Modular Solution
- Easily deployable for installation and maintenance
- Inventory Control Skid
- Turbomachinery Skid – integrated sealing and lubrication
- Generator Skid
The turbomachinery skid layout consists of the following major components: core assembly, oil reservoir, skid, oil cooler, generator, seal rack, control panel, recuperator, recovery compressor etc.

- **Core (G/B) assembly** includes two compressors and two expanders mounted on the gearbox.
- Size of the main skid will be approximately 9m(29.53’)Lx4.2m(13.78’)W. Second skid 6.9m(22.64’)Lx4.2m(13.78’)W will be used inline with the main skid for the generator, clutch & startup motor for the package.
- Height of the package will be around 11.8ft (3.6m.) To avoid the extra height of the package for the shipment some pipe & generator cooling sections can be shipped loose.

### Weight

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight</th>
</tr>
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<tbody>
<tr>
<td>Core assembly</td>
<td>47,620 lb (21.6 metric Ton)</td>
</tr>
<tr>
<td>Power block skid &amp; LOS</td>
<td>44,093 lb (20 metric Ton)</td>
</tr>
<tr>
<td>Skid generator</td>
<td>19,842 lb (9 metric Ton)</td>
</tr>
<tr>
<td>Generator</td>
<td>55,116 lb (25 metric Ton)</td>
</tr>
<tr>
<td>Startup motor</td>
<td>3,307 lb (1.5 metric ton)</td>
</tr>
<tr>
<td>Recuperator</td>
<td>33,069 lb (15 metric ton)</td>
</tr>
<tr>
<td>Aux equipment &amp; others</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>218,258 lb (99 metric ton)</strong></td>
</tr>
</tbody>
</table>
Super-Critical CO₂ Power System – Application Focused Approach

Integrally Geared Closed Loop Brayton Cycle

- **Design Flexibility** (Stage optimization)
- **Reliability** (25 year design life)
- **Service and Maintenance** (OEM Network)
- **Cycle Adaptability** (Recompression, Split Recuperated, Re-Heat)
- **Durability** (Wide Range Technology)
- **Modular Deployment** (Reduced I&C costs)
- **Competitive CAPEX** (Use of conventional technology controls costs)

**Goal is to promote a commercially acceptable product:**
- Service and Maintenance
- Reliable
- Flexible
- Good CAPEX
- Cutting Edge Efficiency
- Modular for easy Deployment
Customer Acceptance of Market Readiness

1) Technical ability and risk reductions
   • TRL is useful guide,
   • Customers want to see evidence of reliability “endurance” testing

2) Commercial Capability
   • Warranty – Pricing - Guarantees
     o ability to identify launch customers and take financial loss on first unit(s) if required.
     o CAPEX competitive to entrenched technologies
   • Installation & Commissioning – expertise to manage site logistics

3) Service and maintenance support
   • Coming from an organization that is newer to Americas and familiar to new products, the most common question is always “how will you support this product.” This is a major weakness of new/smaller organizations.
   • Large organizations have the ability to leverage existing installations capabilities
Thank You