Low-leakage seals for utility-scale sCO$_2$ turbines
DE-FE24007

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Outline

• Program Overview
• Recap of subscale testing (2017-2019)
• Radial Seal Testing (2020)
• 24-inch Seal Fabrication (2020-2021)
• 24-inch rig commissioning, seal assembly, ongoing tests (2021)
Overview of Utility-scale sCO₂ Seals Program

Phase 1 Concept Design

- 50 MWₑ and 450 MWₑ Turbine layouts
- Face seal concept 24-inch, 1100 psi

Phase 2 Detail design & testing to attain TRL6

- 24-inch sCO₂ test rig Concept Design
- 24-inch sCO₂ Seals Rig Operational
- 14-inch Seal Fabrication
- 14-inch Hot Testing

Concept Design

- 24-inch sCO₂ Loop & stiffness tests
- Coatings Tests
- Air Stiffness Tests
- Subscale demo 5-inch face seal

50 MWₑ and 450 MWₑ Turbine layouts

Face seal concept 24-inch, 1100 psi

Heat Transfer Tests

24-inch sCO₂ rig design & commissioning

Design of 24-inch face seals

Radial seal tests

Design of radial seals

Design of 14-inch face seals

24-inch sCO₂ Seals Rig Operational

GE Public Class 1
End Seals in sCO\textsubscript{2} turbines

- Face seals are worth \(\sim 0.55\%\) points cycle efficiency compared to labyrinth seals.
- Face seals needed for utility-scale sCO\textsubscript{2} turbines (24-inch diameter, 1000 psia pressure differential) not readily available.

Face seals worth \(\sim 0.55\%\) points cycle efficiency for large sCO\textsubscript{2} cycles
Seal Working Principle
Film-riding Seals working principle

Film-riding seals operate with very thin films (0.001 to 0.002 inch) separating the rotor & seal

- Seal equilibrium – balance of forces
- Opening force
  - Hydrostatic pressurization/hydrodynamic grooves
  - Positive film stiffness; force increases with reducing film thickness
- Film stiffness
  - Needed for faithful dynamic tracking against inertia, friction, pressure
  - Loss can lead to seal rubs and seal failure
- sCO2 working fluid has unique challenges

Typical film-riding face seal

Thin “constant” gap
At equilibrium gap,
Opening force = Closing Force

Film Thickness or Gap

Force

Closing Force
Equilibrium Gap
Opening Force

Variable, large gap

Graph: Film stiffness
Slope of force-gap curve

P_high
P_supply > P_high
P_high
P_low
P_low
P_high

Thin “constant” gap
At equilibrium gap,
Opening force = Closing Force

- Rotor
- Casing
- Spring
- Stationary Ring
- Feed port
- Bearing Face
Face Seals and Radial Seals

Both types of seals are important depending on sealing location, size envelope & operating condition requirements

- Film & sealing on axial face
- Need to withstand rotor-stator axial motion
- Film & sealing on radial face
- Need to withstand rotor-stator radial motion
Quick Re-cap of Testing
(2017-2019)
Summary of Tests to Date

Room temp Pin-on-disk Coatings tests

CrC/CrN, AlTiN(Mo,W)S2, DLCs identified as optimal coatings

3-inch diameter, Static Medium temp tests with sCO2 (IGTI 2018. 2019)

Measured & Predicted HTCs match reducing thermal model uncertainty

5-inch diameter, Rotating Room Temp tests with Air

Hydrostatic lift with sCO2 working fluid, excellent match with CFD

Split Seal demo in air, Low leakage ~0.45 mils, excellent match with design tools
Radial Seal Testing Summary
(2020)
Radial Seal Testing

Radial Seal Assembly

Seal Assembly with Rotor

Seal assembled in GE rig

GE Public Class 1
High-speed rotating tests (room temp rig) completed to successfully demonstrate TRL3 for Radial Seal Technology

Radial Seal Testing
24-inch Seal Testing
(Rig Assembly)
Test rig overview

- Back-to-back seal arrangement
- Thrust balanced
- Open- and closed-loop
- Measure thermal and leakage performance

Conditions: 
75 bar, 400°F max
1-10 bar

Rotor: Disk ~ 24”
3600 rpm
Air side exhaust stack
Heater HX
Burner
From pump
To rig
Open-loop vent

Stainless piping: upstream of rig / from heater
Painted CS piping: downstream of rig
Pump loop installation completed/Pump Debugging Complete

- Pump & tanks inspected
- Piping modifications complete
- Pump loop instrumentation & alternate power supply arrangement completed
- Pump troubleshooting – DGS failure
- DGS replacement completed
- Test rig commissioning with Pump Flow Loop -- ongoing
24-inch seal Assembly

1. Seal assembled
2. Seal attached to end cap
3. End Cap Assembly
4. PV Center Piece Assembly
5. Second End Cap (without seal)
6. Test Rig ready for second seal

24-inch seal testing commences Nov 2021
High-temp Dry Gas Seals for sCO$_2$ turbines
DE-FE0031924

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Outline

• Overview
• Commercial DGS Failures & Need for High-temp DGS
• Technical Approach
• Thermal Modeling and Plan for testing DGS
Overview

- 10 MW_e scale – Improved reliability of DGS and validation of Seal Design Tools
- 100 MW_e scale – High-temp seal to enable modular sCO_2 Coal FIRST turbines
DGS Reliability Issue – 10 MW\textsubscript{e} scale

DGS Failure Leading Root Cause:
- Incorrect seal-system integration
- Seal film capability exceeded during operation

Failed DGS – SunShot Turbine Test at SwRI (2015-2017)
Failed DGS – Apollo Compressor Test (2019)

Program Goal # 1
Ensure efficiency realization by investigating DGS reliability issues
Value of High-temp DGS Development

- State-of-the-art low-temp (200 °C) commercial DGS
  - 0.5% to 1.3% cycle efficiency
  - Limit operating ramp rates of turbines

- High-temp DGS (up to 700 °C)
  - Enable 0.7% to 1.9% cycle efficiency
  - Enable alternative turbine architectures
    - better turbine ramp rates & operation flexibility
    - Higher ramp rates

<table>
<thead>
<tr>
<th>Turbomachinery</th>
<th>Application</th>
<th>Location and Temperature</th>
<th>Cycle Efficiency Benefit</th>
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<tr>
<td>10 MWₐ sCO₂ turbine</td>
<td>WHR, CSP, NGPC, Coal FIRST risk reduction</td>
<td>Shaft-end labyrinth seals (200°C)</td>
<td>0 (baseline)</td>
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<tr>
<td></td>
<td></td>
<td>Shaft-end DGS (200°C)</td>
<td>1.32%</td>
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<td>Shaft-end and Balance-piston DGS (700°C)</td>
<td>1.96%</td>
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<td>100 MWₐ sCO₂ turbine</td>
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<td>0.85%</td>
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Task Structure

**Task 1** Project Management (GE)
- Co-ordination, Reports, finances, Mtgs

**Task 2 10 MW_e-scale DGS**
- Understand existing seal failure data (GE/SwRI)
- Analyze Commercial DGS (GE)
  - Measure seal geometry/CAD
  - CFD Model
  - Thermal model in Apollo machine
  - Mech deformation studies
- Modify commercial DGS (GE with seal vendor)
- Instrumented Flowserve DGS test at SwRI in Apollo compressor (SwRI)
- Validated Design Tool & Root cause (GE)

**Task 3 100 MW_e-scale seal**
- Design High-Temp Field Trial Seal (GE)
  - Seal cross-section
  - CFD Model
  - Thermal model in Apollo machine
  - Mech deformation studies
- GE Rig Test (Existing hardware from Ongoing Program) (GE)
  - Oxidize hardware
  - GE rig tests
Thermal Modeling of DGS in Compressor

- In-house thermal solver accounts for CO2 real-gas properties, windage, CFD-based leakage flows, heat transfer coefficients
- High temperatures (and large thermal deformation) predicted near Drive-End DGS due to a combination of large heat generation and low cooling flow
- Compressor modifications and DGS fabrication (with sensors) ongoing to test and validate predictions of thermal model in Feb 2022