Low-leakage seals for utility-scale sCO_2 turbines
DE-FE24007

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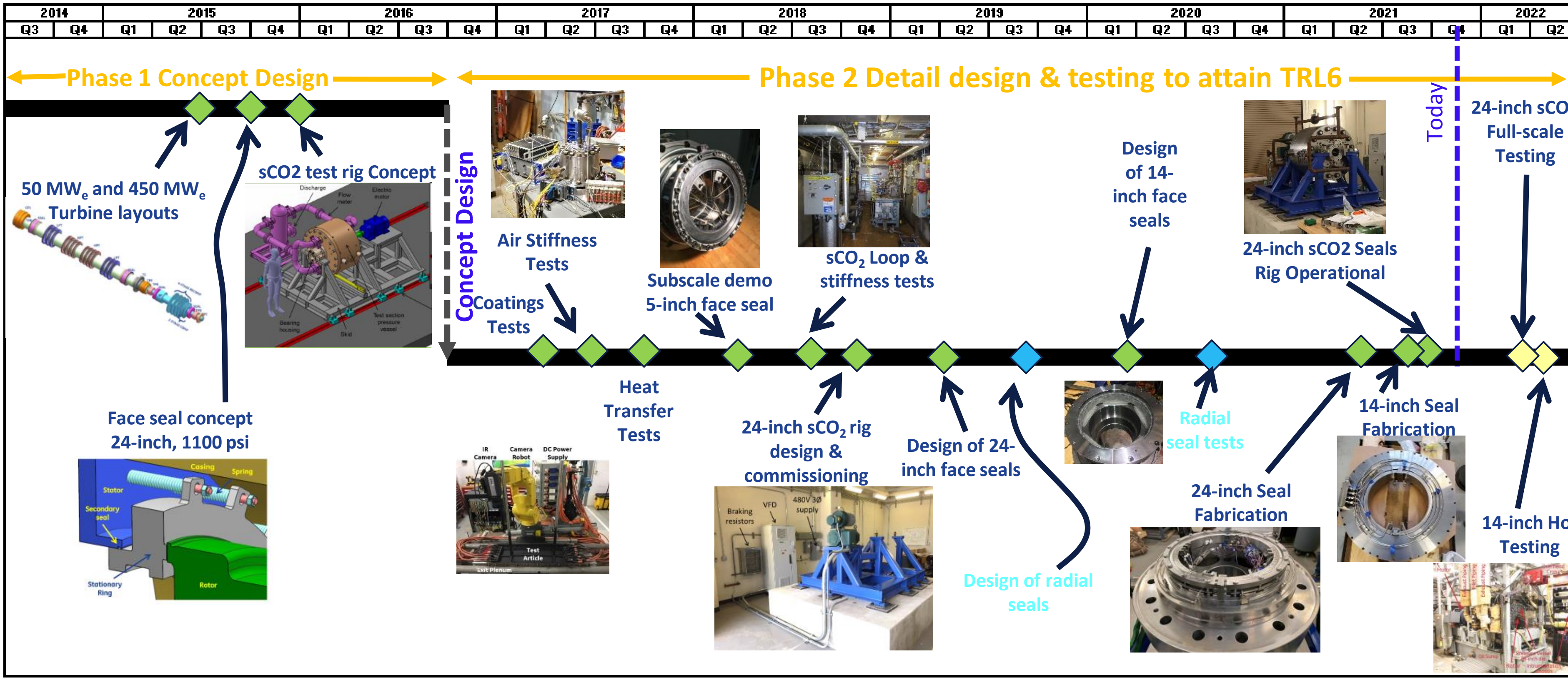
Outline

- 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 sCO_2 Seals Program



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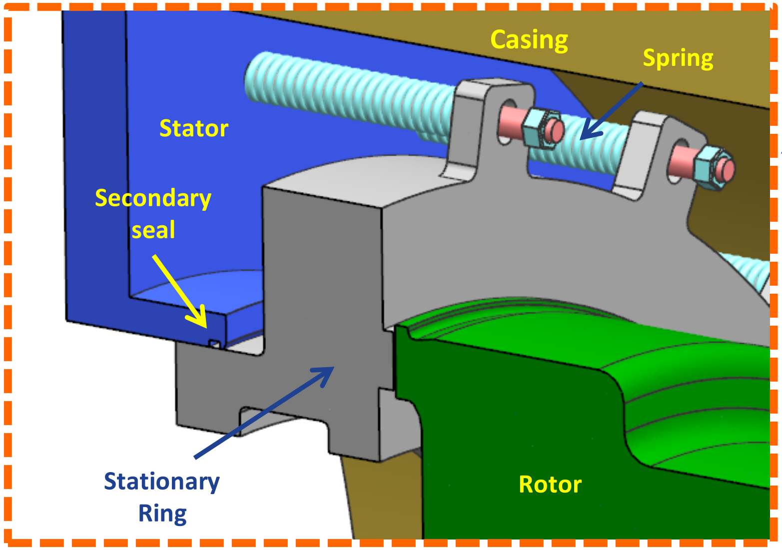
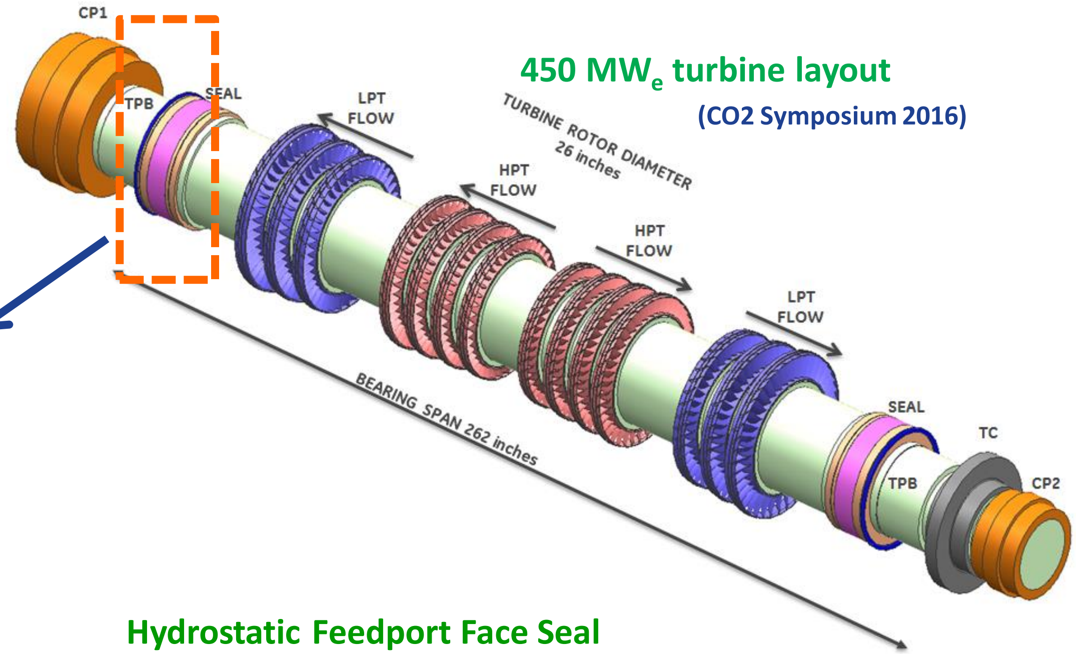
End Seals in sCO_2 turbines

Face Seal for Shaft Ends



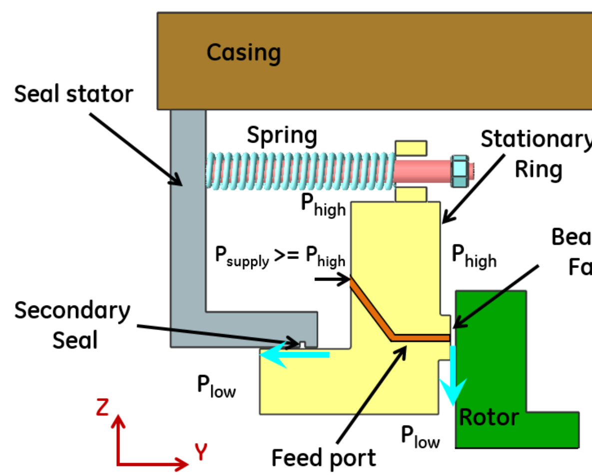
450 MW_e turbine layout

(CO2 Symposium 2016)



- Face seals are worth ~0.55% points cycle efficiency compared to labyrinth seals
- Face seals needed for utility-scale sCO_2 turbines (24-inch diameter, 1000 psia pressure differential) not readily available

Hydrostatic Feedport Face Seal



Face seals worth ~0.55% points cycle efficiency for large sCO_2 cycles

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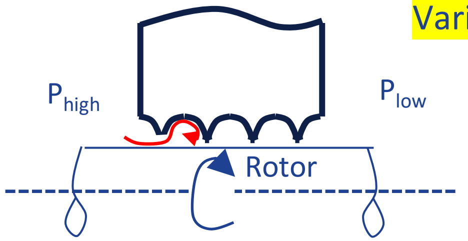
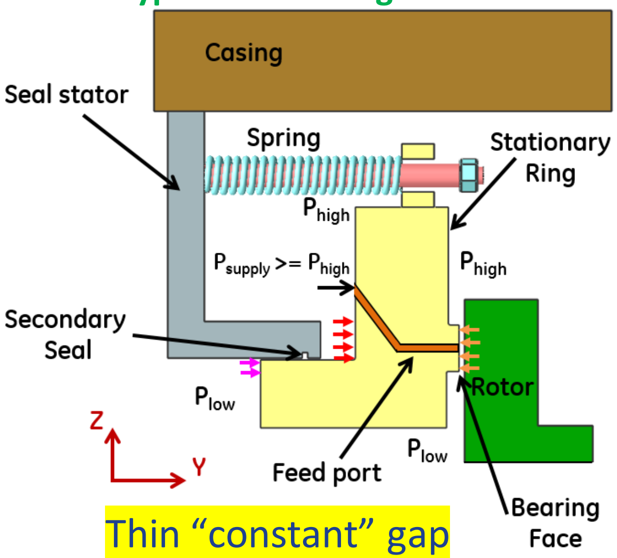
Seal Working Principle

Film-riding Seals working principle

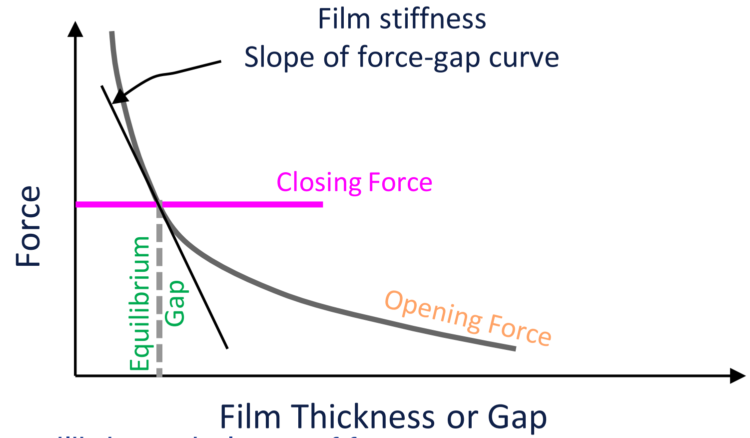


Variable, large gap

Typical film-riding face seal



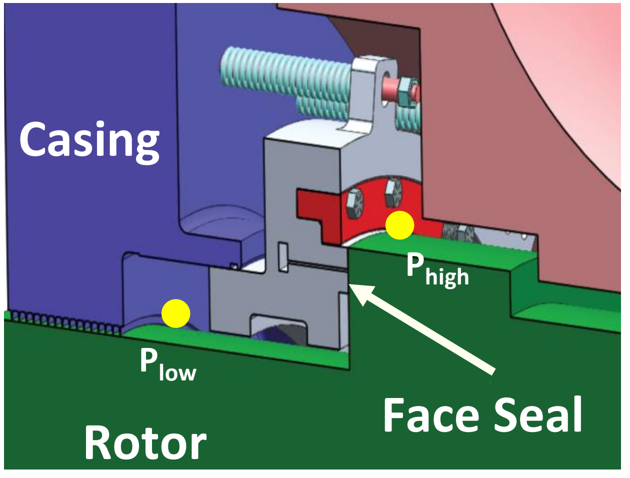
Thin “constant” gap
At equilibrium gap,
Opening force = Closing Force

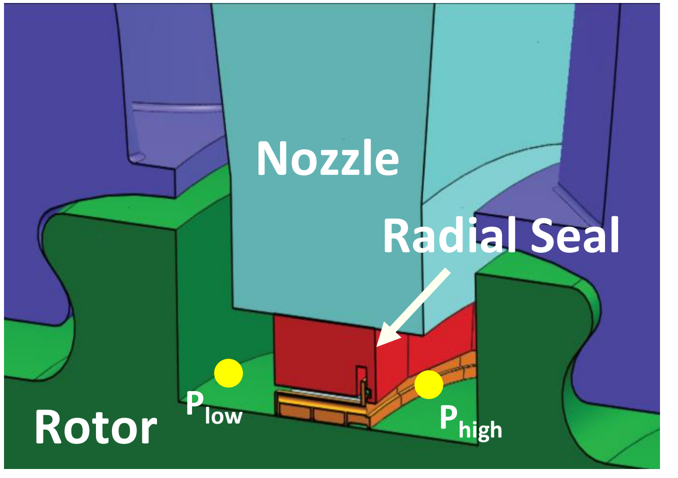


- Seal equilibrium – balance of forces
- Opening force
  - Hydrostatic pressurization/hydrodynamic grooves
  - Positive film stiffness; force increases with reducing film thickness
- Film stiffness
  - Needed for faithful dynamic tracking against inertia, friction, pressure
  - Loss can lead to seal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

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

Face Seals and Radial Seals





- Film & sealing on axial face
- Need to withstand rotor-stator axial motion

- Film & sealing on radial face
- Need to withstand rotor-stator radial motion

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

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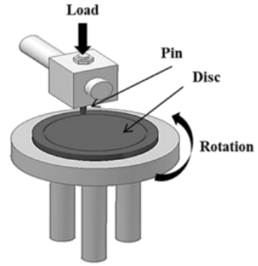
Quick Re-cap of Testing (2017-2019)

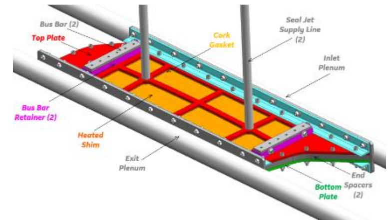
Summary of Tests to Date

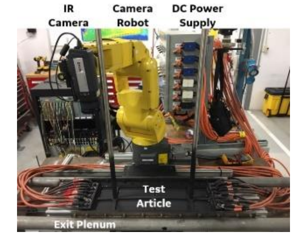
Room temp Pin-on-disk Coatings tests



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

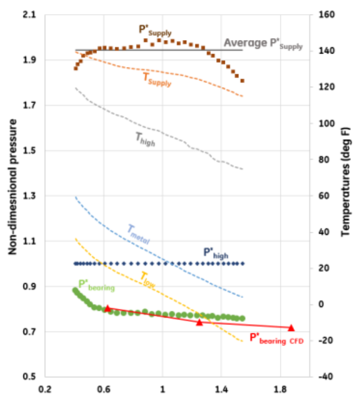
Room temp Static Flow tests to measure Heat Transfer Coeff. (IGTI 2018)





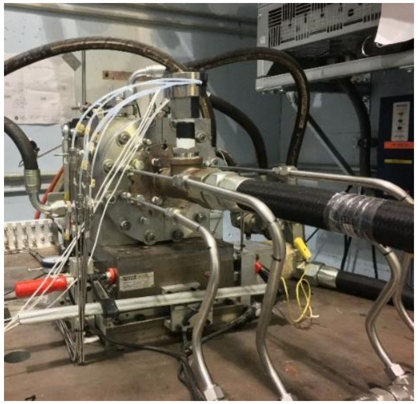
Measured & Predicted HTCs match reducing thermal model uncertainty

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



Hydrostatic lift with sCO2 working fluid, excellent match with CFD

5-inch diameter, Rotating Room Temp tests with Air



Split Seal demo in air, Low leakage ~0.45 mils, excellent match with design tools

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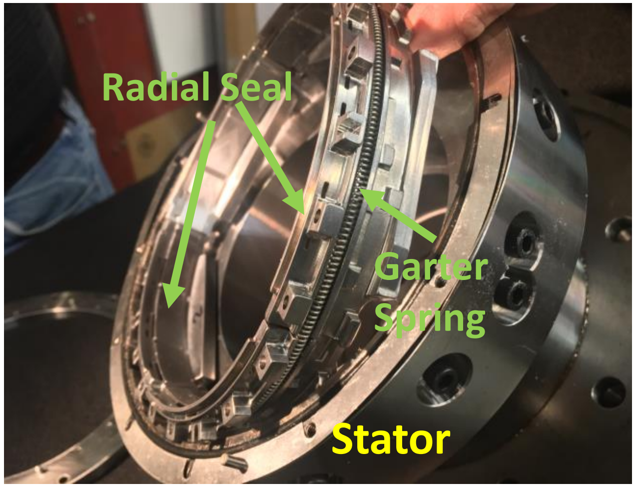
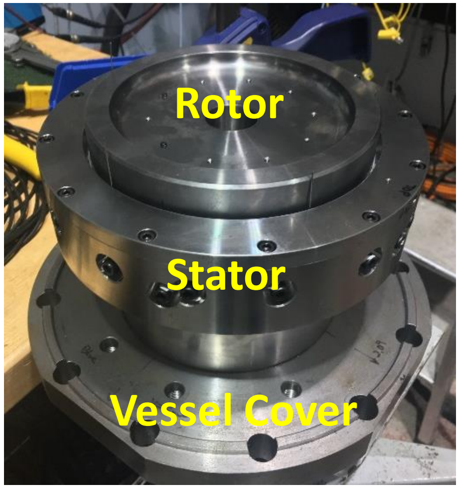
Radial Seal Testing Summary (2020)

Radial Seal Testing

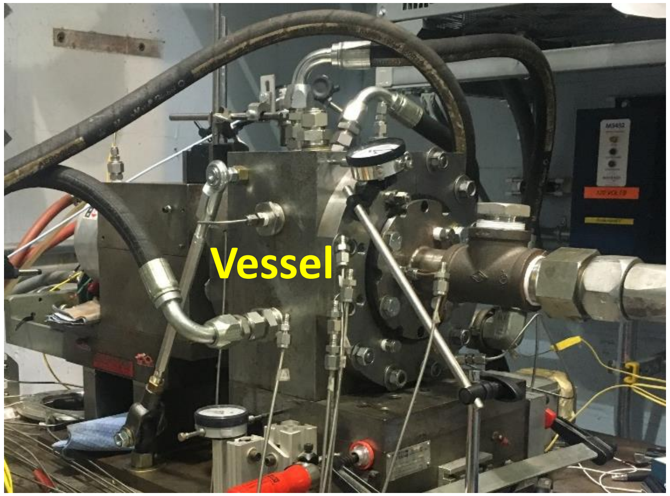
Radial Seal Assembly



Seal Assembly with Rotor



Seal assembled in GE rig



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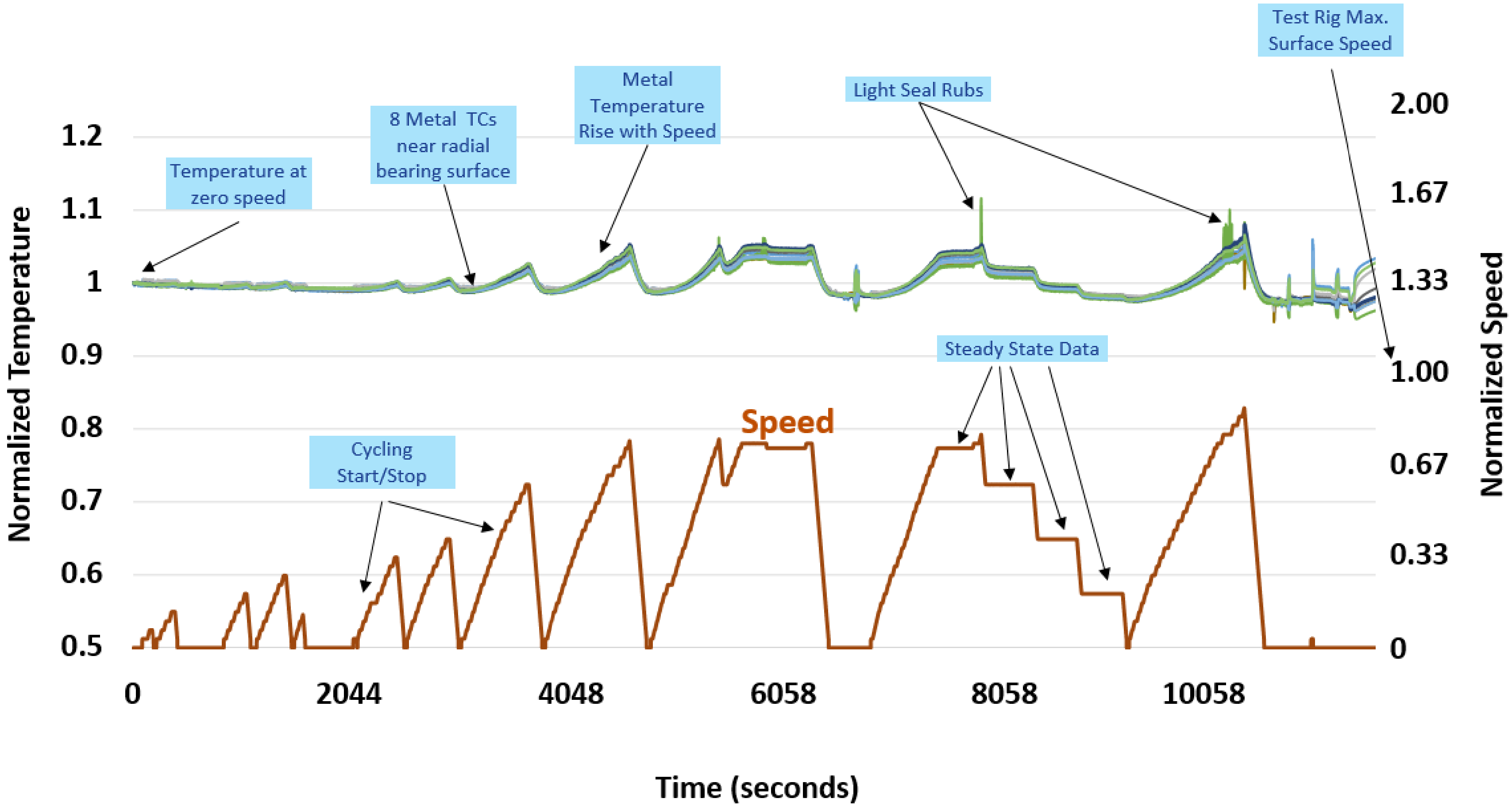
Radial Seal Testing



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

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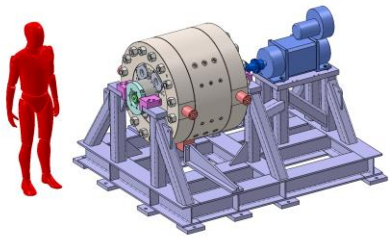
24-inch Seal Testing

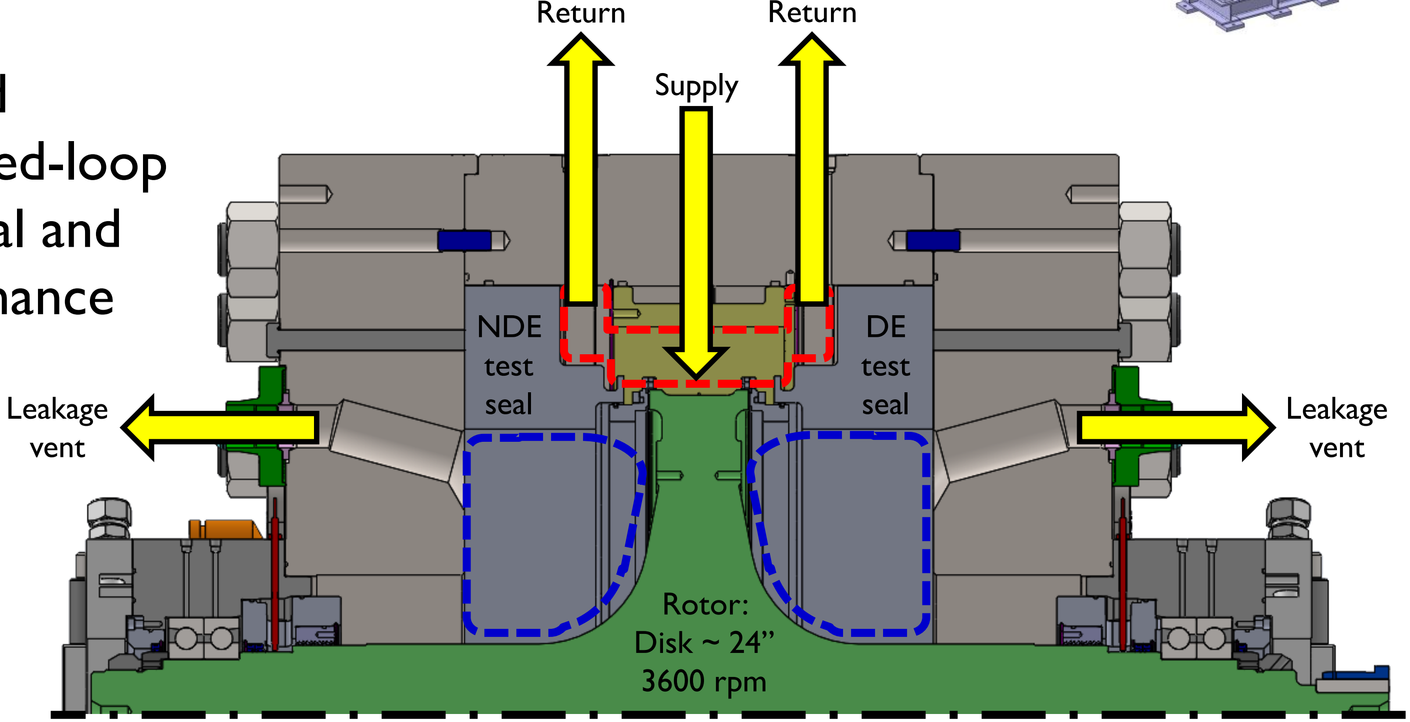
(Rig Assembly)

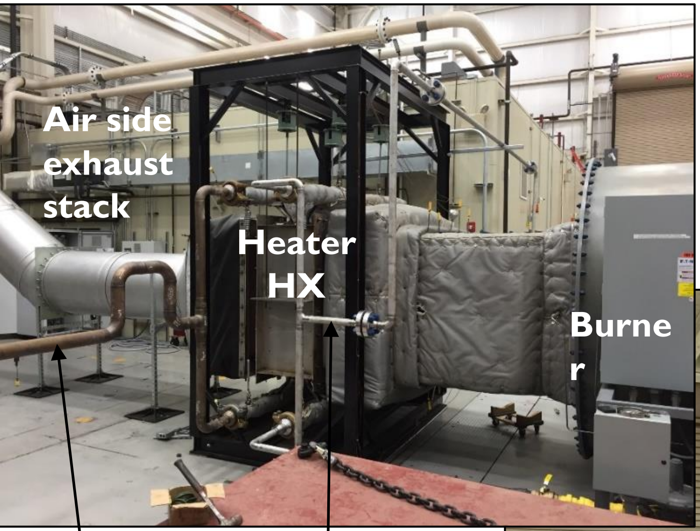
Test rig overview



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

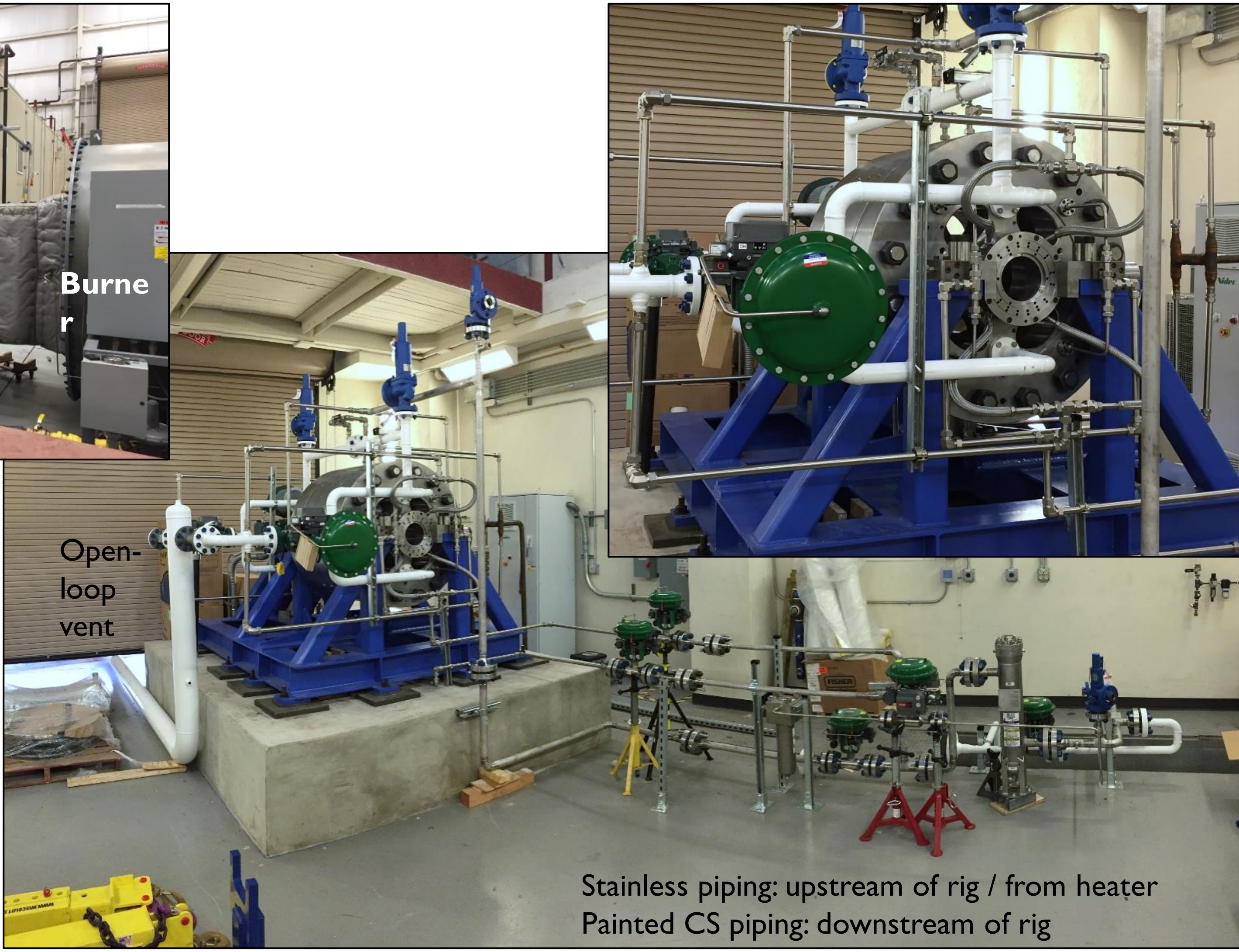
Conditions:
75 bar, 400°F max
1-10 bar





From pump

To 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

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24-inch seal Assembly

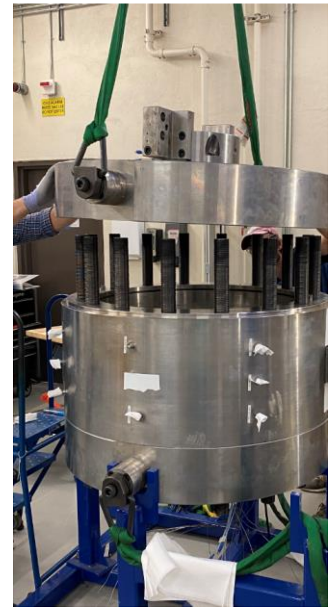
1. Seal assembled

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

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24-inch seal testing commences Nov 2021

High-temp Dry Gas Seals for sCO_2 turbines DE-FE0031924

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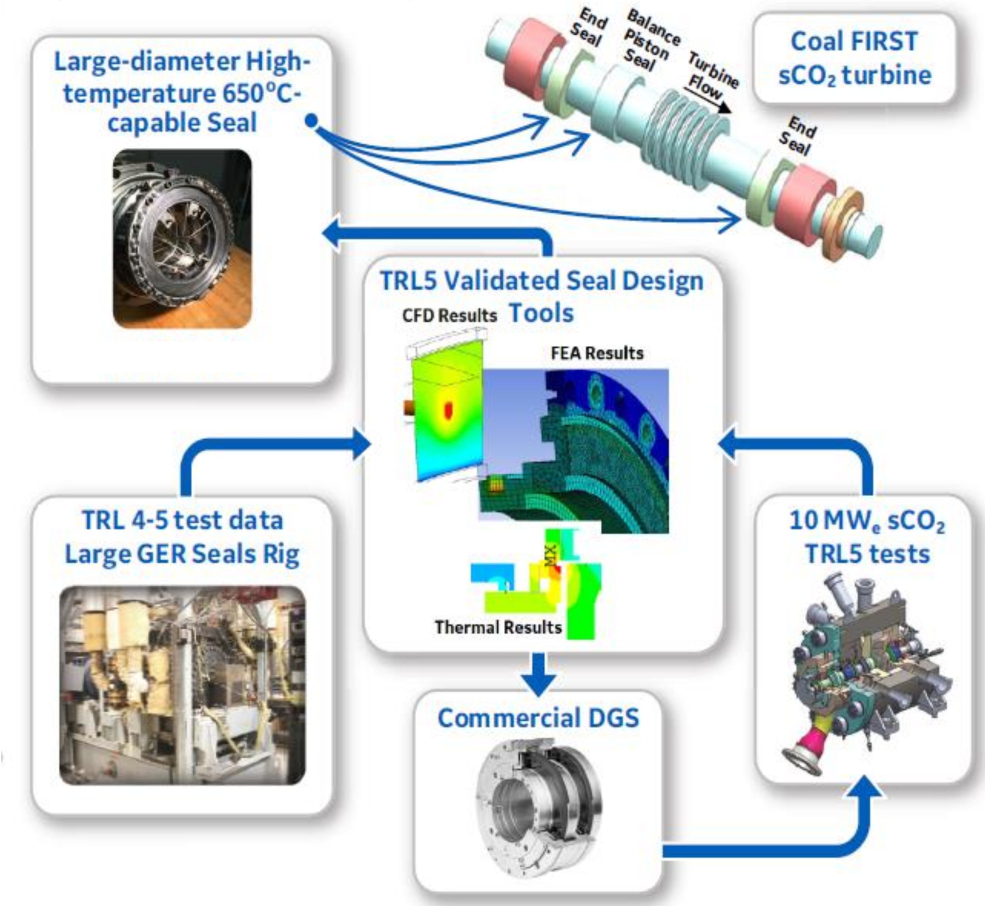
Outline

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

Overview

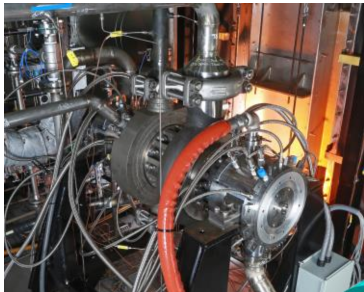
18-month, $1.25MM Program to Develop High-temperature Dry Gas Seals (DGS) for sCO_2 turbines

Program Objective: *Large-diameter, High-temperature 650°C-capable DGS design for a 100 MW_e Coal FIRST plant using TRL5-validated seal design tools*

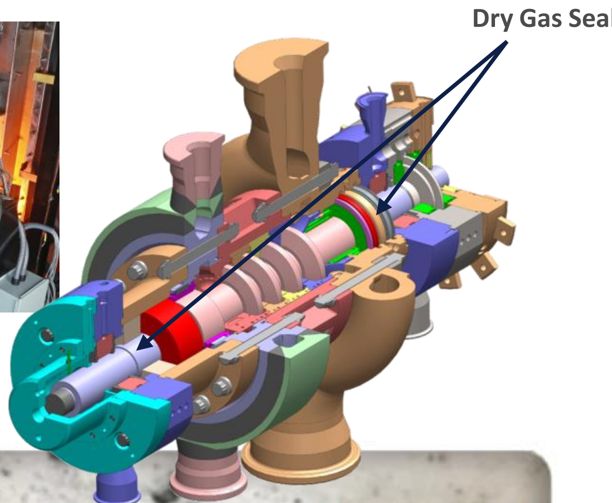


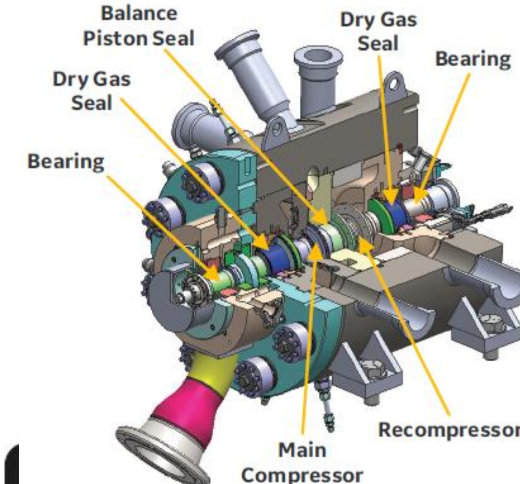
- 10 MW_e scale – Improved reliability of DGS and validation of Seal Design Tools
- 100 MW_e scale – High-temp seal to enable modular sCO_2 Coal FIRST turbines

DGS Reliability Issue – 10 MW_e scale



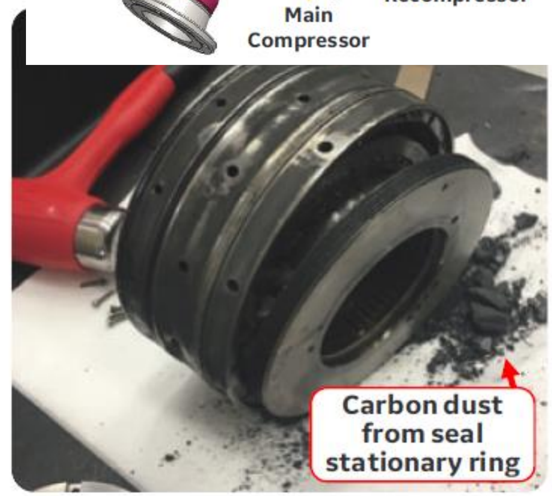
10 MW_e SunShot Turbine





4 MW_e Apollo Compressor

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



Failed DGS – Apollo Compressor Test (2019)

DGS Failure Leading Root Cause:

- Incorrect seal-system integration
- Seal film capability exceeded during operation

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

Program Goal # 1
Ensure efficiency realization by increasing reliability

Program Goal # 2
Enable even better (efficient & operationally flexible) Coal FIRST turbines

Turbomachinery	Application	Location and Temperature	Cycle Efficiency Benefit
10 MW_e sCO_2 turbine	WHR, CSP, NGPC, Coal FIRST risk reduction	Shaft-end labyrinth seals (200°C)	0 (baseline)
		Shaft-end DGS (200°C)	1.32%
		Shaft-end and Balance-piston DGS (700°C)	1.96%
10 MW_e sCO_2 com-pressor	WHR, CSP, NGPC, Coal FIRST risk reduction	Shaft-end labyrinth seals (200°C)	0 (baseline)
		Shaft-end DGS (200°C)	1.32%
		Shaft-end and Balance-piston DGS (200°C)	1.9%
100 MW_e sCO_2 turbine	Coal FIRST	Shaft-end labyrinth seals (200°C)	0 (baseline)
		Shaft-end DGS (200°C)	0.71%
		Shaft-end and Balance-piston DGS (700°C)	0.85%
450 MW_e sCO_2 turbine	Fossil indirect coal plant	Shaft-end labyrinth seals (200°C)	0 (baseline)
		Shaft-end DGS (200°C)	0.52%

Goal # 1 Reliability

Goal # 2 Higher -Temps

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

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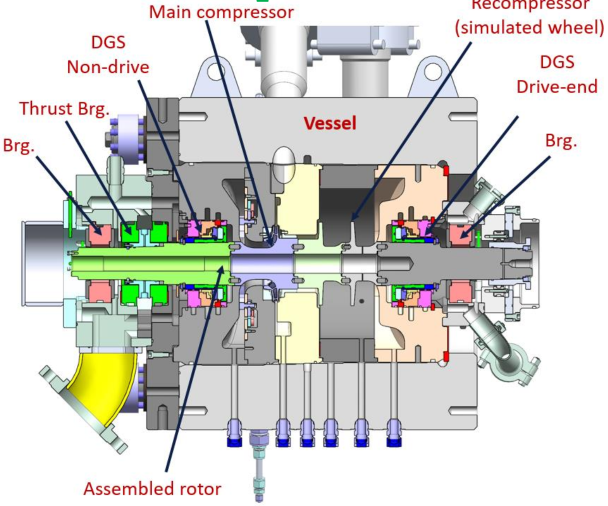
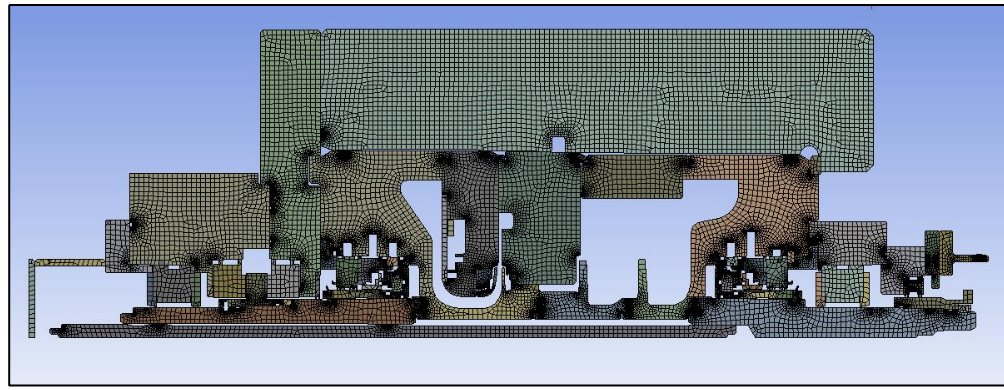
Thermal Modeling of DGS in Compressor

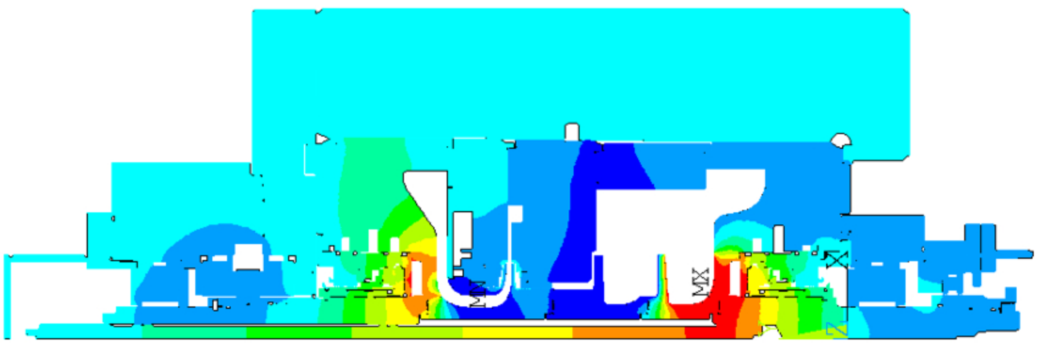
Existing sCO_2 compressor c/s



In-house FE-based thermal solver



Temperature prediction for compressor



Existing sCO_2 compressor at SwRI

- 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