Low-leakage seals for utility-scale sCO_2 turbines

GE Global Research

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Outline

- Value of face seals – utility-scale sCO_2 turbines
- Face Seal Concept
- Analyses of Face Seal
  - Fluid Analyses
    - Reynolds equation model
    - 3D CFD model
  - Mechanical Analysis
  - Thermal Analysis
- Progress overview & Next steps

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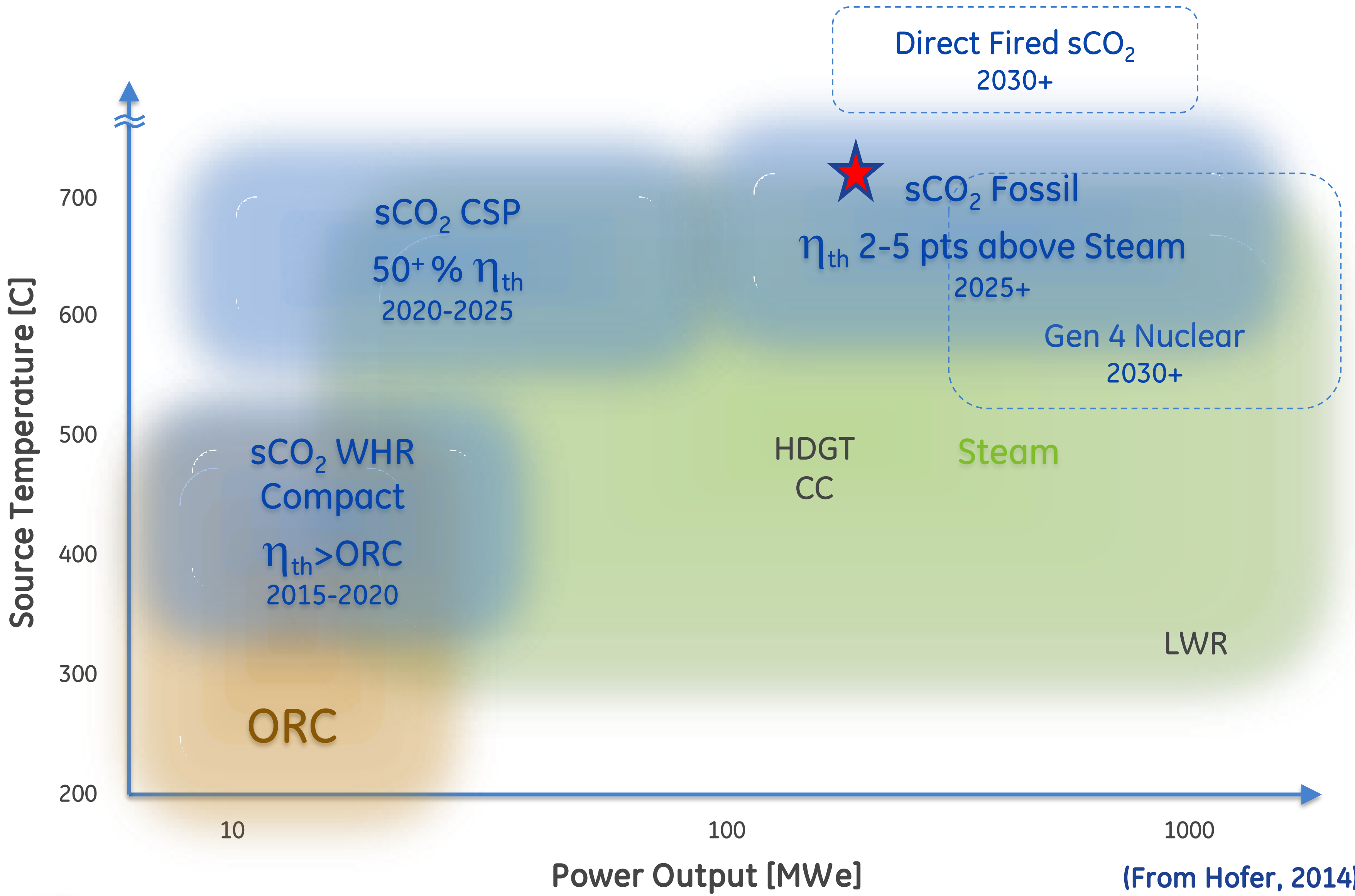
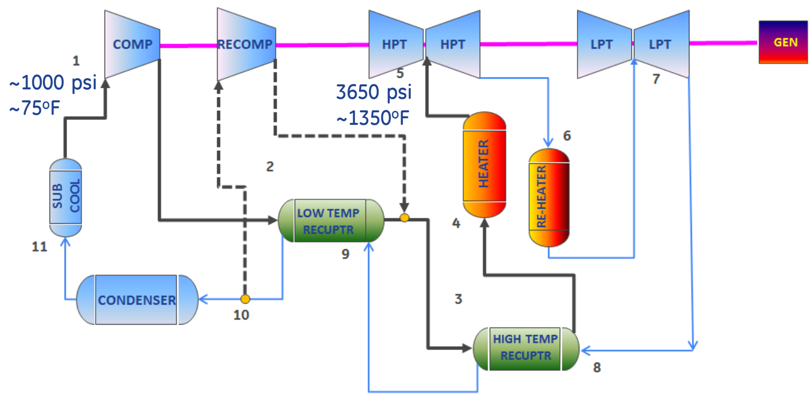
sCO_2 Application Space



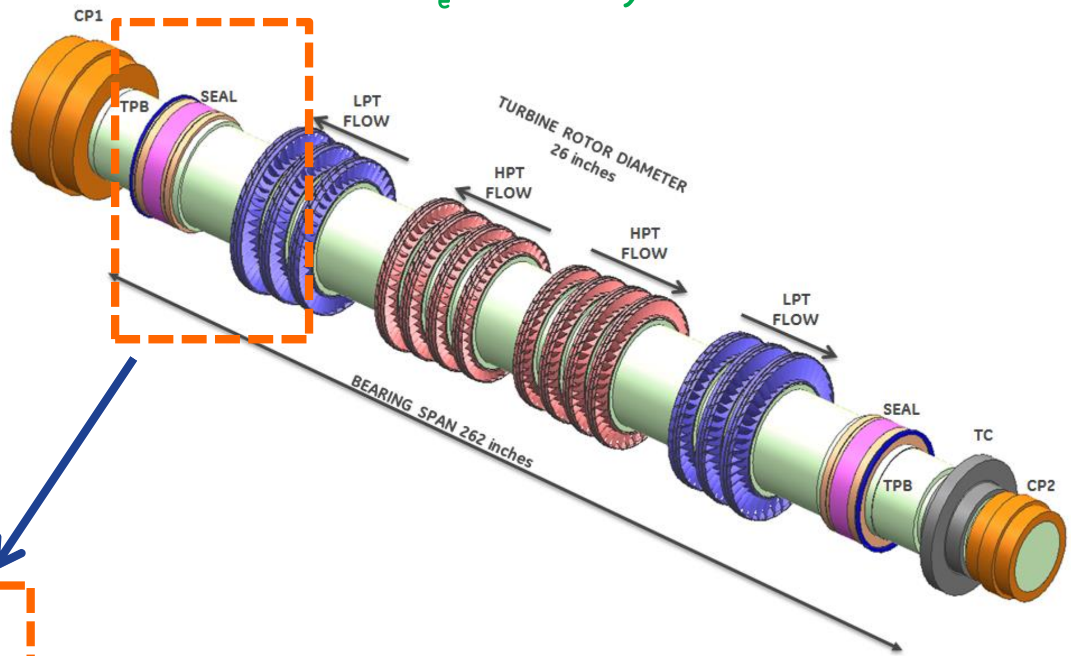
(From Hofer, 2014)

Layout of End Seals in sCO_2 turbines

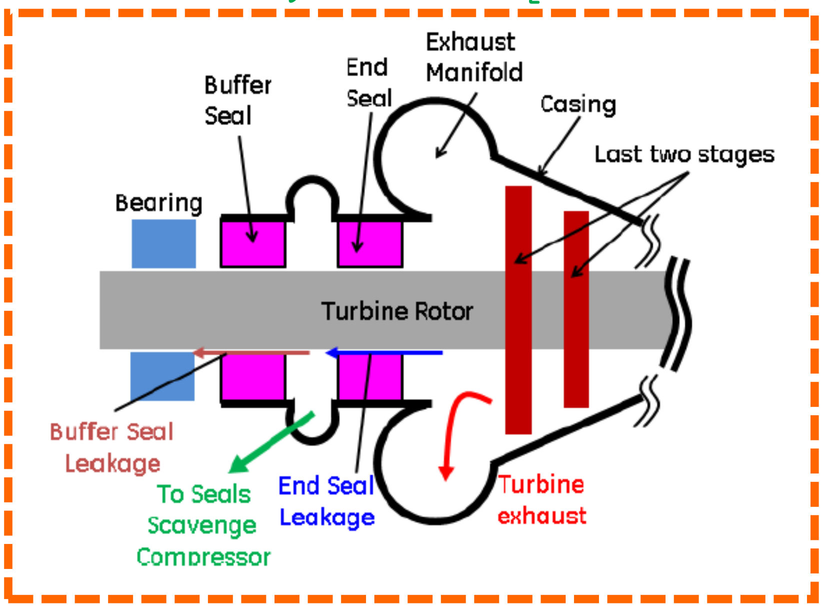
450 MW_e cycle – 51.9% efficient cycle



450 MW_e turbine layout (From Bidkar et. al, 2016)



End Seal layout for a sCO_2 turbine

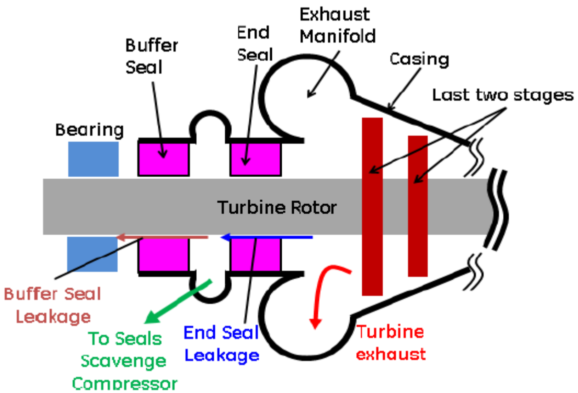


- End seals needed for shielding bearings from high-temp exhaust
- Turbine exhaust typically ~1000 psi pressure
- Seal leakage to atmospheric pressure needs to be recompressed using a scavenge compressor

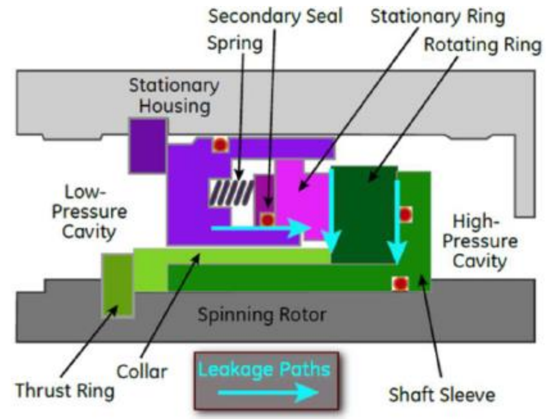
sCO_2 cycles are closed loop & seal leakage flow needs to be recompressed

Need for low-leakage face seals

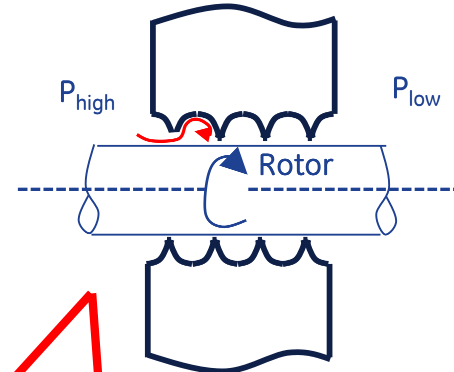
End Seal layout for a sCO_2



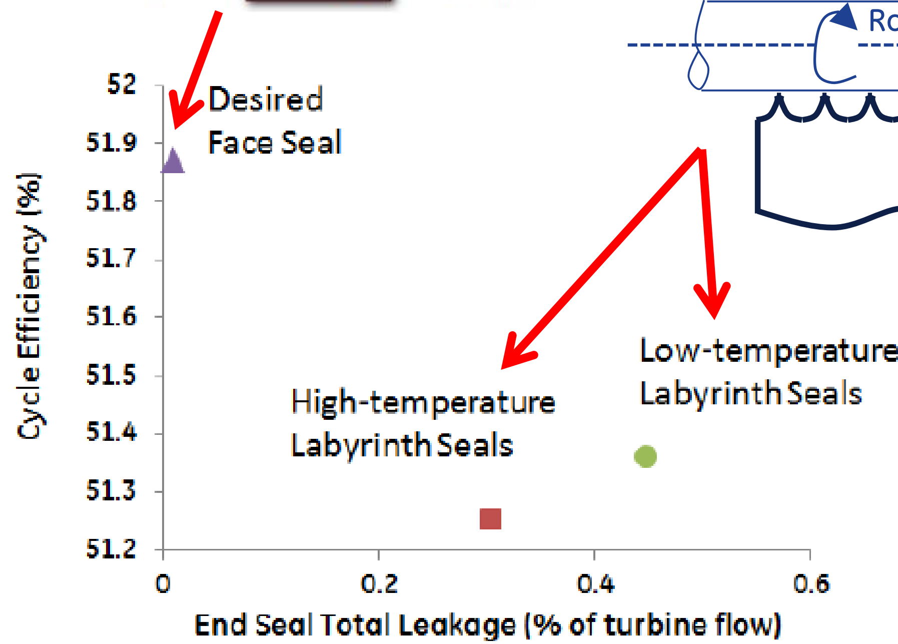
NEW TECHNOLOGY
Face seal



EXISTING TECHNOLOGY
Radial Labyrinth seal



- Leakage flow calculated for existing technology (labyrinth seals) and new technology (face seals)
- Multi-stage centrifugal compressor designed as a scavenge compressor
- Comparison of labyrinth seals and face seals shows a 0.55% points cycle benefit for face seals



Face seals are worth ~0.55% points cycle efficiency compared to labyrinth seals

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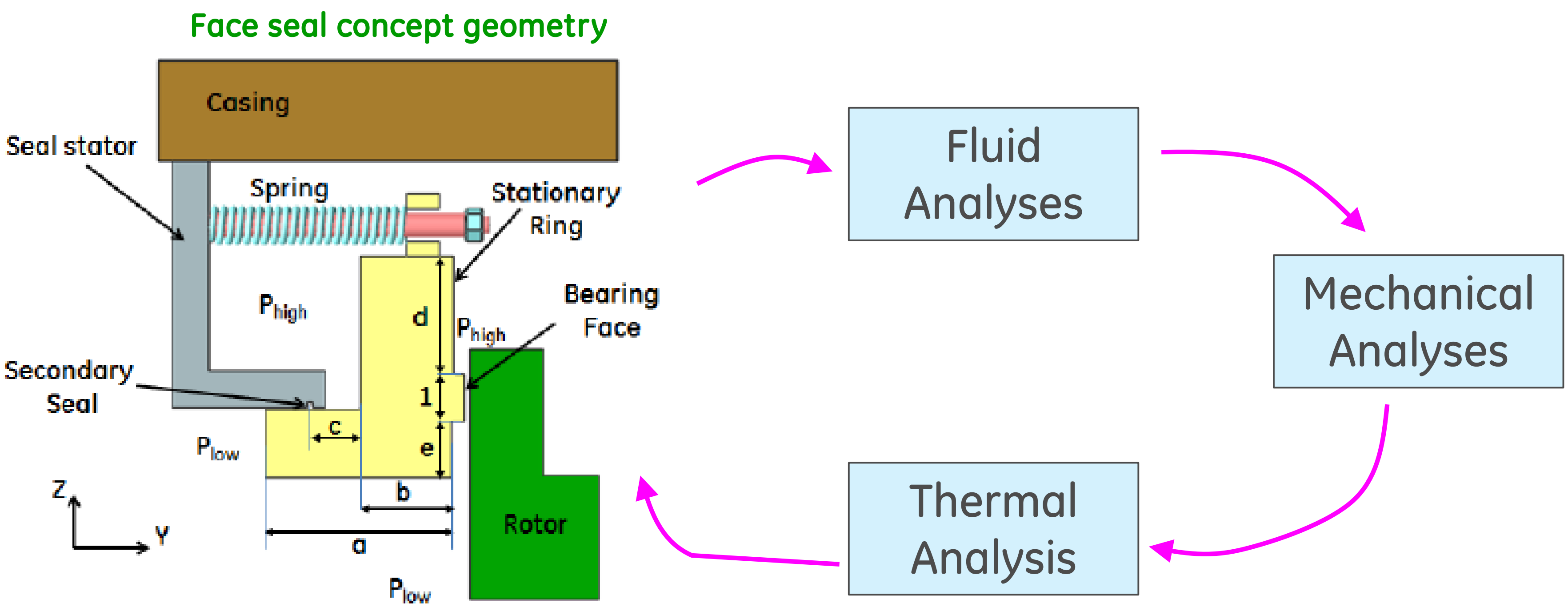
Face Seals for utility-scale sCO_2 turbines



- Face seals needed for utility-scale sCO2 turbines (24-inch diameter, 1000 psia pressure differential) not readily available
- Concept design explored using fluid, mechanical and thermal analyses

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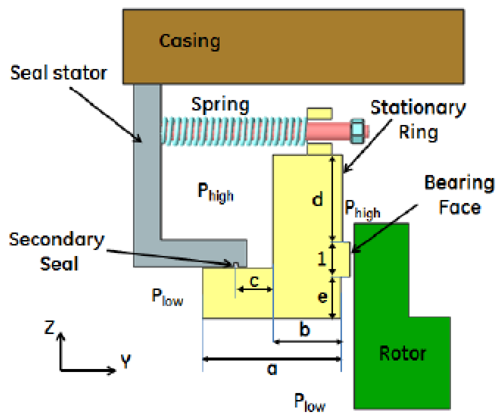
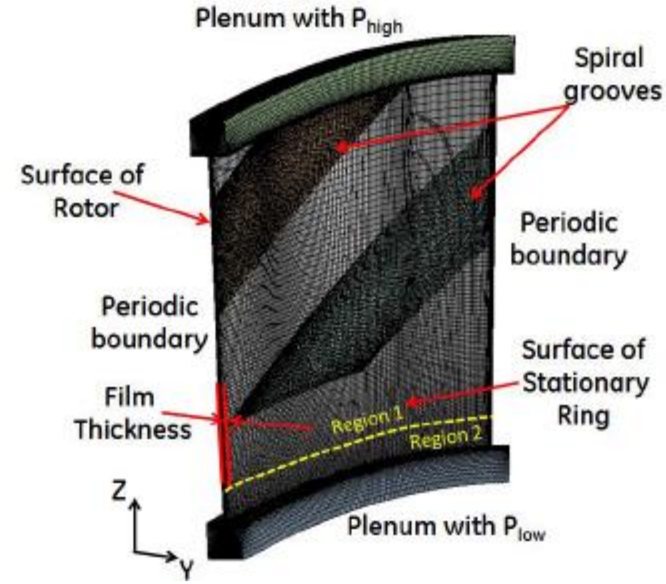
sCO_2 Face Seals – Fluid Analyses

Face seal concept geometry



Typical domain for flow analysis



Approach # 1: Reynolds equation

Region 1

$$\frac{\partial}{\partial r}\left(r\frac{ph^3}{\mu}\frac{\partial p}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial \theta}\left(\frac{ph^3}{\mu}\frac{\partial p}{\partial \theta}\right)=6\omega r\frac{\partial}{\partial \theta}(ph)$$

Region 2

$$\frac{dp}{p}=\frac{\gamma M^2}{1-M^2}\left(\frac{dA}{A}\right)-\frac{\gamma M^2[1+(\gamma-1)M^2]}{2(1-M^2)}\left(\frac{4C_f dr}{D_h}\right)$$

$$\frac{d\rho}{\rho}=\frac{M^2}{1-M^2}\left(\frac{dA}{A}\right)-\frac{\gamma M^2}{2(1-M^2)}\left(\frac{4C_f dr}{D_h}\right)$$

$$\frac{dM}{M}=\frac{-[1+0.5\,(\gamma-1)M^2]}{1-M^2}\left(\frac{dA}{A}\right)+\frac{\gamma M^2[1+0.5\,(\gamma-1)M^2]}{2(1-M^2)}\left(\frac{4C_f dr}{D_h}\right)$$

- Fluid analyses goal: Predict pressure on the bearing face, predict leakage & windage heat generation
- Two approaches used for analyzing the fluid flow
  - Approach # 1: Reynolds equation
  - Approach # 2: ANSYS 3D CFD with CO_2 real gas properties
- Compare the results and validity of the two approaches

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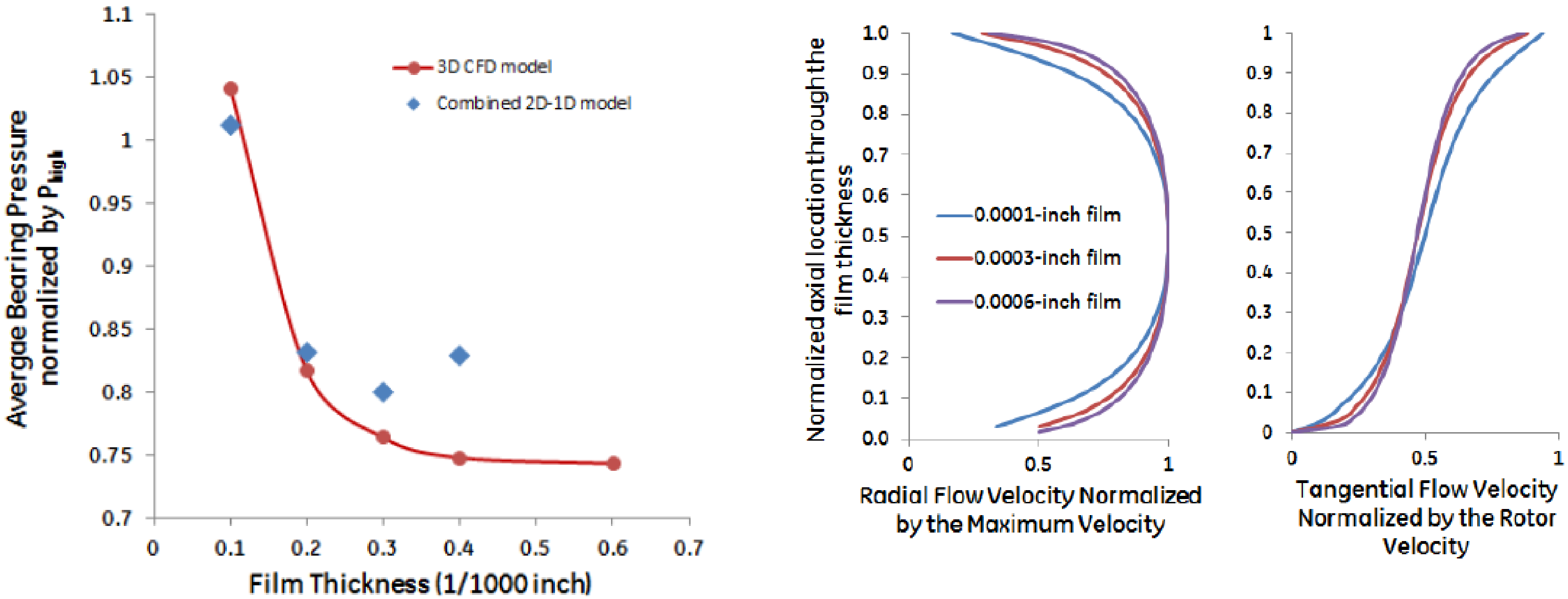
sCO_2 Face Seals – Fluid Analyses



- Bearing pressure predictions match well for Approach # 1 (Reynolds equation) and Approach # 2 (ANSYS 3D CFX) for small film thickness
- Increasing film thickness leads to turbulent flow and breakdown of Approach # 1 assumptions
- sCO_2 films show larger heat generation (compared to air) due to higher density

Higher density of sCO_2 needs turbulent flow modeling & full 3D modeling not possible with conventional 2D-1D models

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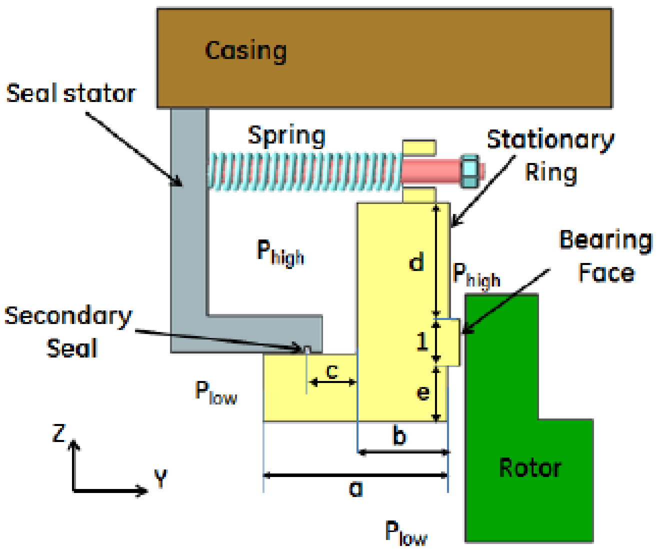
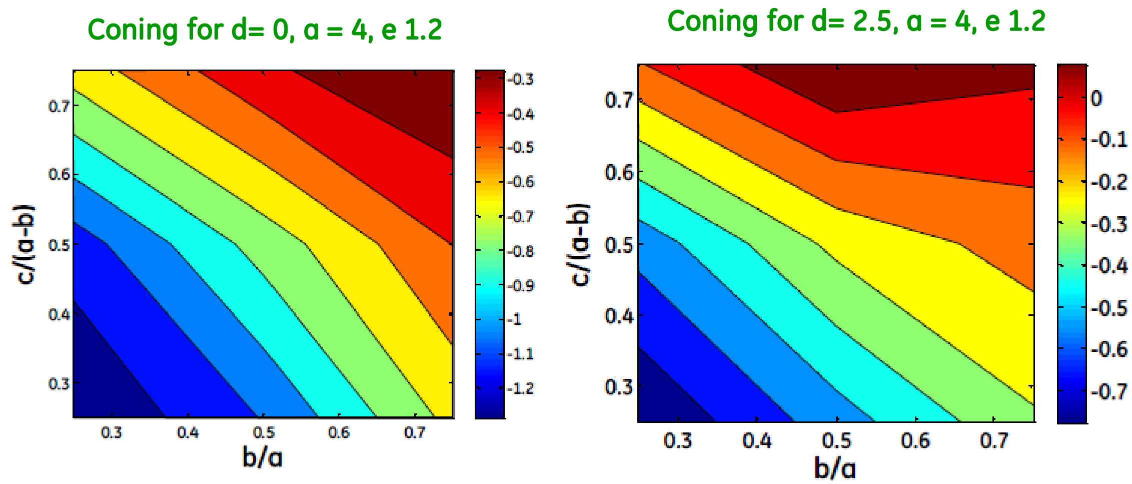
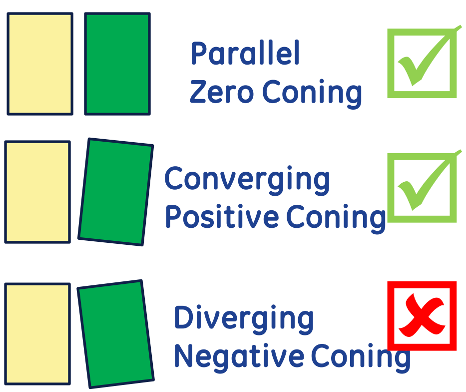
sCO_2 Face Seals – Structural Analysis

Face seal concept geometry





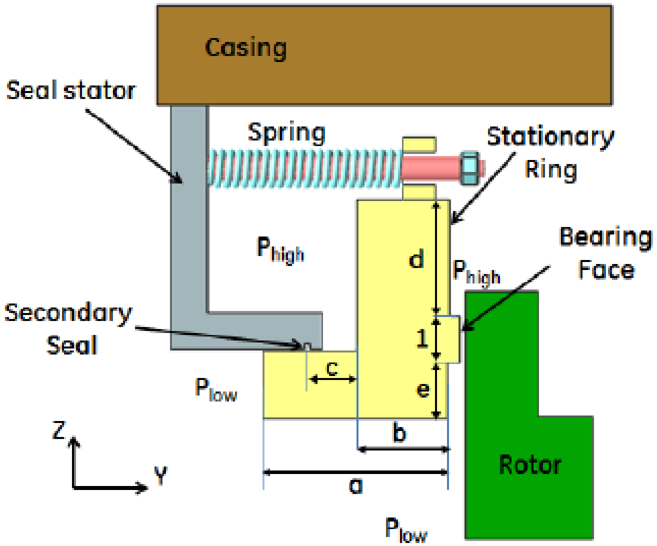


- Coning is the angular mismatch between the bearing face & the rotor
- Parametric Finite-element Model to analyze effect of geometry on coning sensitivity
- Isothermal FEM with pressure loads from the CFD model
- Increasing dimension 'd' leads to positive coning

Parametric Finite Element Model used to explore the design space and optimize the seal cross-section for small positive coning

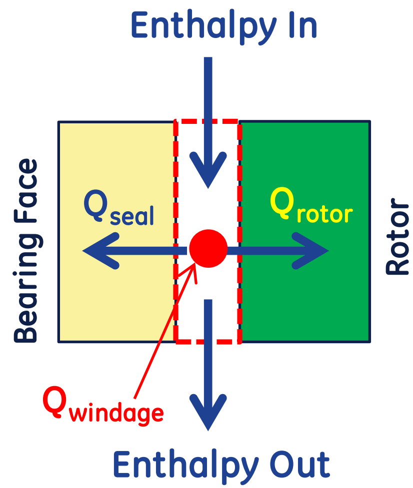
sCO_2 Face Seals – Thermal Analysis

Face seal concept geometry

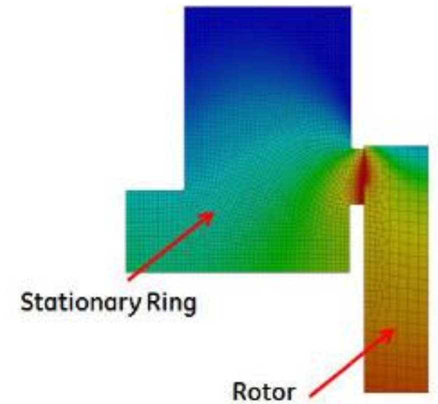


Energy balance for film

$$\dot{m}_{leak} h_{in} + \dot{Q}_{windage} = \dot{Q}_{rotor} + \dot{Q}_{seal} + \dot{m}_{leak} h_{out}$$



Temperature predictions



- Leakage flow, windage heat generation from CFD, and sCO_2 properties used as an input to the thermal model
- Heat transfer coefficients and thermal boundary conditions using local flow properties
- Advection model (energy conservation) used with ANSYS to predict metal temperatures
- Combined pressure-temperature loads used for predicting coning

Based on the fluid, structural & thermal analyses, a net pressure-thermal coning of about 0.0005 inches is possible

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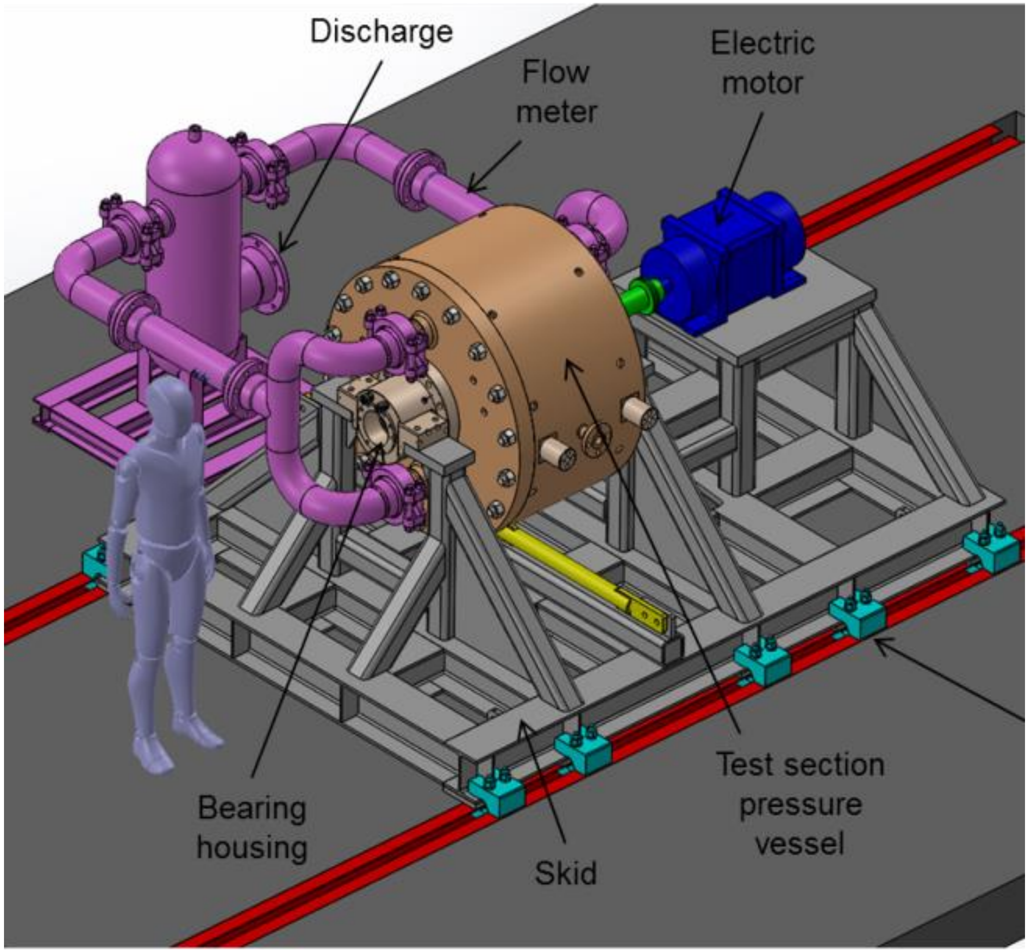
sCO_2 Seals Test Rig Concept



Full-scale test rig concept developed for face seal testing

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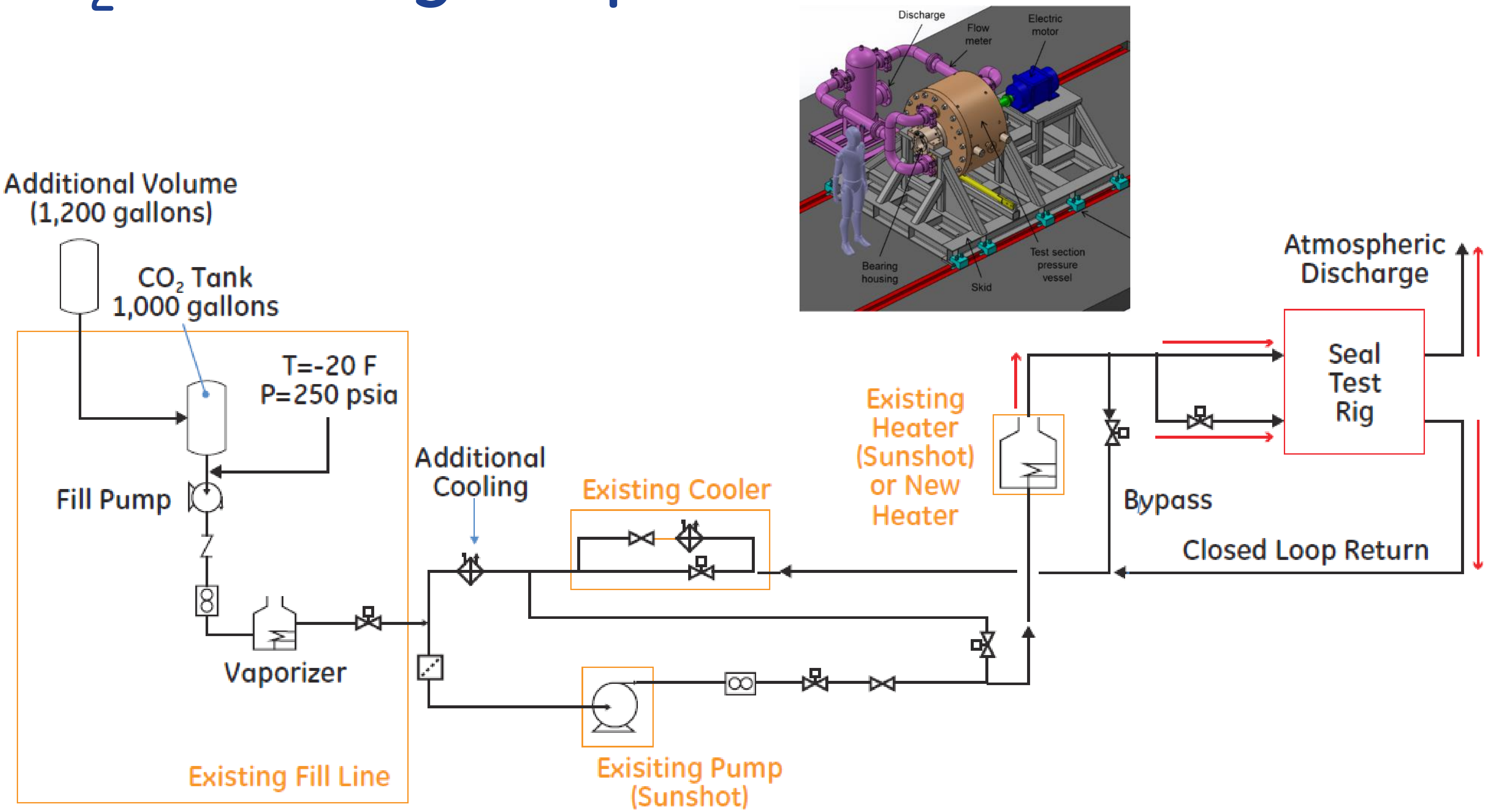
sCO_2 Seals Rig Loop



Full-scale test rig to be coupled to existing CO_2 loop at Southwest Research

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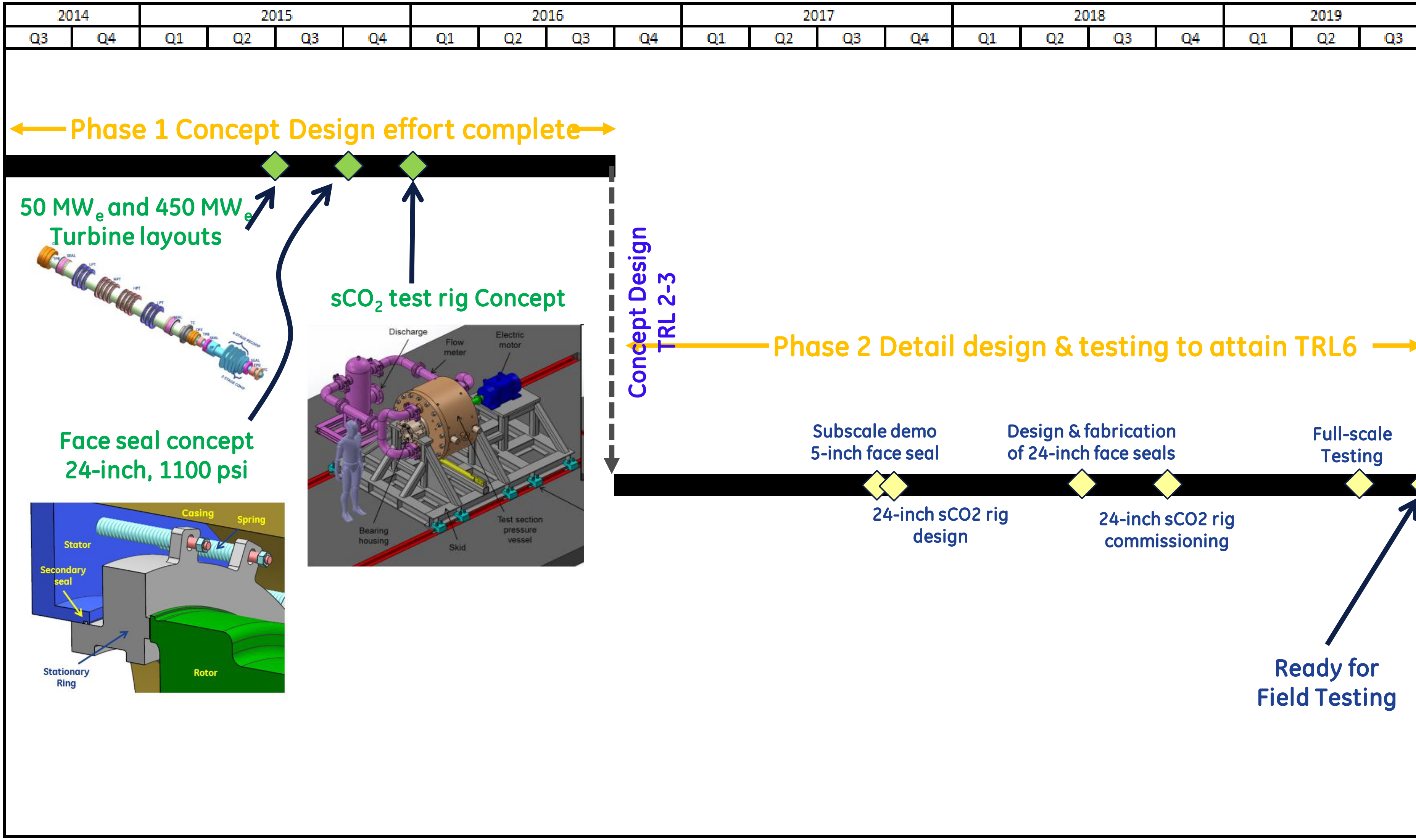
Progress Overview & Next Steps



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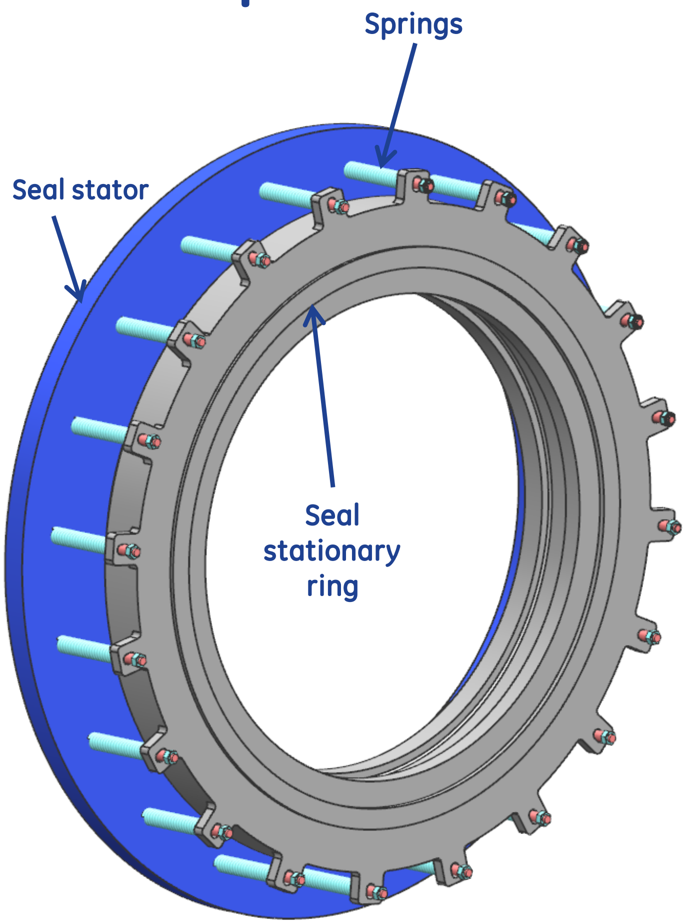
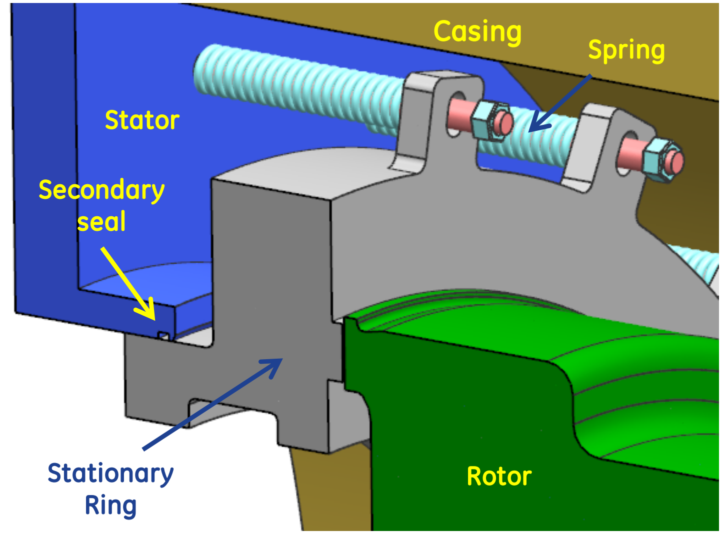
Summary and Conclusions

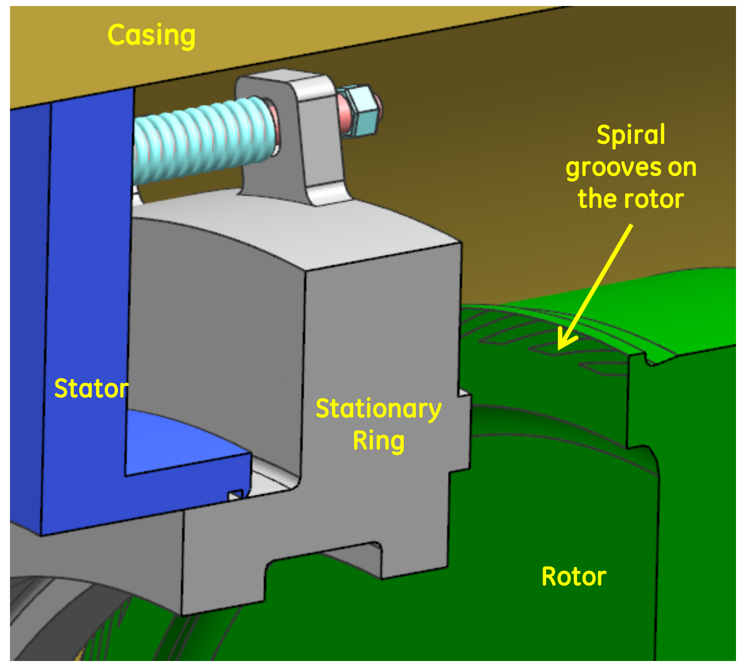
- Value of Face Seals
  - Face seals can enable a 0.55% points benefit over present labyrinth seals technology
- Unavailability of face seals for utility-scale sCO_2 turbines
- Face seal concept
  - Importance of 3D CFD with real gas properties
  - Coning analyses with pressure/thermal loads to show basic feasibility of the concept
- sCO2 Seals rig concept completed
- Plans for subscale & full-scale testing of seals

BACK-UP

Seal Concept







- Springs & pressure bias the stationary ring towards the rotor
- Spiral grooves generate separating force
- Seal tracks rotor axial transients

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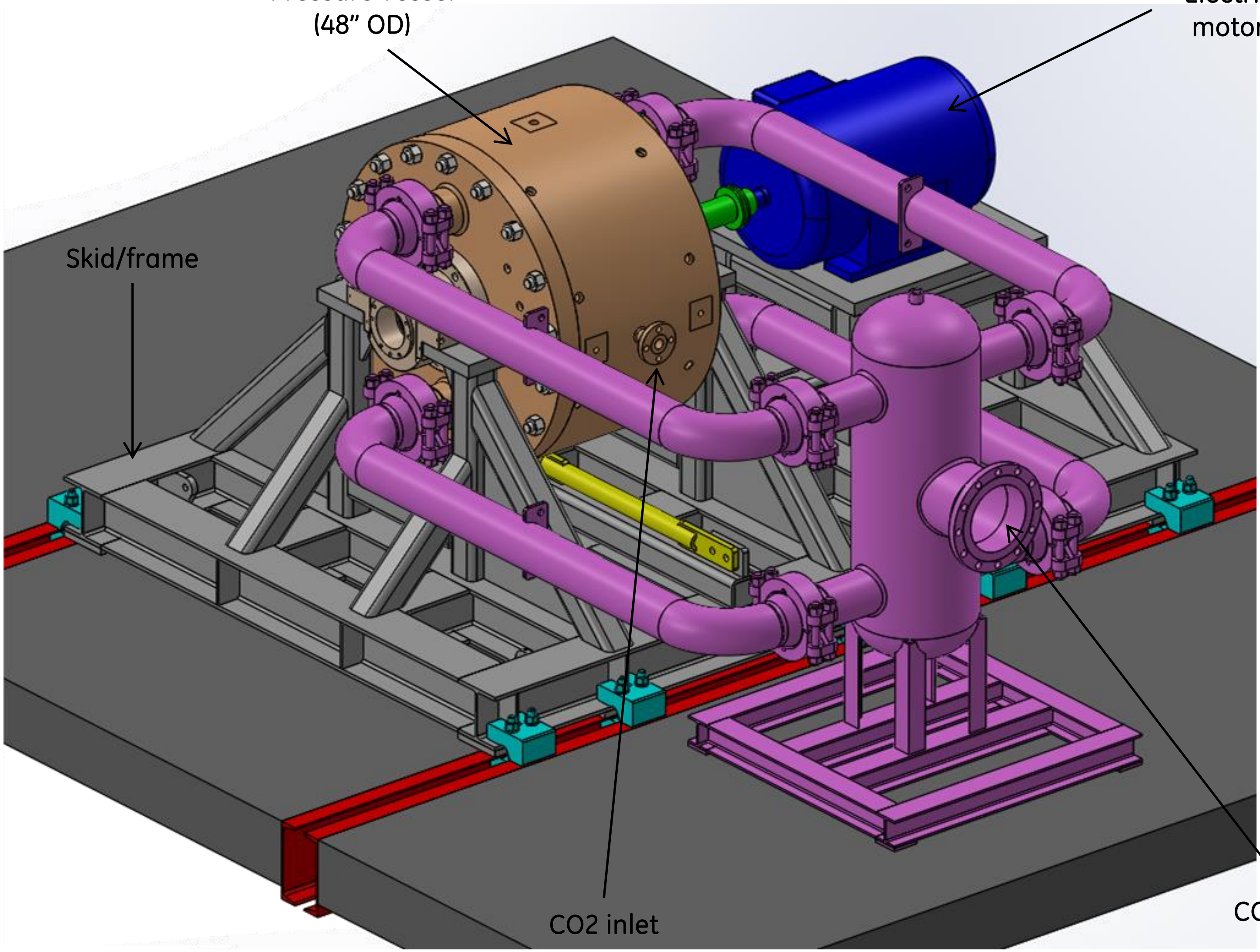
sCO_2 Seals test rig concept

sCO2 Test Loop Concept



Seal test rig concept developed for high pressure, high temperatures and large diameter seals