Test Rig Design for Large Supercritical CO_2 Turbine Seals

Presented by:

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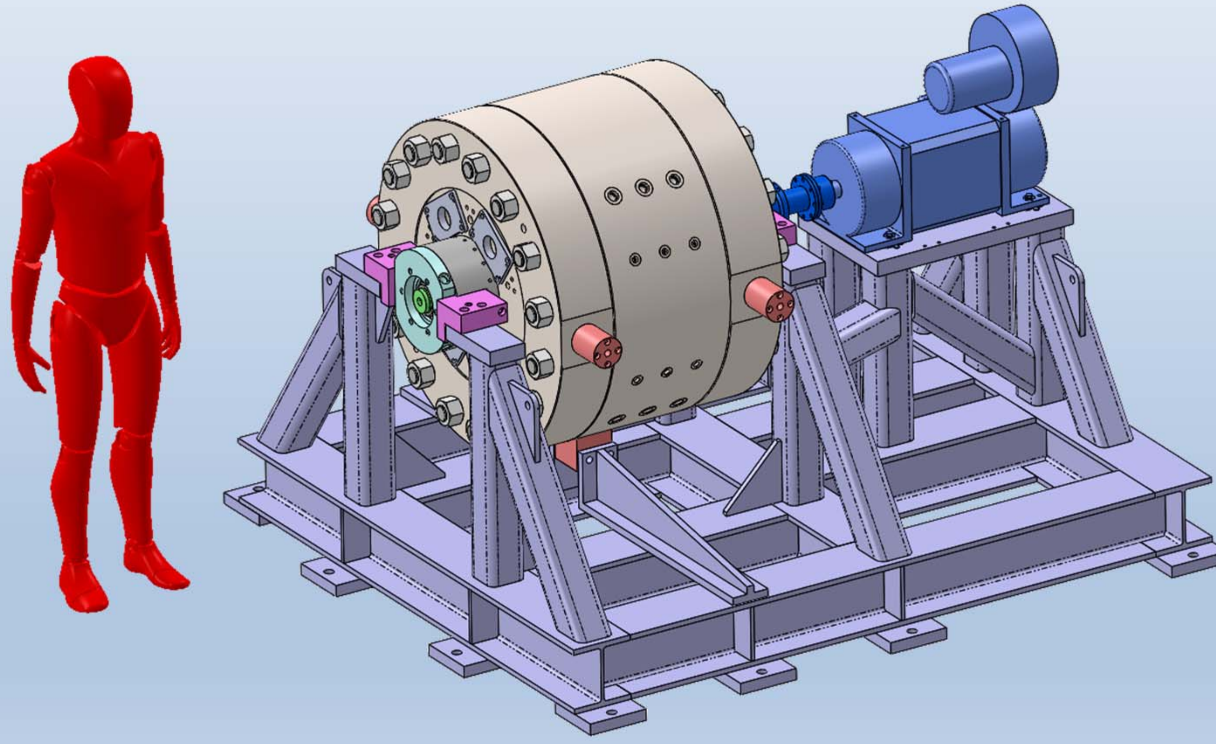

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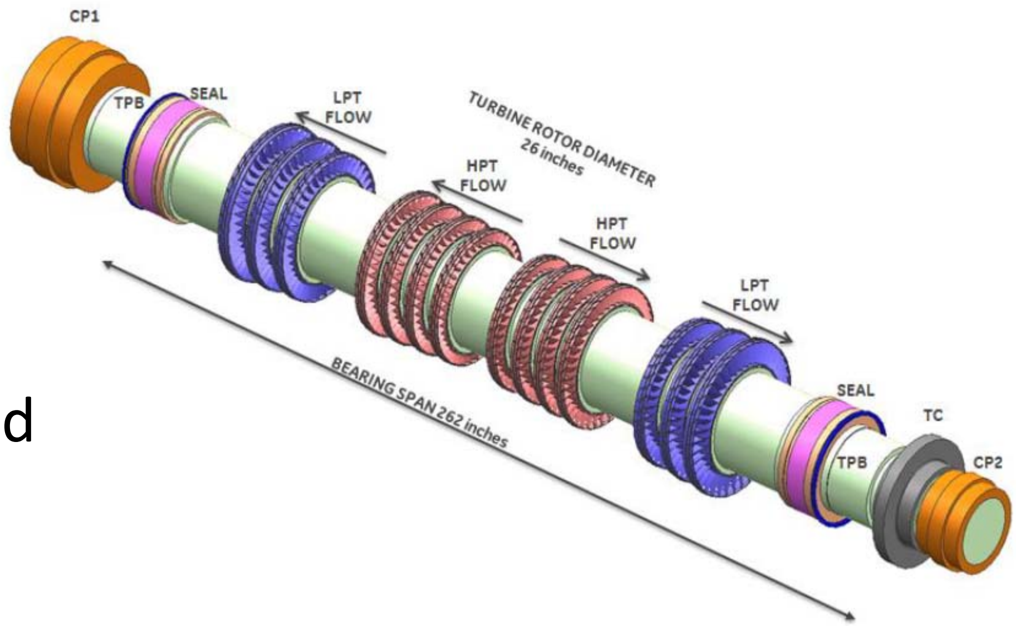
Utility-scale sCO_2 turbines require advanced seals

- Utility-scale ~ 450 MW_e
- Shaft end seal requirements
  - P_{high} ~ 75 bar
  - Diameter ~ 24 in.
- sCO_2 poses unique challenge for end seals compared to gas or steam turbines
- Film-riding face seals vs. labys **<u>increase cycle efficiency 0.6-0.8 points</u>**
- Seals at this size, pressure do not exist

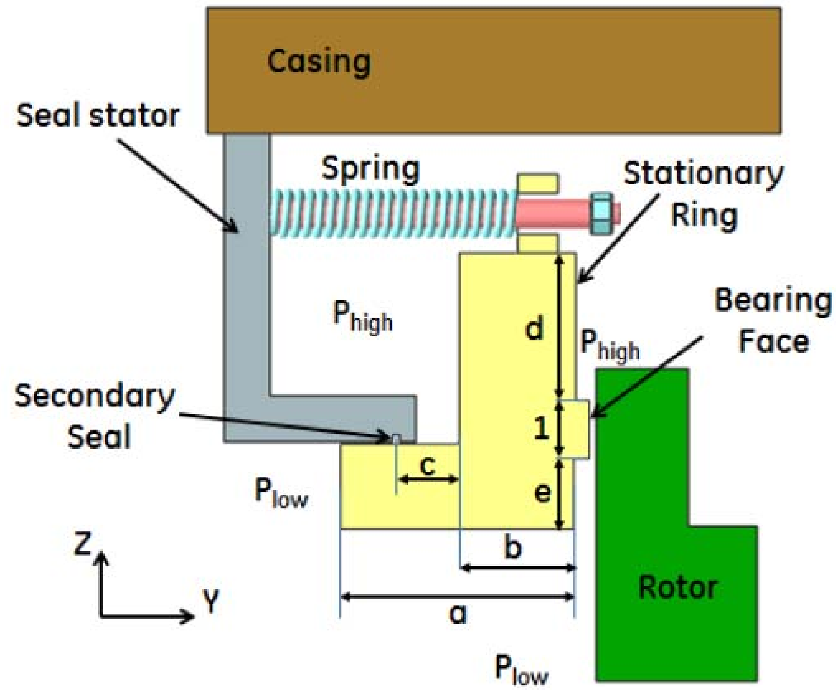


Bidkar et al., 2016, "Conceptual Designs of 50 MW_e and 450 MW_e Supercritical CO_2 Turbomachinery Trains for Power Generation from Coal. Part 1: Cycle and Turbine," The 5th International Supercritical CO_2 Power Cycles Symposium, March 28-31, San Antonio, TX.

Current research developing large sCO_2 face seal

Current DOE project activities

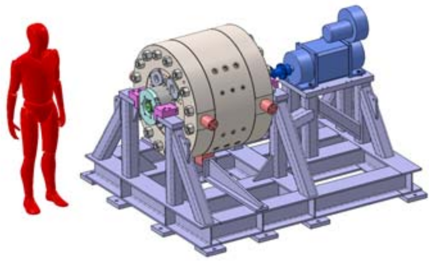
- Detailed design of new face seal technology
- Reduced-size prototype testing
- **Detailed design of full-scale seal test rig**
- *Construction & commissioning of full-scale test rig (2018)*
- *Full-scale seal testing (2019)*

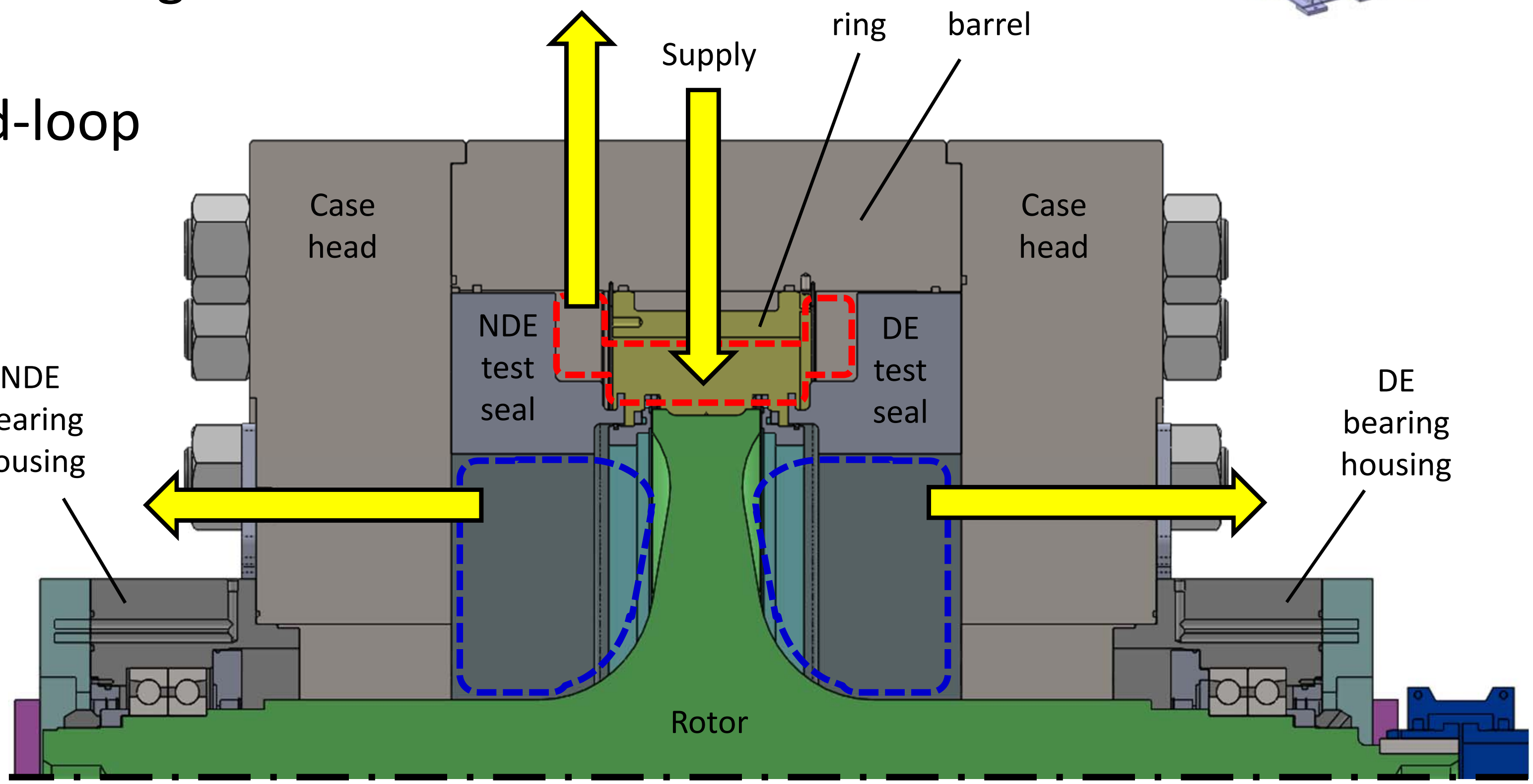


Bidkar et al., 2016, "Low-Leakage Shaft End Seals for Utility-Scale Supercritical CO_2 Turboexpanders," Paper No. GT2016-56979, ASME Turbo Expo 2016, June 13-17, Seoul, South Korea.

Test rig overview

- Back-to-back seal arrangement
- Thrust balanced
- Open- and closed-loop

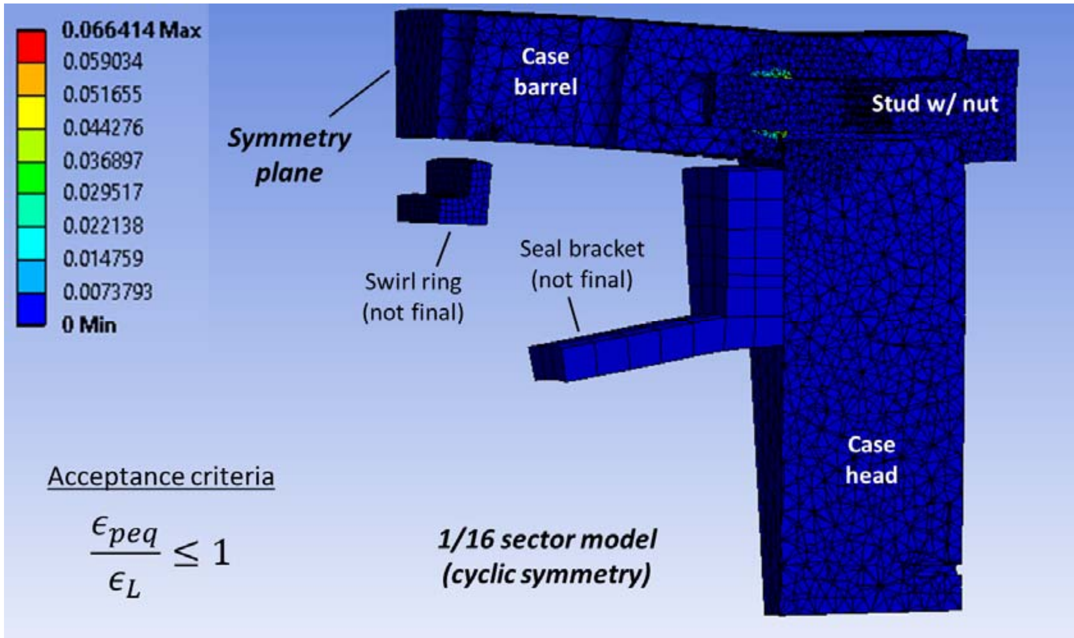




Conditions:
75 bar, 400°F max
1-10 bar

Casing design limited by deflections

- Design by ASME BPVC, VIII-2
  - Linear elastic
  - **Elastic-plastic**
  - Cyclic loading (ratcheting)
- Stress design exceeds BPVC requirements
- Increased wall thickness to limit deflections to 0.0005”

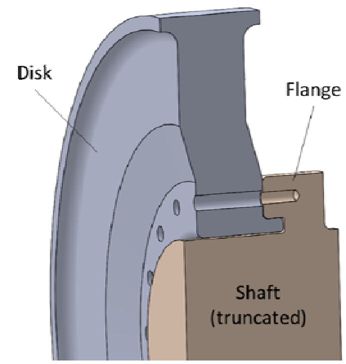


Elastic-plastic analysis solution, thinner walls than current design

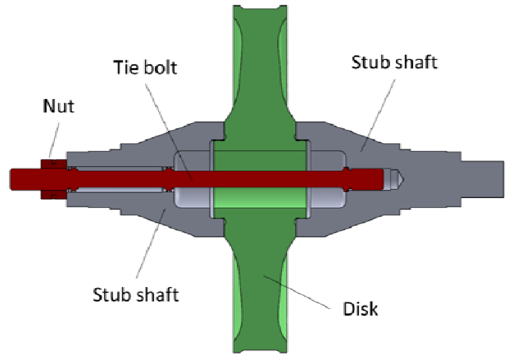
Multi-piece rotor concepts evaluated, not selected

- Perceived advantages of multi-piece rotor
  - Less wasteful material use assuming standard cylinder shapes
  - Replacement disk cheaper than entire rotor
  - Tie bolt concept lighter, more rigid than solid shaft (improved rotordynamics)
- Actual advantages of single-piece rotor
  - Simpler design
  - Near-net-shape forging cost reasonable
  - Less overall machining
  - Greater burst margin
  - Negligible difference in repair cost
  - Critical speed separation margin > 100%

Earlier multi-piece rotor concepts

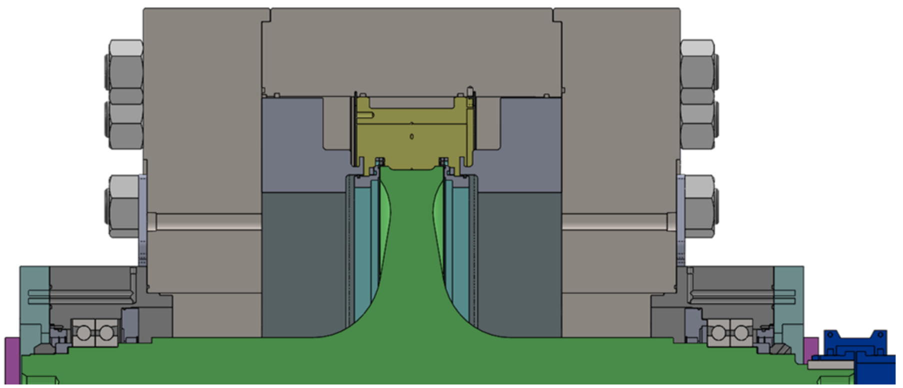


(a) Flange Disk Concept

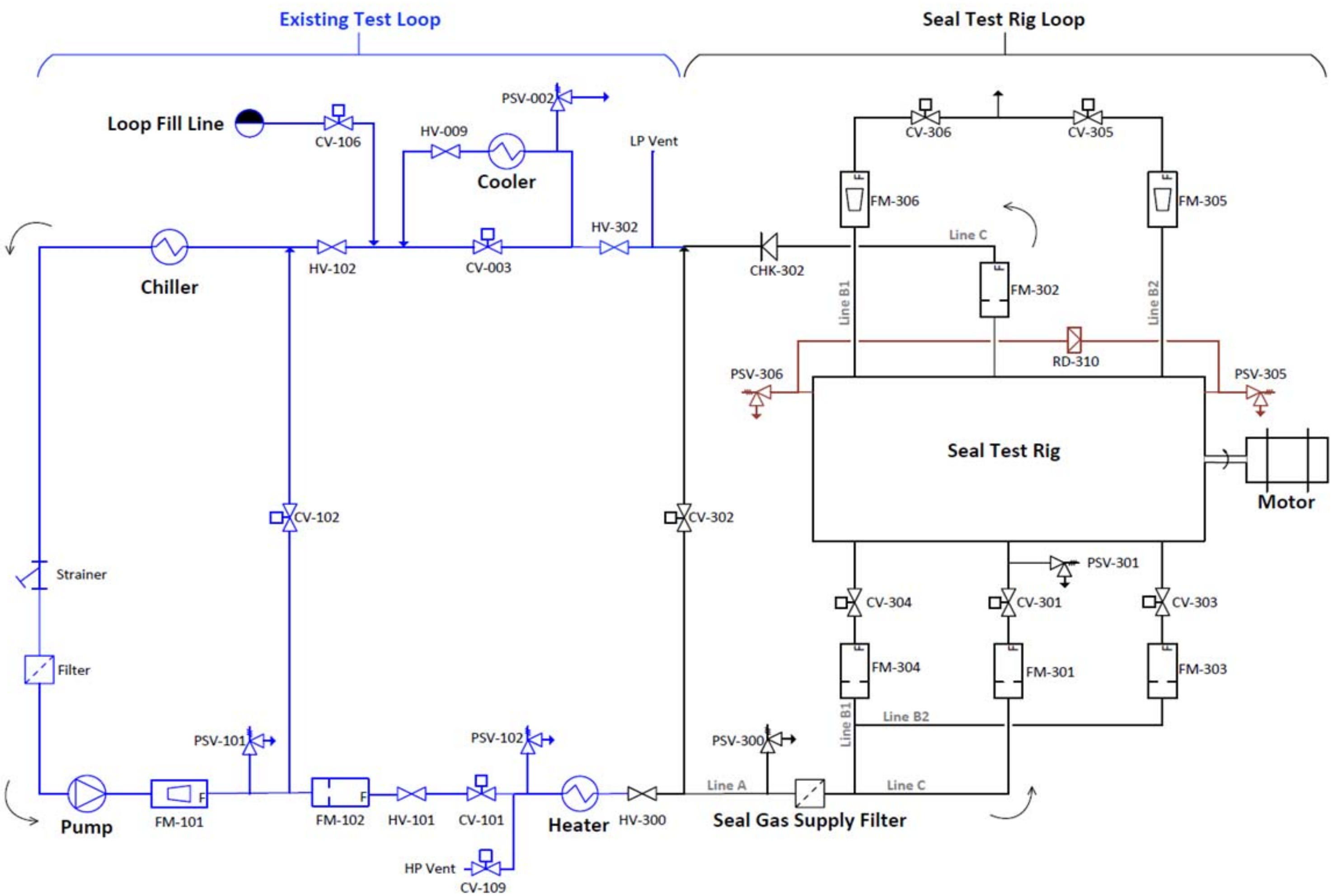


(b) Tie Bolt Rotor Design

Current: single piece rotor

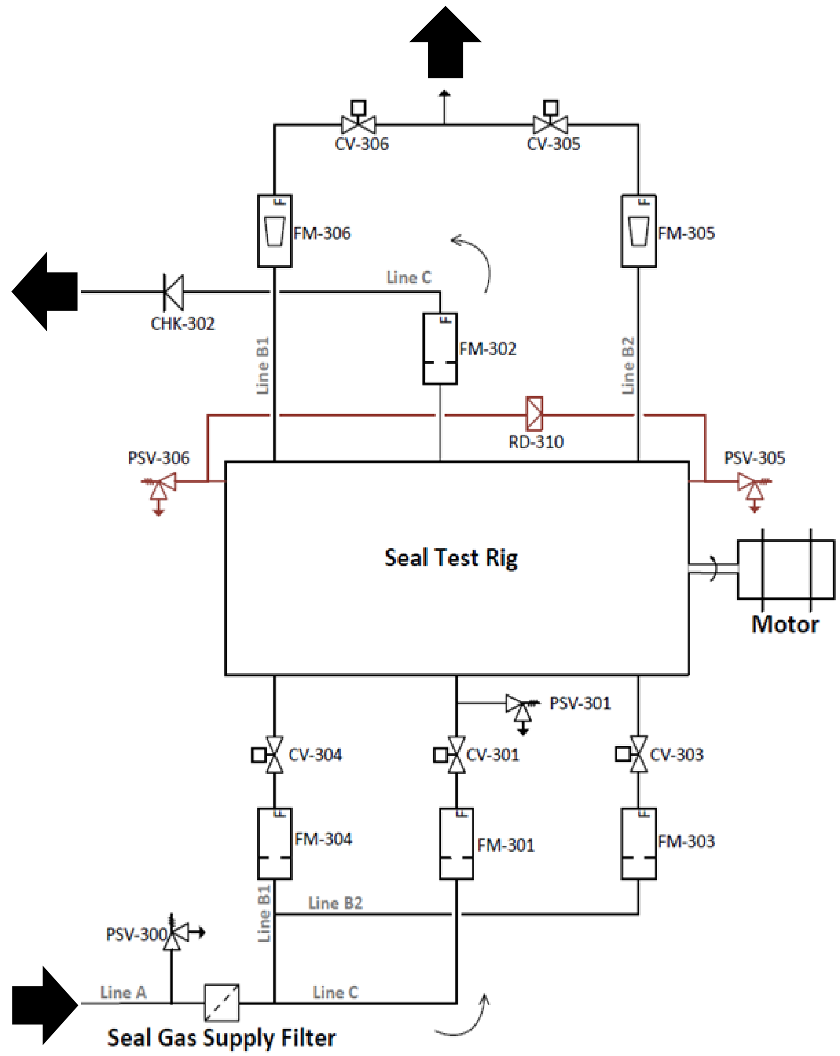


Flow loop leverages existing sCO_2 facility



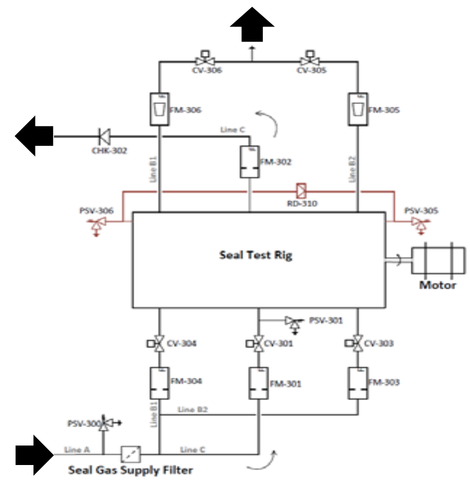
Flow loop design

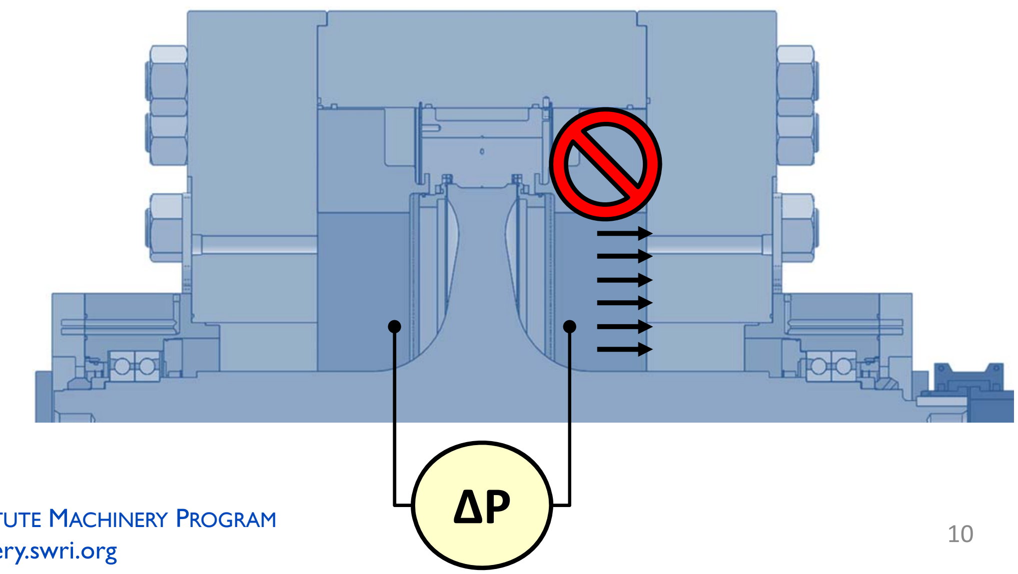
- Less challenging than other sCO_2 projects due to lower temperature
- Upstream piping
  - 316 stainless steel
  - 3 micron filter
- Downstream piping
  - Carbon steel



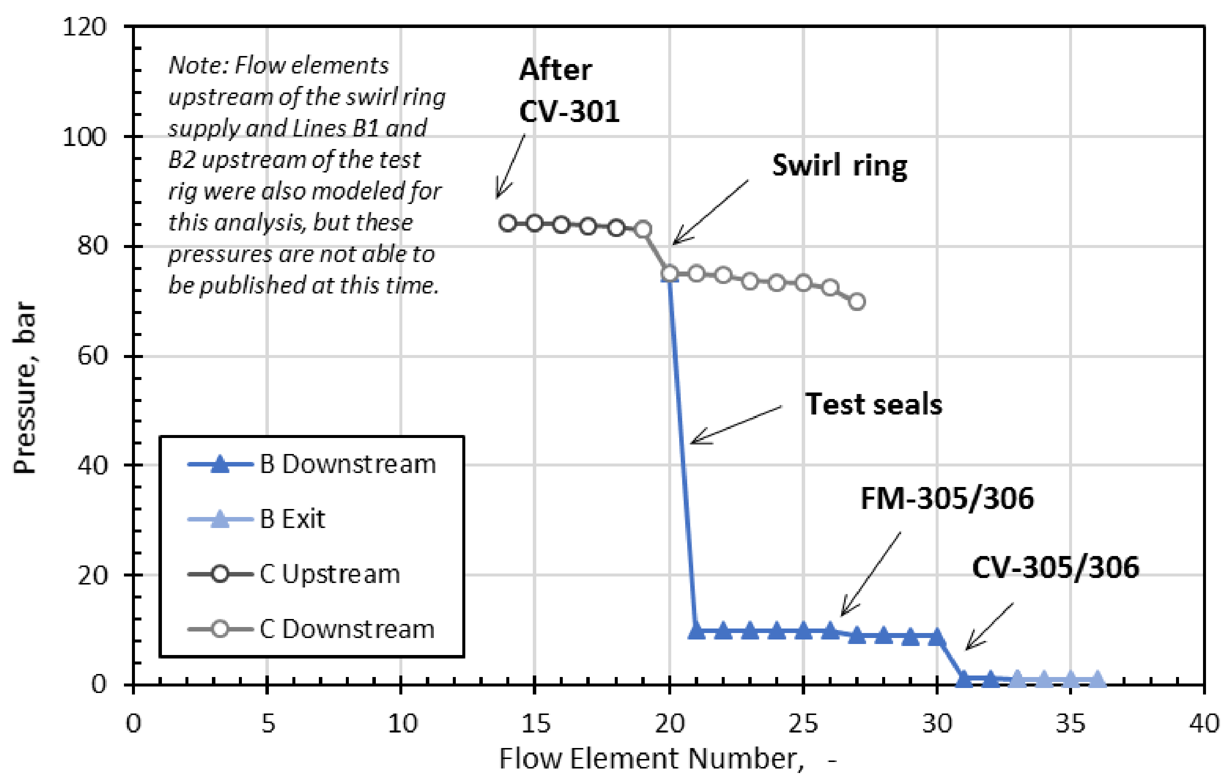
Flow network analysis

- Quantify pressure drops
- Size piping
- Cases
  - Design conditions
  - Test seal failure
    - Maximum downstream pressure
    - Maximum ΔP / thrust force

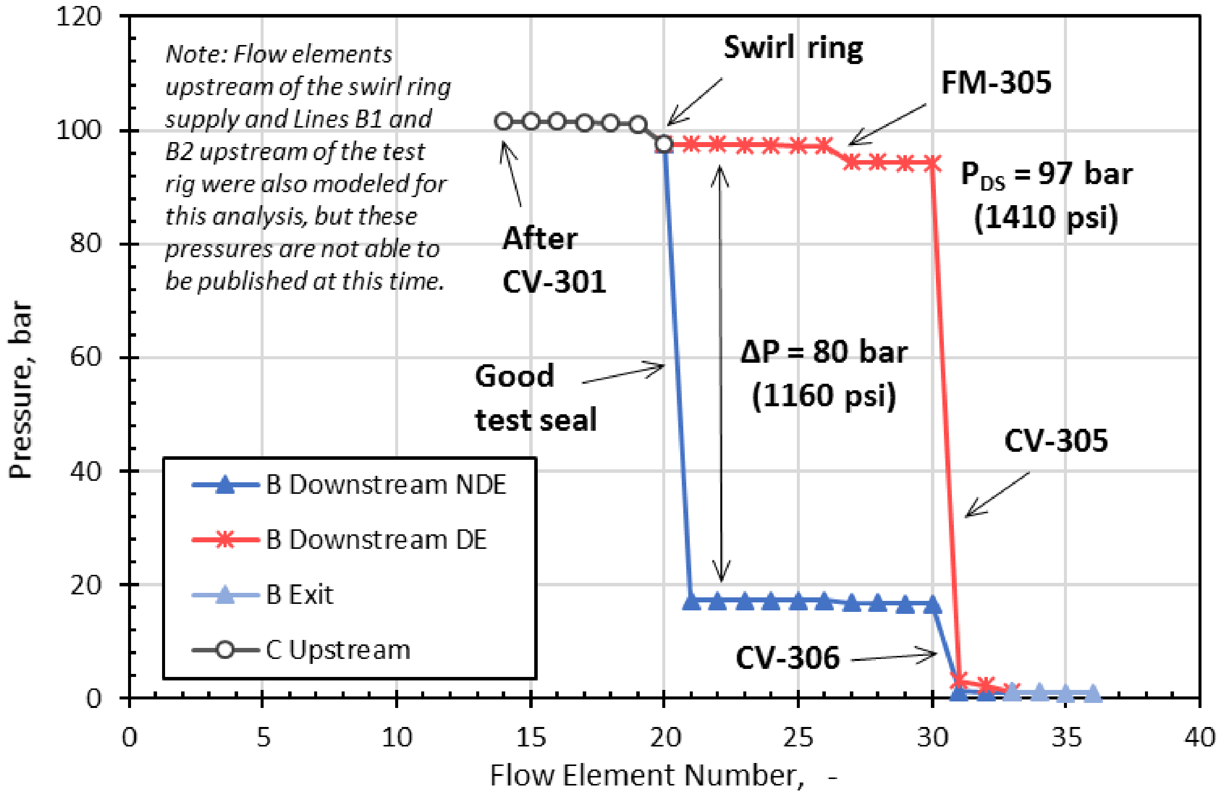




Design case pressure drops



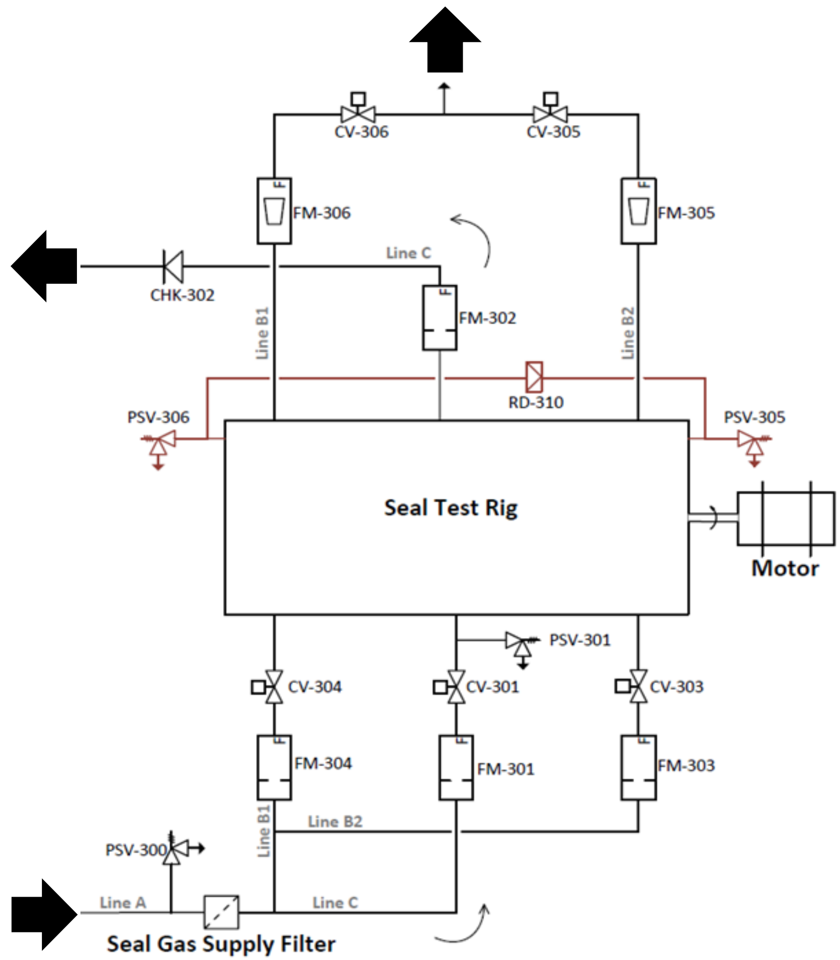
Seal failure without protection results in excessive downstream pressure and thrust force



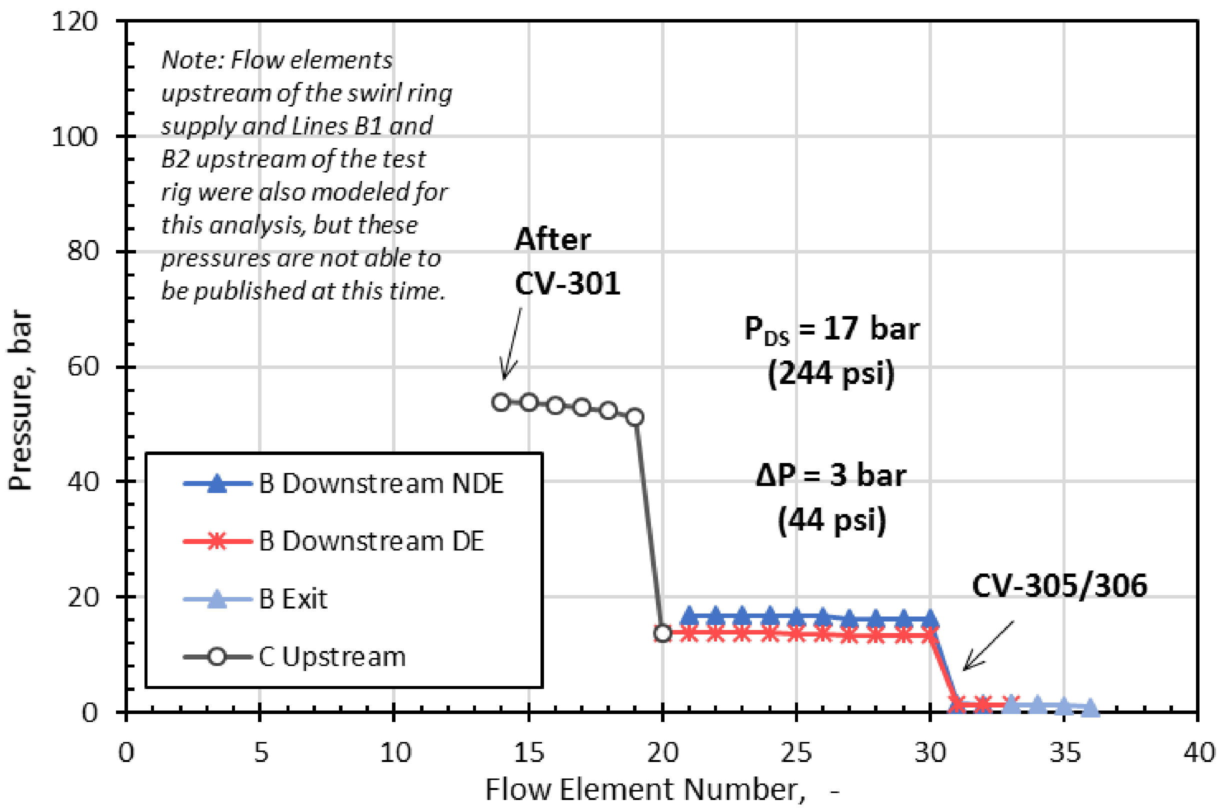
- Simulated DE seal as no restriction (failure)
- Assume all valve settings at same set point
- Assume supply pressure from pump remains unchanged
- Allow flow rates to increase due to less restriction (conservative)

Mitigation approach utilizes PSVs and rupture disk

- PSVs protect downstream cavities from excessive pressure
  - 200 psi set point
  - Sized to handle flow of seal supply
- Rupture disk protects from excessive ΔP
- Check valve on return line prevents back flow into rig



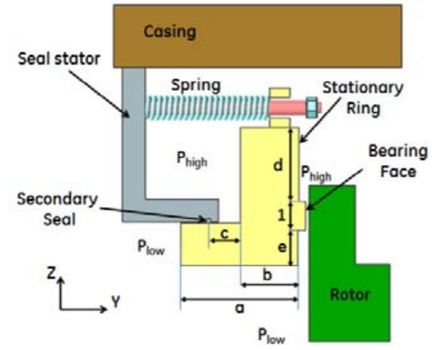
Mitigation features ensure rig safety in seal failure

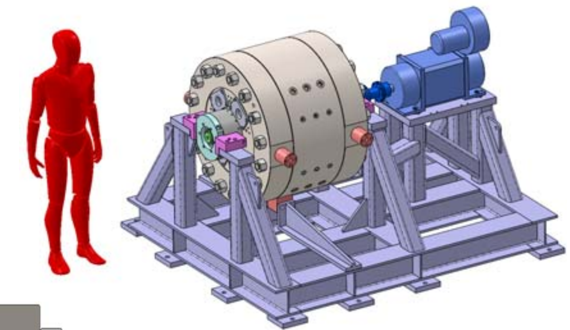


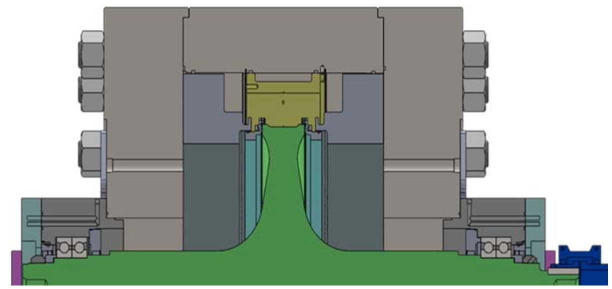
- Downstream pressures and ΔP acceptable
- Only PSV on failed seal side simulated – second PSV and rupture disk offer redundant protection
- Decrease in supply pressure due to increase in mass flow through CV-301

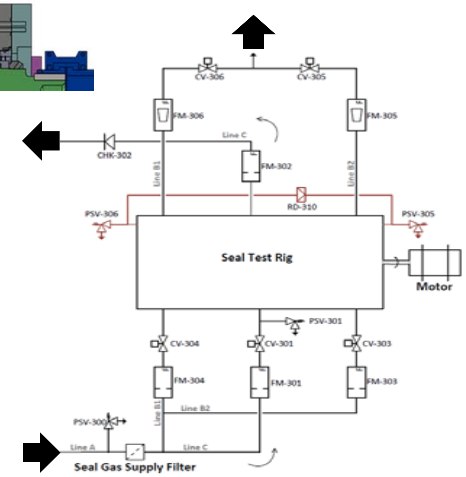
Summary & Conclusions

- Currently developing seal technology for utility-scale sCO_2 turbines
- Full-scale test rig detail design being completed
- Casing design limited by deflection control
- Single-piece rotor design more cost-effective, simpler
- Loop design considered seal failure scenario to limit downstream pressure, rotor thrust force









Thank you… Any questions?

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Major flow elements (backup)

Tag	Parameter Description	Units	Design Case	Failure Scenario 1	Failure Scenario 2
Line A	Mass Flow (norm.)	-	1.000	1.053	1.588
	Supply Pressure	-	P_{supply}	P_{supply}	P_{supply}
CV-301	Mass Flow (norm.)	-	0.817	0.613	0.954
	Restriction Bore Diameter Ratio	-	0.315	0.315	0.315
CV-303	Mass Flow (norm.)	-	0.093	0.353	0.551
	Restriction Bore Diameter Ratio	-	0.472	0.472	0.472
CV-304	Mass Flow (norm.)	-	0.093	0.087	0.084
	Restriction Bore Diameter Ratio	-	0.472	0.472	0.472
Swirl Ring	Upstream Pressure	*bar*	83.0	101.0	51.0
	Downstream Pressure	*bar*	75.0	97.5	13.8
	K factor	-	1.86	1.86	1.86
Seal DE	Downstream Pressure	*bar*	10.0	97.5	13.8
	K factor	-	4.46	*NA*	*NA*
Seal NDE	Downstream Pressure	*bar*	10.0	17.3	16.8
	K factor	-	4.46	4.46	4.46
Line C DS	Mass Flow (norm.)	-	0.712	*NA*	*NA*
	Return Pressure	*bar*	70.0	*NA*	*NA*
CV-305	Mass Flow (norm.)	-	0.146	0.913	0.111
	Restriction Bore Diameter Ratio	-	0.165	0.165	0.165
CV-306	Mass Flow (norm.)	-	0.146	0.140	0.135
	Restriction Bore Diameter Ratio	-	0.165	0.165	0.165
Exit Tee	Pressure Match	-	ΔP = 0	ΔP = 0	ΔP = 0
Exit	Ambient Pressure	*bar*	1	1	1