STEP 10 MWe SCO_2 Turbine Design, Assembly and Commissioning

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Supercritical Transformational Electric Power (STEP Demo) Project

Demonstrate an integrated electricity generating power plant using transformational sCO2-based power cycle technology

Demonstrate pathway to efficiency **> 50%**

Demonstrate cycle operability at **>700°C** turbine inlet temperature and 10 MWe net power generation

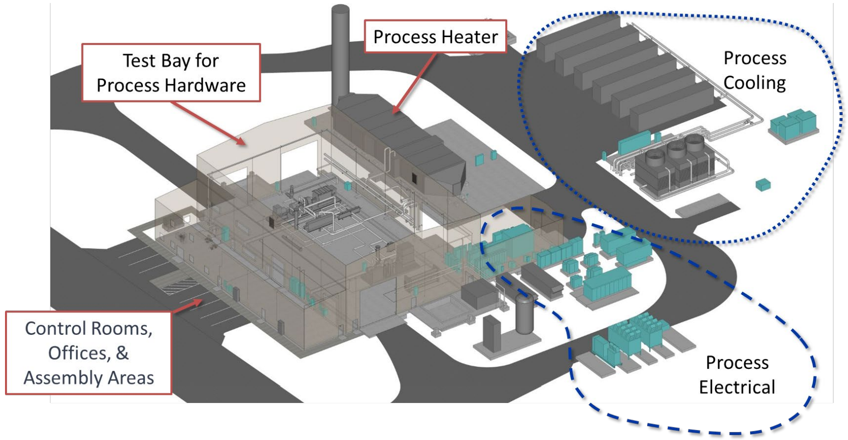
Quantify performance benefits:

- 2-5% point net plant efficiency improvement
- 3-4% reduction in LCOE
- Reduced emissions, fuel, and water usage

Develop a **reconfigurable and flexible test facility**

- Available for Testing future sCO2 equipment & systems

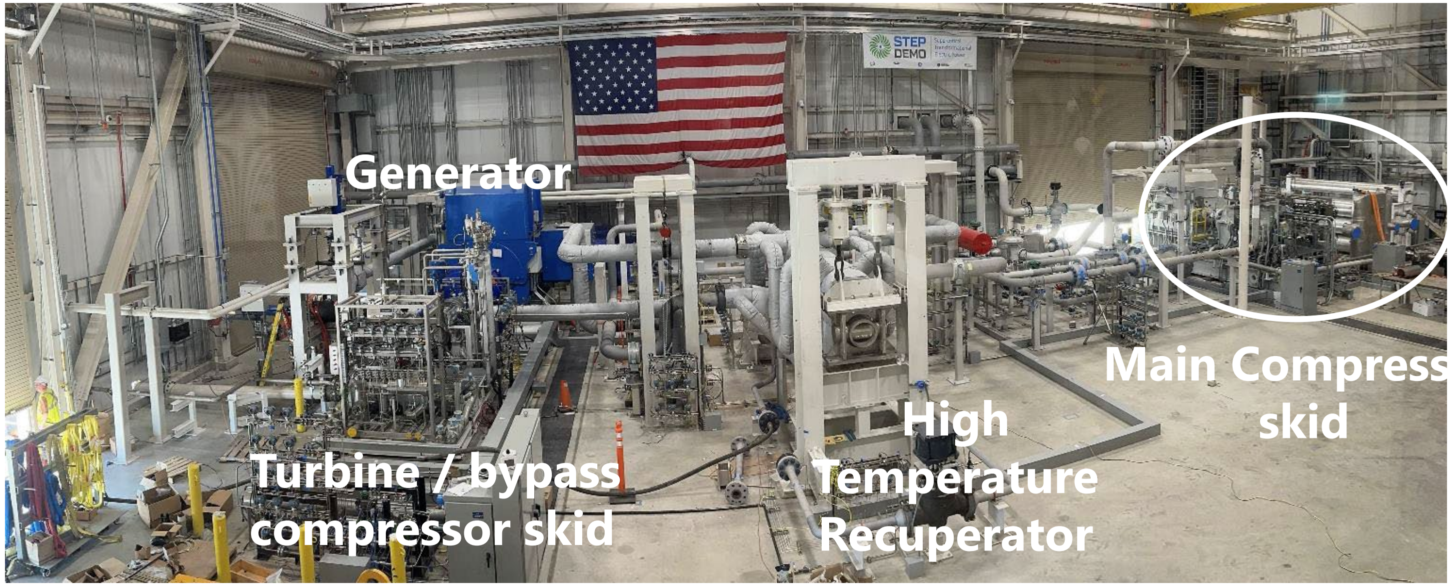
Achieved **mechanical completion** October 2023



Marion, J., Macadam, S., McClung, A., Mortzheim, J., 2022, "The STEP 10 MWe sCO2 Pilot Demonstration Status Update," GT2022-83588, Proceedings of the ASME Turbo Expo 2022, Rotterdam, The Netherlands, June 13-17, 2022

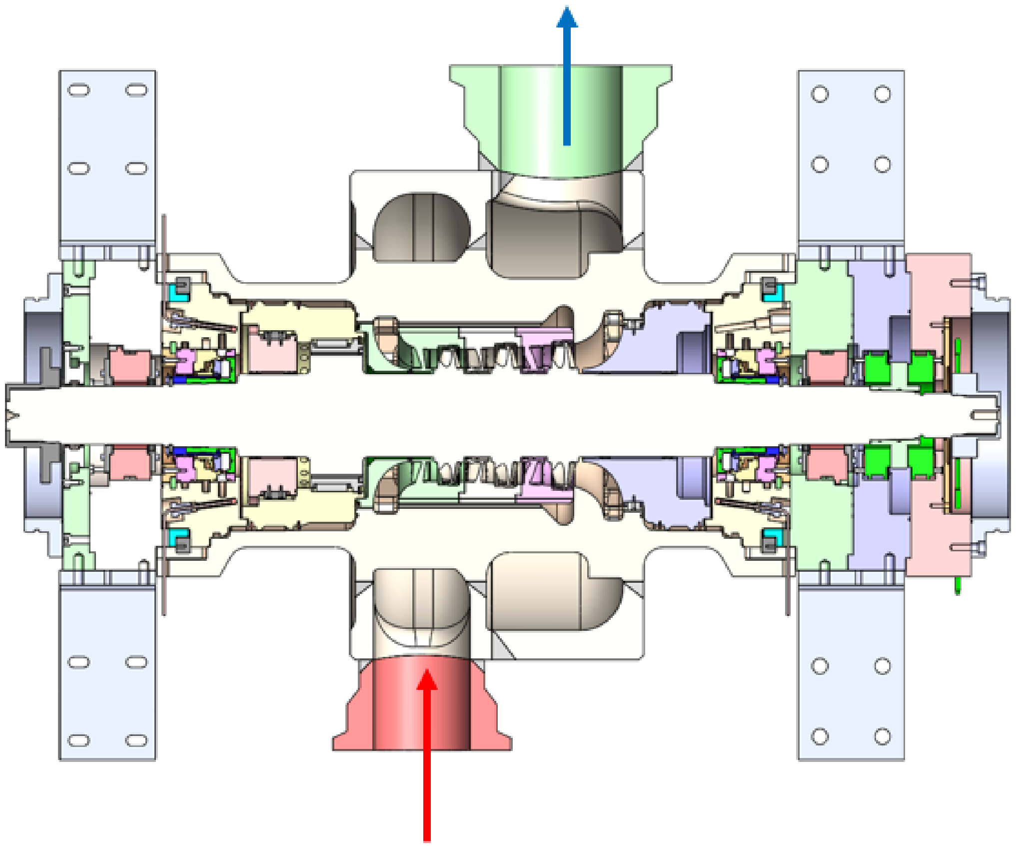
STEP Notable Achievements

- Built the world's largest indirect-fired sCO2 power plant at 10 MWe
- Achieved Mechanical Completion for the Simple Cycle Configuration
- Successfully demonstrated full loop operation
- At ~1/10 the size of an equivalent steam turbine, has the world's highest power density for a terrestrial turbine
- 16 MW (20,000 hp) produced by 80 kg (180 lb) rotor (200 kW/kg)

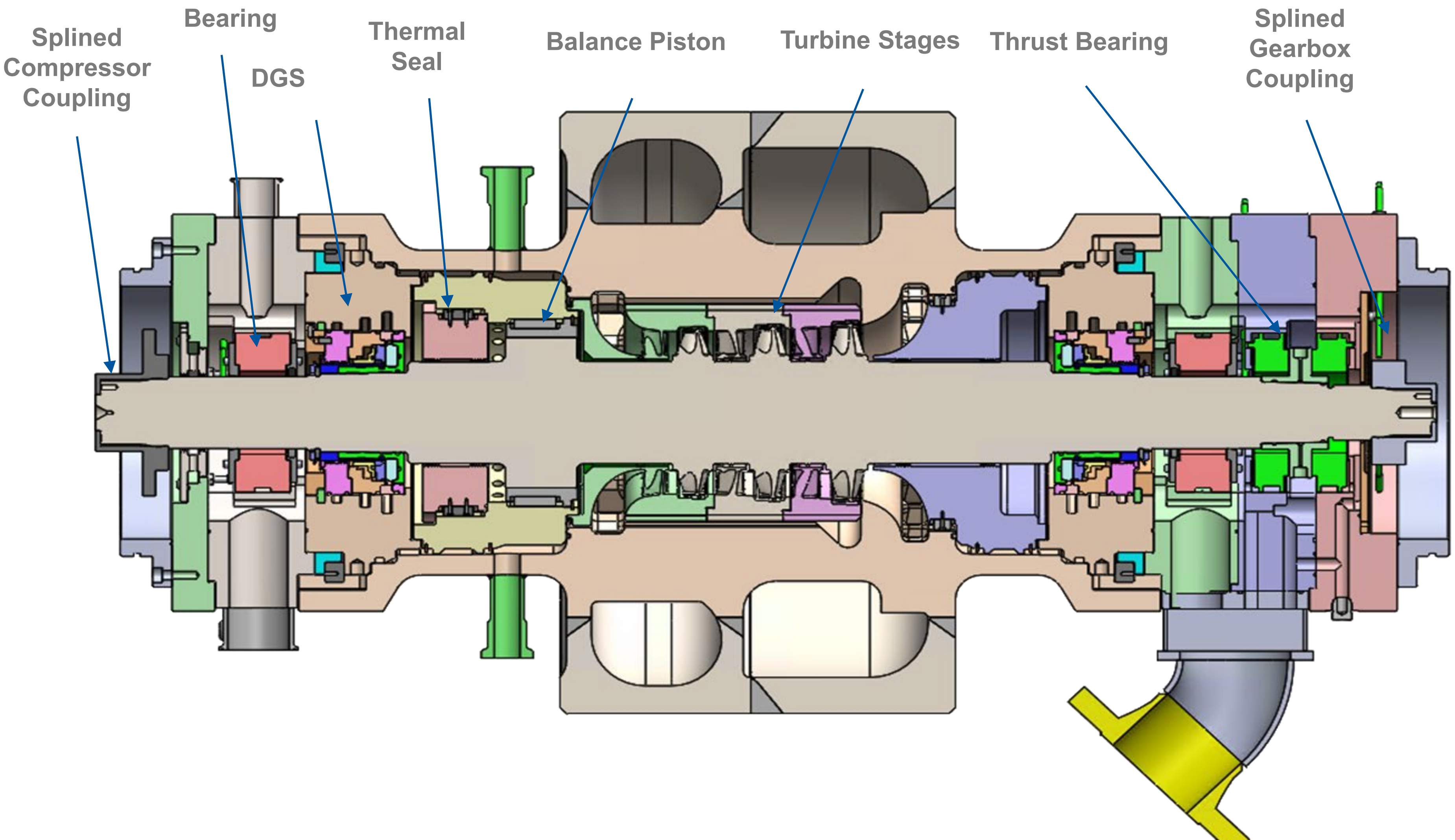


Section View of the STEP Turbine with Design Conditions

- Inlet Flow
  - 3,626 psi at 1,319F
  - 227.4 lbm/s
  - Single Inlet – 5.00" ID at Turbine
  - Velocity – 210.8 ft/s
- Exit Flow
  - 1,307 psi at 1,086F
  - 223.9 lbm/s
  - Single Exit – 6.35" ID at Turbine
  - 298.6 ft/s
- Rotor
  - Design Speed: 27,000 rpm
  - Max Continuous: 28,350 rpm
  - 16 MW (13.5 MW Generator and 2.5 MW Compressor)
  - API 617
- Case
  - Two design conditions
  - Inlet: 4,130 psi at 1330F
  - Exit: 2,600 psi at 1150F
  - ASME Section VIII Division II
  - API 612
- Life
  - Creep Rupture: 10,000 hr
  - Low Cycle Fatigue: 11,000 cycles

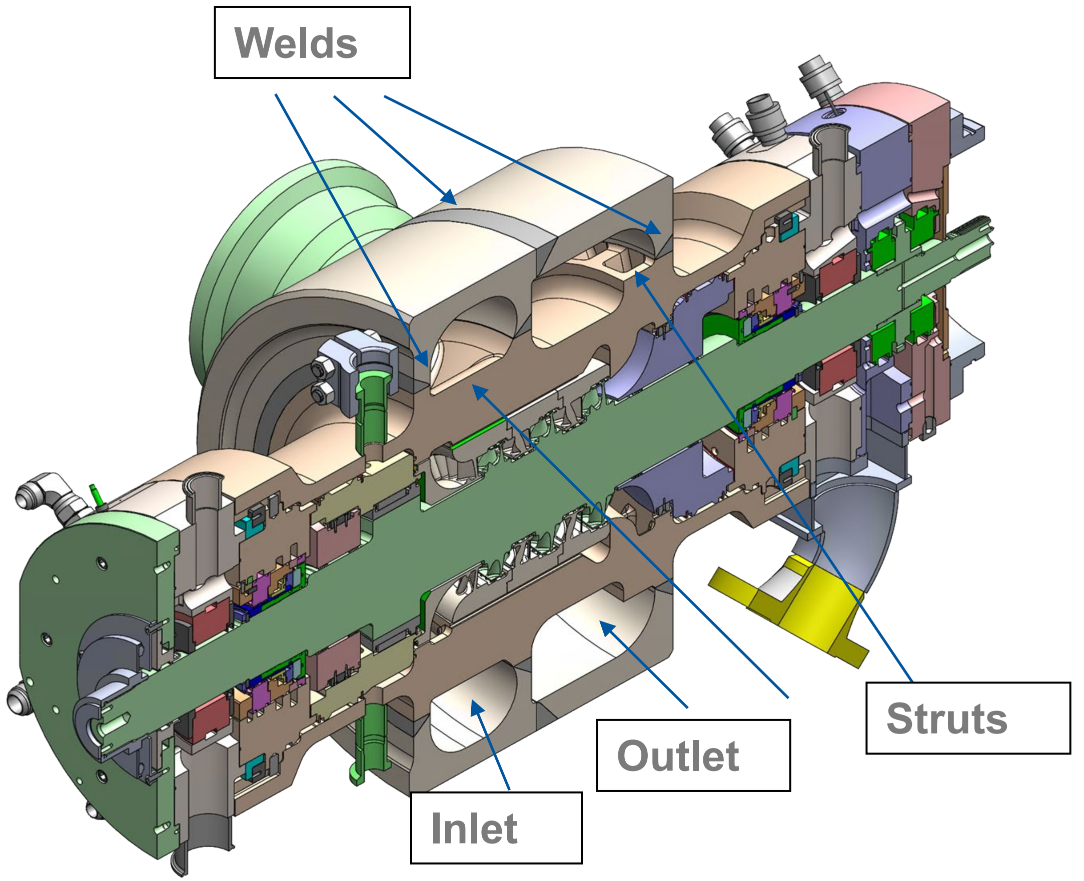


Cross-section of the STEP Turbine



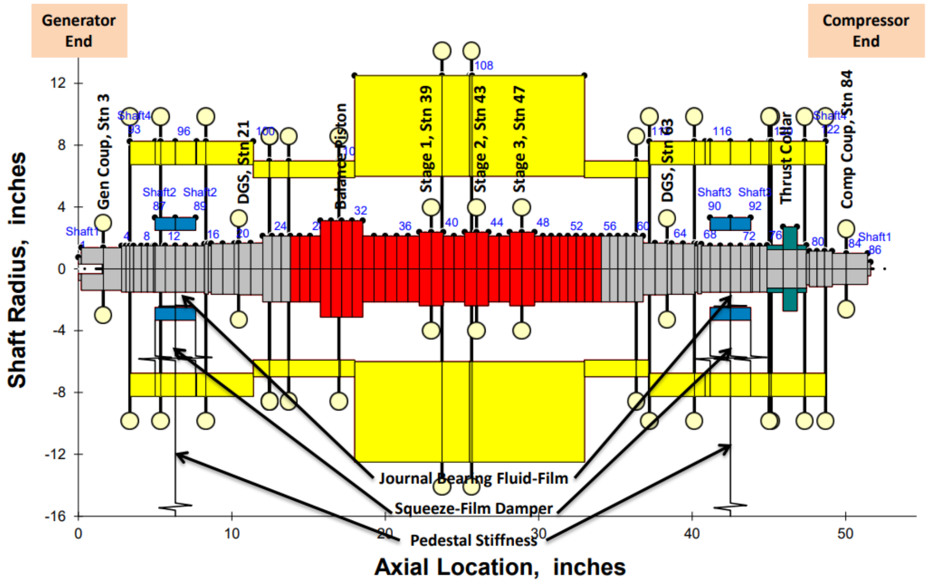
Isometric View of STEP Case Showing Weld Placement

- Monolithic casing barrel with fabricated plenums and nozzles
- Full penetration welds
- No high temperature case joints
- Case heads retained with shear rings and sealed with polymer seals
- Dry gas seals and bearings similar to Sunshot



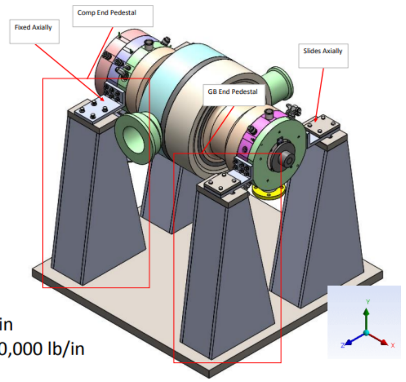
Rotordynamic Modeling

- Model included rotor, bearings, squeeze-film dampers, labyrinth and damper seals, and casing
- Pedestal stiffness derived by FEA and confirmed by modal testing



GB End Pedestal Stiffness (Individual)		
Axis	k (lbf/in)	
x	0	
y	904,975	Kyy
z	895,725	Kxx

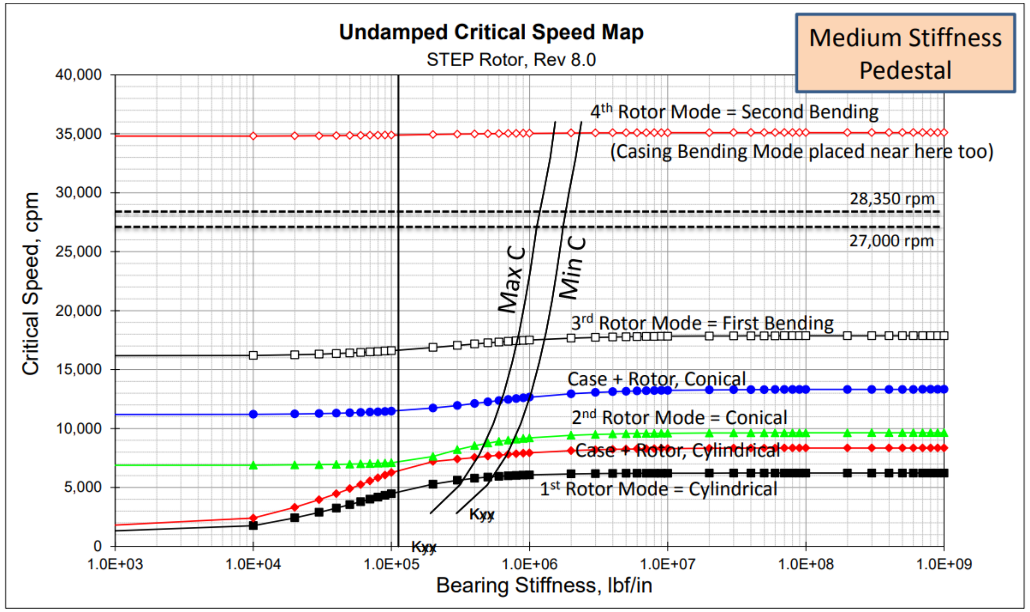
Comp End Pedestal Stiffness (Individual)		
Axis	k (lbf/in)	
x	411,875	
y	904,975	Kyy
z	895,725	Kxx

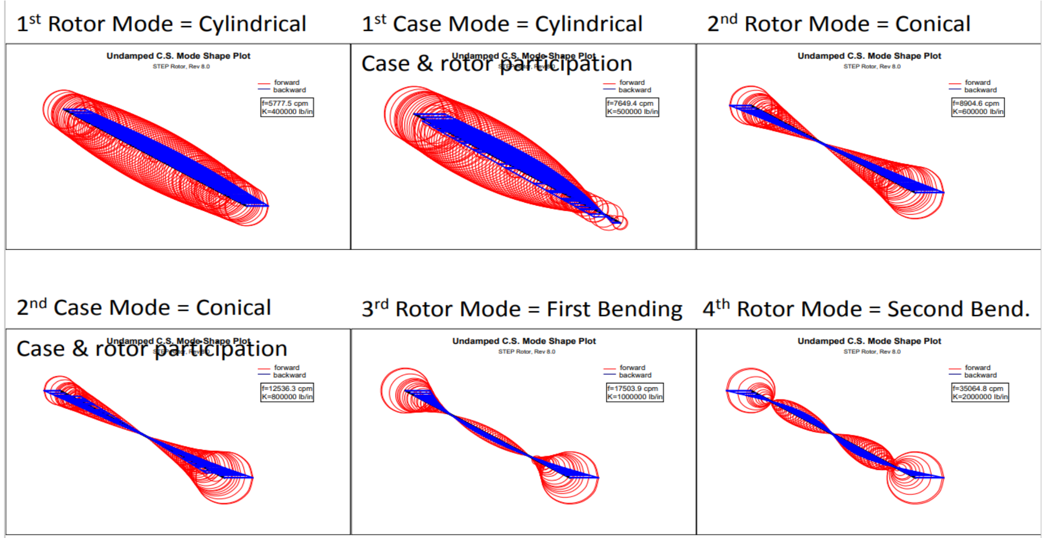


Ki = individual pedestal = ~900,000 lb/in
Kped = per bearing end = 2*Ki = ~1,800,000 lb/in

Rotordynamic Modeling

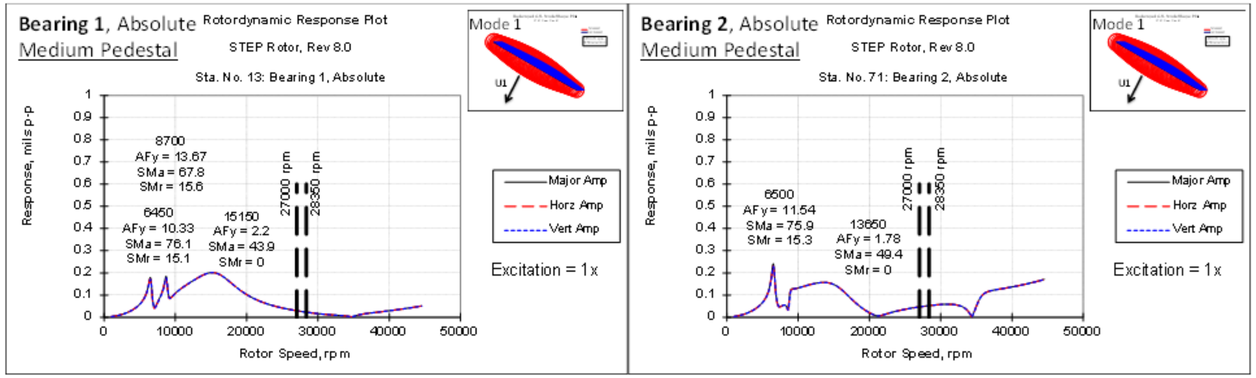
- 3 rotor modes and 2 casing modes traversed up to running speed
- Good separation margin from 4th rotor mode (2nd bending mode)



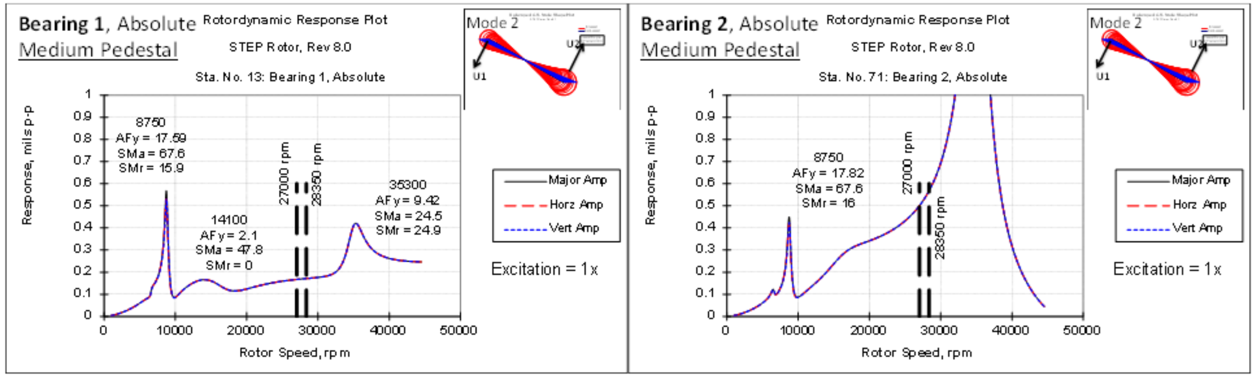


Rotordynamic Unbalance Response

- Model shows low response when traversing casing and rotor modes
- Meets API separation margins



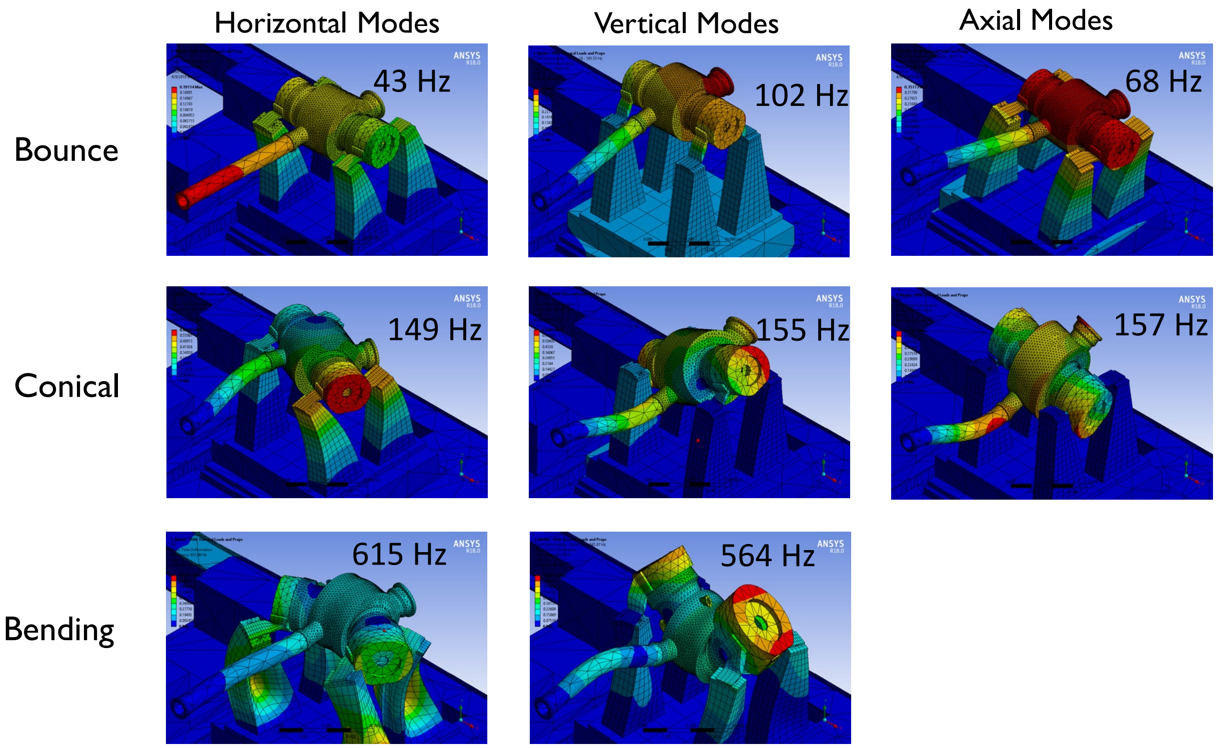
STEP Turbine Predicted Lateral Response at Journal Bearing Unbalance Applied Mid-Span Unbalance



STEP Turbine Predicted Lateral Response at Journal Unbalance Applied to Both Ends Out-Of-Phase

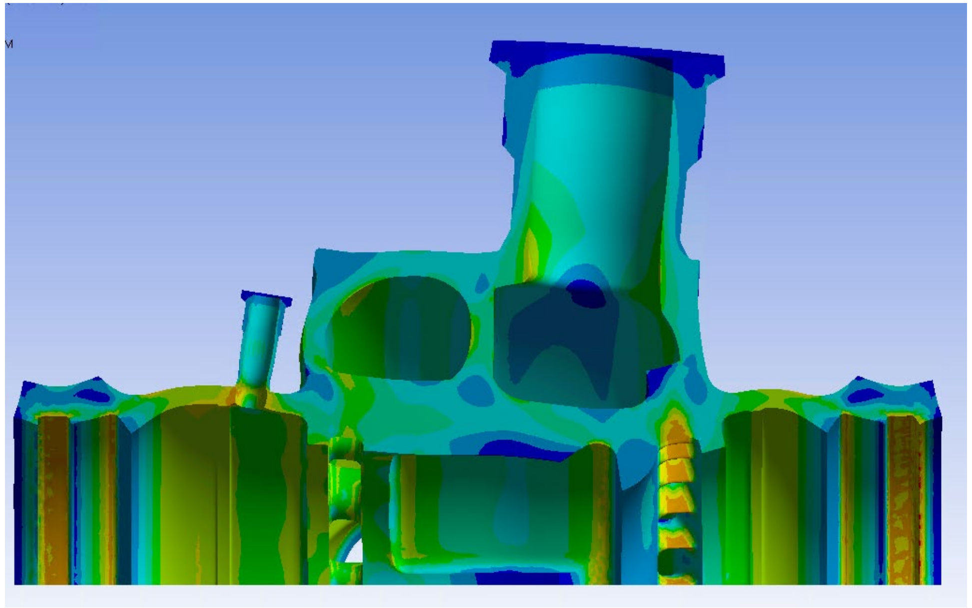
Turbine Case Predicted Natural Frequencies and Mode Shapes using FEA

- Pedestal stiffness designed to keep casing rigid body modes at low frequency
- Less rotational energy to excite these modes
- Frequency and mode shape confirmed with modal testing



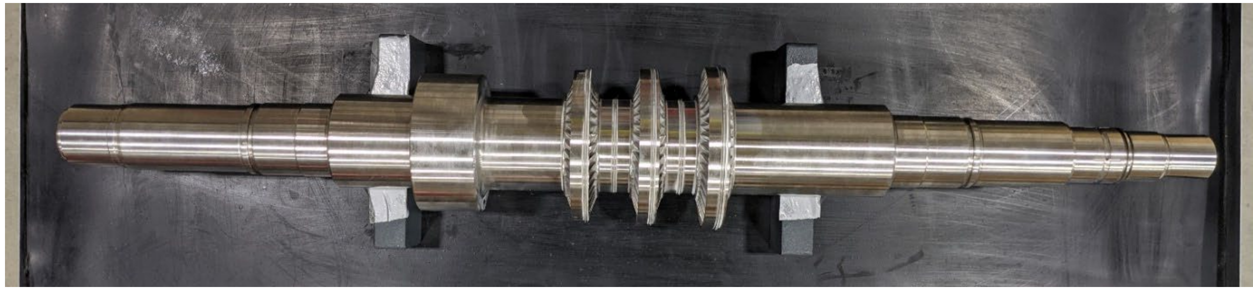
Case Design

- Designed to accommodate 265 bar, 715°C inlet conditions
- In accordance with ASME Boiler and Pressure Vessel Code, Section VIII, Div. 2
- Utilizes Inconel 625, Grade 2 material to 10,000 hour life
- Production model to use IN740H or Haynes 282 to achieve 100,000 hr life
- Low stress near weld joints
- Transient FEA performed to verify adequate LCF



Rotor Manufacturing

- Made from Nimonic 105 heat treated forging
- Airfoil shapes cut using a 5-axis electrode discharge machining (EDM) by Baker Hughes
- Different shops used for rotor final machining, grind, spline cutting, and balance
- Spline test piece made of IN718 and trial fit

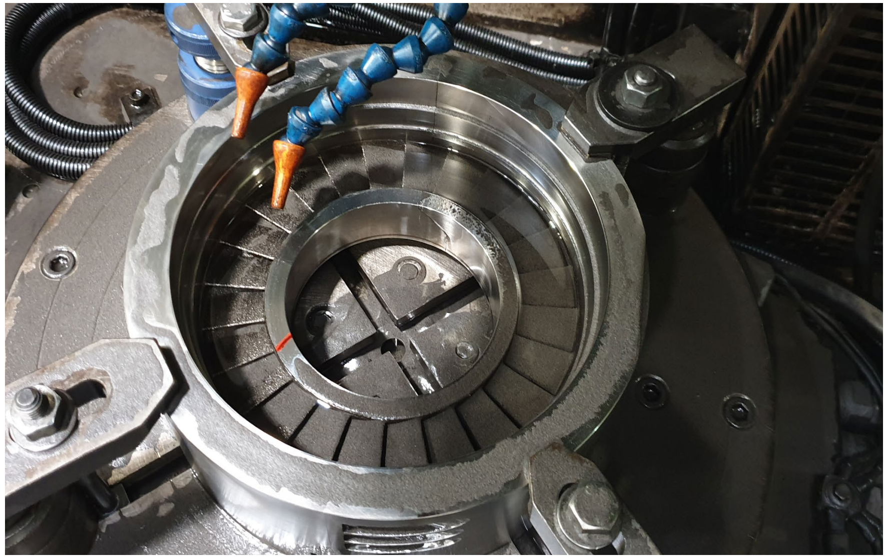


Turbine rotor following rough machining and EDM

Close up of EDM Turbine Blades with Spline Test Piece

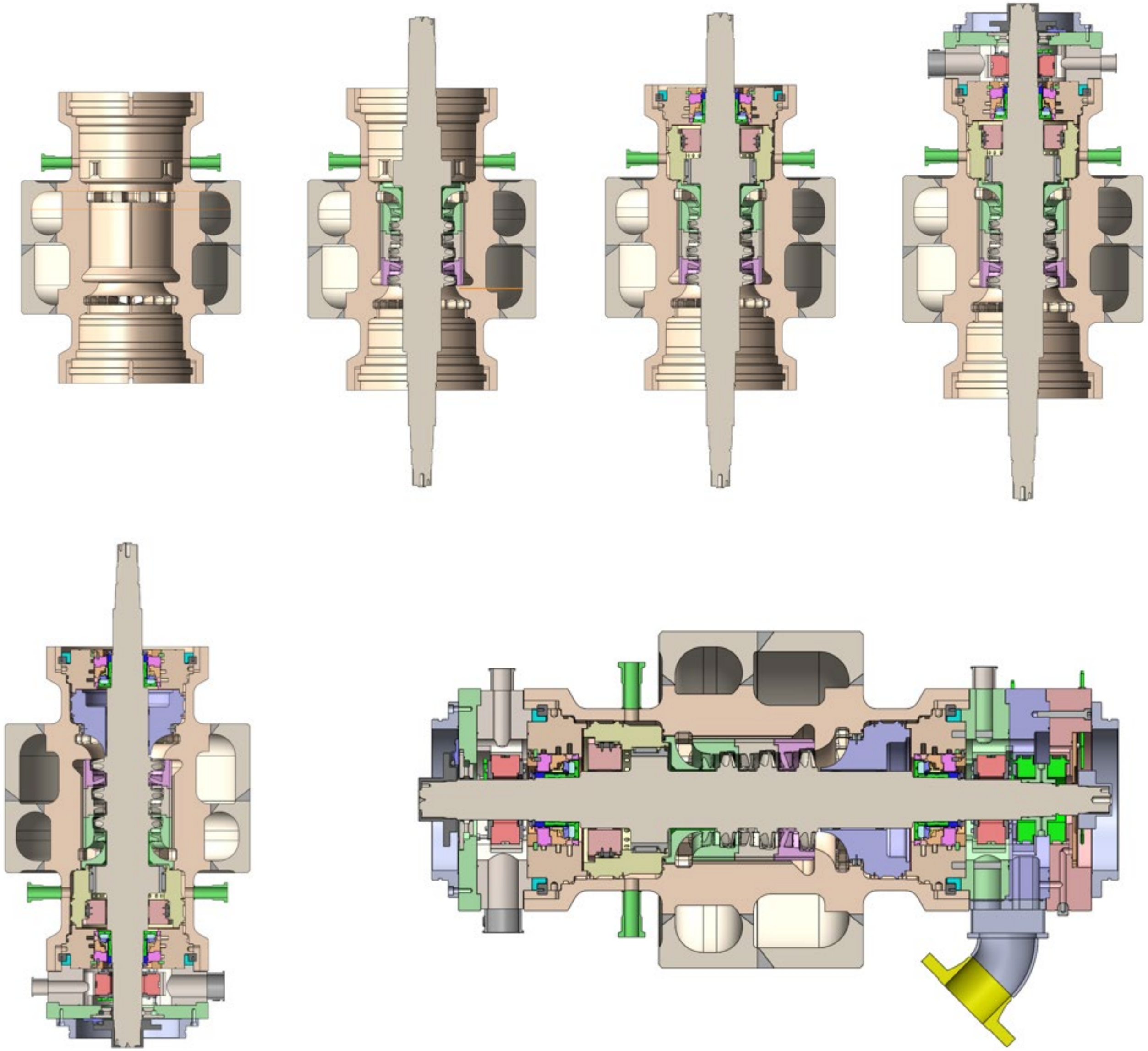
Stator Manufacturing

- 5-axis EDM also used to manufacture the turbine stators
- High temperature abradable labyrinth seal coatings applied and final machined



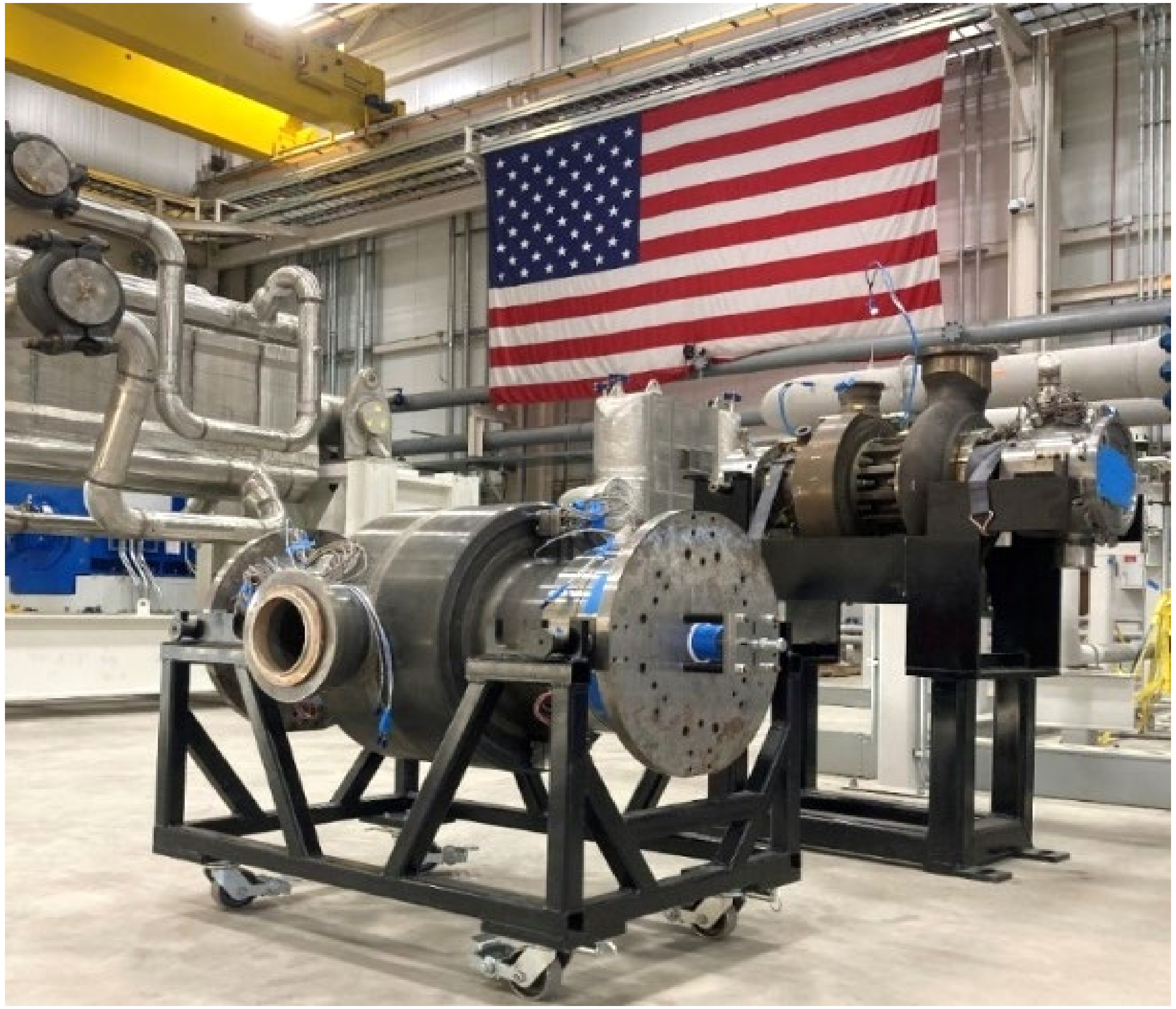
Turbine Assembly Steps

- Assembly performed vertically and flipped to complete assembly.

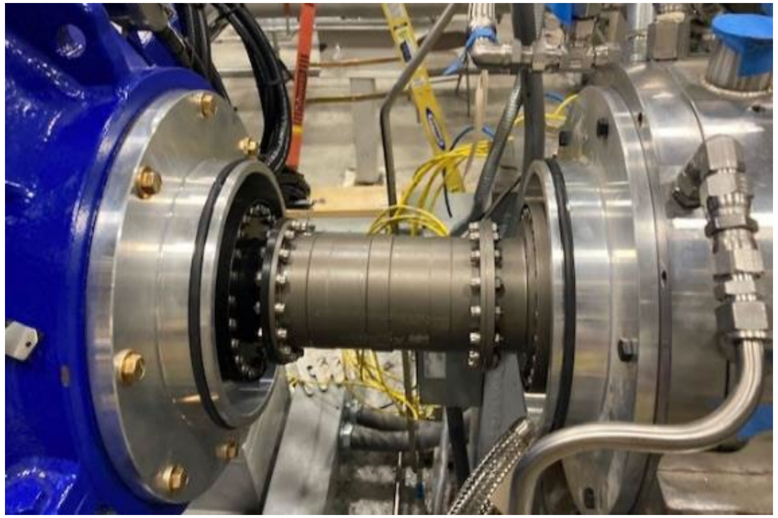


Turbine Assembly

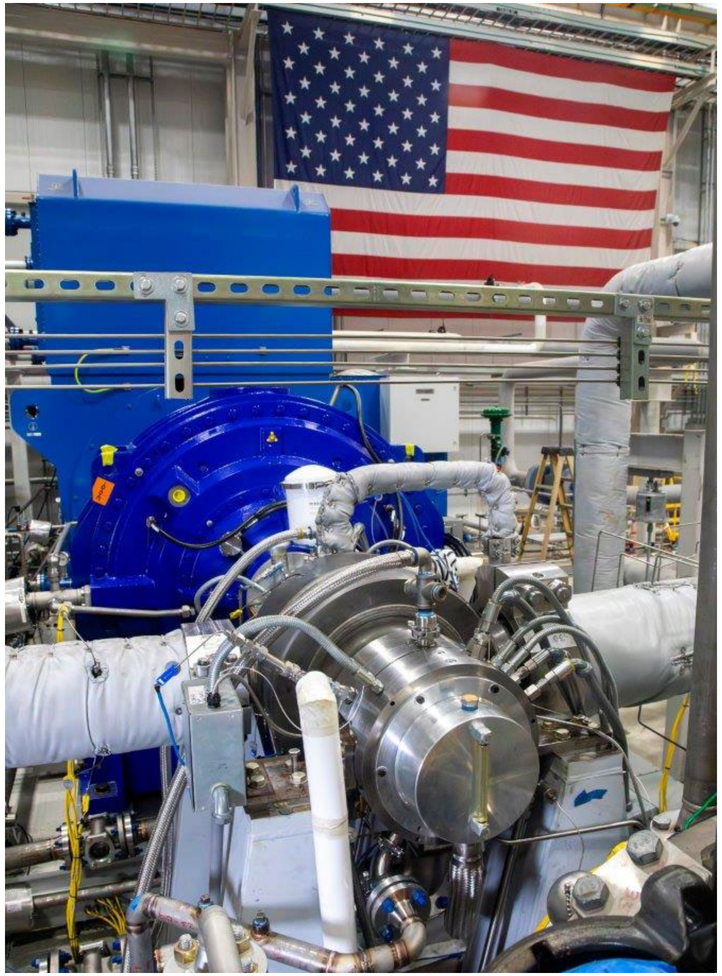
Final Turbine Assembly

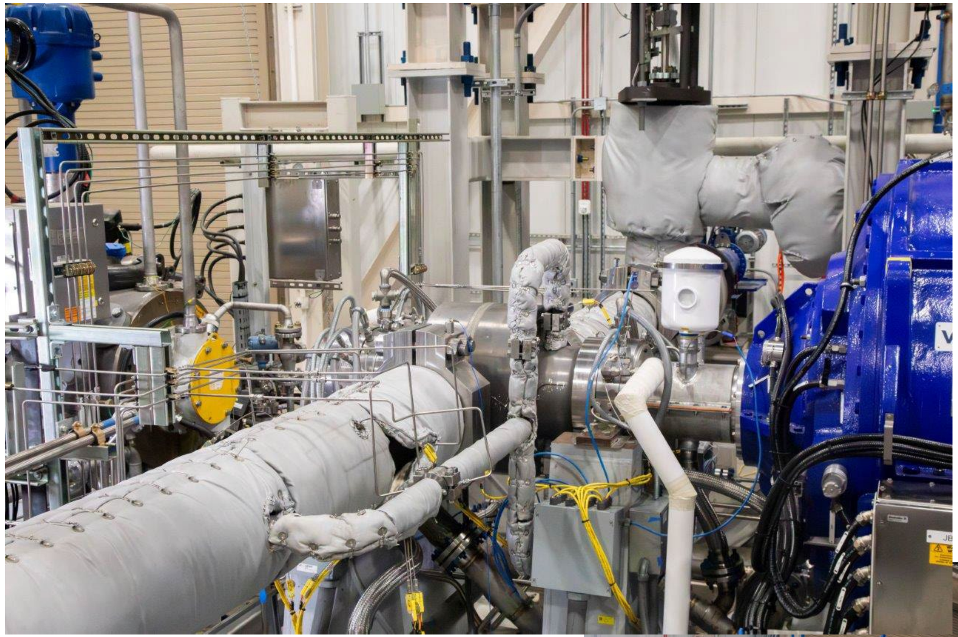


Turbine Skid Assembly



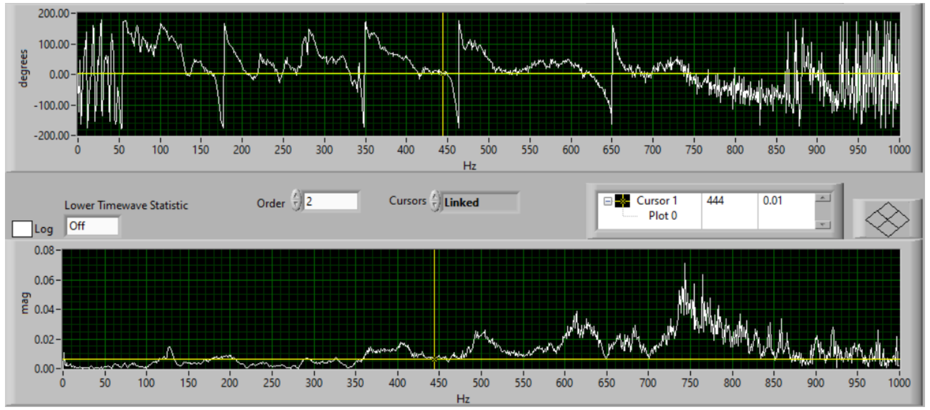
Fully Assembled Turbine Skid



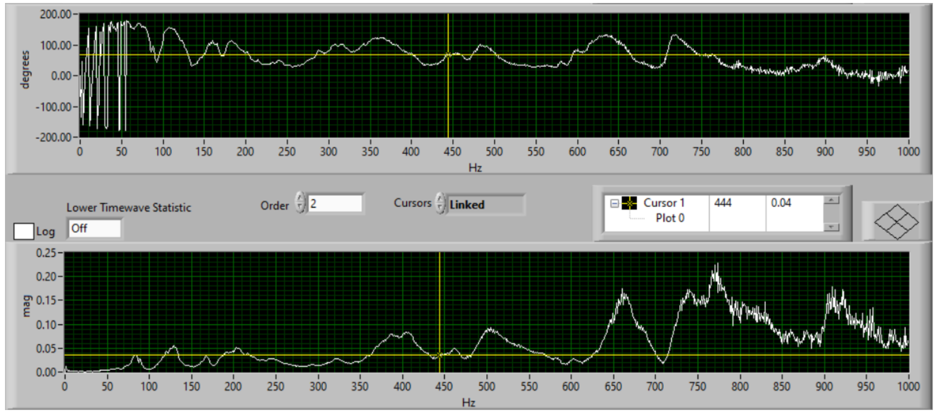


Turbine Case Modal Testing

Mode Axis	Mode Type	FEA Predicted Mode Frequency (Hz)	Rotordynamics Model with Casing	Measured Frequency (Hz)
	Bounce	43	127	85
Horizontal	Conical	149		128
	2nd Con.		209	216
	Bending	615		378
	Bounce	102	127	85
Vertical	Conical	155		129
	2nd Con.		209	198
	Bending	564		505
Axial	Rocking	68		85
	Conical	157		



Modal Test, Horizontal, DE Bearing Housing

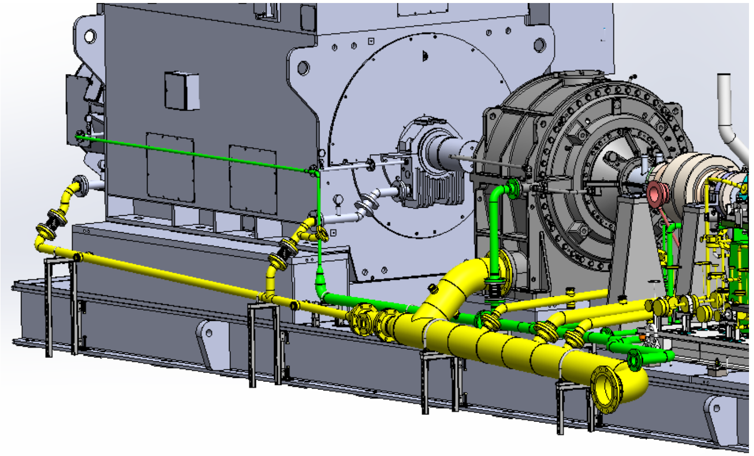


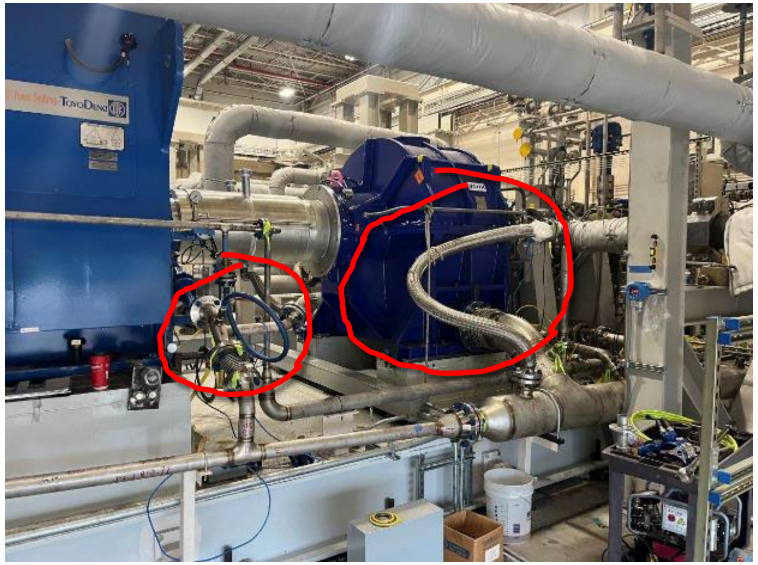
Modal Test, Vertical, DE Bearing Housing

OIL SYSTEM COMMISSIONING

Green Piping = Supply
Yellow Piping = Drains

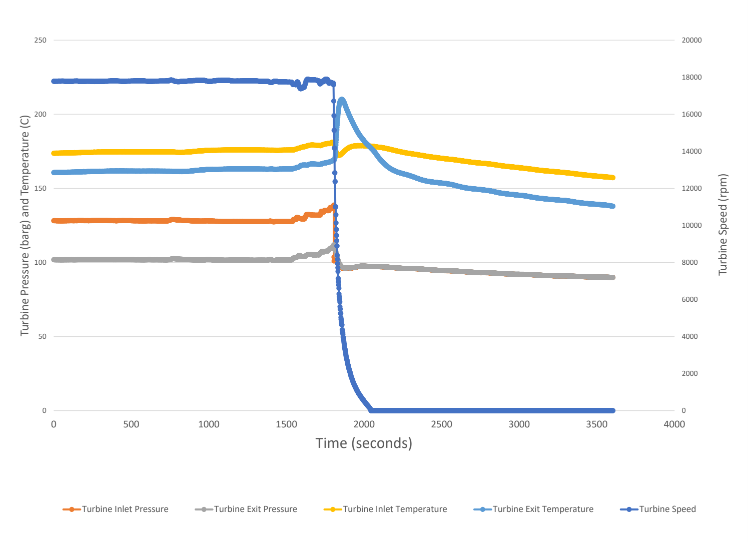
- Designed in accordance to API 614
- Gravity drain back to lube oil skid
- Flushing performed until ISO 4406 was met for particle counts

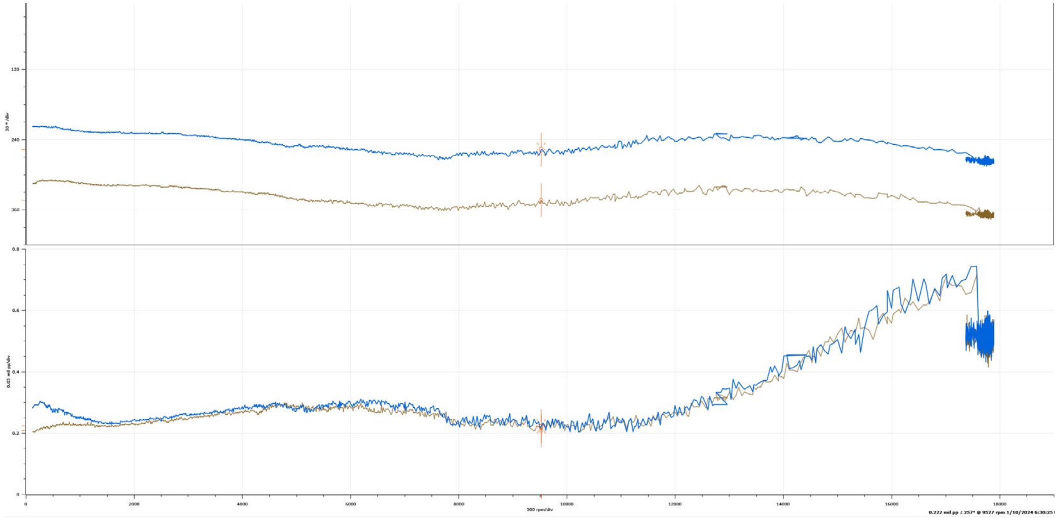


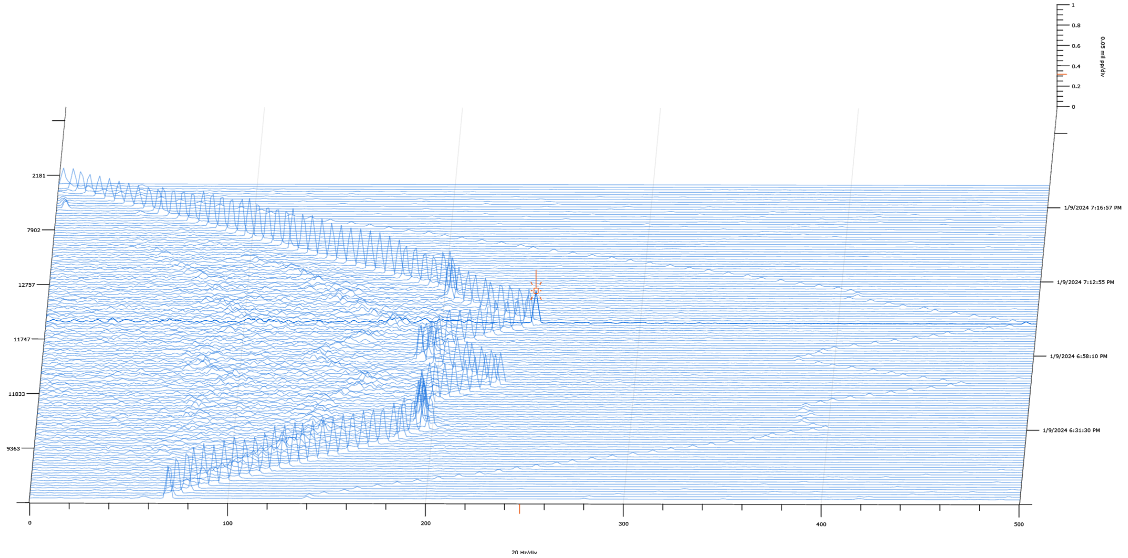


Turbine Commissioning

- First spin achieved Dec. 2023
- Labyrinth seal break-in completed
- Turbine inlet temperature of 175C and speed of 18 krpm achieved to date
- Low vibrations and critical speed response
- Speed and temperature control operational
- Turbine control and trip valve performing well

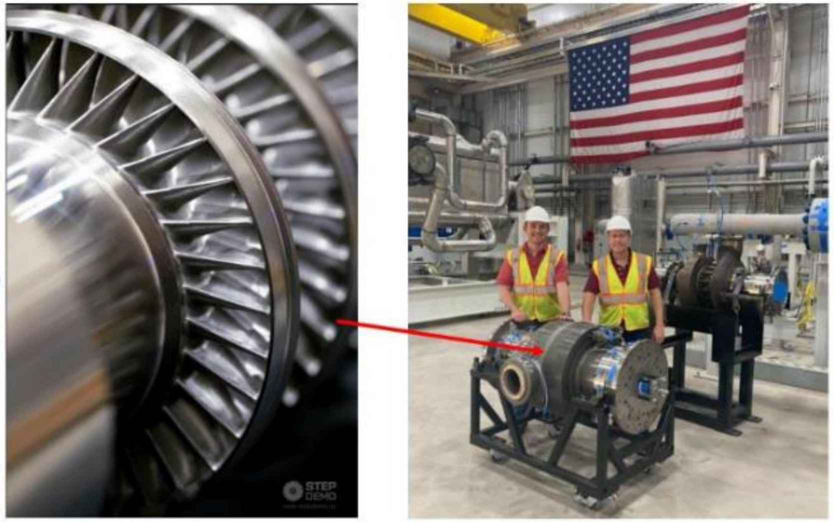






Lessons Learned to Date

- Thermal management is key to dry gas seal life (from Sunshot)
  - Delivery of warm seal gas is required at all times when the system is pressurized near the critical pressure (>50 bar)
- The turbine case was designed with vibrational modes in the operating speed range
  - Designed to keep modes at low speeds to minimize excitation
  - Validated by modal testing
- Low vibration and critical speed response matched predictions
- Thermal management is key to turbine dry gas seal life, even during pressurized holds



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Summary

- STEP Turbine successfully assembled with no component rework
- Installed on the turbine skid, rough aligned, piped, final aligned, wired, and pressure checked
- Ancillary systems, including the lubrication skid and dry gas seal panel, have been flushed, pressure checked, and commissioned
- Turbine design incorporated lessons learned from Sunshot with these enhancements:
  - Single-piece turbine case (eliminate hot casing joints and bolts)
  - Heads that use polymer seals and shear rings at the cool end
  - Improved thermal management design to reduce shock cooling
  - Reduced stage count from 4 to 3 with larger shaft diameter
  - Radial and thrust bearings, dry gas seals, damper labyrinth seals identical to Sunshot
- High-power density makes coupling design with high torque capacity and low weight challenging
- Work continuing to commission the turbine to achieve 27 krpm and 500°C

SwRI STEP Team