SCO_2 Turbomachinery Prototype Design, Manufacturing, and Testing

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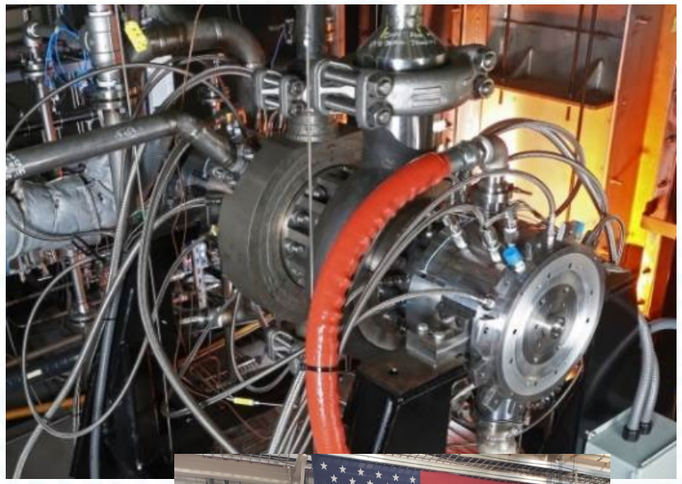
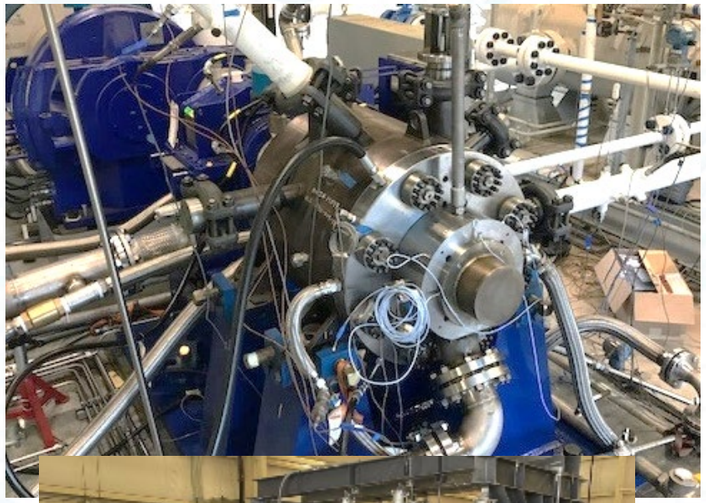
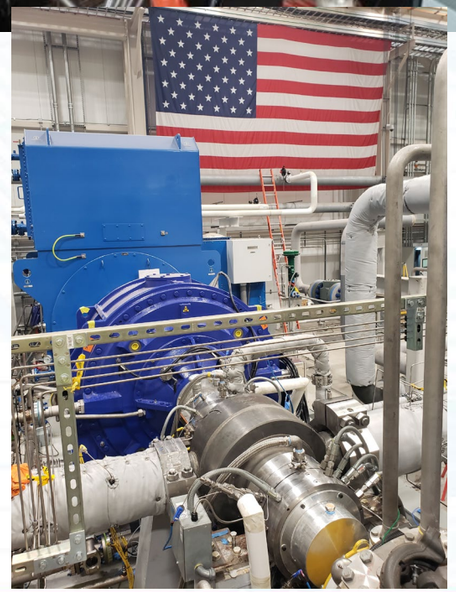
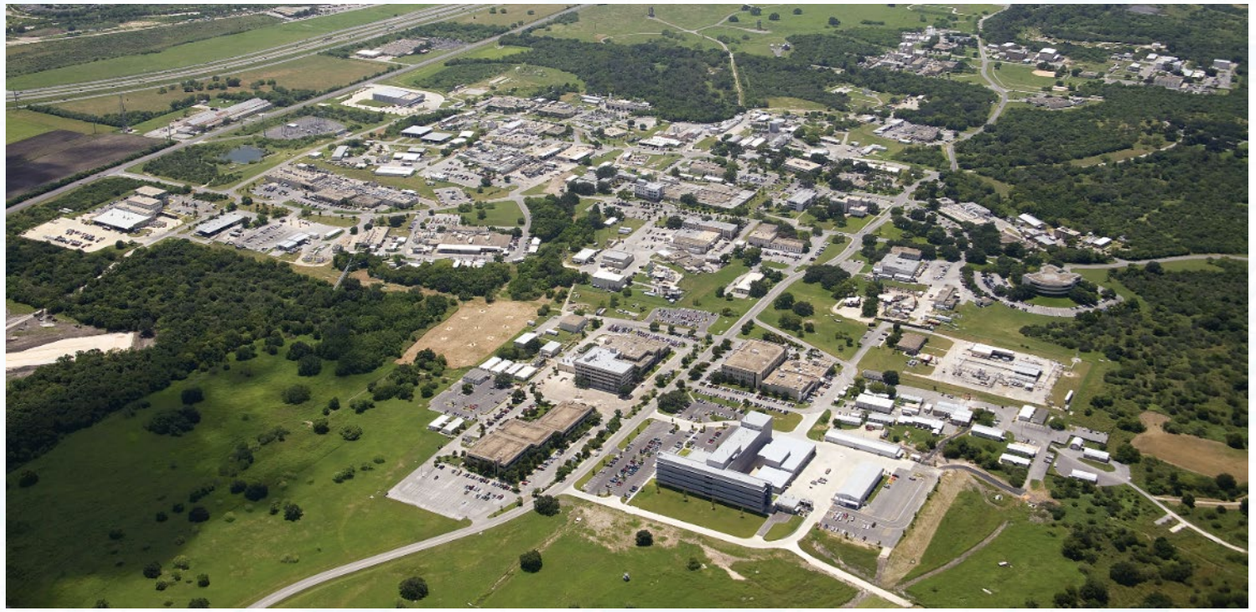


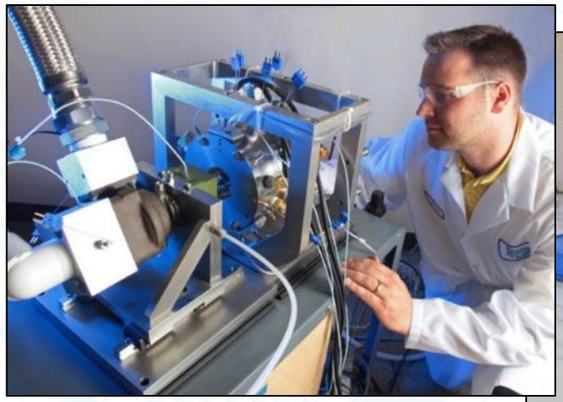




SwRI is an Applied Research & Development Company

- Founded in 1947, based in San Antonio, Texas
- 501 (c)(3) nonprofit corporation
  - Internal Research
  - New Laboratories
- ~$680M Annual revenue from contract work for industry and government clients
- Almost 3000 employees
- 1,700-acre facility; 2.3 million square feet of laboratories & offices
- Flexible IP policy





Prototype Development

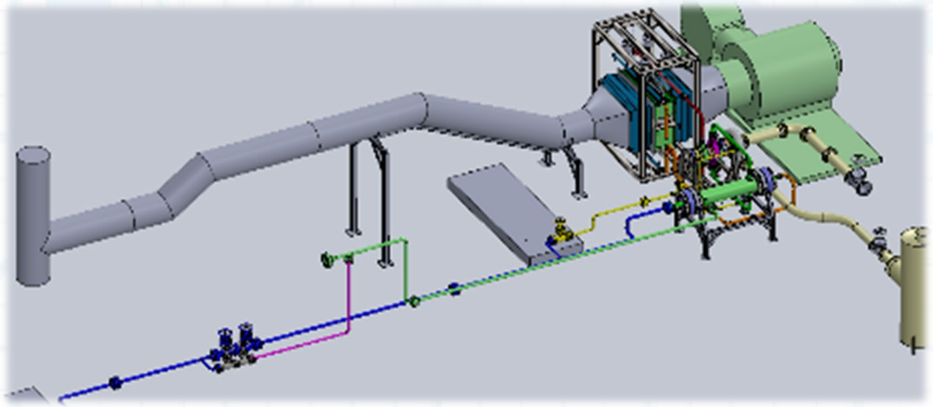
- SwRI has led the development of over 10 SCO_2 turbomachines and test rigs including test loop development
- SwRI has expertise in aerodynamics, rotordynamics, blade dynamics, heat transfer, combustion, machine design, materials, and manufacturing
- Significant hardware and test facility capability

SunShot: Development of a High Efficiency 700°C SCO_2 Turbo-Expander

Innovation: This MW-scale sCO_2 turbo-expander and heat exchanger are a critical step in increasing energy conversion efficiency to >50%, while reducing power block costs.
GE with SwRI developed a 10 MWe-scale sCO_2 turbo-expander optimized for concentrating solar power plant duty cycle profile.
Thar developed a compact, high temperature recuperator.

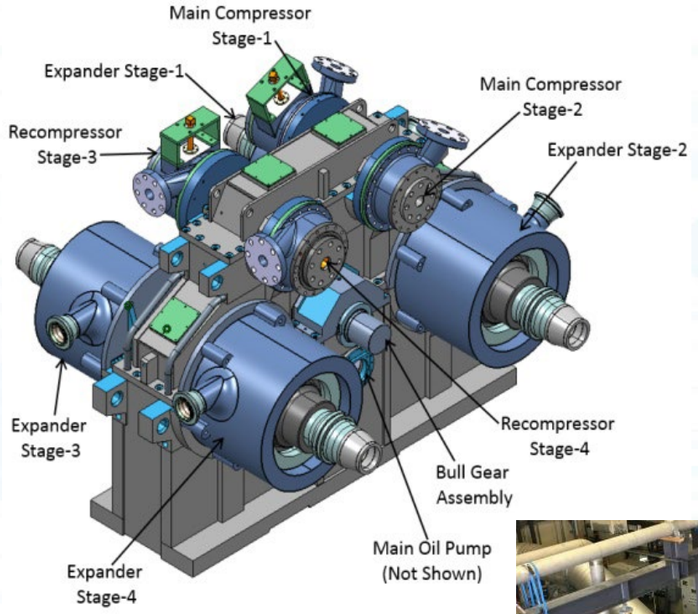
SwRI Test Facility provided 1MWe sCO_2 flow at high temperatures and pressures to enable operating validation of the expander and recuperator performance.

Testing completed December 2018 demonstrating successful operation up to 715°C, 245 bar, and 27 krpm.

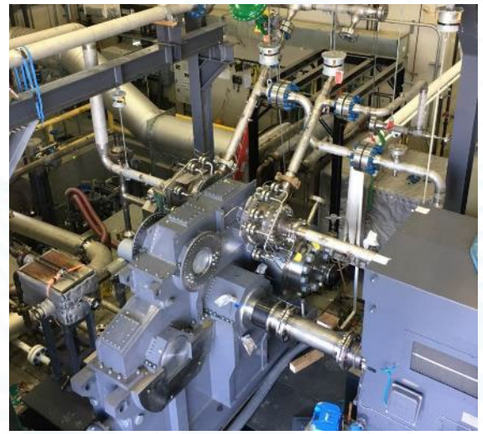


Ultra High Efficiency Integrally-Geared sCO_2 Compander (SwRI, Hanwha for DOE EERE)

- Design a sCO_2 integrally geared compander (IGC)
  - Combining compression and expansion stages into a single integrally geared housing connected to a low speed motor/generator.
- Benefits:
  - Reduced footprint
  - Potential cost reduction up to 35%
  - Utilizes a low speed commercially available driver/generator
  - Modular (Small Industrial [5MW] to Small Utility [50 MW])
  - High efficiency over a wide range of operating conditions
  - Improved cycle controllability
  - Reduced mechanical complexity ➔ improved reliability and reduced maintenance
  - Achieved 280 bar and 720C

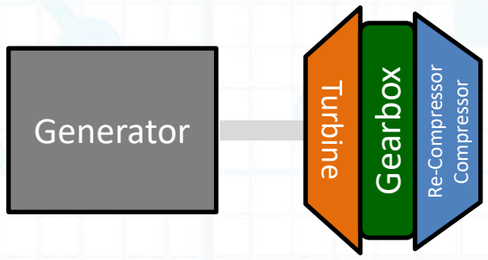


Compander Design

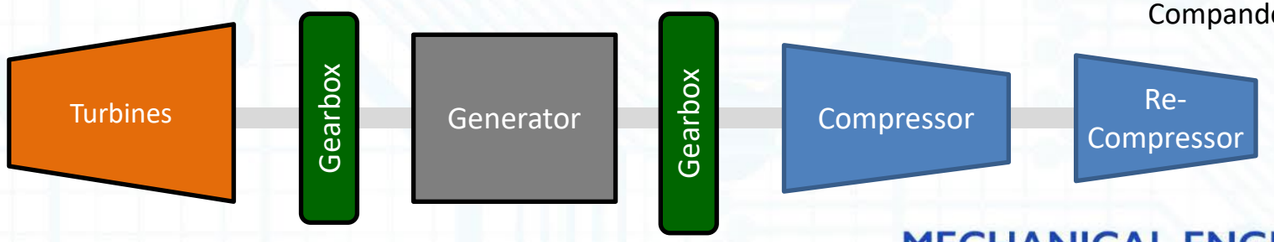


Compander in Test Loop Nov 2020

Typical IGC Package



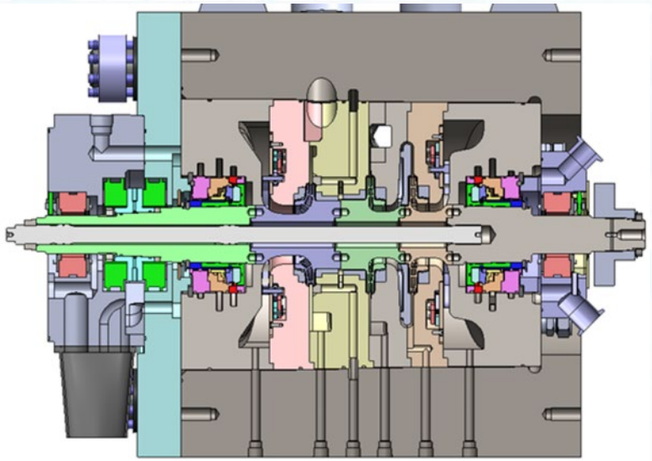
Conventional Turbomachinery Train

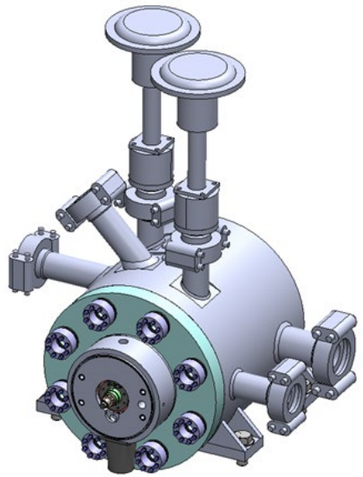


GE-Apollo High-Efficiency sCO_2 Centrifugal Compressor Development (GE, SwRI for DOE EERE)

PROJECT OBJECTIVES

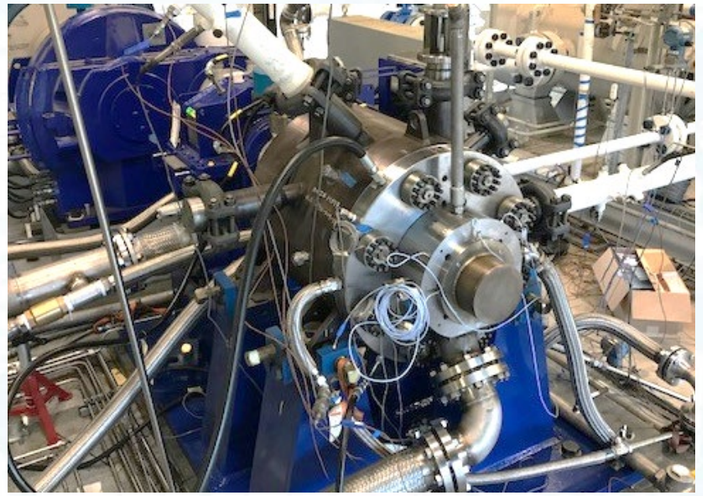
- Develop high-efficiency sCO_2 compression system
  - Main Compressor Efficiency of 80%
  - Preliminary Design completion June 2016
- High efficiency centrifugal impeller
- Variable IGV/OGV
- Advanced aerodynamic design provided by GE will be implemented into the detail compressor design provided by SwRI.





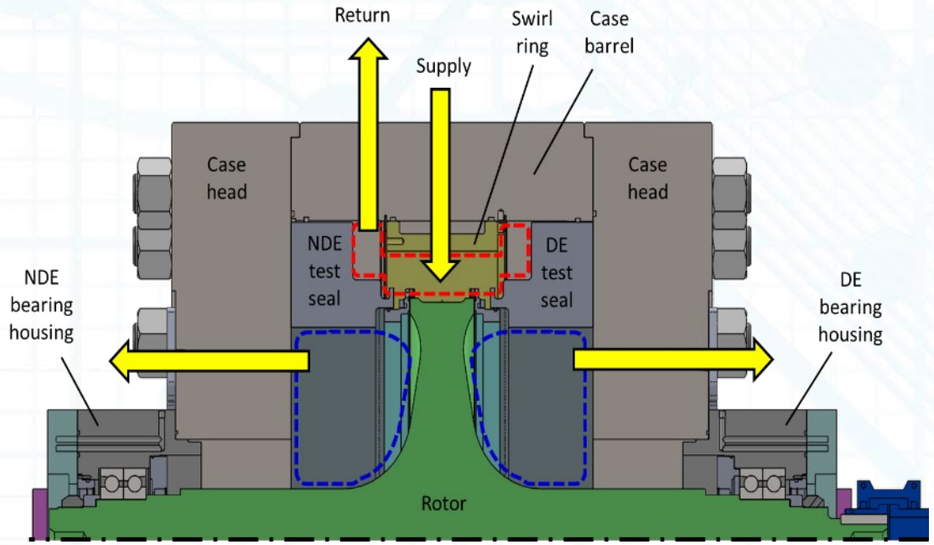
KEY RESULTS AND OUTCOMES

- Full scale testing of a 10 MWe sCO_2 Compressors
- Extended flow range to accommodate swings in ambient temperature
- SwRI sCO_2 Test Facility will verify compressor mechanical and aerodynamic performance over a range of operating conditions
- Testing completed October 2020



Testing of Shaft End Seals for Utility Scale sCO_2 Turbines (GE, SwRI for DOE NETL)

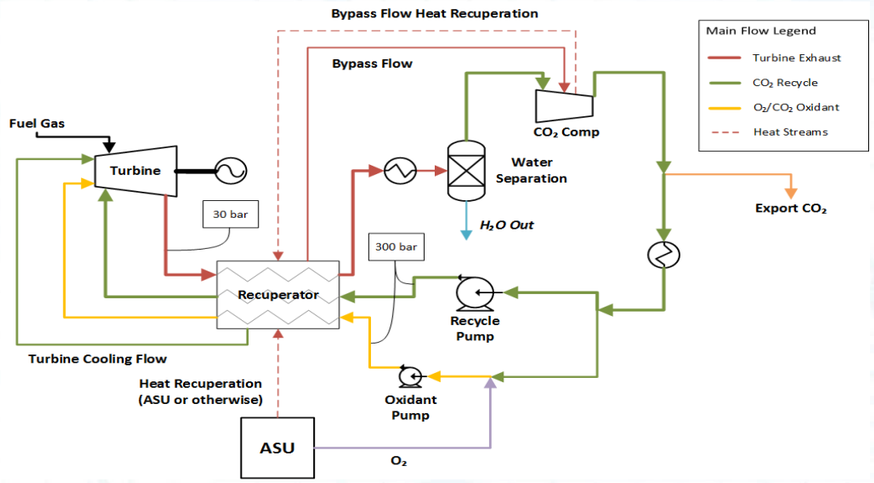
- Utility scale (450 MWe) sCO_2 turbines require ~24 in. end seals to seal ~75 bar
- Film-riding face seals vs. labyrinths increase cycle efficiency 0.6-0.8 points
- Seals at size, pressure do not exist



- GE developing large diameter face seal technology
- SwRI developing rig to test full-scale seal prototype with sCO_2
  - Utilize SunShot pump, heater
  - Leakage and thermal performance
- Testing completed 2023

SCO2 Oxy-Fuel Turbine Development
(SwRI, GE, Air Liquide, 8 Rivers, Purdue, UCF, EPRI for DOE NETL)

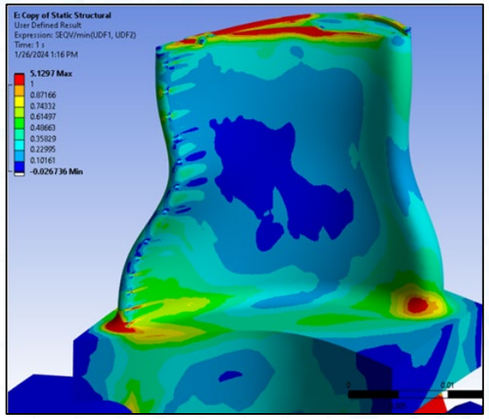
- Conceptual and detail design
- Turbine Inlet: 305 bar @ 1,150°C
- Turbine Exhaust: 30 bar
- Turbine Power: ~450 MW_{mech} (300 MWe Cycle)
- Cooling flow supplied to the turbine @ 400°C
- 3600 rpm direct drive to generator and compressor

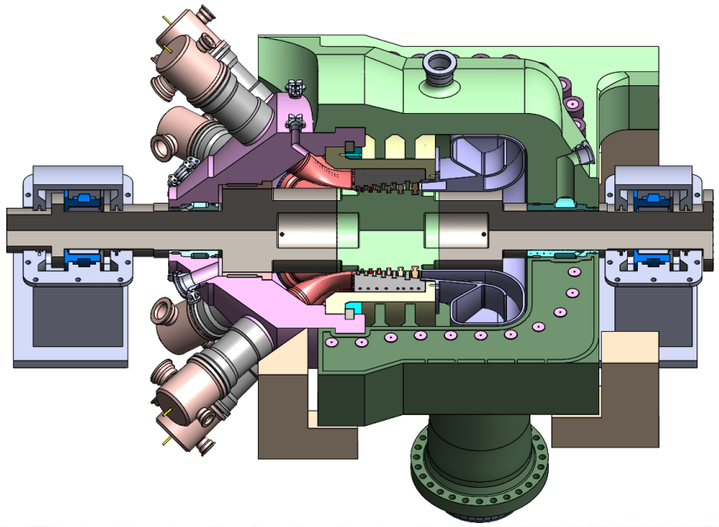


1150°C Autoclave

Internal Blade Cooling Heat Transfer Testing

1150°C Cooled Turbine Blade Design





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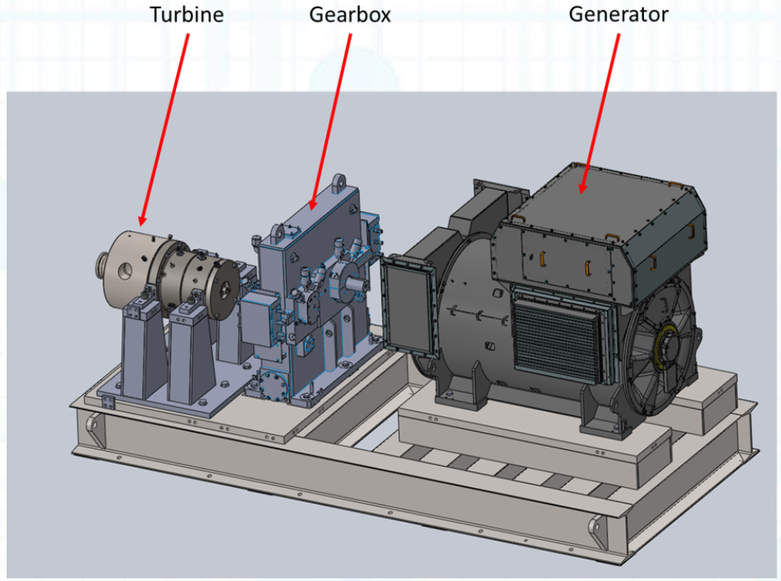
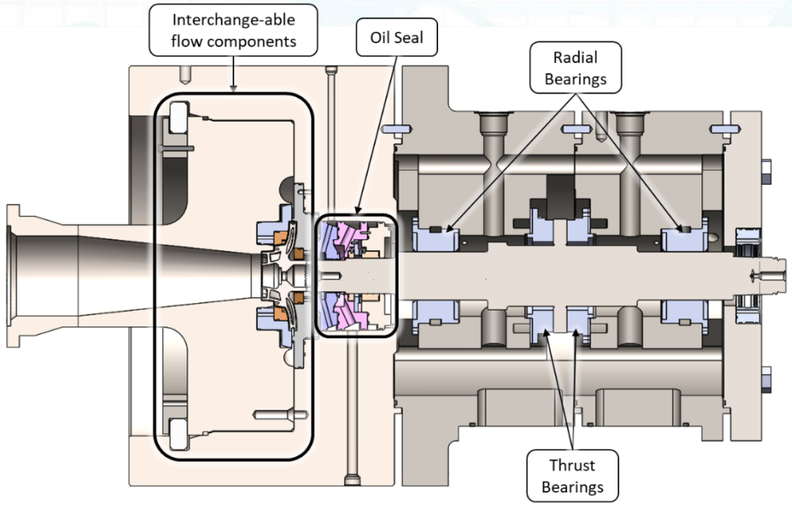
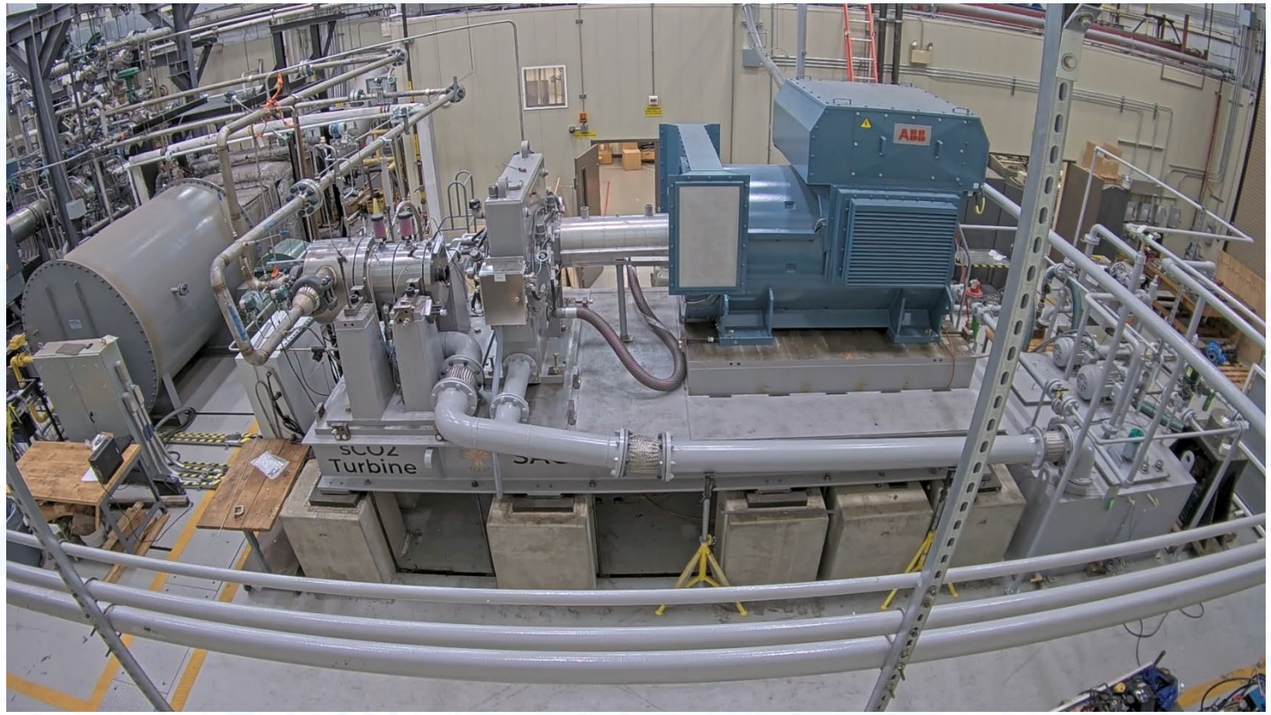
SCO_2 Geothermal Turbine



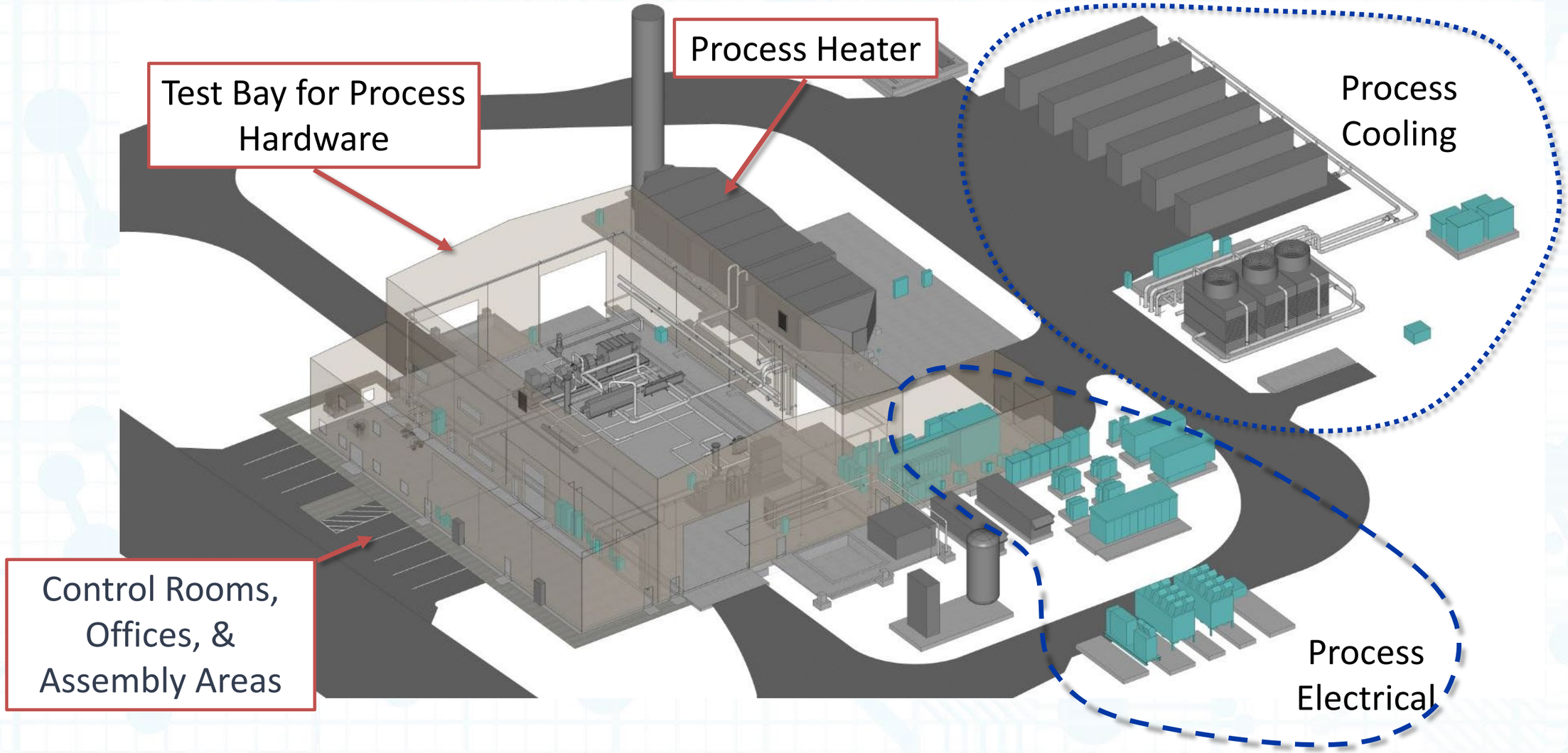
Condition	Range
Power Output	0.5 to 3MWe Output
Operating Speed	22,000 RPM
Inlet Pressure	22.5 MPa max
Outlet Pressure	10 MPa max
Inlet temperature	175°C max

1988-2023



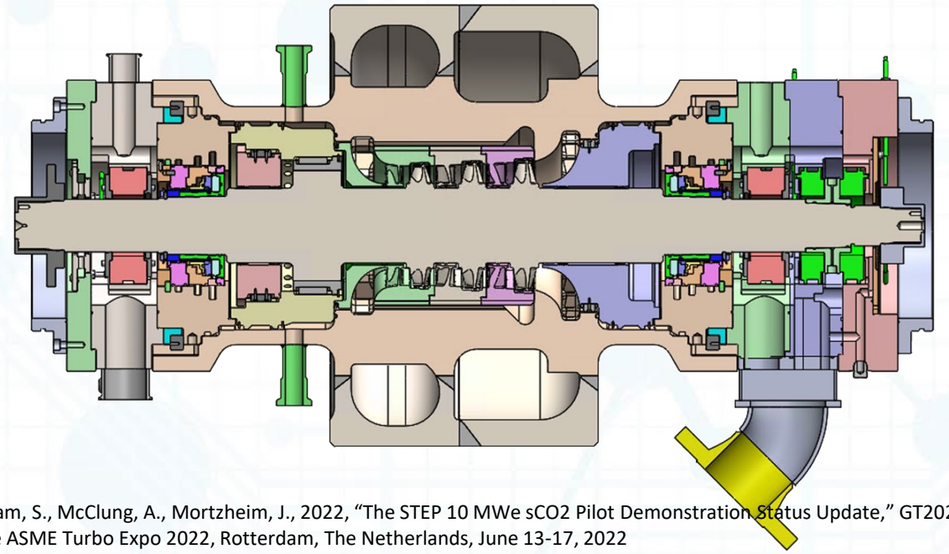


Supercritical Transformational Electric Power (STEP) Pilot Plant Test Facility

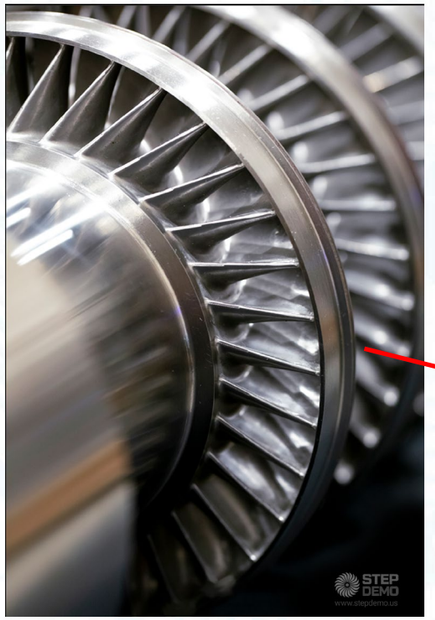


STEP Demo Turbine

- Advance Turbine from TRL 6 (Engineering Prototype) to TRL 7 (Full Scale Prototype)
- Based on Sunshot Design
- 3 stages, monolithic nickel alloy blade/shaft
- 16 MW shaft power
- 26,650 rpm design speed
- Rotor weight = 85 kg
- Highest power density of any industrial turbine
- Inlet conditions: 265 bar, 715°C
- Fluid film bearings with SFD
- Dry gas seals
- Single Inlet / Single Outlet connections
- Fabricated Inconel 625 barrel style casing
- Assembled and first spin achieved December 2023
- 18,000 rpm at 200C turbine inlet conditions achieved to date



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



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