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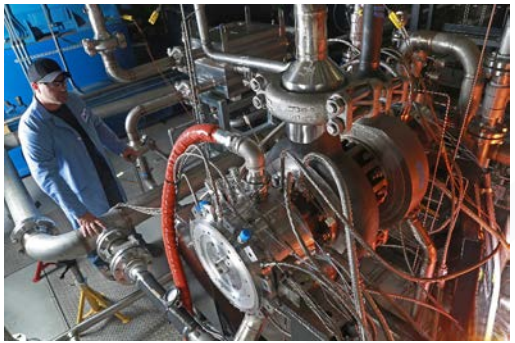
SOLAR ENERGY TECHNOLOGIES OFFICE

SETO CSP Program Summit 2019



Development of a High Efficiency Hot Gas Turbo-Expander and Low Cost Heat Exchangers for Optimized CSP sCO_2 Operation

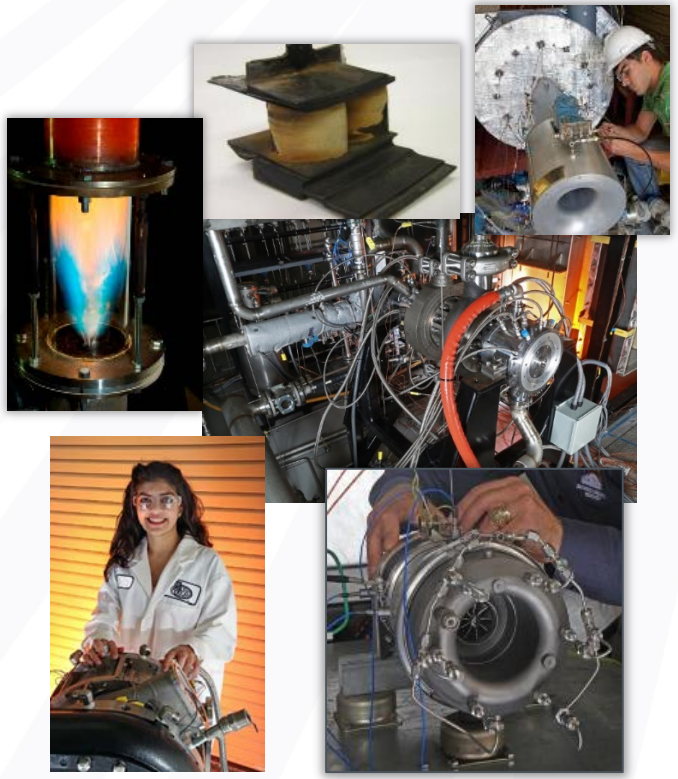
J. Jeffrey Moore, Ph.D.

Southwest Research Institute

energy.gov/solar-office

Southwest Research Institute

- Founded in 1947, 2600 employees today
- Machinery Department
  - Mechanical Engineering Division Focus on applied engineering research and development
  - Design, Fabrication, and Testing
- Specialties
  - Turbomachinery design and testing
  - Root cause failure analysis
  - Test stand design
  - Performance testing
  - Thermodynamic cycles analysis
- Active DOE Programs in
  - Power Generation
  - Energy Storage
  - Renewable Energy
  - Improved Fossil Energy



Sunshot Team

Jeff Moore

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Stefan Cich

Jason Mortzheim

Doug Hofer

Supercritical CO2 Cycle Applications

Improved efficiency and power block

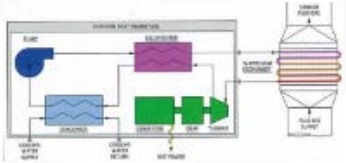
Primary Power
- High grade heat
- Optimized for system efficiency
- 0.3-2000 MWe

Concentrating Solar Power

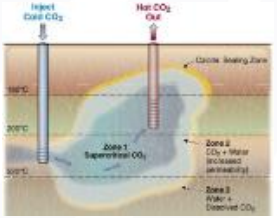
Fossil Fuel

Nuclear

Bottoming Cycles
- Low grade heat
- Optimized for net power
- 2-10 MWe



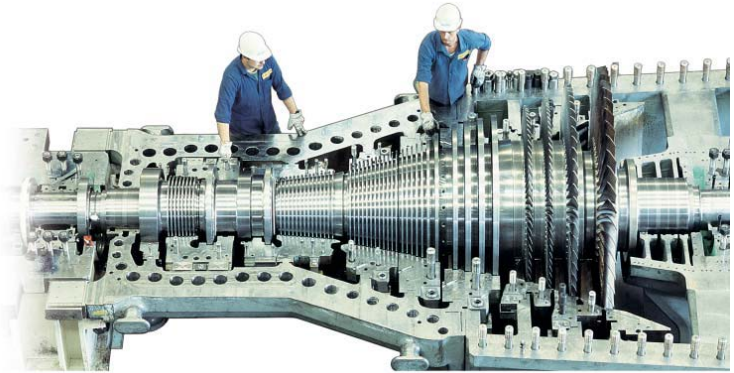
Waste Heat Recovery



Geothermal

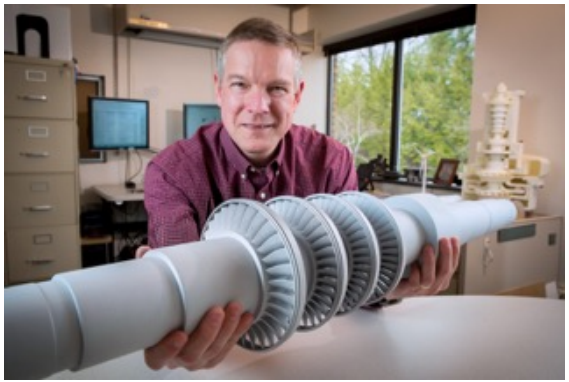
Smaller Turbomachinery

20 MW Steam Turbine



16 MW sCO_2 Turbine

- 150 lb rotor, 7” dia, 27,000 RPM



Sunshot Project Objectives

- Develop a novel, high-efficiency supercritical CO_2 (sCO_2) hot-gas turbo-expander optimized for the highly transient solar power plant duty cycle profile
  - Advances the state-of-the-art from a current Technology Readiness Level (TRL) 3 to TRL 6
- Develop novel recuperator technology for sCO_2 applications to reduce manufacturing costs
- Develop a 1-MWe sCO_2 test loop
- Technology development helping to achieve CSP at $0.06/kW-hr levelized cost of electricity, increasing energy conversion efficiency to greater than 50%, and reducing total power block cost to below $1200/kW installed

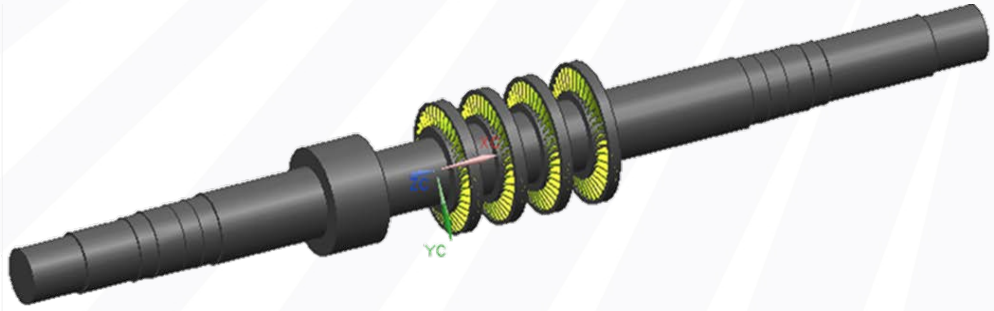
Funding Partners

- Total project cost: $9.8 million
  - Department of Energy 70%
  - General Electric: 10%
  - Thar Energy 8%
  - EPRI 4%
  - Navy Nuclear Lab 4%
  - Saudi Aramco 3%
  - SwRI 1%

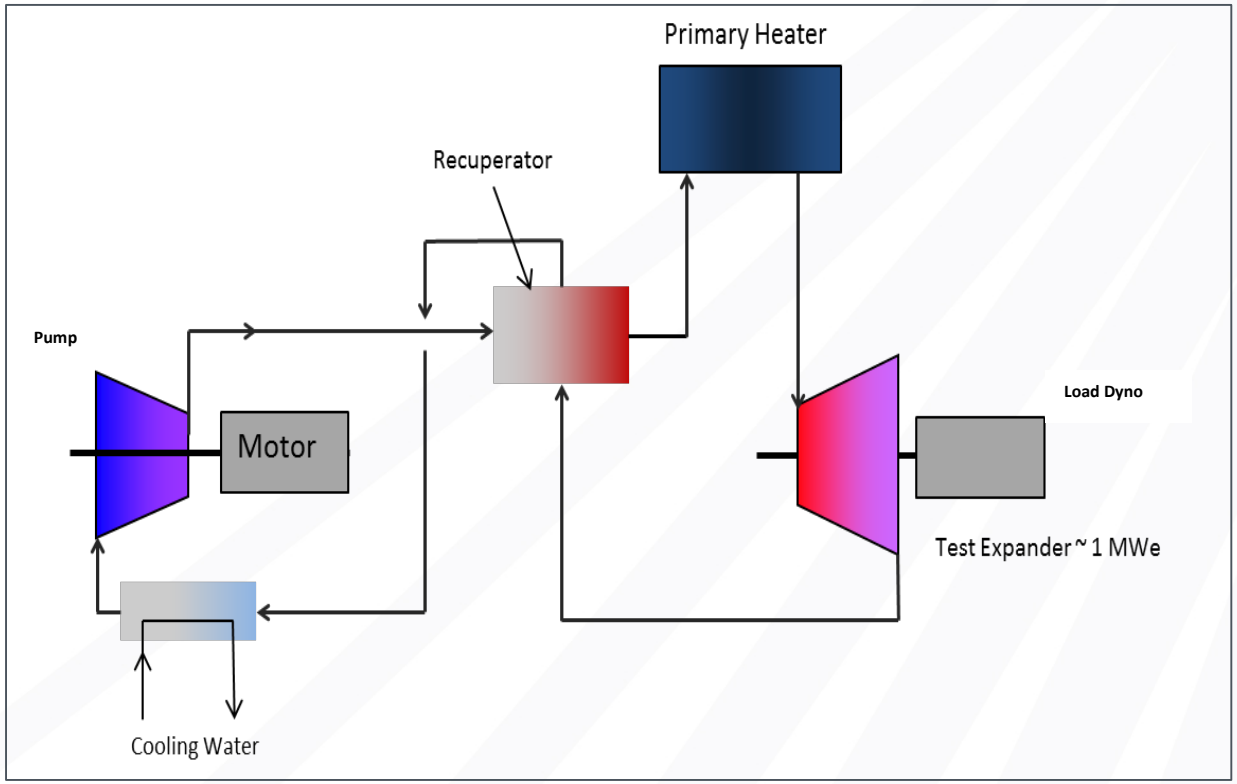
Sunshot Program Overview

System targets:
- 10 MWe net module size
- 50% net thermal efficiency

Expander targets:
- ~14 MW shaft power
- >700°C inlet temp
- >85% aero efficiency
- Multi-stage axial



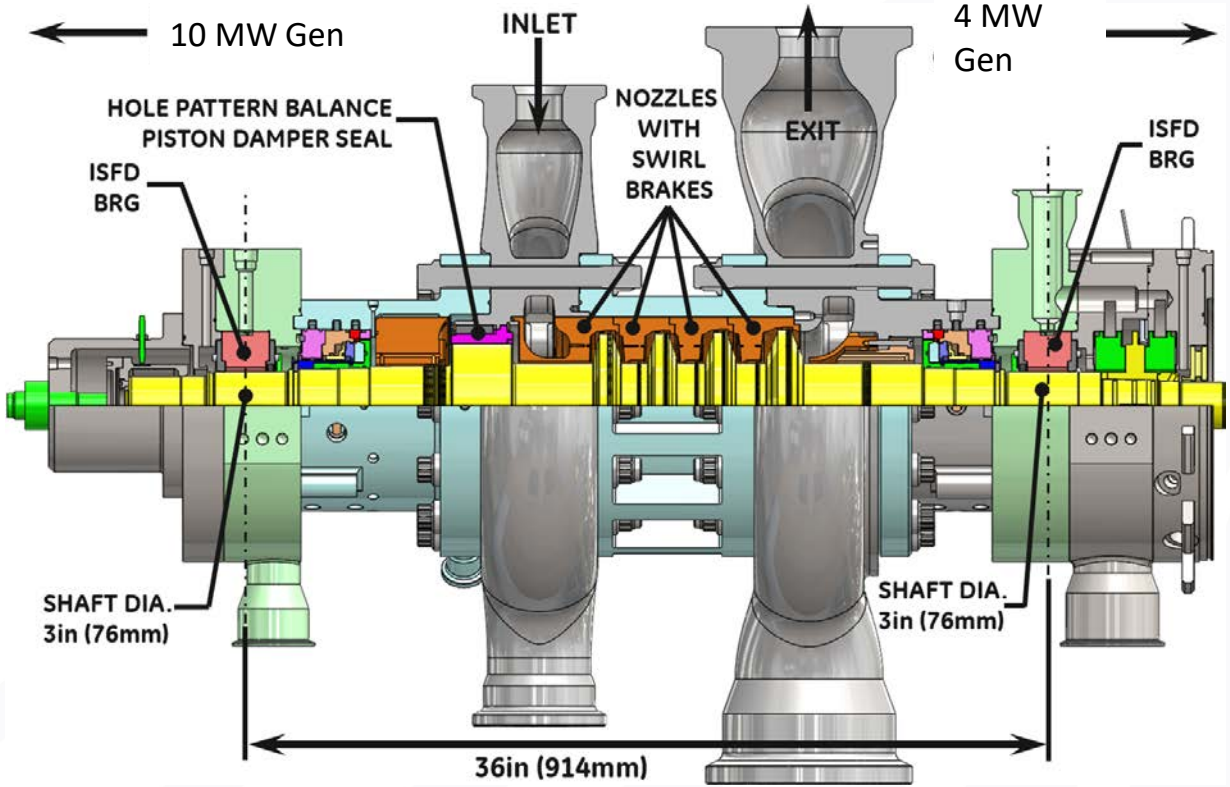
Simple sCO2 Recuperated Cycle for Test Loop



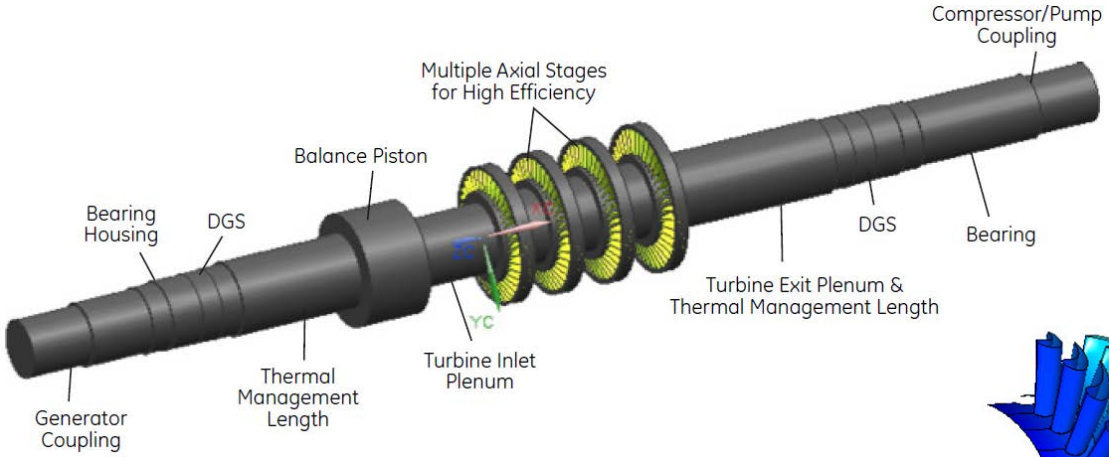
Loop Operating Conditions

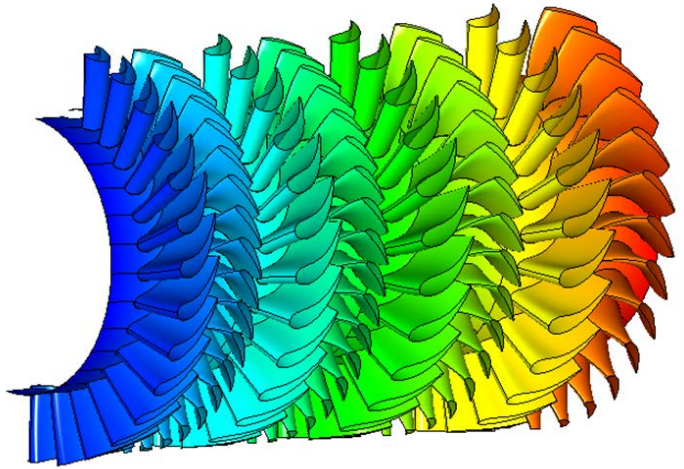
Component	T out, °C (°F)	P out, bar (psi)	Flow, kg/s (lb/s)
Pump	29.22 (84.60)	255.0 (3698)	9.910 (21.85)
Recuperator-Heat	470.0 (878.0)	252.3 (3659)	8.410 (18.54)
Heater	715.0 (1319)	250.9 (3639)	
Expander	685.7 (1266)	86 (1247)	
Recuperator-Cool	79.58 (175.2)	84 (1218)	9.910 (21.85)
PreCooler	10.00 (50.00)	83 (1204)	

Sunshot Turbine Design



Rotor Design

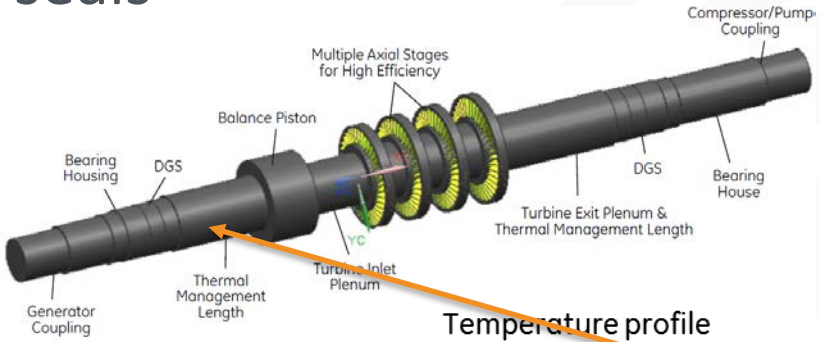




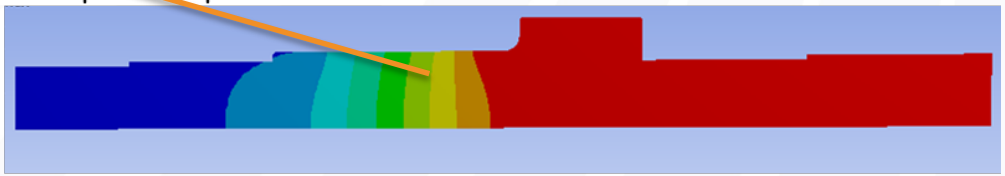
4-Stage Axial Flow Design

Thermal Management Region

- Temperature gradient at shaft ends required due to dry gas seals



Temperature profile

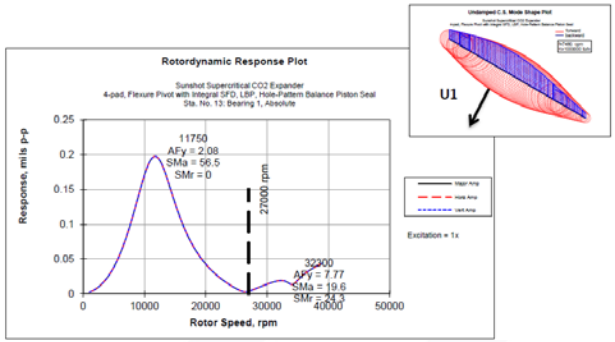


Temperature profile in the shaft and stator piece in the thermal management region

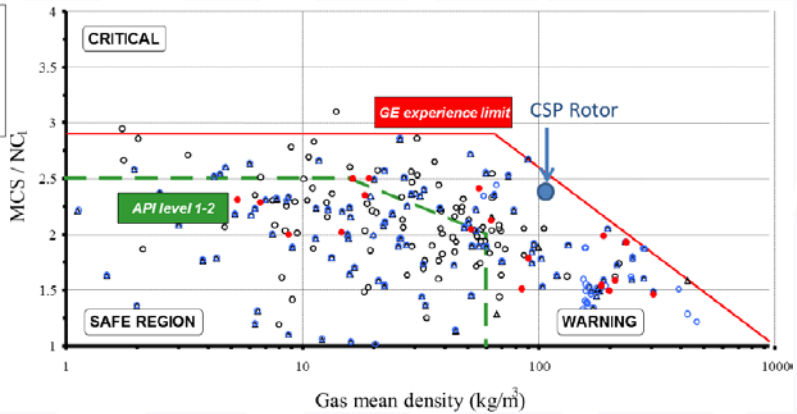
(Blue = 50ºC, Red = 715ºC) (Kalra, et. al, 2014)

Rotordynamics

- Long flexible rotor and high gas density makes rotordynamics challenging



Rotordynamic Prediction for First Critical Speed

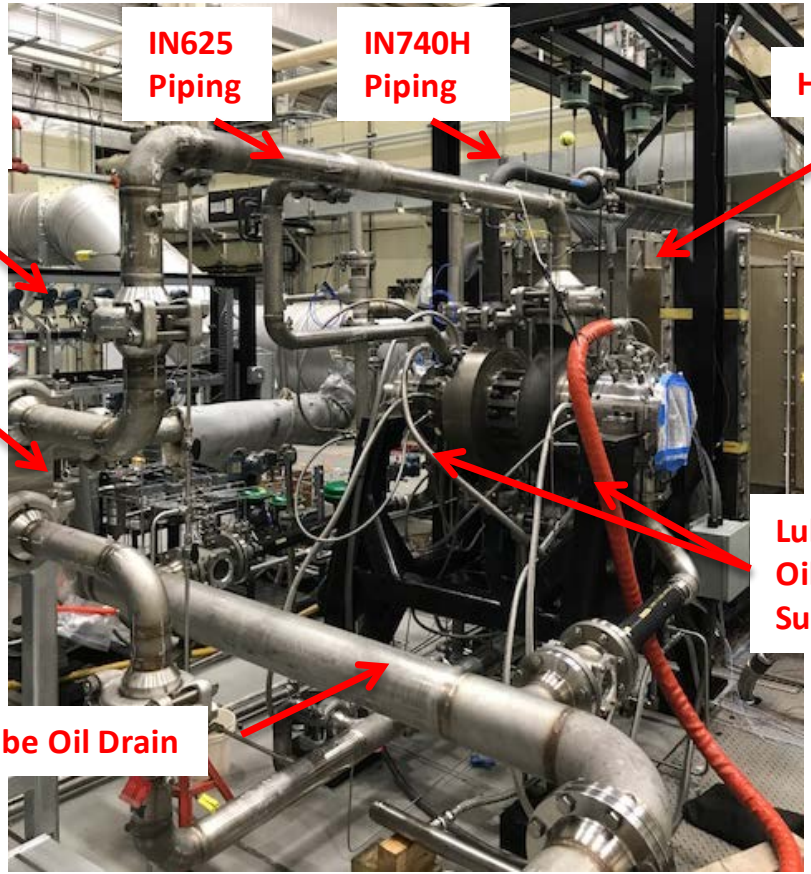


Rotordynamic Experience Chart from Moore (2006) with Sunshot Turbine Rotor Added

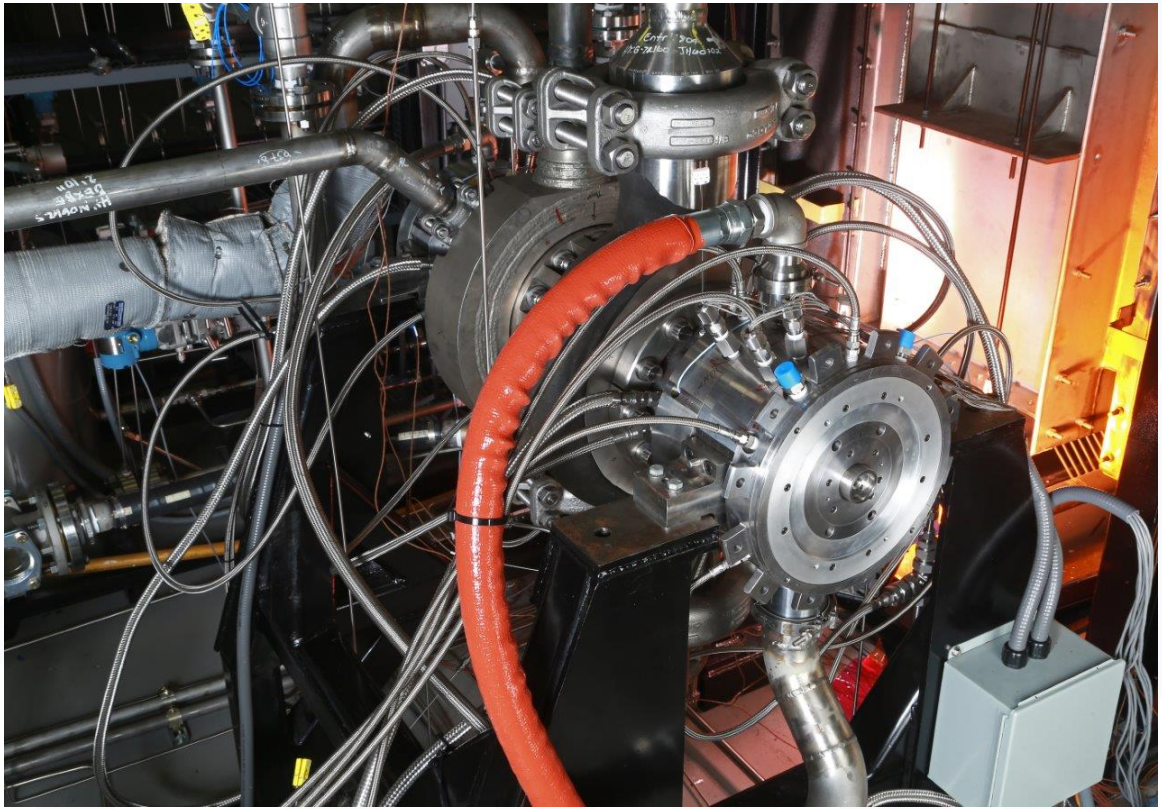
Turbine Assembly

- Assembly completed with no major issues
- All fits and seal clearances verified
- Rotor runout met specifications
- Axial end-play adjusted with shim packs
- Radial bearing clearances verified
- Thermal seal instrumentation added

Test Loop Components



Assembled Turbine Casing on Test Stand

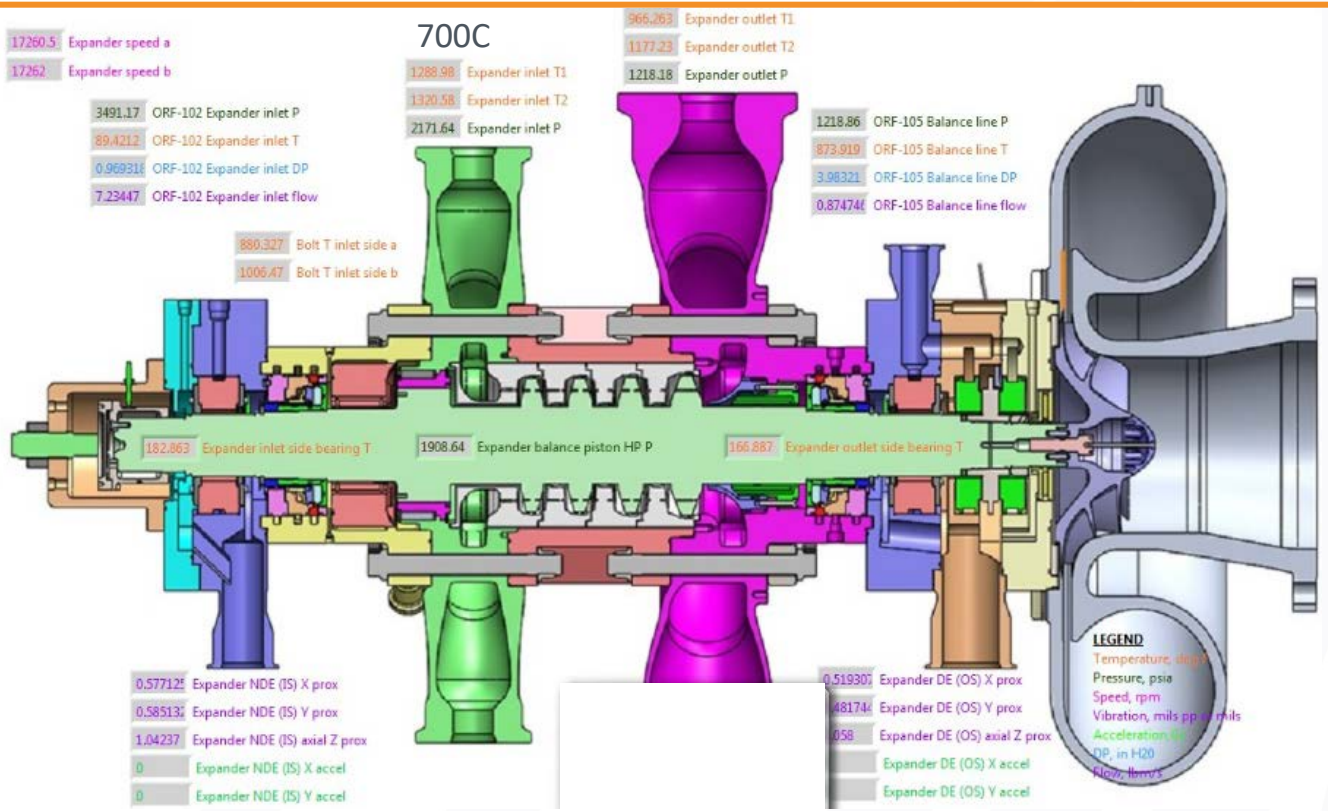


Final Assembled Turbine Test Rig

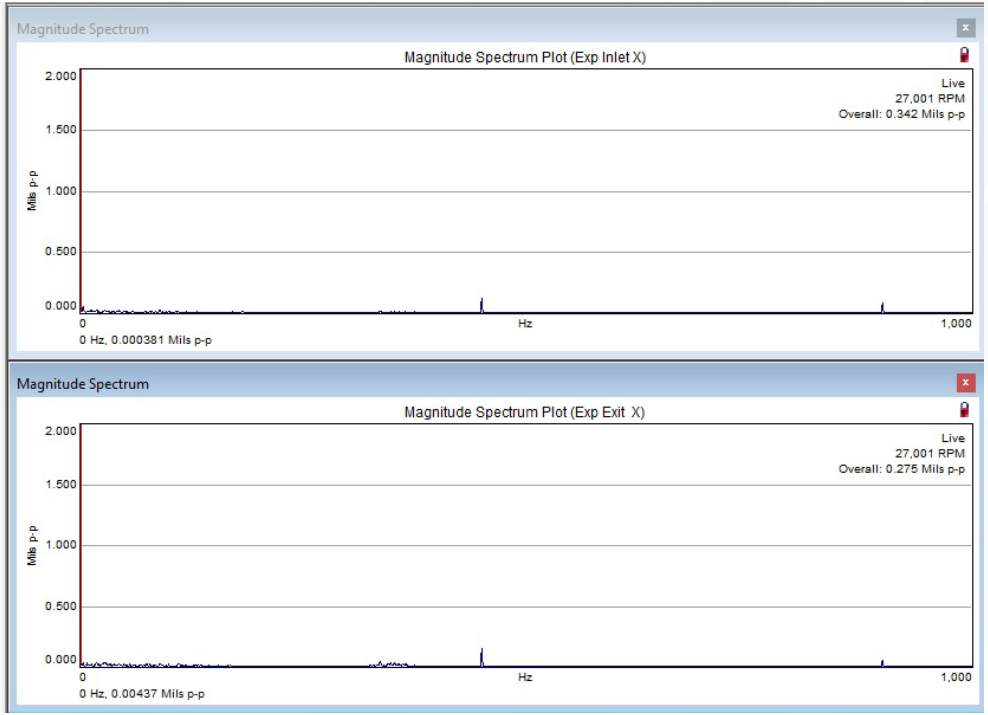
Project Achievements

- Sunshot
  - 27,000 rpm; 1,320F; 3,500 psi
  - 12 total turbine starts with 3 controlled shutdowns and 9 observed trips
  - 37.5 hours of turbine operation
- FOCUS
  - Tested both thermals seals to similar operating conditions
  - 1020F; 21,000 rpm
  - Matched similar dry gas seal flows
  - Obtained thermal seal and case temperatures

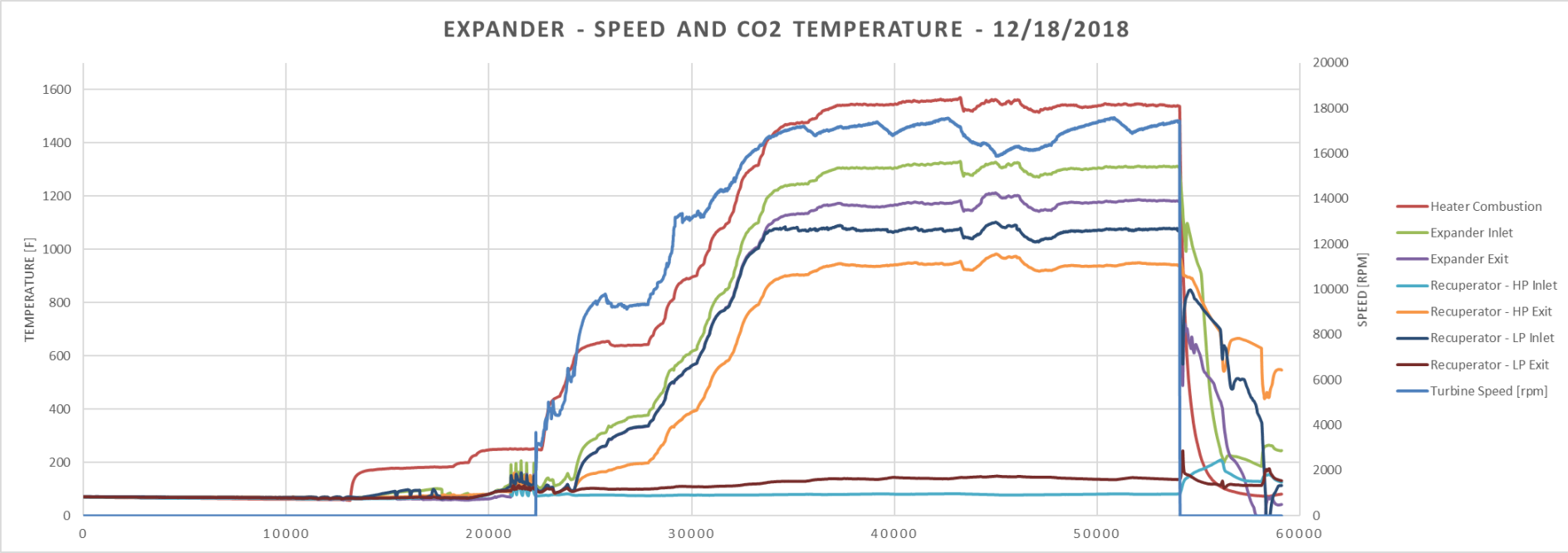
Test Results – 700C+



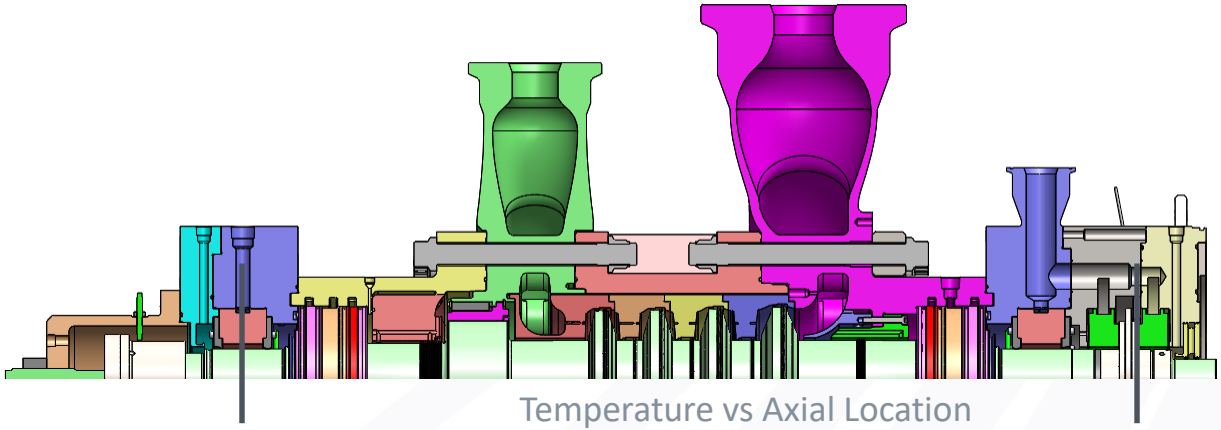
Turbine Vibration Spectrum at 27,000 rpm

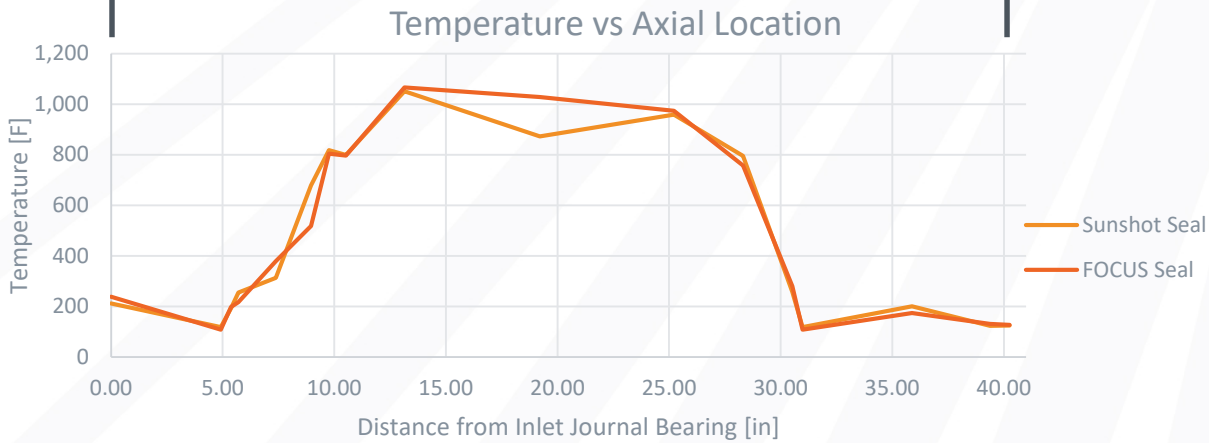


Loop Temperatures

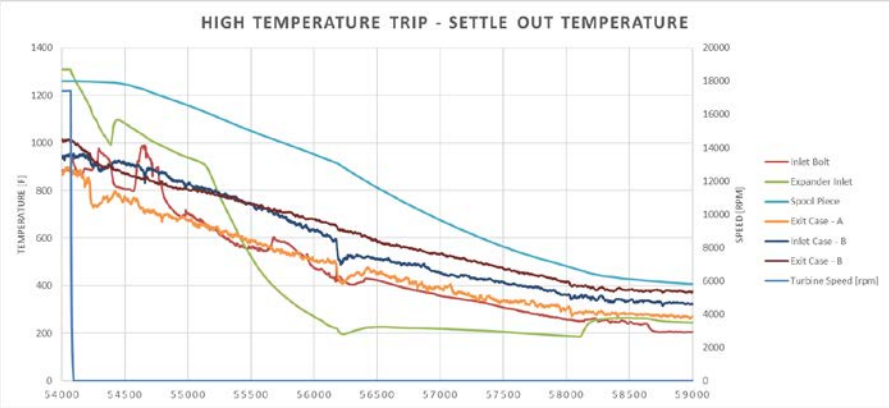


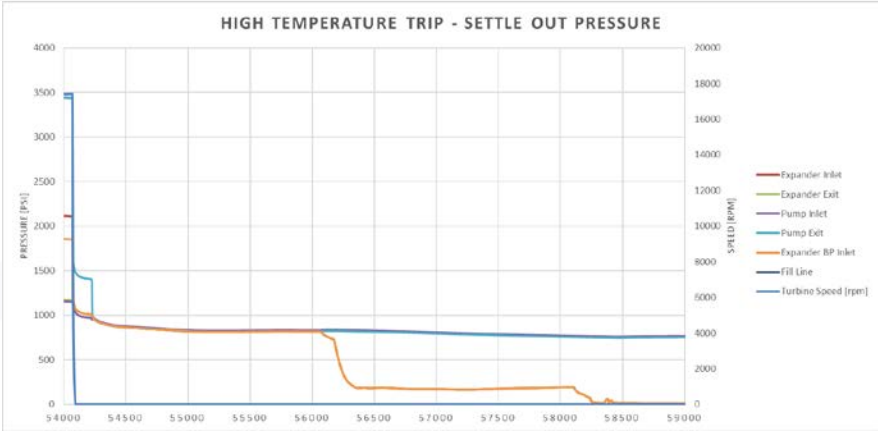
Thermal Seal Performance





Turbine Transients





- Two maximum condition trips
  - Highest temperature trip after 1,320F was reached
  - Highest pressure trip after 27,000 rpm was reached
- High temperature trip
  - Settle pressure is reached in less than 10 seconds
- Turbine case cooled down at a similar rate with or without dry gas seal flow

Summary

- Turbine performance met all mechanical and performance objectives
  - Achieved design temperature of 715C, design speed of 27000 rpm, and near design pressure of 3600 psi.
  - Thermal seal maintained acceptable dry gas seal operating temperature with near linear profile.
  - Vibration well less than 0.5 mils with no signs of instability
  - Low critical speed response (good bearing damping and balance)
  - Good thrust balanced and low thrust bearing temperature
  - Many shutdown transients tolerated
  - Modified dry gas seal met requirements
  - Modified dry gas seal panel maintained warm seal gas preventing dry ice formation
- Test Loop performed well meeting all project objectives
- Highest temperature SCO2 turbine in the world

Acknowledgements

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