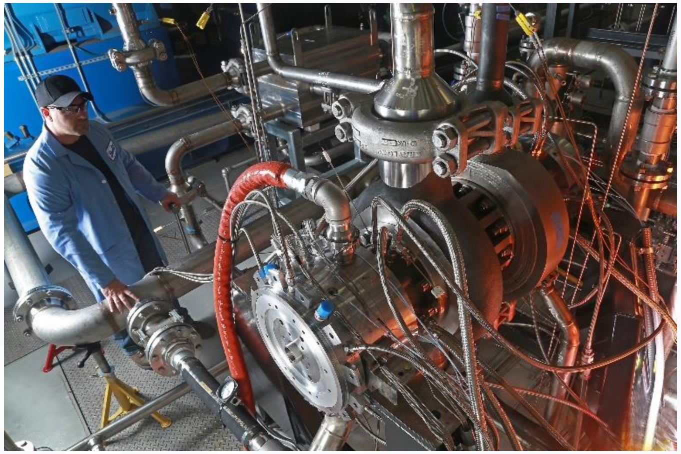
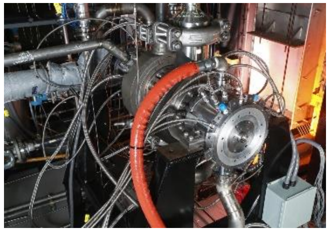
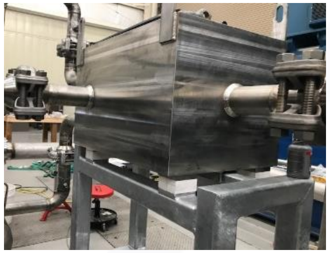
SunShot
U.S. Department of Energy







# TESTING OF A 1 MWe SUPERCRITICAL $CO_2$ TEST LOOP

**Jeff Moore, Ph.D.**

Southwest Research Institute (SwRI)

energy.gov/sunshot

# Sunshot Team

# Project Objectives

- To 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
  - This $sCO_2$ turbo-expander design advances the state-of-the-art from a current Technology Readiness Level (TRL) 3 to TRL 6
- To optimize novel recuperator technology for $sCO_2$ applications to reduce their manufacturing costs
- The $sCO_2$ turbo-expander and heat exchanger will be tested in a 1-MWe $sCO_2$ test loop, fabricated to demonstrate the performance of components along with the overall optimized $sCO_2$ Brayton cycle
- The scalable $sCO_2$ turbo-expander and improved heat exchanger address and close two critical technology gaps required for an optimized concentrating solar power (CSP) $sCO_2$ plant and provide a major stepping stone on the pathway to achieving 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

# Sunshot Program Overview

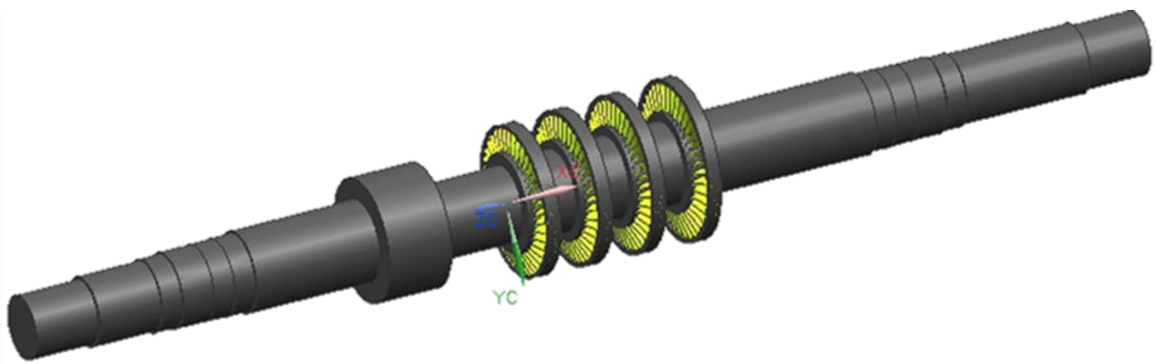
Team: SwRI, GE, KAPL, Thar Energy, Navy Nuclear Laboratory, Aramco, EPRI, US DOE

Project: 5-year, $10 million program to develop & test an expander & recuperator for $sCO_2$ power generation from CSP

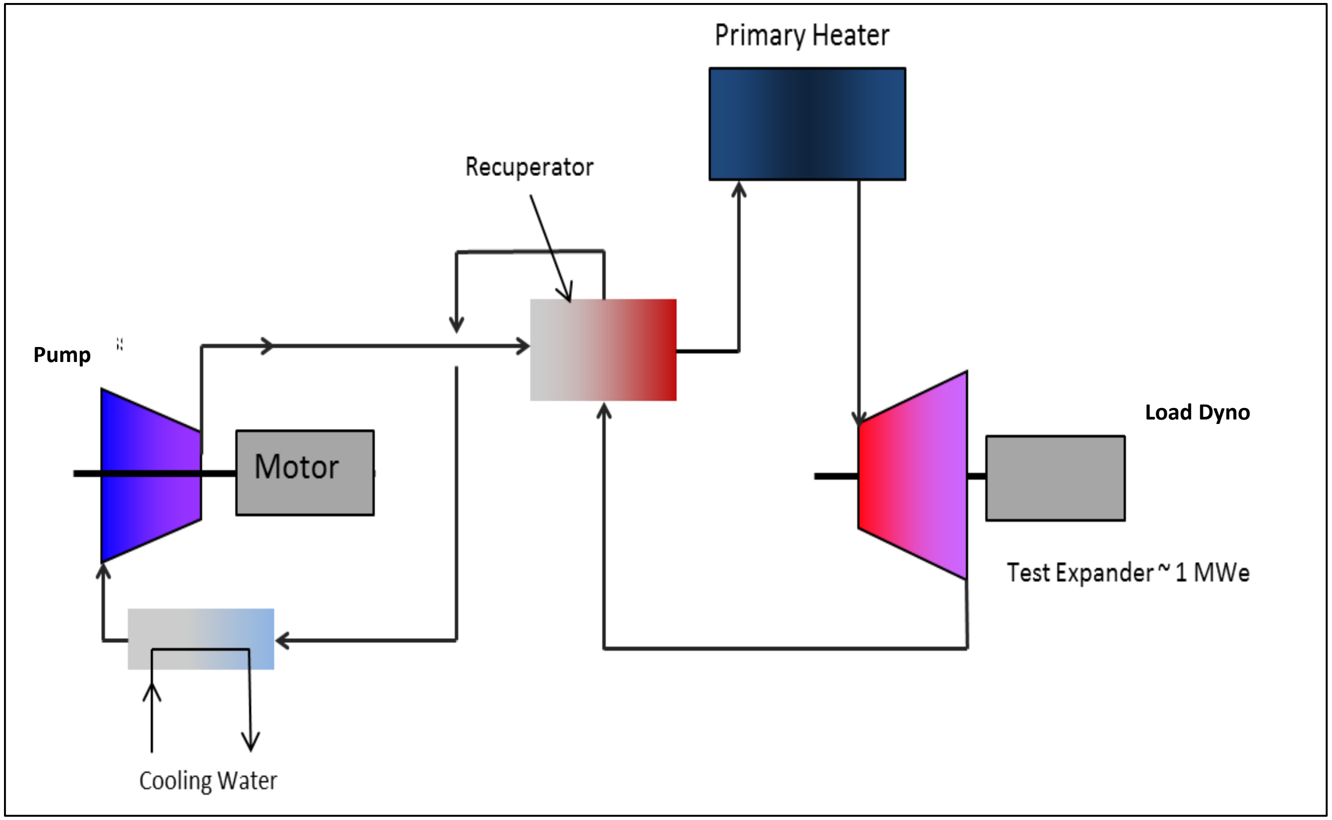
Schedule: Expander, recuperator, and test loop design complete

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



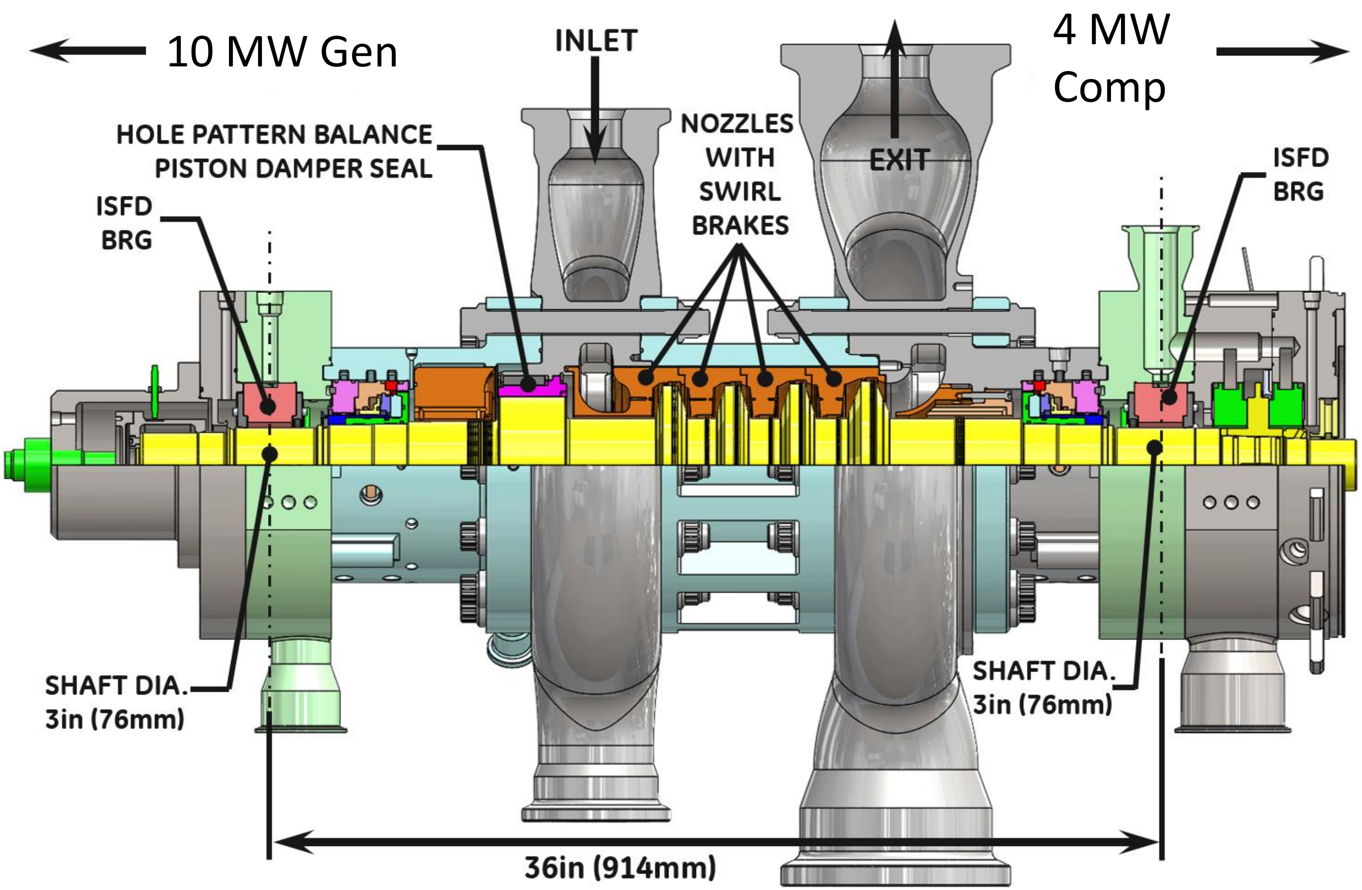
# Simple $sCO_2$ Recuperated Cycle for Test Loop



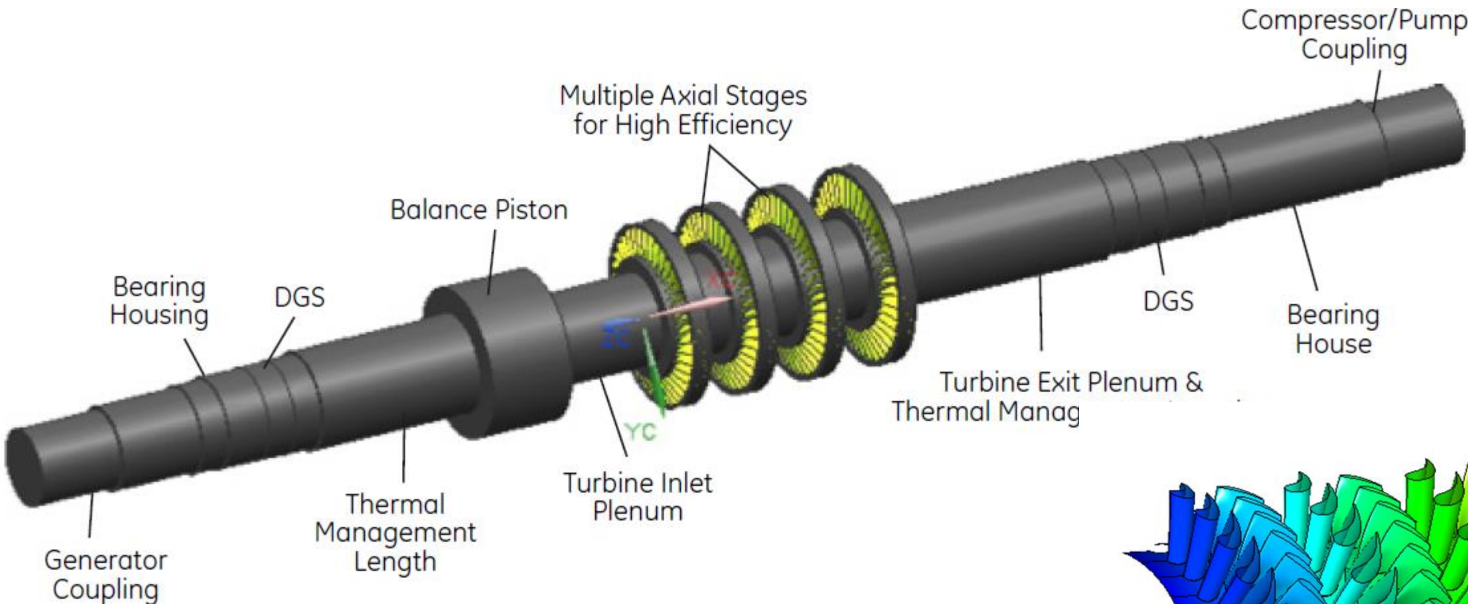
# Loop Operating Conditions

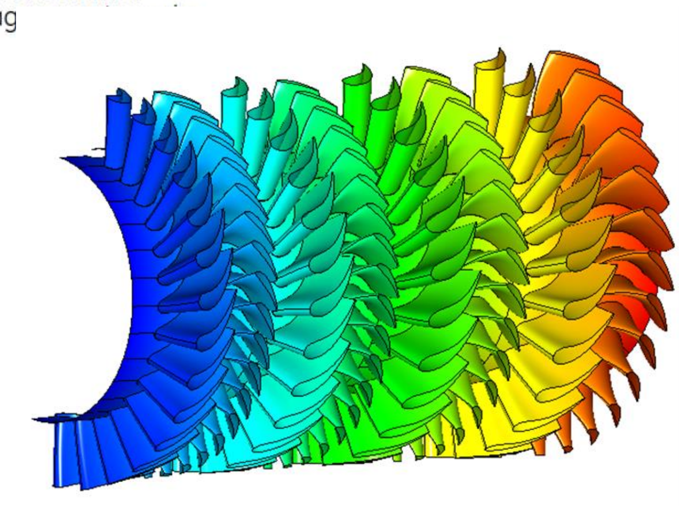
| Component | T out, °C (°F) | P out, bar (psi) | Flow, kg/s (lb/s) |
|---|---|---|---|
| Pump | 29.22 (84.60) | 255.0 (3698) | 9.910 (21.85) |
| Recuperator-Heat | 470.0 (878.0) | 252.3 (3659) | |
| Heater | 715.0 (1319) | 250.9 (3639) | 8.410 (18.54) |
| Expander | 685.7 (1266) | 86 (1247) | |
| Recuperator-Cool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

# Sunshot Turbine Design



# Rotor Design

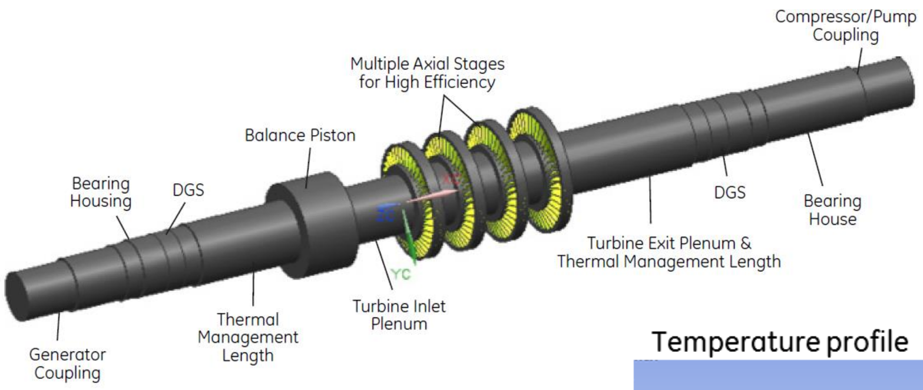


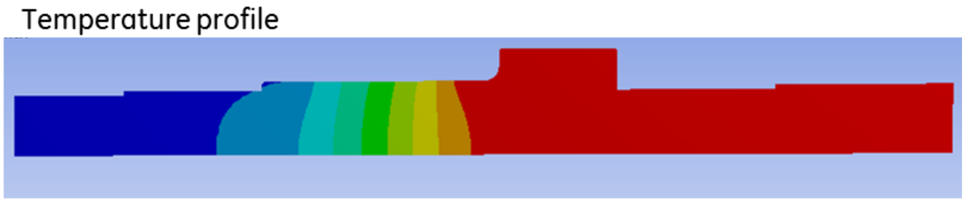
4-Stage Axial Flow Design

# Thermal Management Region

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



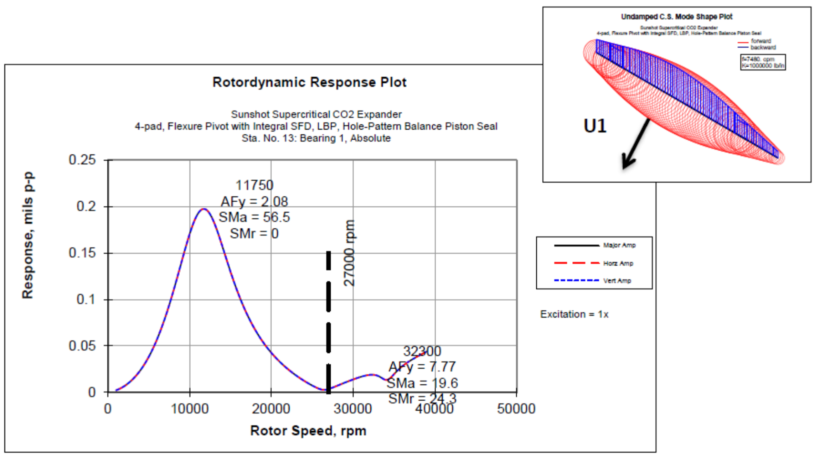

Temperature profile in the shaft and stator piece in the thermal management region



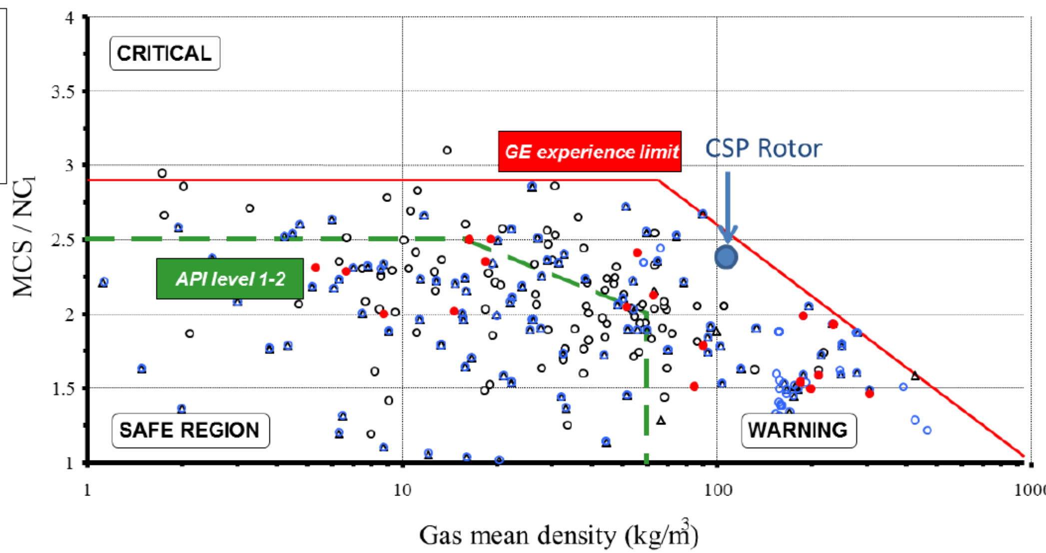

(Blue = 50ºC, Red = 715ºC) (Kalra, et. al, 2014)

# Rotordynamics

- Long flexible rotor and high gas density makes rotordynamics challenging




Rotordynamic Prediction for First Critical Speed



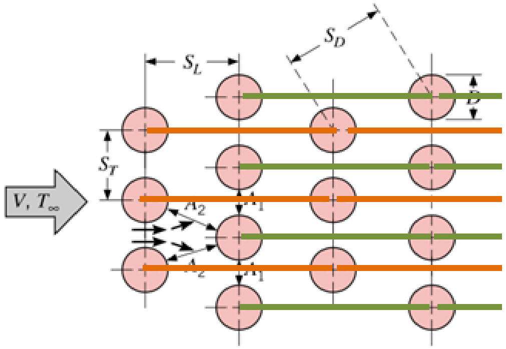

Rotordynamic Experience Chart from Moore (2006) with Sunshot Turbine Rotor Added

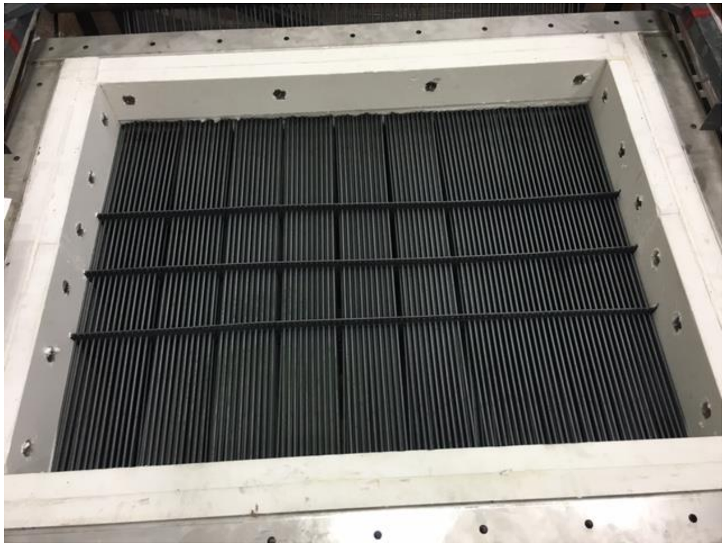
# 40 MMBtu/hr (11.7 MW) Heater

| | Recuperator Outlet/ Heater Inlet | Heater Outlet/ Turbine Inlet |
|---|---|---|
| Temperature | 470°C | 715°C |
| Pressure | 251.9 bar | 250.9 bar |
| Mass flow rate of $CO_2$ | 8.410 kg/s | 8.410 kg/s |

# Heater Heat Exchanger

- Staggered tube configuration
- Designed by SwRI and Thar
- Manufactured by Thar
- First Inconel 740H heat exchanger



# Recuperator Development

- Sourced Printed Circuit Heat Exchanger (PCHE)from Vacuum Process Engineering (VPE) for Recuperator
- Plates are chemically etched and diffusion bonded in a large vacuum furnace.

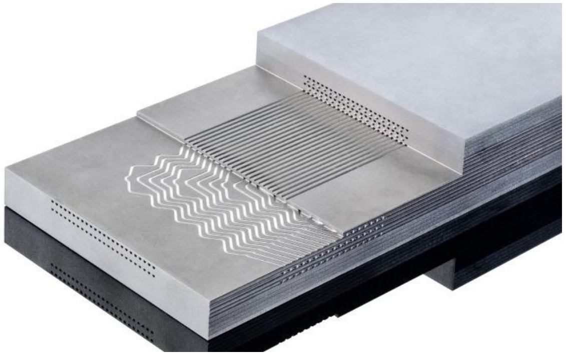
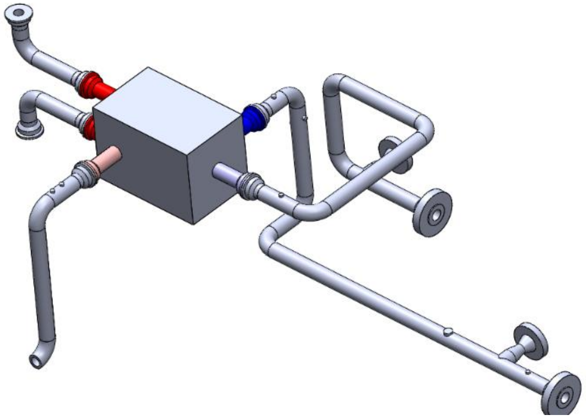
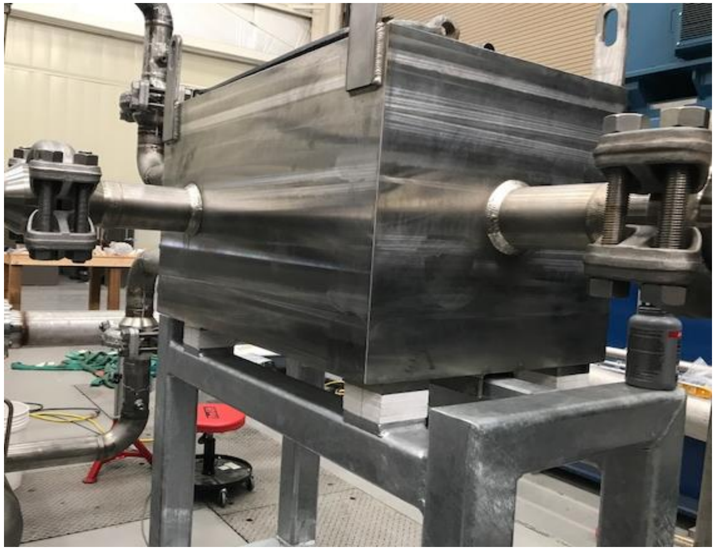


Image courtesy of vpei.com

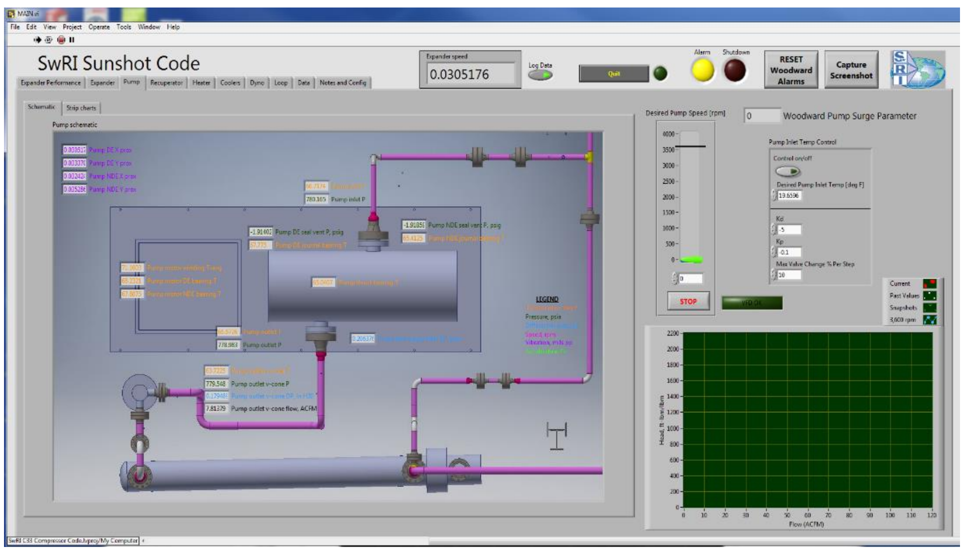


# VPE Recuperator on Stand



# Dense Phase Pump

- 12 stage, 3600 rpm pump
- Provided by BHGE
- 80 to 250 bar at 15 kg/sec



# Turbine Assembly

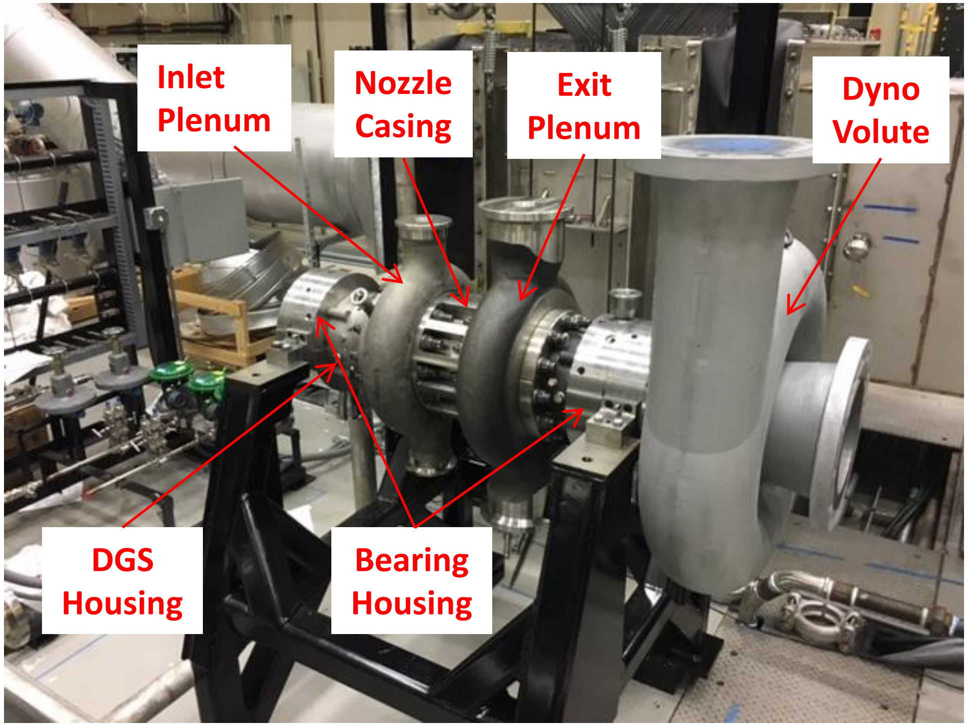
- Assembly completed with no major issues
- All fits and seal clearances verified
- Rotor runout met specifications
- Axial end-play adjusted with shim packs
- Radial bearing clearances verified
- Thermal seal instrumentation added

# Turbine Assembly Completed

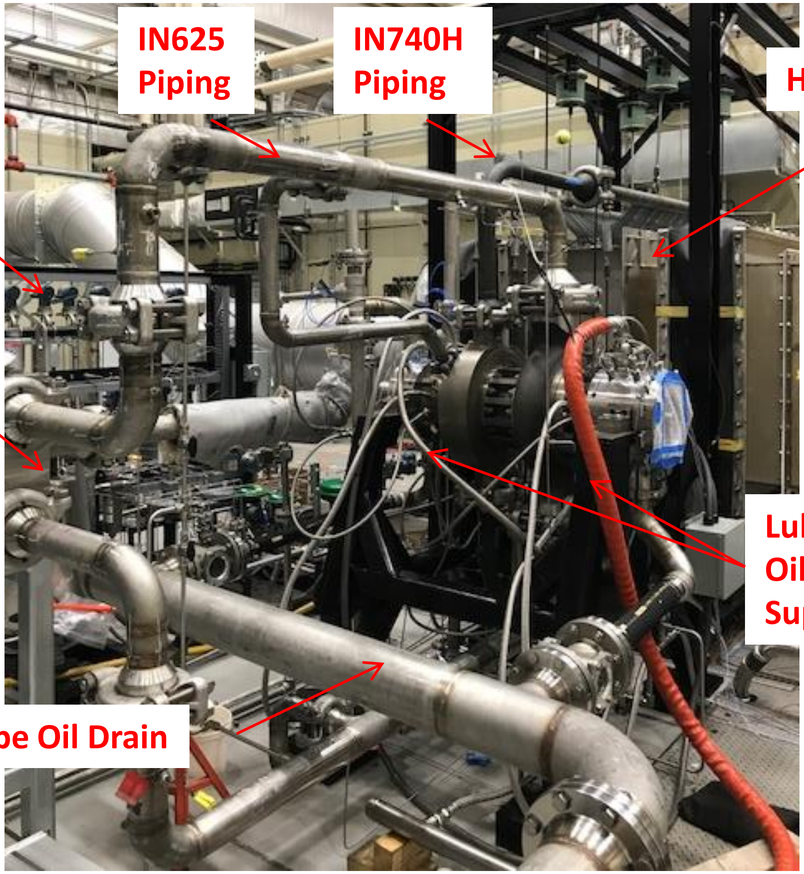
- Turbine assembled and installed on test stand
- Connections made to turbine in this order:
  - Large piping
  - Small piping
  - Lube oil supply and drain
  - Instrumentation

# Turbo-Machinery Fabrication

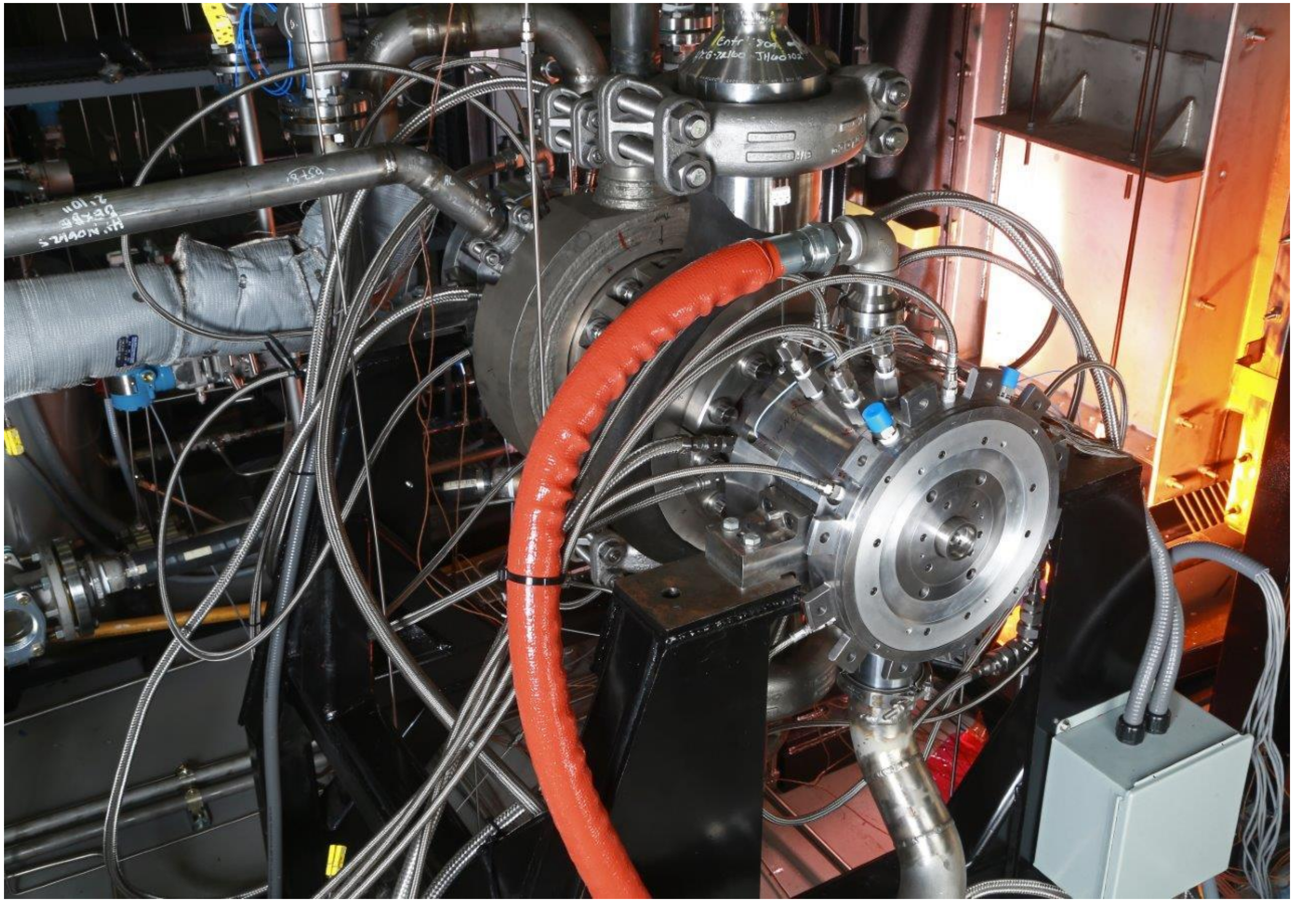
**Turbine Case Assembly**



# Test Loop Components



# Assembled Turbine Casing on Operating Stand



# Final Assembled Turbine Test Rig

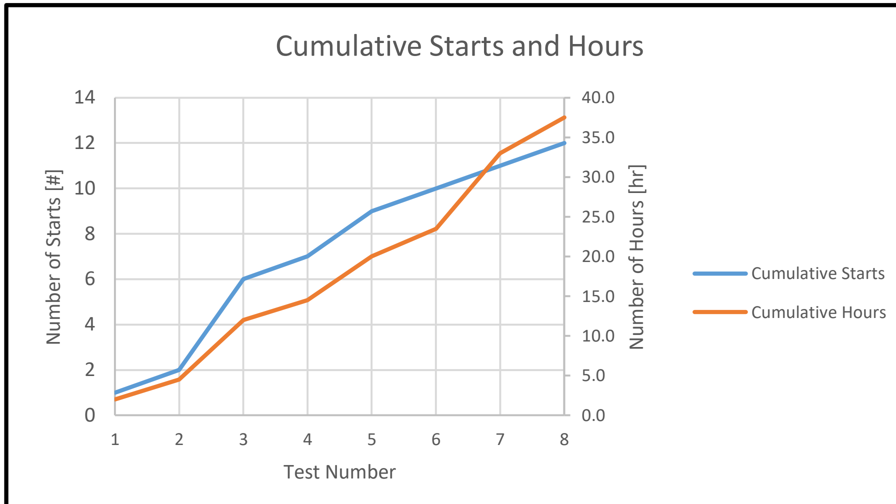
SunShot U.S. Department of Energy

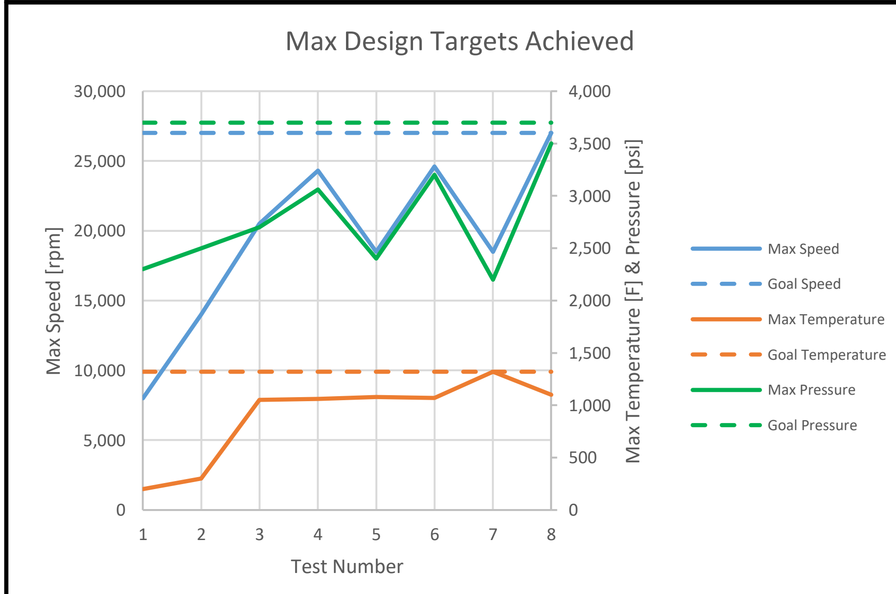
# Turbine Design Operating Points

| | Speed (rpm) | Turbine Inlet Temp. °C (°F) | Turbine Inlet Pressure bar (psi) | Turbine Exit Pressure bar (psi) |
|---|---|---|---|---|
| 1st Design Point | 21,000 | 550°C (1022°F) | ~200 bar (3000 psi) | 80 bar (1160 psi) |
| 2nd Design Point | 27,000 | 715°C (1319°F) | ~250 bar (3625 psi) | 80 bar (1160 psi) |

# Project Achievements

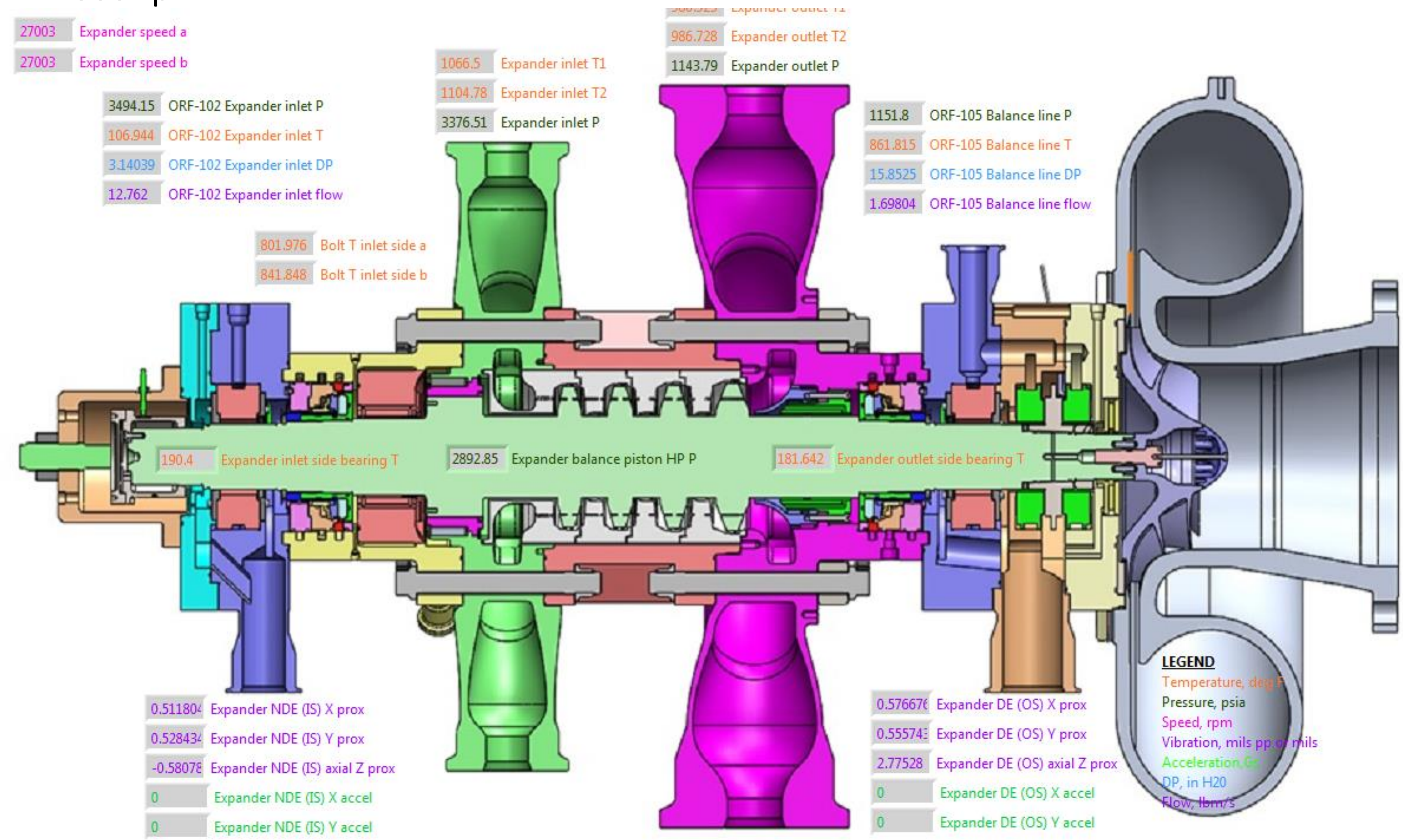
- SunShot
  - 27,000 rpm; 1,320F; 3,500 psi
  - 12 total turbine starts with 3 controlled shutdowns and 9 observed trips
  - 37.5 hours of turbine operation
  - Observed transients to determine how the loop performs to fast shutdowns to help with future designs
  - Observed necessary trips and how the loop operated after and how to bring everything back online
- 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



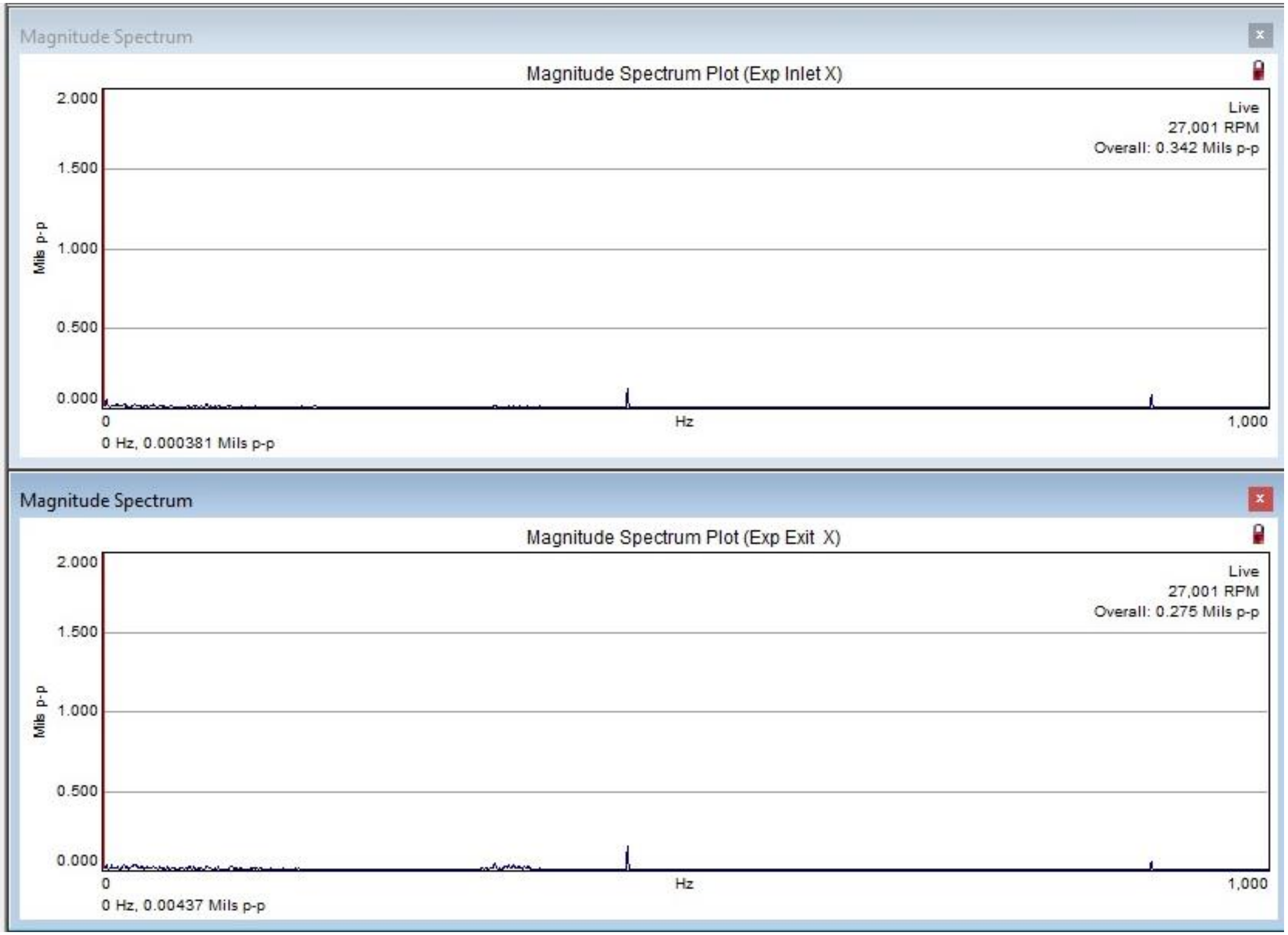



# Test Results – 27,000 rpm

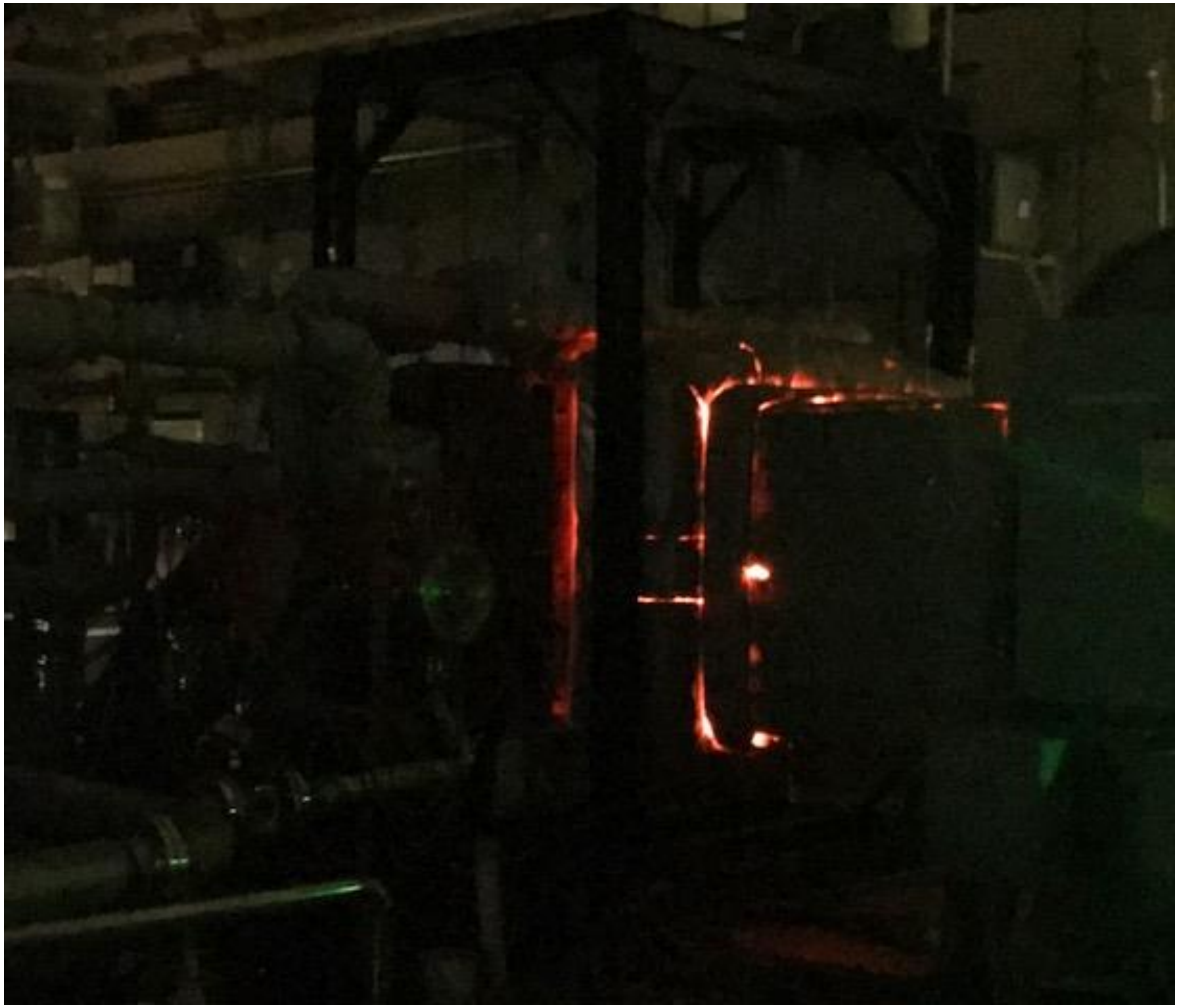
## 27000 rpm



# Turbine Vibration Spectrum at 27,000 rpm

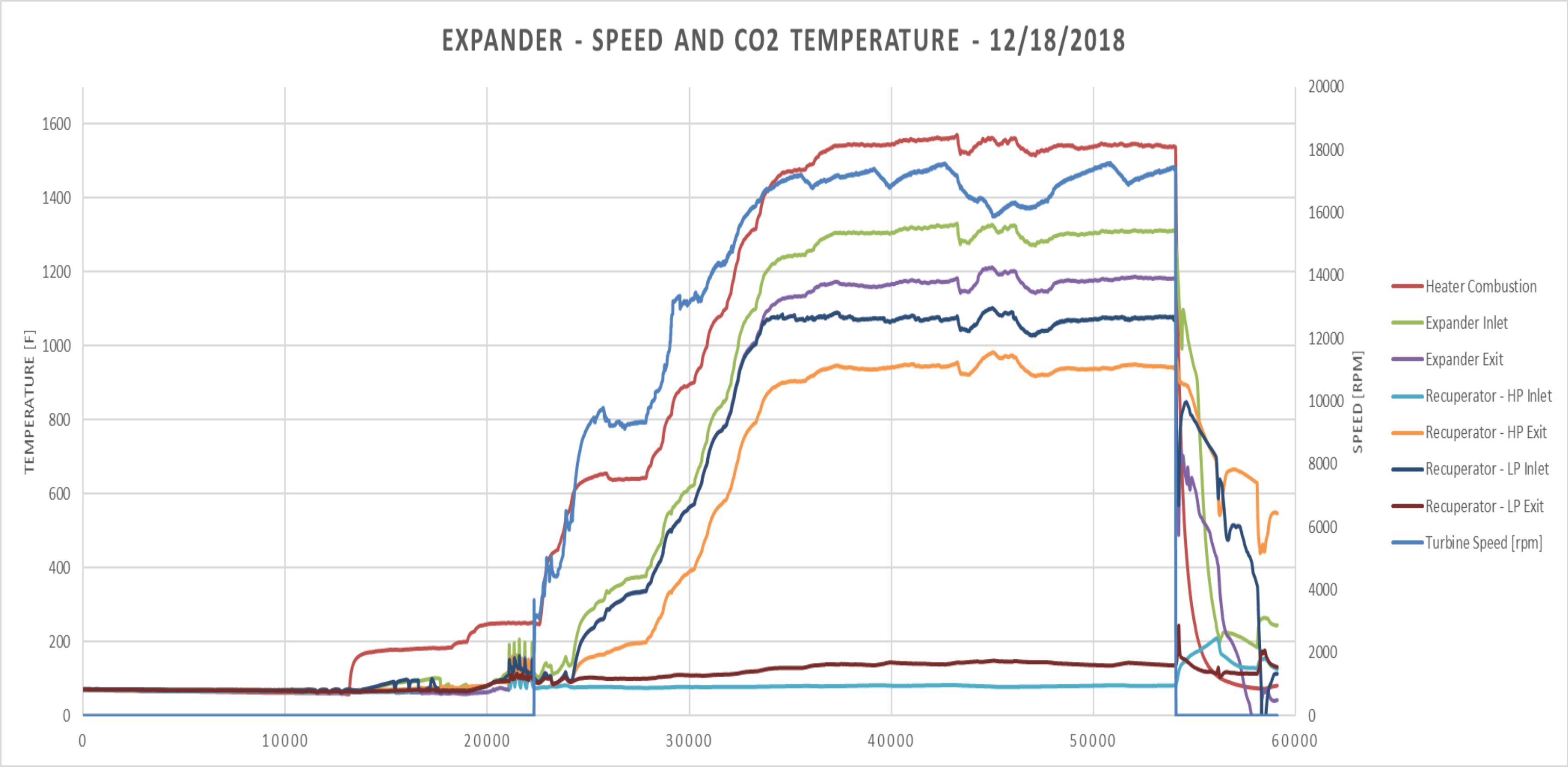


# Heater at 1750F (954C)

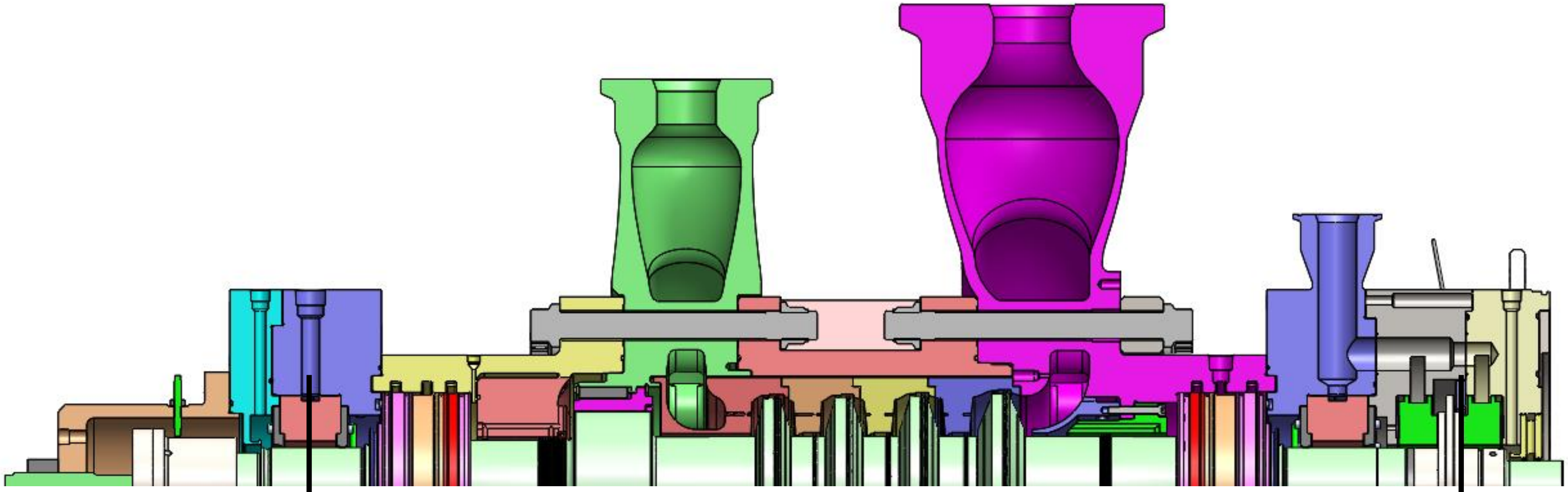


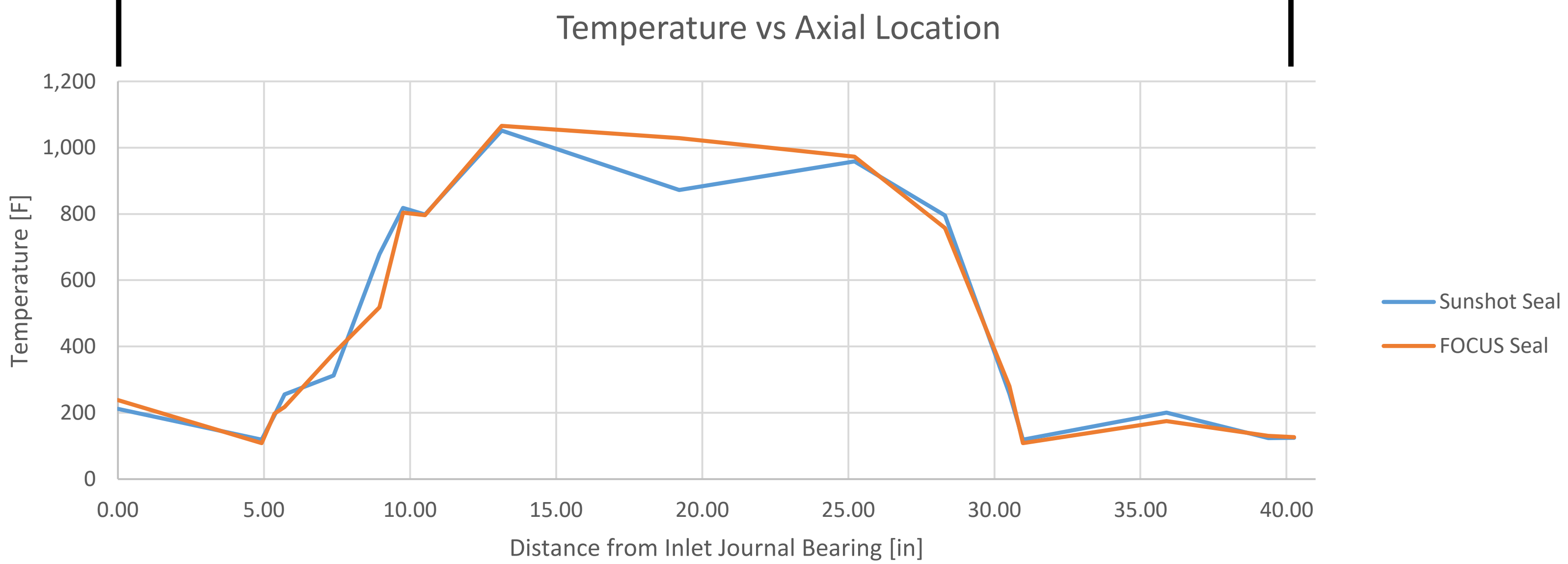
# Loop Temperatures

## 6 Hour 715C Endurance Test

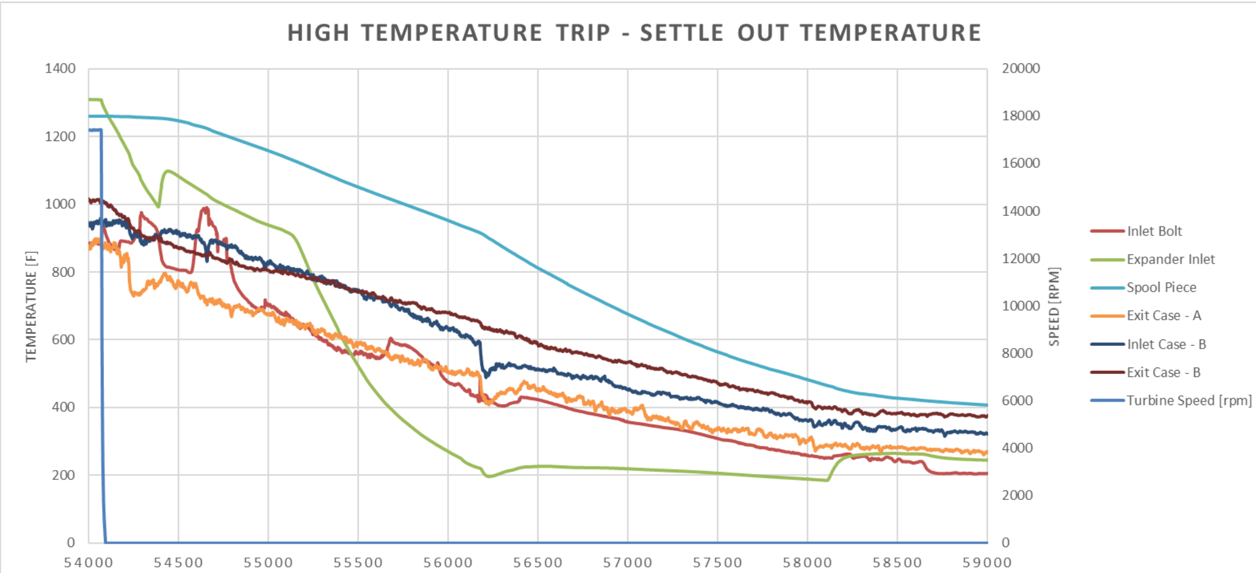


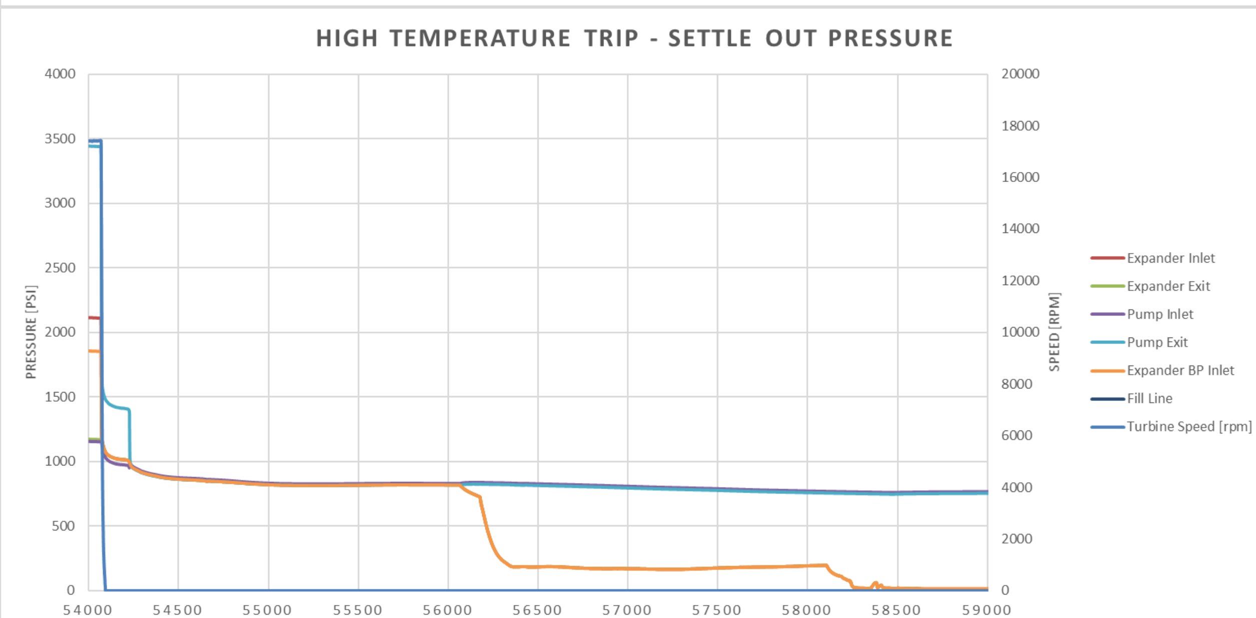
# Thermal Seal Performance





# Turbine Transients




- Two trips evaluated
  - 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
  - Dry gas seal flow still buffering turbine seals. Turned off after 30 minutes and turbine section vented

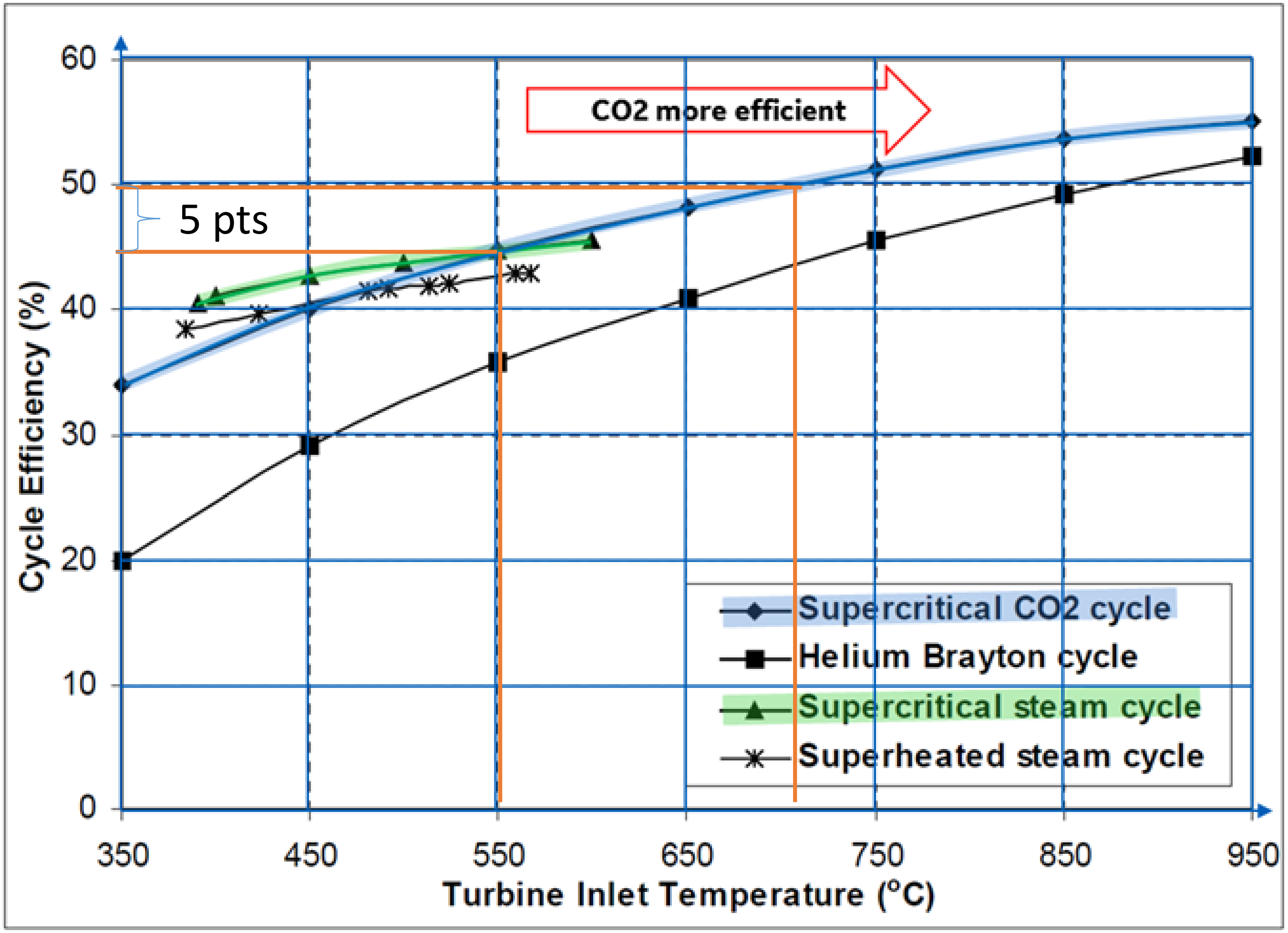
# Summary

- Turbine performance met mechanical and performance objectives.
  - Achieved design temperature of 715C, design speed of 27000 rpm, and near design pressure of 250 bar.
  - Highest temperature $SCO_2$ turbine to date.
  - 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 balance and low thrust bearing temperature
  - Radial bearing temperatures low following modification
  - Many shutdown transients tolerated
    - Some leakage experienced out case joints due to loss of bolt preload
    - Being addressed with single piece case design with STEP
  - Modified dry gas seal panel maintained warm seal gas preventing dry ice formation

# Challenges with 700C Plant Design

- 700C yields greater efficiency than 550C but requires advanced nickel alloys for the hot section
- Material strength is creep limited above 600C
- Piping Materials
  - 316 stainless ($8/lb) (up to 600C)
  - 347 stainless ($9/lb) (up to 600C)
  - P91 (9 % chromium, 1 % molybdenum) ($6/lb) (up to 450C due to spalling at higher temperatures)
  - IN625 ($45-60/lb 8" and up) (up to 650C) (age hardening occurs above 650C)
  - IN740H ($36/lb 8-10" from Special Metals) (up to 800C)
- Forging and bar stock costs:
  - IN 718 ($36/lb)
  - Waspalloy ($40/lb)
  - Nimonic 105 ($47/lb)
  - Haynes 282 ($19) (bar)
  - IN740H ($22/lb) (bar)
- Inconel 740H primary heater and interconnecting piping required to avoid age hardening of IN625 above 650C.

# RCBC Cycle Efficiency vs. Turbine Inlet Temperature




Dostal, MIT-ANP-TR-100, March 2004

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