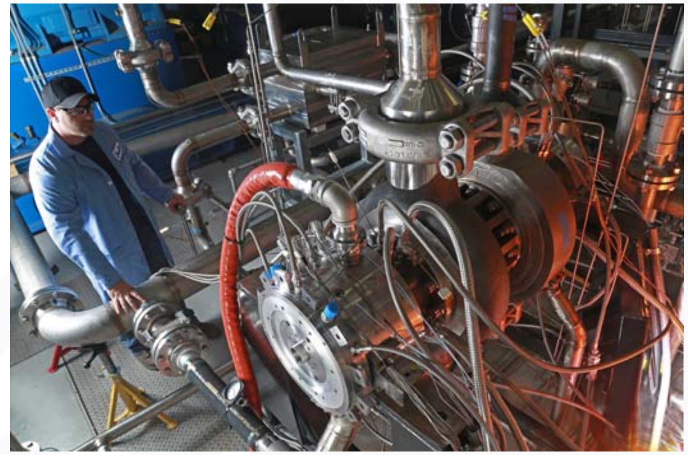
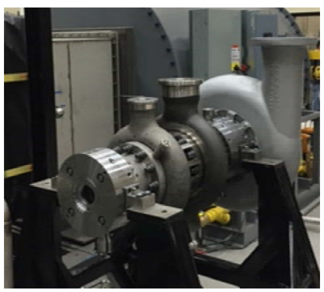
SunShot
U.S. Department of Energy





Commissioning of a 1 MWe Supercritical CO_2 Test Loop

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energy.gov/sunshot

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

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Team: SwRI, GE, KAPL, and Thar Energy

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

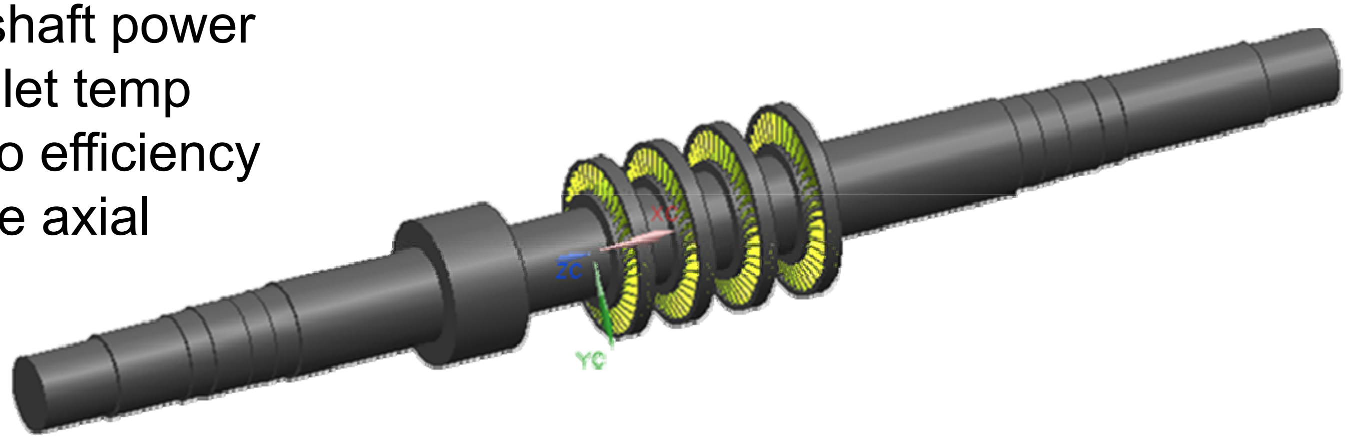
Schedule: Expander, recuperator, and test loop design complete

System targets:

- 10 MWe net module size
- 50% net thermal efficiency

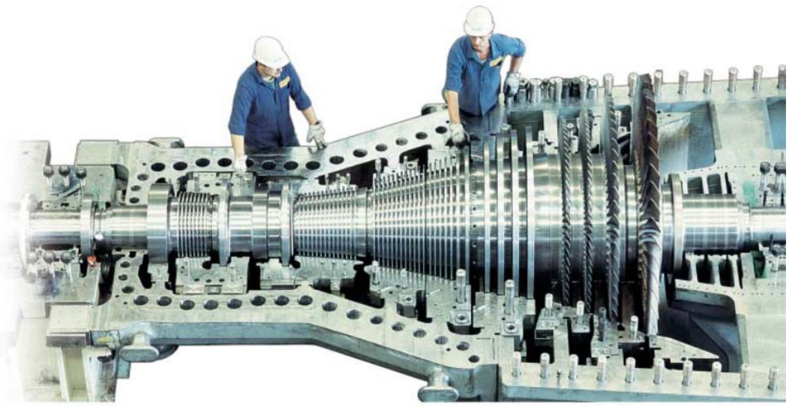
Expander targets:

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

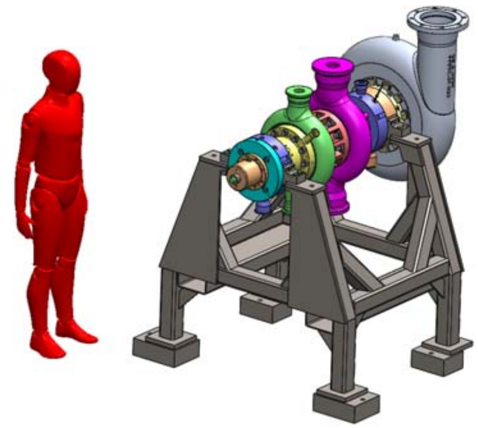


Motivation for sCO_2 Cycles over Steam

20 MW steam turbine

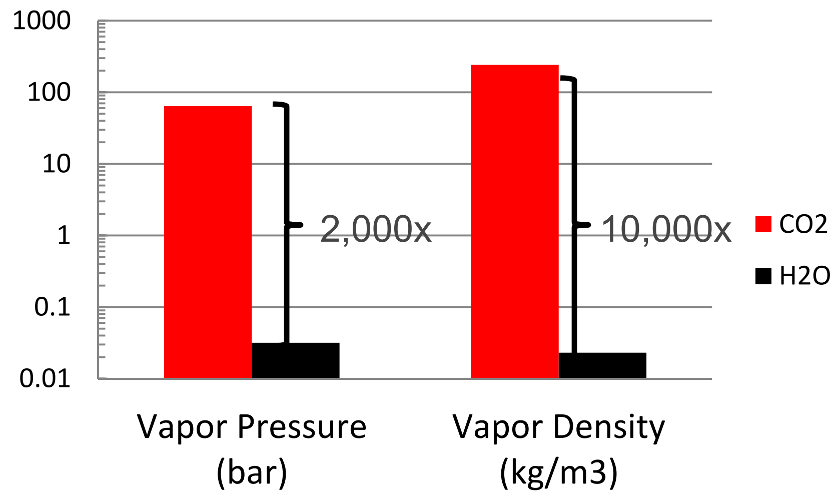


14 MW sCO_2 turbine

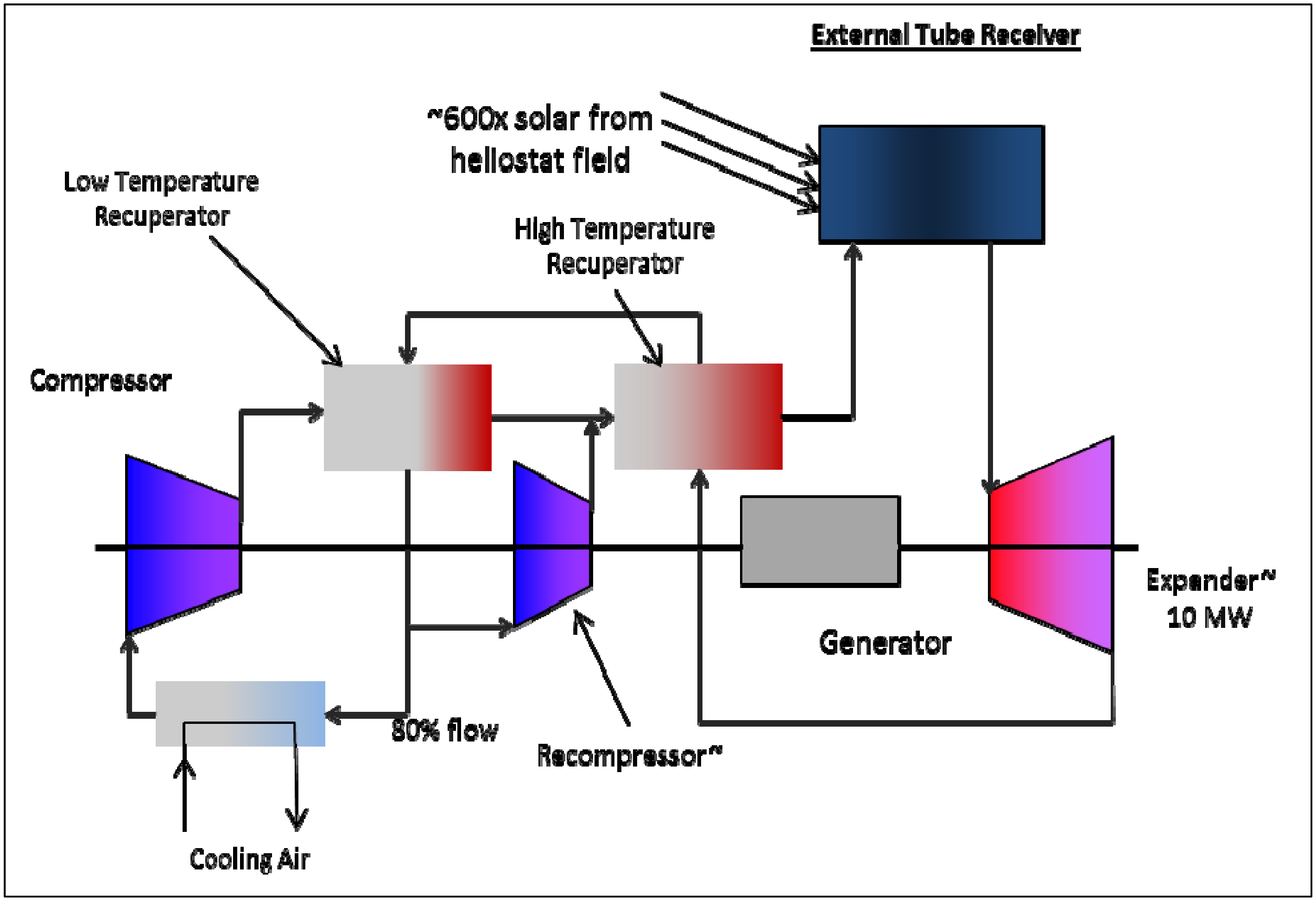


150 lb rotor
7” rotor tip diameter
27,000 rpm

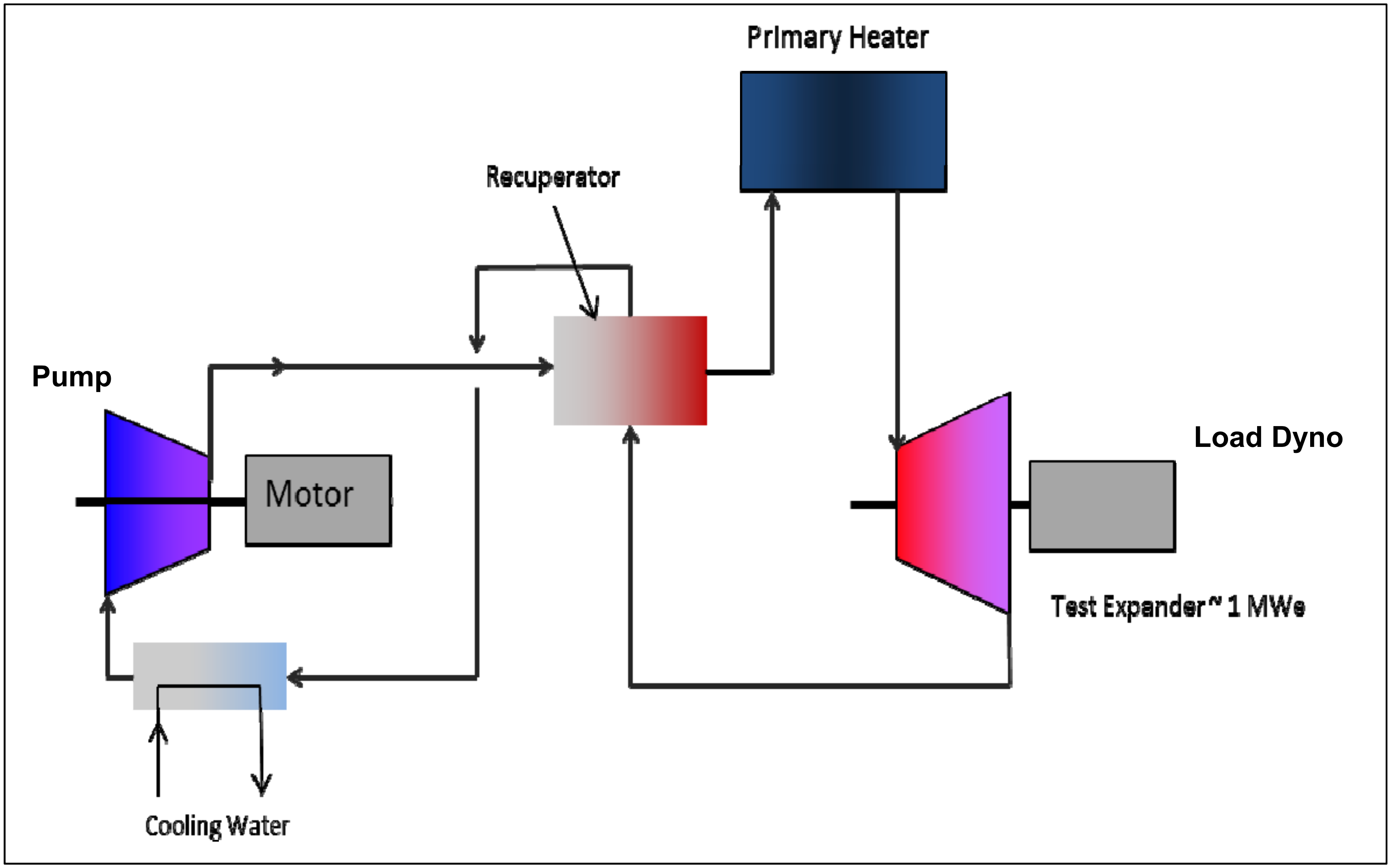
Vapor properties at 25°C (77°F) condenser



Recompression sCO_2 Cycle



Simple sCO_2 Recuperated Cycle for Test Loop



Loop Operating Conditions

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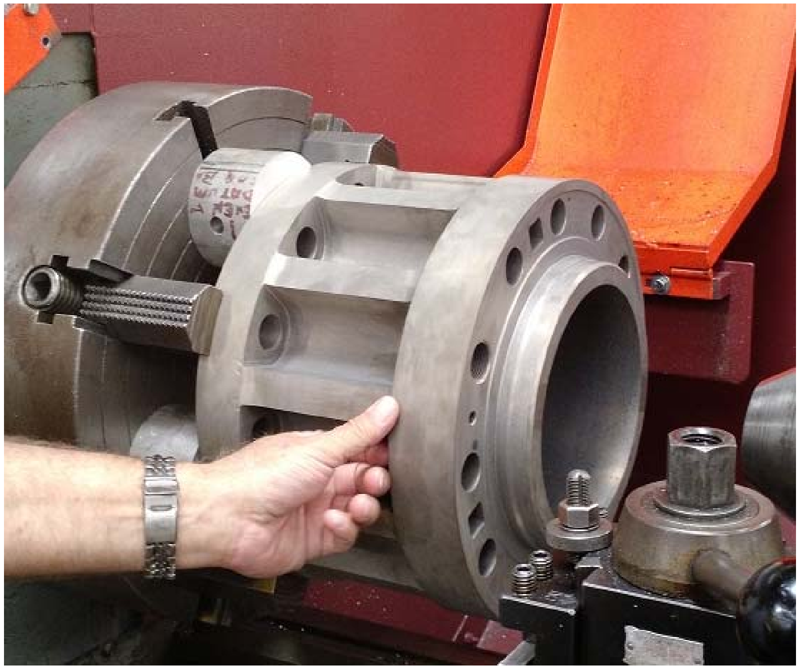
Component	T out, °C (°F)	P out, bar (psi)	Flow, kg/s (lb/s)
Pump	29.22 (84.60)	255.0 (3698)	9.910 (21.85)
Recuperator-Heat	470.0 (878.0)	252.3 (3659)	8.410 (18.54)
Heater	715.0 (1319)	250.9 (3639)	
Expander	685.7 (1266)	86 (1247)	
Recuperator-Cool	79.58 (175.2)	84 (1218)	9.910 (21.85)
PreCooler	10.00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

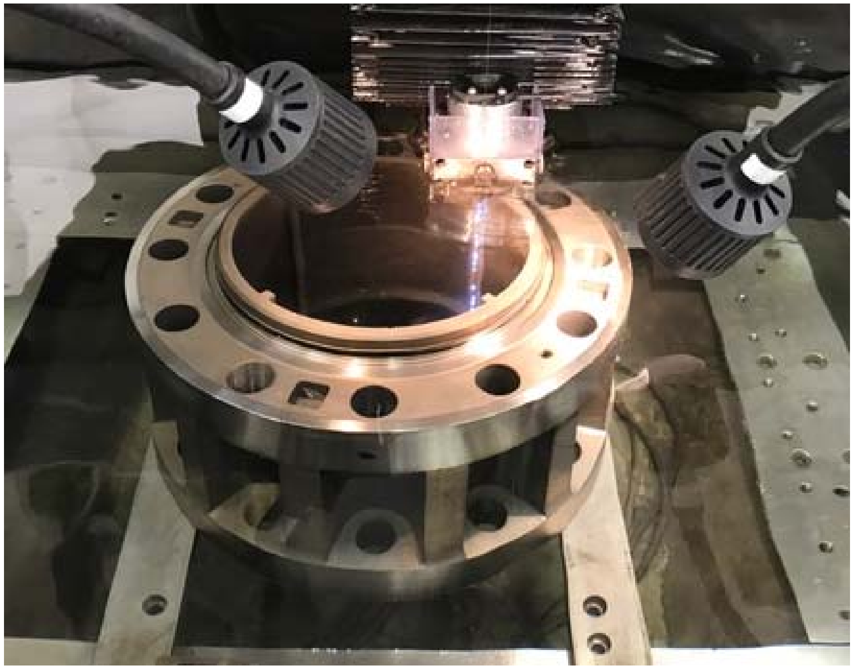
Project Schedule

- Work has been divided into three phases that emulate development process from TRL3 to TRL6
- **Phase I –** Turbomachinery, heat exchanger, and flow loop design (24 months)
- **Phase II –** Component fabrication and test loop commissioning (33 months)
- **Phase III –** Performance and endurance testing (6 months)

Nozzle Casing – Rough Machine

- Machining, welding, and heat treat complete





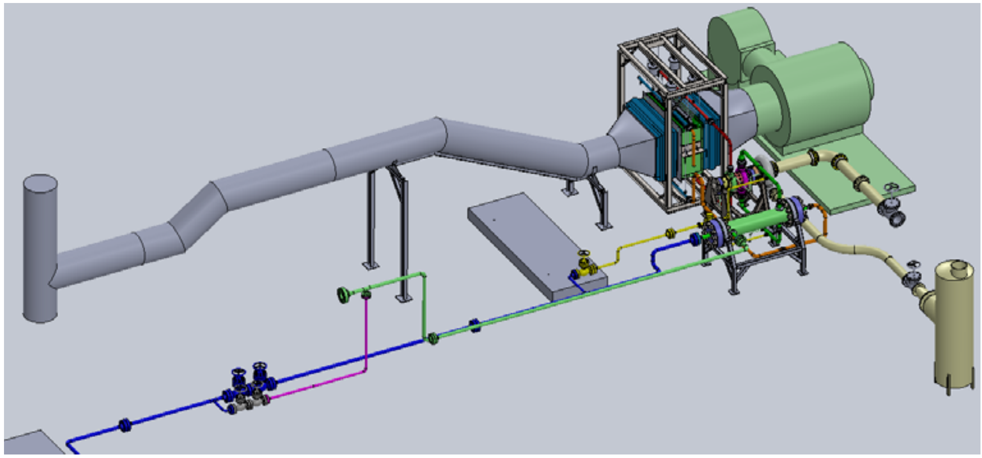
Turbine Inlet - Welding and Heat Treat Complete

- Welding and heat treat completed
- Final machining completed

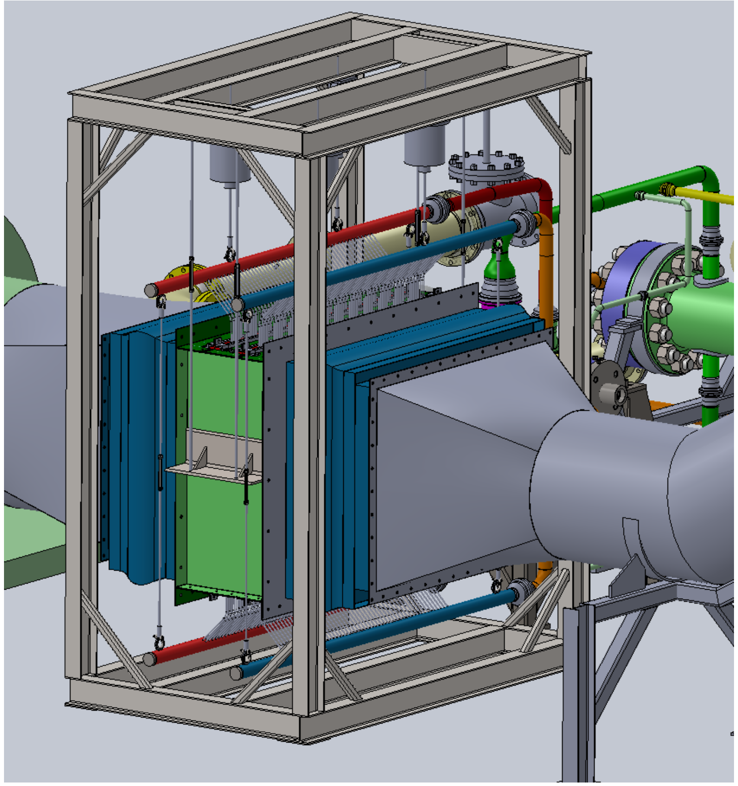
Turbine Key Achievements

- Largest scale, highest temperature SCO2 expander developed to date
- Employs industrial bearings and seals which can be scaled to utility scale
- One-piece rotor manufacturing developed to eliminate blade to rotor attachment
- Shrouded blades maintain highest efficiency
- Rotordynamic design to accommodate high density gas and high speed
- Casting issues overcome with a fabricated case design

Task 2.3: Test Loop Hardware Acquisition and Installation



Overview of Burner/Blower, Heat Exchanger, and Exhaust Ducting in Relationship to the SunShot Turbine and Recuperator



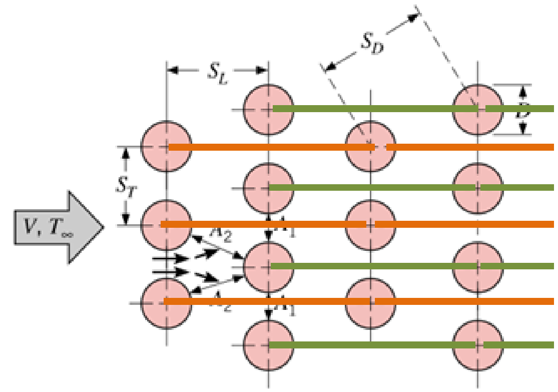
Close-up of the Heat Exchanger with the Associated Support Structure, Spring Can Supports, Expansion Joints, etc.

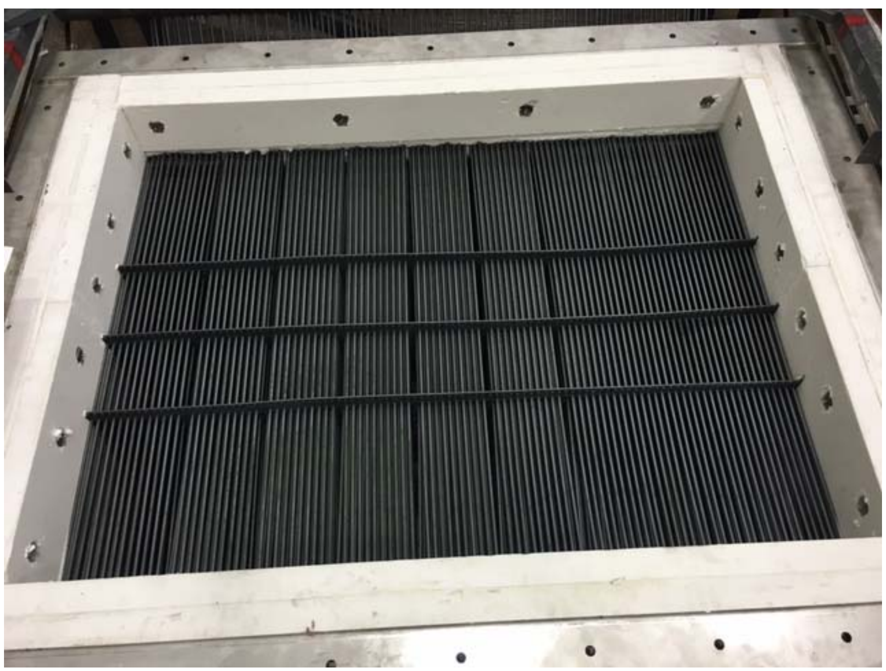
40 MMBtu/hr (11.7 MW) Heater

	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

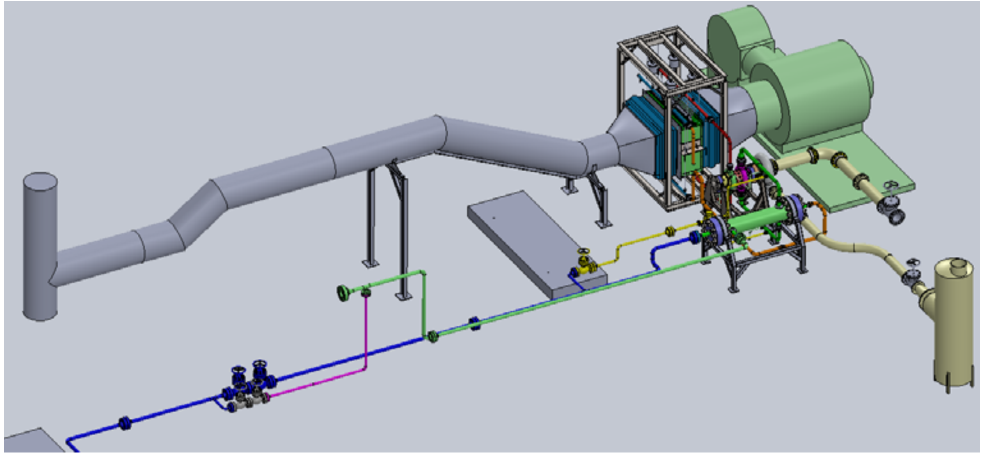
Heater HX

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





Primary Heater



Overview of Burner/Blower, Heat Exchanger, and Exhaust Ducting in Relationship to the SunShot Turbine and Recuperator

Heat Exchanger with the Associated Support Structure, Spring Can Supports, Expansion Joints, etc.

Dayco Heater

Heater exhaust system installed.

Firing of Gas Heater

- Heater was test fired to 1000F
- Heater temperature control system tuned

Thar Recuperator Development

- Milestone: Delivery of 5-MWt compact recuperator and performance qualification testing to demonstrate that performance specifications are met.
- Completion Target Metrics:
  - Test unit size 50-kW scale up 100:1 for Phase 3.
  - Capacity (% of design) = Design goal is minimum of 80% of 35 MW/m^3 (i.e., 27 MW/m^3).
  - Pressure drop (% of design) < 1.5 times of bench-scale performance
  - Cost (% of design) < Goal is not more than 1.5 times \$50/kW (i.e., no more than \$75/kW)

ThárEnergy

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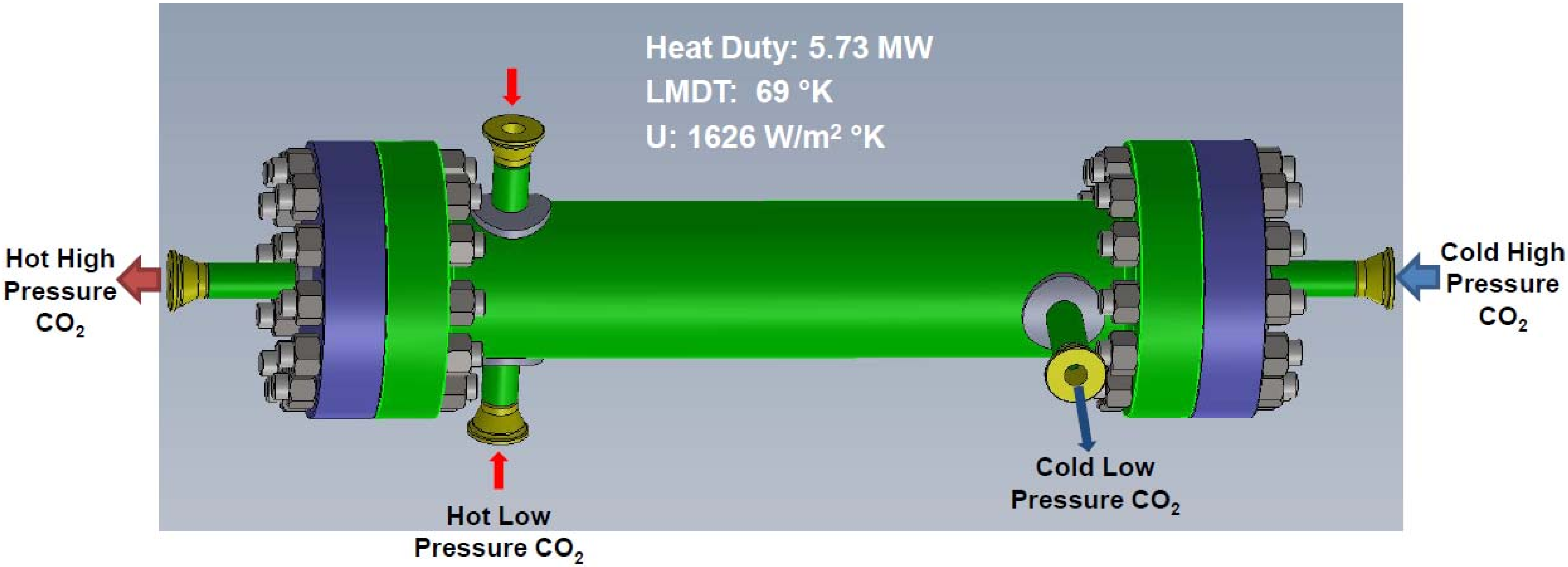
Recuperator HX Operating Conditions



Low Pressure CO_2 (Hour-Glass)

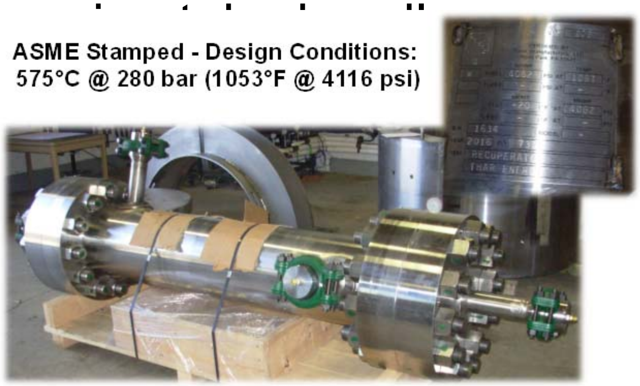
- **9.910 kg/s**
- **T_{IN} = 567°C (1053°F)**
- **T_{OUT} = 80°C (175°F)**
- **P_{IN} = 86 Bar (1247 psi)**
- **ΔP = 1.4 Bar (20.3 psi)**

High Pressure CO_2 (Tubes)

- **8.347 kg/s**
- **T_{IN} = 29°C (85°F)**
- **T_{OUT} = 470°C (878°F)**
- **P_{IN} = 255 Bar (3698 psi)**
- **ΔP = 1.4 Bar (20.3 psi)**

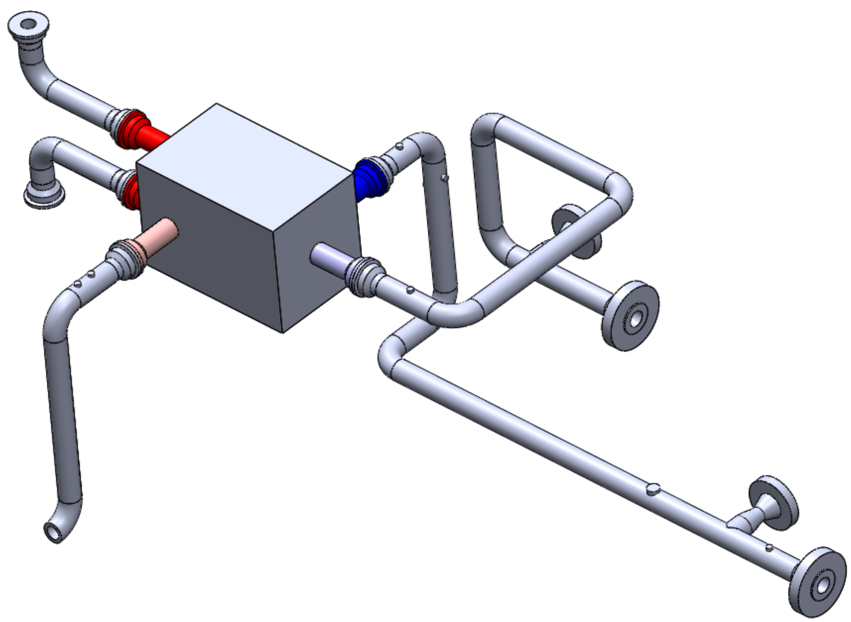
Thar Recuperator Development

- The delta pressure across the HX was designed to meet the milestone of being less than 1.5 times the bench-scale performance.
- The capacity of the 20,000 micro-tube tube bundle is calculated at 89 MW/m^3, exceeding the design goal of 35 MW/m^3.
- The pressure vessel fabrication and tube bundle was completed and passed the hydro test and received an ASME stamp.
- QA/QC of the tube bundle indicated that there was to be a delay in the delivery of the recuperator. This lead to a decision point to install a backup recuperator that had been ordered. Thar continues reviewing all stages in micro-tube recuperator fabrication in light of lessons learned from the fabrication of the first generation SunShot



Recuperator Contingency Plan

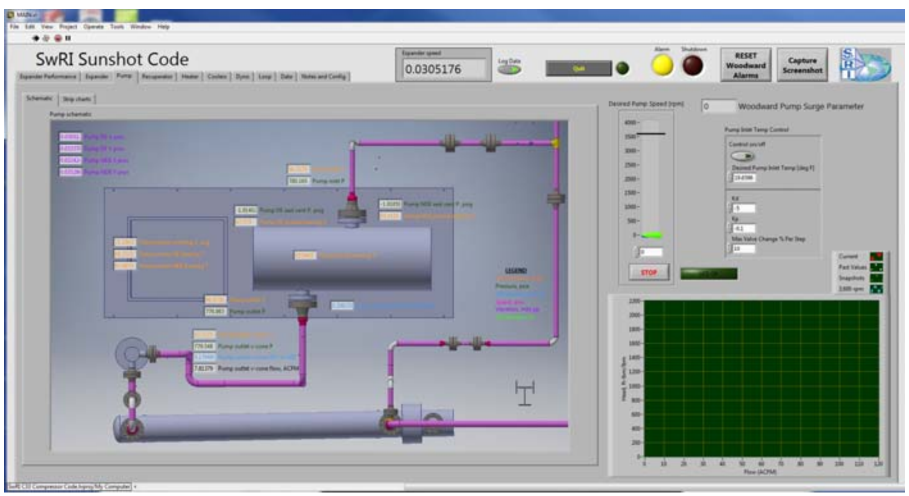
- Issued PO to Vacuum Process Engineering (VPE) for Alternative Recuperator
- Printed Circuit Heat Exchanger (PCHE)
- Delivered in April, 2017
- Required piping rework



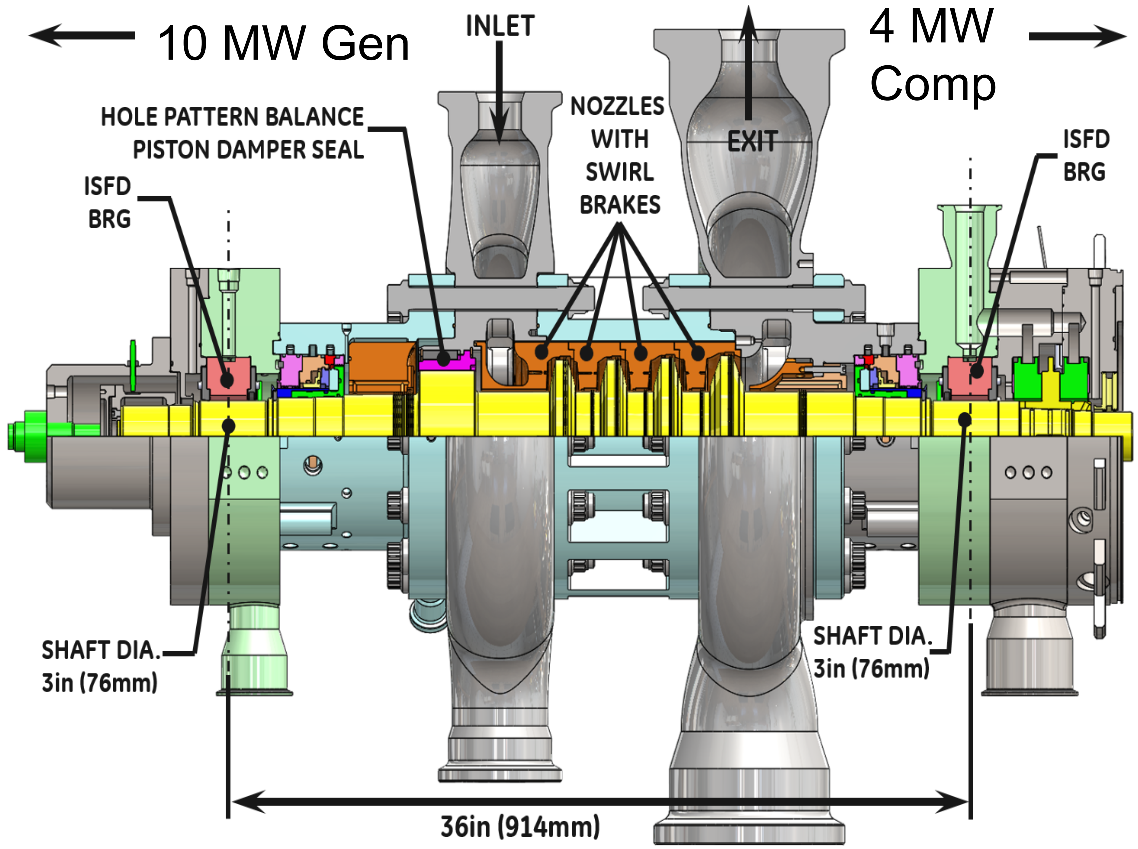
VPE Recuperator on Stand

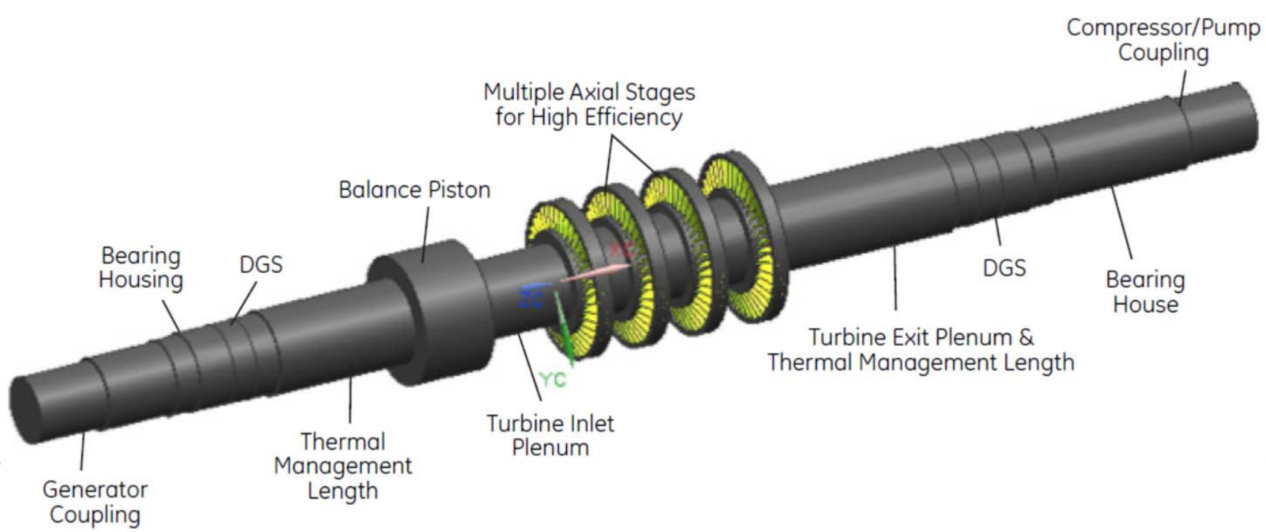
Pump Commissioning Test

- Loop pressure checked
- Pump commissioning complete
- Pump spun at low speed



Final Turbine Design





Turbine Assembly

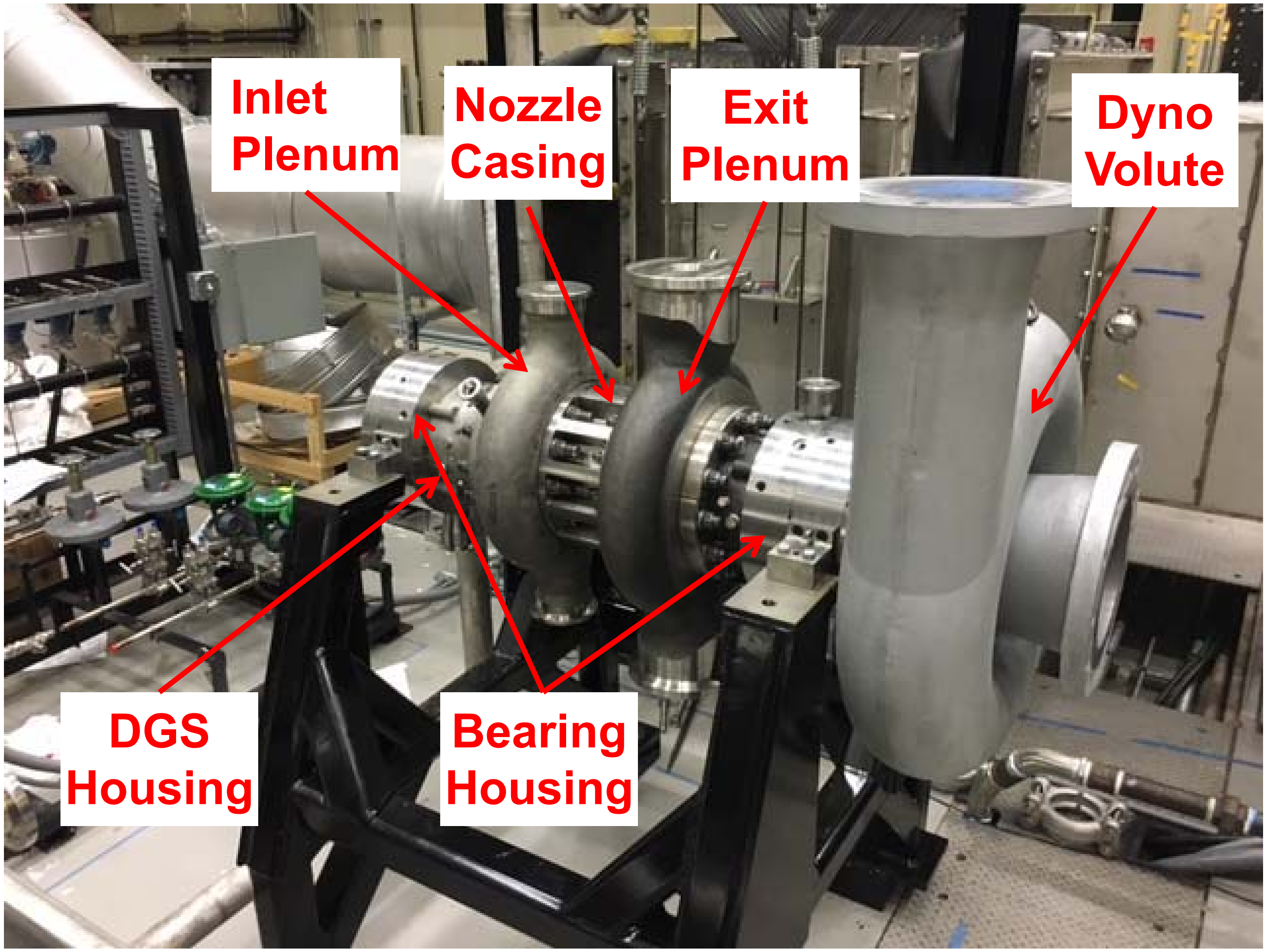
- Assembly completed with no major issues
- All fits and seal clearances verified
- Rotor runout met specifications
- Axial end-play adjusted with shim packs
- Radial bearing clearances verified
- Thermal seal instrumentation added

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
- Dynamometer not installed for initial commissioning tests

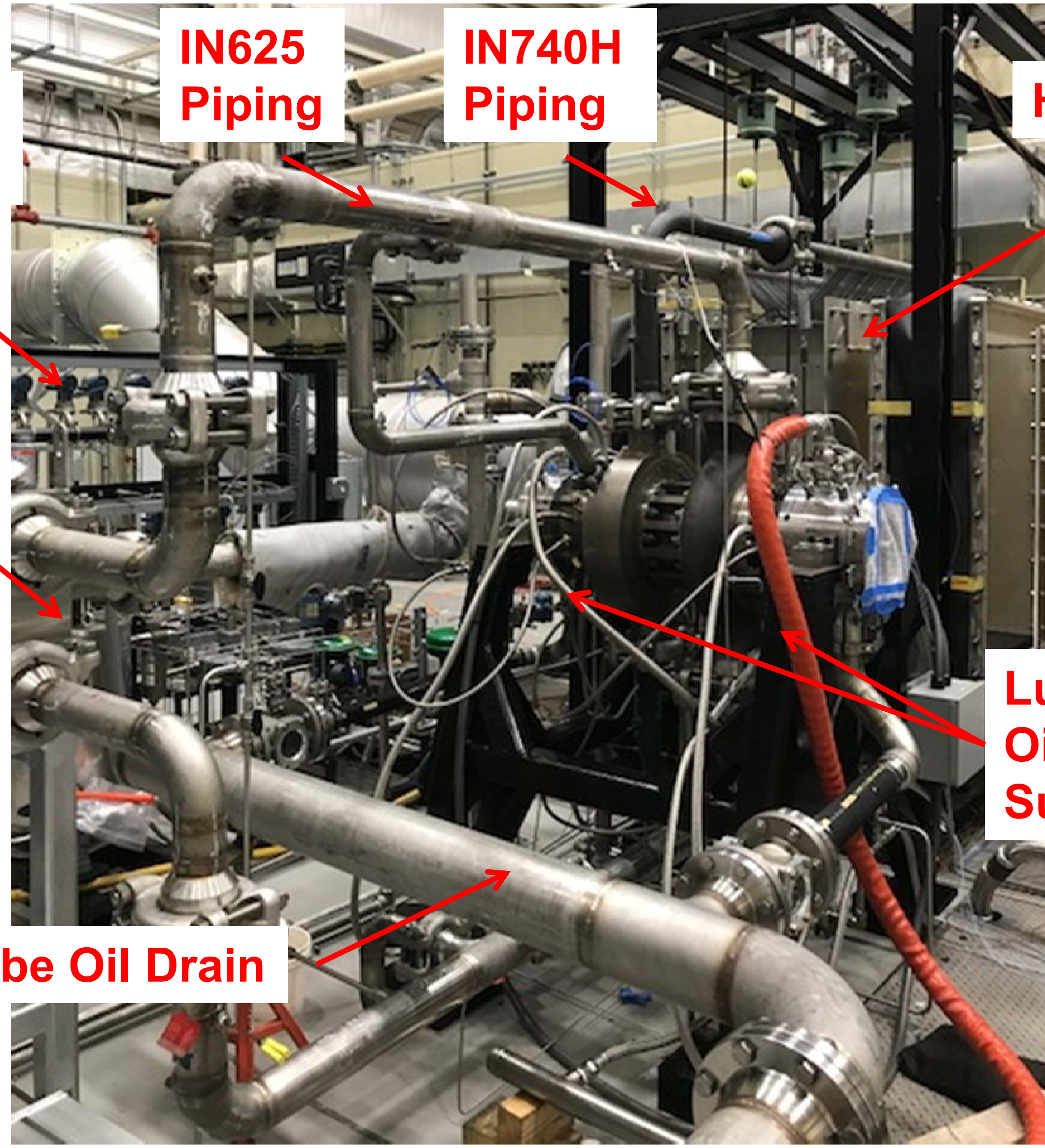
Task 2.2: Turbo-Machinery Fabrication

Turbine Case Assembly

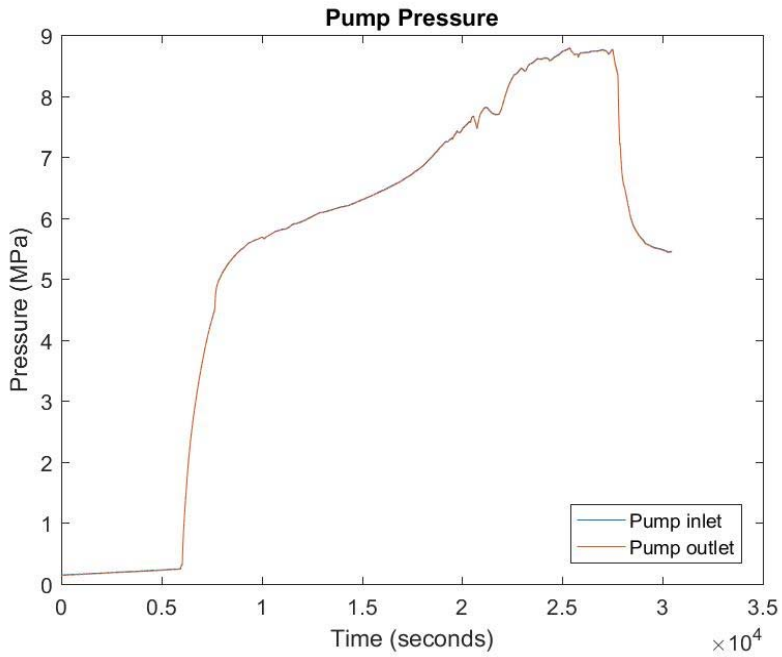


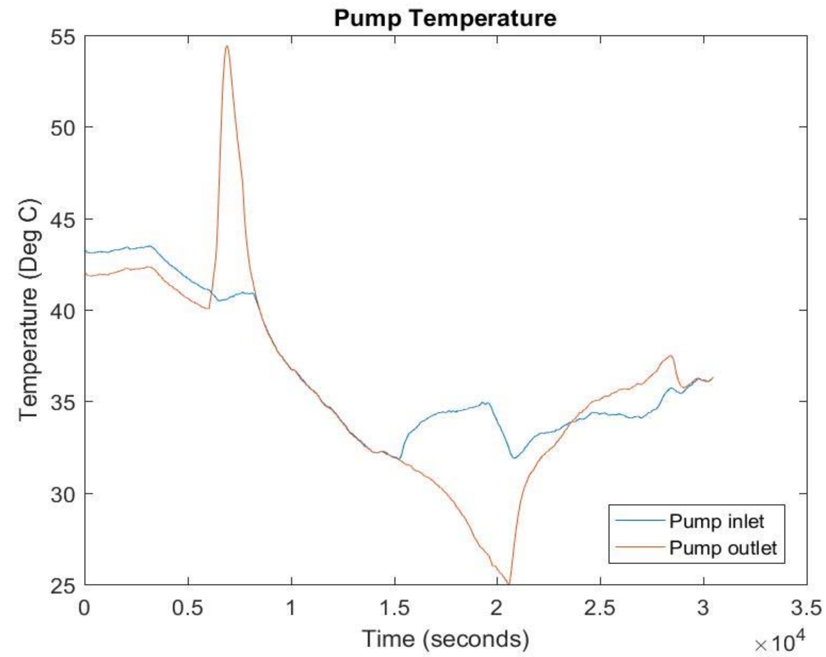
10 MW Frame Size SCO2 Turbine

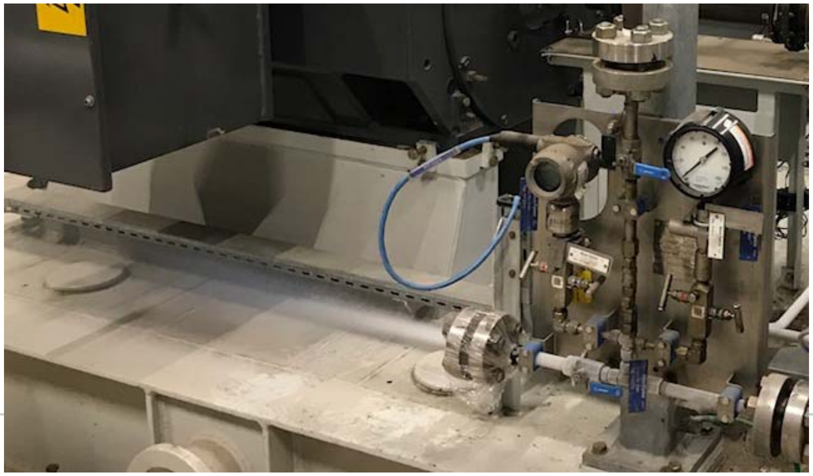
Test Loop Components



Loop Pressurization







Commissioning Procedure

#	Test Name	Test Description	Dyno	Heater	Speed	TIT	TEP	Exit Criteria
S1	Slow roll, init. seal break-in, and rotordyn. instrum. check	Spin turbine up to 2,000 rpm and immediately shut down. Confirm that tachometer was triggering and proximity probes were functioning properly. Repeat spin up and shut down procedure with increasing target speeds in approximately 1,000-2,000 rpm increments up to 5,000 rpm. This will allow abradable seals to safely cut-in during transients in case there is rubbing.	Impeller removed.	Off	5,000 rpm	47°C (or max pump discharge)	80 bar	Observe all rotordynamics instrumentation functioning properly.
S2	ESD and overspeed trip check	Spin turbine up to 5,000 rpm and activate the ESD switch to confirm its function. Set overspeed trip value to 4,000 rpm. Attempt to spin turbine up to 5,000 rpm and confirm that the overspeed trip functions properly.	Impeller removed.	Off	5,000 rpm	47°C (or max pump discharge)	80 bar	Observe ESD and overspeed trip sequences are functioning properly.
S3	Seal break-in, trim balance	Spin turbine up to target speed and immediately shut down. This will allow abradable seals to safely cut-in during transients in case there is rubbing. Execute trim balancing as necessary to reduce vibration levels below limit. Increase target speed from 5,000 rpm in approximately 1,000-3,000 rpm increments up to 18,000 rpm. Capture coast down Bode plot from maximum speed.	Impeller removed.	Off	18,000 rpm	47°C (or max pump discharge)	80 bar	Observe normal vibration within amplitude limits and without signs of rubbing across speed range. Confirm bearing and SFD performance. Confirm rotordynamics model prediction of unbalance response *without dyno impeller*; tune model if necessary.
S4	Cold test, limited speed	Operate up to 21,000 rpm. Achieve steady state conditions. Capture coast down Bode plot from maximum speed.	Impeller removed.	Off	21,000 rpm	47°C (or max pump discharge)	80 bar	Successfully operate at 1 steady-state condition.
S5	Dyno impeller break-in	Spin turbine up to target speed and immediately shut down. Execute trim balancing as necessary to reduce vibration levels below limit. Increase target speed in approximately 1,000-3,000 rpm increments up to maximum speed (power-limited without heating turbine flow). Capture coast down Bode plot from maximum speed.	Impeller attached; adjust flow control valves for min power (within safe operating range).	Off	12,000 rpm (or maximum power-limited speed)	47°C (or max pump discharge)	80 bar	Observe normal vibration within amplitude limits and without signs of rubbing across speed range. Confirm rotordynamics model prediction of unbalance response *with dyno impeller*; tune model if necessary.

Commissioning Procedure

S6	Warm test, limited speed	Operate up to 21,000 rpm (or maximum power-limited speed) with heater off. Fire heater to increase TIT to 150°C (rate < 5°C/min), verify thermal seal performance, and make appropriate adjustments to DGS cooling flow. Slowly increase TIT to 550°C (rate < 5°C/min), modify cooling flow as necessary. Obtain 5 steady-state operating points from min to max dyno flow; adjust TIP to maintain speed, TIT, and TEP.	Impeller attached; adjust dyno flow from min to max (or within safe operating range) for 5 steady-state points.	Fired	21,000 rpm	550°C	80 bar	Successfully operate at 5 steady-state conditions. Document transient and steady state performance for all components in the loop. Document required DGS flow rates.
S7	Warm test, full speed	*This test may be a continuation of a successful limited speed warm test without shutdown (if not, refer to previous procedures).* Increase speed to 27,000 rpm. Achieve steady state conditions. Obtain 5 steady-state operating points from min to max dyno flow; adjust TIP to maintain speed, TIT, and TEP.	Impeller attached; adjust dyno flow from min to max (or within safe operating range) for 5 steady-state points.	Fired	21,000 rpm (or maximum power-limited speed)	550°C	80 bar	Successfully operate at 5 steady-state conditions. Document transient and steady state performance for all components in the loop.
S8	Hot test, full speed	*This test may be a continuation of a successful full speed warm test without shutdown (if not, refer to previous procedures).* Slowly increase TIT to 715°C (rate < 5°C/min). Achieve steady state conditions. Obtain 5 steady-state operating points from min to max dyno flow; adjust TIP to maintain speed, TIT, and TEP.	Impeller attached; adjust dyno flow from min to max (or within safe operating range) for 5 steady-state points.	Fired	27,000 rpm	715°C	80 bar	Successfully operate at 5 steady-state conditions. Document transient and steady state performance for all components in the loop.
S9	Normal shutdown from max TIT	*This test may be a continuation of a successful full speed hot test without shutdown (if not, refer to previous procedures).* Slowly decrease TIT to 200°C (rate < 5°C/min). Turn off burner, but maintain air blower flow. Reduce speed to 5,000 rpm. After heater air exit temperature reaches 150°C, stop turbine and pump.	Impeller attached.	Fired	27,000 rpm	715°C	80 bar	Successfully shut down. Document transient performance for all components in the loop.

TIT = Turbine inlet temperature
TIP = Turbine inlet pressure
TEP = Turbine exhaust pressure
DGS = Dry gas seal
SFD = Squeeze film damper
ESD = Emergency shut down

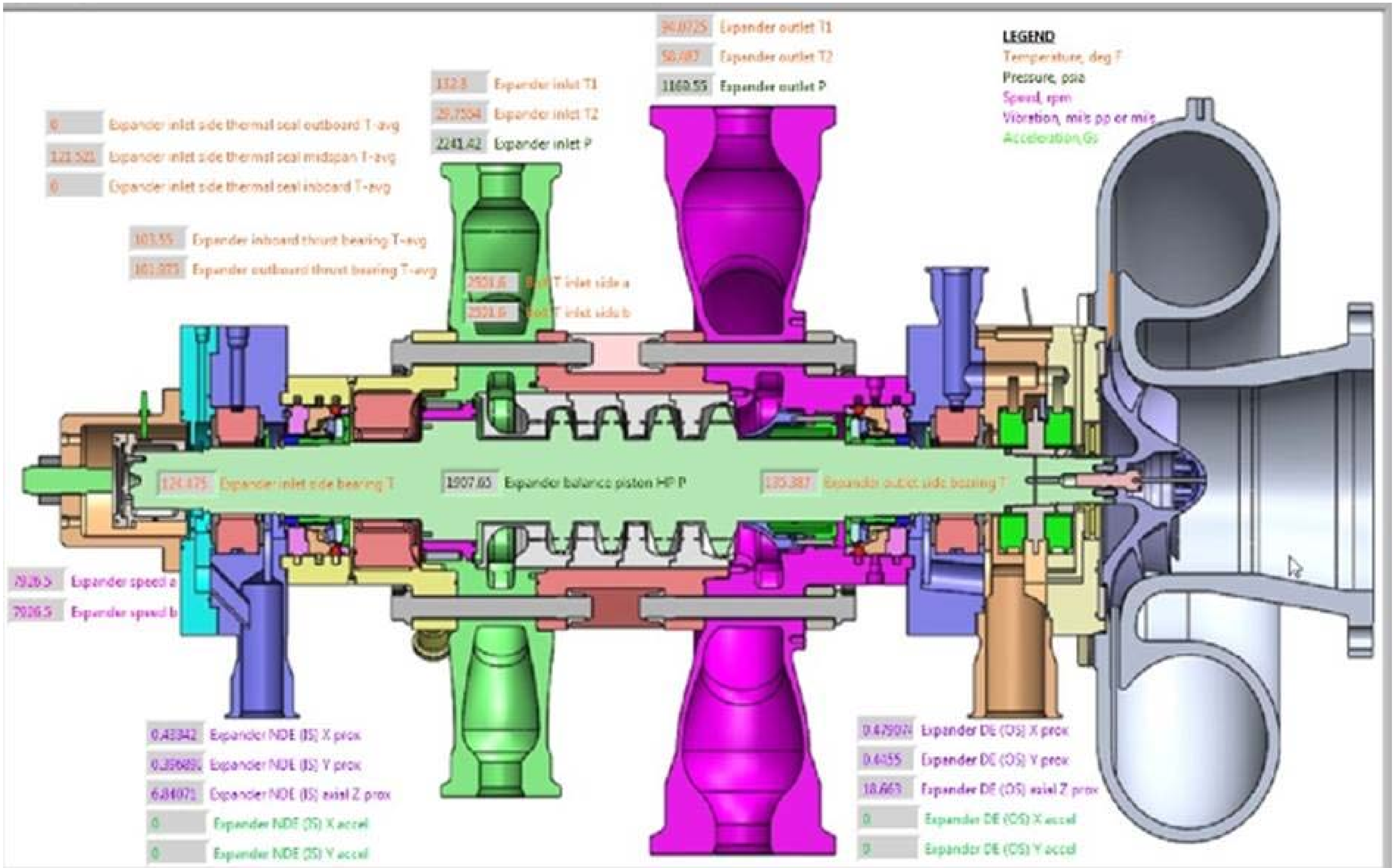
Summary of Turbine Operating Limits

Measured Quantity	Limit	Action if Limit Exceeded
Synchronous (1x) vibration factory acceptance with proximity probes	0.7 mil p-p (ISO 7919 Zone A)	Reduce speed or change load condition to try to eliminate high vibration, or shut down. Evaluate possible causes for high vibrations and correct (e.g. trim balance)
Subsynchronous (*n*x, *n*<1) vibrations measured with proximity probes	0.18 mil p-p	Reduce speed or change load condition to try to eliminate subsynchronous vibration presence, or shut down. Evaluate possible causes for subsynchronous vibrations and correct, if possible, or justify setting higher limit.
Overall vibration Amplitude measured with proximity probes	1.5	Alarm – Reduce speed or change load condition to try to eliminate high vibration, or shut down. Evaluate possible causes for high vibrations and correct, if possible, or justify setting higher limit.
	1.8 mil p-p *Note: Based on experience chart.*	Shut down – determine the cause for the high vibration and correct it or justify setting a higher limit.
Housing acceleration measured with accelerometers	0.25 in/s RMS velocity (factory acceptance).	Reduce speed or change load condition to try to reduce acceleration amplitude, or shut down. Evaluate possible causes for high acceleration amplitude and correct, if possible, or justify setting higher limit.
Oil supply temperature	130 °F	Evaluate lube oil cooler and reduce supply temperature
Oil drain temperature	50 °F above oil inlet temperature.	Shut down and determine the cause for the high oil temperature rise and correct it or justify setting a higher limit.
DGS Casing temperature	350 °F	Decrease turbine TIT or increase seal gas flow rate.
DGS pressure	1500 psi	Decrease loop pressure.
Casing temperature?	1320 °F (715°C)	Reduce burner temperature
Casing temperature rate	670°C/hr, increasing	Turn down heater temperature or flow.
	670°C/hr, decreasing	Turn up heater temperature or flow.
Heater air	1700 °F	Reduce fuel flow rate.

Summary of Loop Operating Limits

Measured Quantity	Limit	Action if Limit Exceeded
Loop low pressure limit	1600 psi (PSV set point)	Vent loop
Loop high pressure limit	3950 psi (turbine case rating)	Vent loop
Turbine inlet temperature limit	1320 °F	Reduce heater fuel flow
Turbine exhaust temperature limit	1270 °F	Reduce heater fuel flow
Carbon steel pipe temperature limit	600 °F (900# ANSI Flange Limit)	Reduce heater fuel flow
Precooler inlet temperature limit	500 °F	Reduce heater fuel flow

Turbine Commissioning



Summary of Commissioning Activities

- Turbine assembly complete and installed in loop
- Recuperator installed including piping rework
- Piping cleanout and leak test
- Dry gas seal supply commissioning
- Lube oil commissioning
- Final instrumentation installation
- Control system checks
- Turbine was first spun Dec. 21, 2017
  - Break-in complete
  - Speed increased to 13,000 rpm traversing first critical speed
  - Vibrations very low (<0.25 mils p-p)
- Testing has continued through March, 2018.
- To date, turbine inlet conditions of 550C, 200 bar at 24,000 rpm have been achieved.

Discussion

Questions???