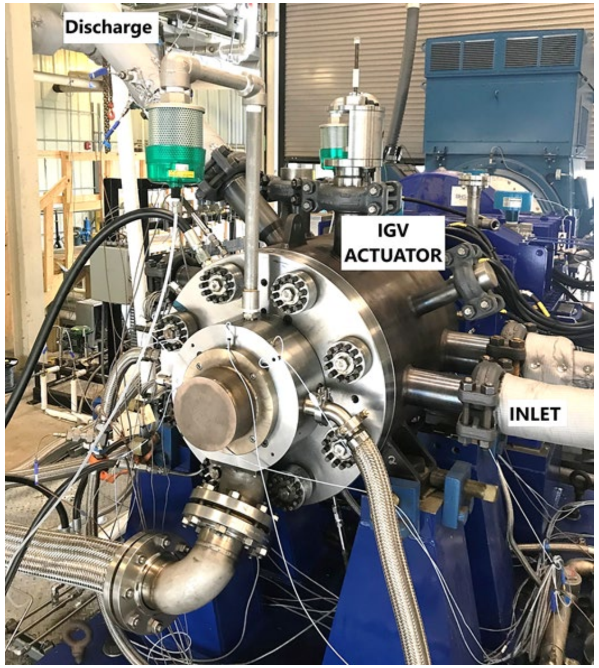
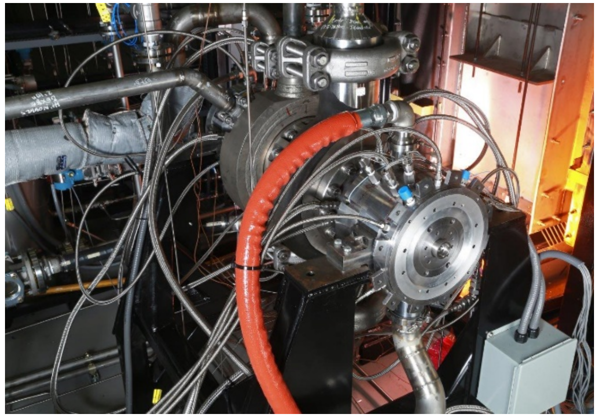
# Development of $sCO_2$ Turbomachinery and its Application to Energy Storage




Jeff Moore, Ph.D.

**Southwest Research Institute**


Thermal-Mechanical-Chemical-Energy-Storage Workshop

August 10-11, 2021

San Antonio, TX

# Introduction

- Energy storage technologies are rapidly developing in response to increasingly large fluctuations in power demand and availability from intermittent resources including renewables
- New cycles require custom turbomachinery designs
- $SCO_2$ power cycles are being developed for both indirect and direct fired configurations
- $SCO_2$ cycles being considered for energy storage
- This presentation focuses on development of SCO2 turbomachinery to meet these challenging requirements

# Thermochemical ES: $CO_2$ Phase Change

- **Combined with Thermal ES, which uses excess solar energy and stores in molten salt.**
- **Excess energy from the grid is used to cool liquid $CO_2$ to solid (dry ice)**
- **Release heat from salt to expand $CO_2$ from solid to supercritical fluid**
- Turbomachinery Integration
    - Turbine development for high-temperature, high-pressure $CO_2$
- Current TRL: 2-3
    - Component tests
- Technology Gaps
- Expected Performance
    - 68% efficiency
- R&D Activities
    - GE GRC through the ARPA-E FOCUS program
    - Echogen Power Systems with ARPA-E DAYS

E Q

**Charge**
Energy to cool liquid
$CO_2$ to solid
Heat into molten salt

**Store**
$CO_2$ as solid (dry ice)
Heat in molten salt

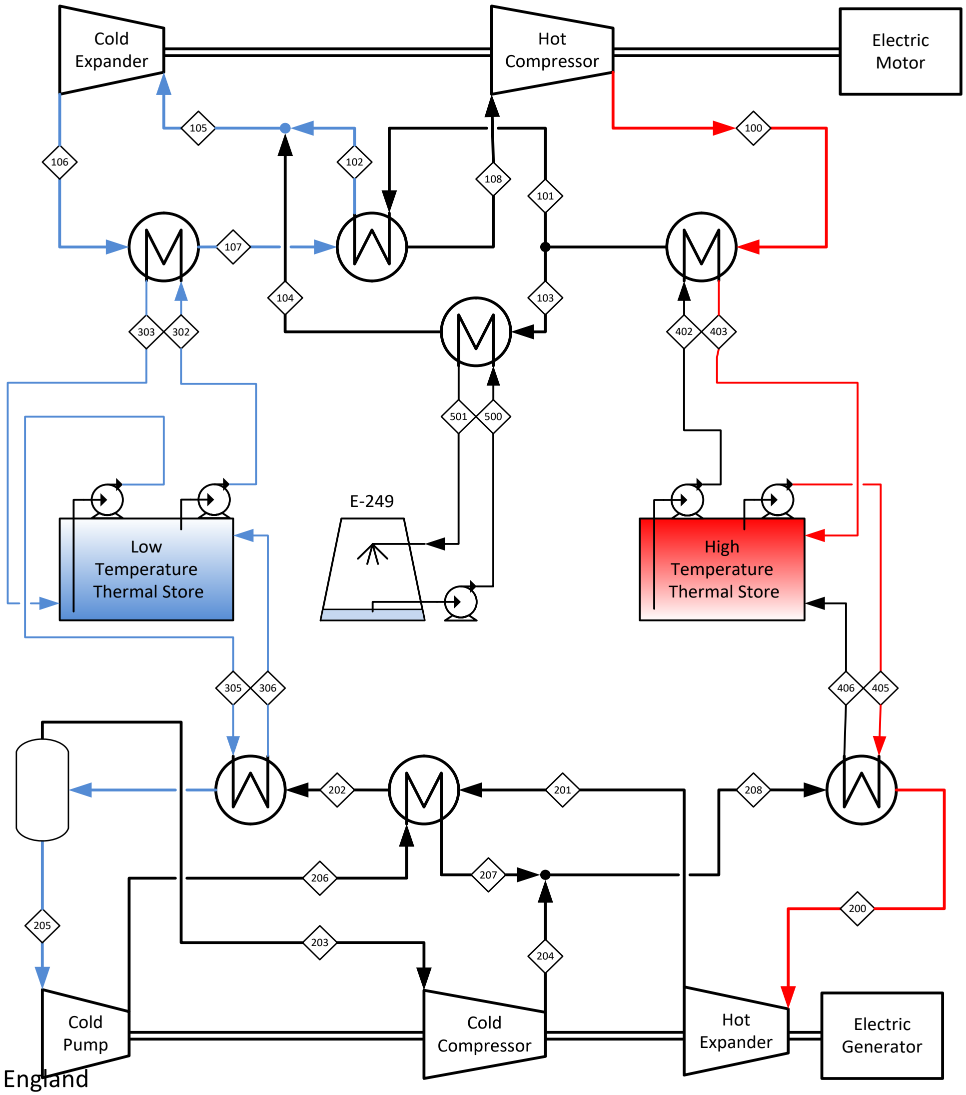
**Discharge**
Use heat from salt to change
solid $CO_2$ into $sCO_2$
Expand $sCO_2$ across turbine

GE GRC

# Trans-critical CO2 cycle

- Permits water ice cold storage, modest hot storage temperature (580°C)
- Competitive with ideal gas cycles at higher pressures

| Parameter | Unit | Ideal gas cycle | Transcritical $CO_2$ Alt 1 | Transcritical $CO_2$ Alt 2 |
|---|---|---|---|---|
| Round Trip Efficiency | % | 57.86 | 51.54 | 61.24 |
| Heat Pump COP | – | 1.31 | 1.78 | 1.34 |
| Engine Efficiency | – | 0.44 | 0.29 | 0.46 |
| Charging Pr | – | 3.82 | 7.63 | 14.23 |
| Discharging Pr | – | 5.17 | 6.78 | 15.11 |
| Cycle Max Temperature | °F | 1050.0 | 610.0 | 1049.0 |
| Cycle Min Temperature | °F | −73.6 | 23.0 | 23.0 |
| Cycle Max Pressure | psia | 500.0 | 3905.0 | 8702.3 |

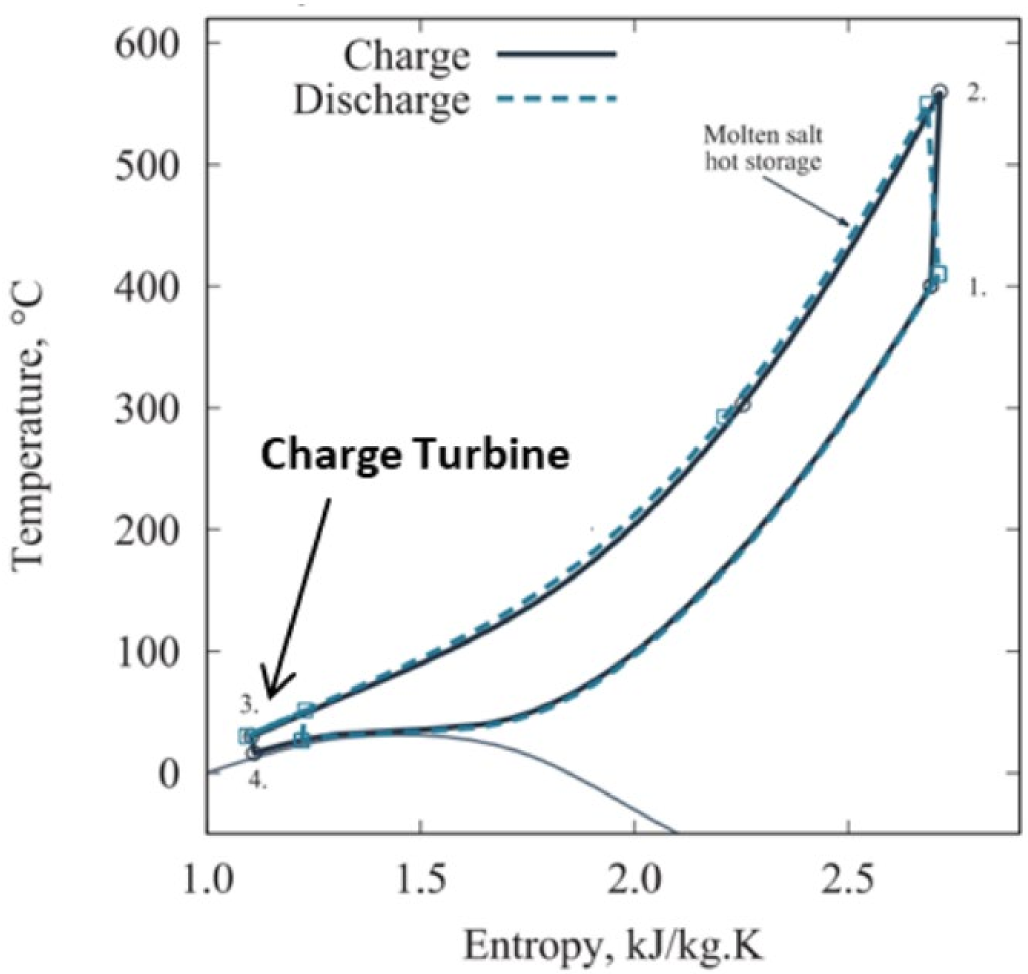



Ref: Brun, K., Allison, T., Dennis, R., 2021, ***Thermal, Mechanical, and Hybrid Chemical Energy Storage Systems***, Elsevier Academic Press, London, England
Contribution by Jason Kerth, Siemens Energy

Process schematic, Transcritical-CO2 cycle

# Echogen Hybrid PTES

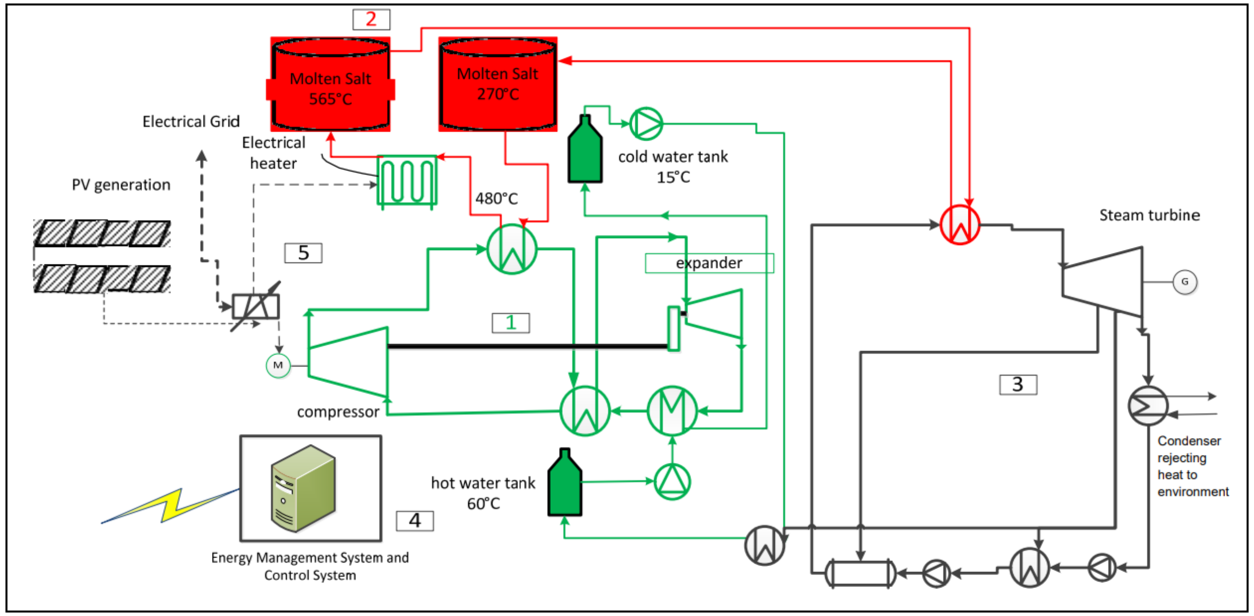
- PTES runs as a heat pump using heat of compression
  - Molten salt thermal storage
- Condensing SCO2 Charge Cycle for cold storage
  - Research proposed to understand effects of multi-phase flow on turbine reliability
  - Will utilize SCO2 pump loop at SwRI to test condensing turbine
- SwRI and Flowserve supporting development




[1] McTigue, Farres-Antunez, Ellingwood, Neises, White, 2020, "Pumped thermal electricity storage with supercritical CO2 cycles and solar heat input," AIP Conference Proceedings 2303, 190024.

# GE SCO2/Steam Pumped Heat Cycle

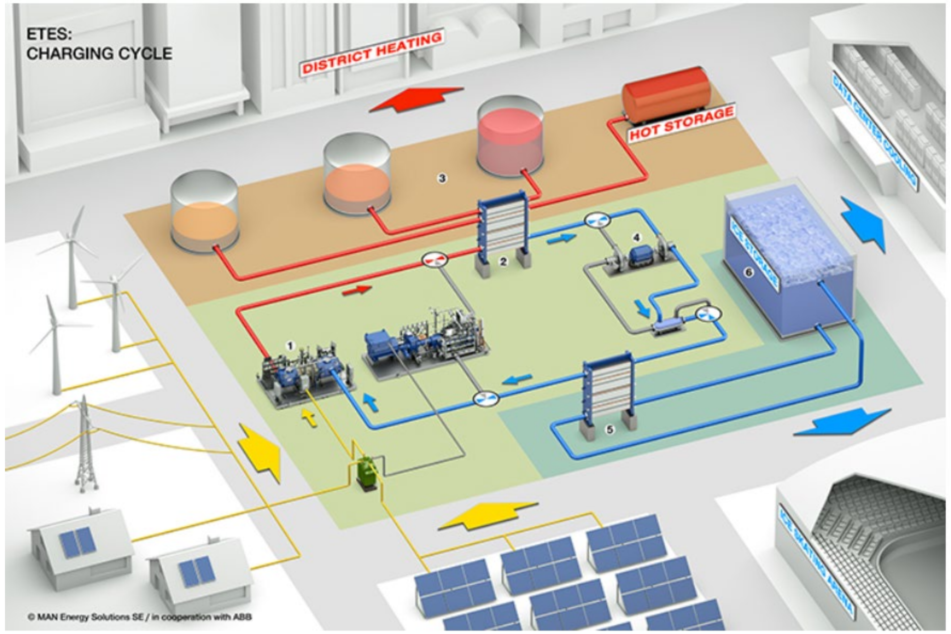
- SCO2 heat pump with molten salt thermal storage for charge cycle up to 480°C (current SCO2 compressor limit)
- Electric resistive heating used to heat to 565°C
- Discharge cycle using standard water steam cycle.
- Cold storage as water
- Leverages existing equipment as much as possible




Aga, V., Conte, E., Carroni, R., Burcker, B., Ramond, M., 2016, "Supercritical CO2-Based Heat Pump Cycle for Electrical Energy Storage for Utility Scale Dispatchable Renewable Energy Power Plants," 5th International Symposium - Supercritical CO2 Power Cycles March 28-31, 2016, San Antonio, Texas

# MAN/ABB Electro-Thermal Energy Storage (ETES)

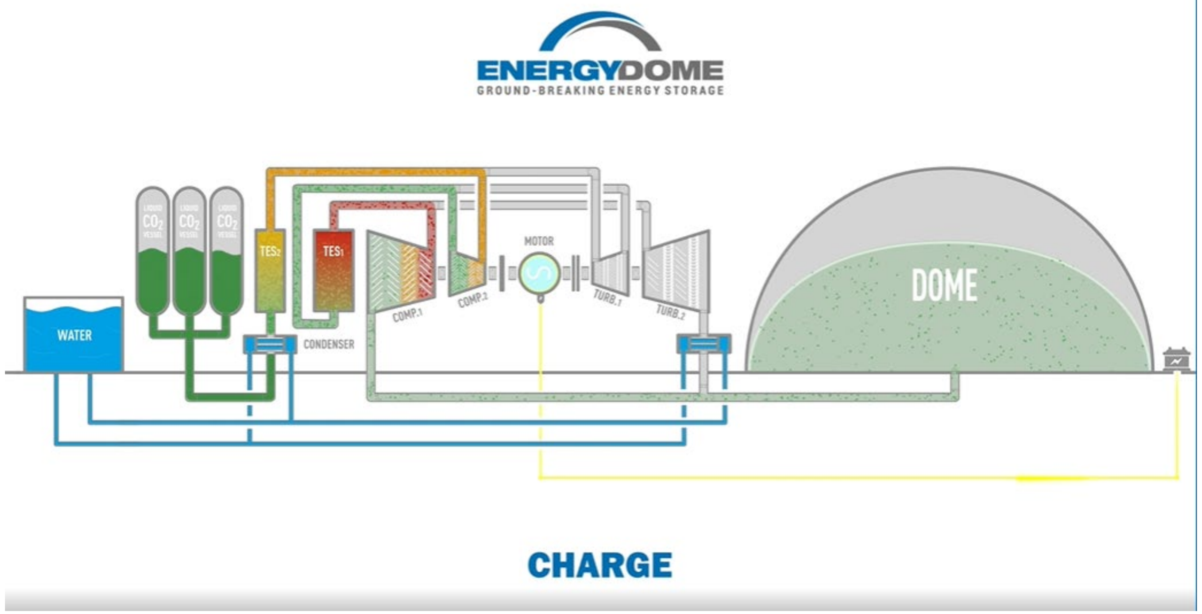
- Provides electricity, heating, and cooling on demand for variety of industries and buildings
- Targeting process industries, data centers, power producers, utilities, and large facilities
- Leverages HOFIM™ hermetically sealed compressor
- Use ice for cold storage and hot water for hot stores
- Using hot and cold stores directly results in overall process efficiency up to 70%.




https://www.man-es.com/discover/a-tale-of-fire-and-ice

# EnergyDome Liquid CO2 Storage

- Compresses CO2 from atmospheric pressure to pressure that can be liquified at ambient temperature (700-1000 psi, 48-69 bar)
- Heat of compressor stored as hot water
- Discharge cycle expands through reheat turbine
- Low pressure CO2 storage in large dome.
- Claim RTE>75%
- Not site dependent




https://energydome.it/co2-battery/

# Oxygen Storage Incorporated into the Allam-Fetvedt $SCO_2$ Oxy-Fuel Direct-Fired Power Cycle

## Technology Summary

- *Apply liquid oxygen (LOX) storage to a natural gas, direct-fired $SCO_2$ power cycle*
- *Air Separation Unit (ASU) operated during low LMP and at part-load during medium LMP*
- *LOX stored and utilized during high LMP*

## Technology Impact

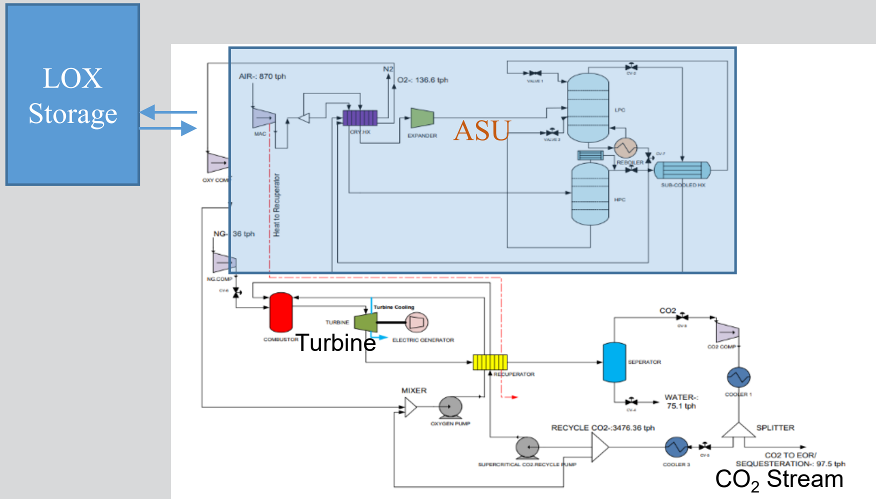
*Provides up to 20% greater power plant output (with the same fuel burn) during high demand by reducing the parasitic load of the ASU while maintaining zero NOx and SOx emissions and producing pipeline quality $CO_2$*

## Proposed Targets

| Metric | State of the Art | Proposed |
|---|---|---|
| | *NGCC with CCS* | *Allam Cycle with O2 Storage* |
| *Operating Cost (Fuel) $/MWh-net* | *$45.87 NGCC with CCS* | *$34.76 Allam Cycle with O2 Storage* |
| Net Plant Efficiency | 50.6% | 66.8% (ASU burden removed) |

NetPower 50 MWt Pilot Plant


Air Liquide Liquid $O_2$ Storage

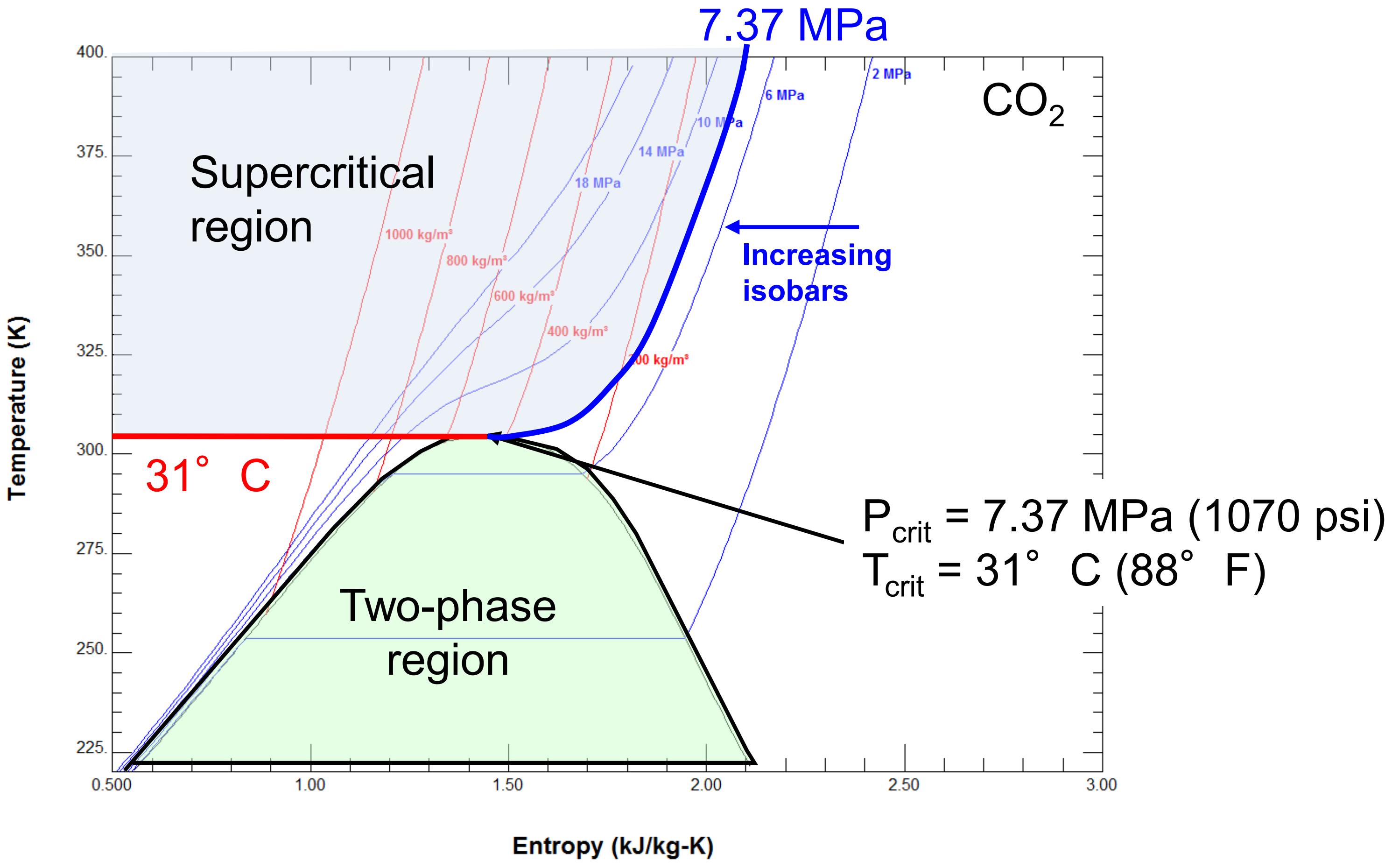



Allam-Fetvedt Cycle Incorporating Oxygen Storage

***Carbon-free natural gas fired power generation with 20% less operating cost using liquid oxygen energy storage***

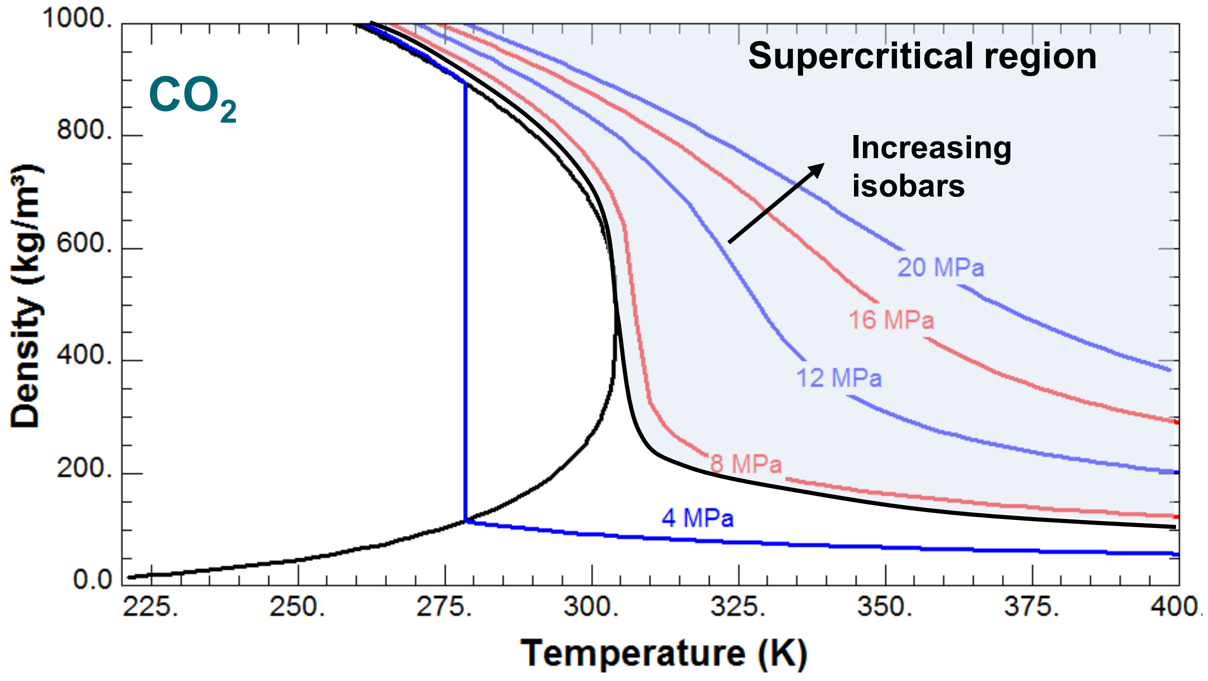
# Introduction to sCO2

# A fluid is supercritical if the pressure and temperature are greater than the critical values



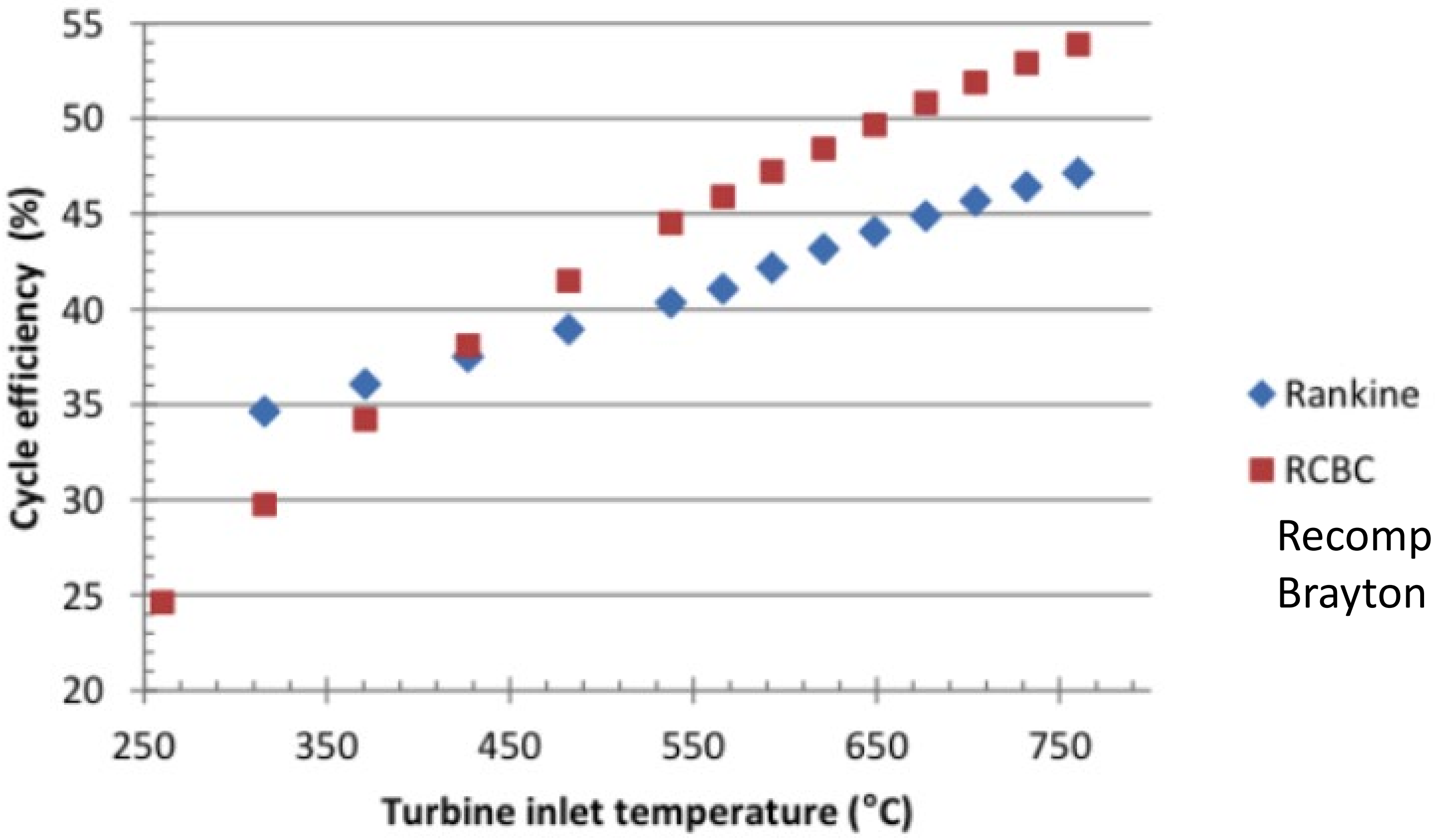

*REFPROP (2007), EOS $CO_2$: Span & Wagner (1996)*

# Fluid density sharply decreases near the critical point




*REFPROP (2007)*

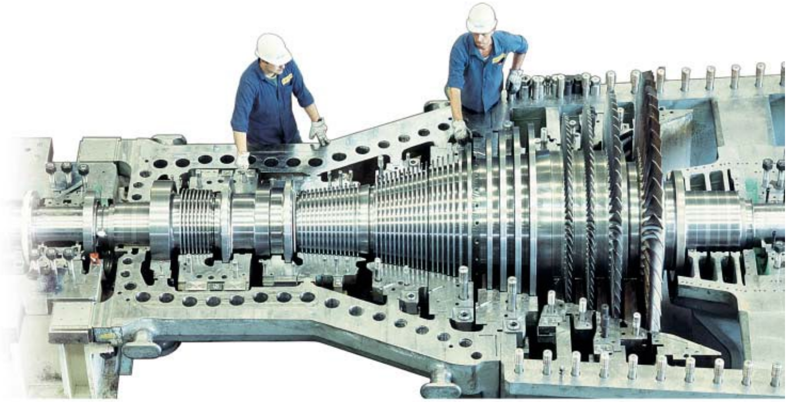
# Cycle Efficiency



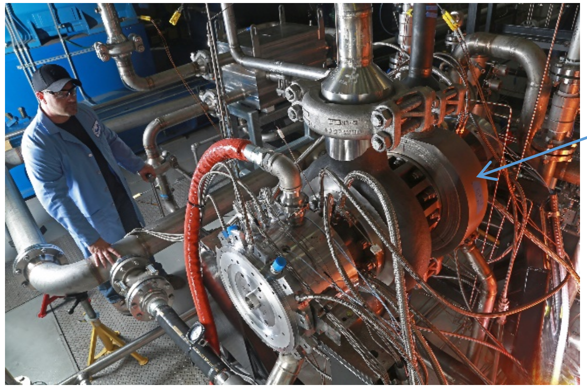

Recompression Brayton Cycle

# Motivation for sCO2 Cycles over Steam

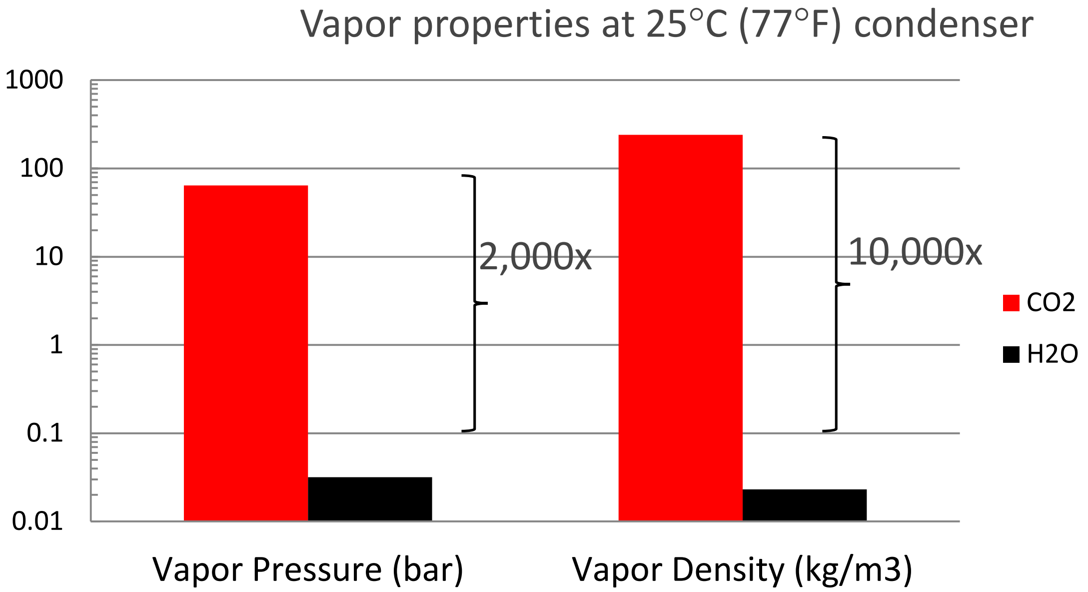
20 MW Steam Turbine



15 MW $sCO_2$ Turbine



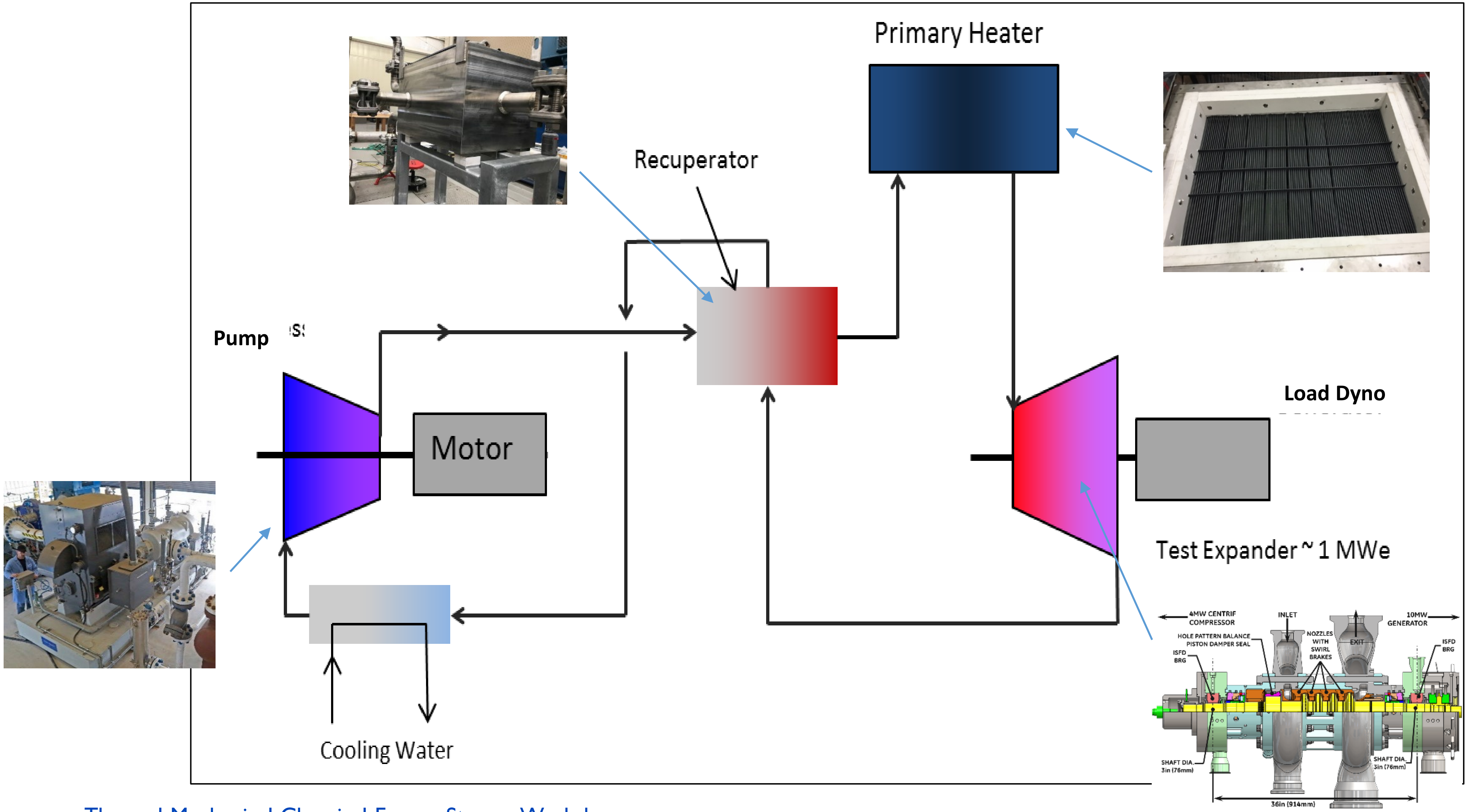
180 lb rotor
7" rotor tip diameter
27,000 rpm
20,000 hp!



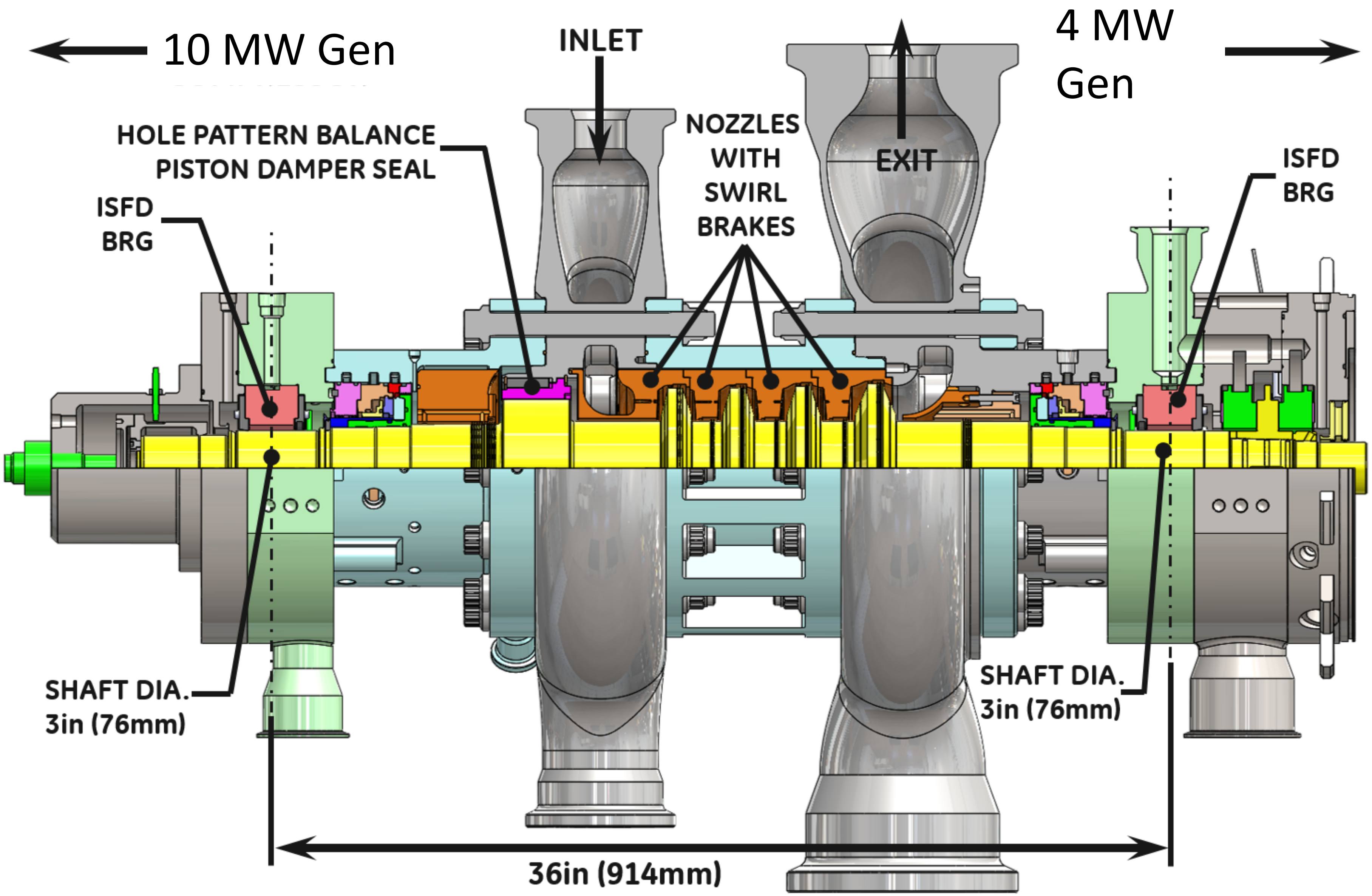
# Sunshot Program (2013-2018)

- Develop and test 1 MW scale turbine and recuperator
- Partners: SwRI, General Electric GRC, Thar Energy, Aramco Services Co., Navy Nuclear Laboratory, and Electric Power Research Institute (EPRI)
- Developed 10 MWe Turbine Frame Size with 1 MW flow path
- Funded by EERE within US Dept. of Energy
- Completed Testing in Dec. 2018 Achieving Full Temperature (715C), Full Pressure (250 bar), and Full Speed (27,000 rpm)
- At the time, the Highest Temperature SCO2 Turbine in the Literature
- New cycle required development of new expander, compressor, and recuperator

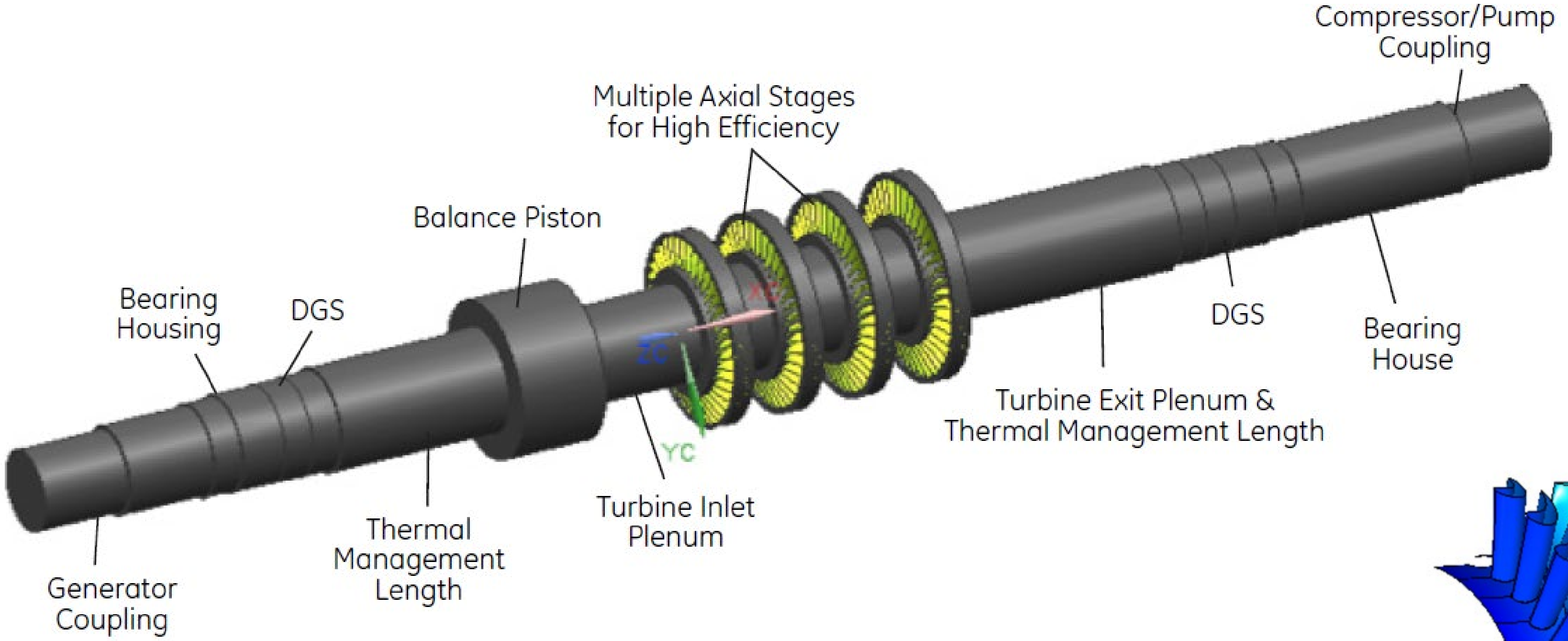
# SUNSHOT: Simple $sCO_2$ Recuperated Cycle for Test Loop

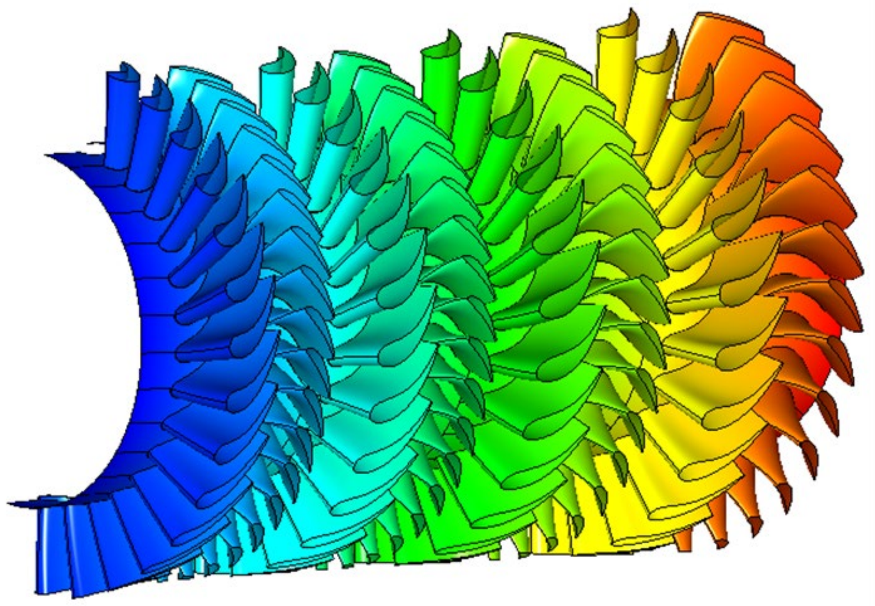


# Sunshot Turbine Design



# Rotor Design

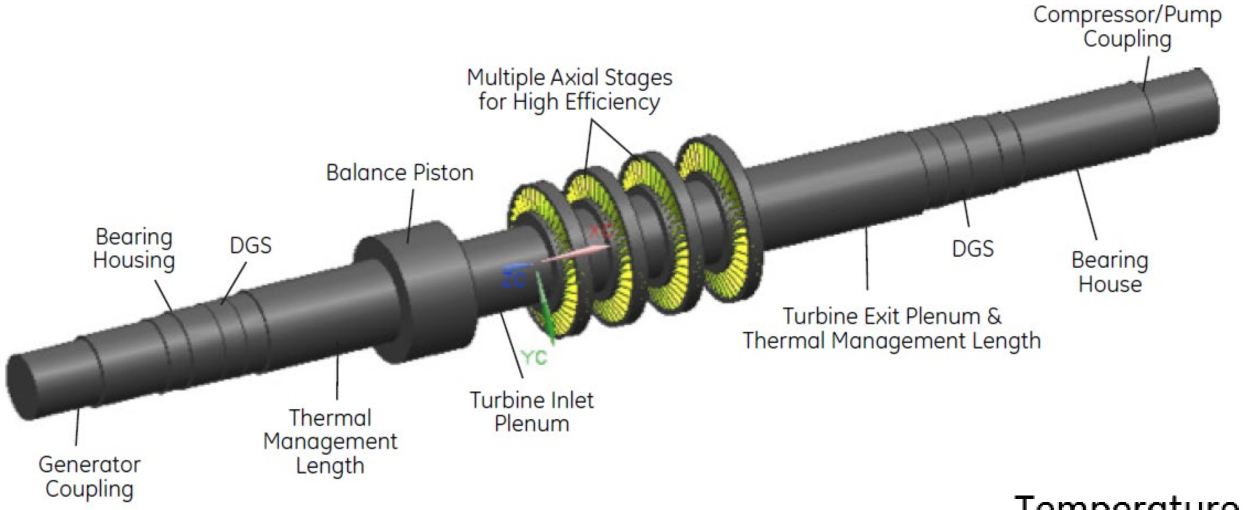


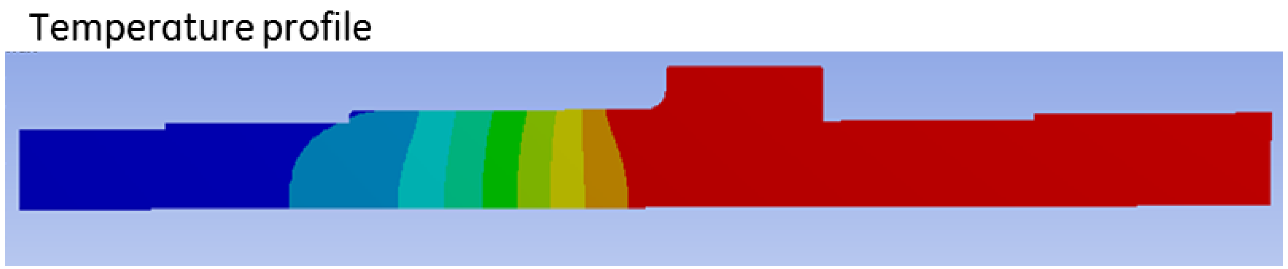
4-Stage Axial Flow Design

# Thermal Management Region

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



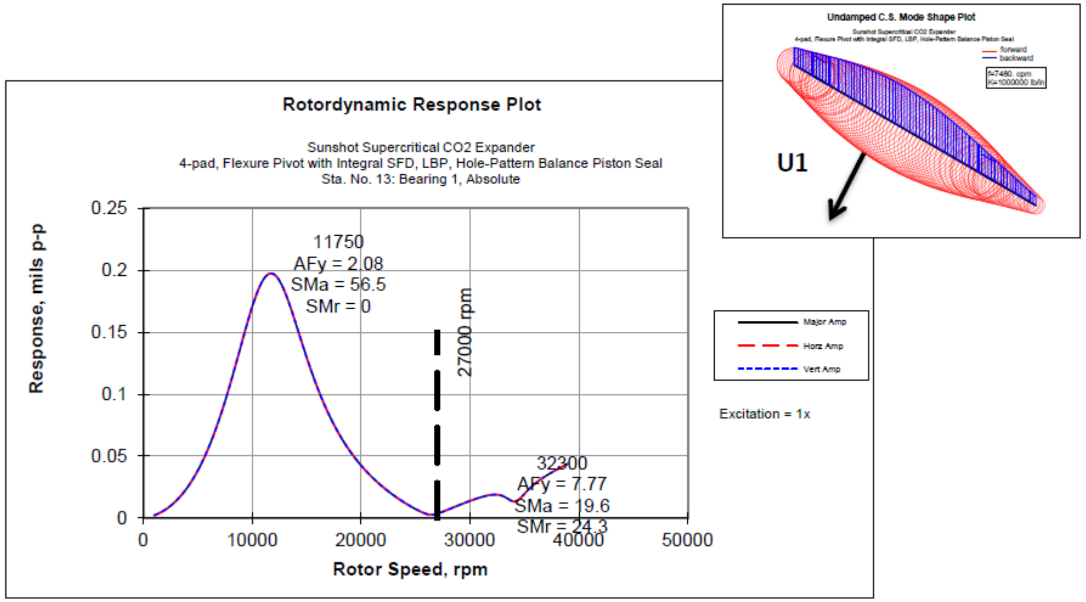

Temperature profile in the shaft and stator piece in the thermal management region



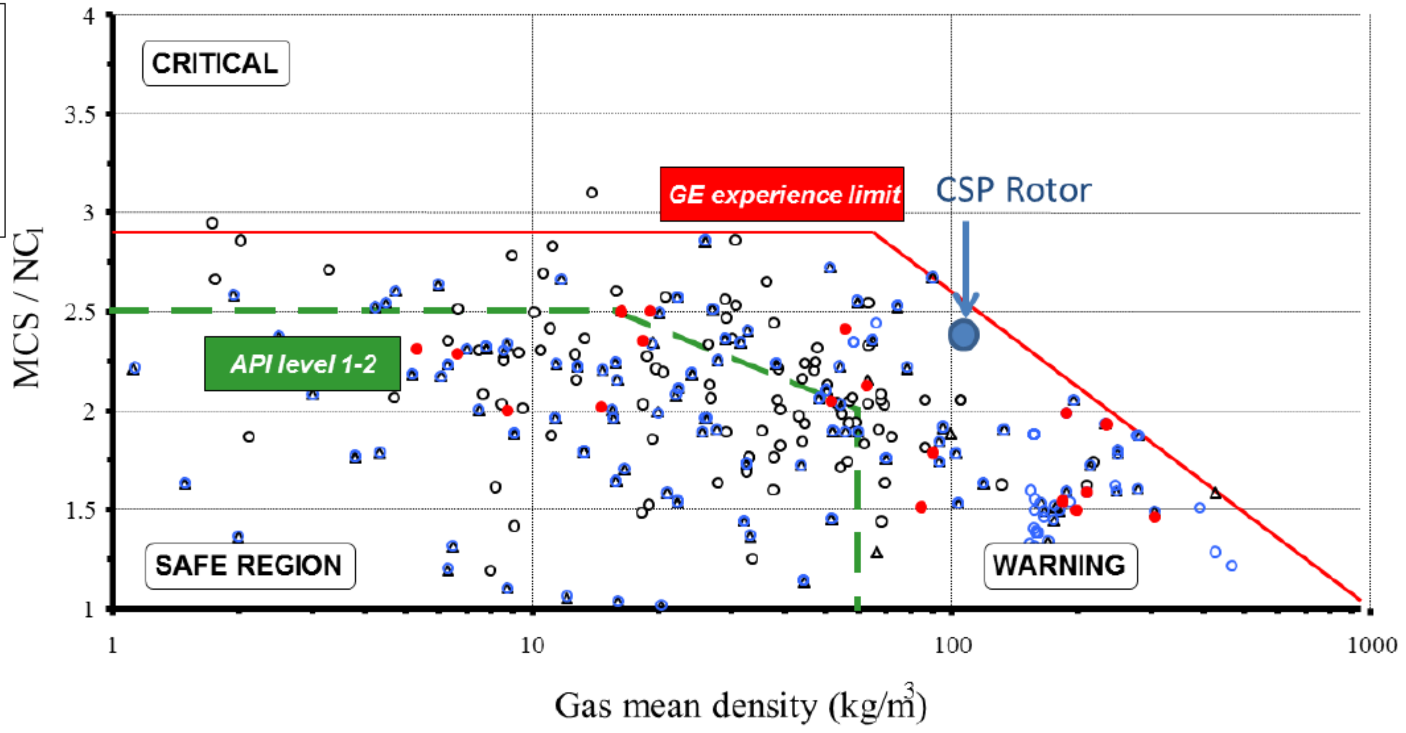

(Blue = 50ºC, Red = 715ºC) (Kalra, et. al, 2014)

# Rotordynamics

- Long flexible rotor and high gas density makes rotordynamics challenging

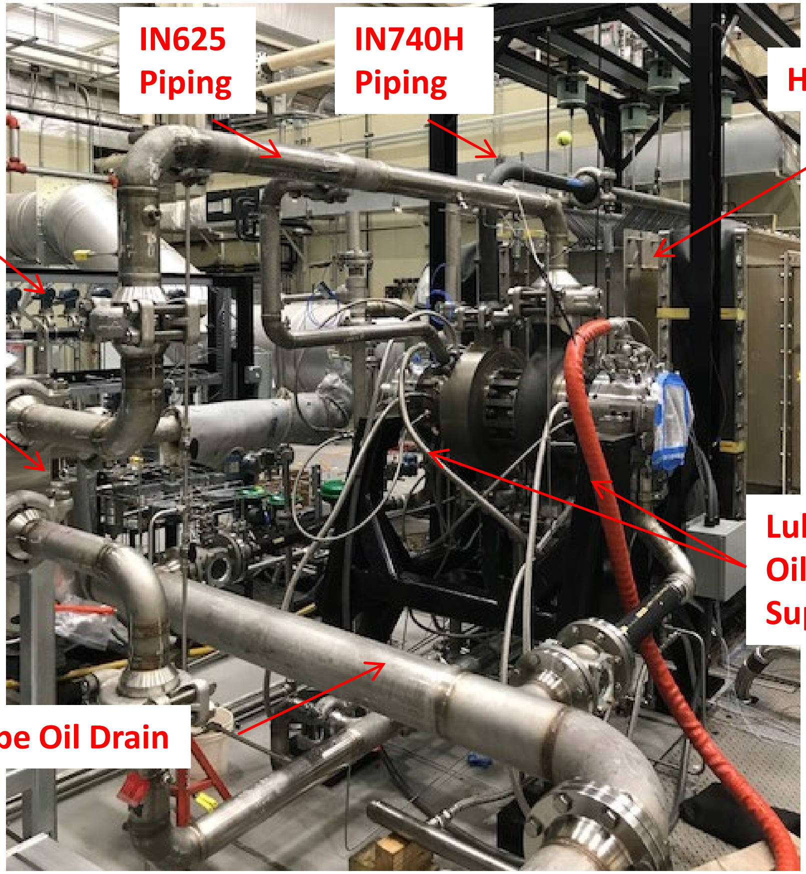



Rotordynamic Prediction for First Critical Speed

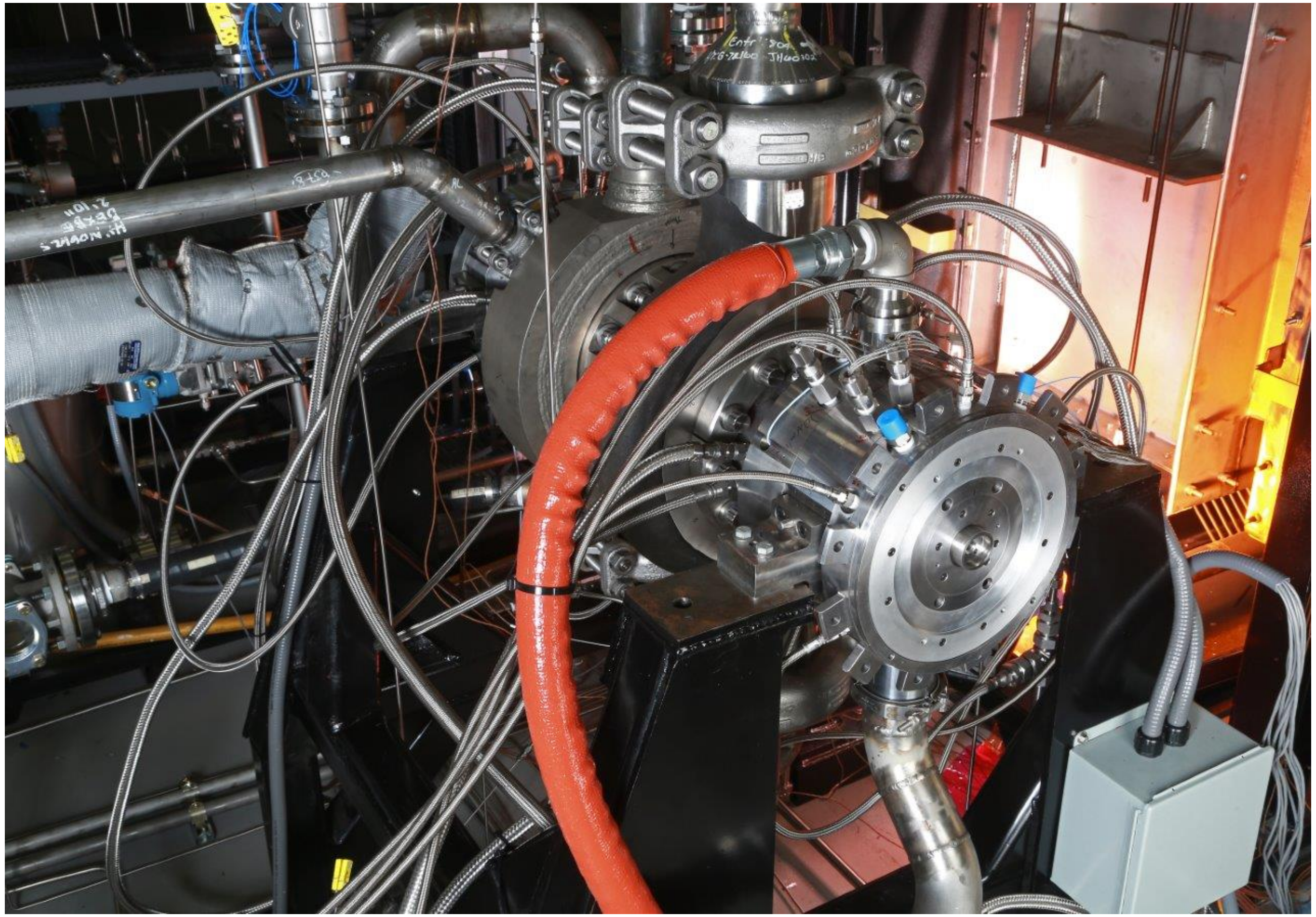



Rotordynamic Experience Chart from Moore (2006) with Sunshot Turbine Rotor Added

# Sunshot Test Loop Components



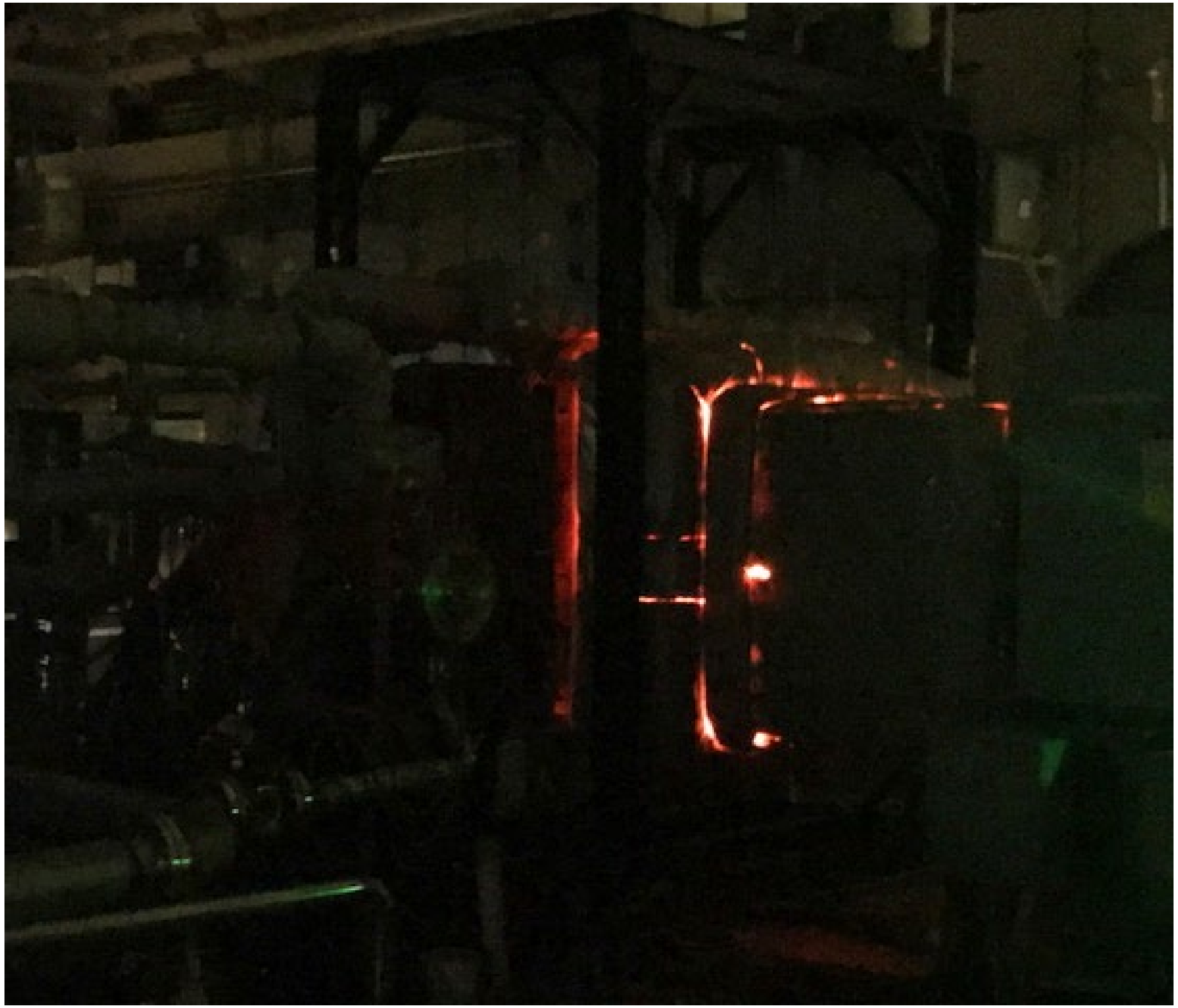
# Assembled Turbine Casing on Operating Stand



# Turbine Design Operating Points

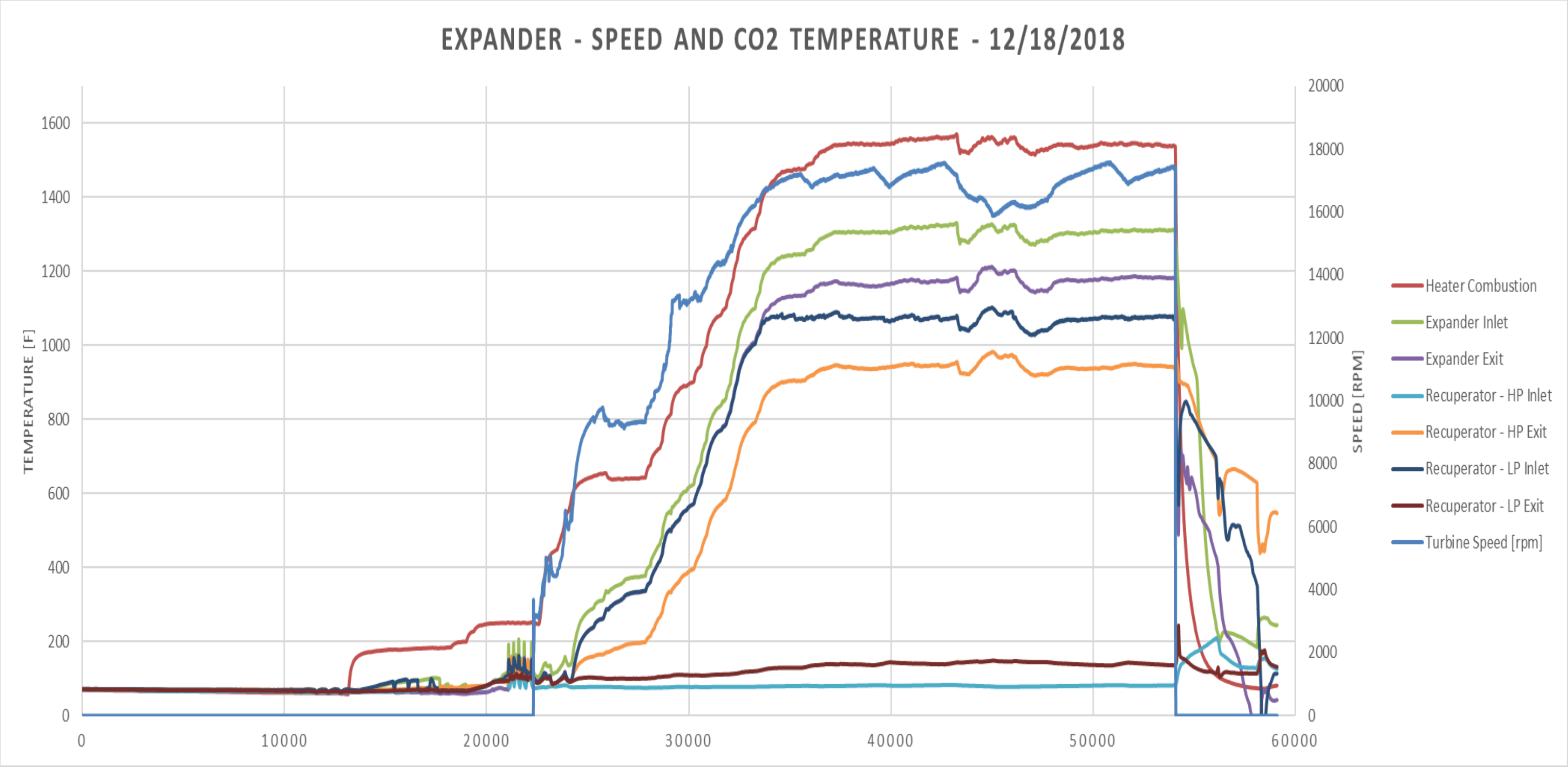
| | Speed (rpm) | Turbine Inlet Temp. °C (°F) | Turbine Inlet Pressure bar (psi) | Turbine Exit Pressure bar (psi) |
|---|---|---|---|---|
| 1st Design Point | 21,000 | 550°C (1022°F) | ~200 bar (3000 psi) | 80 bar (1160 psi) |
| 2nd Design Point | 27,000 | 715°C (1319°F) | ~250 bar (3625 psi) | 80 bar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

# Heater at 1750F (954C)

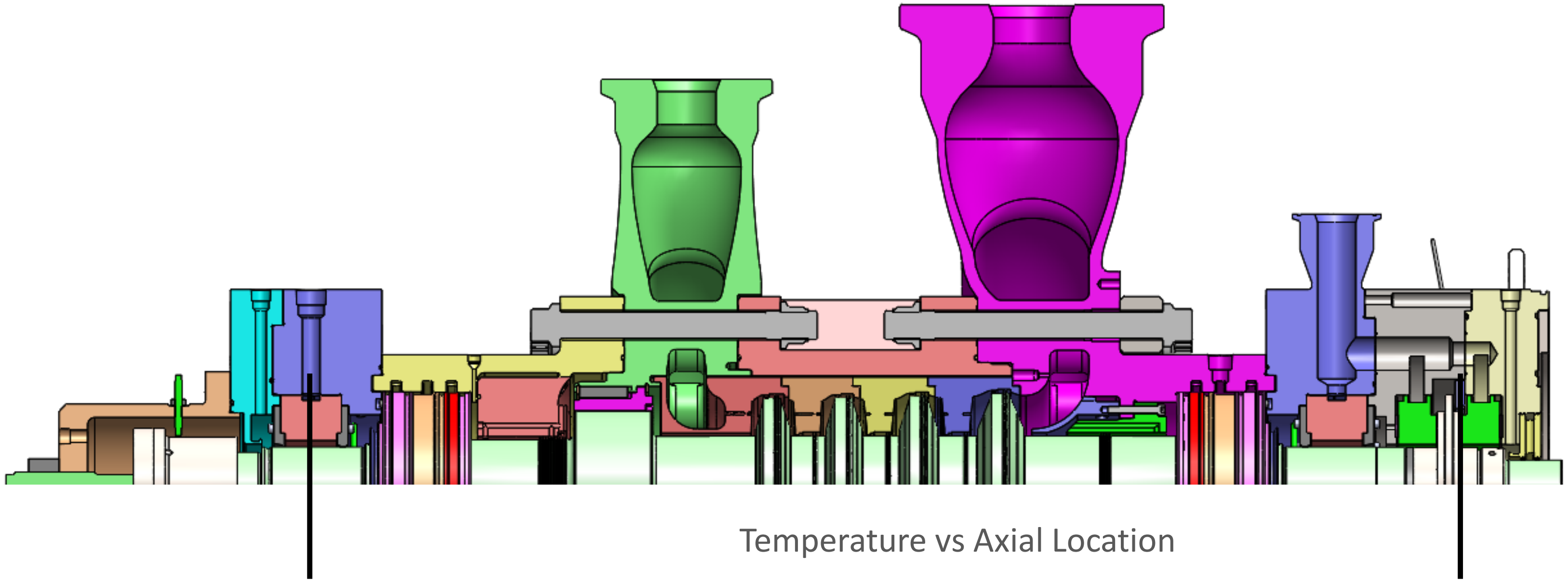


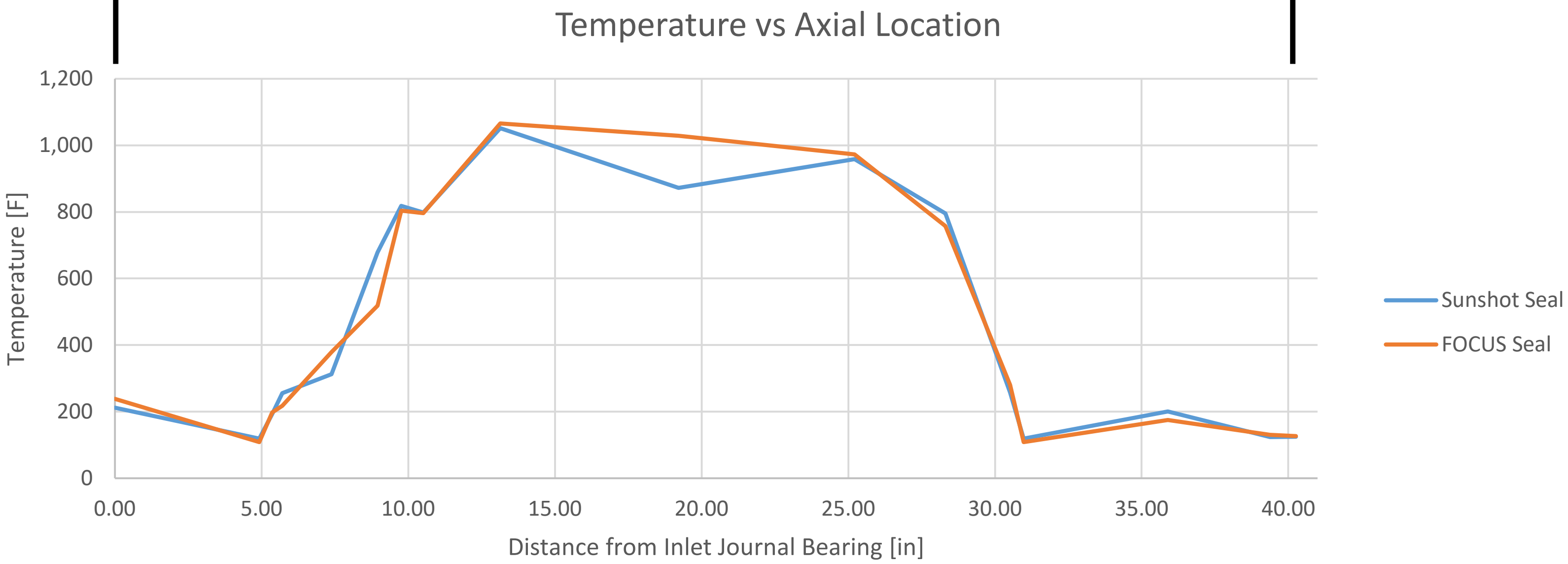
# Loop Temperatures

6 Hour 715C Endurance Test



# Sunshot Measured Thermal Seal Performance

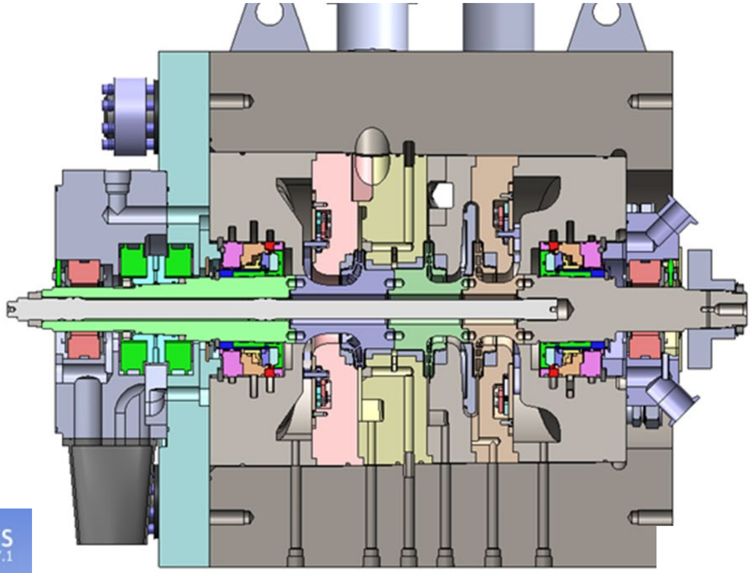


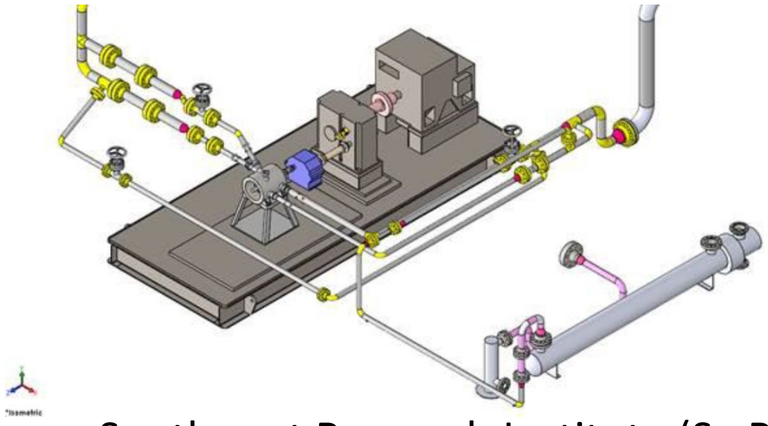


# Sunshot Turbine Summary

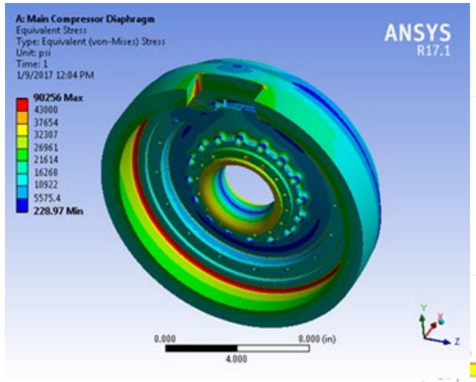
- Turbine performance met mechanical and performance objectives.
  - Achieved design temperature of 715C, design speed of 27000 rpm, and near design pressure of 250 bar.
  - Highest temperature $SCO_2$ turbine in the literature.
  - Thermal seal maintained acceptable dry gas seal operating temperature 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
  - Low radial bearing temperatures following clearance 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

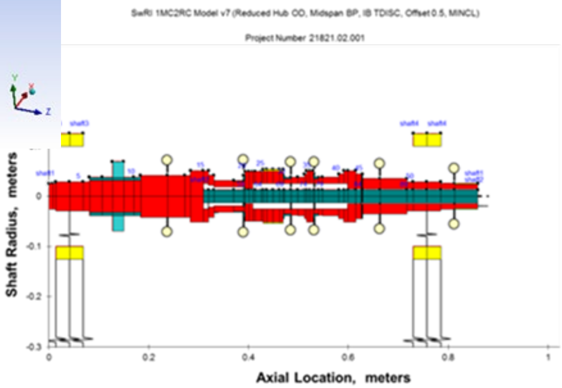
# Apollo Compressor Design and Test Loop (2017-2021)

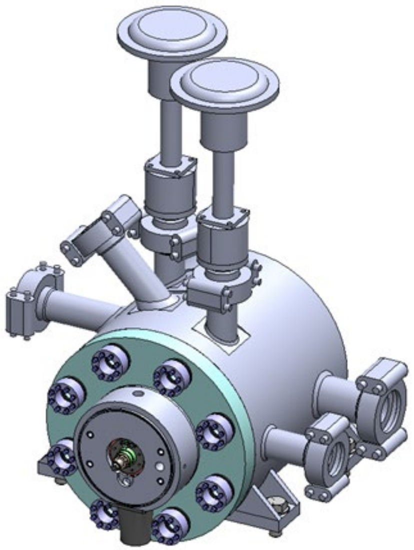


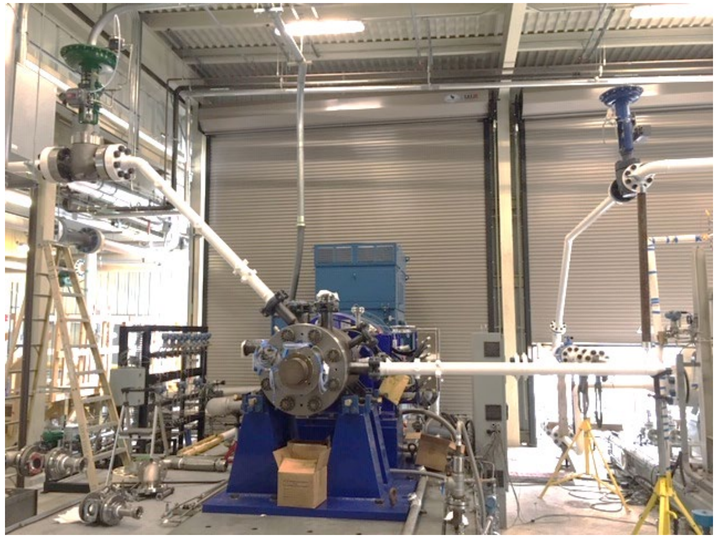


Southwest Research Institute (SwRI)
$sCO_2$ Test Loop



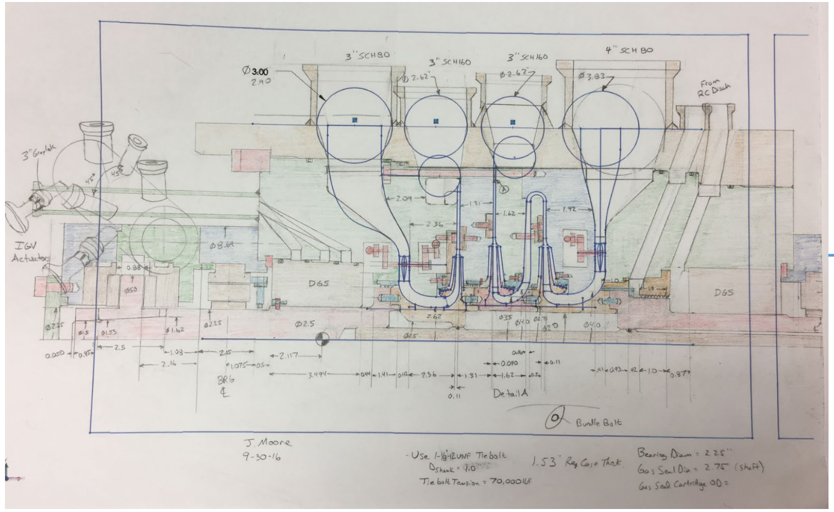


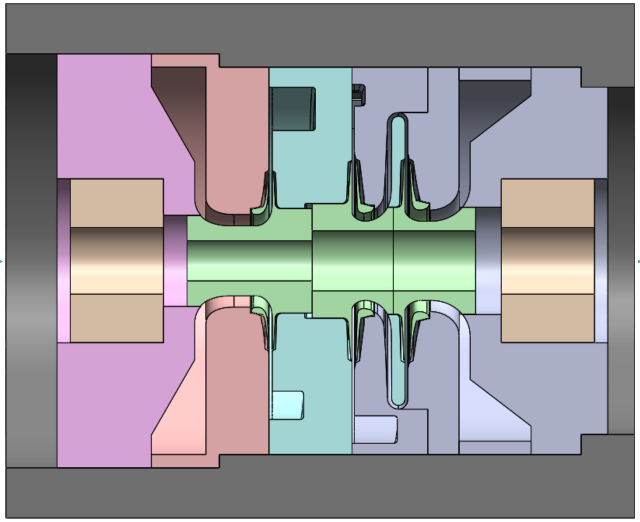
Testing has leveraged existing SwRI Sunshot loop with modifications

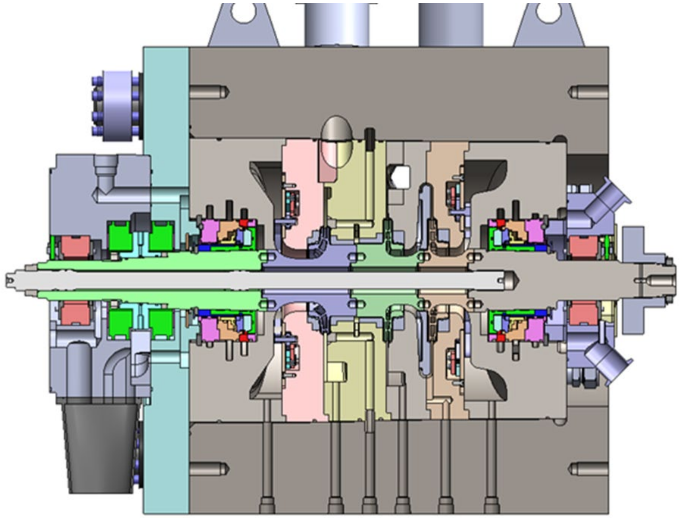
# Apollo Compressor Design Goals & Challenges

- Main compressor has very high pressure rise (2400 psi) and low head due to high inlet density
  - Requires high power, small diameter impeller
- Compressor casing that would be rated to 4,800 psia (25% above peak operating pressure)
  - Thick walls and large heads
  - Large retaining features (bolts or shear rings)
- Compressor package that included both Main and Bypass compressor that could be directly coupled to turbine for the $sCO_2$ power cycle
  - Longer rotor with large mass in middle of the shaft
  - High critical speed ratio of operation with high density flow
- Handle density swings up to 2X and flow ranges up to 3X
  - Meet target discharge pressure and mass flow over a wide range of suction pressures and temperatures
  - Requires flow control enhancement using Actuated IGVs
- Rotating speed of 27,000 rpm to match target turbine
  - High speed seals (same as Sunshot)
- Internal Bundle design
  - Ease of assembly / disassembly
  - Requires a tightly packaged system with many critical internal features

# Design Evolution



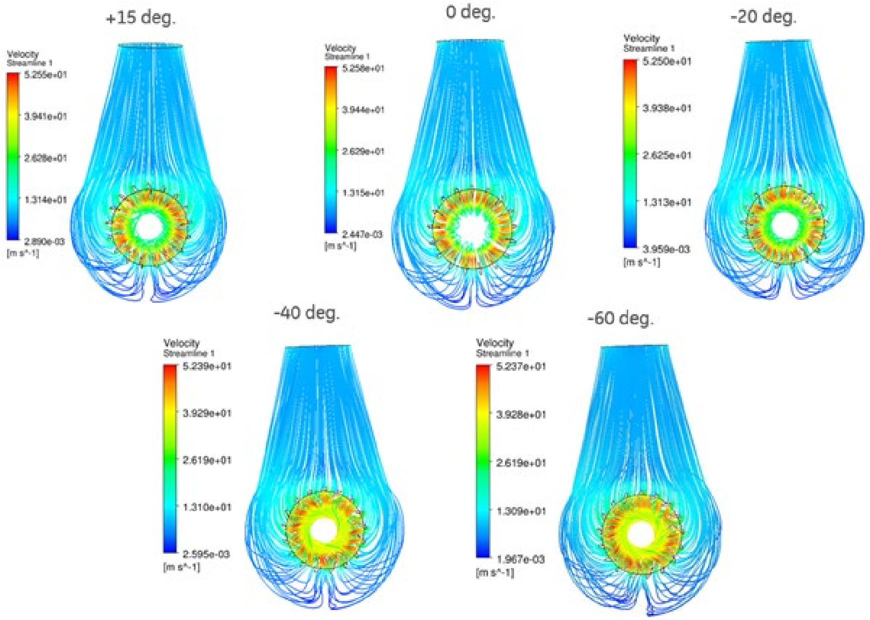


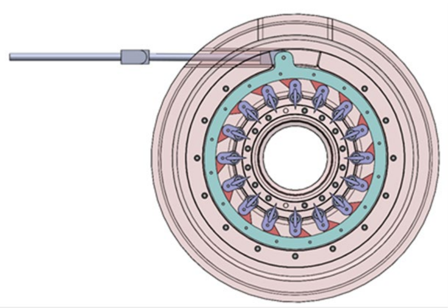


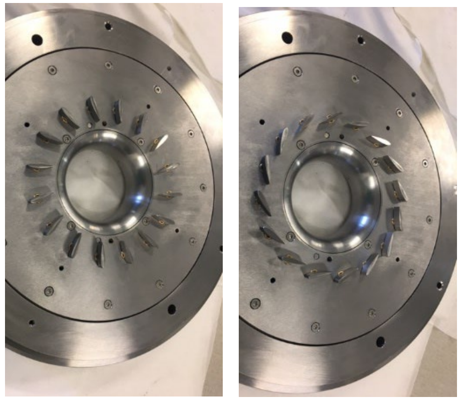
- Advance the design from conceptual sketch to manufactured hardware
- Pass various design review (Conceptual, Preliminary, and Detailed)
- Meet design codes
  - API 617: Compressor Packages
  - API 684: Rotordynamic
  - ASME VIII-2: Pressure containment
  - PTC 10: Compressor testing
- Full drawing and manufacturing review of all components

# Variable IGV Design

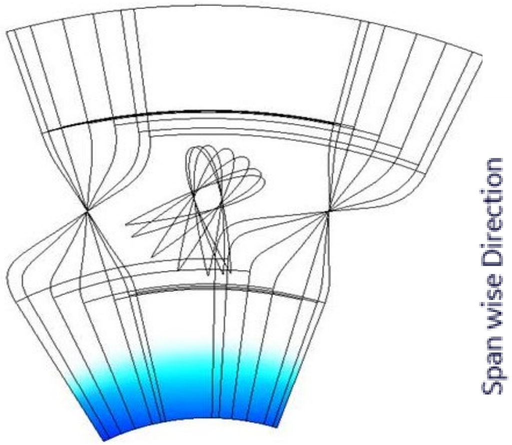
17 Radial IGVs in baseline design

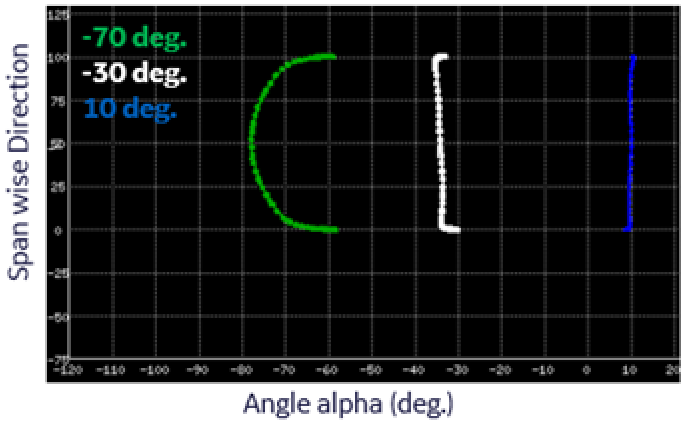



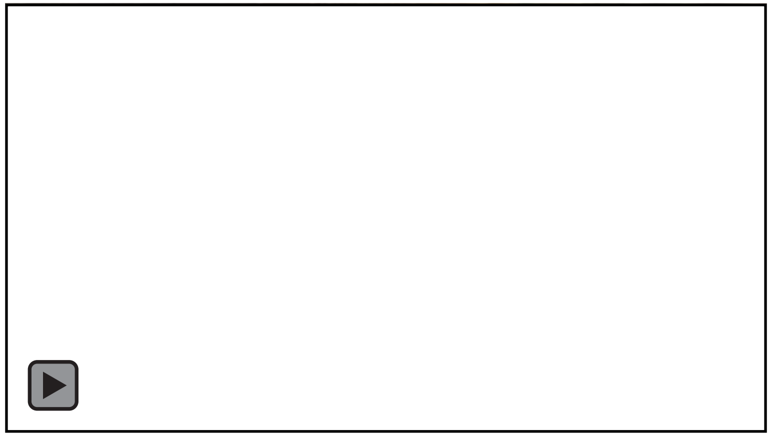





IGV Mechanism using external actuator

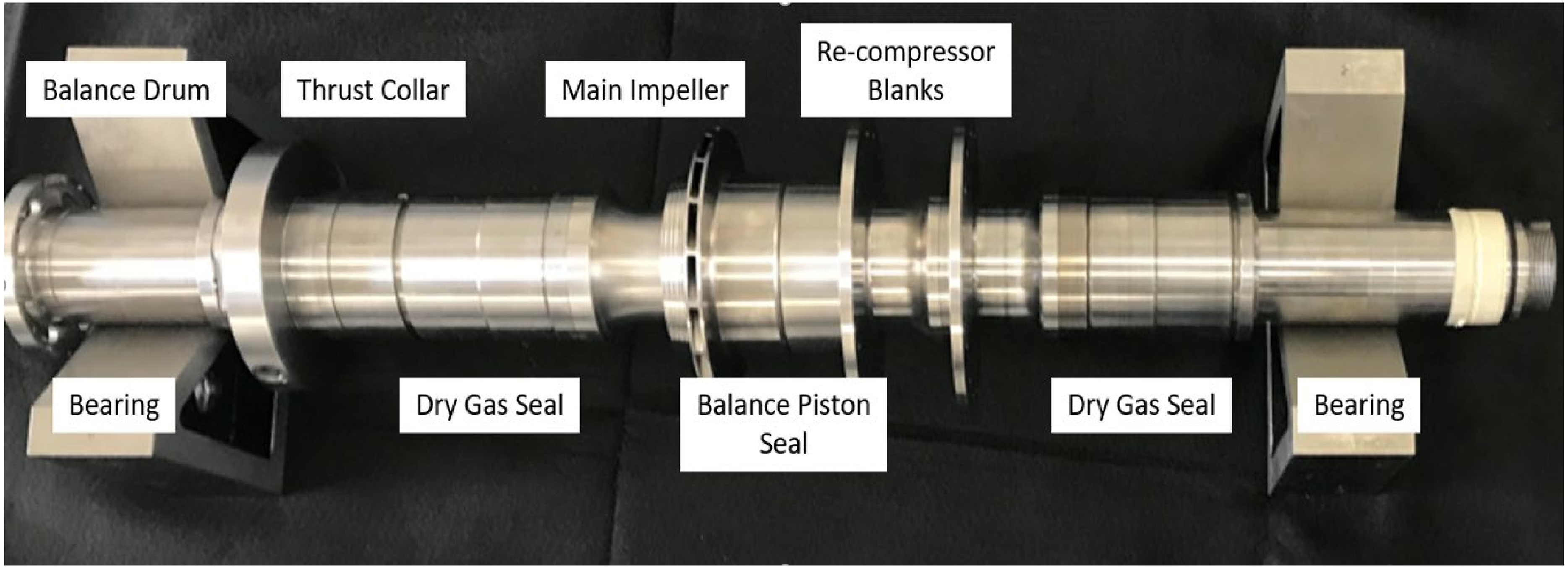




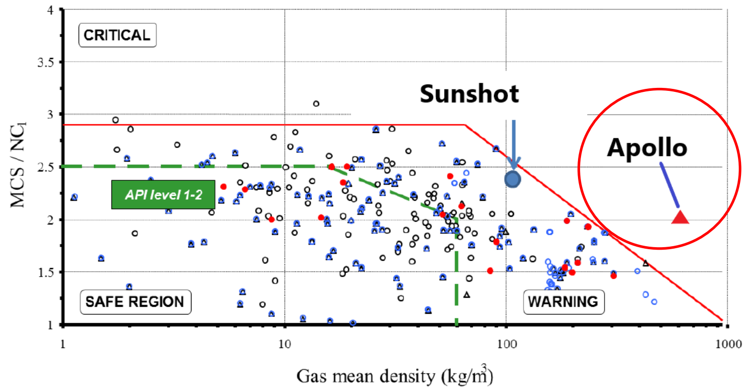
# Assembled Compressor Rotor

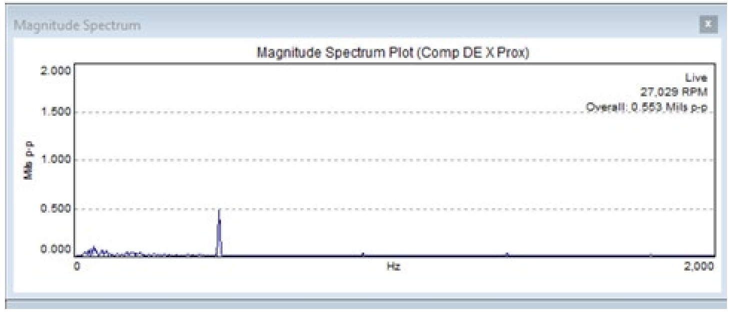
- Built-up Rotor Design with Tie-bolt
- Impeller Hub Manufactured Integral to Impeller due small impeller hub diameter

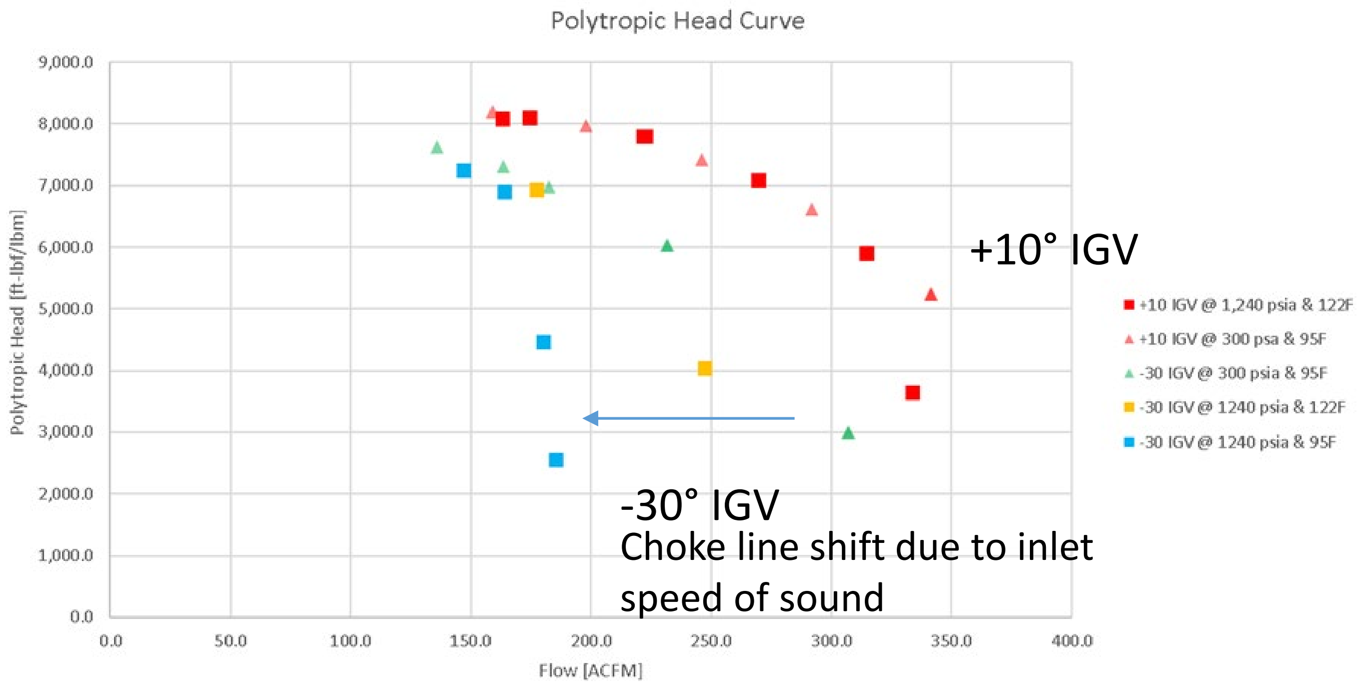


# Test Data

- Rotordynamic stability a concern due to high fluid density
- Bearing modifications required to manage fluid induced forces due to high density by eliminating squeeze film dampers
- Performance data shows strong effect of inlet temperature



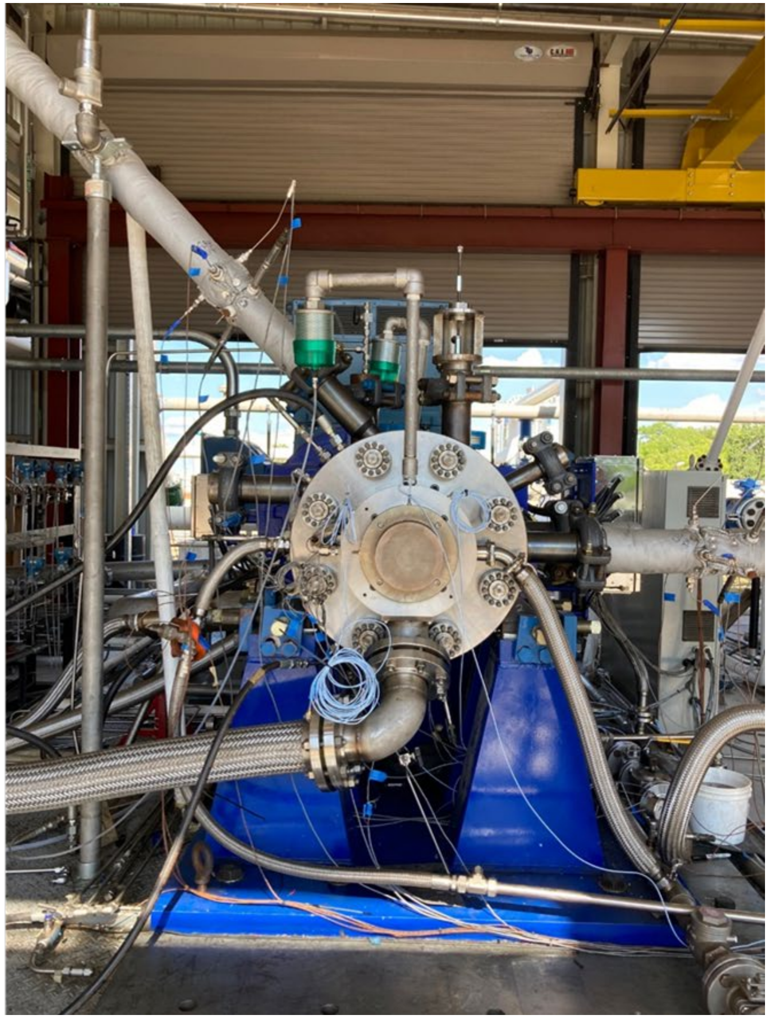



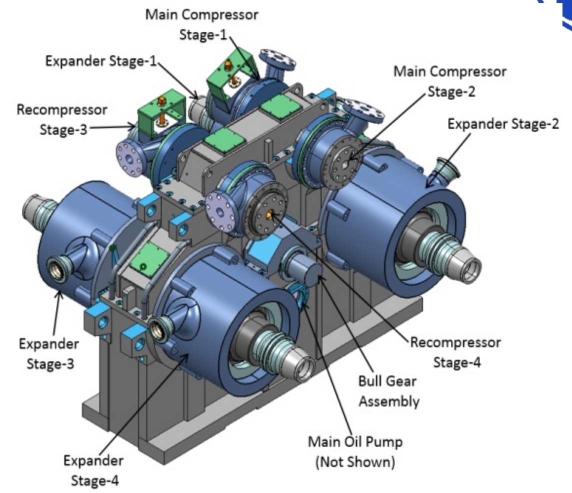
# Apollo Compressor Testing

Notable Achievements:

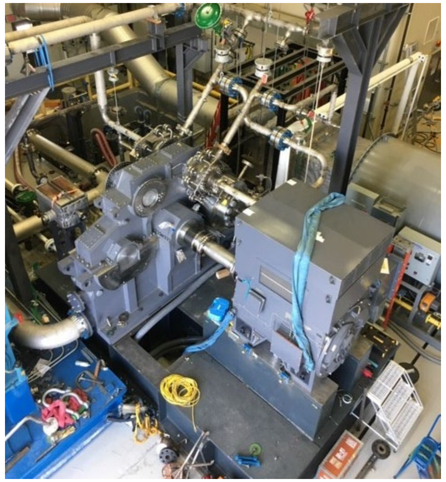
- **World Record density: 720 kg/m$^3$**
- Smallest impeller manufactured by BHGE.
- Mechanically well-behaved demonstrating high pressure $CO_2$ compression possible.
- Highlighted challenges with measuring CO2 properties near the liquid-vapor dome.



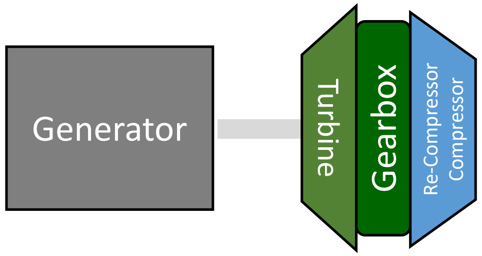
# Ultra High Efficiency Integrally-Geared sCO2 Compander
# *(SwRI, Hanwha for DOE EERE) (2017-2021)*



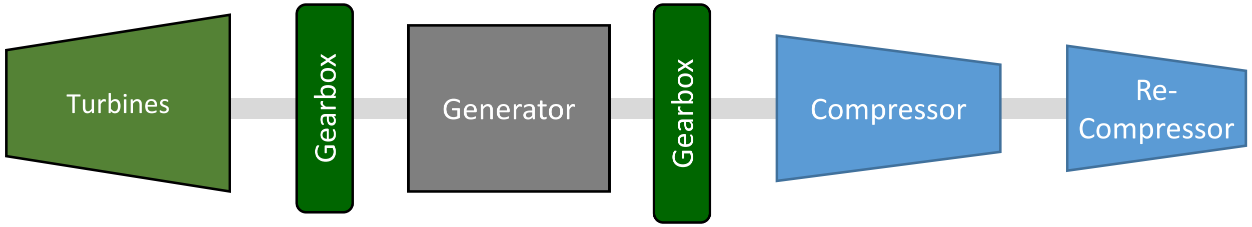

- Design a sCO2 integrally geared compander (IGC)
  - Combining compression and expansion stages into a single integrally geared housing connected to a low speed motor/generator.
- Benefits:
  - Reduced footprint
  - Potential cost reduction up to 35%
  - Utilizes a low speed commercially available driver/generator
  - 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 720°C and full pressure with low vibrations



**Typical IGC Package**

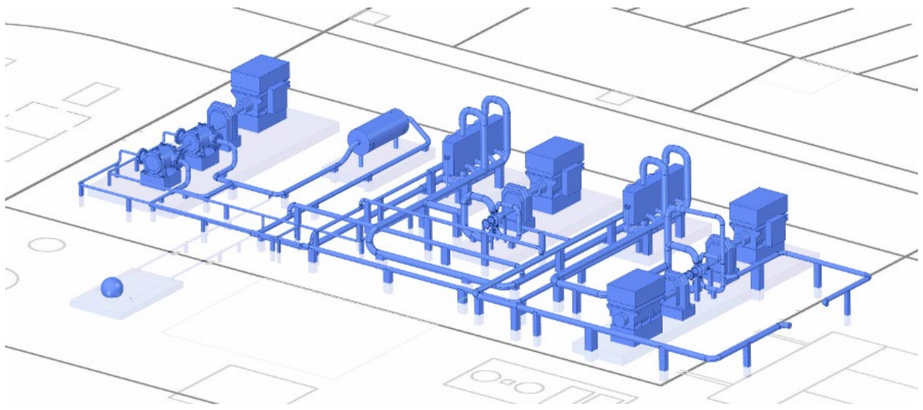



**Conventional Turbomachinery Train**



# Supercritical Transformational Electric Power (STEP) Pilot Plant Test Facility (2017-2022)

- Design, construct, and operate a 10 MWe sCO2 Pilot Plant Test Facility
- Advance the state of the art for high temperature sCO2 systems
- Project team includes Gas Technology Institute, SwRI, and General Electric Global Research
- Six year, $110 million project with $80 million funded by DOE-NETL
- Test facility located at SwRI



STEP
A U.S. DEPARTMENT OF ENERGY PROJECT
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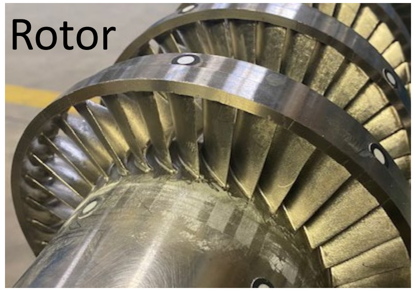
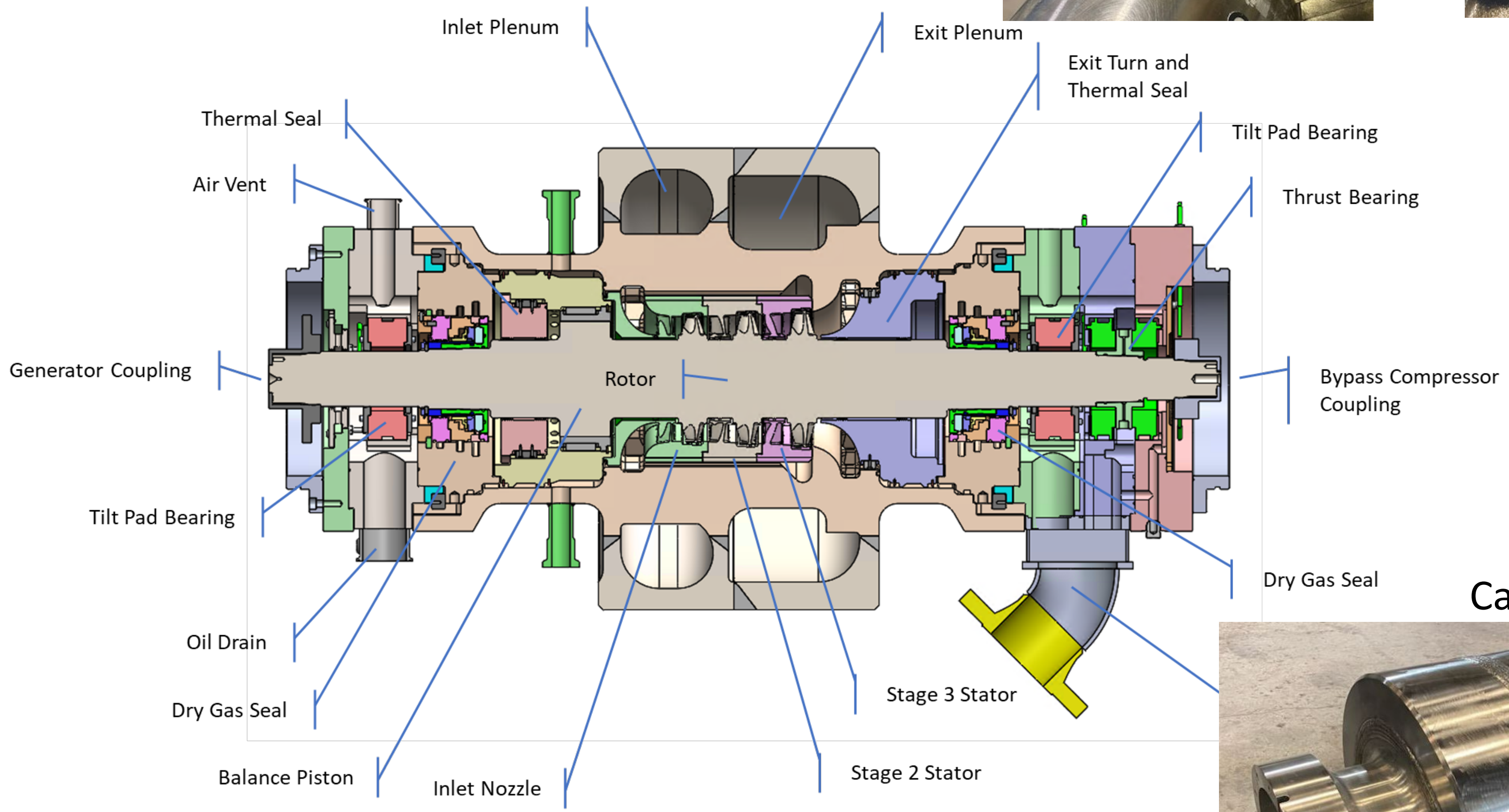
# STEP 10 MWe Turbine

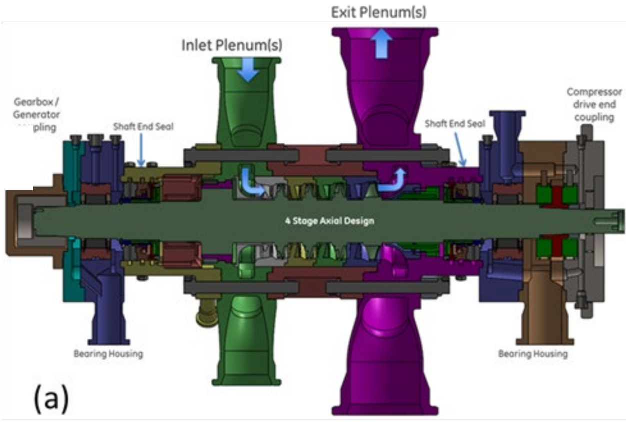
Monolithic Rotor and Stators




Stator Nozzle




Sunshot Turbine

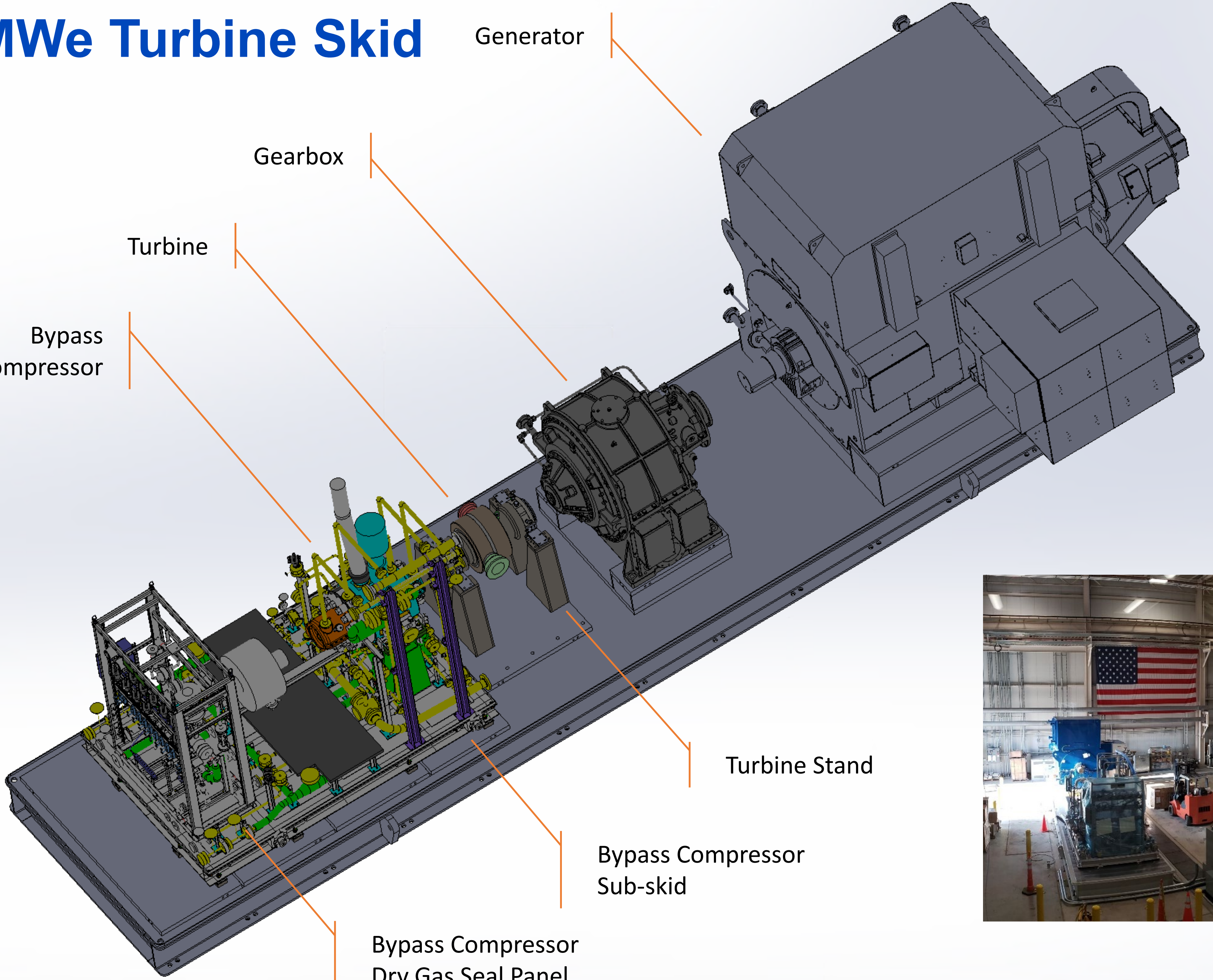



Casing

1-Piece Fabricated Inconel Casing

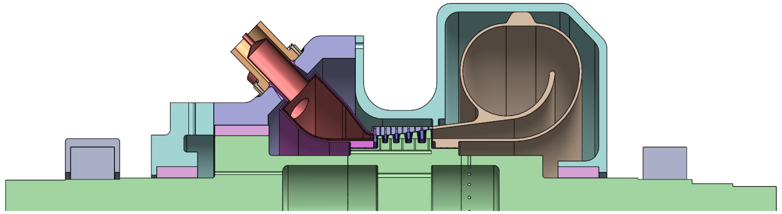
- Sunshot was Design Basis
- Monolithic Fabricated Case
- Same One-Piece Rotor
- Similar bearing and dry gas seal design
- 3 vs. 4 stages

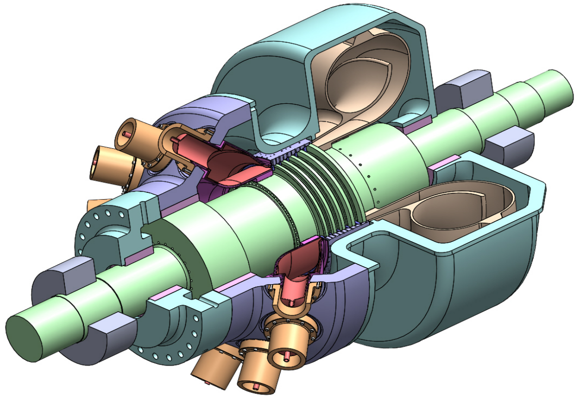
# STEP 10 MWe Turbine Skid

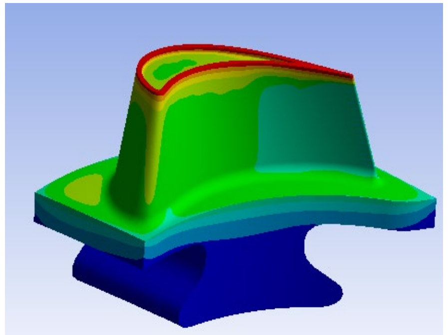


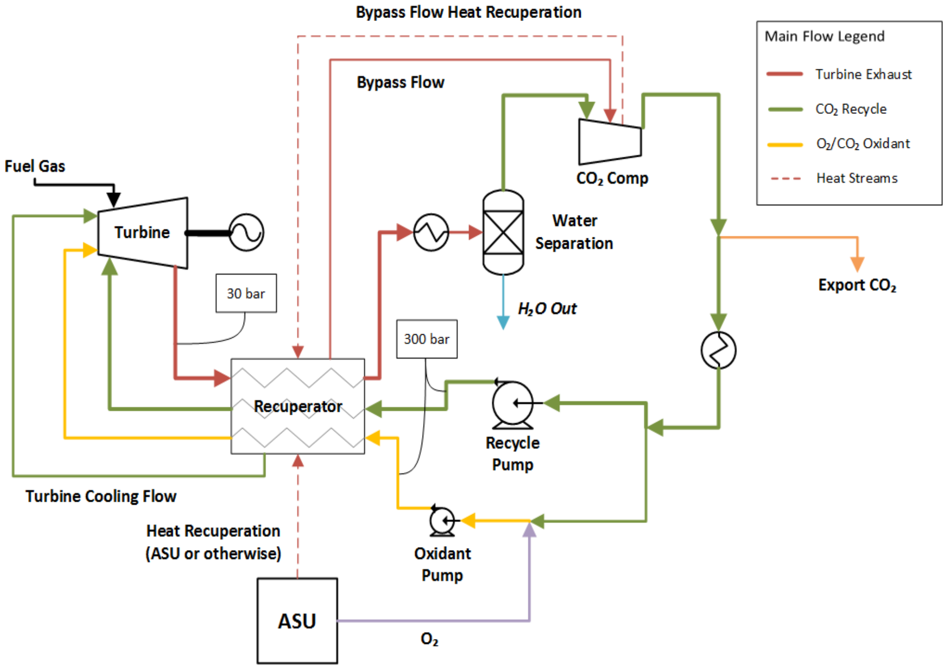

# Direct-Fired Oxy-Fuel Turbine Development

- Developing a 300 MWe Utility Scale Oxy-Fuel Turbine with 1150 °C turbine inlet temperature at 300 bar using Allam-Fetvedt cycle
- Significantly improve the state-of-the-art for thermal efficiency (approaching 60%) and results in a high-pressure stream of $CO_2$ simplifying carbon capture, making the power plant emission-free.
- Funded under the DOE 21st Century CT program further developing oxy-fuel turbine design and performing material, combustion kinetics, and heat transfer testing for both natural gas and coal syn-gas.









# Summary

- Unique power or energy storage cycles require unique equipment designs to implement them
- $SCO_2$ power cycles showing good promise to improve cycle efficiencies
- High fluid density and low cycle pressure ratio greatly reduces equipment size for $SCO_2$ cycles
- $SCO_2$ cycles have application to energy storage for both thermochemical and pumped heat applications
- For the direct-fired Allam-Fetvedt cycle, both fuel (hydrogen) and oxidizer (LOX) may be used to store energy

# Questions?

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