State of the Art in Supercritical Carbon Dioxide Power Systems

Tim Allison, Ph.D.
Director, Machinery Department
Southwest Research Institute

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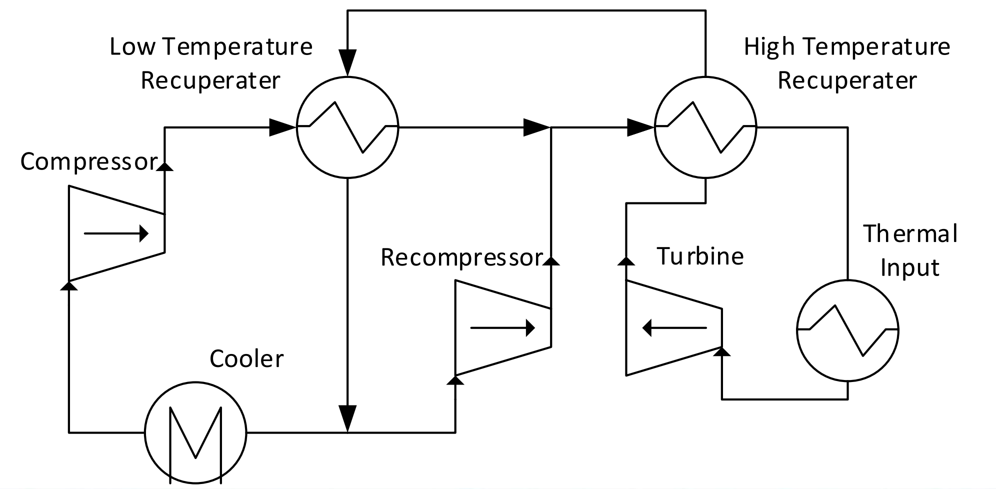
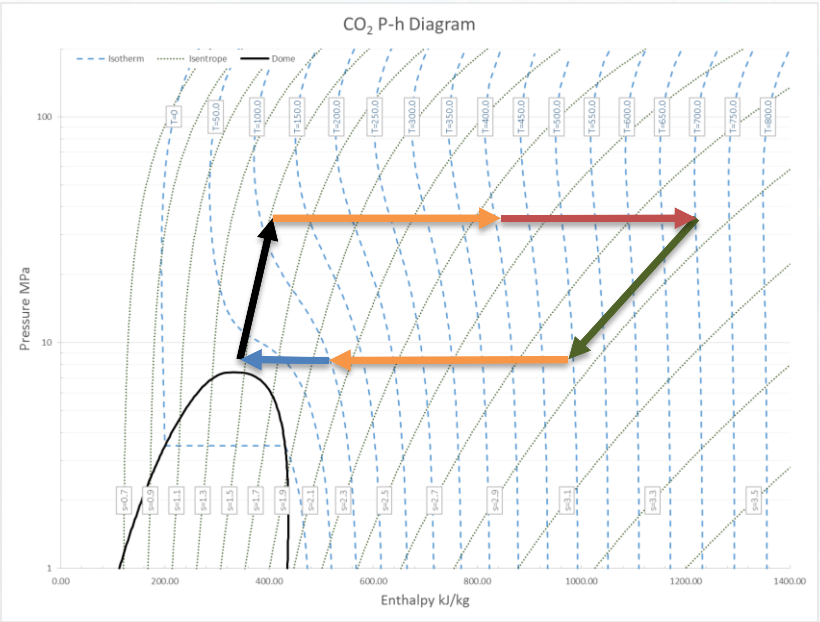
Supercritical Carbon Dioxide (sCO_2) Cycles

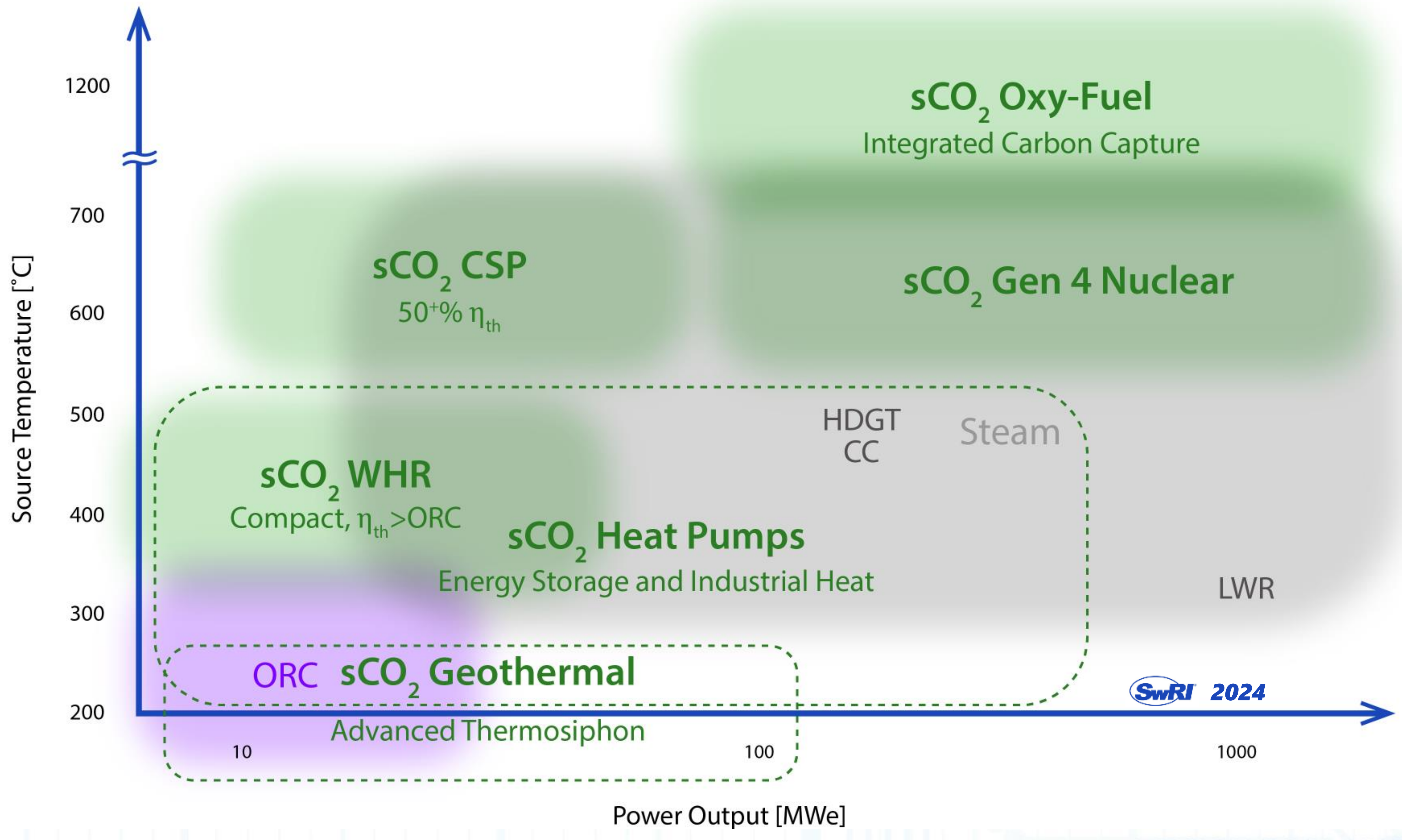
- Investigated since early 1900s, revisited since 1999, enabled by new technologies
- Favorable fluid properties:
  - Inert
  - Non-toxic at low concentrations
  - Unfreezable above 5.11 atm
  - Thermally stable at temperatures up to1700 °C
  - High density → turbine power density ~10x steam turbines
  - High thermal conductivity, low viscosity → compact heat exchangers
- No "boiler" → eliminates staffing requirements
- Potential for lower $/kW due to higher efficiencies, power densities,
- Commercial systems announced, heat pumps in construction



Recompression Brayton Cycle achieving >50% thermal efficiency over ~700 °C turbine Inlet



sCO_2 Power System Application Space



CO_2 Cycles – Versatile Tool for the Energy Transition

Potential Impact by 2050

Path to Net-Zero

Small WHR
25% of SCGT Installed Base
9.3 GW_e 10,700 GWh_e/yr
4 MM tpa

Industrial Heat Pumps
10% of Industrial Heat
138 GW_{th} 970,000 GWh_{th}/yr
25.6 MM tpa CO_2

Concentrated Solar
5% of Total Solar
14 GW_e 98,500 GWh_e/yr
37.0 MM tpa CO_2

Electro-Thermal Energy Storage
25% of Total Storage
40.9 GW_e 89,500 GWh_e/yr
33.6 MM tpa CO_2

OxyFuel with CCS
10% of NG fueled generation
13.3 GW_e 93,100 GWh_e/yr
35 MM tpa CO_2

Next Gen Nuclear
10% of Total Nuclear
8 GWe 62,500 GWh_e/yr
23.5 MM tpa CO_2

Adv Geothermal
10% of Geothermal
8.5 GW_e 60,000 GWh_e/yr
22.5 MM tpa CO_2

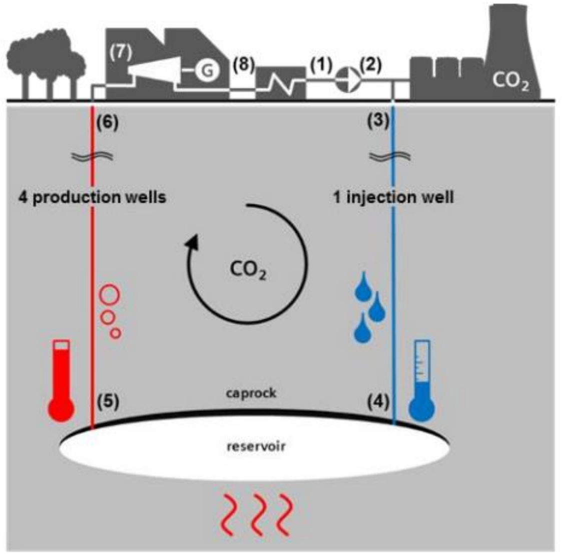
Total Potential
181.2 MM tpa CO_2
~12% of Current Electric Power Emissions

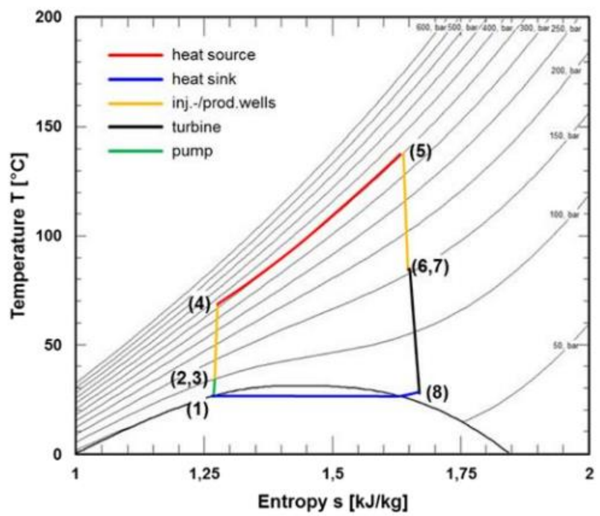
% = Assumed market penetration
GW_e or GW_{th} = installed capacity
GWh_e /yr or GWh_{th}/yr = energy delivered
MM tpa = million tonnes CO_2 per annum reduced
Primary data source: eia annual energy outlook

SwRI 2024

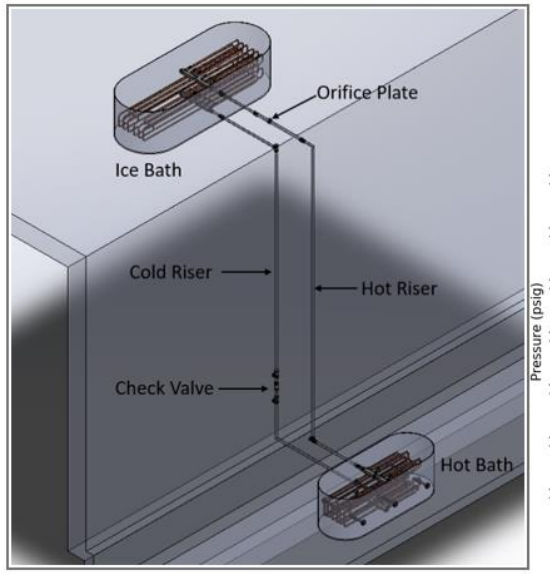
Why is sCO_2 Interesting for Geothermal Applications?

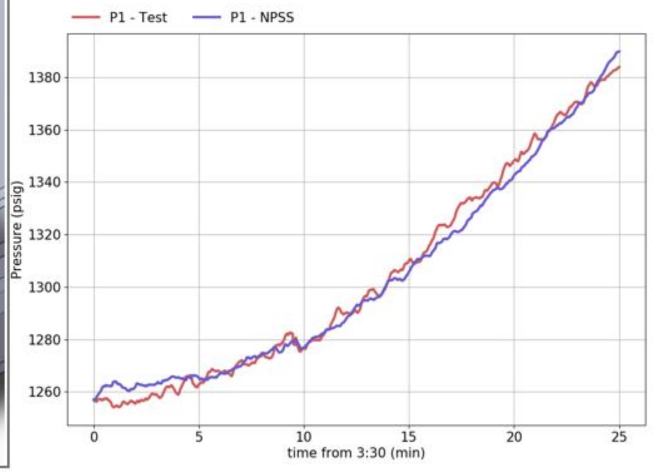
- Higher efficiencies than organic Rankine cycles at higher source temperatures
- Higher efficiencies at smaller scales than higher-temperature steam Rankine systems
  - Higher efficiency also means lower cooling costs/footprint
- Thermosiphon effect reduces or eliminates pumping/compression parasitics, improving efficiency
  - Highly sensitive to bore diameter
- All fluids benefit from more complex cycles at higher temperatures





Thermosiphon concept and cycle (Siemens NGP) [Sudhoff *et al*, 2019]

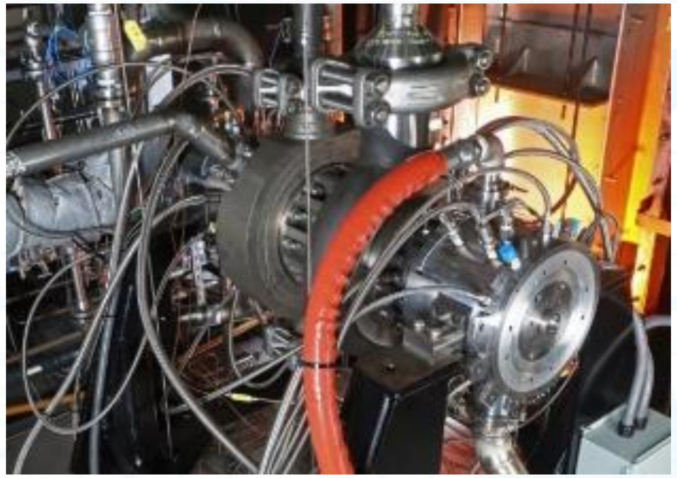




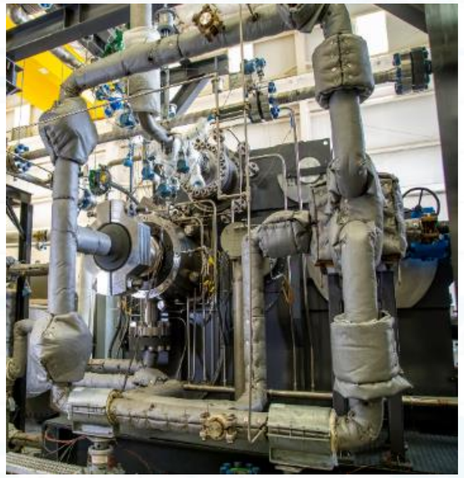
Thermosiphon testing and transient simulation results

Past Development Work for sCO_2 Cycles, Components, Systems

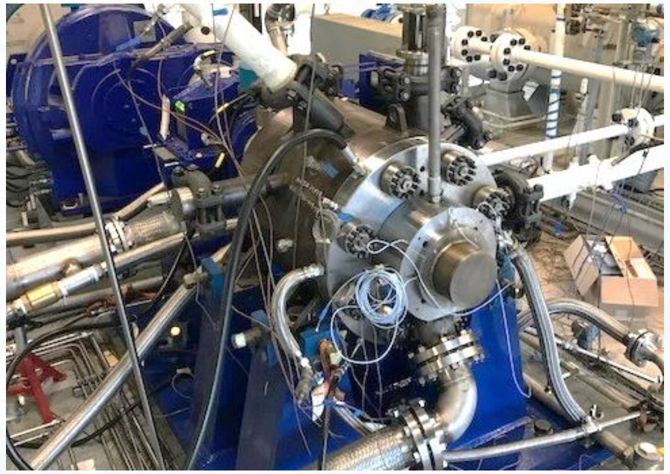
Design, Fabrication, Testing of 10 MWe-Scale Machinery



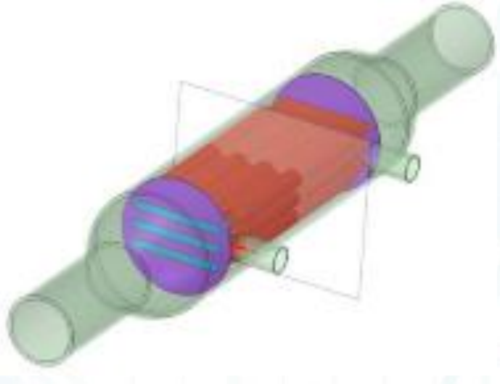
SunShot 10 MWe-scale Axial Turbine w/GE
Test at 715 °C, 27000 rpm, 1/10th flow



Hanwha Integrally-Geared 10 MWe-scale Radial Turbine/Compressor: Test at 720 °C, full-flow compressor 1/10 flow turbine

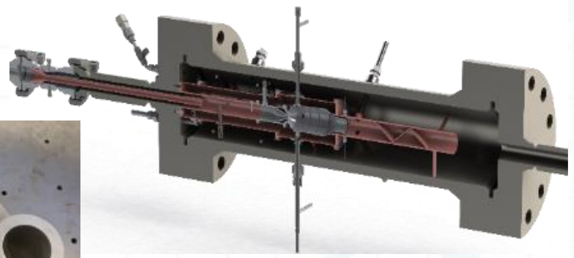


GE APOLLO 10 MWe Centrifugal Compressor w/ GE: Full-Scale Test at 27000 rpm

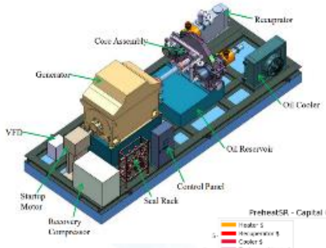


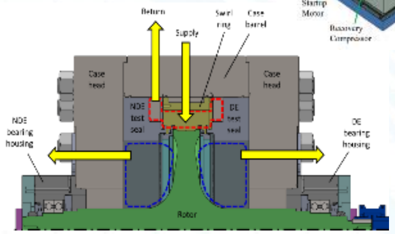
Heat Exchanger Development and Testing:

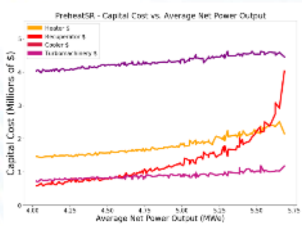
Primary Heaters, Recuperators, Wet/Dry Coolers

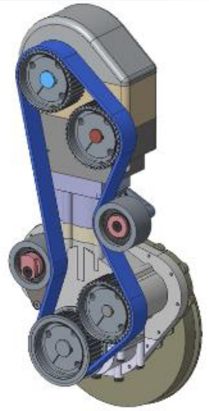


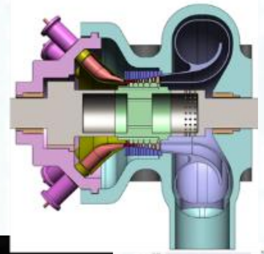
Oxy-Combustor Development and Testing

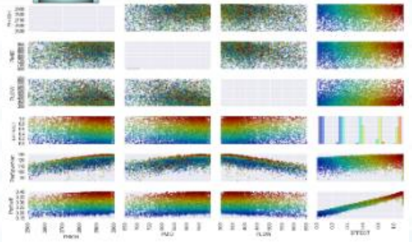








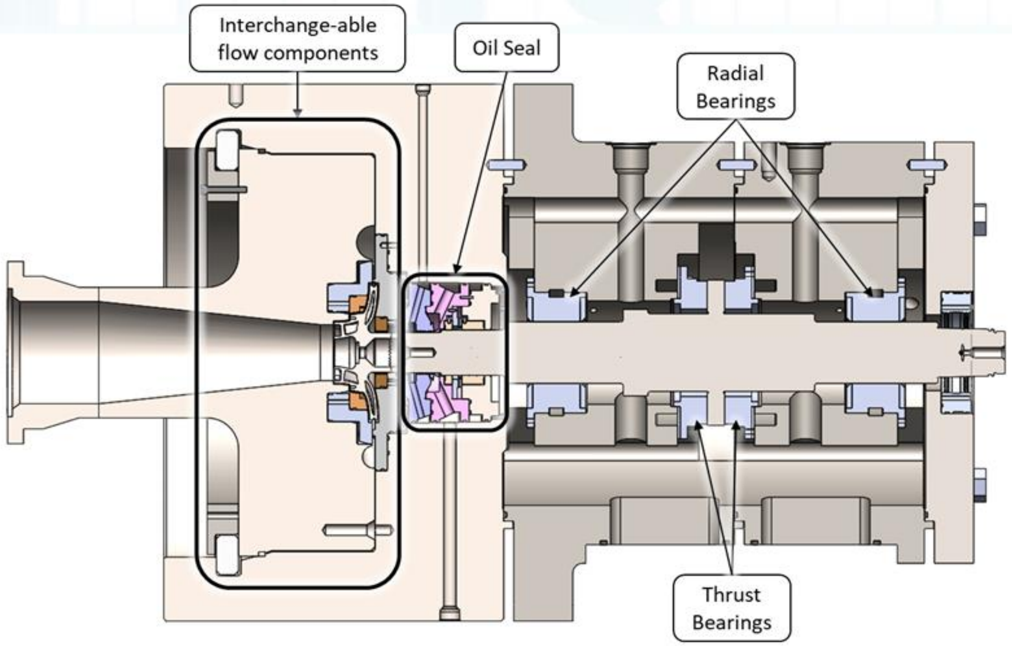




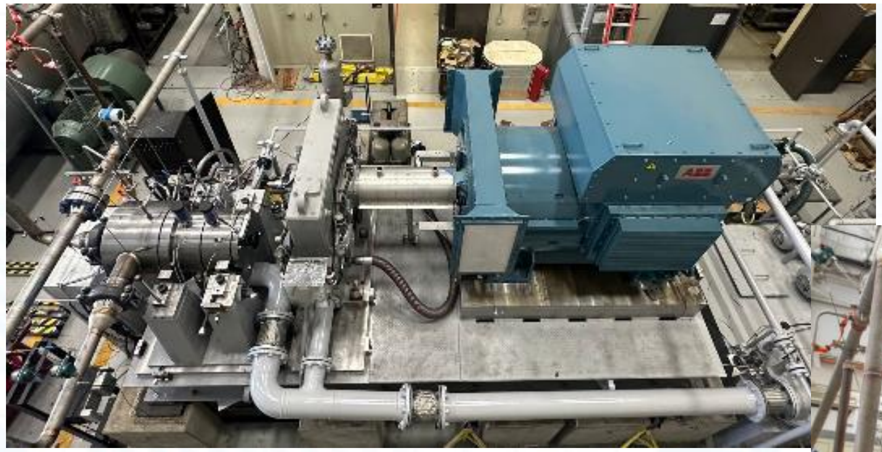
…and Seals, Economics, System Optimization, Advanced Cycles, Aero Testing, Machine Design

Sage Geosystems sCO2 Geothermal Turbine

- Geothermal turbine design and testing for Sage Geosystems
- Incorporates modular overhung aero component design and oil seals
- 3 MW design for 175 °C inlet temperature, approx. 10:1 speed-reducing gearbox
- High-speed testing completed July 2024
- Generator-loaded10-hr test at 150 °C completed September 2024



Sage turbine cross-section and major components



Sage turbine on test stand

Supercritical Transformational Electric Power (STEP) Demo Project

- $169.7*M project to design, construct, commission, and operate a 10 MWe sCO_2 demonstration power plant * Current contract: $158.6 MM/ $126.9 MM Federal / currently BP2
- **Objectives:**
  - Advance sCO_2 power from TRL3 to TRL7
  - Demonstrate pathway to net plant efficiency > 50%
  - Demonstrate control and operability at 500°C and $\geq$700°C turbine inlet temperatures with 10 MWe power generation
- **Project Partners:**
- **Industry Co-Funders:**

www.STEPdemo.us

STEP Project Objectives and SwRI Roles

Verify System Performance & Operability:

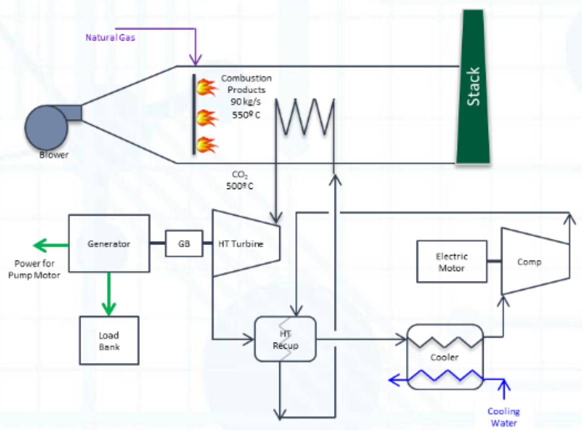
- Quantify component and system performance
- Demonstrate operation across control parameters
- Measure transient response through start-up, load change, and shutdown

Reconfigurable facility:

- Accommodate future testing

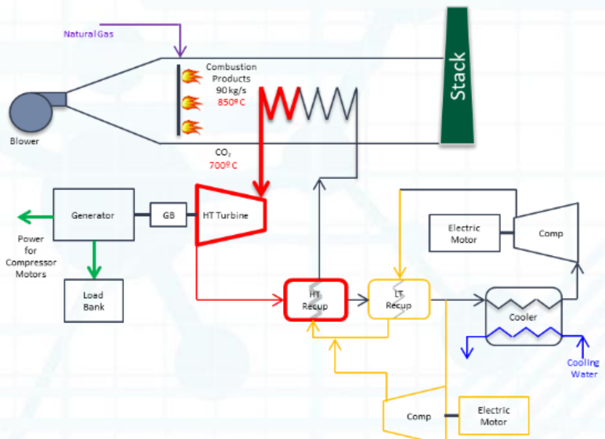
SwRI Roles:

- Host Site
- System integration and operation
- Data acquisition and controls
- Piping
- Turbine design and fabrication (with GE)
- Heater protection valve



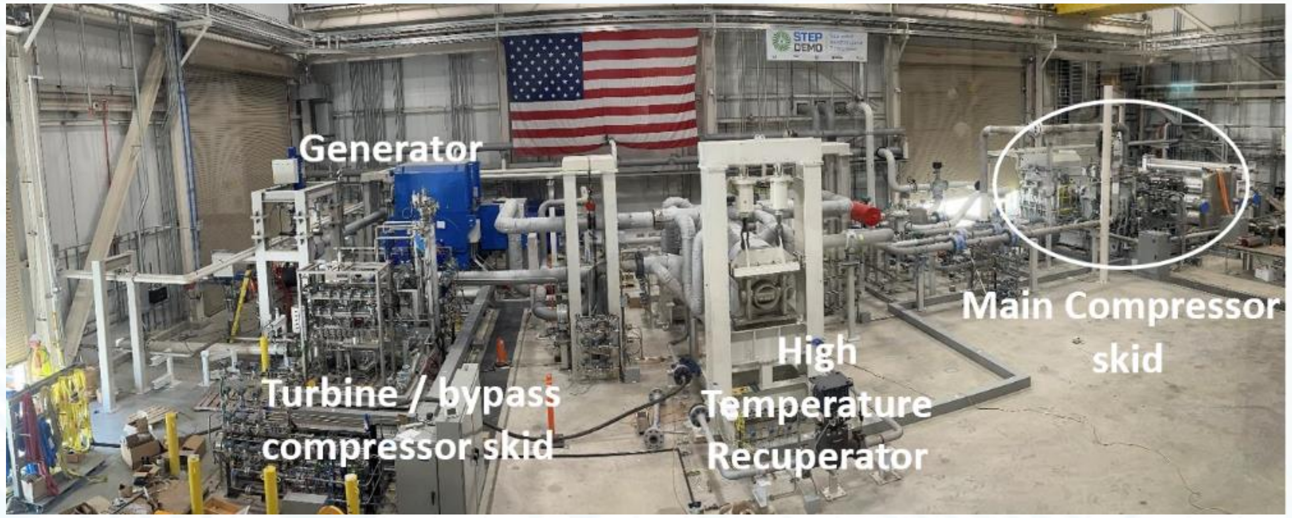
Simple Cycle

- Shortest time to initial data
- Controls & safety
- Component performance
- Steady & transient cycle data



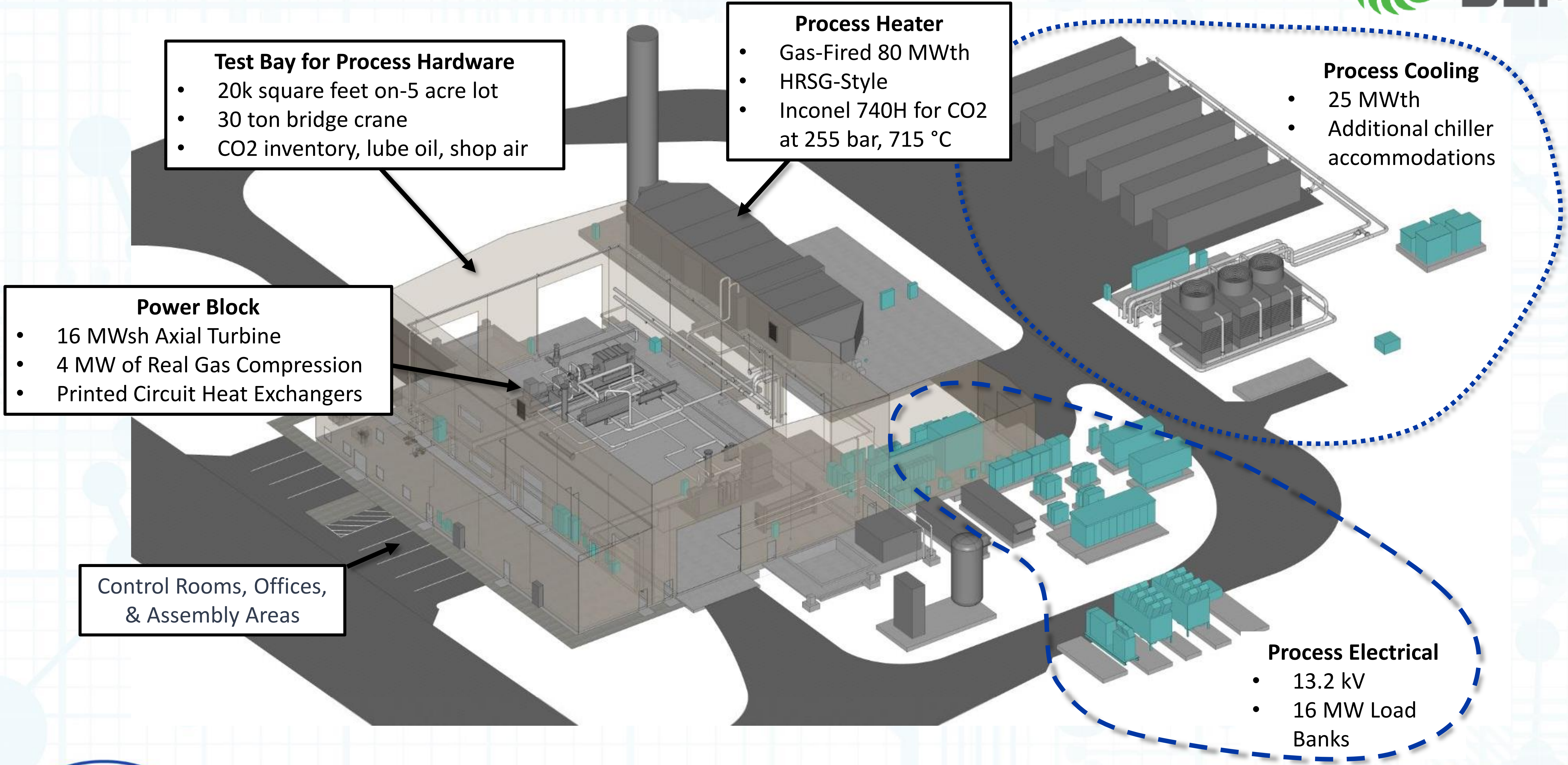
Recompression Cycle

- Inventory management
- Starting transients
- Parallel compressor control
- SOA component efficiencies
- Cycle efficiency > 50%

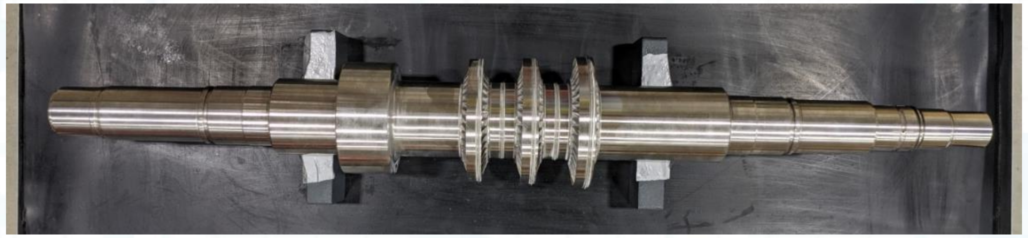


STEP Facility Layout & Specifications

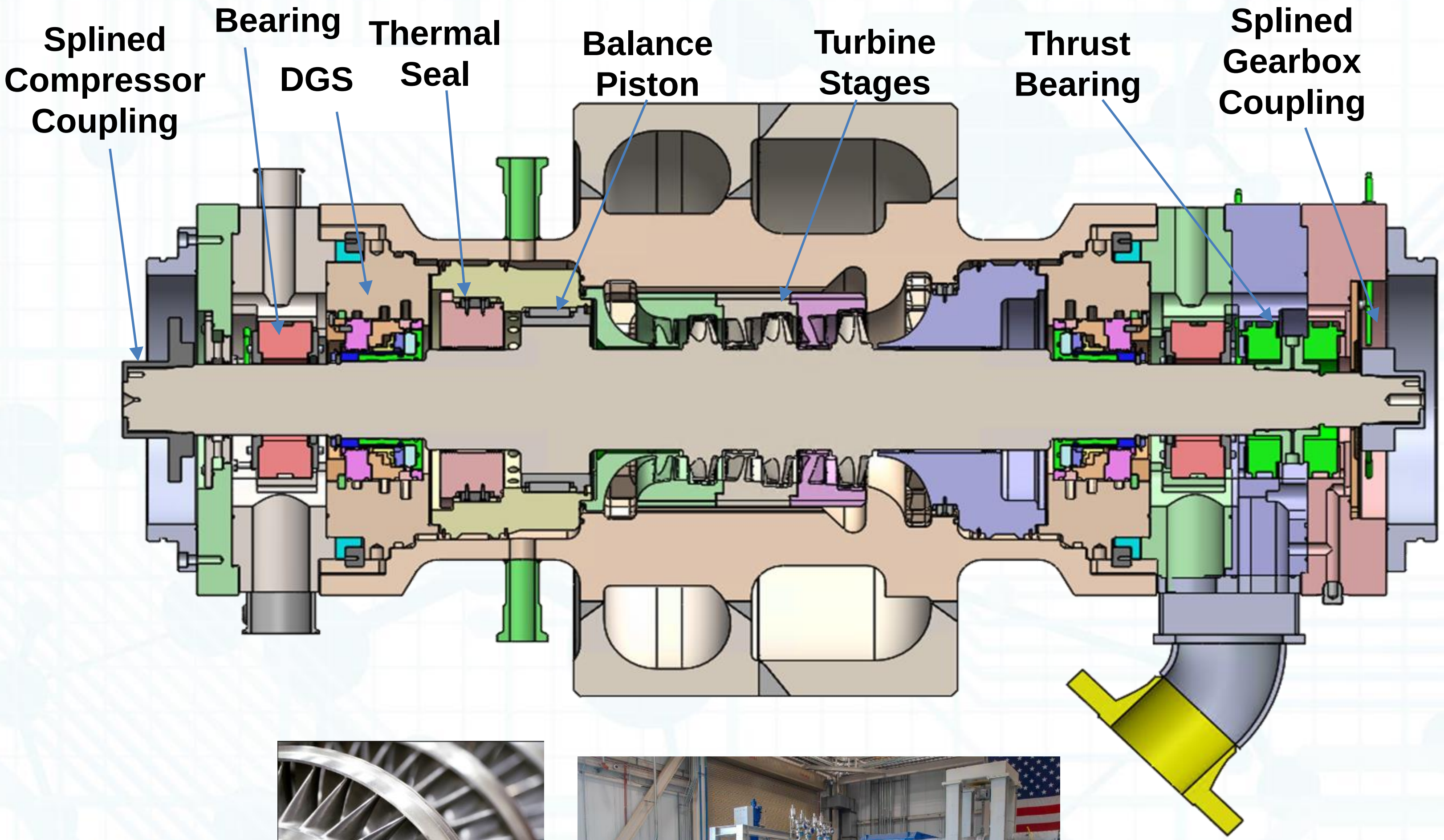
STEP DEMO



STEP Turbine Achievements

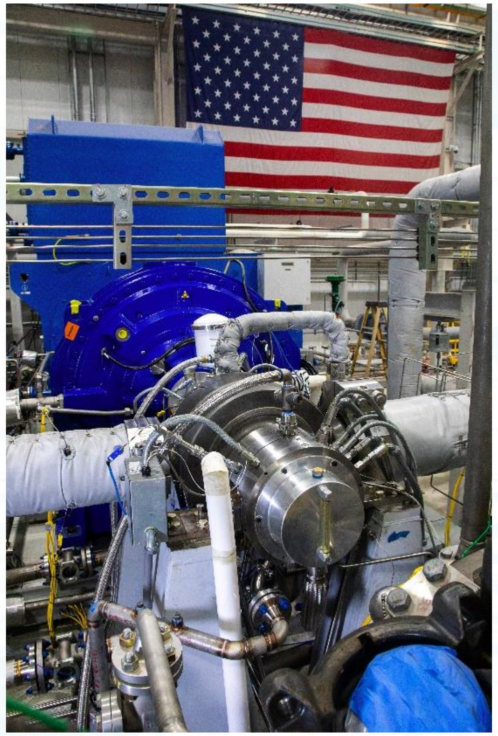


- ~1/10 the size of an equivalent steam turbine
- The world's highest power density industrial terrestrial turbine
- 16 MW (21,000 hp) produced by 86 kg (190 lb) rotor (186 kW/kg)
- Made from Nimonic 105 heat treated forging
- Airfoil shapes cut using a 5-axis electrode discharge machining (EDM) by Baker Hughes



STEP sCO_2 Technology Maturation Achievements

- Successfully demonstrated gas-fired indirect sCO_2 plant operation at 500 °C simple recuperated cycle "max" conditions generating ~4 MW net power while grid-synchronized
- All major components commercially procured except turbine jointly designed by GE Vernova and SwRI:
  - Compressors: Baker Hughes
  - Heat Exchangers: Parker Heatric, Optimus, Vacuum Process Engineering
  - Heater Protection Valve and 500 °C Turbine Trip Valve: SchuF, AVS/HORA
  - Plant Controller: GE Mark VI
- Demonstrated repeatability through multiple operations, also safely demonstrated fast and slow trips
- Plant design details available to JIP members
- Some risks remain:
  - High-temperature operation, esp. >600 °C
  - Long-duration testing



Conclusions

- sCO_2 systems have progressed through many component and now system development activities to increase technology readiness level
- Low- and medium-temperature systems are commercially available and have active commercial projects via companies like Hanwha, MAN Energy Systems, Echogen Power Systems, and others for waste heat recovery, heat pumps, and energy storage
- STEP demonstration has advanced simple recuperated sCO_2 cycles up to 500 °C through full-scale pilot testing
- Opportunities exist in geothermal, but are configuration-dependent. Clear efficiency advantages for thermosiphon-based and high-temperature geothermal applications.