Technology Developments for Geothermal Power and Energy Storage

SOUTHWEST RESEARCH INSTITUTE®

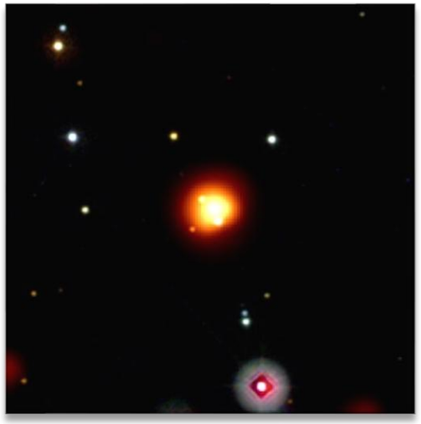
SAME San Antonio Post Meeting
February 25, 2026

Tim Allison, Ph.D.
Director, Machinery Department

SwRI is an Applied Research & Development Company

- Founded in 1947, based in San Antonio, Texas
- 501 (c)(3) nonprofit corporation
  - Internal Research
  - New Laboratories
- ~$900M Annual revenue from contract work for industry and government clients
- Over 3,000 employees
- 1,500-acre facility; 2.3 million square feet of laboratories & offices
- Customer-Centric IP policy

Deep Sea to Deep Space®...



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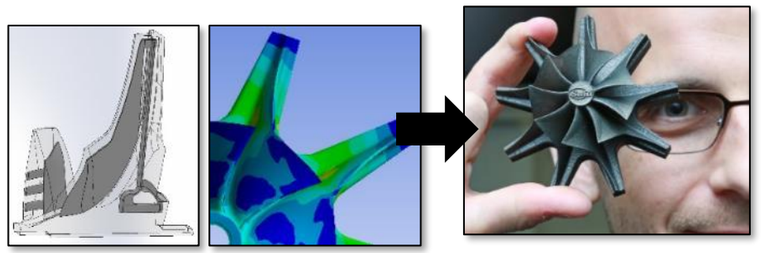
SwRI Machinery Department

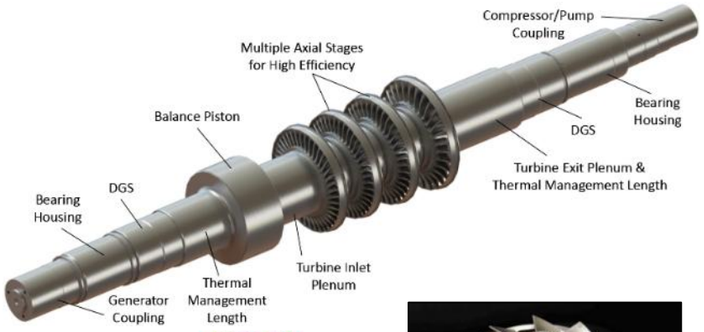
Applied Research centered around Rotating Machinery and associated systems for

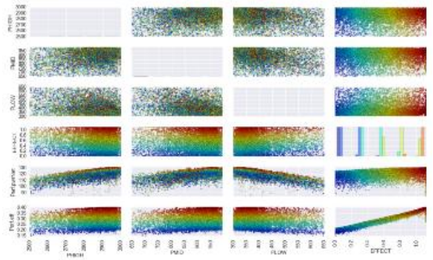
- Oil & Gas
- Aerospace Propulsion
- Power Generation
- Industrial Machinery

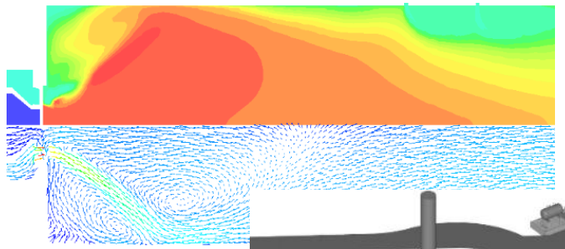
Expertise including developing technologies, prototype demonstration, and mature products and systems

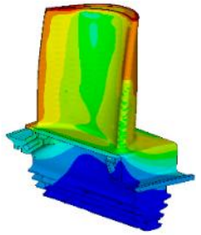
- >85 Staff
- 5 labs; open/closed-loop test facilities; powertrains up to 15 MW shaft power
- New flammable gas lab capable of hydrogen, hydrocarbons, organic fluids
- Field testing and troubleshooting
- Support OEMs in transitioning new technologies to products

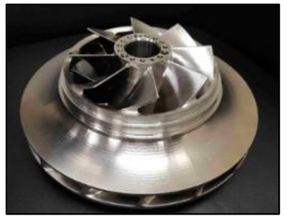


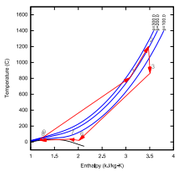


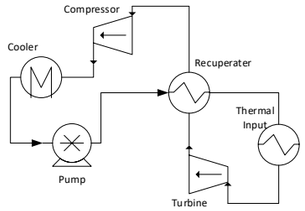


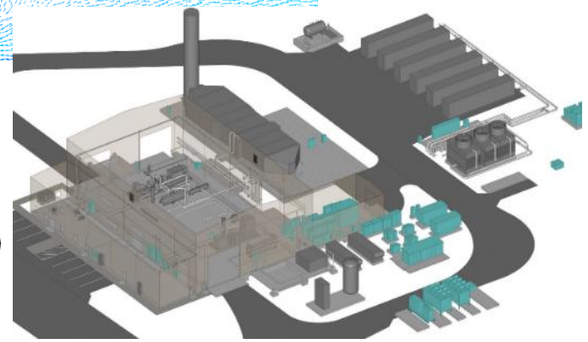


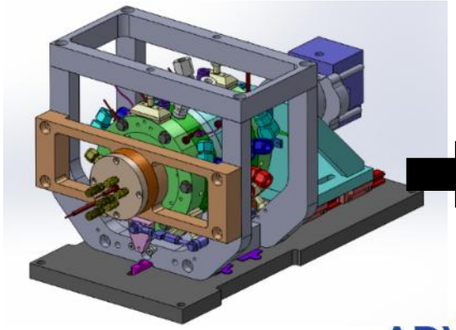


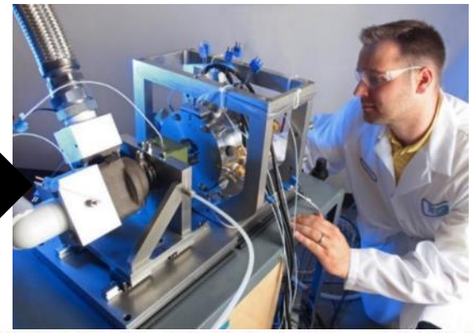


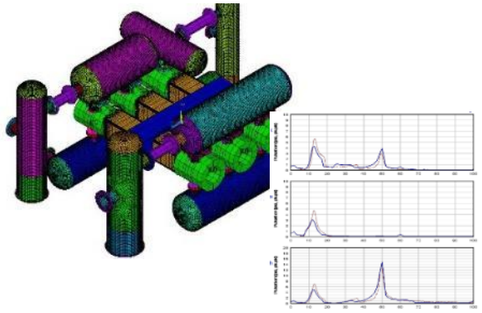












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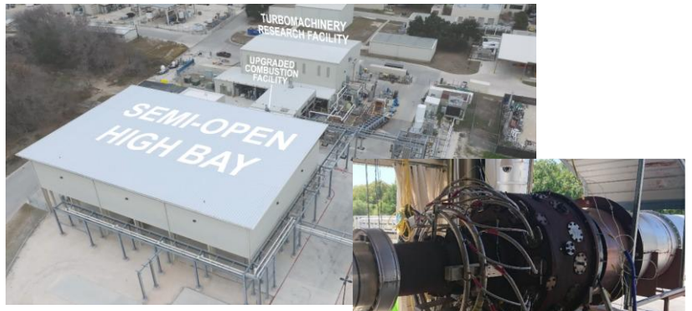
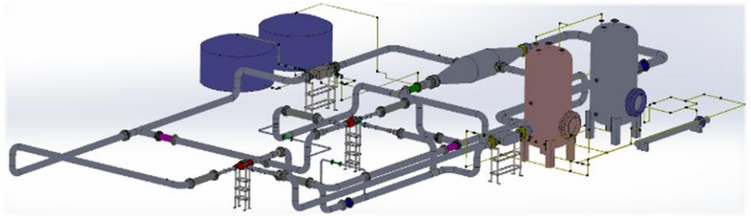
Energy R&D at SwRI

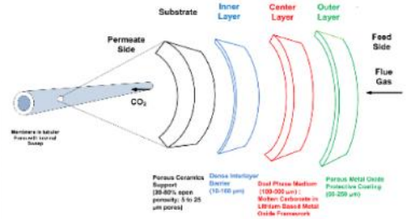
Supercritical CO_2 Power Systems



Gas Turbines

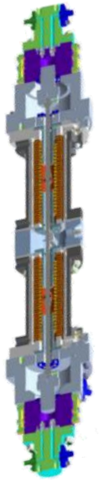


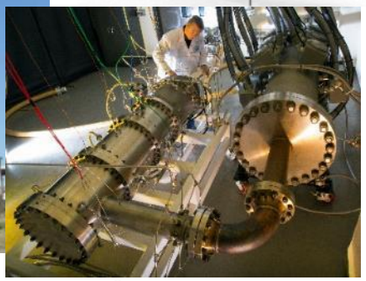
Energy Storage



Carbon Capture, Transport, Utilization

Low-Carbon Fuels (Hydrogen, Ammonia)





Industrial Processes / Onsite Power and Heat

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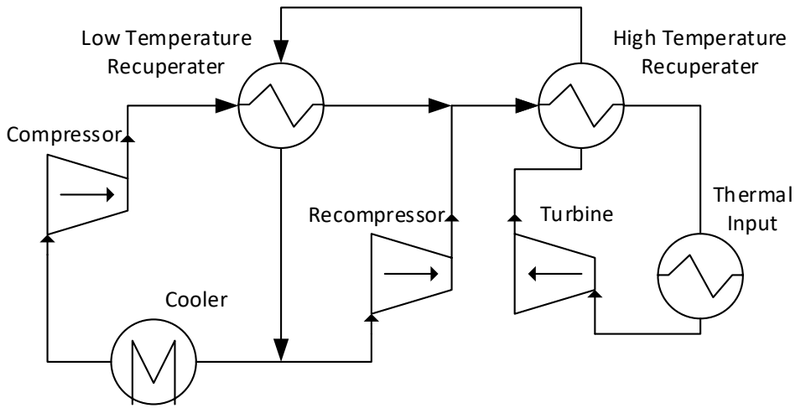
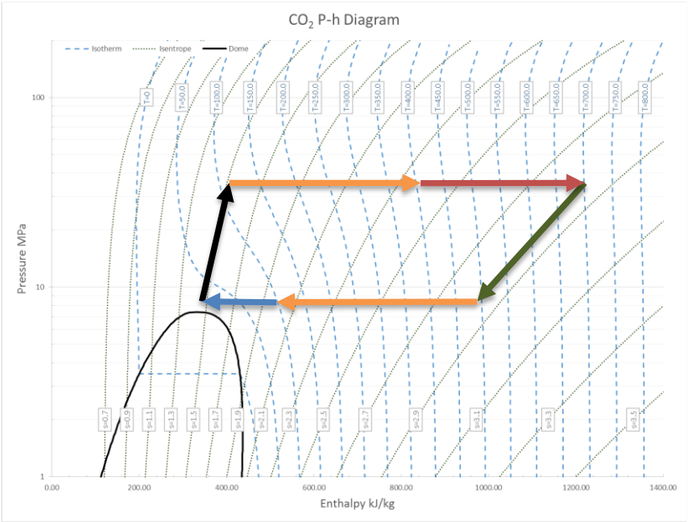
Supercritical Carbon Dioxide (sCO_2) Cycles

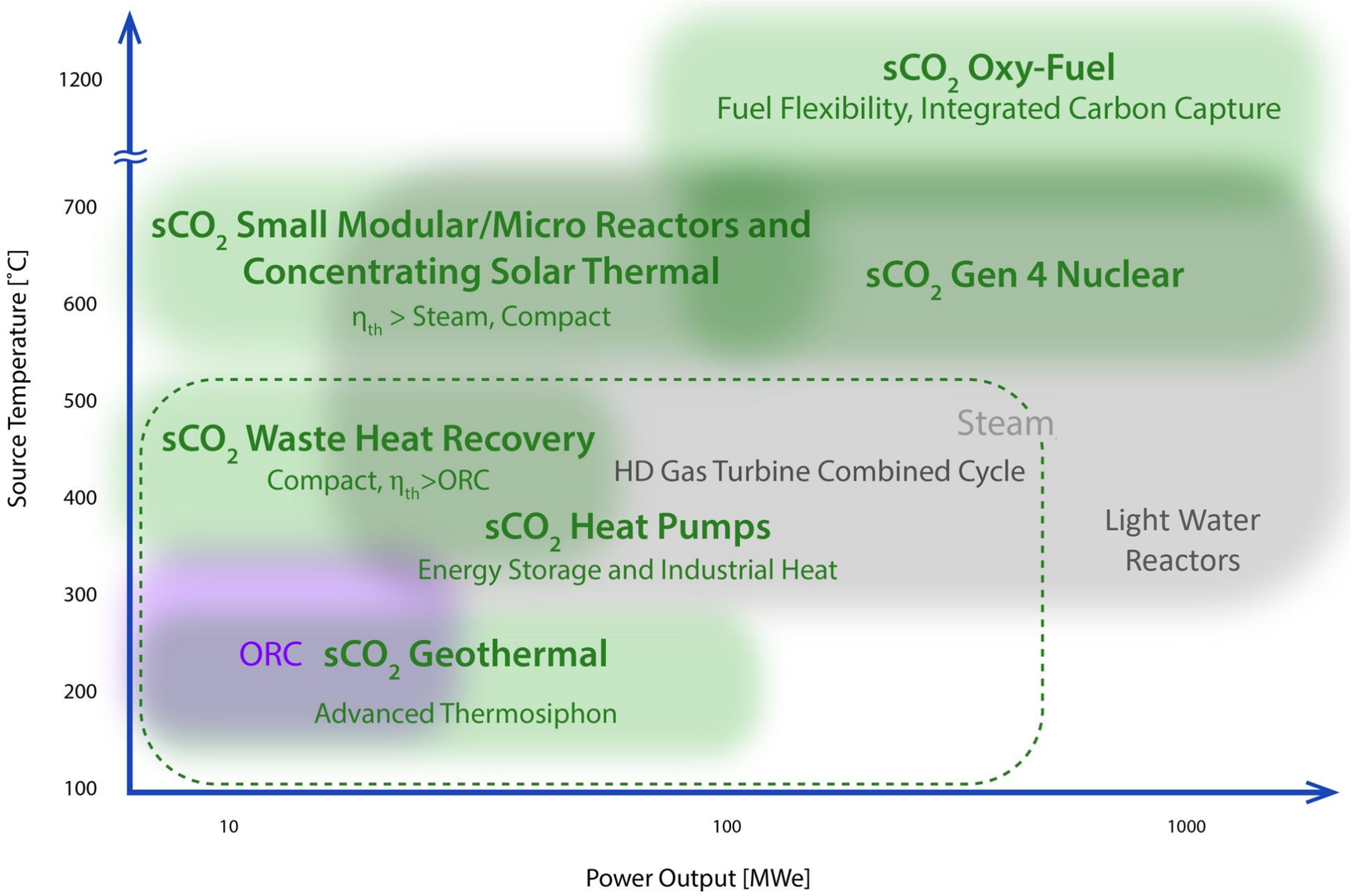
- Investigated since early 1900s, revisited since 1999, enabled by new technologies
- Favorable fluid properties relative to steam:
  - Inert
  - Non-toxic at low concentrations
  - Unfreezable above 5.11 atm
  - Thermally stable at temperatures up to1700 °C
  - High density → turbine power density ~10x 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,
- Nearing commercialization…
  - 70 MW heat pump in operation since Dec 2024 by Everllence
- STEP 10 MWe Demonstration achieved Simple Cycle operation Sept 2024



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

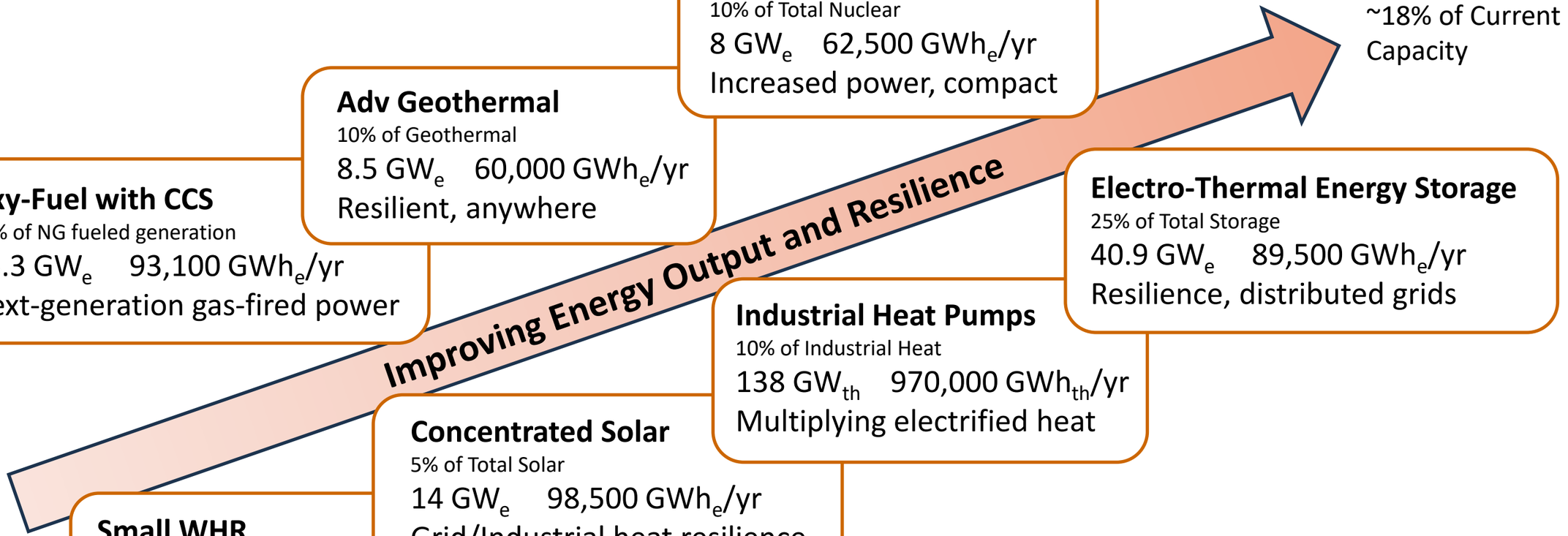


sCO_2 Power System Application Space



sCO_2 Applications – Unleashing Energy Innovation

Potential U.S. Electric and Energy Impacts by 2050



Total Potential
232 GW, 1.4 TWh/yr
~18% of Current US Electric Capacity

Next Gen Nuclear
10% of Total Nuclear
8 GW_e 62,500 GWh_e/yr
Increased power, compact

Adv Geothermal
10% of Geothermal
8.5 GW_e 60,000 GWh_e/yr
Resilient, anywhere

Oxy-Fuel with CCS
10% of NG fueled generation
13.3 GW_e 93,100 GWh_e/yr
Next-generation gas-fired power

Electro-Thermal Energy Storage
25% of Total Storage
40.9 GW_e 89,500 GWh_e/yr
Resilience, distributed grids

Industrial Heat Pumps
10% of Industrial Heat
138 GW_{th} 970,000 GWh_{th}/yr
Multiplying electrified heat

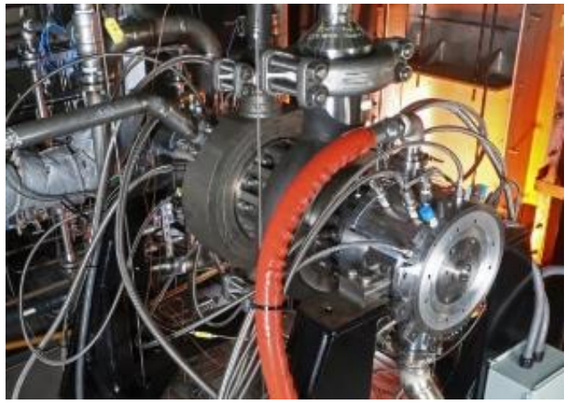
Concentrated Solar
5% of Total Solar
14 GW_e 98,500 GWh_e/yr
Grid/Industrial heat resilience

Small WHR
25% of SCGT Installed Base
9.3 GW_e 10,700 GWh_e/yr
Increased power >30%

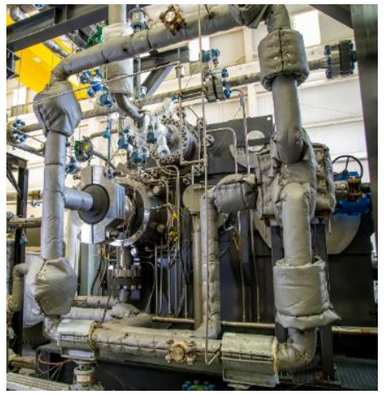
% = Assumed market penetration
GW_e or GW_{th} = installed capacity
GWh_e /yr or GWh_{th}/yr = energy delivered
Primary data source: eia annual energy outlook

SwRI Development Work for sCO_2 Cycles, Components, Systems

Design, Fabrication, Testing of 10 MWe-Scale Machinery

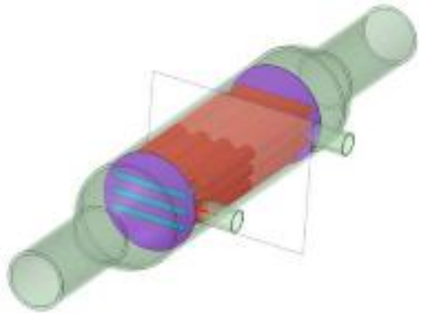


SunShot 10 MWe-scale Axial Turbine w/GE
Test at 715 °C, 27000 rpm, 1/10th flow



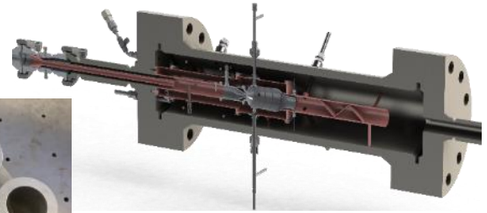
Hanwha Integrally-Geared 10 MWe-scale Radial Turbine/Compressor: Test at 720 °C, full-flow compressor 1/10 flow turbine

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

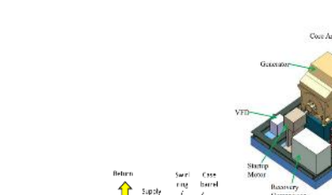


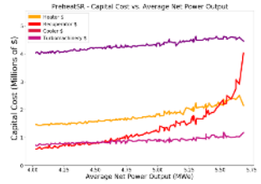
Heat Exchanger Development and Testing:

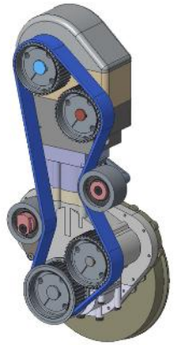
Primary Heaters, Recuperators, Wet/Dry Coolers

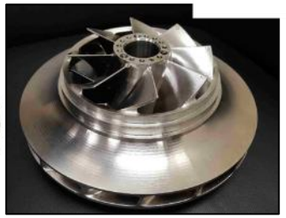


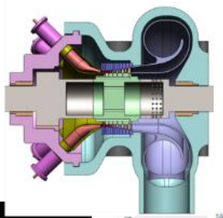
Oxy-Combustor Development and Testing

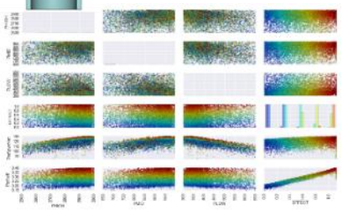












…and Seals, Economics, System Optimization, Advanced Cycles, Aero Testing, Machine Design

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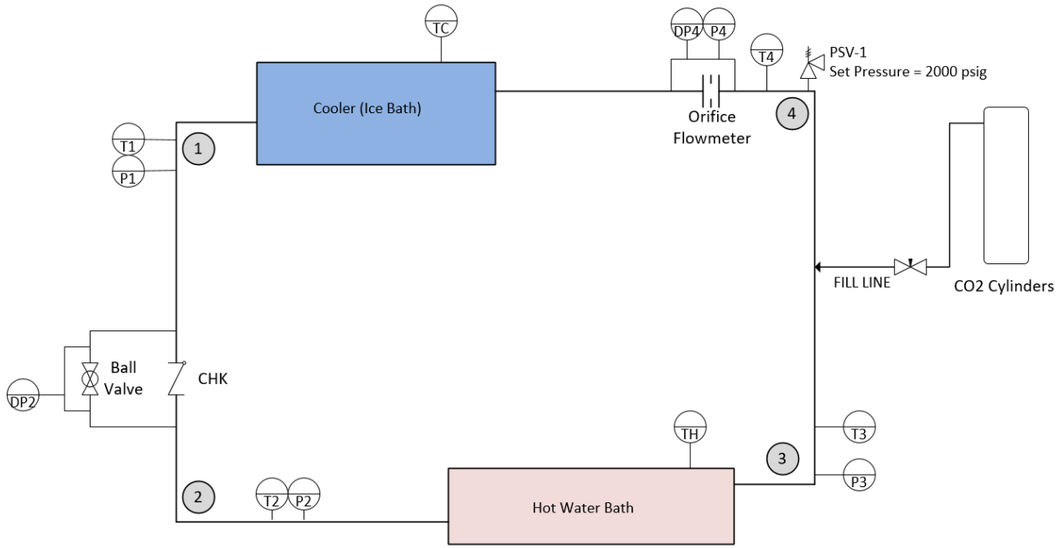
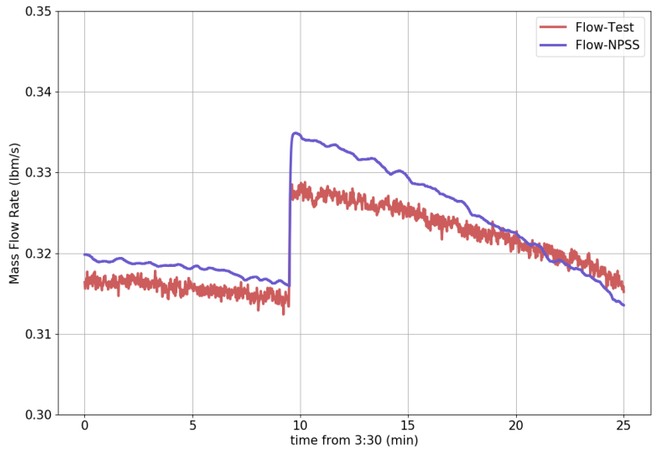
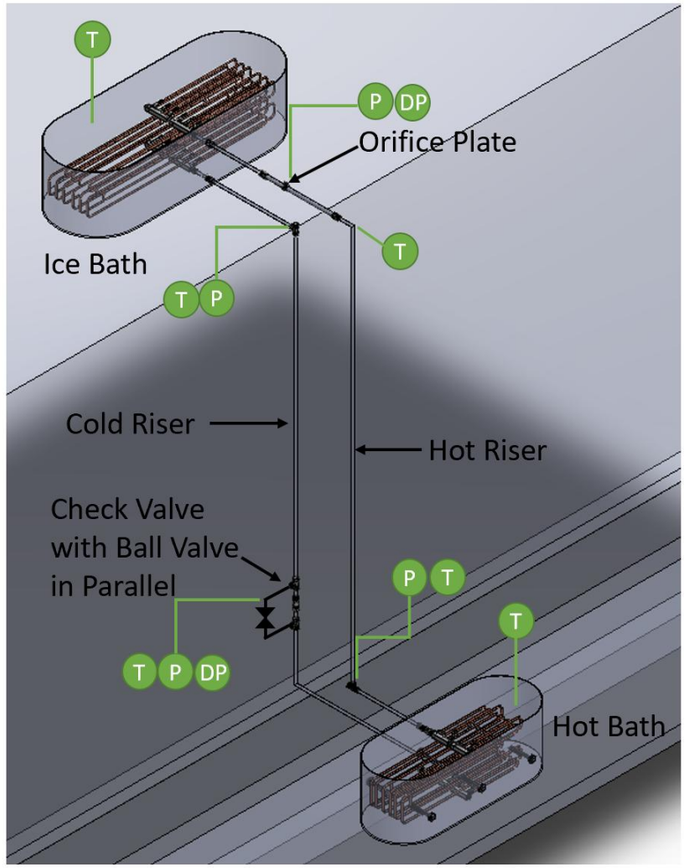
Natural Convection Modeling & Testing



Lab-Scale Natural Convection P&ID

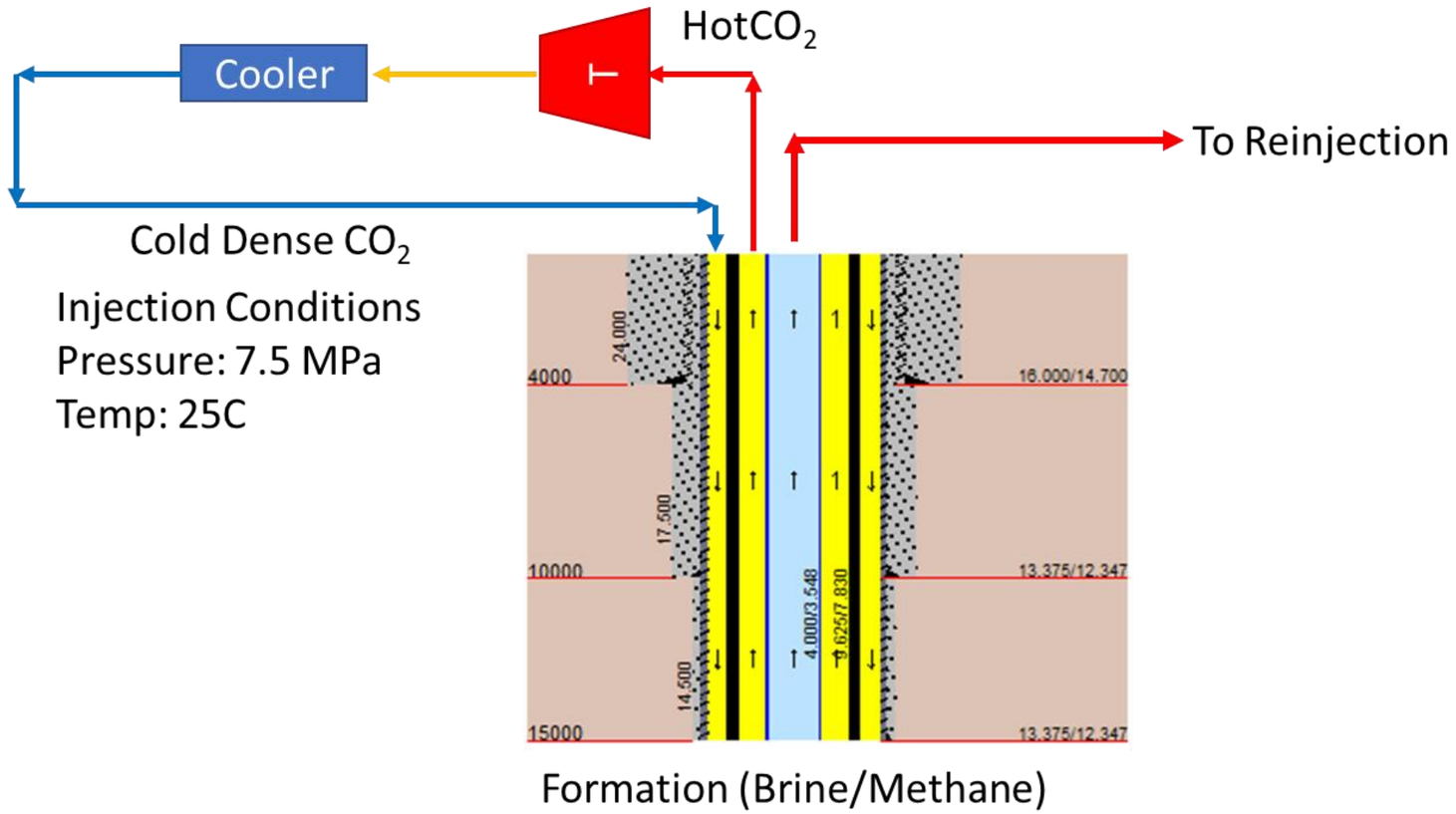


Lab-Scale Natural Convection Test Data



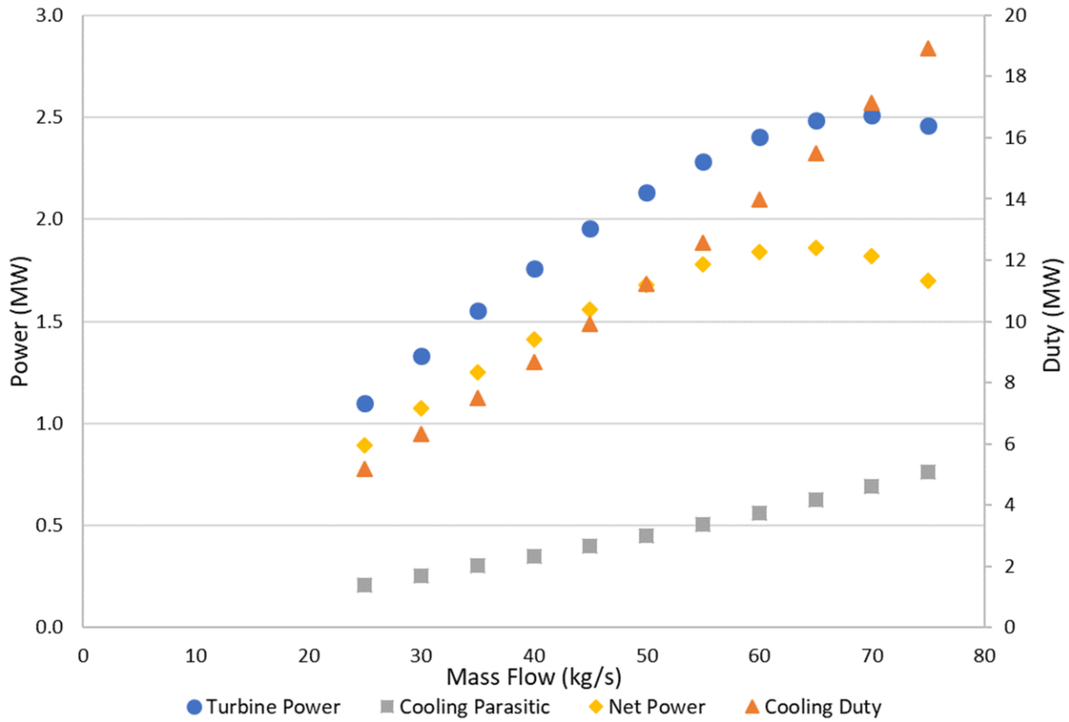
Lab-Scale Natural Convection Test Loop

Geothermal Thermosiphon Modeling



Geopressured formation with closed loop thermosiphon

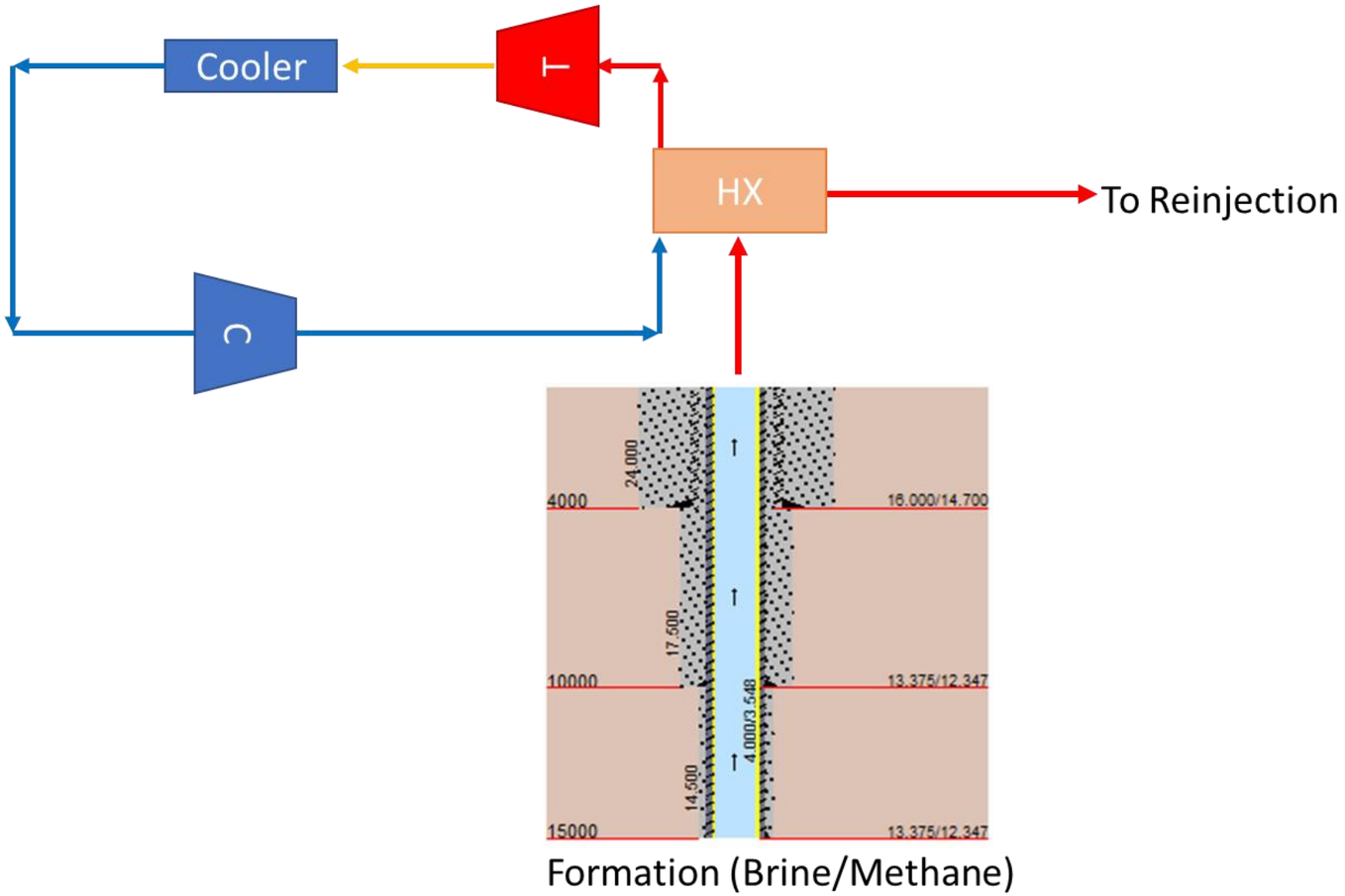
Model Description



Geopressured formation with closed loop thermosiphon

Results

Cycle Modeling

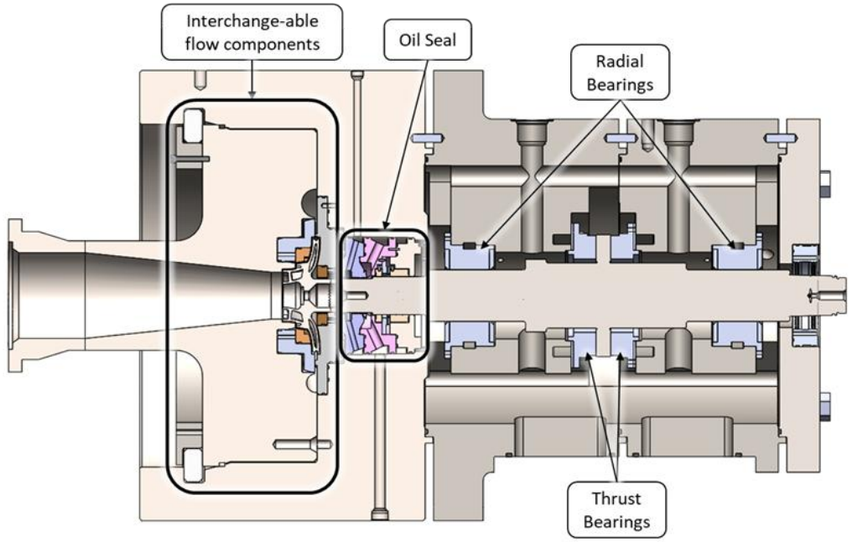


Geopressured formation with Binary Plant

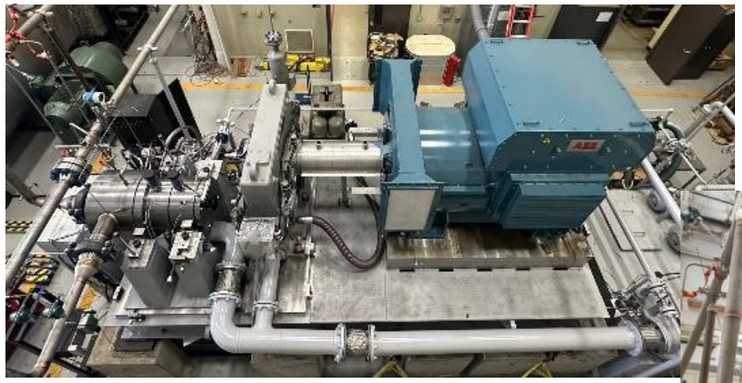
- Binary Plants
- Thermosiphon
- Organic Rankine Cycles
- sCO2
- Alternate refrigerants/mixtures

Sage Geosystems sCO_2 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

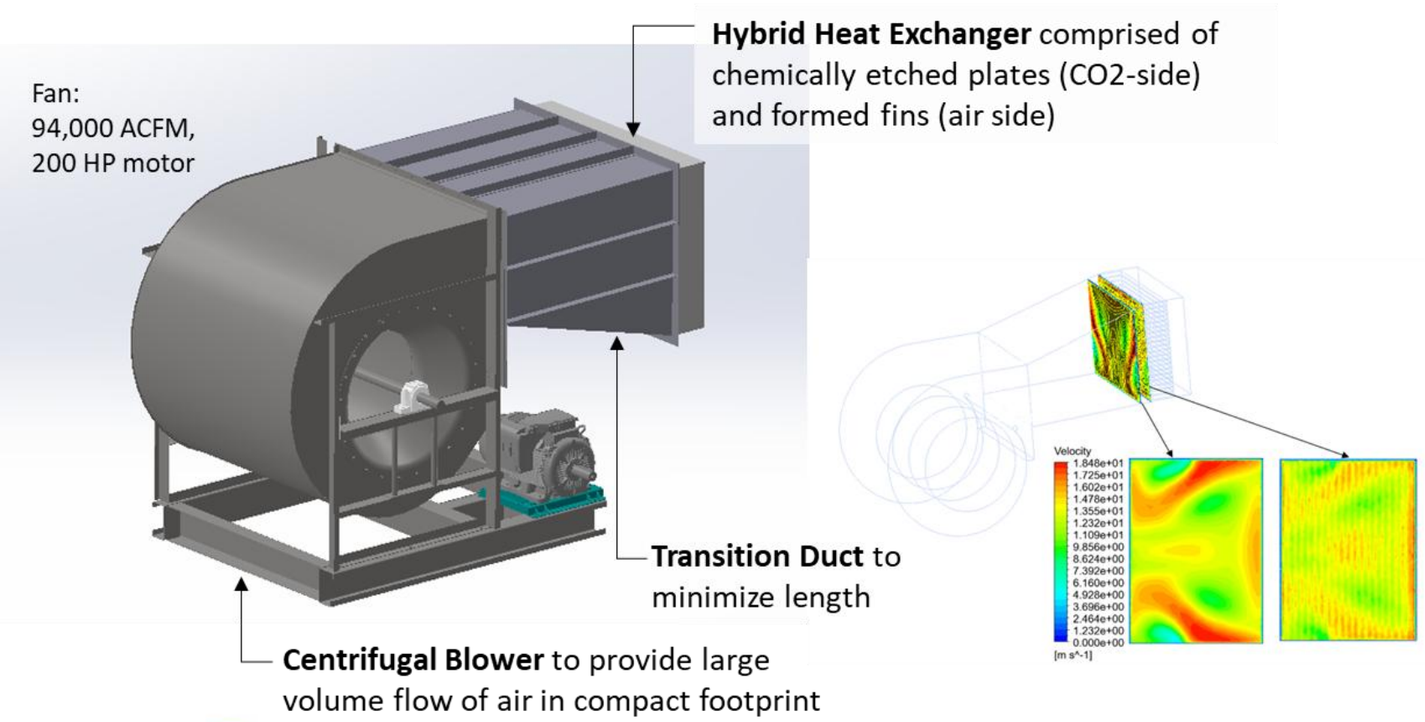


Sage turbine on test stand

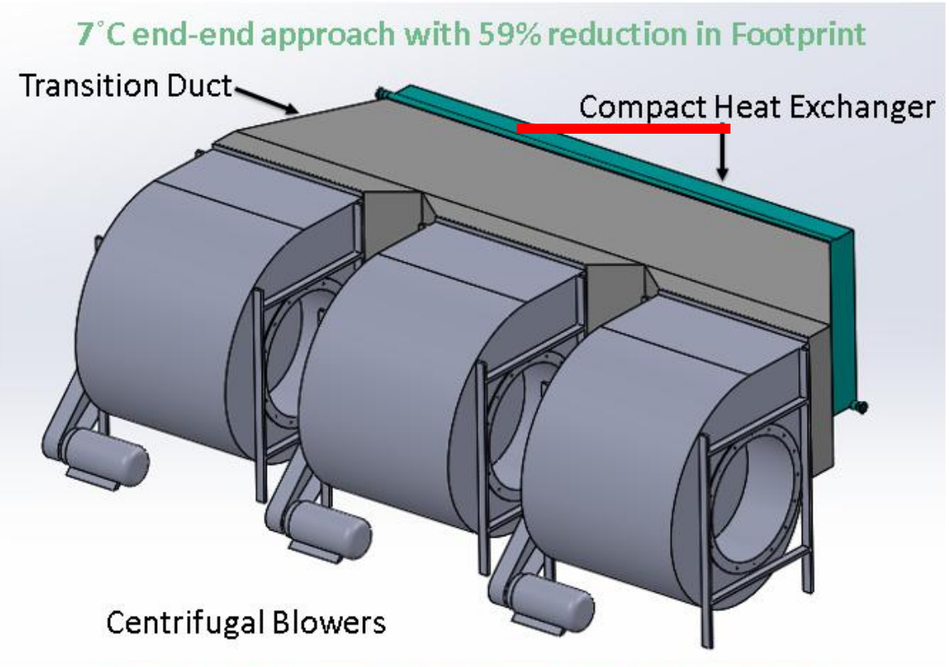
Improved Cooling for sCO_2 Cycles

- Development of a dry cooler system that can meet the requirements of an sCO2 power cycle while
  i. Reducing installation footprint as compared to the state of the art
  ii. Improving on LCOE
- Partnered with VPE and supported by DOE EERE.
- Investigated alternative novel cooling strategies for the thermosiphon cycle

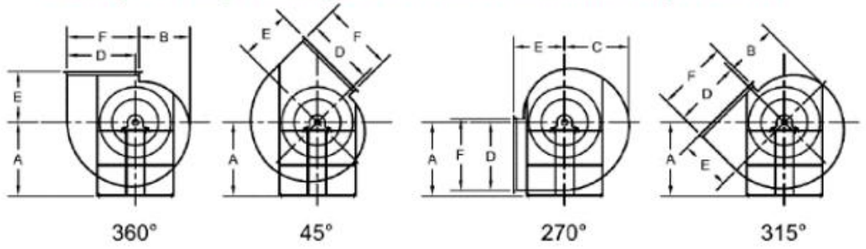
1 MWth Demonstration Unit



5 MWth Commercial Module



Concept is easily reconfigurable to meet installation requirements.



Supercritical Transformational Electric Power (STEP) Demo Project

STEP DEMO GTI ENERGY

- $169.7M project to design, construct, commission, and operate a 10 MWe sCO_2 demonstration power plant
- **Objectives:**
  - Advance sCO_2 power from TRL3 to TRL7
  - Demonstrate pathway to net plant efficiency > 50%
  - Demonstrate control and operability at 500°C and ≥700°C turbine inlet temperatures with 10 MWe power generation
- **Project Partners:**

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY | GTI ENERGY | SwRI | GE VERNOVA

- **Industry Co-Funders:**

KEPCO KOREA ELECTRIC CORPORATION | PETROBRAS | Natural Resources Canada / Ressources naturelles Canada / Canada | Southern Company | TEXAS COMMISSION ON ENVIRONMENTAL QUALITY | ENGIE | SPECTRUM IMPACT | CSIRO | AMERICAN ELECTRIC POWER BOUNDLESS ENERGY | EGAT Power for Thai Happiness

www.STEPdemo.us

STEP Project Objectives and SwRI Roles

Verify System Performance & Operability:

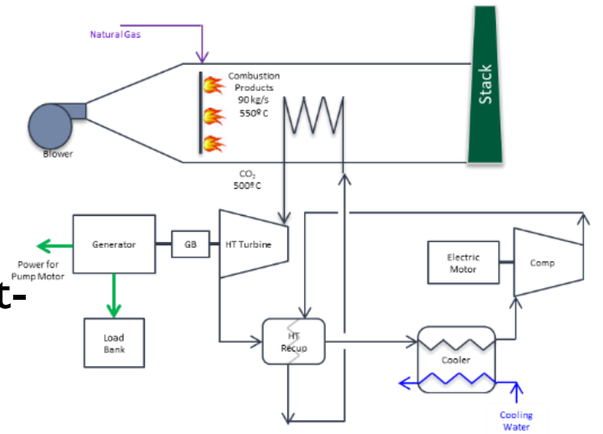
- Quantify component and system performance
- Demonstrate operation across control parameters
- Measure transient response through start-up, load change, and shutdown

Reconfigurable facility:

- Accommodate future testing

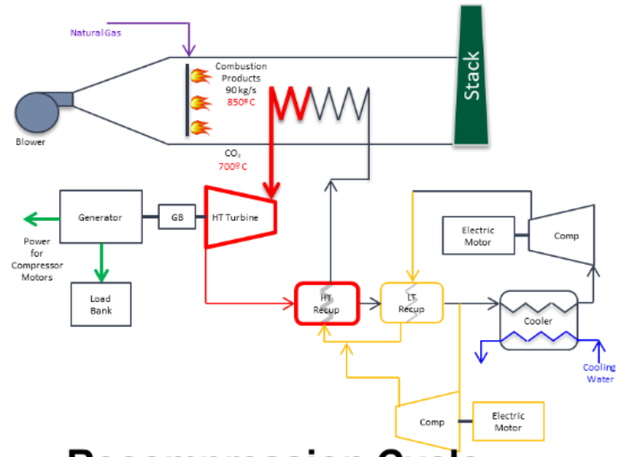
SwRI Roles:

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



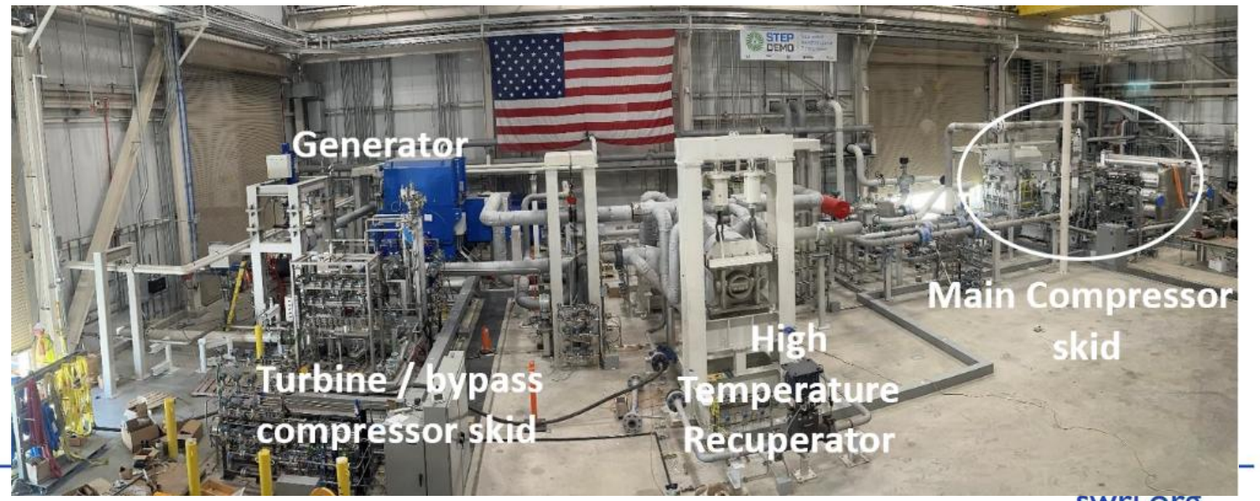
Simple Cycle

- 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

Test Bay for Process Hardware
- 20k square feet on-5 acre lot
- 30 ton bridge crane
- CO2 inventory, lube oil, shop air

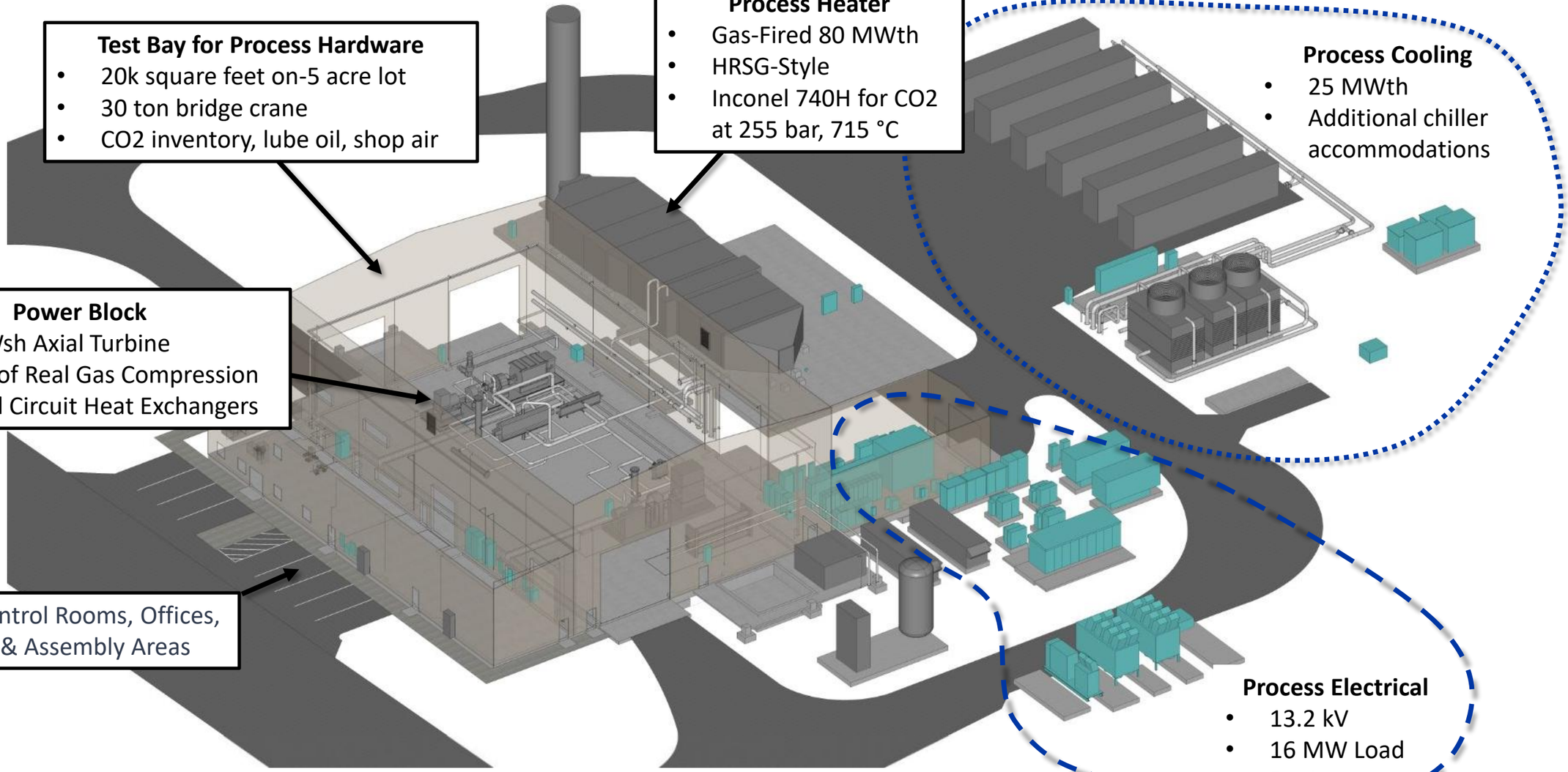
Process Heater
- Gas-Fired 80 MWth
- HRSG-Style
- Inconel 740H for CO2 at 255 bar, 715 °C

Process Cooling
- 25 MWth
- Additional chiller accommodations

Power Block
- 16 MWsh Axial Turbine
- 4 MW of Real Gas Compression
- Printed Circuit Heat Exchangers

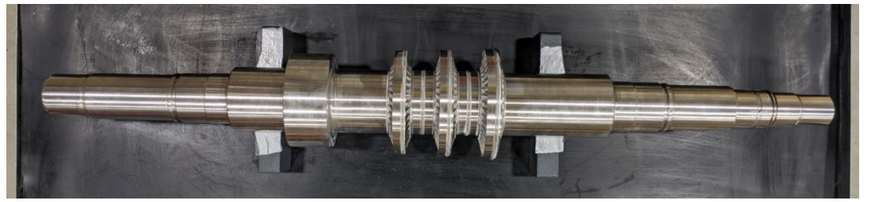
Control Rooms, Offices, & Assembly Areas

Process Electrical
- 13.2 kV
- 16 MW Load Banks



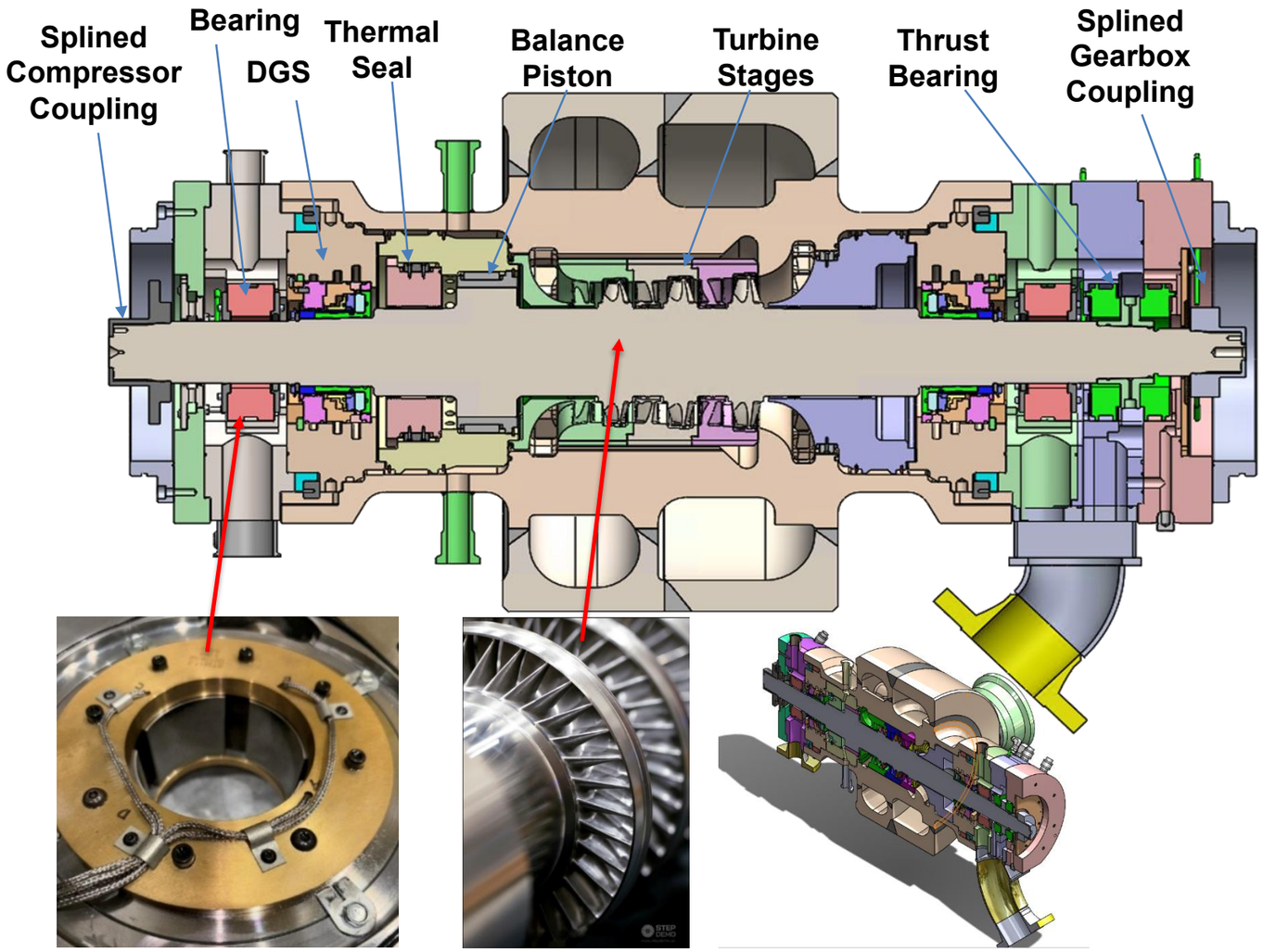
STEP Facility

STEP Turbine Design



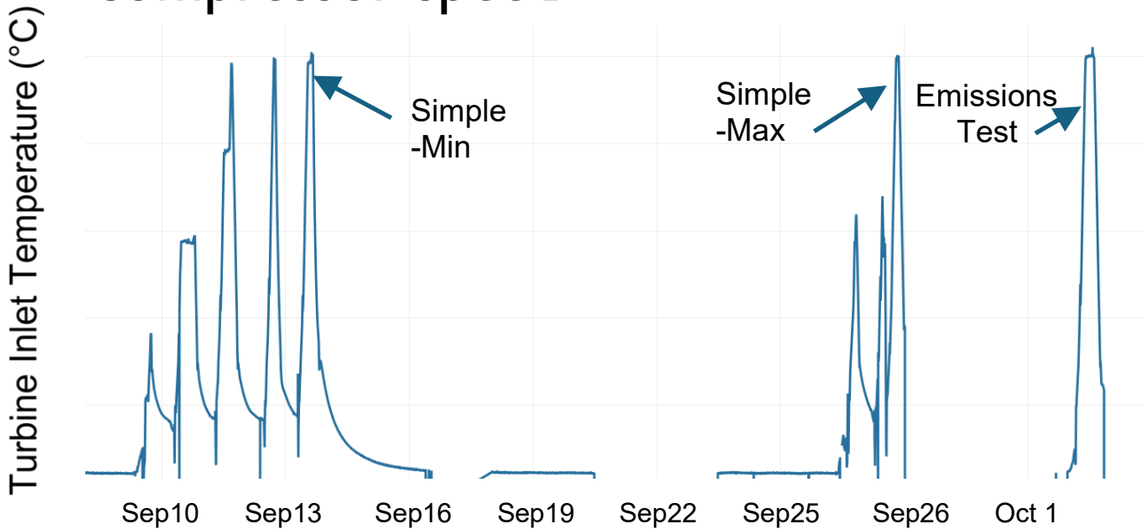
STEP DEMO

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



STEP Simple Cycle Test Program

- Test program of increasing speed, temperature, and power reaching 500°C
- "Simple Max/Min" refer to mass flow, controlled by IGV position and compressor speed

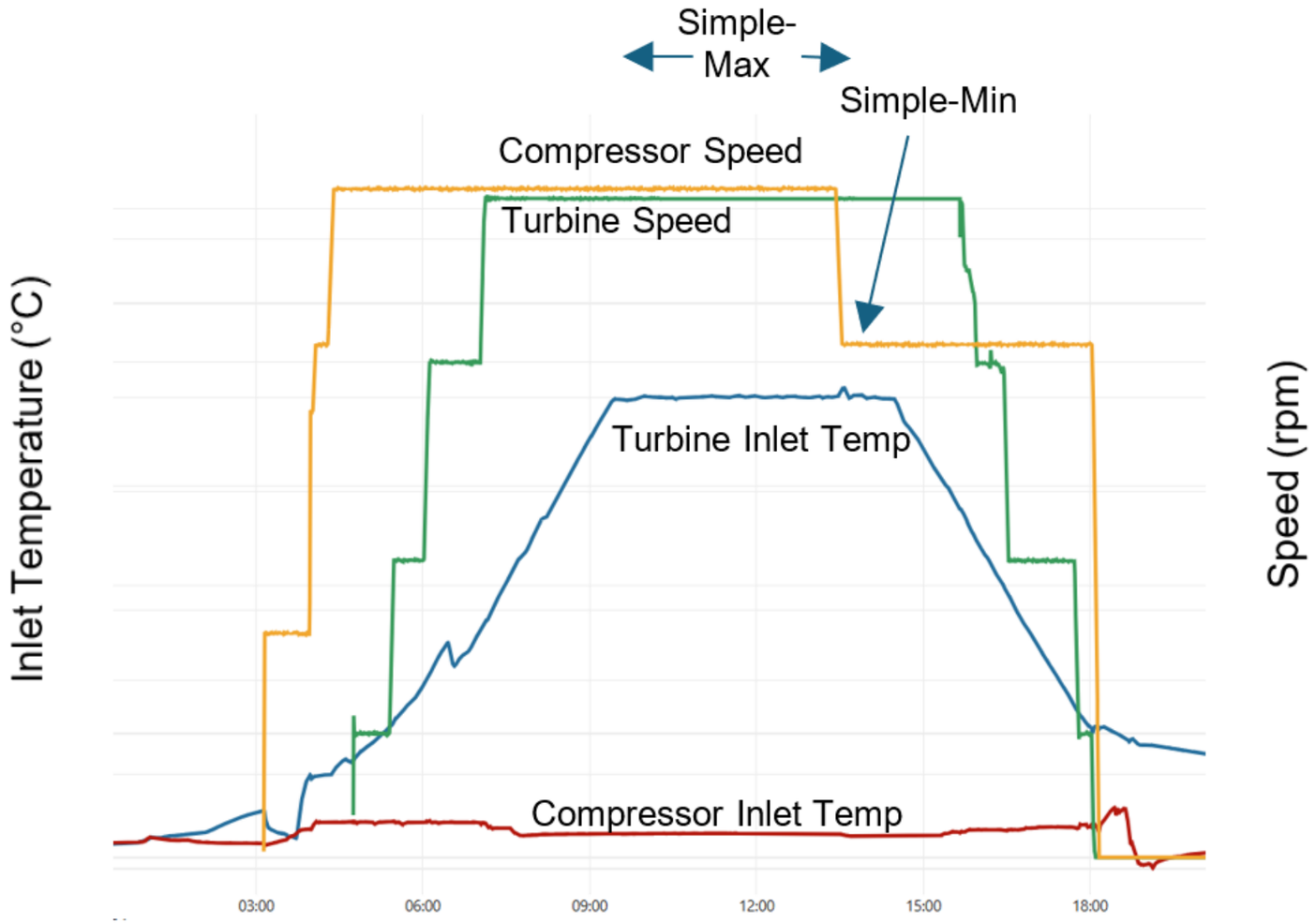


Parameter	Simple-Min	Simple-Max
Turbine Speed	26,620 rpm	26,620 rpm
Inlet/Exit Pressure	164/93 bar	206/94 bar
Inlet Temperature	500°C	500°C
Mass Flow	70.6 kg/s	93.4 kg/s

Goal	Max Power	Trip
Verify turbine at full speed and high temperature with low load to check performance	100 kW on Load Banks	N/A
500°C TIT with Load Banks	150 kW on Load Banks	N/A
Ammonia injection in the heater for emissions reduction	290 kW on Load Banks	Turbine Gearbox vibrations
Achieve Simple Min	2.6 MW on Load Banks	Overvoltage resulting on a turbine overspeed
Grid synchronize	1.1 MW to Grid	No current measured on breaker bus
Achieve Simple Max	8.3 MW aero 7.4 MW generator 3.9 MW to Grid	N/A
Emission Testing at Simple Max, Repeat Simple Min	3.9 MW gross power to Grid	N/A

6-Hour Emissions Test

- A 6-hour emissions test required to verify natural gas heater emissions test
- Both Simple Cycle maximum and minimum power conditions demonstrated

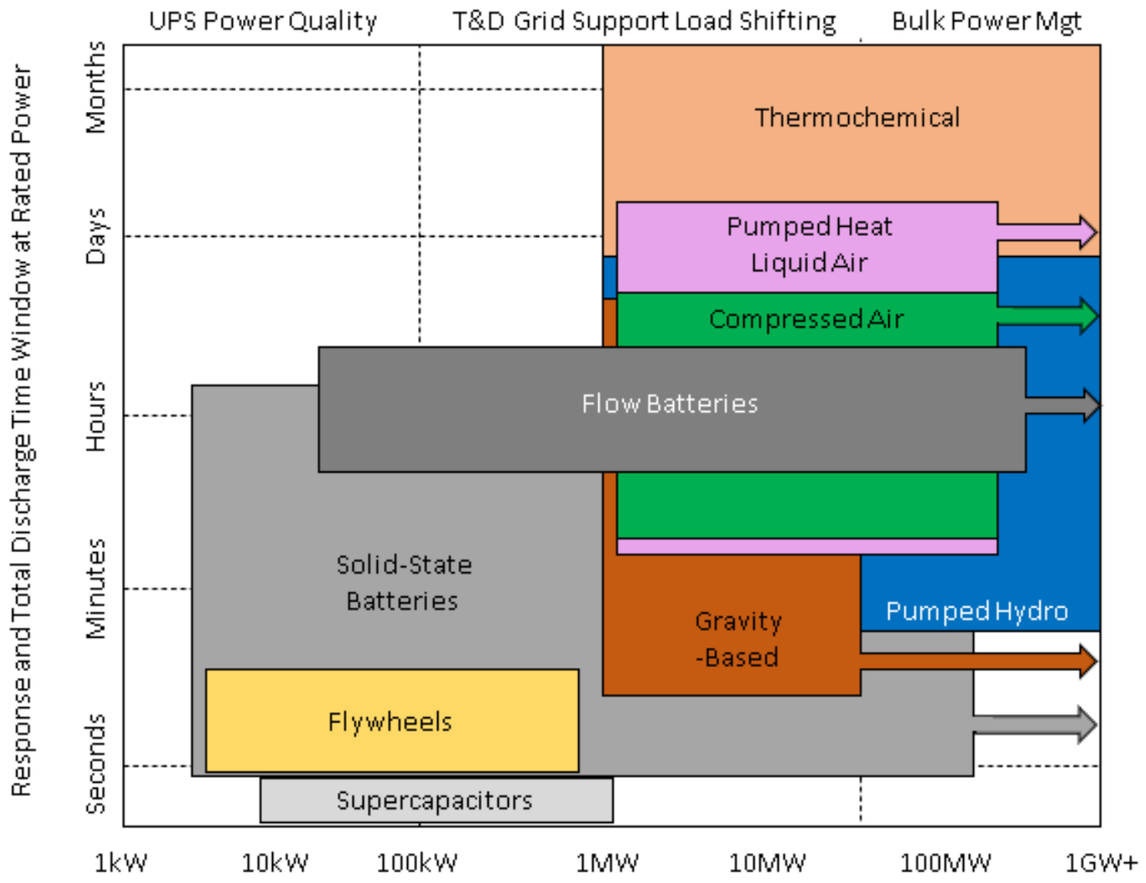


STEP sCO_2 Technology Maturation Achievements

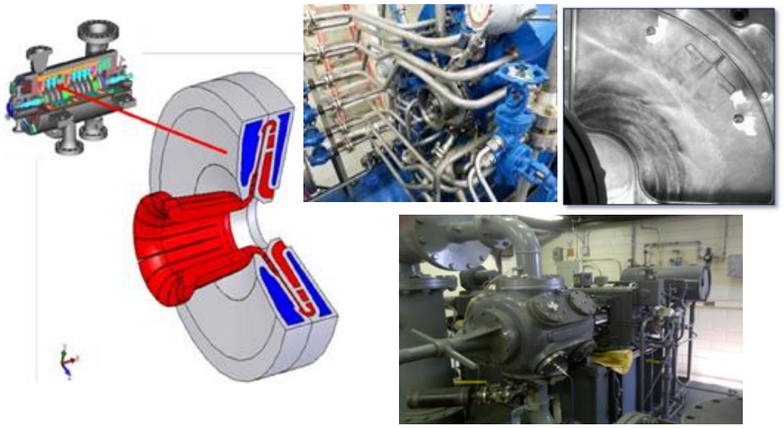
- Successfully demonstrated gas-fired indirect sCO_2 plant operation at 500 °C simple recuperated cycle "max" conditions generating ~4 MW net power while grid-synchronized
- All major components commercially procured except turbine jointly designed by GE Vernova and SwRI:
  - Compressors: Baker Hughes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

Long-Duration Energy Storage Systems

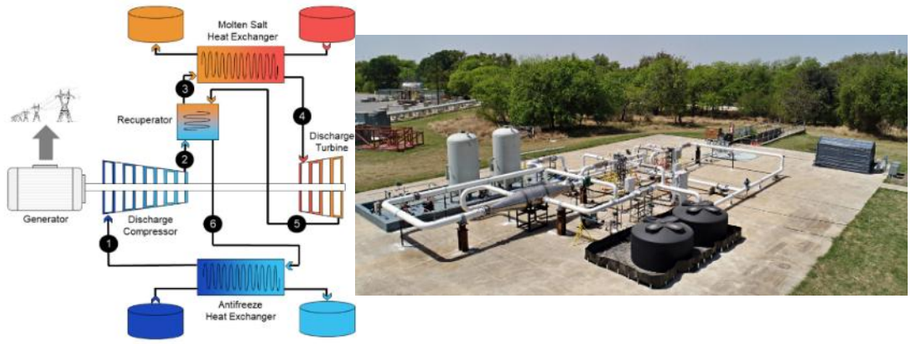
- Decouple power block vs. storage medium to reduce cost
- Leverage turbomachinery supply chain and scalability
- Different size of charge and discharge power blocks can match many use cases
- Avoid sourcing /degradation issues and fire hazards of electrochemical batteries



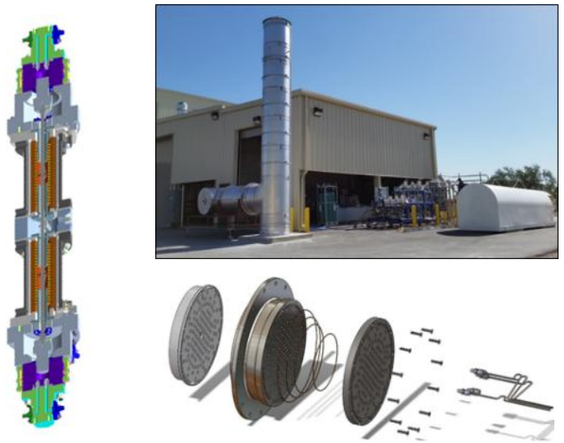
Long-Duration Energy Storage Projects at SwRI



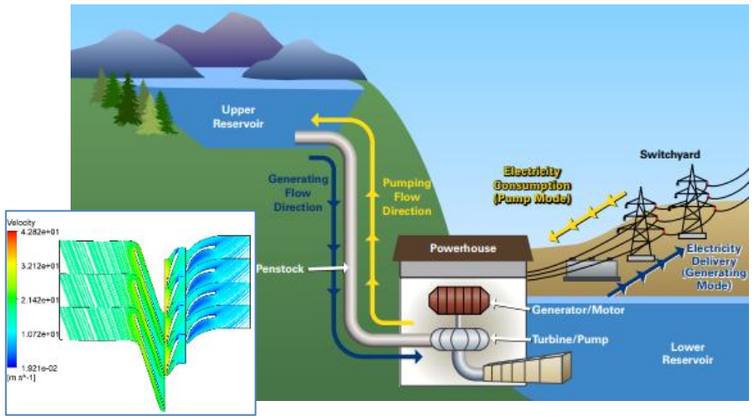
Isothermal and CAES Compressor Development



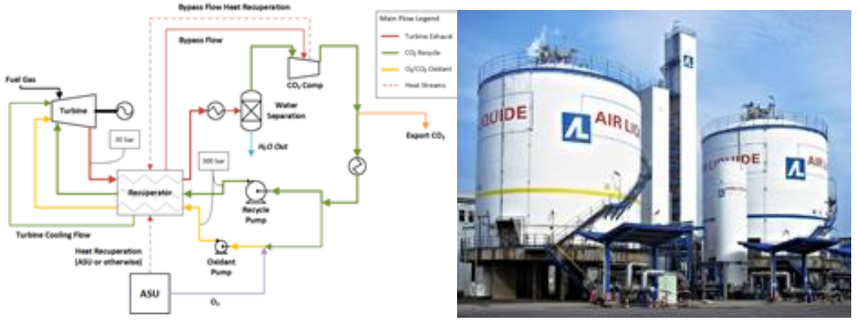
Pumped Thermal Energy Storage Demonstration and Pre-FEED Study



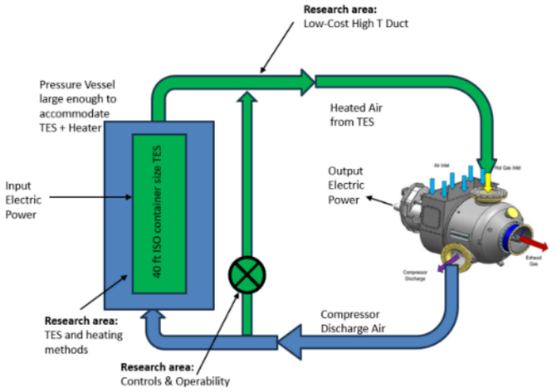
Hydrogen and Ammonia Storage, Compression, Combustion



Pumped Hydro Site Assessments and Geomechanical Pumped Storage Tech Development



Liquid Air/Oxygen Storage Coupled with Decarbonized Combustion



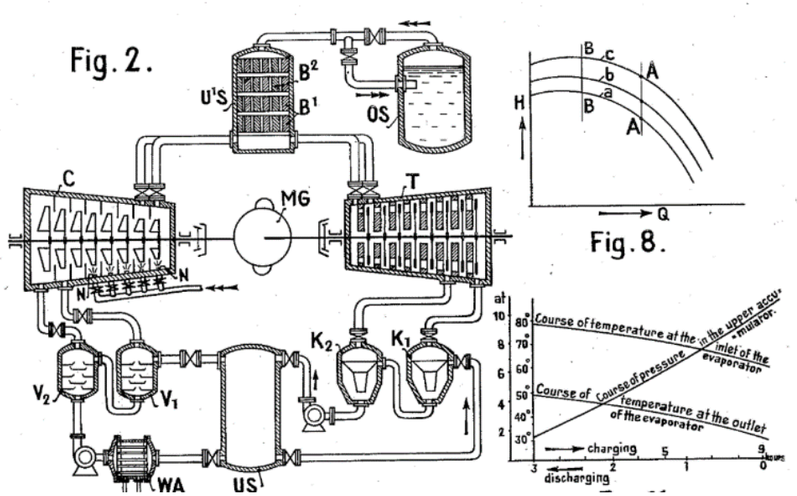
Thermal Energy Storage

Pumped Thermal Energy Storage (PTES)

Working Principles
- Electricity in drives heat pump to charge system
- Heat engine discharges system to produce energy

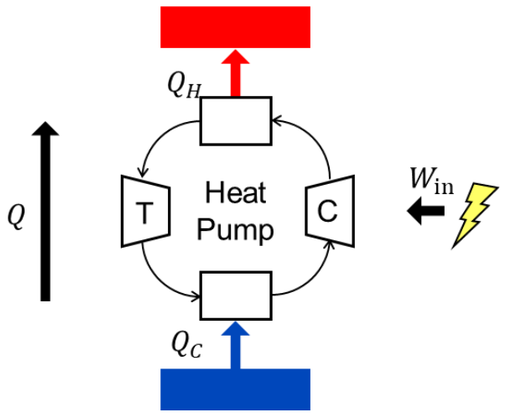
Technology Benefits
- Up to 50-70% RTE
- No geographical constraints
- Leverages many existing technologies

Technology Gaps
- Multiple cycles/fluids
- Large-scale closed-cycle machines
- Reversible turbomachines?

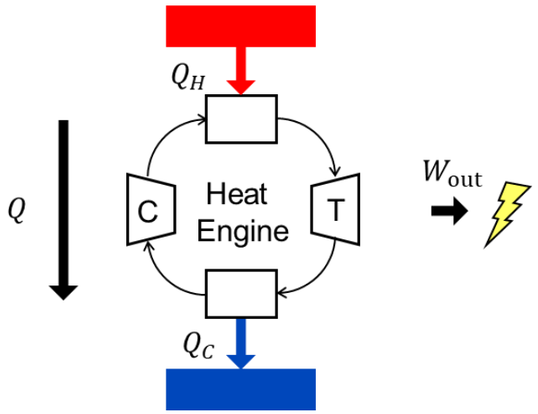


Maguerre, 1924

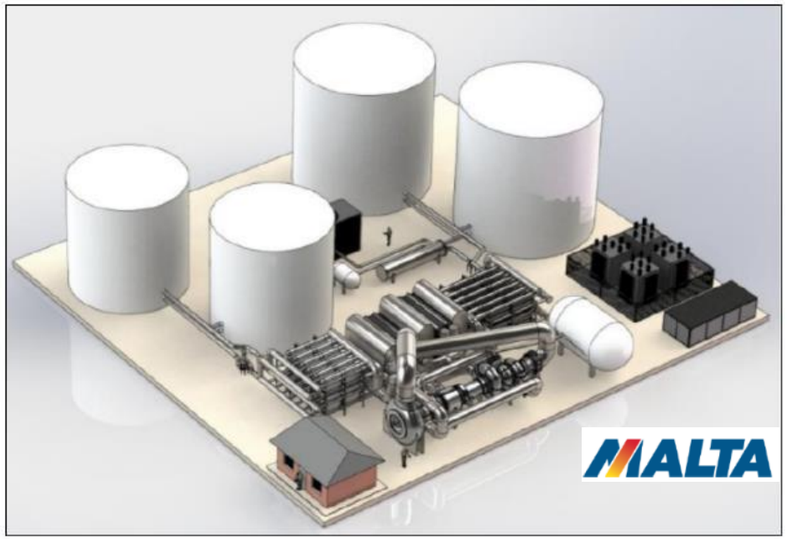
Charge Mode
Use excess energy to run heat pump and store energy in hot and cold reservoirs



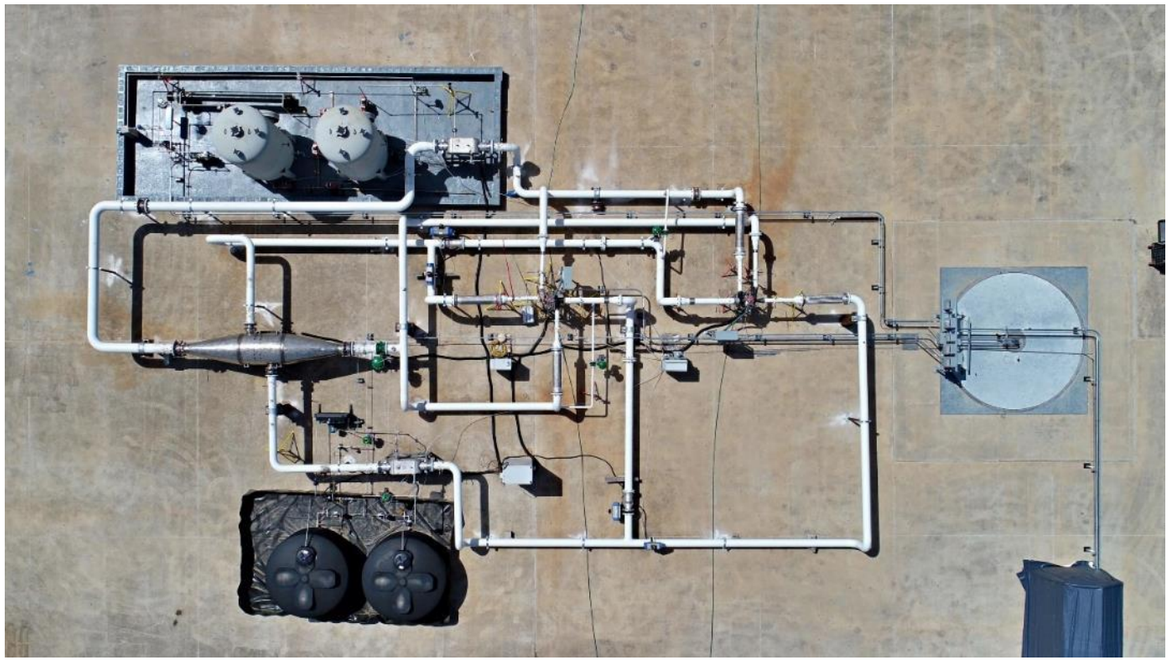
Discharge Mode
Use thermal reservoirs to run heat engine and generate power



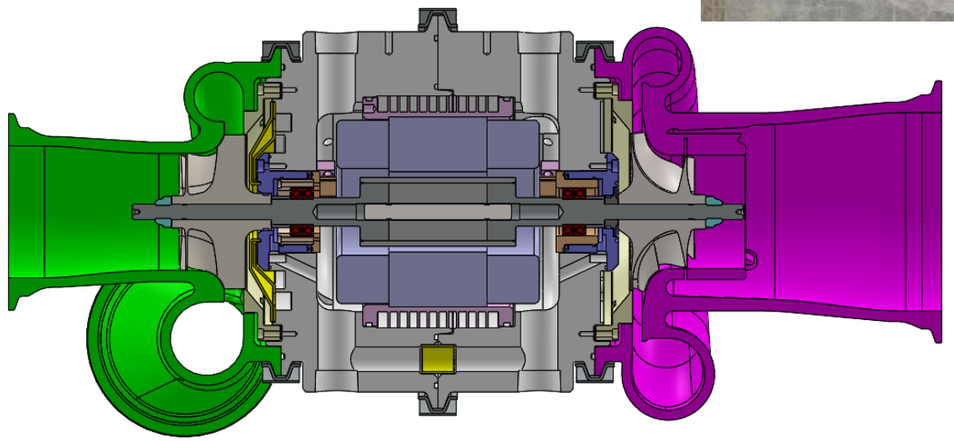
Air Brayton Pumped Thermal Energy Storage Demonstration



- Molten salts at 565°C
- Anti-freeze like fluid at -60°C
- Two separate drivetrains for charge and discharge mode
- Up to 60% RTE
- Targeting ~100 MWe system



- Two new turbine aero designs
- Integrated a motor-generator between the impellers
- New bearing and seal layout
- Thrust balance mechanism
- Incorporated multiple cooling features

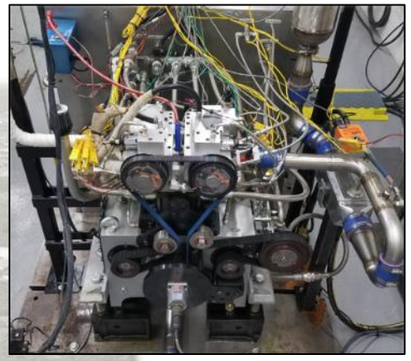


- SwRI-led kW-scale PTES demonstration system focusing on system integration and controls, transients
- 400 °C Thermal oil and 12 °C water glycol
- Two separate drivetrains
- Funded by ARPA-E OPEN18 (DAYS)

Southwest Research Institute and Hydrogen

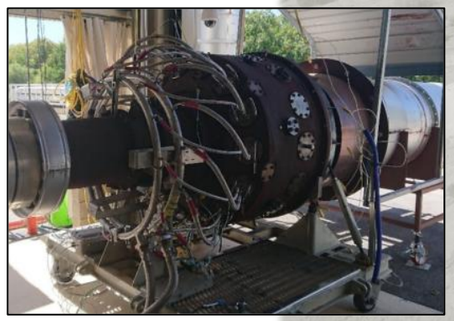
17500 Gallon LH2 Supply

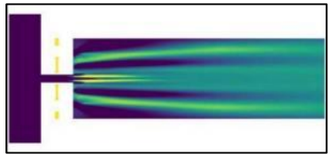
Hydrogen Compressor Development and Test Loop

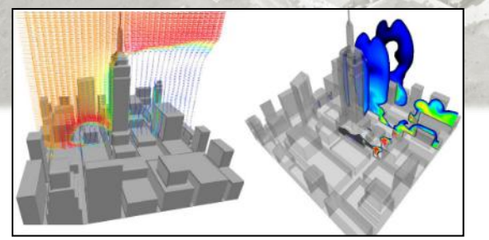


Hydrogen & Ammonia Testing in Combustion Engines

Hydrogen & Ammonia Combustion Testing and Injector Design for Hydrogen







Hydrogen Hazard Assessments and Leak Detection

Material Testing in Hydrogen Environments

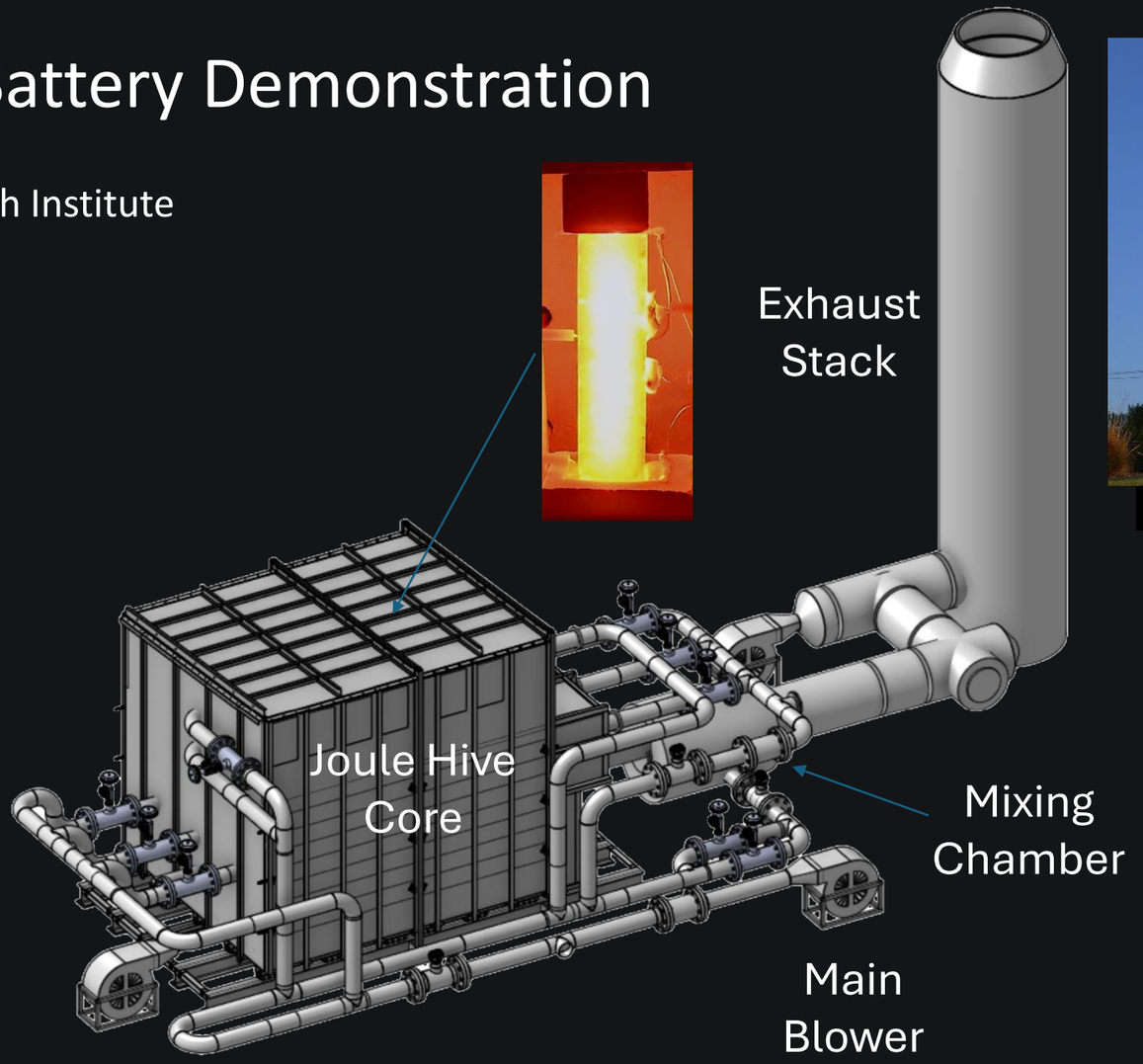
ADVANCED SCIENCE. APPLIED TECHNOLOGY.

swri.org

ELECTRIFIED THERMAL

Joule Hive Thermal Battery Demonstration

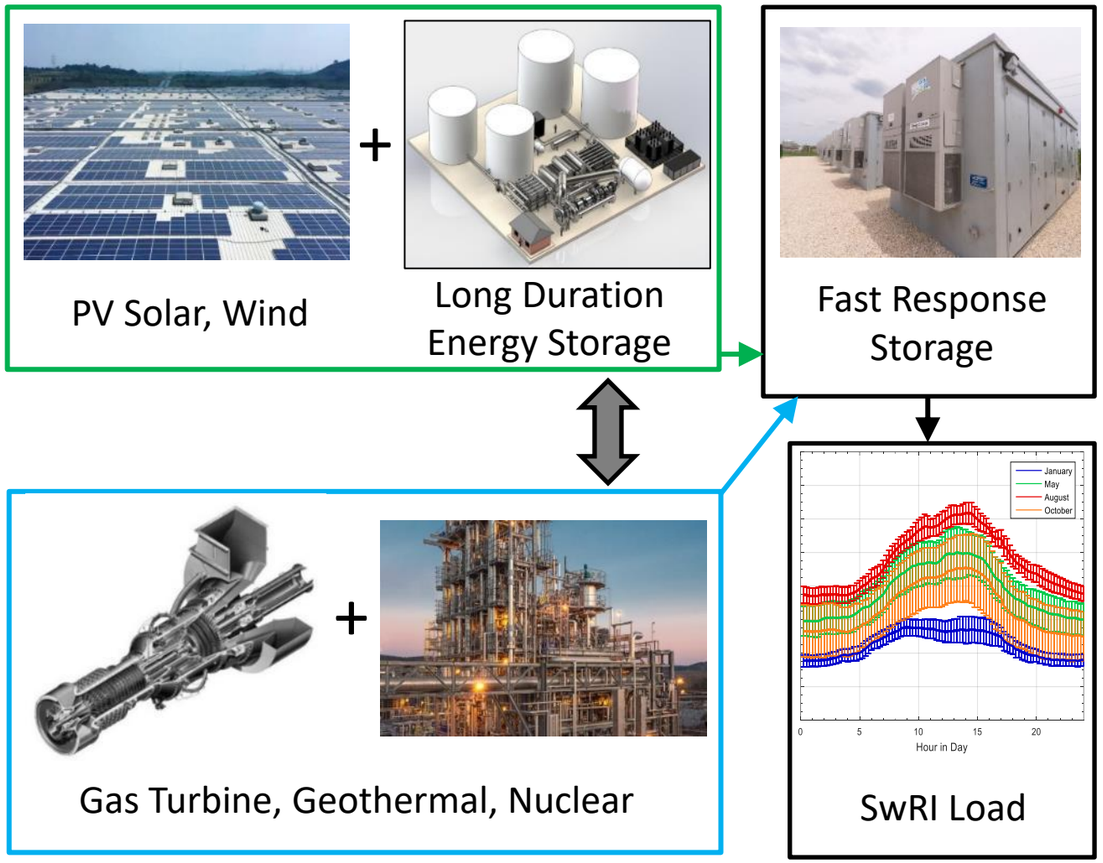
- Located at the Southwest Research Institute
- 13.8 kV voltage (line)
- 5 MWh nominal storage
- 500 kW nominal power
- 1 MW peak power
- 900°C nominal hot gas output
- 1500°C peak hot gas output
- 1700°C peak storage
- Commissioned Dec 2025



Supported by $5M DOE IEDO project:

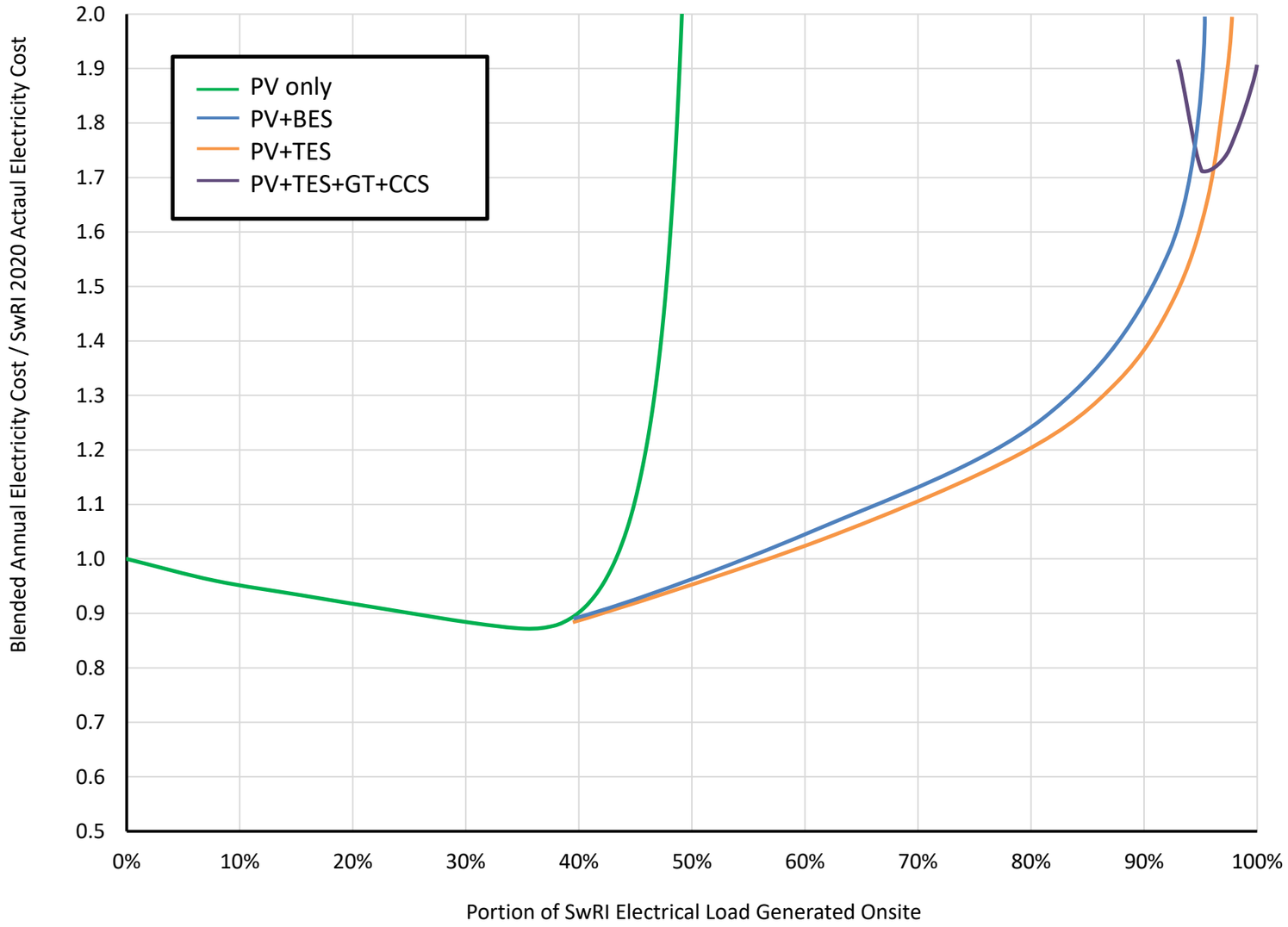
SwRI's "Project Z": Onsite Net-Zero Power

- Project Z: define a zero-carbon emission facility that will supply onsite electric generation and pilot-scale clean power research platform
- Operate as an onsite micro-grid, but use the local utility as a backup
- Pilot-scale clean energy R&D while reducing electricity costs and carbon emissions
- Develop analysis framework and toolset for technoeconomic and generation/load dispatch modeling to evaluate many onsite generation and energy storage technologies
- Define roadmap to net zero behind-the-meter electricity at SwRI



One Pathway to 100% Onsite Electricity

- PV is modular and deployable but cannot meet full energy demand or advance decarbonization beyond 40-50%
- Adding battery energy storage (BES) and thermal energy storage (TES) improves results
  - Storage adds costs but advances decarbonization beyond 80%
  - A dramatic increase in cost is still seen with PV+ES beyond ~90%
- A PV+TES system supplemented by a gas generator with carbon capture can achieve full decarbonization



Questions?

Thank you!

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