

CO₂-Based Systems for Industrial Heat and Power

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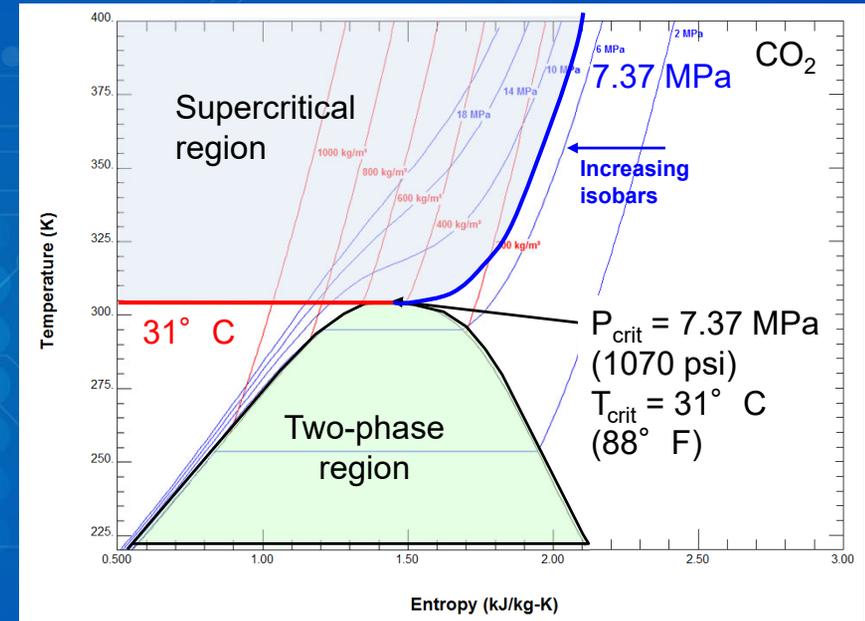
Tim Allison, Director

2nd Industrial Process Emissions Reduction (IPER) Workshop
March 1, 2023

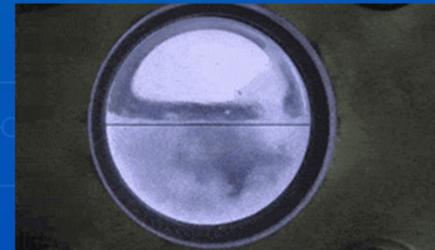


Carbon Dioxide Has Favorable Properties as a Working Fluid

- No freezing/chemistry management
- Thermally stable
- High heat transfer, natural convection near ambient temperature
- High density at liquid/supercritical conditions
- Nonflammable
- Non-toxic
- High diffusivity
- Low surface tension and viscosity
- Widely available, low-cost



REFPROP (2007), EOS CO₂: Span & Wagner (1996)



Transition to Supercritical



Desublimation

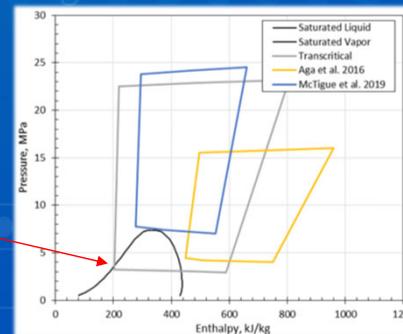
CO₂ (R744) In Heat Pumps

- First commercial application of closed-loop CO₂ systems
- Transcritical and subcritical cycles
- Ozone Depletion / Global Warming Potential = 0.0 / 1.0
- High power density
- High coefficient of performance ~3.8-6.0, up to 8.0
- Thermally stable to high temperatures > 1200 °C
- Large temperature glide for heating at many process temperatures
- R&D Activities
 - Condensing expander
 - Higher temperature systems
 - Pressure exchangers

EcoCute Residential Heat Pump Water Heater, 2001

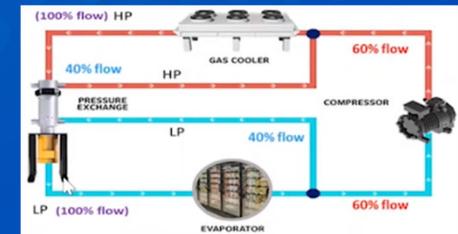


MAN Energy Solutions Heat Pump up to 80 MW



Condensing Expander

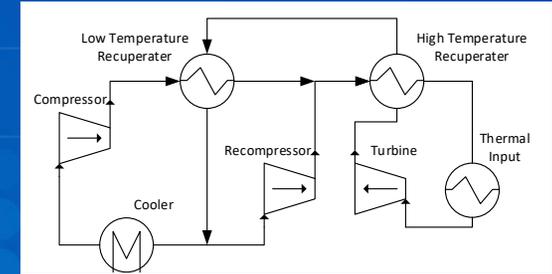
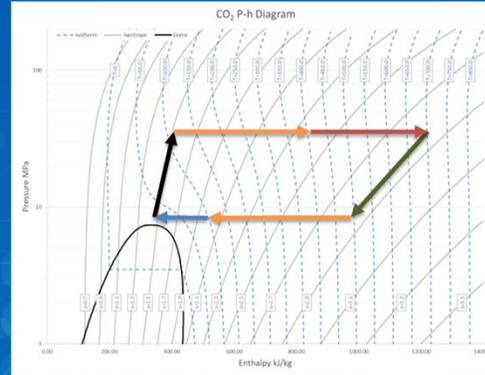
Various CO₂ Heat Pump Cycles



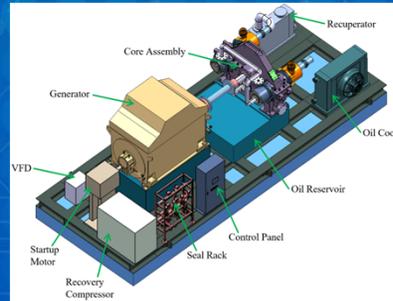
Energy Recovery [1,2]

Supercritical CO₂ in Thermal Power Generation

- Closed-loop cycles
- High thermal efficiency even at small scale
- Low pressure ratio, highly recuperated
- Compact due to high density
 - Modularity, ramp time
 - Cost
- Dry-cooling compatibility
- Many heat sources
 - Waste heat recovery
 - Concentrating solar power
 - Nuclear
 - Geothermal
 - Fossil
- Thermal energy storage (combined with heat pump)

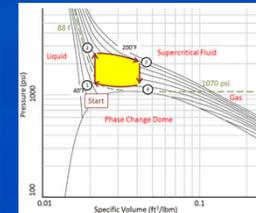
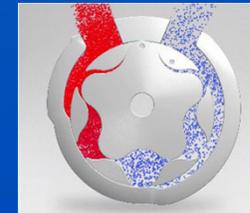
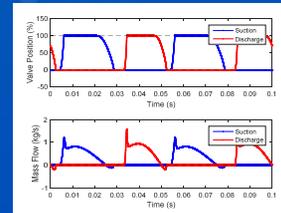


Recompression Brayton Cycle achieving >50% thermal efficiency over ~700 °C turbine Inlet



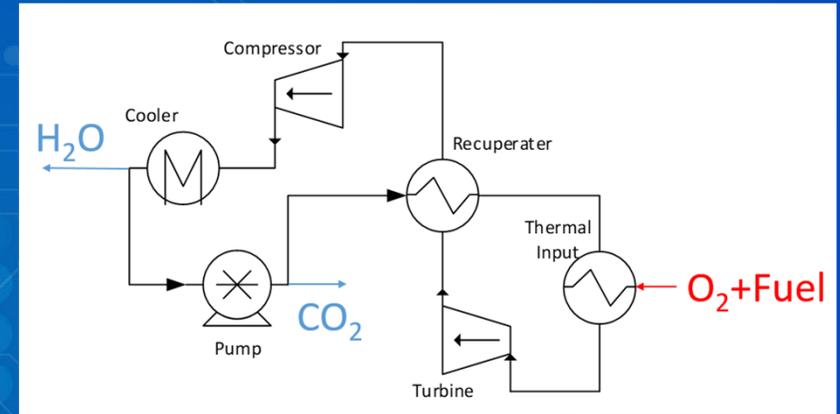
Hanwha Power Systems (left) and Siemens / Echogen (right) ~5-10 MW gas turbine waste heat recovery systems

Positive displacement WHR systems at 10s/100s kW-scale



CO₂ in Oxy-Combustion

- Direct-fired CO₂ cycle
 - Many flavors, including transcritical and supercritical
- $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + \text{Heat}$
- Thermal integration of air separation unit
- R&D
 - Combustor development
 - Turbine development
 - Various fuels
 - Oxygen storage

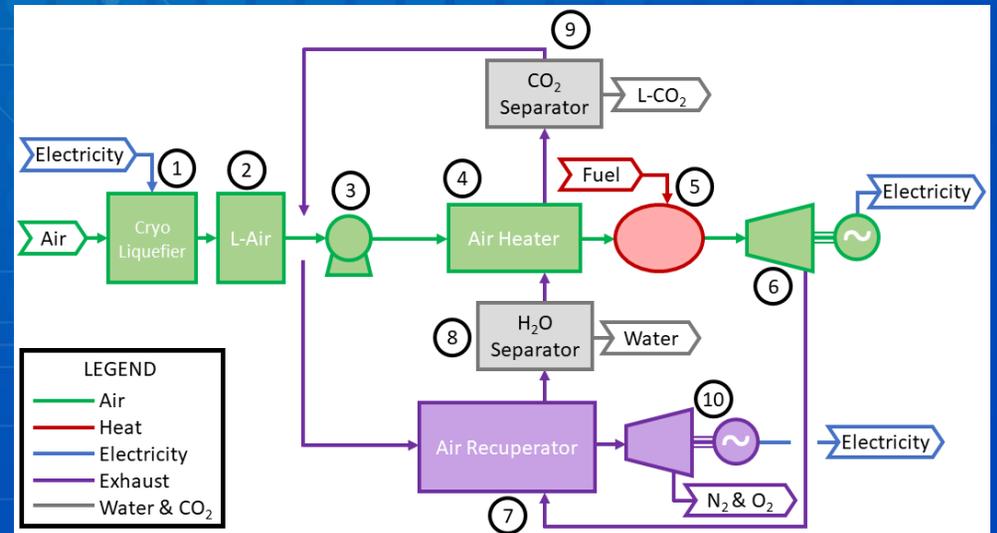
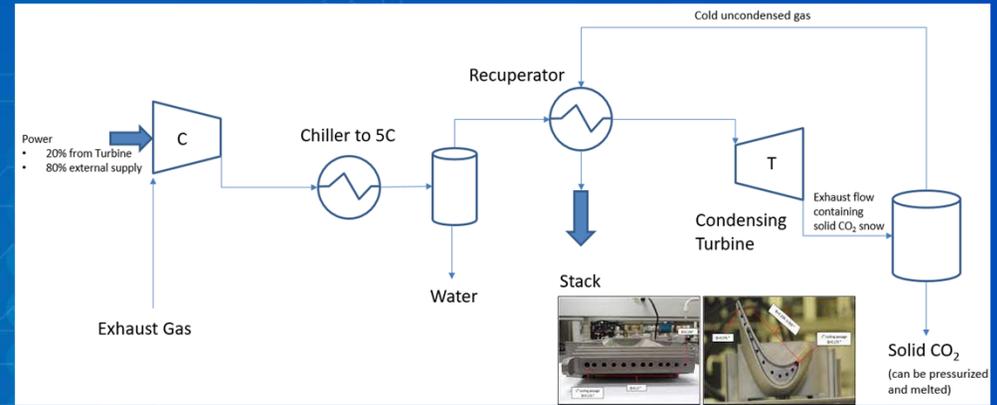


Allam-Fetvedt
Cycle
Demonstration
in La Porte, TX

Image Courtesy NET Power

CO₂ Machinery in Carbon Capture

- Turbomachine-based cryogenic capture
 - Bulk flow work removal rather than surface heat transfer and icing
 - Heated turbine blades
- Coupled with other cryogenic systems
 - Liquid air energy storage comparable to CAES
 - Staged expansion with recuperation allows removal as liquid



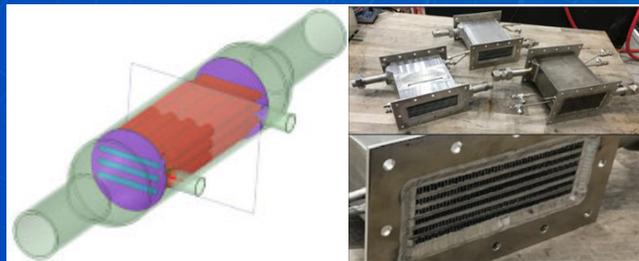
SwRI Experience & Capabilities in sCO₂ Cycles, Components, Systems



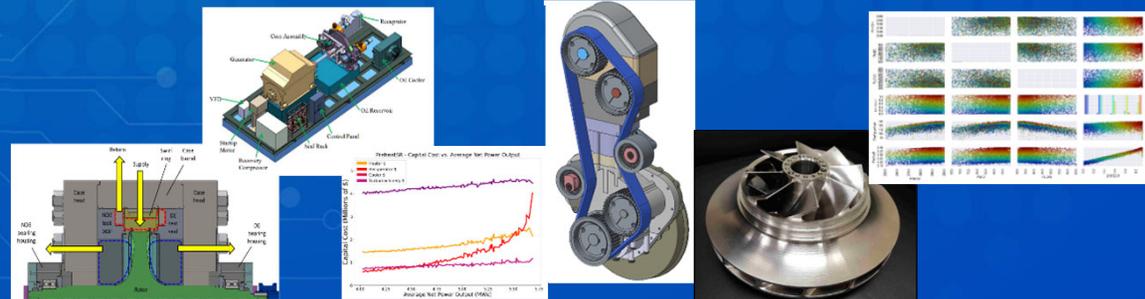
Design, Fabrication, Testing of 10 MWe-Scale Machinery



Oxy-Combustion Development and Testing



Heat exchanger Development and Testing



...and other Components, Cycles, Technoeconomics, Systems

Supercritical Transformational Electric Power (STEP) Project



Scope: Design, construct, commission, and operate a **10 MWe sCO₂ Pilot Plant Test Facility** - reconfigurable to accommodate other testing

Team: Gas Technology Institute (**GTI**[®])
Southwest Research Institute (**SwRI**[®])
General Electric Global Research (**GE-GR**)
U.S. Department of Energy (**DOE NETL**)

Joint Industrial Partners:

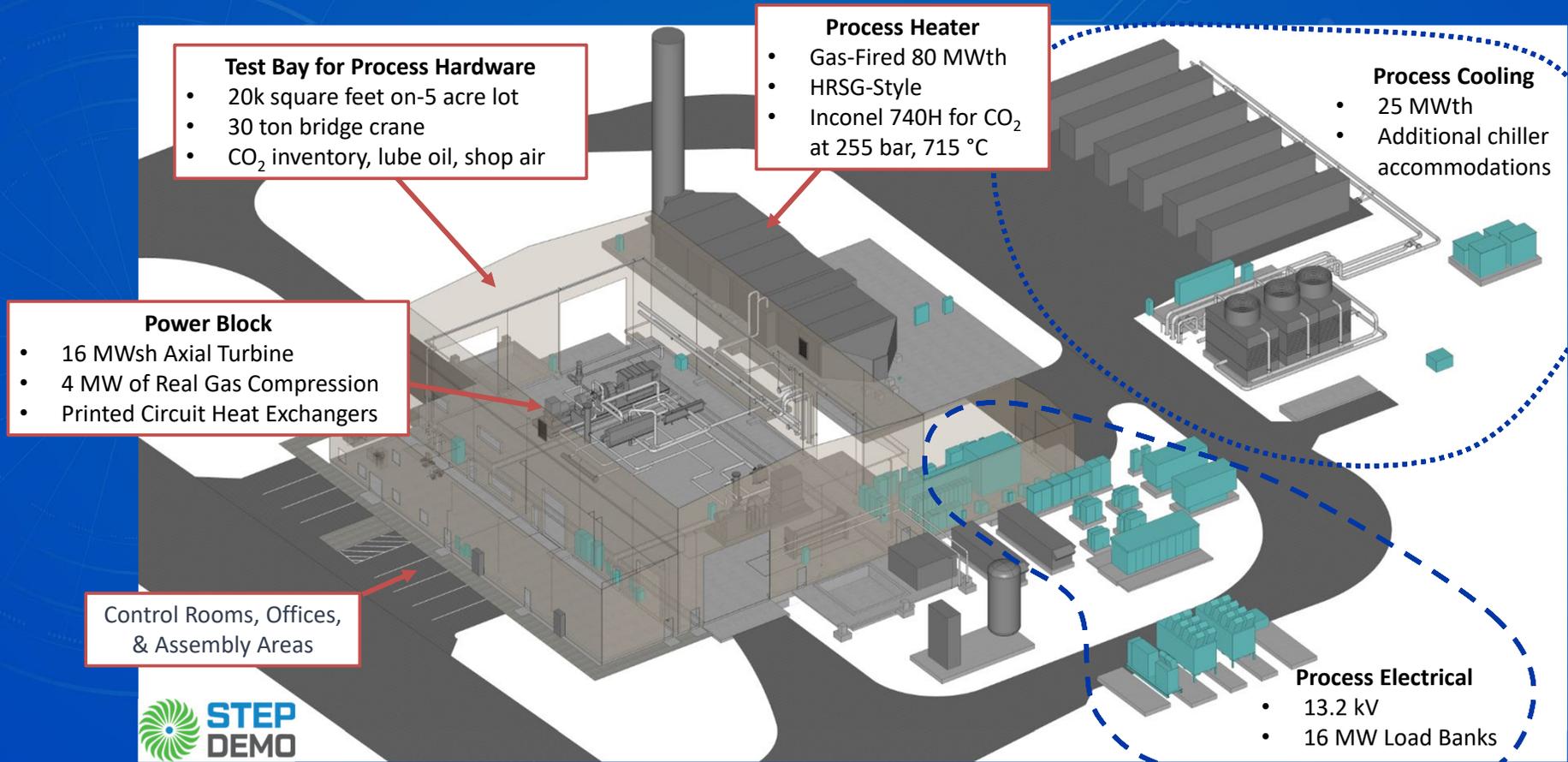


Schedule: Three budget phases (2016-2024)

Cost: \$156MM Total / \$115MM Federal Funding (includes building)



10 MWe-Scale R&D Infrastructure for CO₂



www.STEPdemo.us



Please join us for
a facility tour:

Thursday 3/2
12:35-3:05pm

RSVP to
Dorothea
Martinez at the
registration desk
or

dorothea.martinez@swri.org



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References

- [1] Thatte A., et.al., *Proc. 15th IIR-Gustav Lorentzen Conf. on Natural Refrigerants*, 56, Trondheim, Norway, 2022.
- [2] Thatte A. et.al., *Proc. ASHRAE, TO-22-C041*, Toronto, Canada, 2022.

SwRI's Roles in the STEP Pilot Plant Project

- SwRI is a project partner leveraging past experience to lead tasks and procurements:
 - System integration
 - Data acquisition & controls
 - Piping
 - Turbine design & fabrication (with GE)
 - Heater protection valve
- As host site, SwRI provided \$12.4M general-purpose facility
- Future use cases include expanded testing conditions, full-scale system & component tests, control system development and optimization, more

