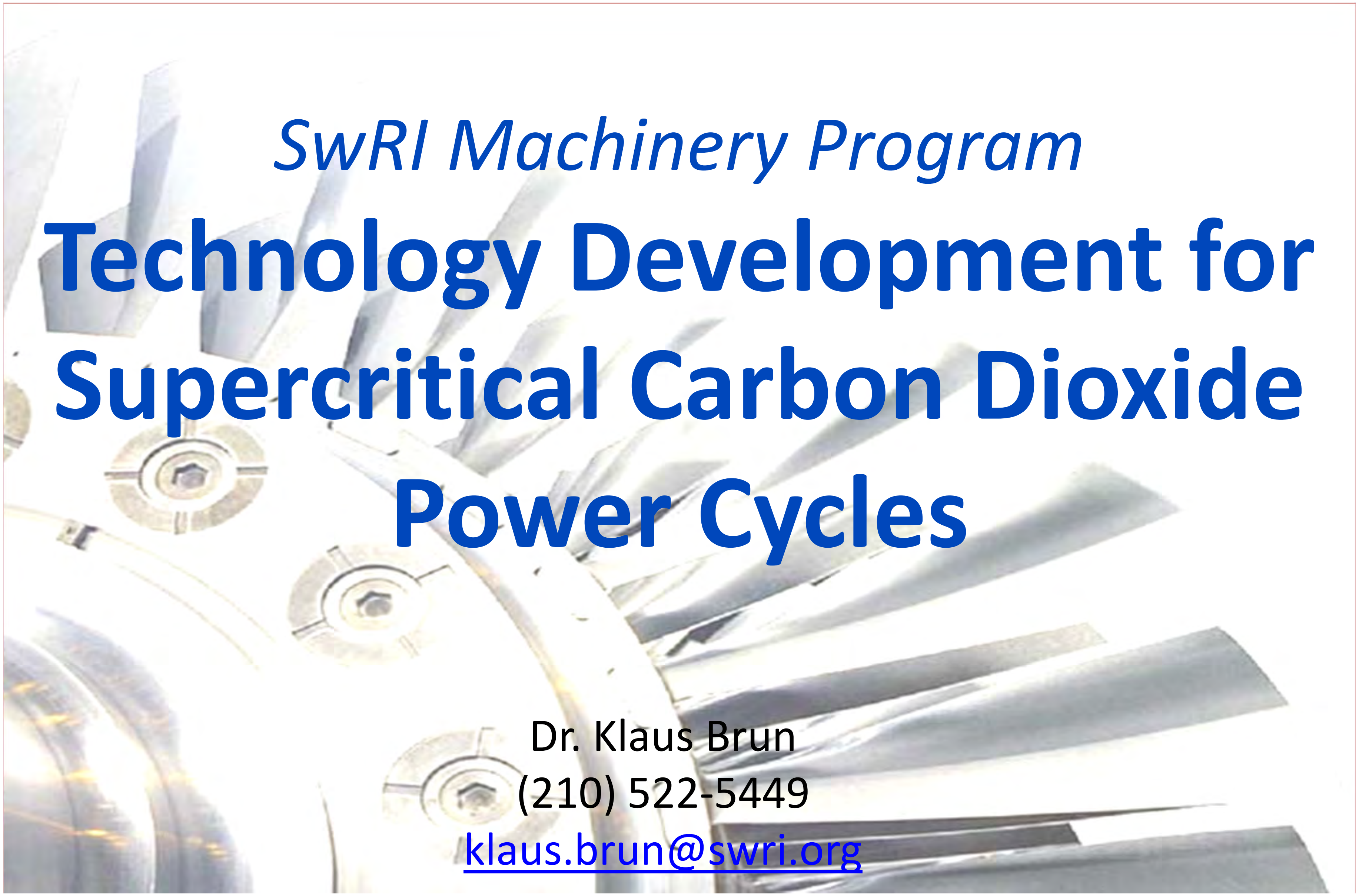

SwRI Machinery Program

Technology Development for Supercritical Carbon Dioxide Power Cycles

Dr. Klaus Brun
(210) 522-5449
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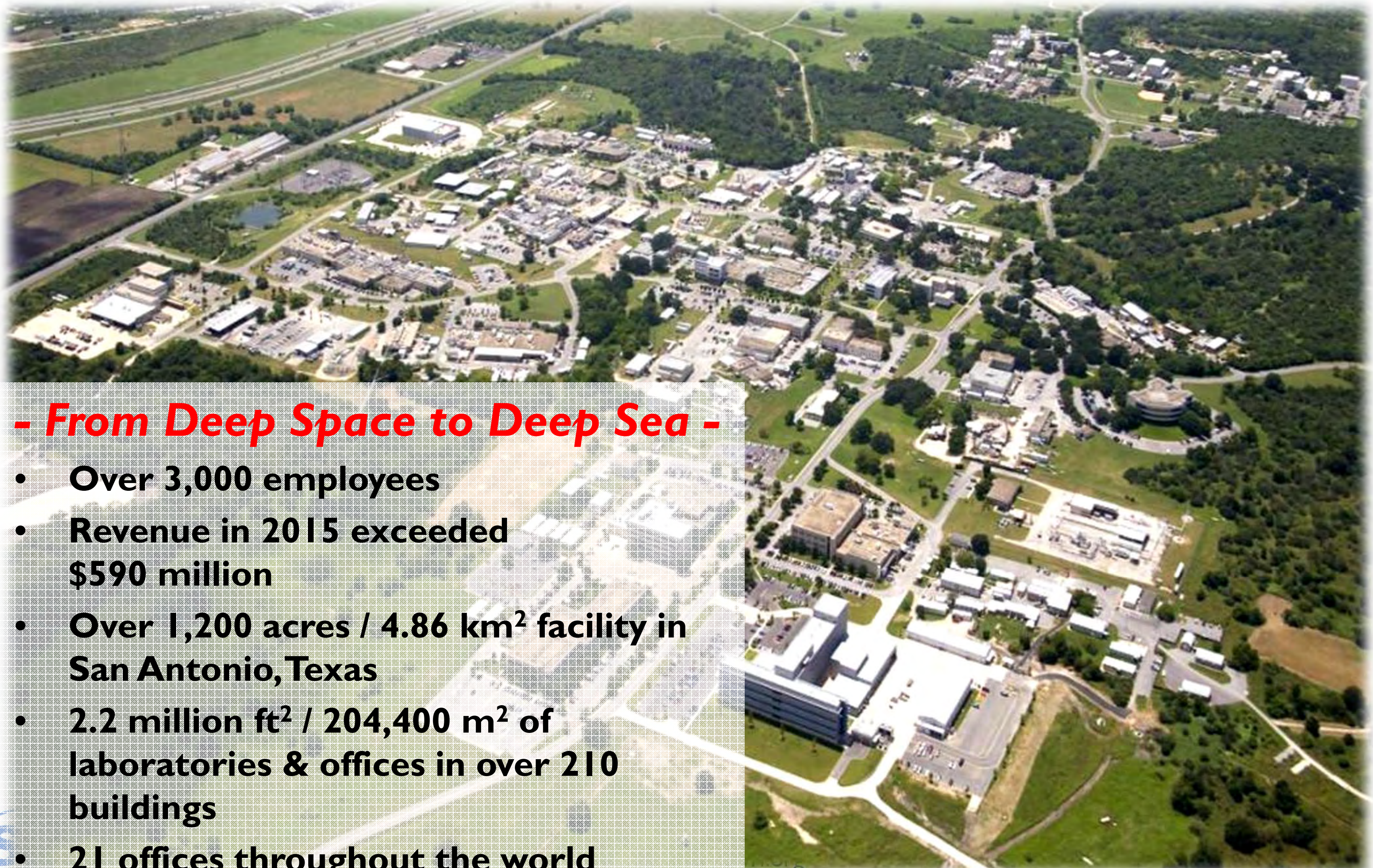
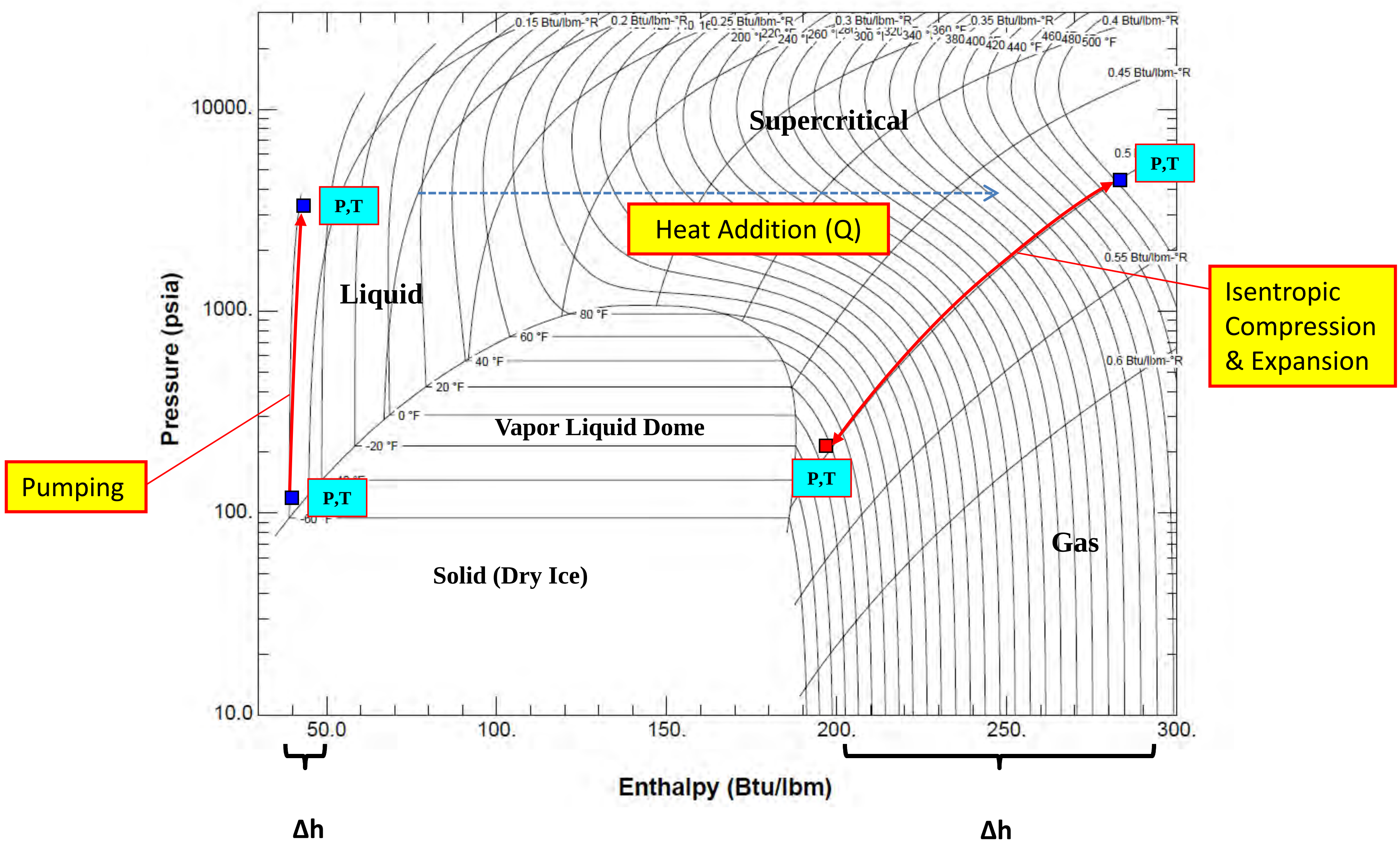
Southwest Research Institute



- From Deep Space to Deep Sea -

- **Over 3,000 employees**
- **Revenue in 2015 exceeded $590 million**
- **Over 1,200 acres / 4.86 km^2 facility in San Antonio, Texas**
- **2.2 million ft^2 / 204,400 m^2 of laboratories & offices in over 210 buildings**
- **21 offices throughout the world**

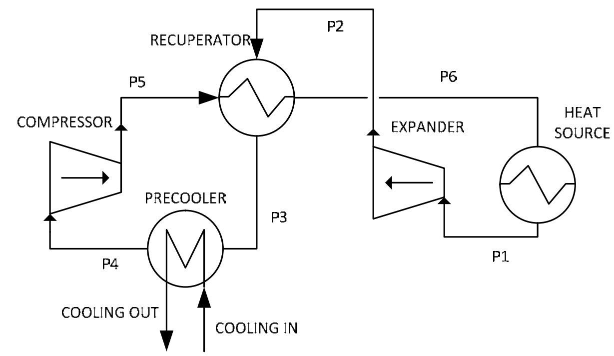
Power Cycles: Pumping, Compression, Expansion



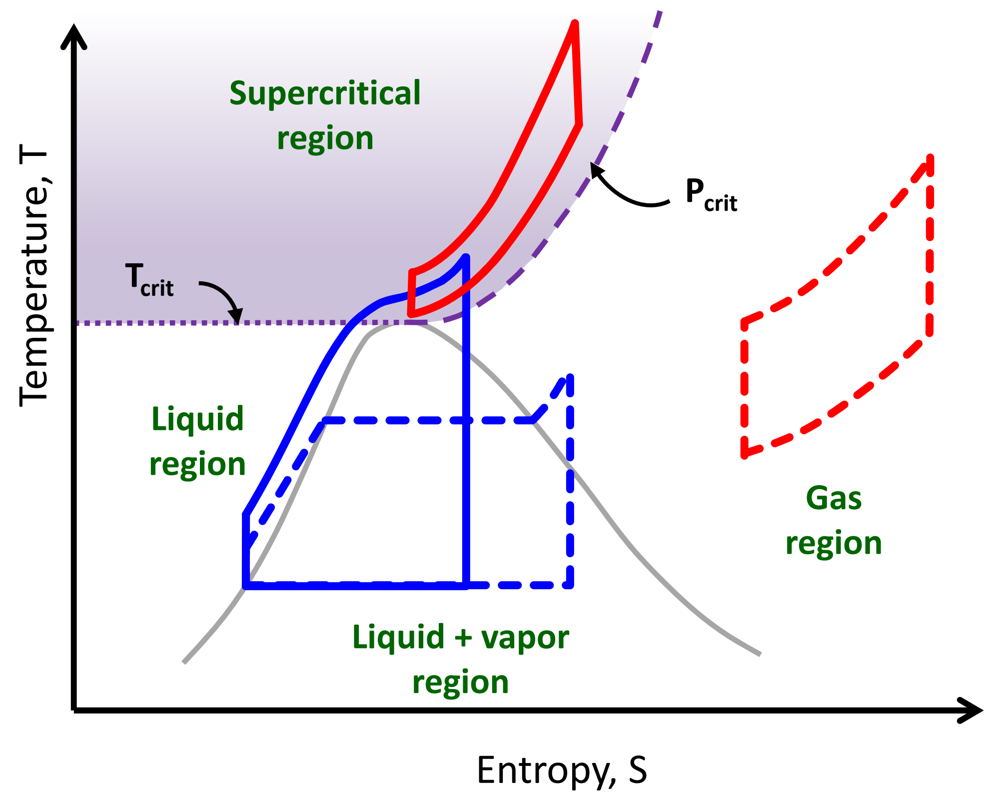
$W = \dot{m}\,\Delta h$ $\qquad W_{net} = \dot{m}\,(\Delta h_{out} - \Delta h_{in})$ $\qquad \eta = W_{net}/Q$

Supercritical Carbon Dioxide (sCO2) Cycles

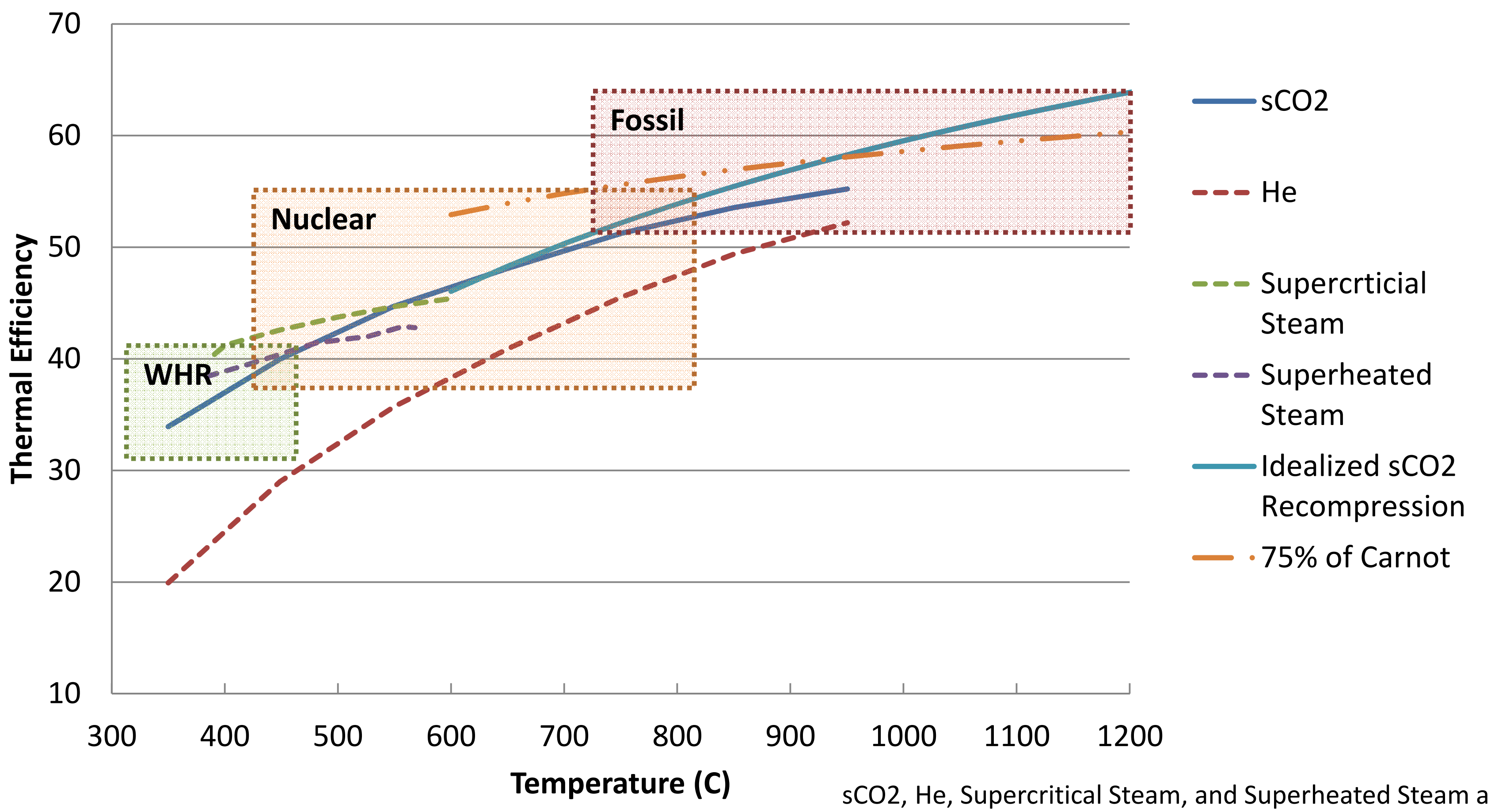
- Closed Cycle using CO2 as the working fluid
- Cycle Configurations
  - Vapor Phase
  - Transcritical
  - Supercritical
- Supercritical CO2 has:
  - High fluid density
  - High heat capacity
  - Low viscosity
- 3-5% efficiency gain over conventional cycles (for some applications)



Recuperated Closed Brayton Power Cycle

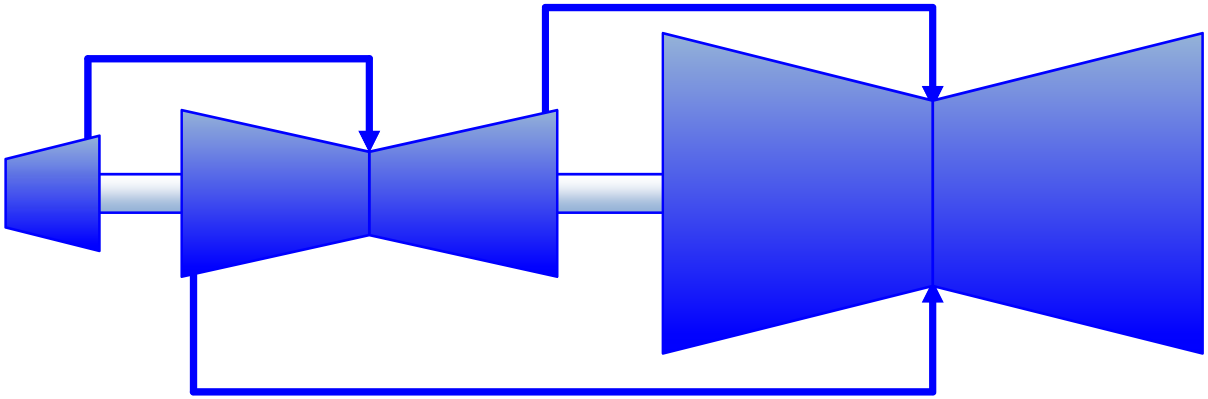


Power Cycle Efficiencies



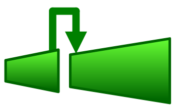
sCO2, He, Supercritical Steam, and Superheated Steam are from Driscol MIT-GFR-045, 2008

Relative Size of Components



5 m

Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries (with casing)



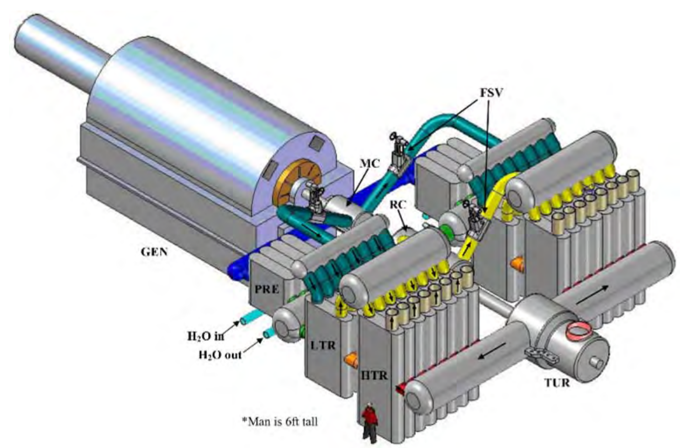
Helium turbine: 17 stages / 333 MW (167 MW_e)
X.L. Yan, L.M. Lidsky (MIT) (without casing)

1 m

sCO_2 turbine: 4 stages / 450 MW (300 MW_e)
(without casing)

Note: Compressors are comparable in size

Source: Wright (2011), Adapted from Dostal (2004)

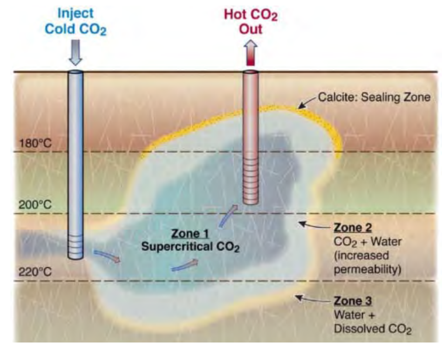


Third Generation 300 MWe S-CO2 Layout from Gibba, Hejzlar, and Driscoll, MIT-GFR-037, 2006

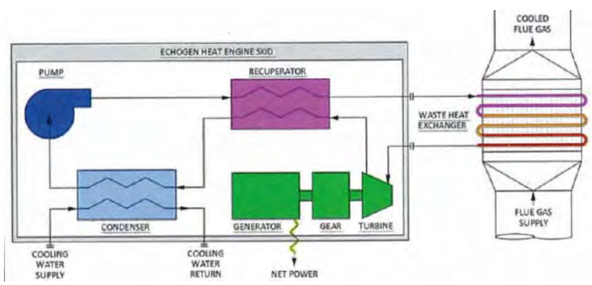
sCO_2 in Power Cycle Applications

Concentrating Solar Power

Fossil Fuel



Geothermal



Waste Heat Recovery

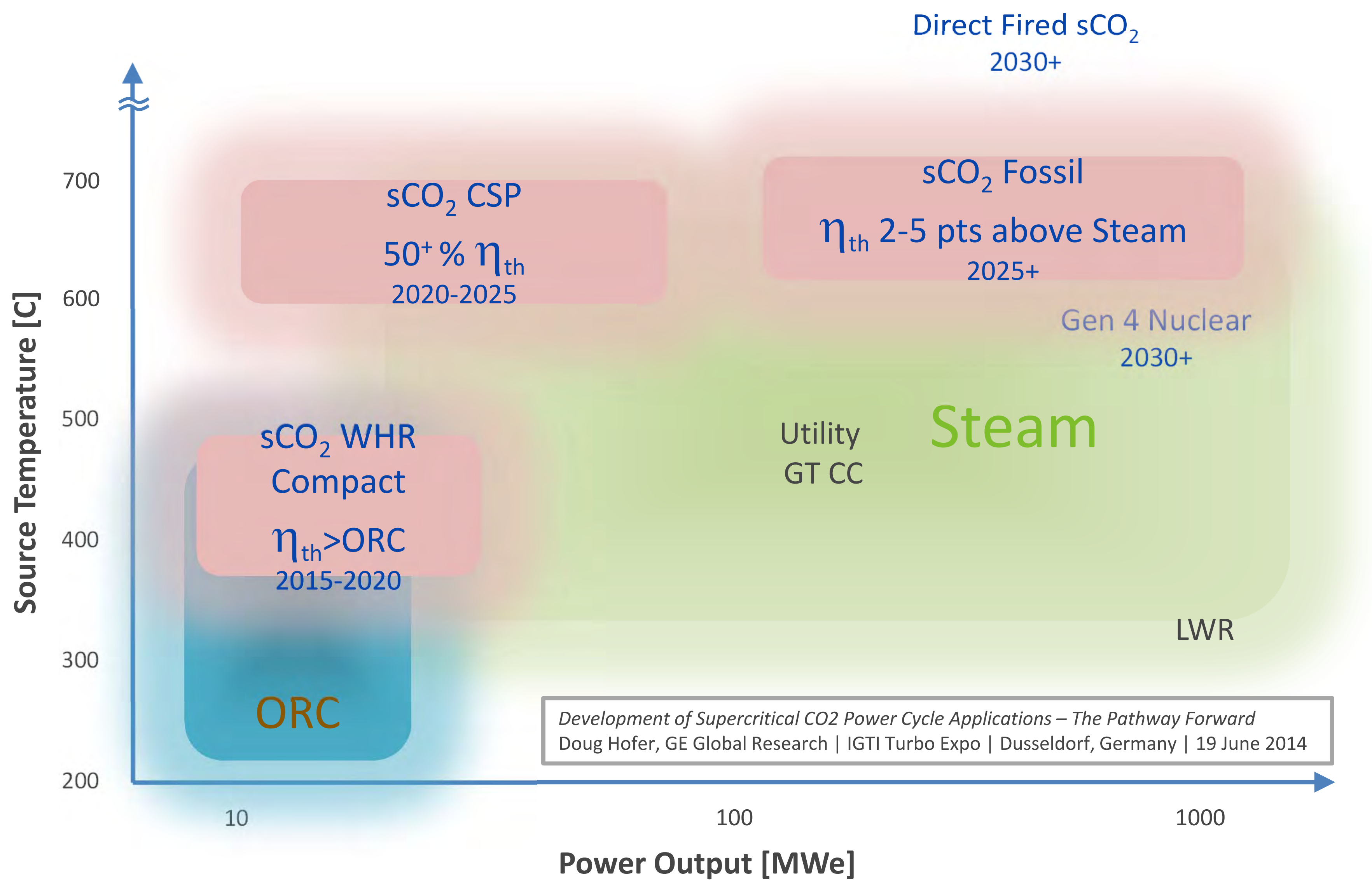
Nuclear

Ship-board Propulsion

"Typical" sCO2 Cycle Conditions

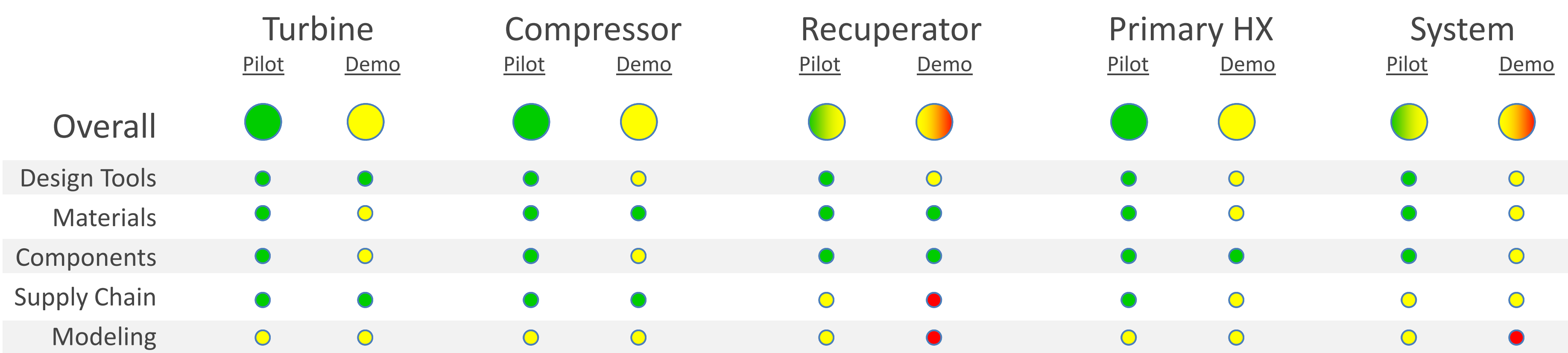
Application	Organization	Motivation	Size [MWe]	Temperature [C]	Pressure [bar]
Nuclear	DOE-NE	Efficiency, Size	300 - 1000	400 - 800	350
Fossil Fuel	DOE-FE	Efficiency, Water Reduction	500 - 1000	550 - 1200	150 - 350
Concentrated Solar Power	DOE-EE	Efficiency, Size, Water Reduction	10, 100	500 - 1000	350
Shipboard Propulsion	DOE-NNSA	Size, Efficiency	10, 100	400 - 800	350
Shipboard House Power	ONR	Size, Efficiency	< 1, 1, 10	230 - 650	150 - 350
Waste Heat Recovery	DOE-EE ONR	Size, Efficiency, Simple Cycles	1, 10, 100	< 230; 230-650	15 - 350
Geothermal	DOE-EERE	Efficiency, Working fluid	1, 10, 50	100 - 300	150

sCO_2 Application Space



Development of Supercritical CO2 Power Cycle Applications – The Pathway Forward
Doug Hofer, GE Global Research | IGTI Turbo Expo | Dusseldorf, Germany | 19 June 2014

Technology Readiness and Gaps @ 550C



Technology Gaps

Turbine
- Long term materials data in CO_2
- Codes & Standards
- Erosion resistance
- Advanced seals
- Off-design/transient modeling
- Hermetic turbo-alternator

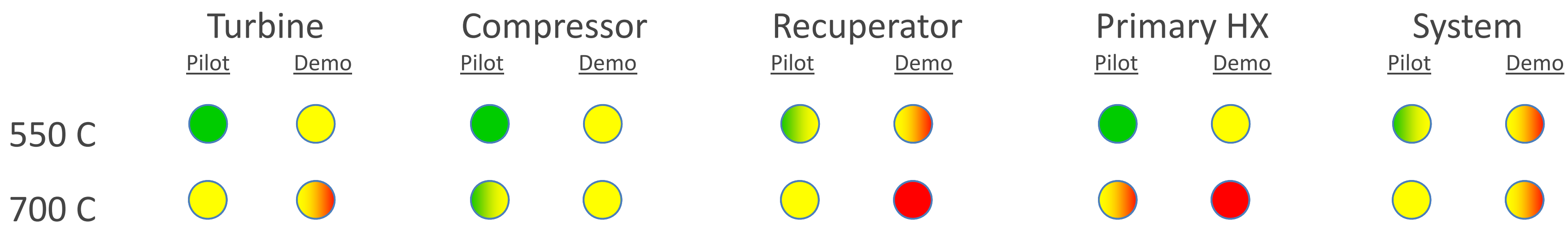
Compressor
- Designs for operation near CO_2 critical pt
- Advanced seals
- Internal bearings
- Off-design/transient modeling
- Hermetic turbo-compressor

Recuperator
- Diversified vendor base – capacity/cost
- Technologies to reduce cost
- Off-design/transient modeling

Primary HX
- Long term materials data in CO_2
- Codes & Standards
- Erosion resistance
- Off-design/transient modeling

System
- Long term materials data in CO_2
- Codes & Standards
- Transient operability including upsets
- System modeling transient/off-design
- Starting systems
- Leakage gas recompression

Technology Readiness and Gaps @ 700C



Additional 700 C Technology Gaps

Turbine	Compressor	Recuperator	Primary HX	System
Long term superalloy materials data in CO_2	Operation and control of parallel compressors for recompression cycle	Long term materials data in CO_2	Long term superalloy materials data in CO_2	Long term superalloy materials data in CO_2
Codes & Standards		Diversified vendor base – capacity/cost	Codes & Standards	Codes & Standards
Thermal management			Furnace designs for low ΔT of primary fluid (air side recuperation)	Transient operability including upsets for complex recompression cycles
High temperature seals and bearings			Materials availability	
Turbine stop and control valve				

- Technology readiness sufficient for development of 550 C prototype
- Challenges for all components at 700 C
- Additional data and experience needed to enable commercialization

Current Technology Development Trends for sCO2 Power Cycles

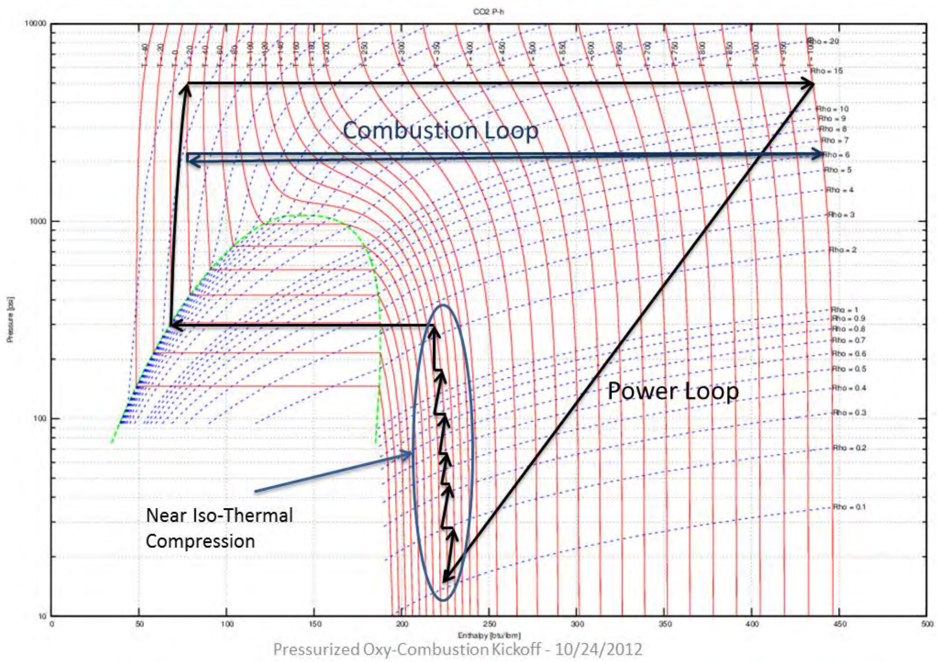
- Technology development is focused on four areas
  - Thermodynamic cycles and thermal integration for specific applications
  - System level design and demonstration
  - Component development and demonstration
  - Oxy-combustion development and demonstration
- Demonstration efforts are focused on **performance**, **operability**, and **scalability**

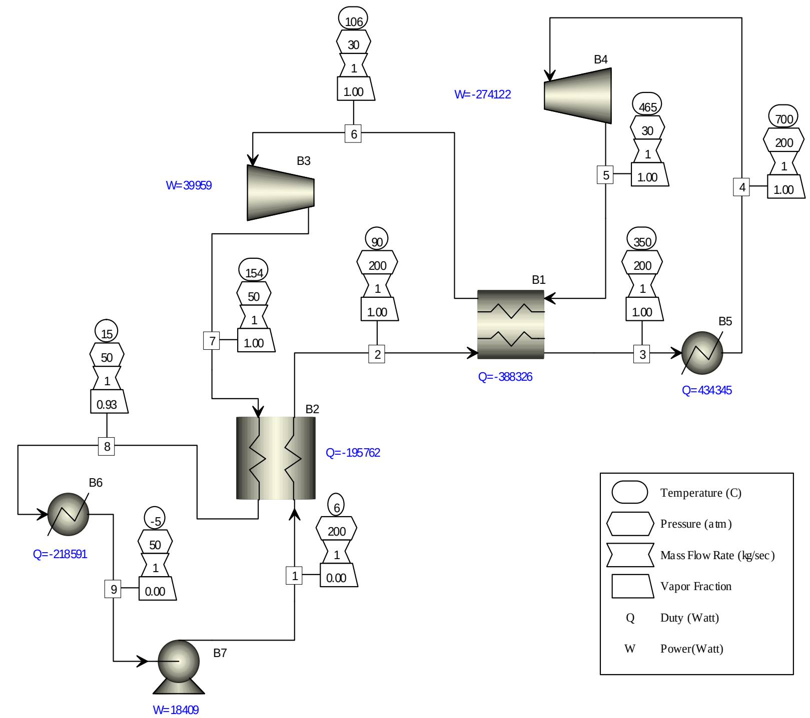
SwRI Technology Development: Cycles and Systems

- Thermodynamic cycles
  - Focus on Thermal Integration
  - Cycle optimization for Fossil based systems, Waste Heat Recovery, and CSP with and without thermal storage
  - Fuel to bus-bar plant models for fossil based systems
- System Design and Demonstration
  - 1 MW scale system and component demonstration (SunShot)
  - 10 MWe Pilot Scale Demonstration (STEP)
  - Preliminary design for commercial Waste Heat Recovery applications

SwRI Technology Development: Components and Heat Source

- Component development efforts
  - Turbomachinery
    - Compact turbine design
    - High efficiency compressor, operabile near the critical point
    - Bearings, seals, and thermal management
  - Heat Exchangers
    - Cost and performance of compact HX
  - Air fired sCO2 heater design
    - HX design and material cost challenges
- Oxy-combustion for direct fired cycles
  - High pressure combustion properties
  - Oxy-combustor design and testing

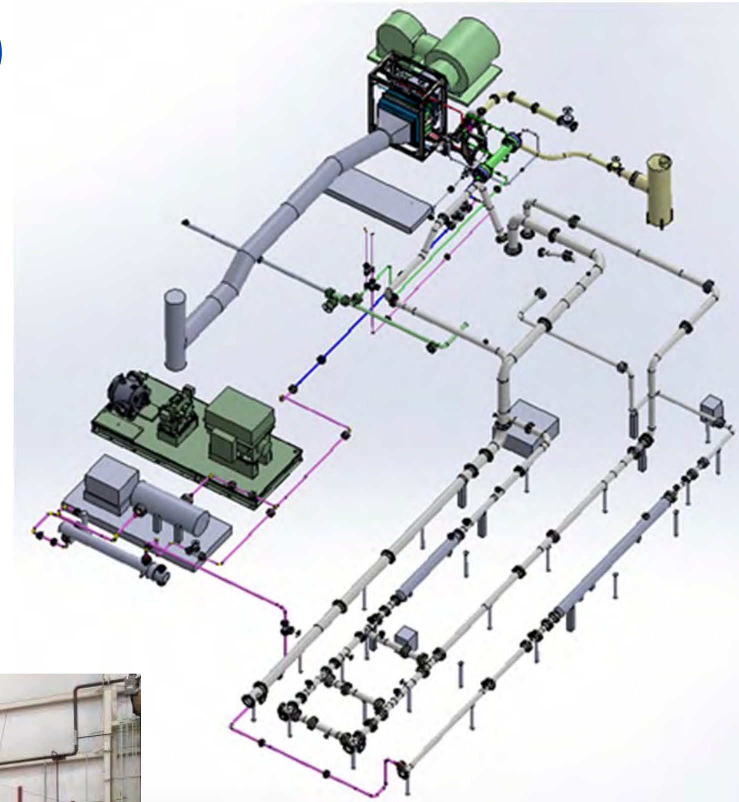




SYSTEM ANALYSIS AND TESTING

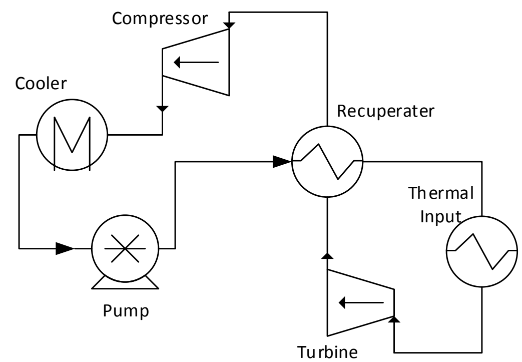
SunShot sCO2 Pilot Loop

- 1 MW simple recuperated sCO2 closed loop
- >715 C heat source (fired NG heater)
- 1/2017 Operational
- Testing of:
  - Equipment (turbine, recuperator,)
  - Cycle dynamics and sequencing (startup, shutdown, upsets)

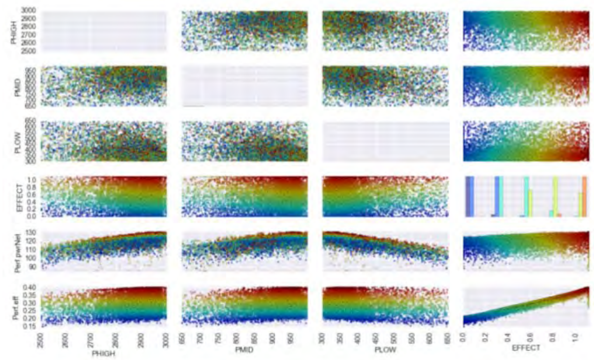


Thermodynamic Simulation

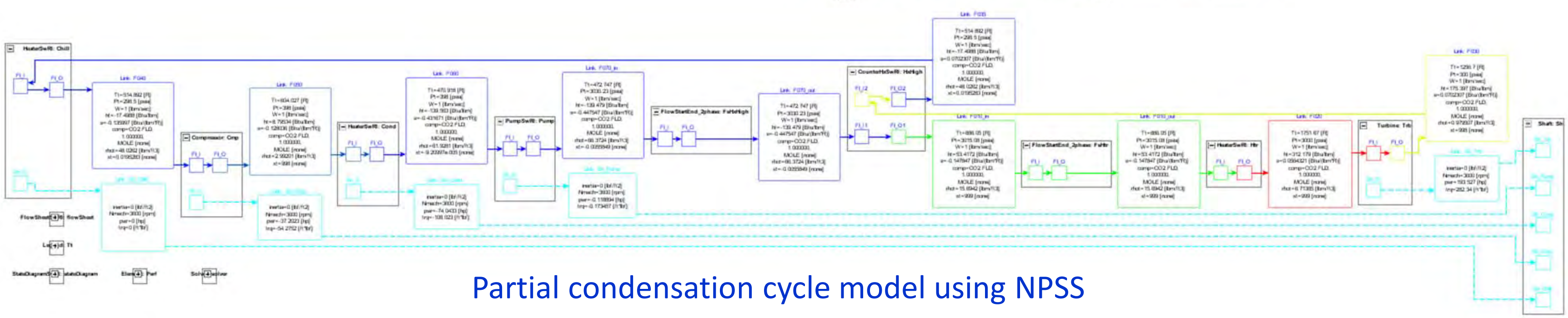
- Validation of steady and dynamic modeling of sCO2 cycles and components.
- Cycles modeled using a variety of tools including Aspen Plus, Aspen Hysys, and NPSS
- Performance evaluated for design and off design operating conditions
- Cycles optimized to achieve desired performance and operating characteristics



Partial Condensation Cycle



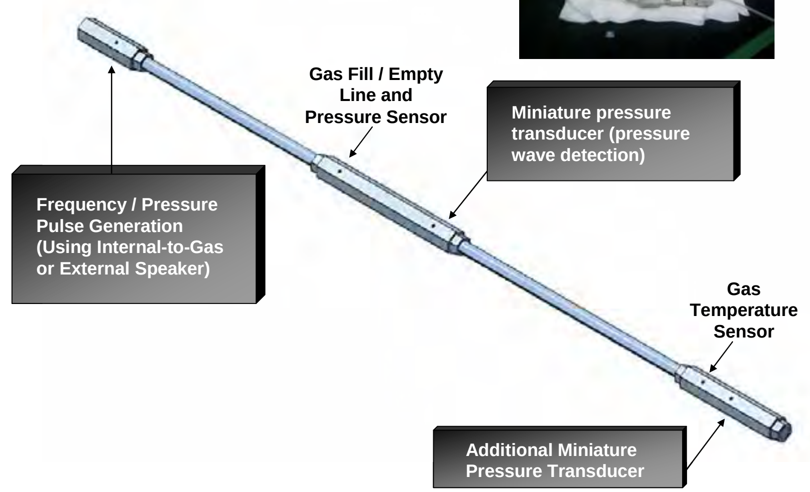
Multivariable Cycle Optimization for Efficiency



Partial condensation cycle model using NPSS

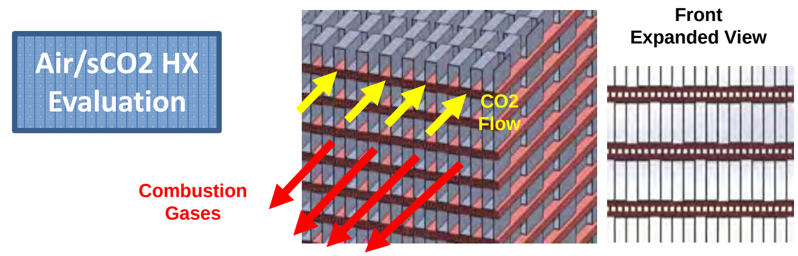
Fundamental Gas Property Testing
(SwRI for DOE, NIST, and Commercial Clients)

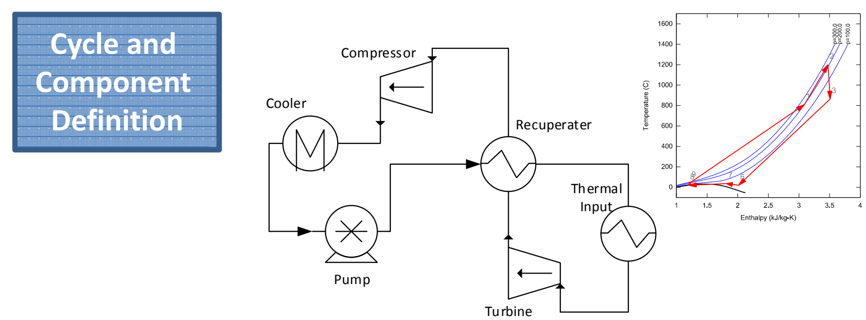
- Fundamental gas property tests for high CO_2 content mixtures, falling outside of typical EOS model limits: speed of sound, specific heat, and density up to 15,000 psi, 500°F.
- Adapted high pressure autoclaves / adiabatic calorimeters for specific heat determination.
- Specialized test methods for speed of sound using high pressure fixture design developed by SwRI.
- Gas sampling and species determination near critical point.
- Controlled long-term tests using for CO_2 / water mixtures to characterize gas-liquid behavior.

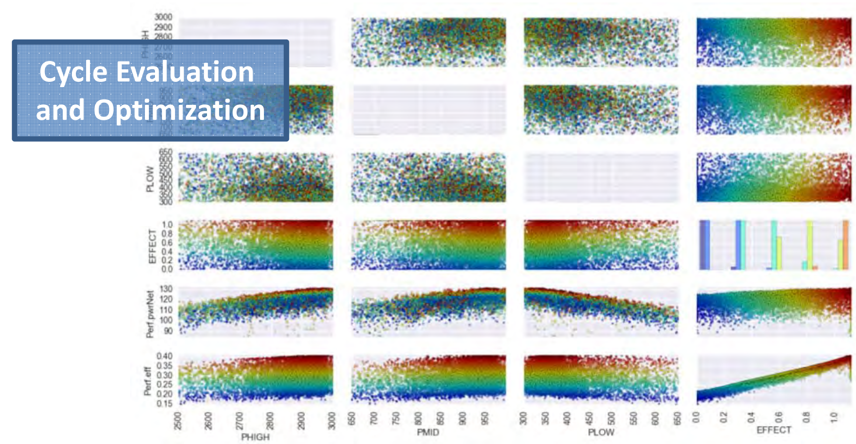


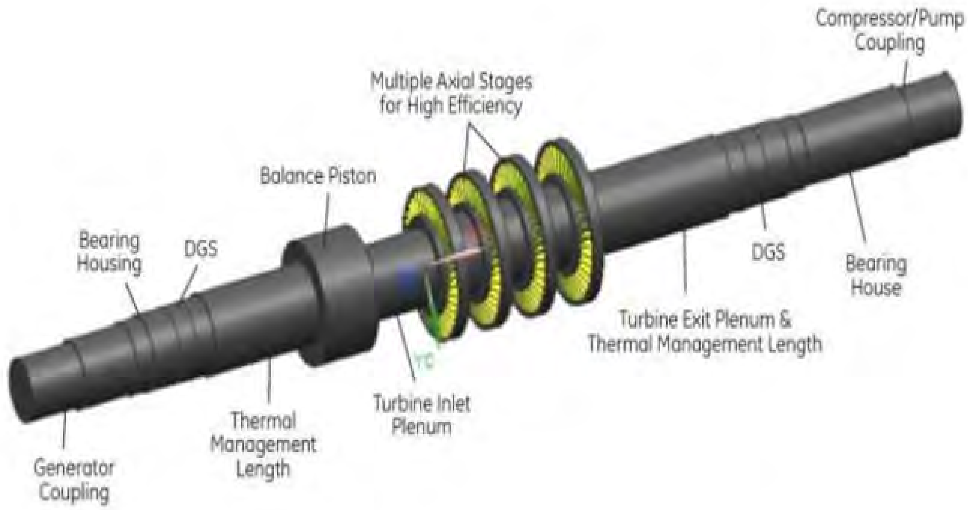
Absorption/Desorption Based High Efficiency Supercritical Carbon Dioxide Power Cycles *(SwRI, Thar Energy for DOE NETL)*

- Technical evaluation of fossil based thermal sources
- Optimization of indirect fossil based sCO2 cycles
- Technical evaluation of air/sCO2 heat exchangers
- Development of a novel Absorption/Desorption sCO2 cycle





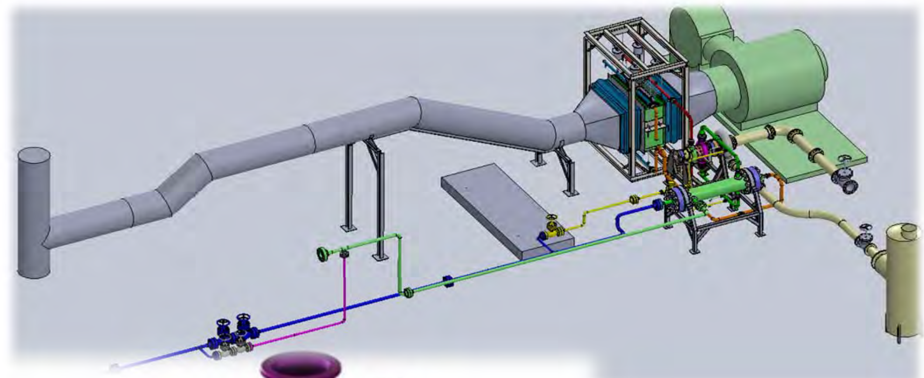


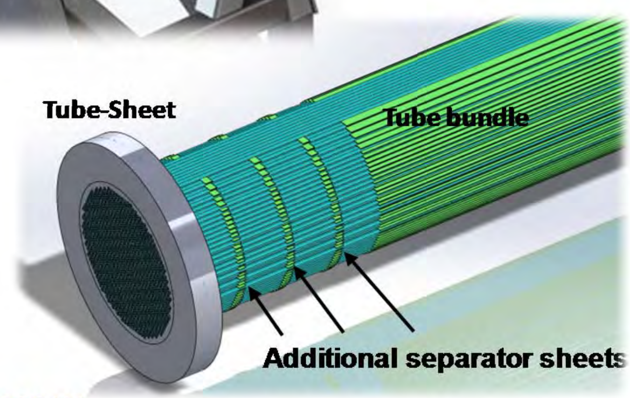


TURBINE DEVELOPMENT

Development of a High Efficiency Hot Gas Turbo-expander and Low Cost Heat Exchangers for Optimized CSP Supercritical CO2 Operation (SwRI, GE, Thar for DOE EERE)

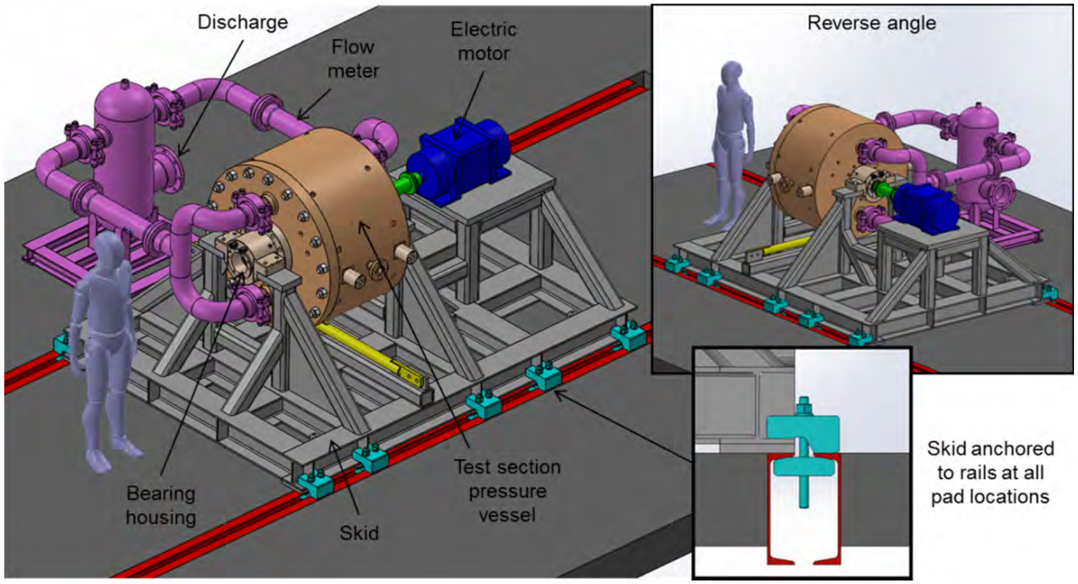
- MW-scale sCO2 turbo-expander and heat exchanger are a critical step in increasing energy conversion efficiency to >50%, while reducing power block costs
- Participants
  - GE with SwRI has developed a MW-scale sCO2 turbo-expander optimized for concentrating solar power plant duty cycle profile
  - Thar has developed a compact, high temperature recuperator
  - KAPL has provided vital testing, design and engineering expertise
- SwRI fabricated a 1 MWe sCO2 test loop to verify expander and recuperator performance
- All components are in the final stages of fabrication and assembly, testing to be completed in 2016





Testing of Shaft End Seals for Utility Scale sCO2 Turbines *(GE, SwRI for DOE NETL)*

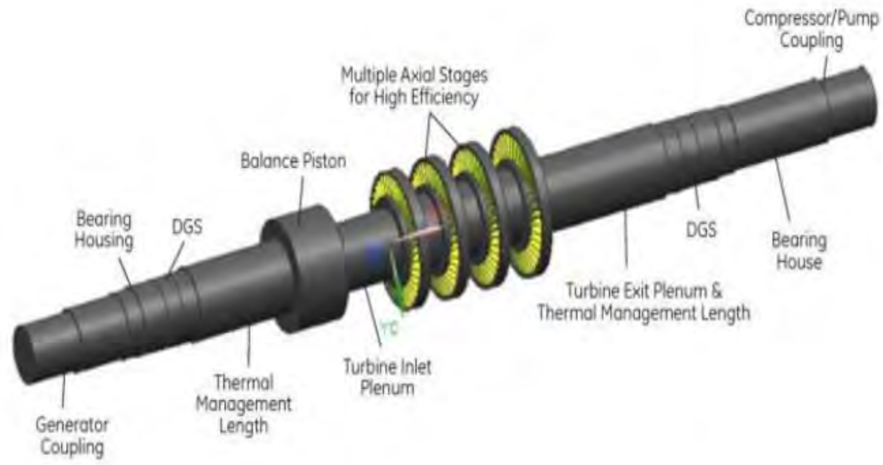
- Utility scale sCO2 power cycles rely on low-leakage shaft end seals to meet high cycle efficiency goals
- Seal technologies for sCO2 compressor conditions currently exist, but they do not for sCO2 turbine conditions
- GE Global Research developing new large diameter face seal technology

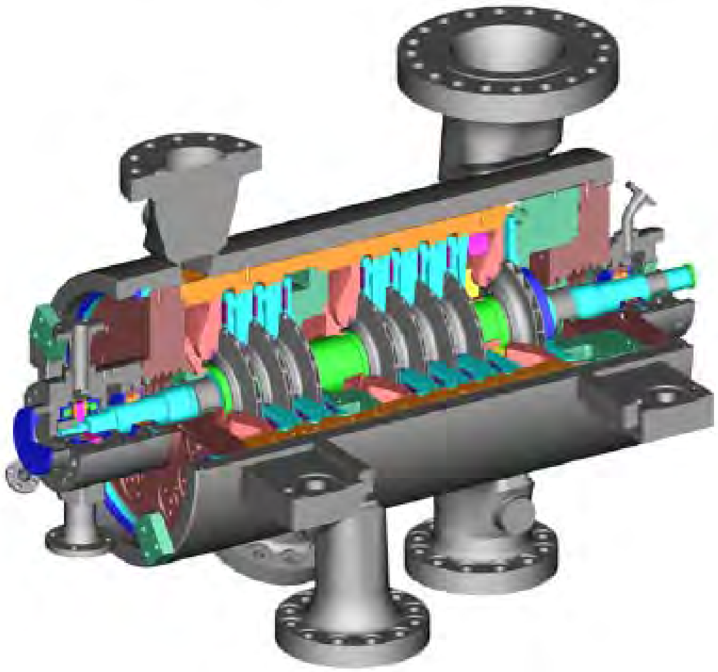


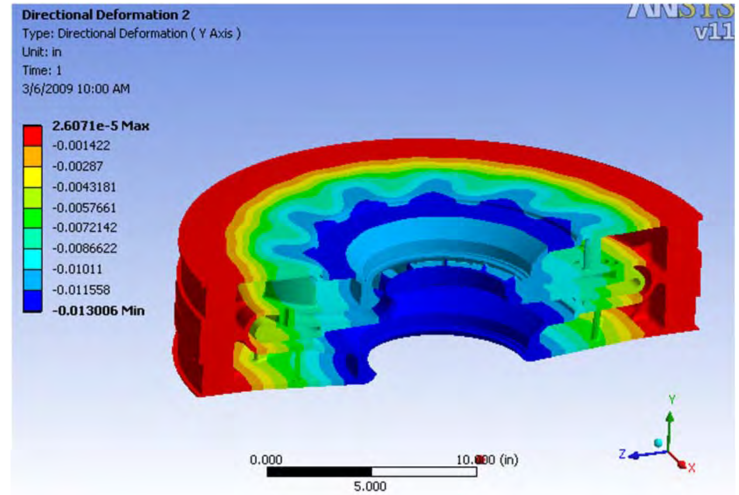
- SwRI developing rig to test full-scale seal prototype with sCO_2
  - Leakage and thermal performance
  - Utilize loop for SunShot test program

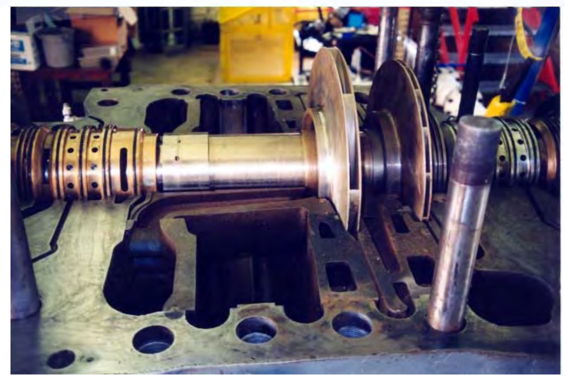
Physics-based Reliability Models for Supercritical CO2 Turbomachinery Components (*GE, SwRI for DOE EERE)*

- Detailed testing of Dry Gas Seals in supercritical CO2 environment to support physics-based reliability models
- Testing SunShot expander seals with detailed flow/pressure, temperature instrumentation
- Seal supply/vent system design and fabrication
  - Clean seal supply
  - Prevent seal overheating
  - Prevent dry ice formation





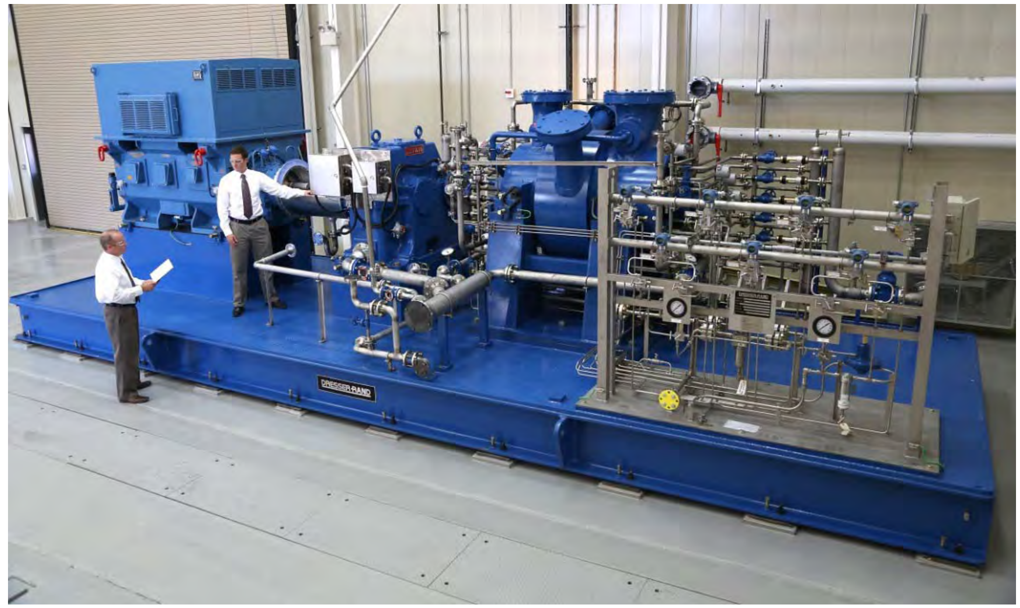


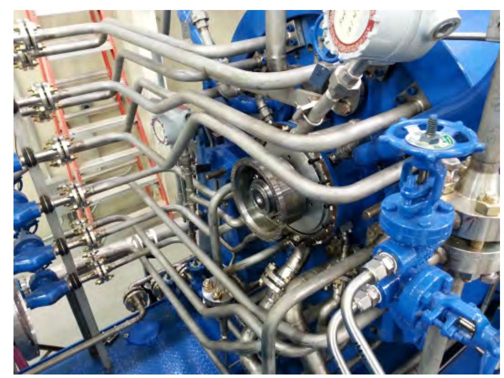


COMPRESSOR DEVELOPMENT

DOE CO2 Compression Project Development of Isothermal Compression (SwRI, Dresser Rand, BP for DOE NETL)

- Pilot-scale demonstration of an internally cooled compressor design
- Isothermal compressor and liquefaction / CO2 pump equipment design
- Thermodynamic analysis of CO2 separation, compression, and transport
- CO2 liquefaction loop for proof of concept demonstration





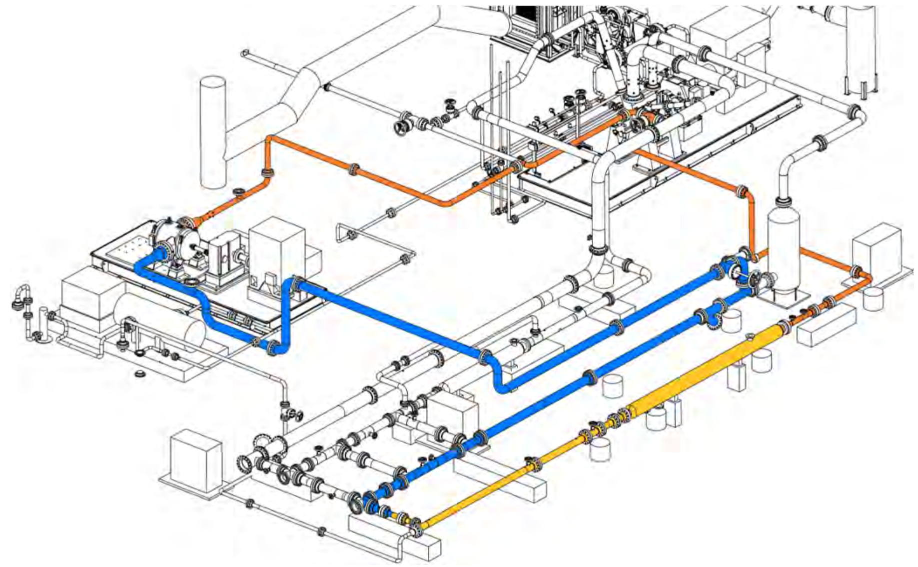
GE-Apollo High-Efficiency sCO2 Centrifugal Compressor Development (GE, SwRI for DOE EERE)

PROJECT OBJECTIVES

- Develop high-efficiency sCO2 compression system
  - High efficiency centrifugal impeller
  - Variable IGV/OGV
- Advanced aerodynamic design provided by GE will be implemented into the detail compressor design provided by SwRI.

KEY RESULTS AND OUTCOMES

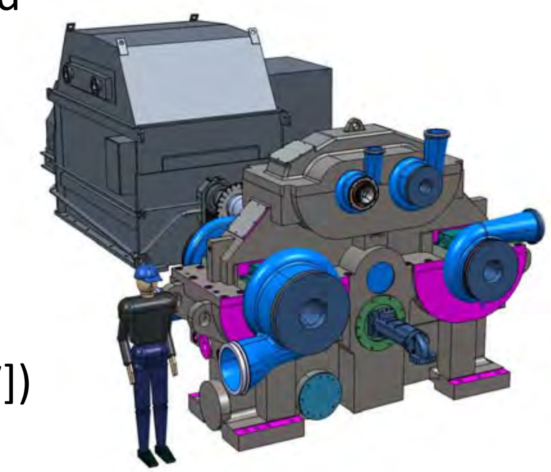
- Full scale testing of a 10 MWe SCO2 Compressors
- Extended flow range to accommodate swings in ambient temperature

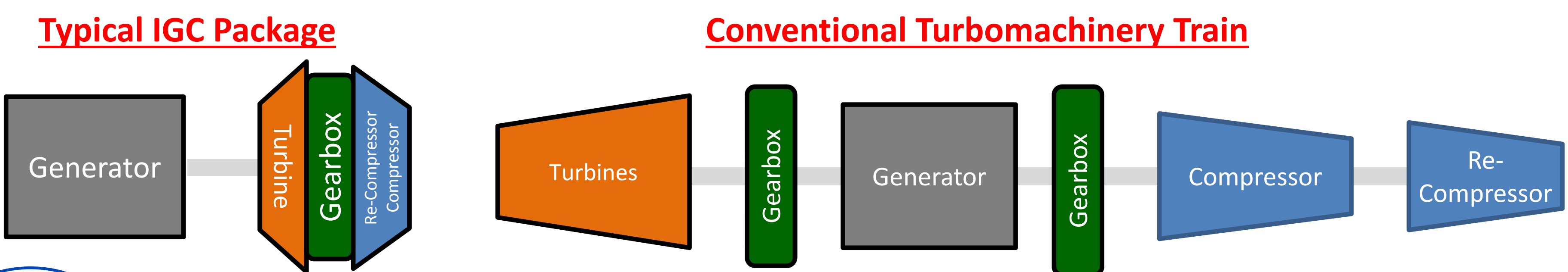


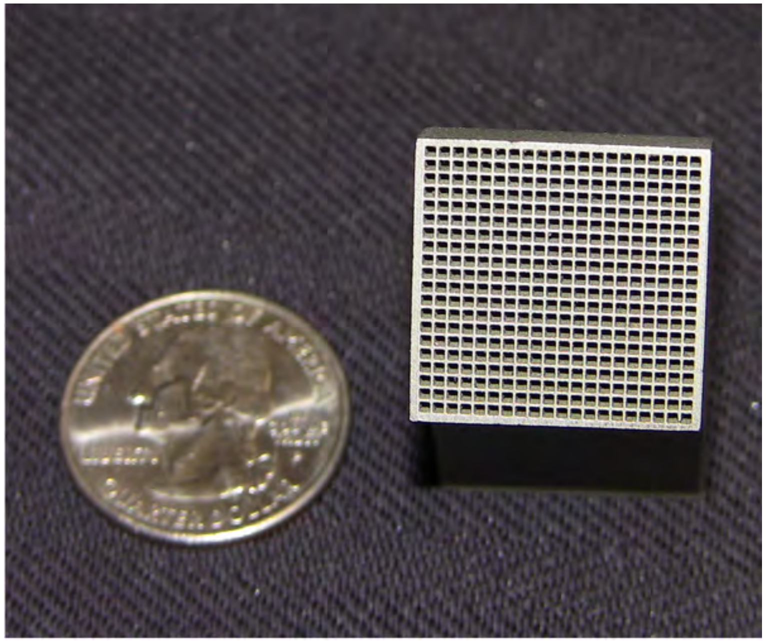
Leverage SwRI SCO2 Test Facility to verify compressor mechanical and aerodynamic performance over a range of operating conditions

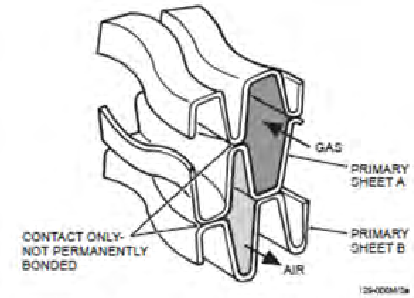
Ultra High Efficiency Integrally-Geared sCO2 Compander *(SwRI, Hanwa for DOE EERE)*

- 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 range of operating conditions
  - Improved cycle controllability
  - Reduced mechanical complexity ➔ improved reliability and reduced maintenance

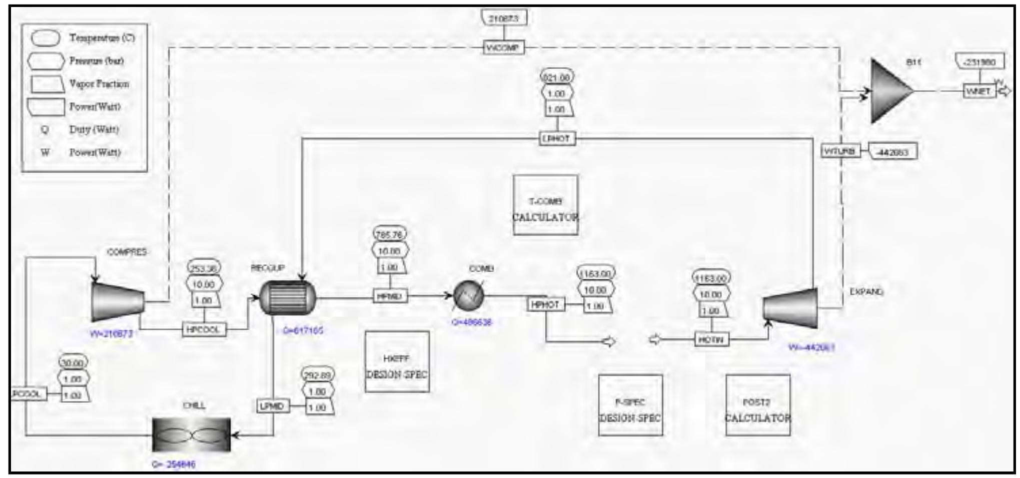








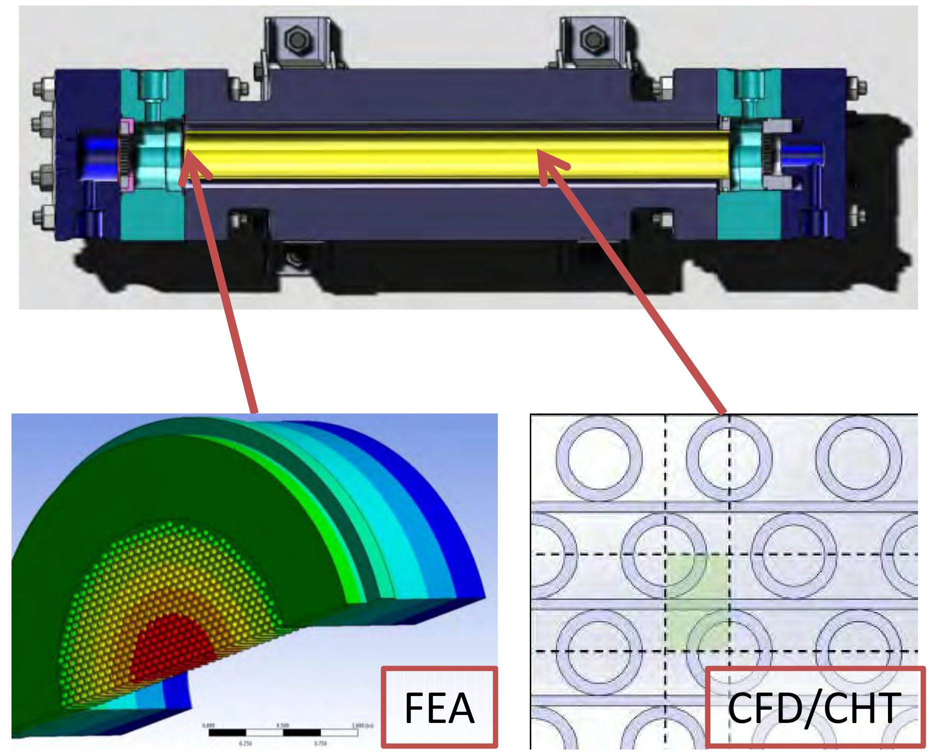
Primary Surface Sheets



HEAT EXCHANGER DEVELOPMENT

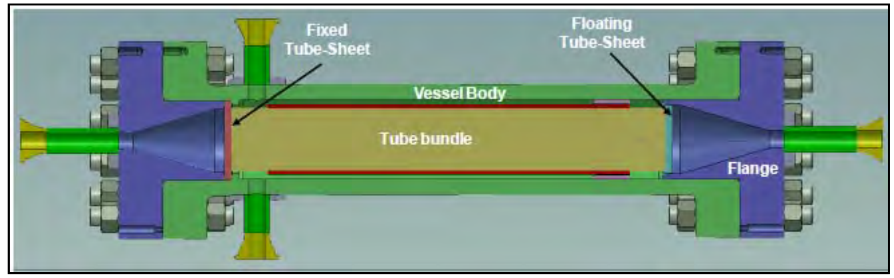
Super-critical CO2 Heat Exchanger Analysis
(*Thar, SwRI for DOE NETL)*

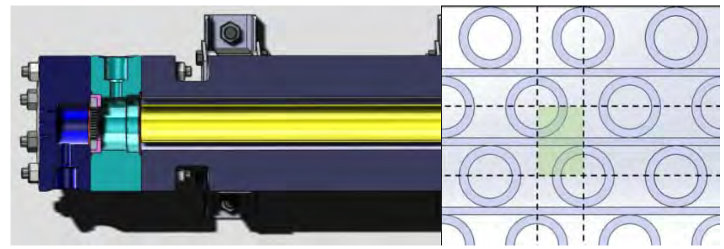
- Analysis of sCO2 power cycle recuperator configurations
- Prediction of pressure drop, flow distribution, and heat transfer using conjugate heat transfer
- FEA based stress predictions to support manufacturing analysis
- Evaluation of alternate configurations with heat transfer improvements

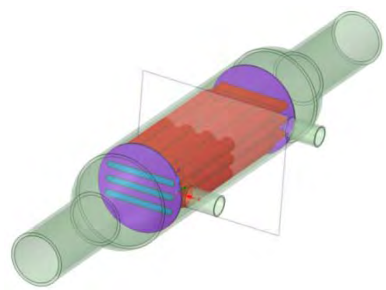


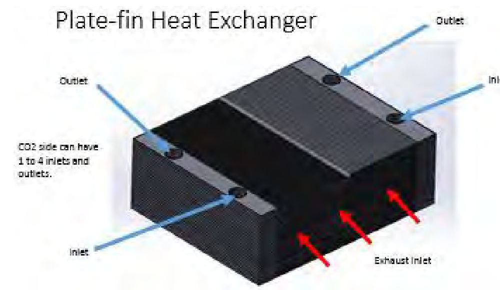
Advancing High Temperature Recuperator Technology for sCO2 Power Cycles
(Thar, SwRI, ORNL, Georgia Tech for DOE NETL)

- Design of a 47MWth compact, high-temperature recuperator for a 10MWe Pilot Scale Demonstration
- Address critical design, materials, and fabrication challenges
  - Target 96% thermal effectiveness
- Evaluate multiple configurations to identify technologies which significantly improve recuperator cost, performance, and scalability
  - Scalable from 10 to 1,000 MWe cycle configurations



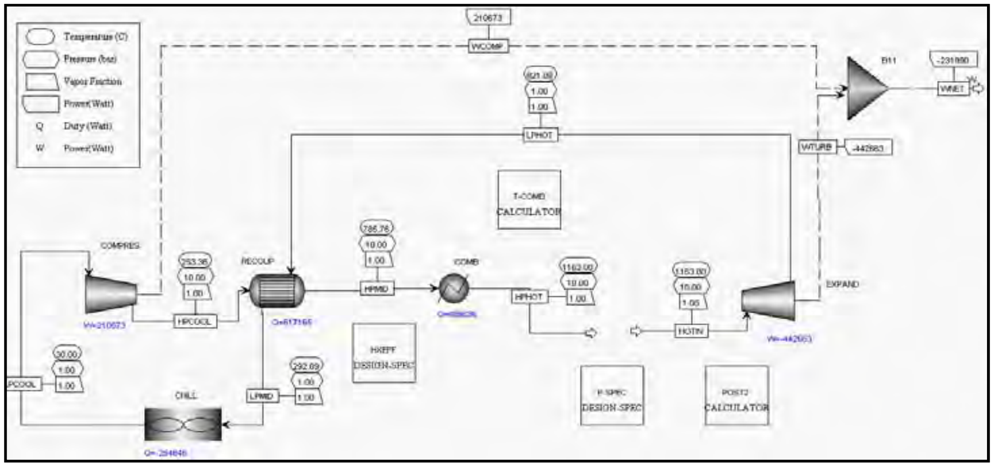


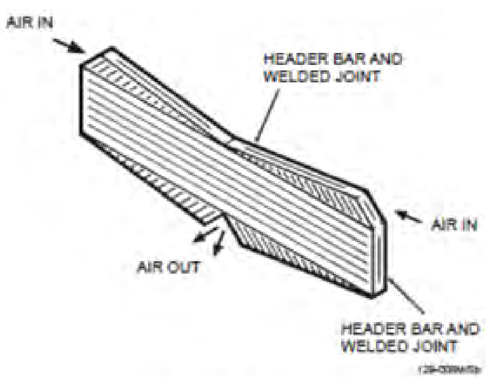




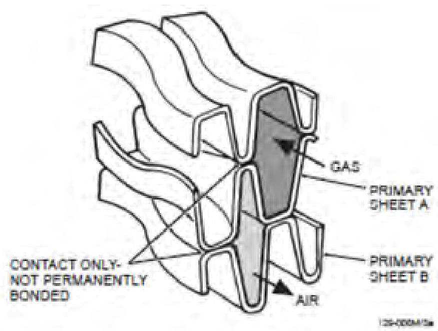
Investigating concepts to for performance, cost, scalability → Concept selection and prototype testing → Preliminary design of 47MWth scale

Thin-Film Primary Surface Heat Exchanger Development *(SwRI, Solar for DOE NETL)*



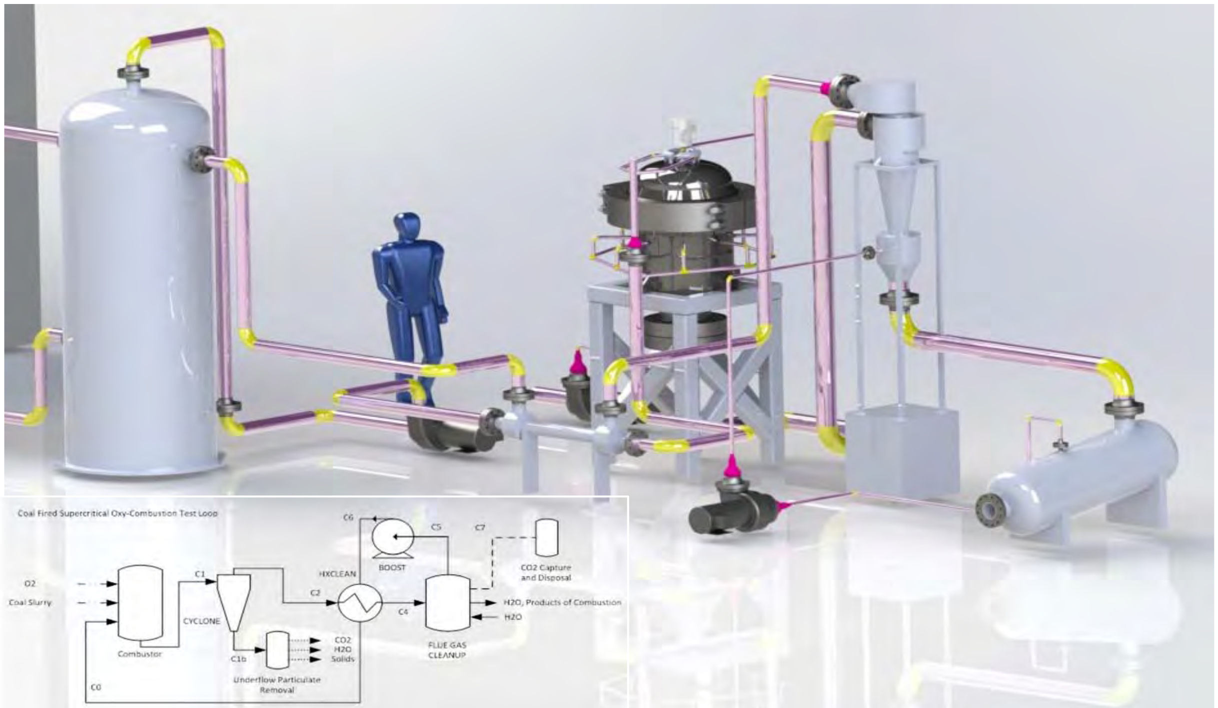


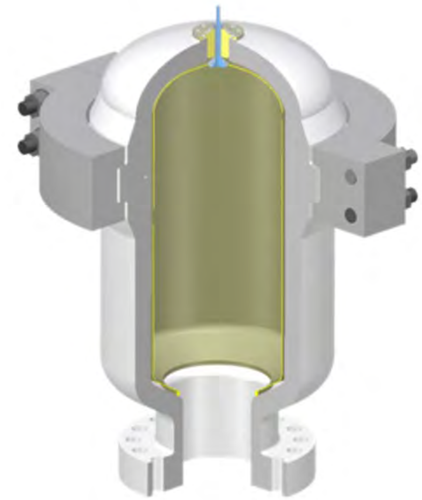
PSR Air Cell



Primary Surface Sheets

- Advance existing proven Mercury 50 recuperator design for operation in CO2 at 1510 F and P = 9 bar
- Low-pressure oxy-fuel recuperated Brayton cycle with 19% higher efficiency than air Brayton cycle
- High temperature coupon testing of candidate materials and coatings in CO2

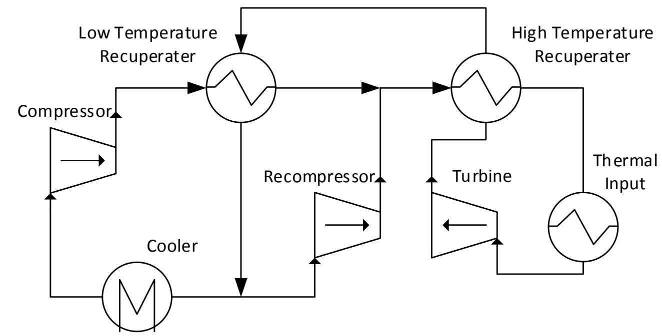


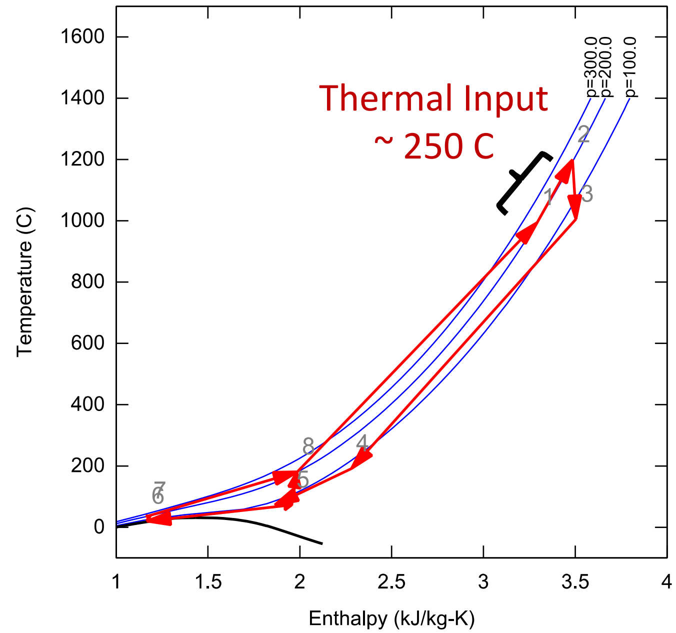


OXY-COMBUSTION

Why Oxy-Combustion?

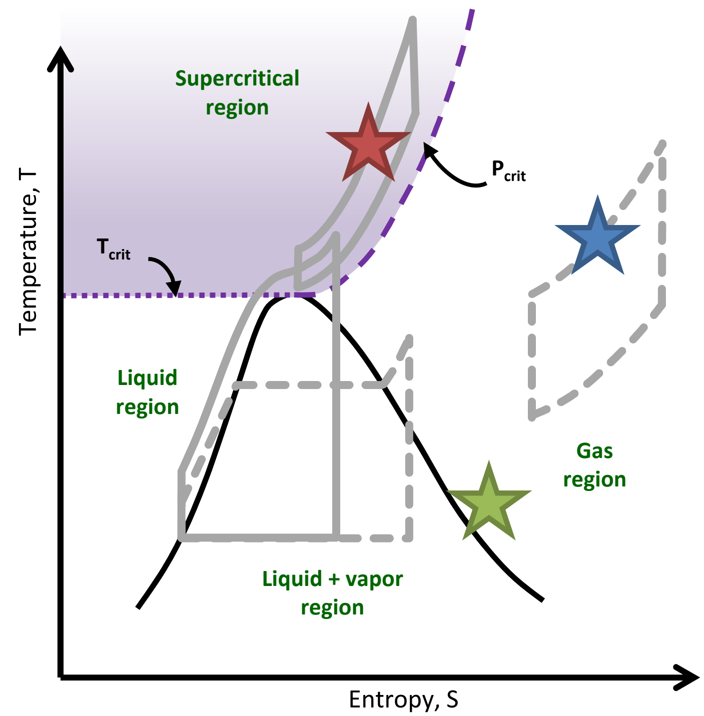
- High efficiency cycles are highly recuperated
- Indirect cycles provide unique thermal integration challenges
- Direct fired configurations remove at least two heat exchangers
- Supercritical oxy-combustion is well suited for integrated CCS





Flavors of Oxy-Combustion

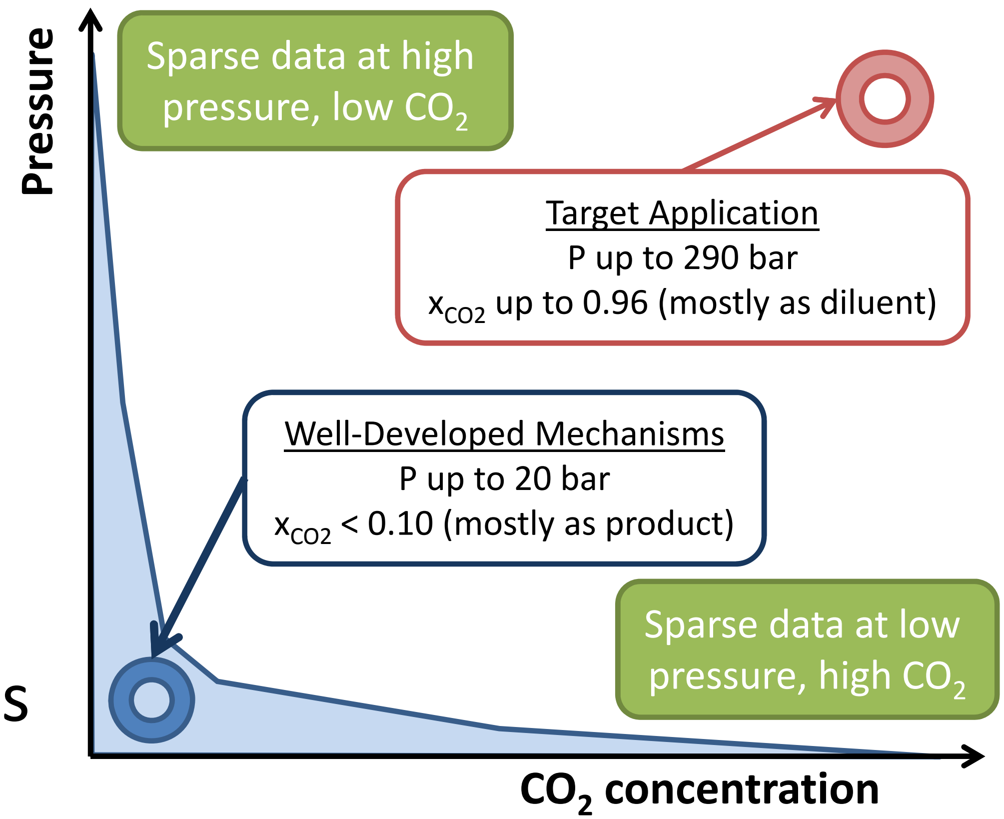
- Flue Gas Recirculation (**Indirect**)
  - Combustion at near ambient pressures
  - Recycled flue gas is mixed with incoming air
  - Increases flame temperatures
  - Increases CO2 concentration for CCS
- Pressurized Oxy-combustion (**Direct Fired**)
  - Combustion at elevated pressure (~ 10 bar)
  - Latent heat is recoverable and heat transfer rates are increased
  - Minimizes air in-leakage



- Supercritical Oxy-combustion (**Direct Fired**)
  - Combustion occurs at supercritical pressures (>74 bar)
  - Required for direct fired sCO2 cycles, compatible with indirect cycles
  - CO2 acts as a solvent in dense phase, accelerating certain reactions
  - Compression requirements drive closed combustion solutions
  - Flue gas cleanup and de-watering at pressure may be challenging

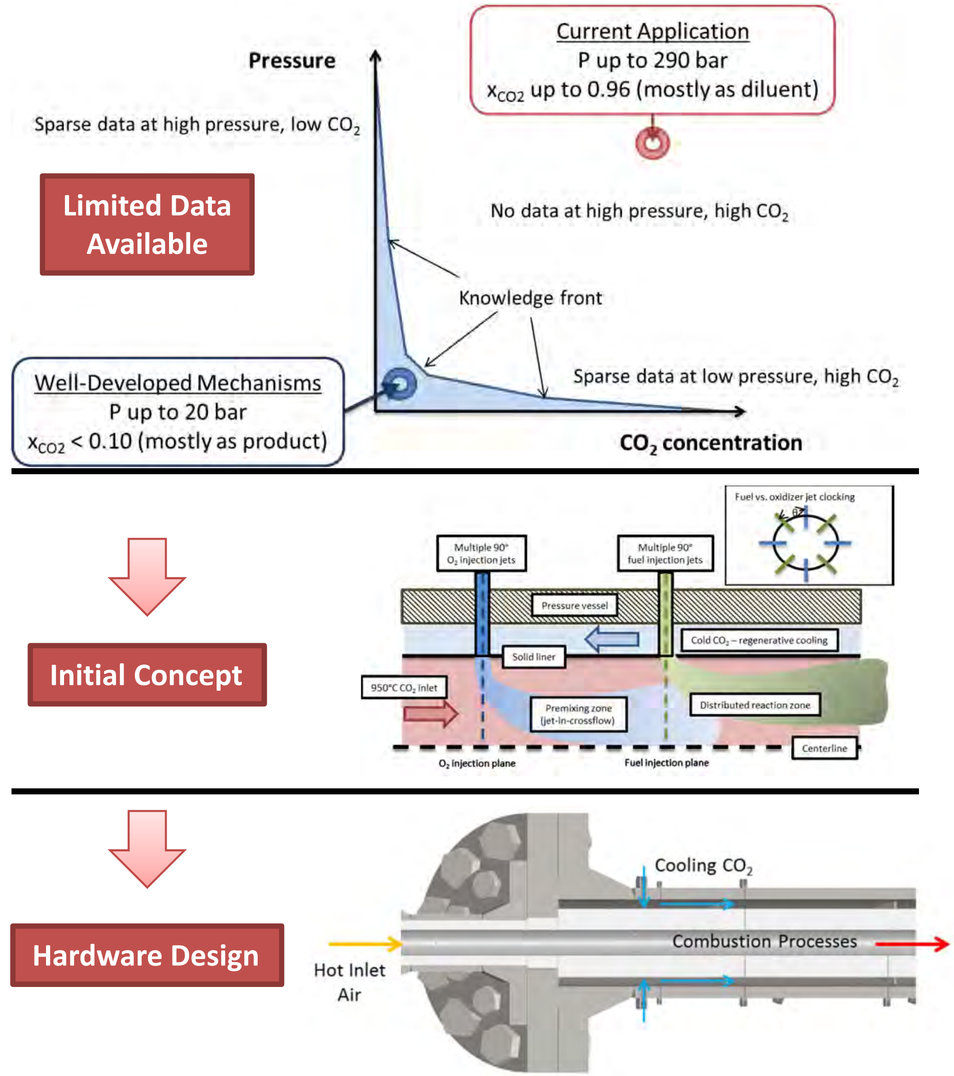
Oxy-Combustion Kinetics

- Existing knowledge centers on low pressure, low CO2 applications
  - Relevant to conventional propulsion/power generation
  - Easier to evaluate experimentally
- No data available at conditions relevant to this application.



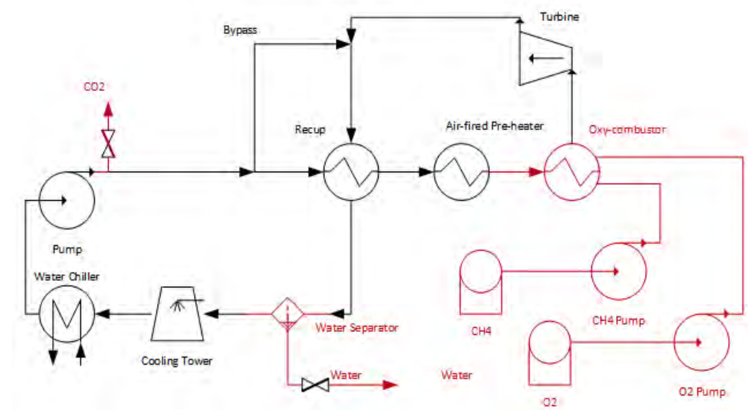
High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion Phase I
(SwRI, Thar for DOE NETL)

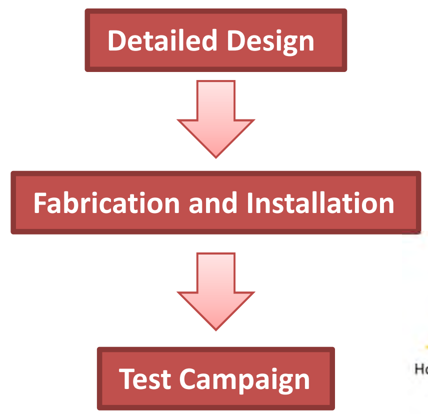
- Optimization of direct fired sCO2 oxy-combustion cycles
  - Target plant efficiency > 52% (LHV)
  - Provide inherent 99% carbon capture
- Oxy-combustor design for High and Low inlet temperature applications
- Identify and develop critical enabling technologies
  - Bench scale kinetics test stand
  - Optical emission spectroscopy (OES) gas analyzer
- Test stand design for pilot scale demonstration
- Phase 2 demonstration awarded, FY17 start

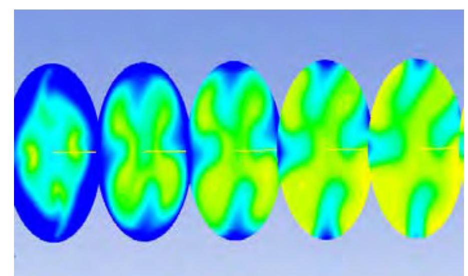


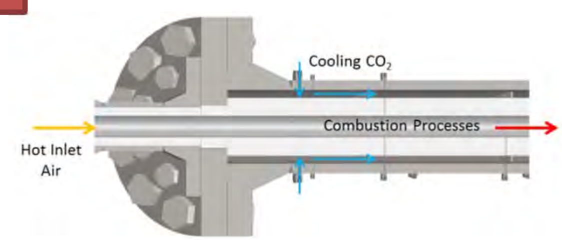
High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion Phase II
(SwRI, Thar for DOE NETL)

- Detailed design of supercritical oxy-fuel combustor from initial Phase I design
  - Design of water separation from combustion products
- Fabricated and assemble combustor test loop utilizing existing hardware at SwRI
- Test campaign to understand combustion processes and combustor performance



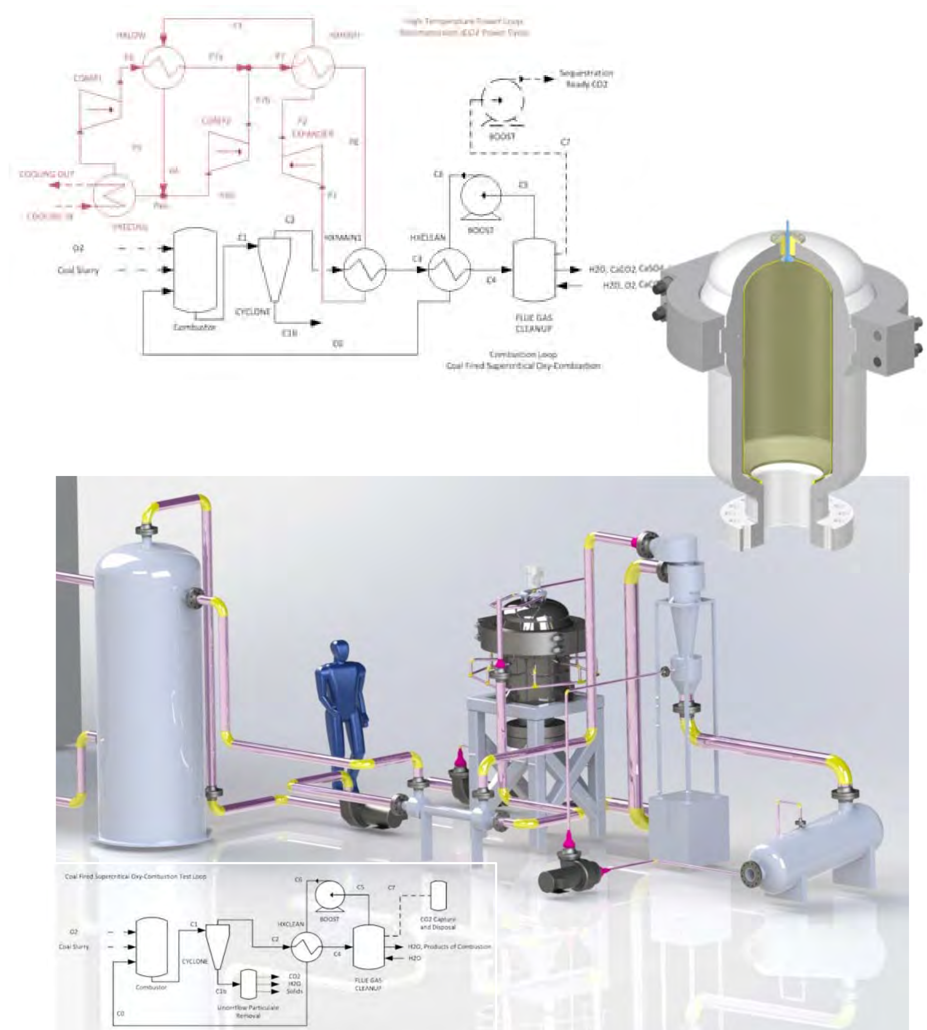






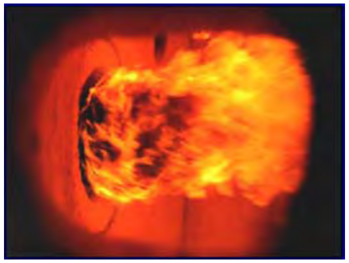
Development of a Supercritical Oxy-combustion Power Cycle With 99% Carbon Capture *(SwRI, Thar for DOE NETL)*

- Evaluation of coal fired oxy-combustion for direct fired sCO2 power cycles
- Direct fired cycle achieves 40% plant efficiency at 650 C Turbine Inlet
- Project highlights
  - Combustor development
  - Cycle modeling and simulation
  - Technical risk assessment
  - Cost estimate for pilot scale demonstration
- Demonstration requires significant technology development

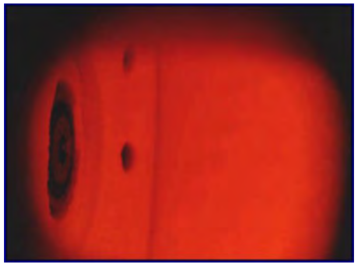


Flameless Pressurized Oxy-Combustion Pilot Plant Planning *(SwRI, ITEA for DOE NETL)*

- Pressurized atmosphere of water and CO2 prevents traditional flame fronts
  - FPO combustion is more locally controllable with more uniform temperatures and improved efficiency
- Almost zero carbon content in incombustible products
  - Traditional: flying and falling ash particles must be filtered and collected from gas stream
  - FPO: slag with near-zero carbon content drains out the bottom of the combustor
- Development of a 50 MWth pilot power plant
  - Team from ITEA, EPRI, GE Global Research, and Jacobs
  - Site selection, preliminary drawings and cost estimates for pilot plant
  - Scale up from existing pilot technology
  - Design of a durable turbomachine in atmosphere of CO2 and water
  - Design of an efficient once-through steam generator

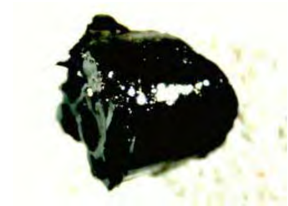


Traditional Combustion with Flame Front

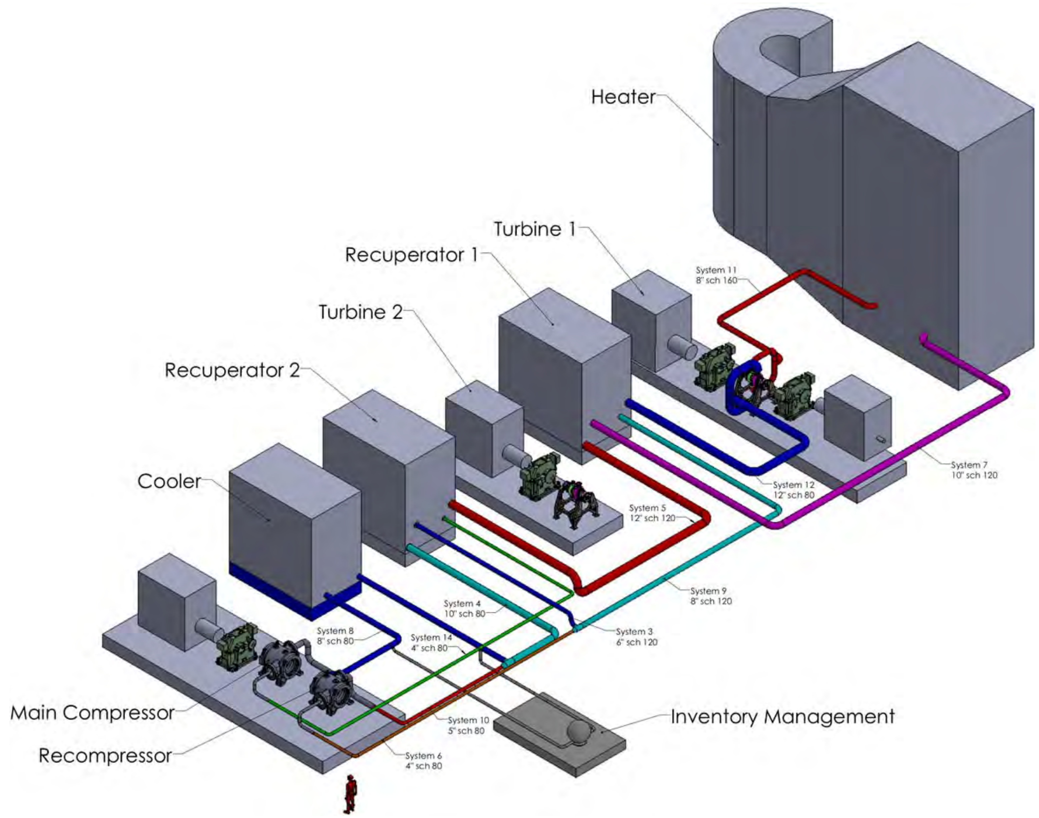


Flameless Pressurized Combustion

Traditional Combustor Products: Particulate



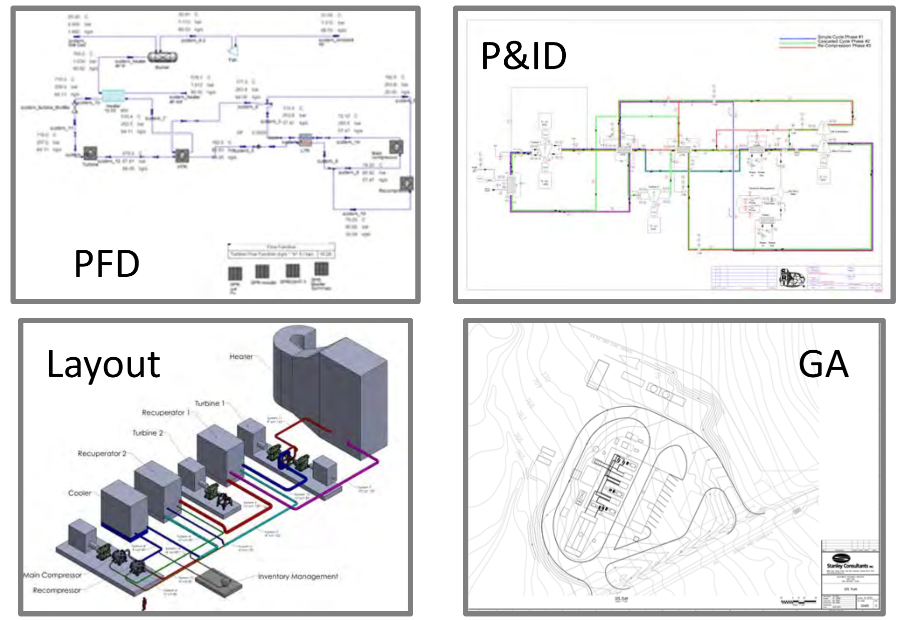
FPO Combustor Products: Near-zero slag

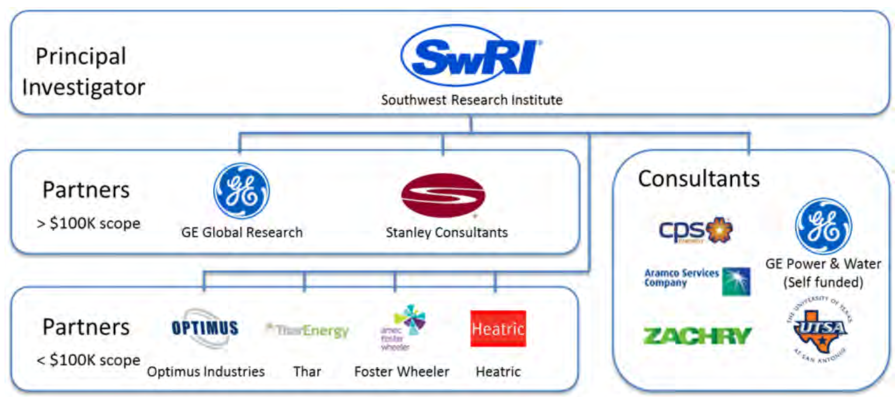


PILOT SCALE SCO2 TECHNOLOGY DEMONSTRATION

Phase 1: Conceptual Design for a Supercritical Carbon Dioxide Power Cycle Test Facility (*SwRI Prime for DOE NE)*

- Conceptual Facility Design addressing DOE requirements and specifications
  - Cycle and component specification
  - Preliminary component design and cost estimates
  - Facility and hardware layout
  - Facility general arrangement
  - Technology development and testing requirements
  - Host Site Evaluation
- Produced a Class 4 Facility Cost Estimate





Thank You Very Much!
Questions?

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