



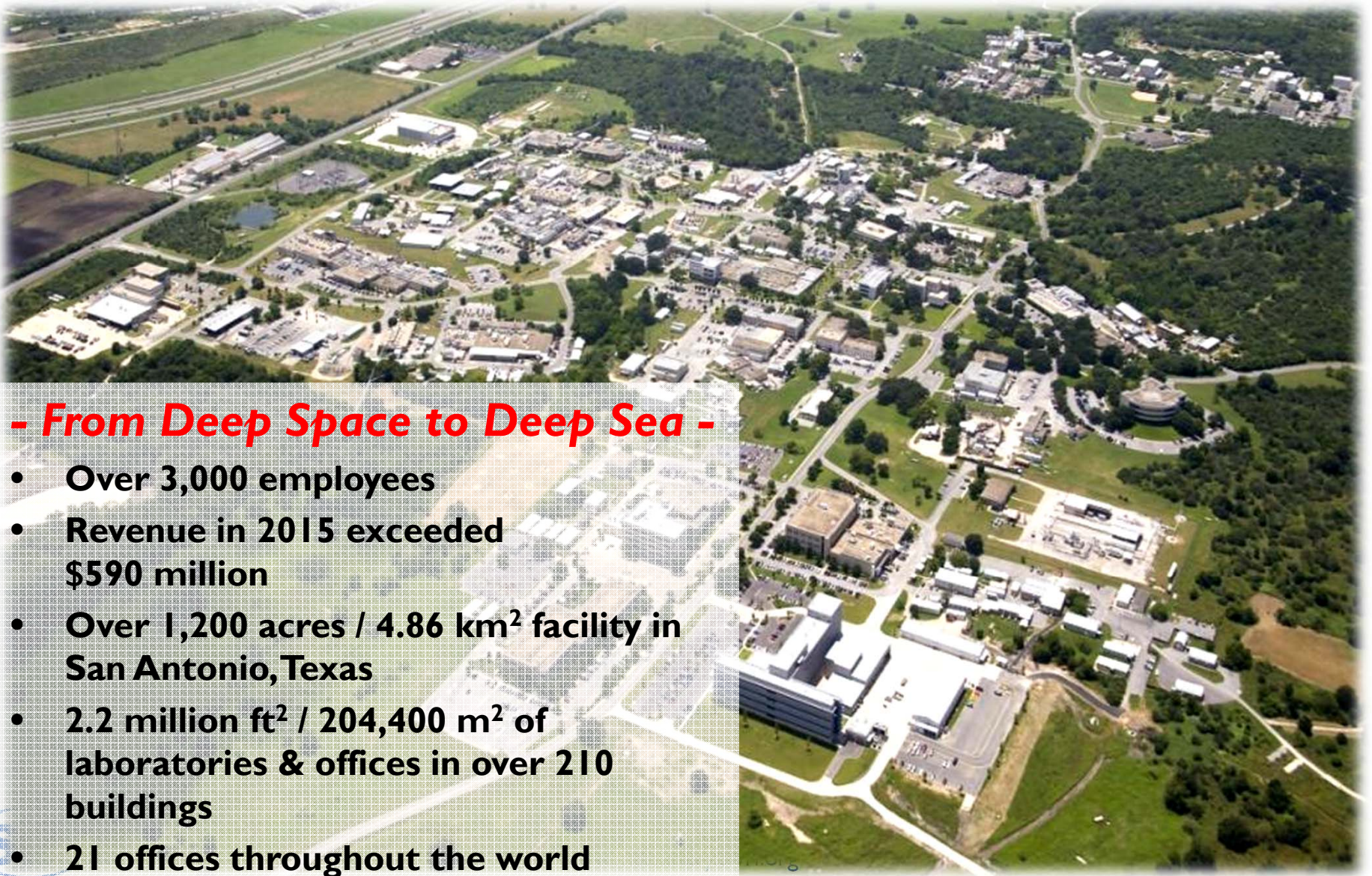
SwRI Machinery Program

Technology Development for Supercritical Carbon Dioxide Power Cycles

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Southwest Research Institute

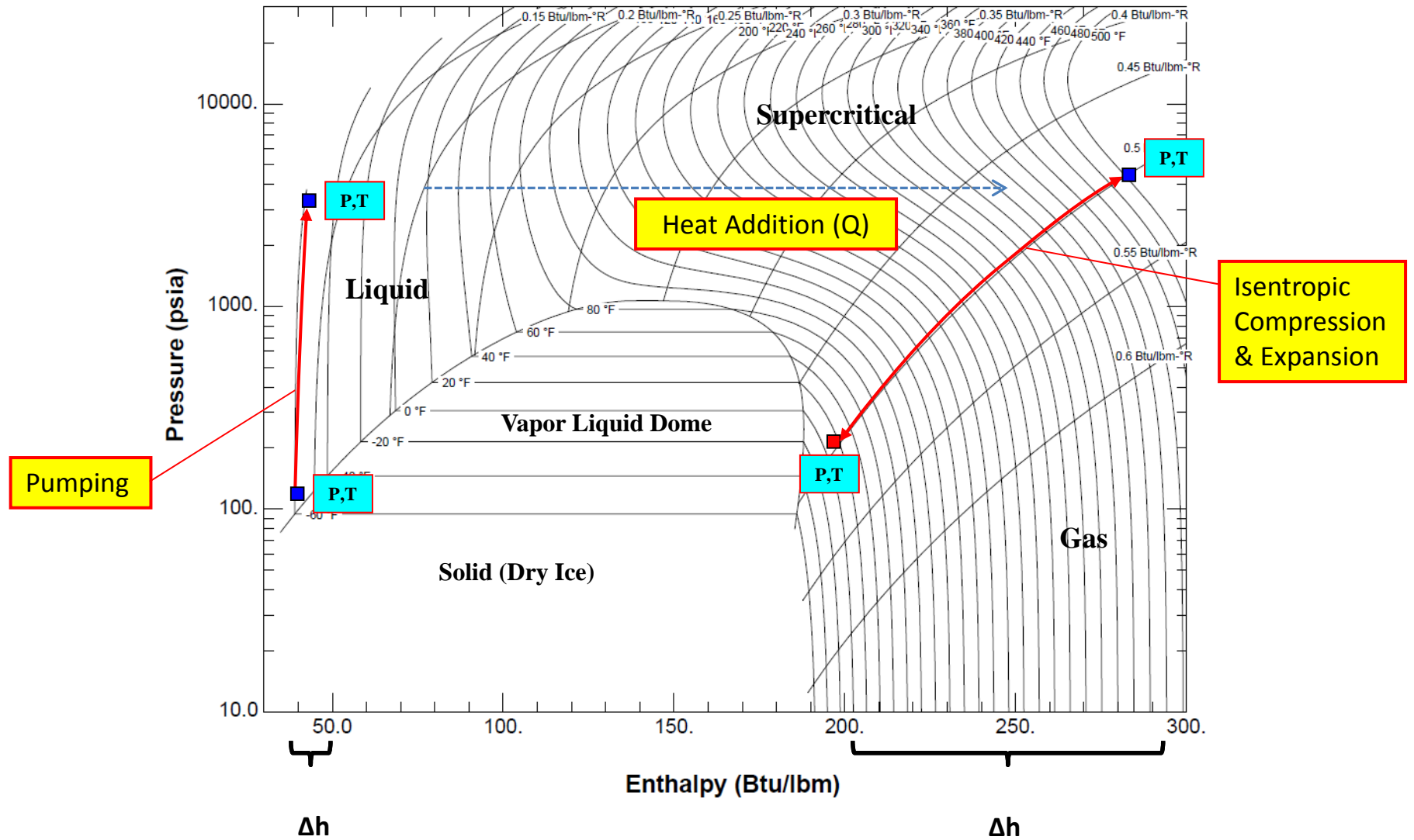


- From Deep Space to Deep Sea -

- **Over 3,000 employees**
- **Revenue in 2015 exceeded \$590 million**
- **Over 1,200 acres / 4.86 km² facility in San Antonio, Texas**
- **2.2 million ft² / 204,400 m² of laboratories & offices in over 210 buildings**
- **21 offices throughout the world**



Power Cycles: Pumping, Compression, Expansion



$$W = \dot{m} \Delta h$$

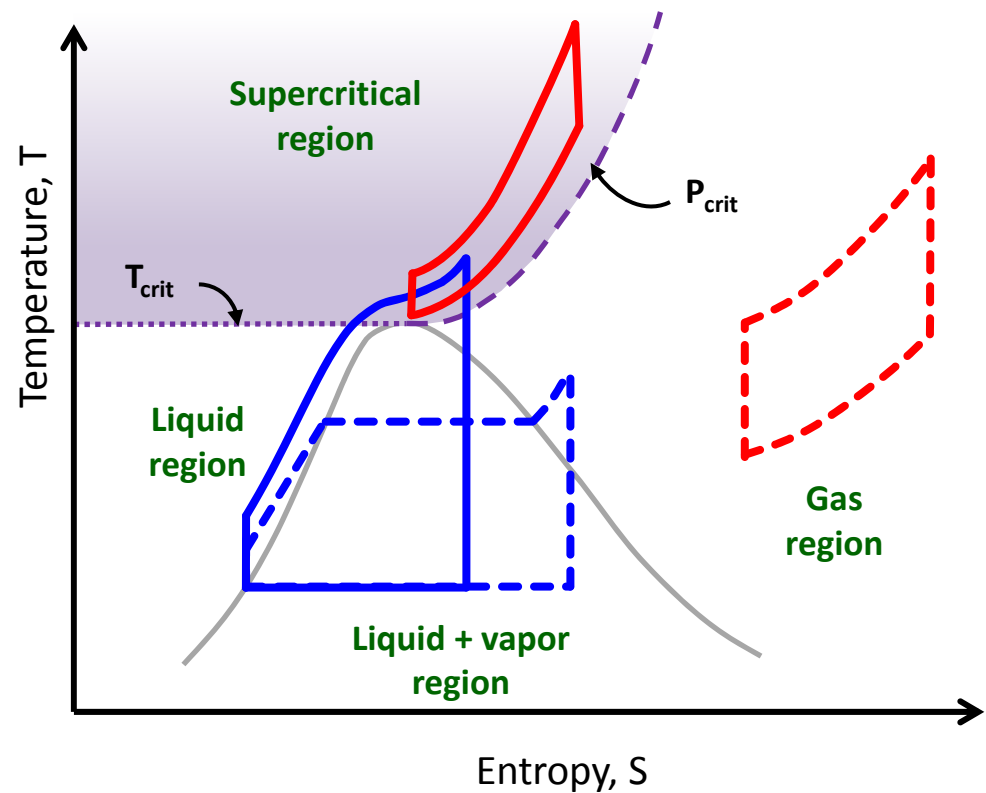
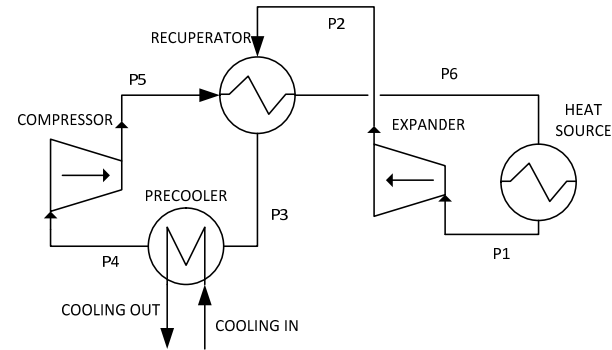
$$W_{\text{net}} = \dot{m} (\Delta h_{\text{out}} - \Delta h_{\text{in}})$$

$$\eta = W_{\text{net}} / Q$$

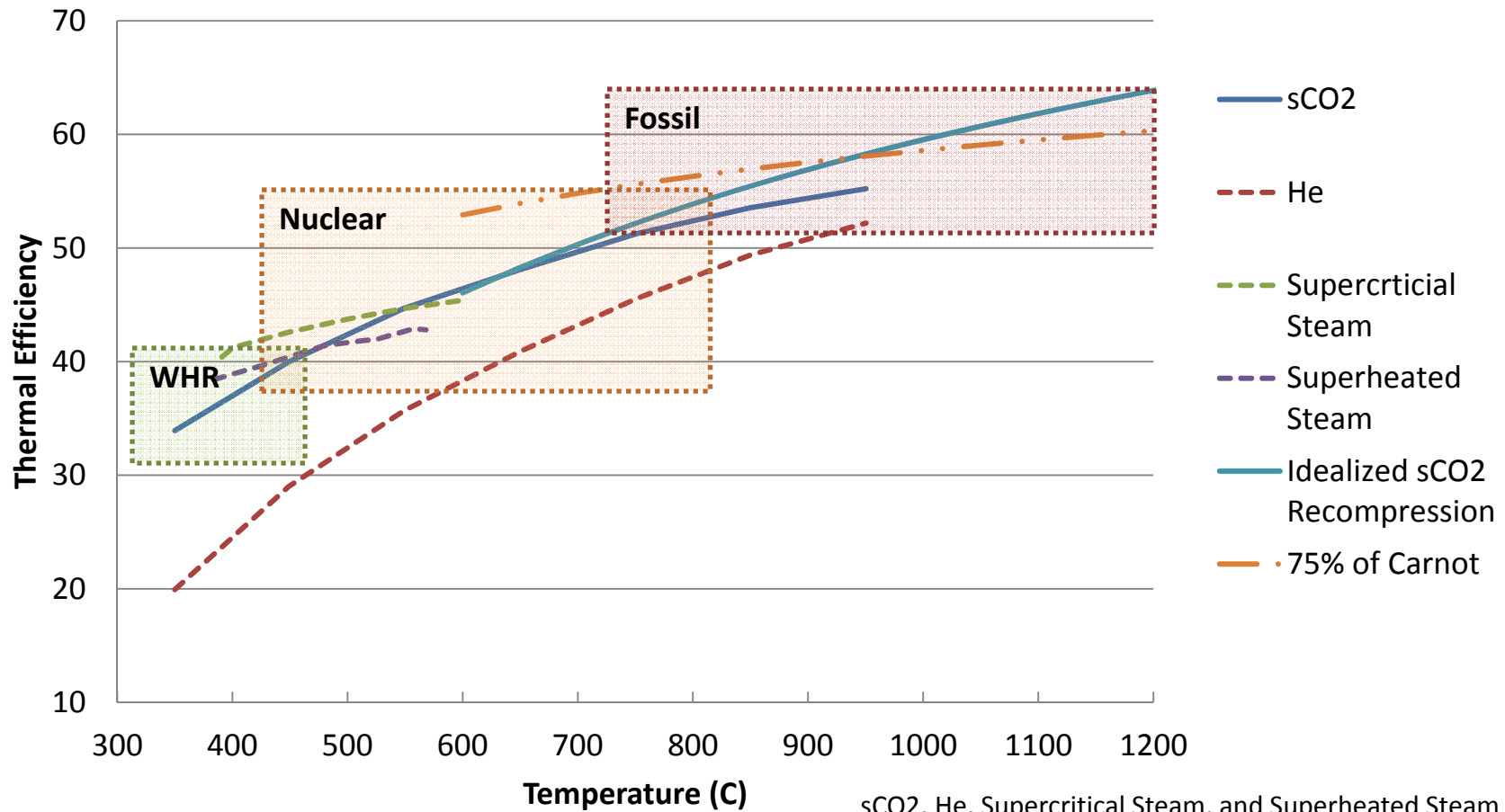


Supercritical Carbon Dioxide (sCO₂) Cycles

- 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)

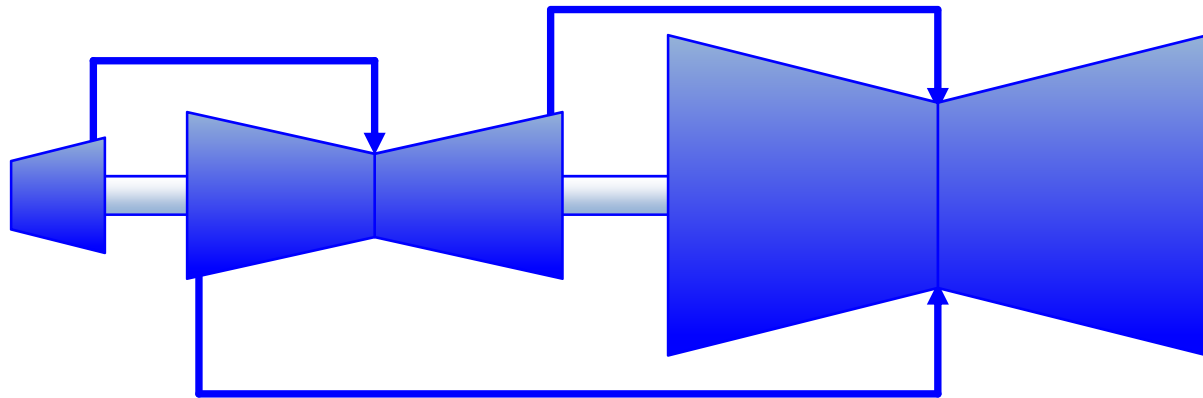


Power Cycle Efficiencies



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

Relative Size of Components



5 m

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



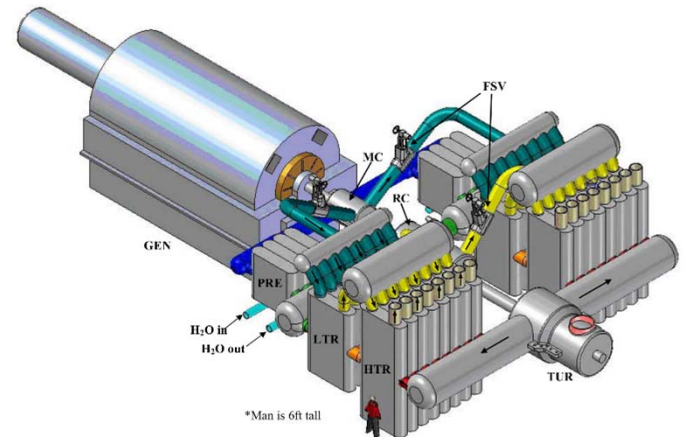
Helium turbine: 17 stages / 333 MW (167 MW_e)
X.L. Yan, L.M. Lidsky (MIT) (without casing)

1 m



sCO₂ turbine: 4 stages / 450 MW (300 MW_e)
(without casing)

Note: Compressors are comparable in size



*Man is 6ft tall

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

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

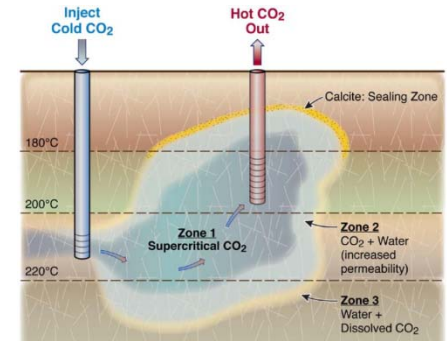
sCO₂ in Power Cycle Applications



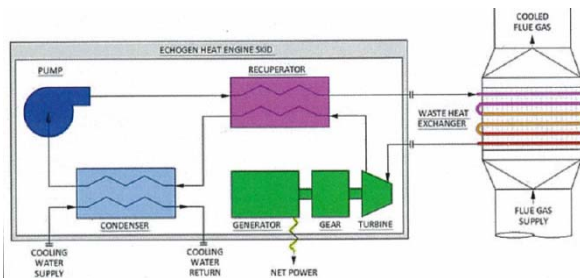
Concentrating
Solar Power



Fossil Fuel



Geothermal



Waste Heat
Recovery



Nuclear

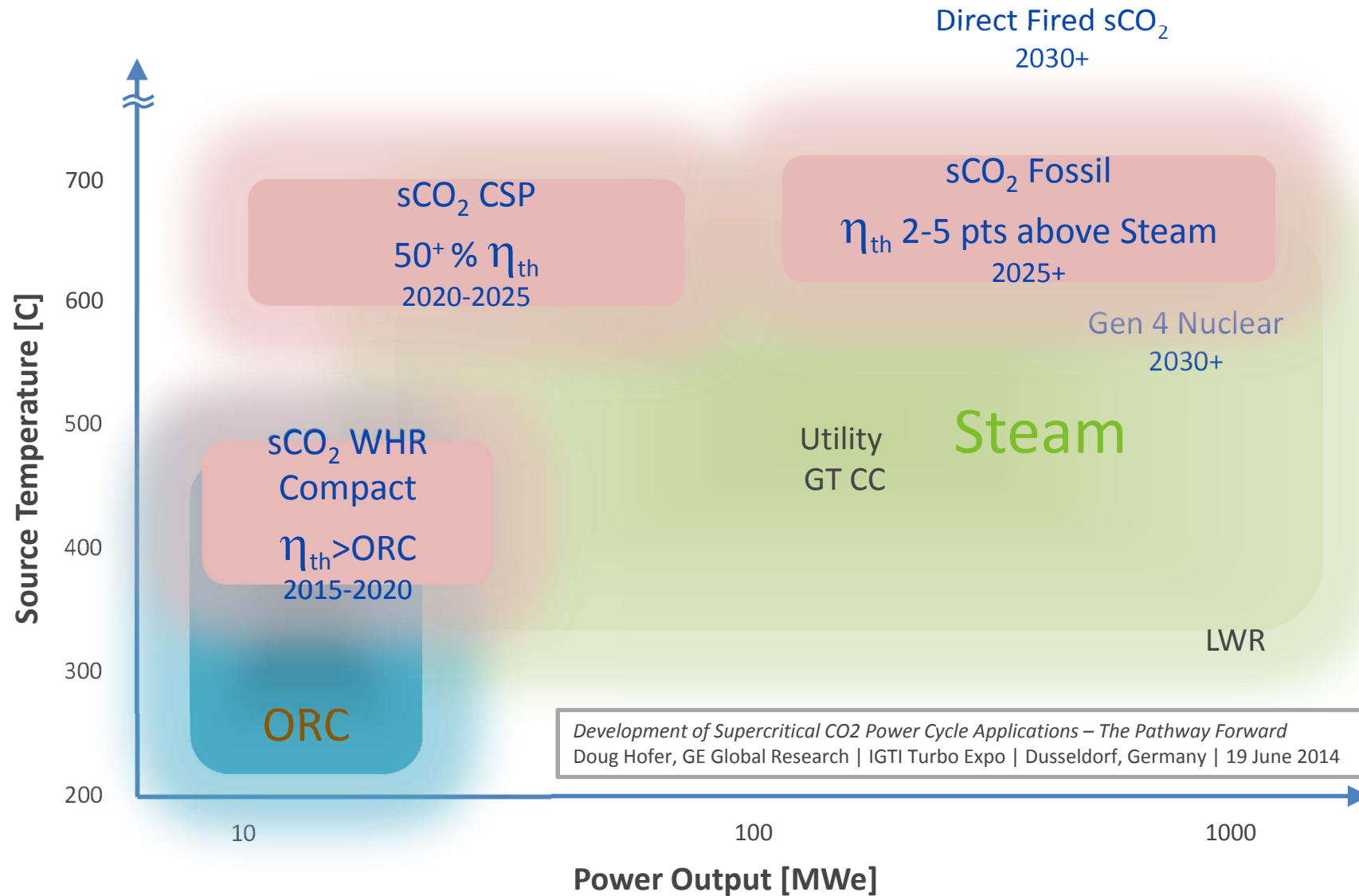


Ship-board
Propulsion

“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

sCO₂ Application Space



Technology Readiness and Gaps @ 550C

	Turbine		Compressor		Recuperator		Primary HX		System	
	Pilot	Demo	Pilot	Demo	Pilot	Demo	Pilot	Demo	Pilot	Demo
Overall										
Design Tools										
Materials										
Components										
Supply Chain										
Modeling										

Technology Gaps

Long term materials data in CO₂
 Codes & Standards
 Erosion resistance
 Advanced seals
 Off-design/transient modeling
 Hermetic turbo-alternator

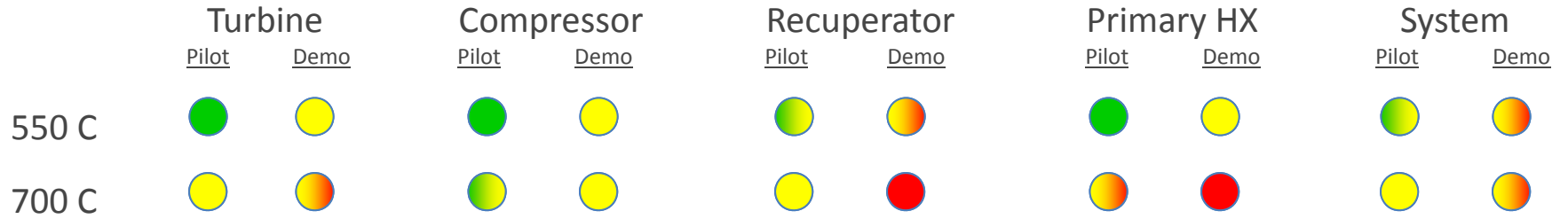
Designs for operation near CO₂ critical pt
 Advanced seals
 Internal bearings
 Off-design/transient modeling
 Hermetic turbo-compressor

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

Long term materials data in CO₂
 Codes & Standards
 Erosion resistance
 Off-design/transient modeling

Long term materials data in CO₂
 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

Long term superalloy materials data in CO₂
Codes & Standards
Thermal management
High temperature seals and bearings
Turbine stop and control valve

Operation and control of parallel compressors for recompression cycle

Long term materials data in CO₂
Diversified vendor base – capacity/cost

Long term superalloy materials data in CO₂
Codes & Standards
Furnace designs for low ΔT of primary fluid (air side recuperation)
Materials availability

Long term superalloy materials data in CO₂
Codes & Standards
Transient operability including upsets for complex recompression cycles

- 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

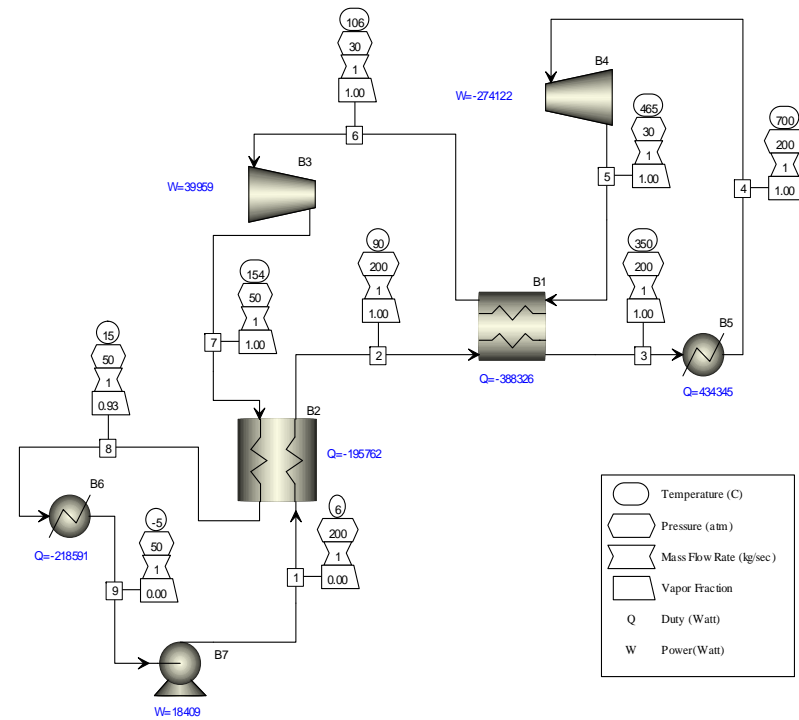
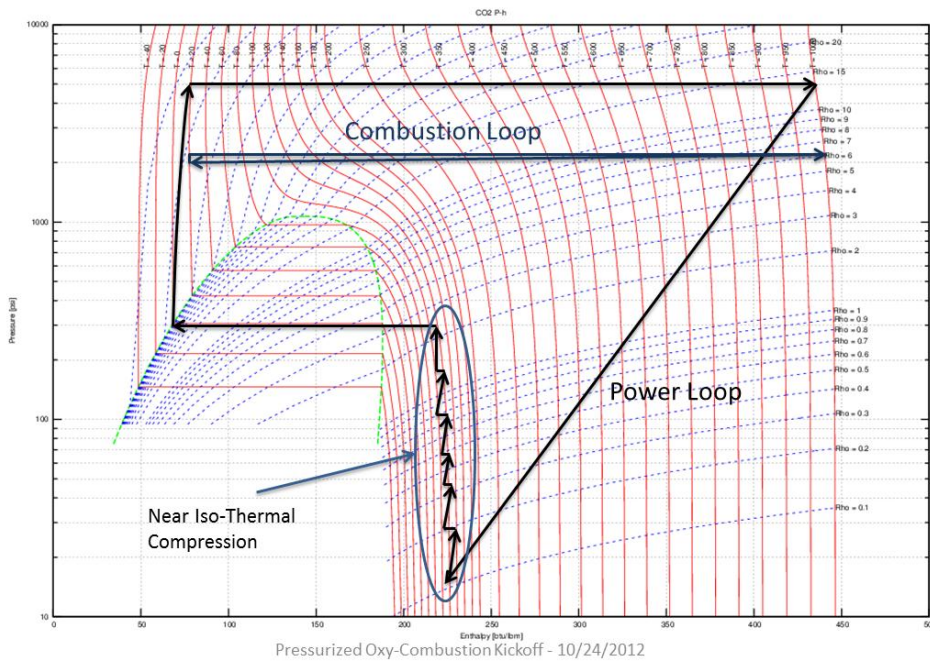
- Technology development is focused on four areas
 - Thermodynamic cycles and thermal integration for specific applications
 - System level design and demonstration
 - Component development and demonstration
 - Oxy-combustion development and demonstration
- Demonstration efforts are focused on **performance,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

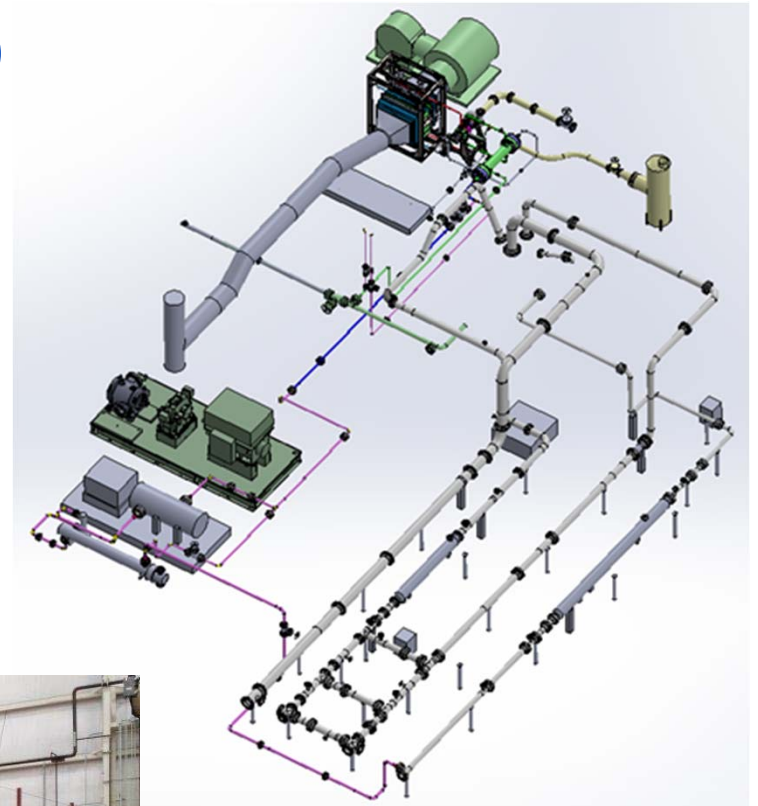
- Component development efforts
 - Turbomachinery
 - Compact turbine design
 - High efficiency compressor, operable near the critical point
 - Bearings, seals, and thermal management
 - Heat Exchangers
 - Cost and performance of compact HX
 - Air fired sCO₂ heater design
 - HX design and material cost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



SYSTEM ANALYSIS AND TESTING

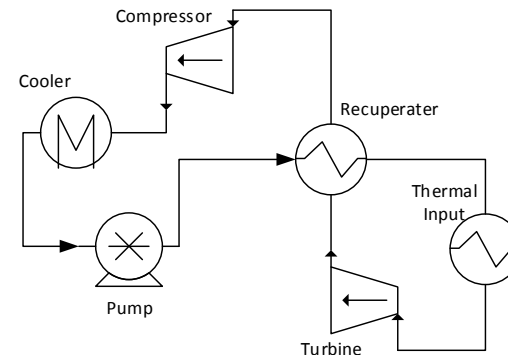
SunShot sCO₂ Pilot Loop

- 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)

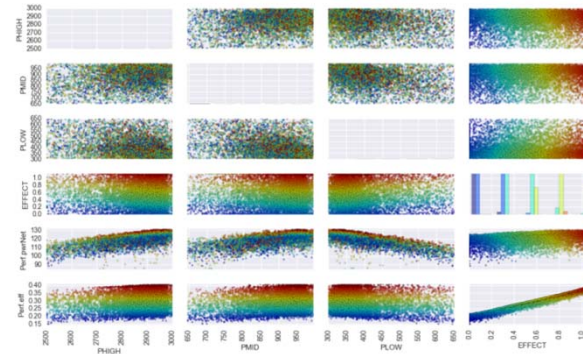


Thermodynamic Simulation

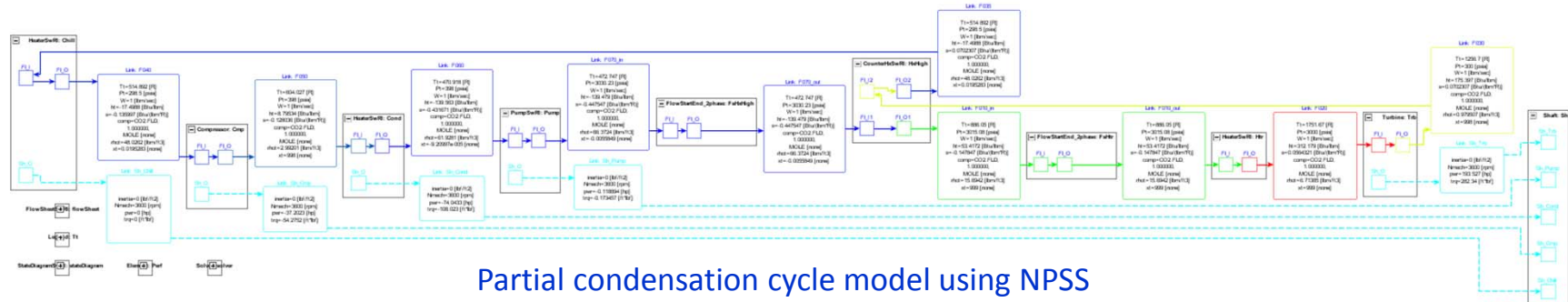
- Validation of steady and dynamic modeling of sCO₂ cycles and components.
- Cycles modeled using a variety of tools including Aspen Plus, Aspen Hysys, and NPSS
- Performance evaluated for design and off design operating conditions
- Cycles optimized to achieve desired performance and operating characteristics



Partial Condensation Cycle



Multivariable Cycle Optimization for Efficiency

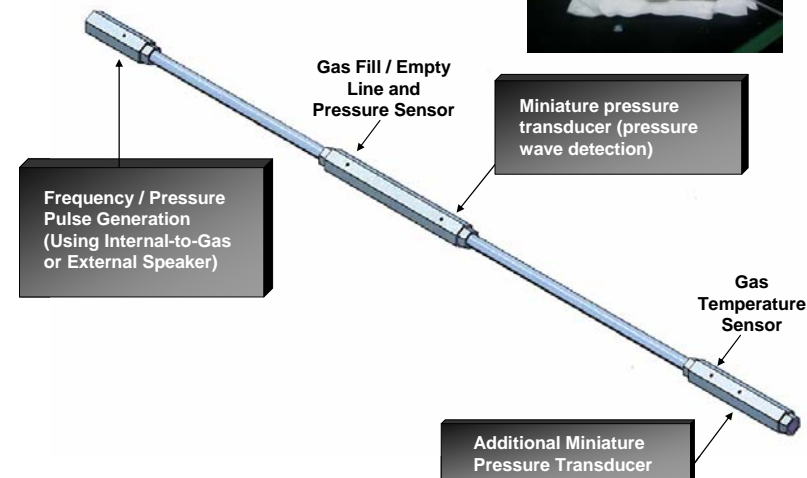


Partial condensation cycle model using NPSS

Fundamental Gas Property Testing

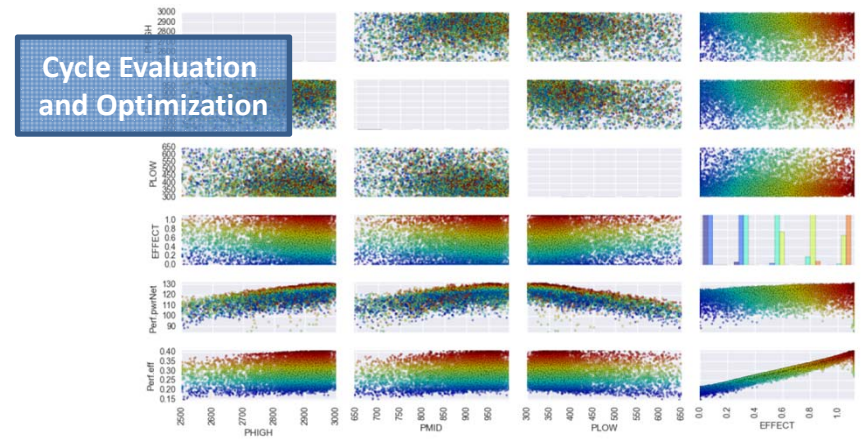
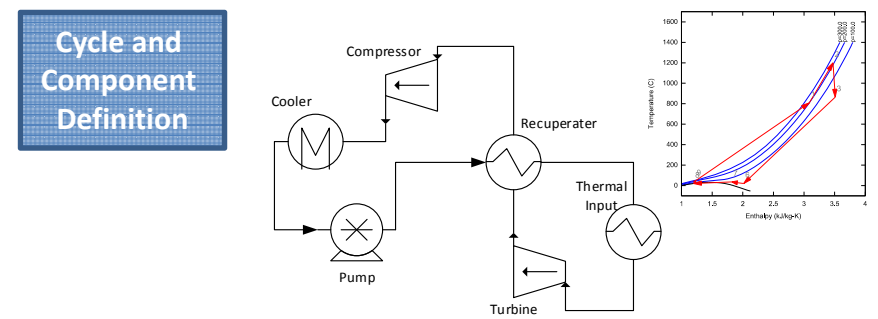
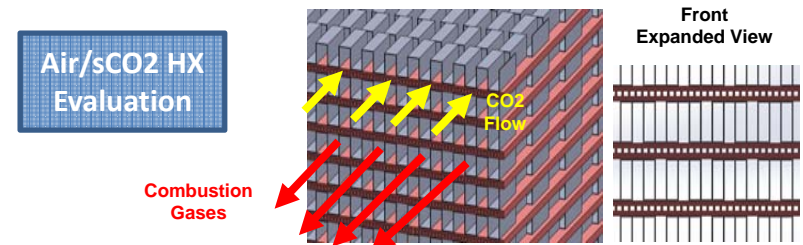
(SwRI for DOE, NIST, and Commercial Clients)

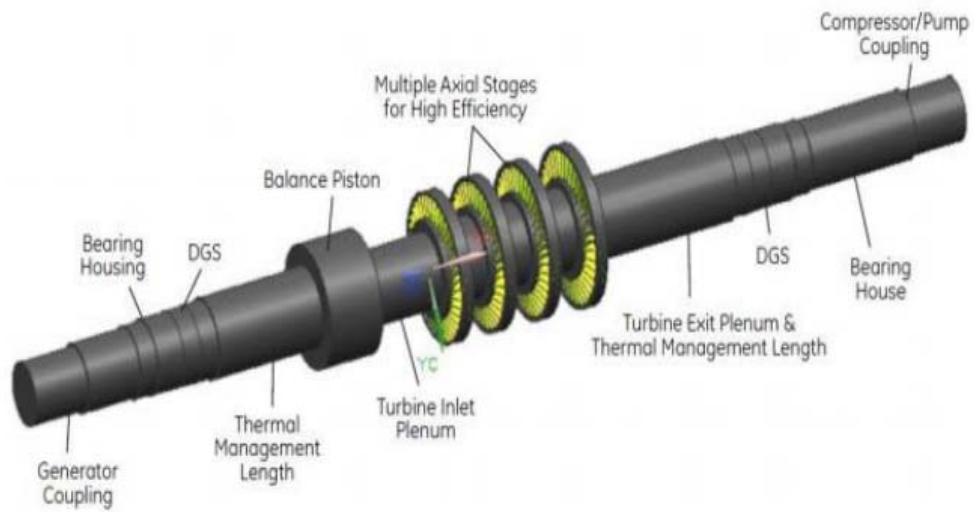
- Fundamental gas property tests for high CO₂ content mixtures, falling outside of typical EOS model limits: speed of sound, specific heat, and density up to 15,000 psi, 500°F.
- Adapted high pressure autoclaves / adiabatic calorimeters for specific heat determination.
- Specialized test methods for 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 CO₂ / 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

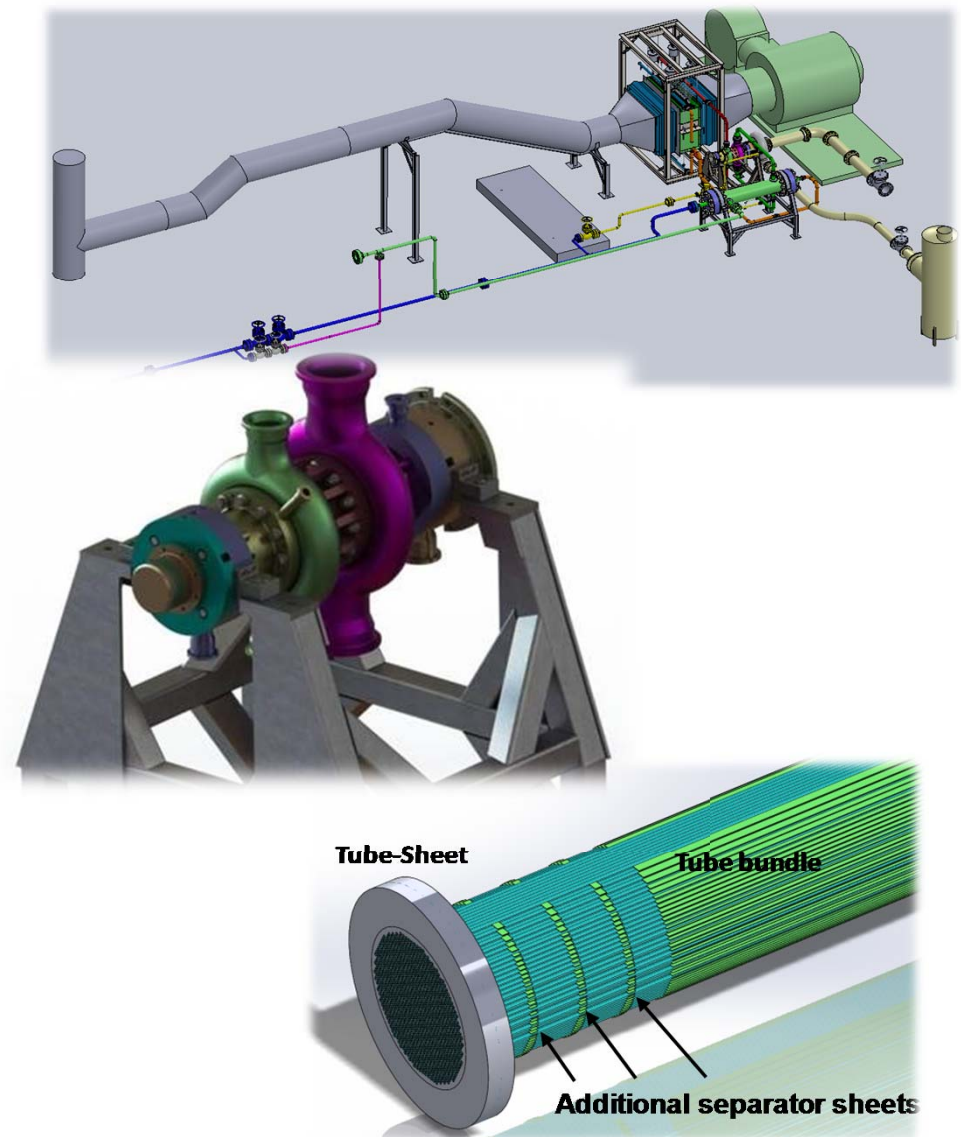




TURBINE DEVELOPMENT

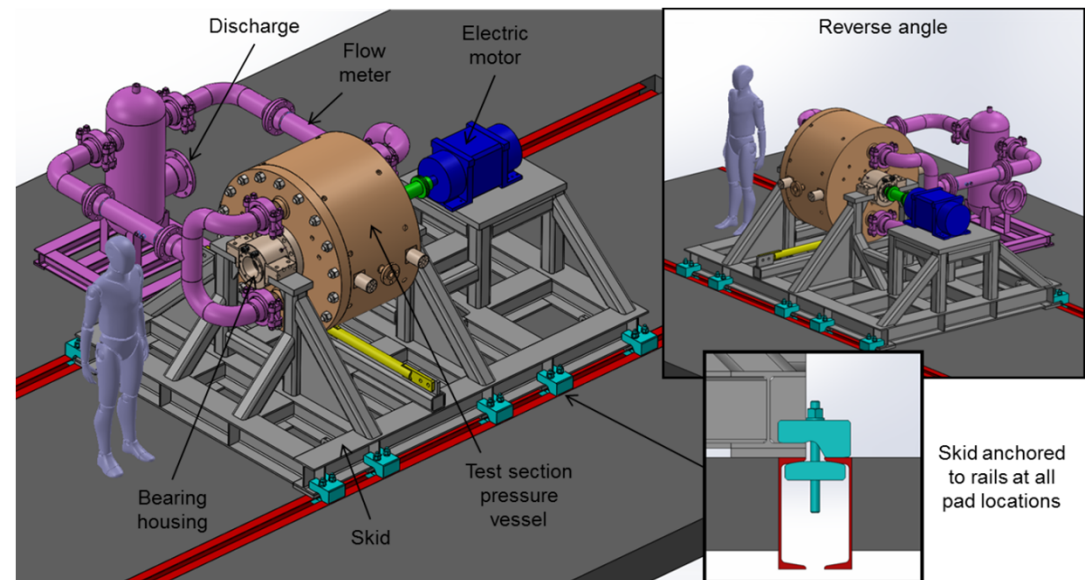
Development of a High Efficiency Hot Gas Turbo-expander and Low Cost Heat Exchangers for Optimized CSP Supercritical CO₂ Operation (SwRI, GE, Thar for DOE EERE)

- 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*)

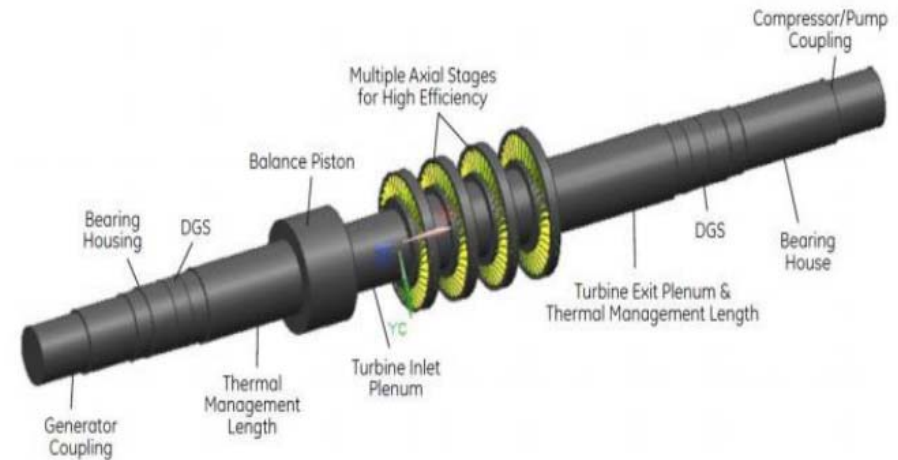
- Utility scale sCO₂ power cycles rely on low-leakage shaft end seals to meet high cycle efficiency goals
- Seal technologies for sCO₂ compressor conditions currently exist, but they do not for sCO₂ turbine conditions
- GE Global Research developing new large diameter face seal technology

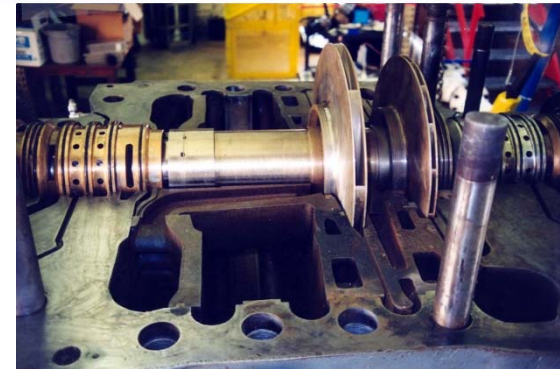
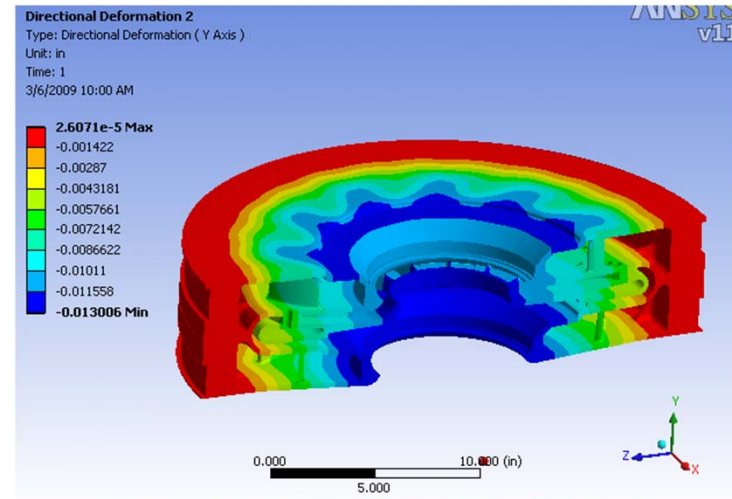
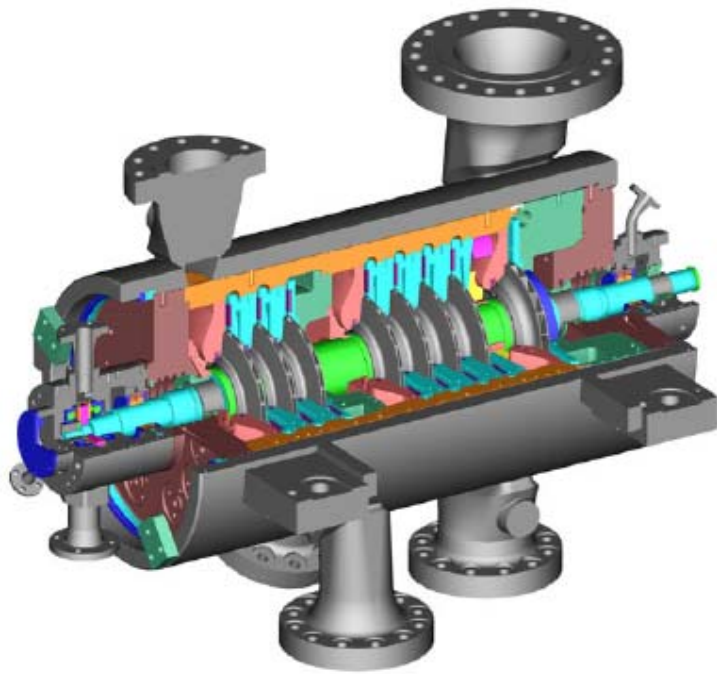


- SwRI developing rig to test full-scale seal prototype with sCO₂
 - Leakage and thermal performance
 - Utilize loop for SunShot test program

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

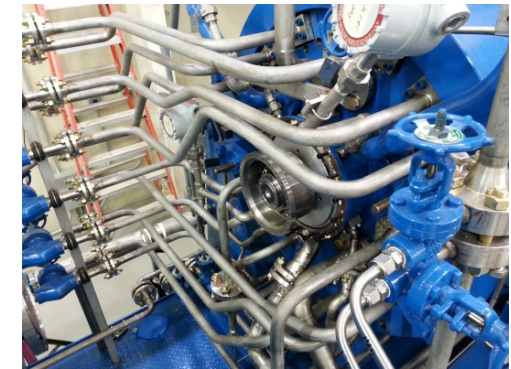
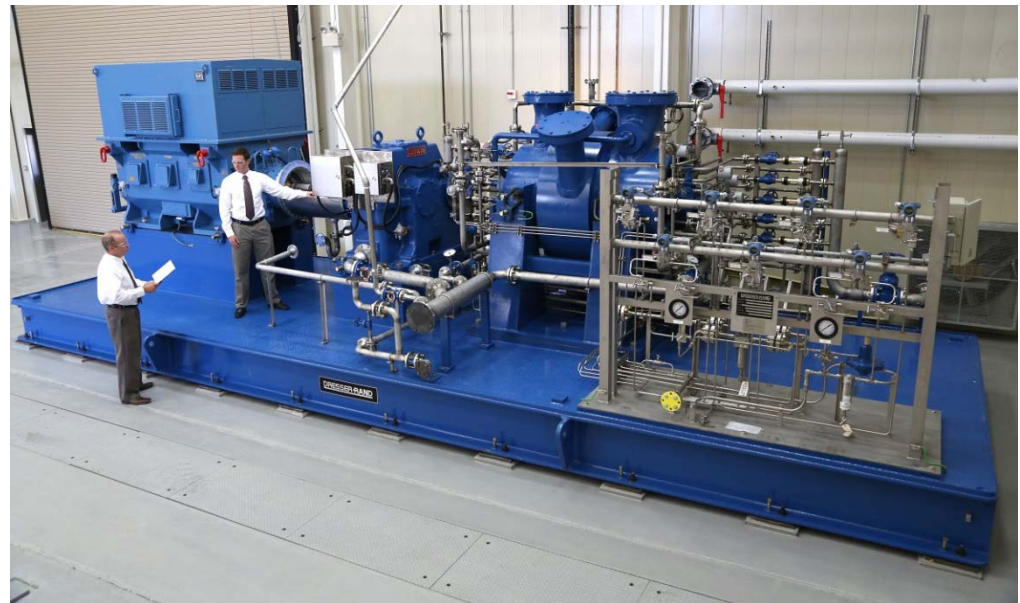




COMPRESSOR DEVELOPMENT

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



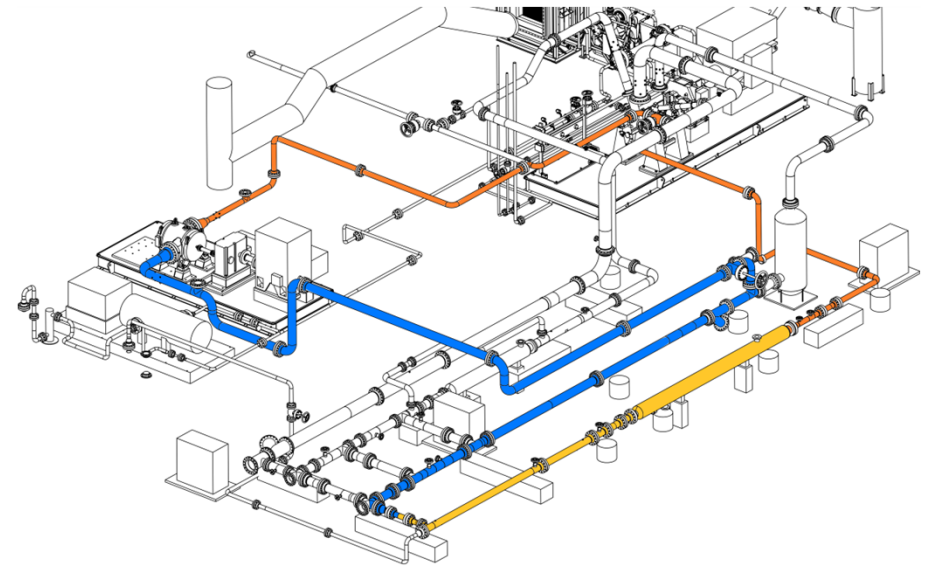
GE-Apollo High-Efficiency sCO₂ Centrifugal Compressor Development (GE, SwRI for DOE EERE)

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

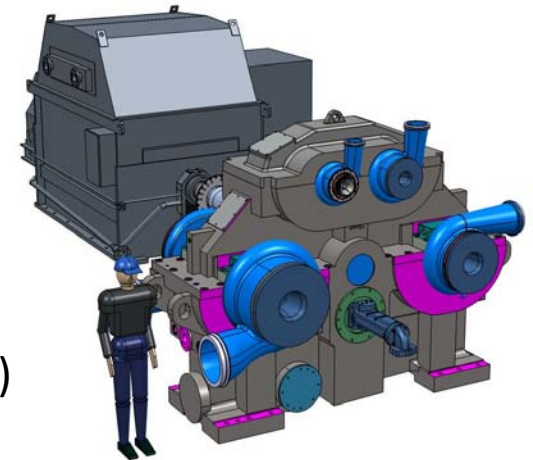
- Full scale testing of a 10 MWe sCO₂ Compressors
- Extended flow range to accommodate swings in ambient temperature



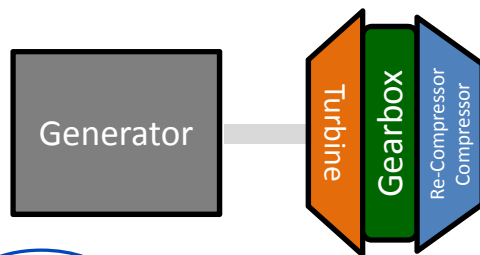
Leverage SwRI sCO₂ Test Facility to verify compressor mechanical and aerodynamic performance over a range of operating conditions

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

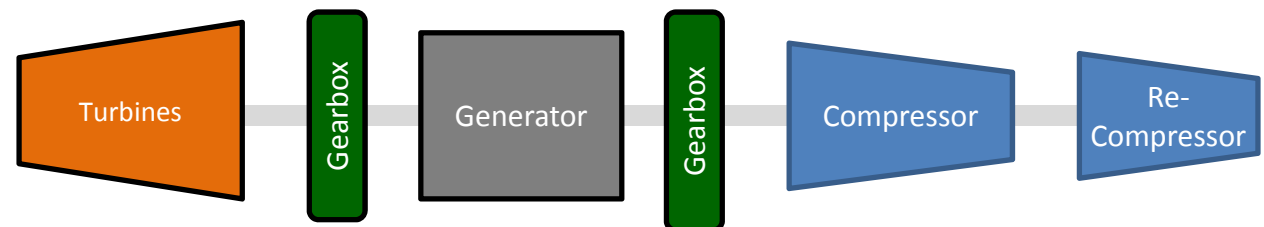
- Design a sCO₂ integrally geared compressor (IGC)
 - Combining compression and expansion stages into a single integrally geared housing connected to a low speed motor/generator.
- Benefits:
 - Reduced footprint
 - Potential cost reduction up to 35%
 - Utilizes a low speed commercially available driver/generator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

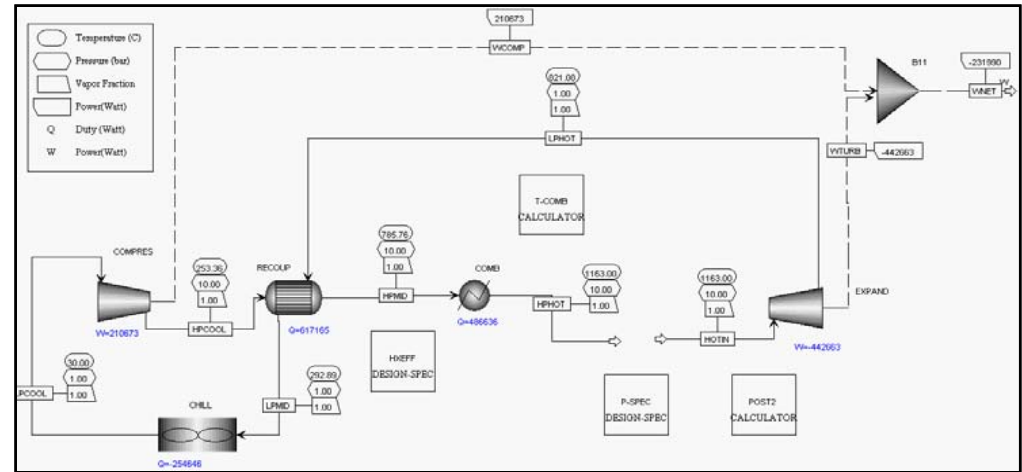
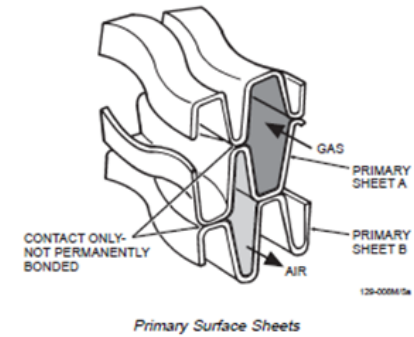
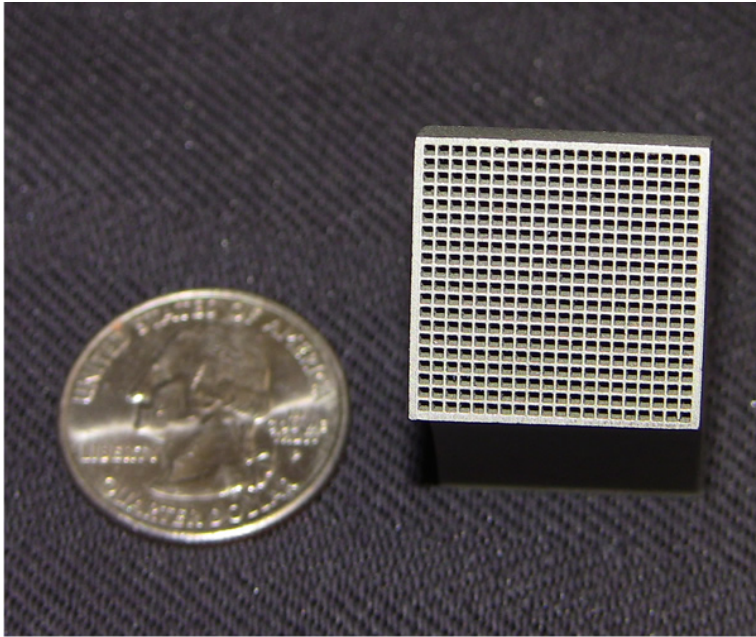


Typical IGC Package



Conventional Turbomachinery Train

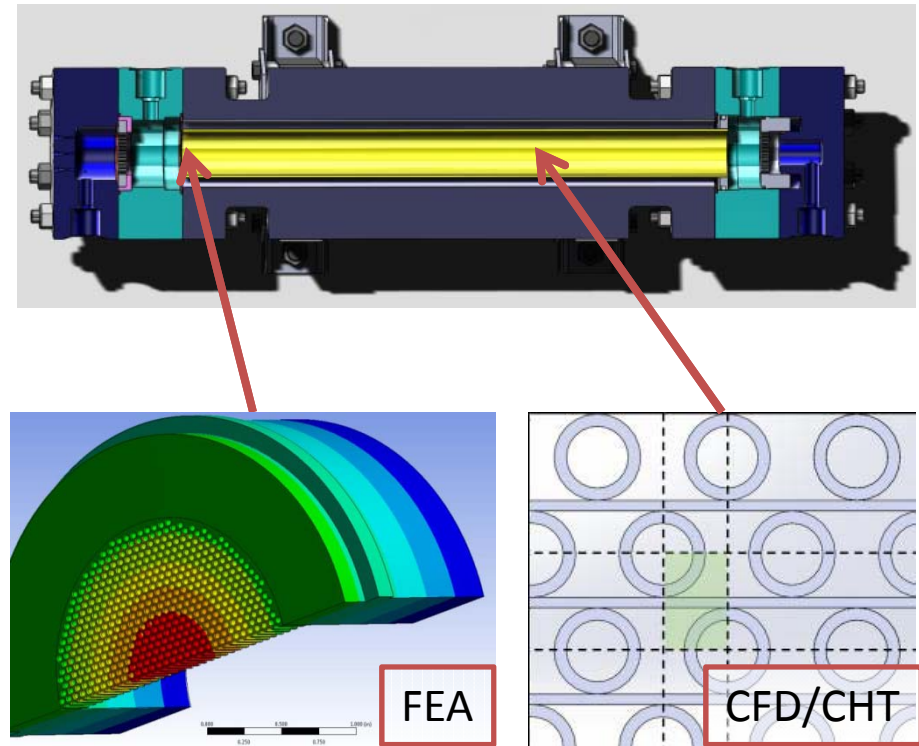




HEAT EXCHANGER DEVELOPMENT

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

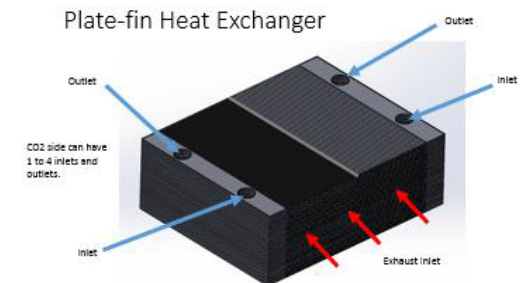
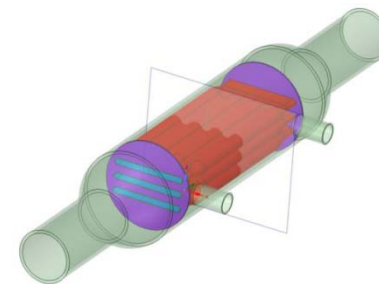
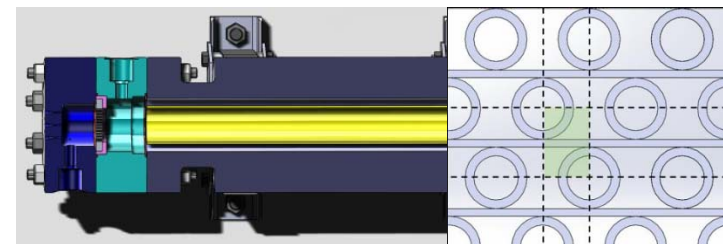
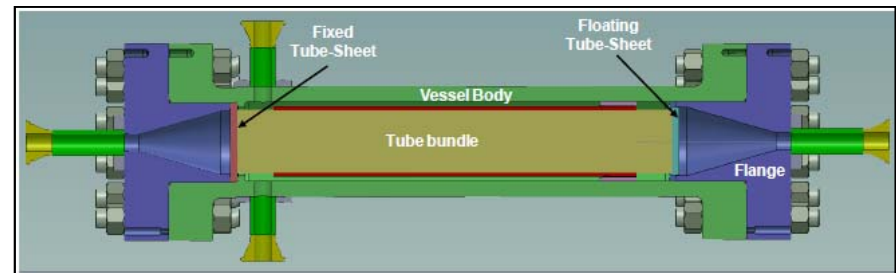
- Analysis of sCO2 power cycle recuperator configurations
- Prediction of pressure drop, flow distribution, and heat transfer using conjugate heat transfer
- FEA based stress predictions to support manufacturing analysis
- Evaluation of alternate configurations with heat transfer improvements



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



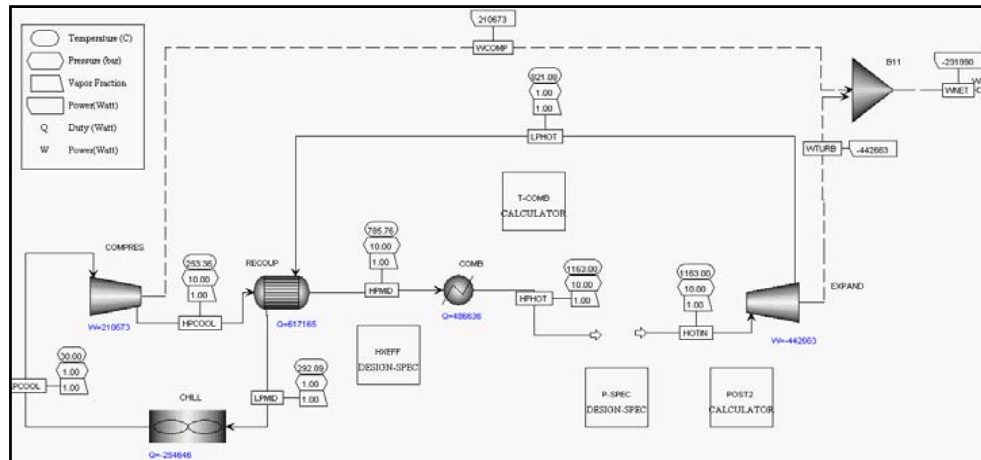
Investigating concepts to for performance, cost, scalability

Concept selection and prototype testing

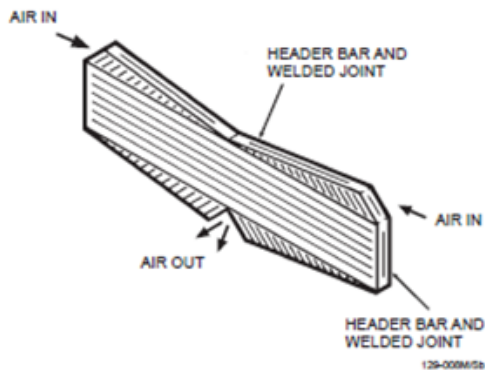
Preliminary design of 47MWth scale



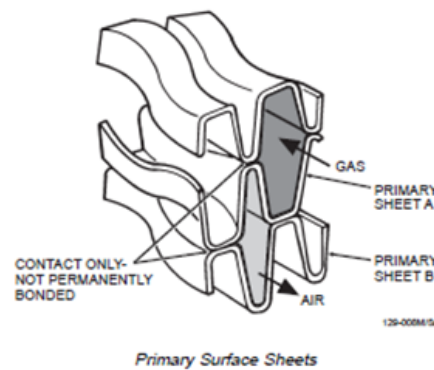
Thin-Film Primary Surface Heat Exchanger Development (SwRI, Solar for DOE NETL)



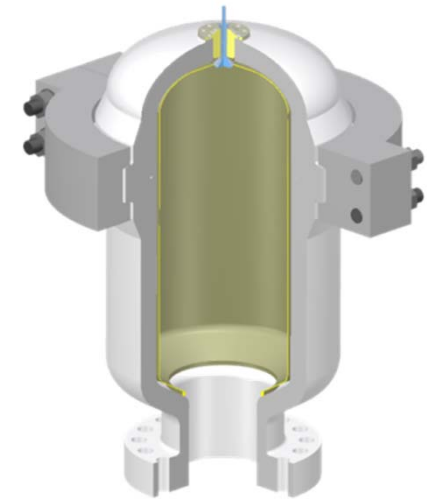
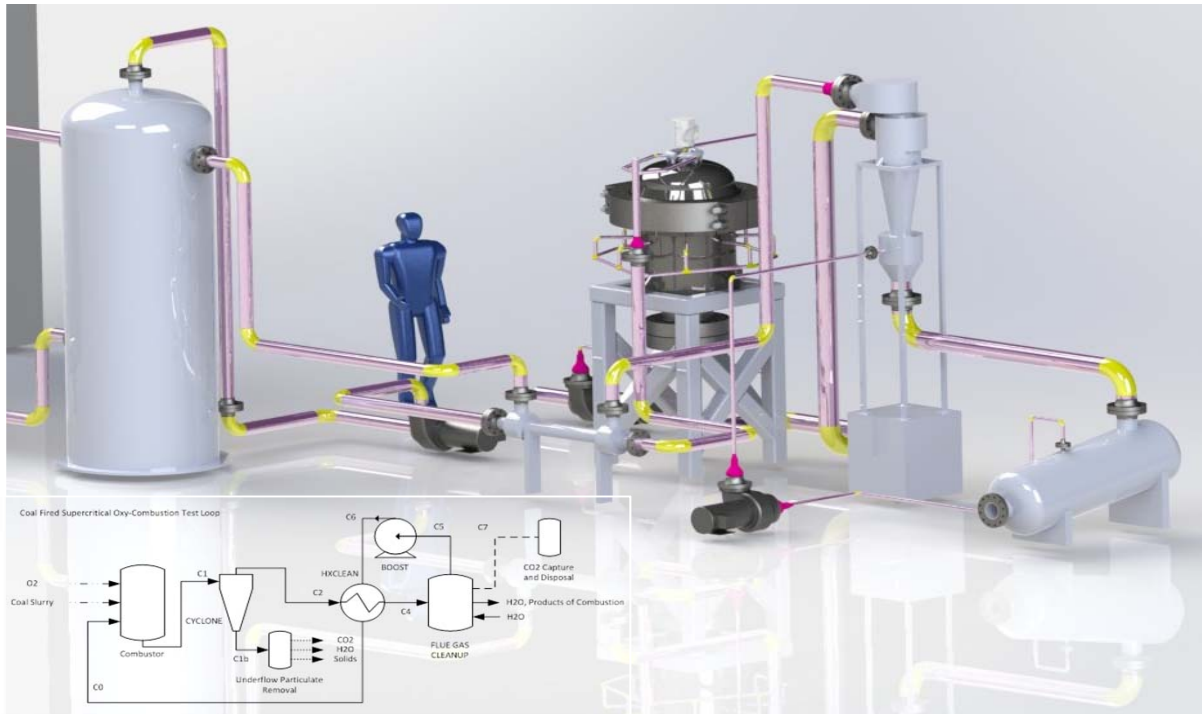
- Advance existing proven Mercury 50 recuperator design for operation in CO₂ at 1510 F and P = 9 bar
- Low-pressure oxy-fuel recuperated Brayton cycle with 19% higher efficiency than air Brayton cycle
- High temperature coupon testing of candidate materials and coatings in CO₂



PSR Air Cell



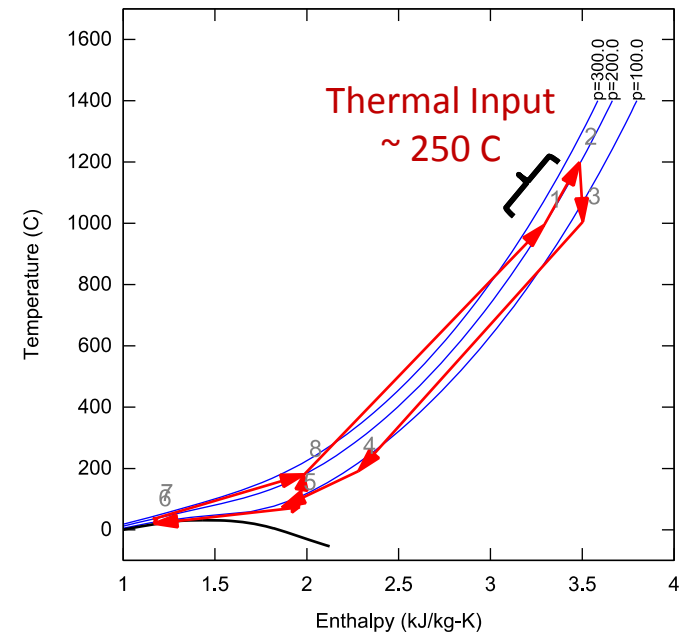
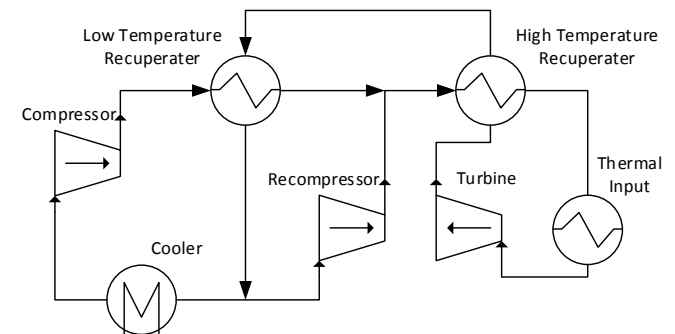
Primary Surface Sheets



OXY-COMBUSTION

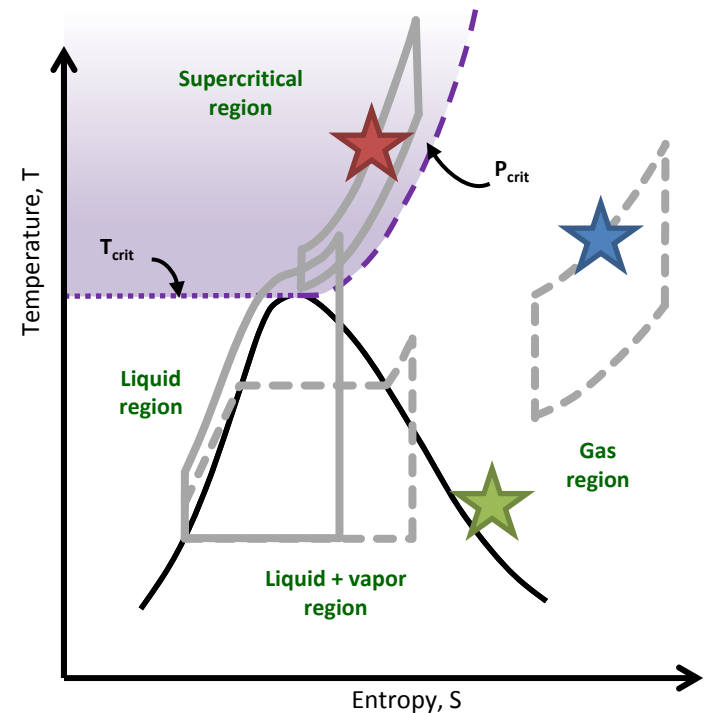
Why Oxy-Combustion?

- 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



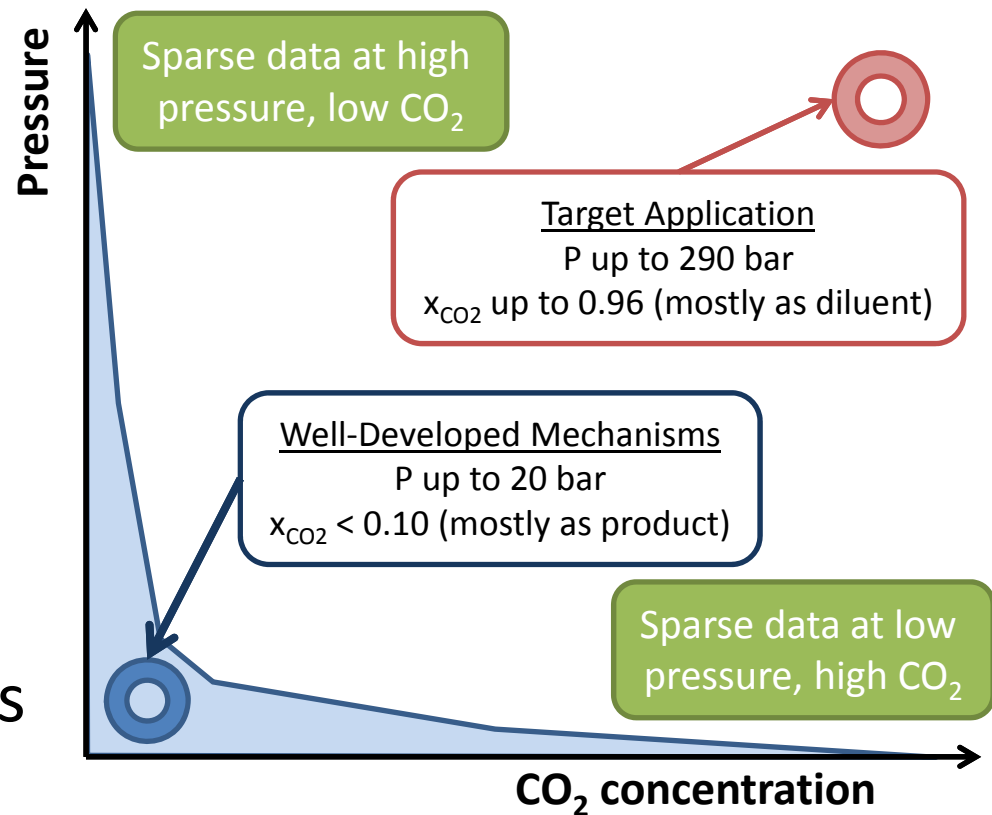
Flavors of Oxy-Combustion

- 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

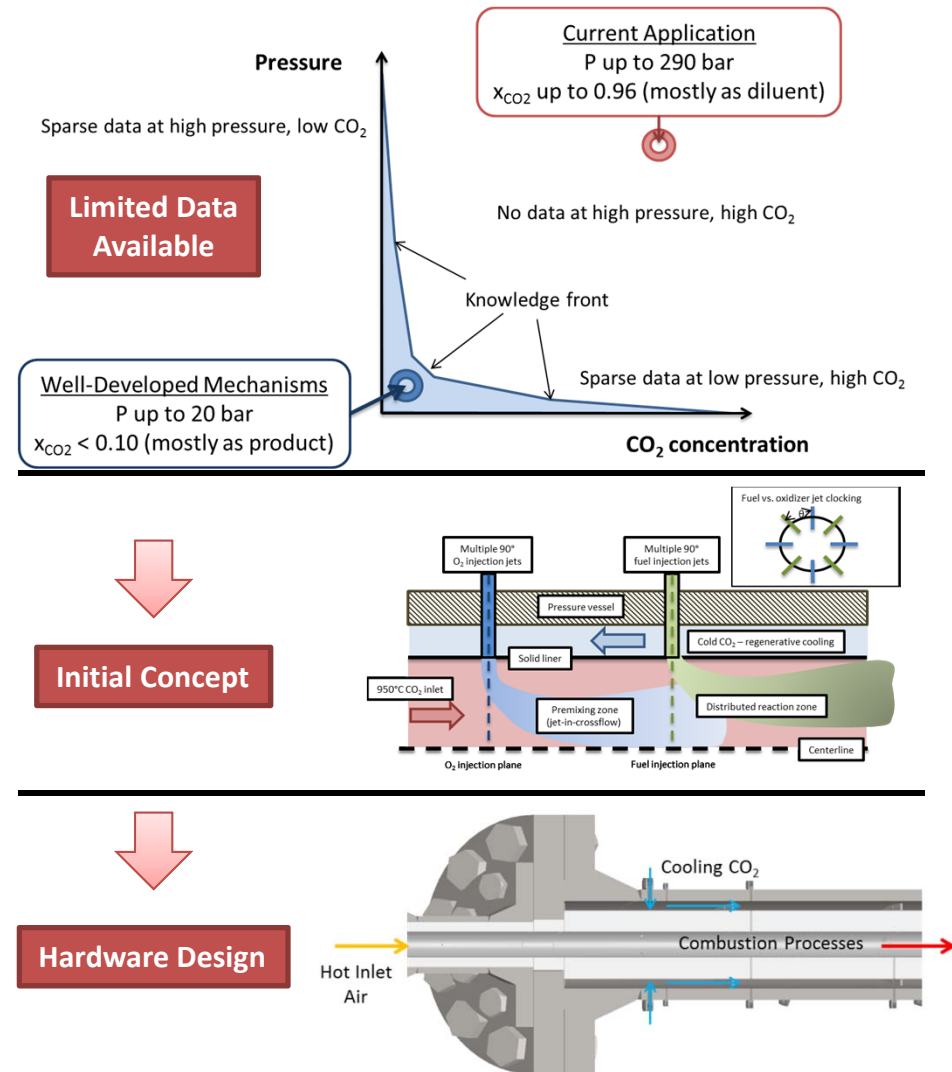
- Existing knowledge centers on low pressure, low CO₂ applications
 - Relevant to conventional propulsion/power generation
 - Easier to evaluate experimentally
- No data available at conditions relevant to this application.



High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion Phase I

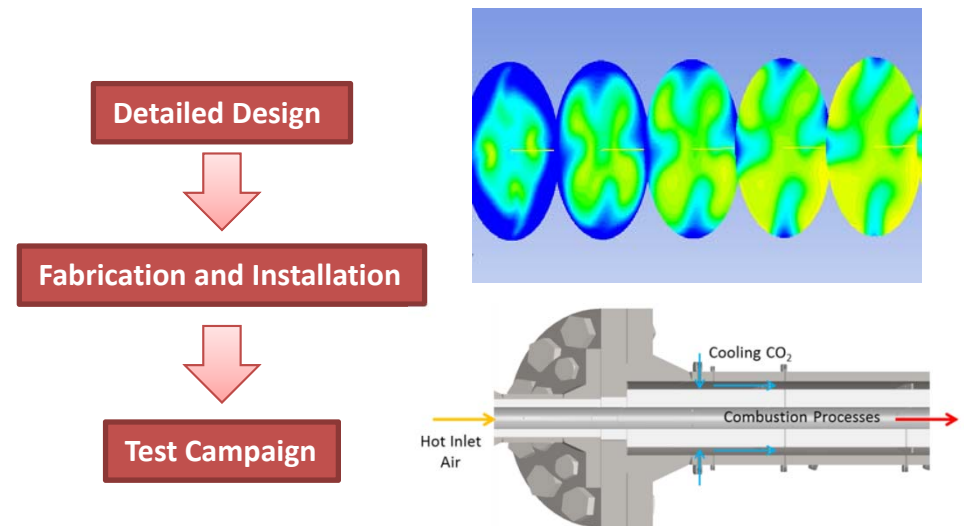
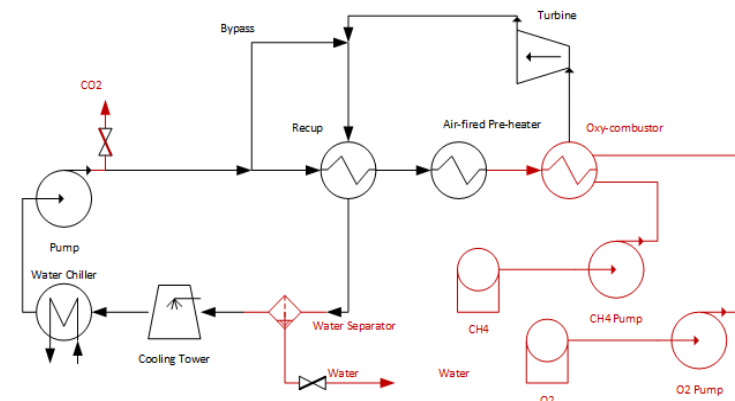
(SwRI, Thar for DOE NETL)

- 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



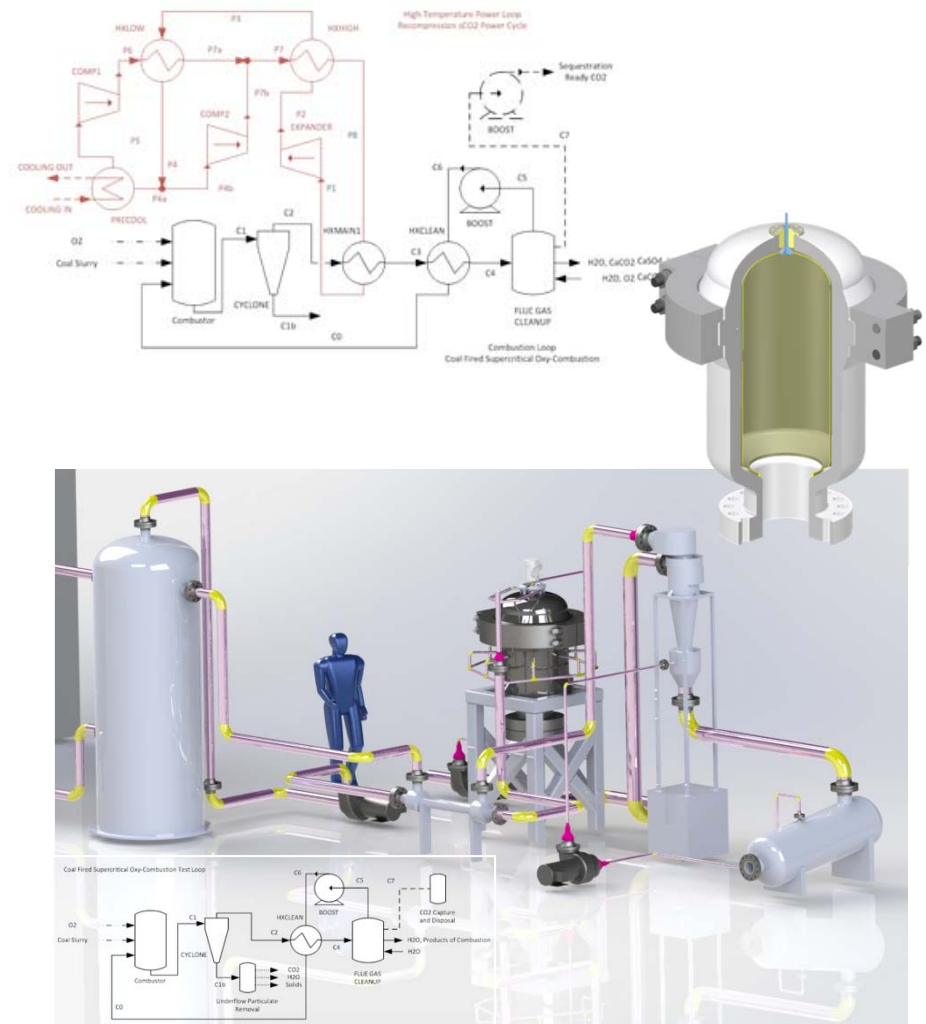
High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion Phase II (SwRI, Thar for DOE NETL)

- 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

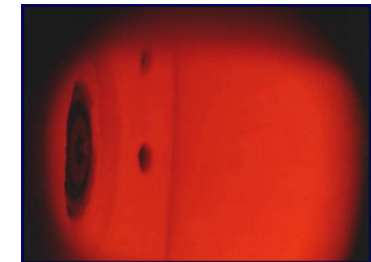


Flameless Pressurized Oxy-Combustion Pilot Plant Planning (*SwRI, ITEA for DOE NETL*)

- 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



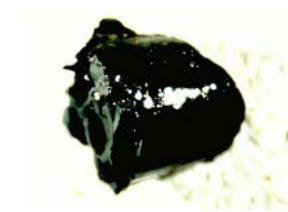
Traditional Combustion with
Flame Front



Flameless Pressurized
Combustion

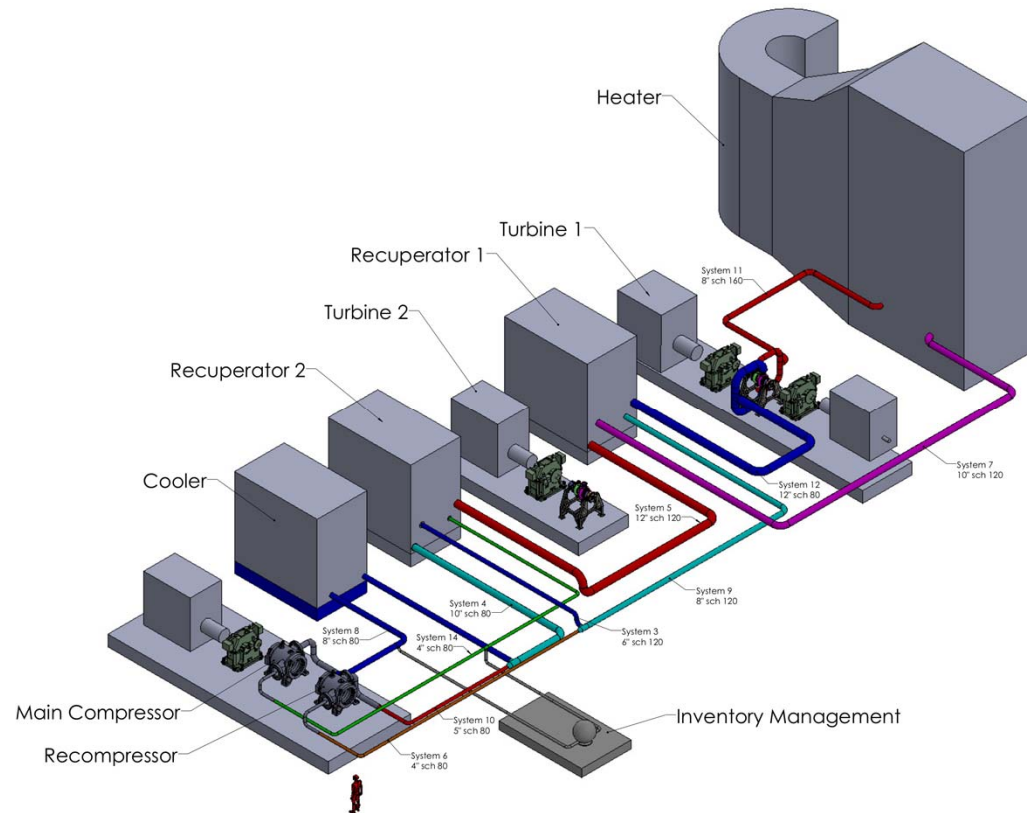


Traditional Combustor
Products: Particulate



FPO Combustor Products:
Near-zero slag

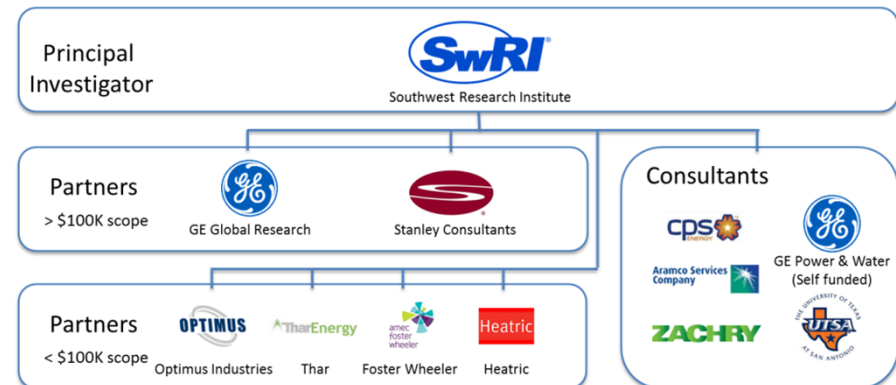
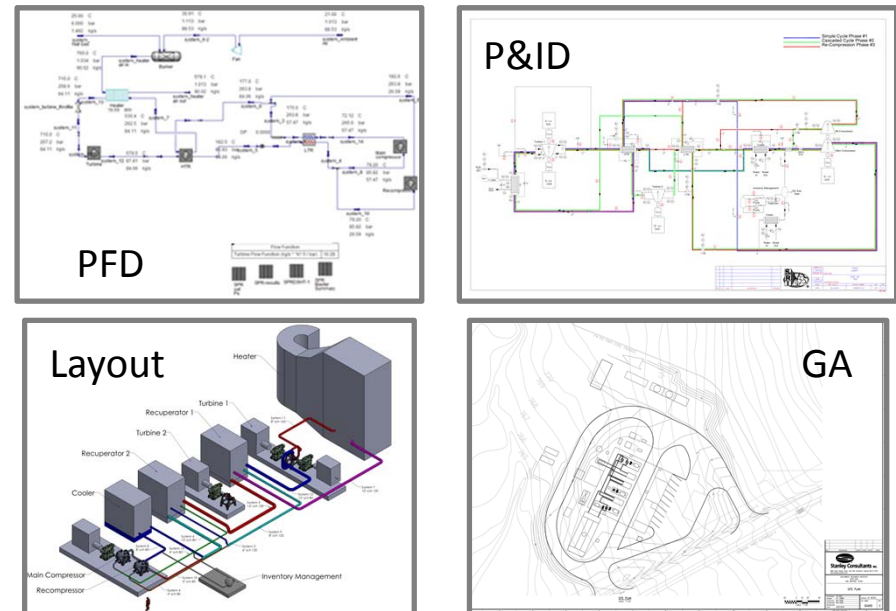




PILOT SCALE CO₂ TECHNOLOGY DEMONSTRATION

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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