Absorption/Desorption Based High Efficiency Supercritical Carbon Dioxide Power Cycles

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Outline

- Participants
- Project and Technical Overview
  - Fossil Based sCO2 Cycles
  - sCO2 "Boiler" Considerations
  - Absorption/Desorption Cycle
- Proposed Scope
  - Objectives
  - Work Breakdown
- Project Management

PROJECT PARTICIPANTS

Southwest Research Institute

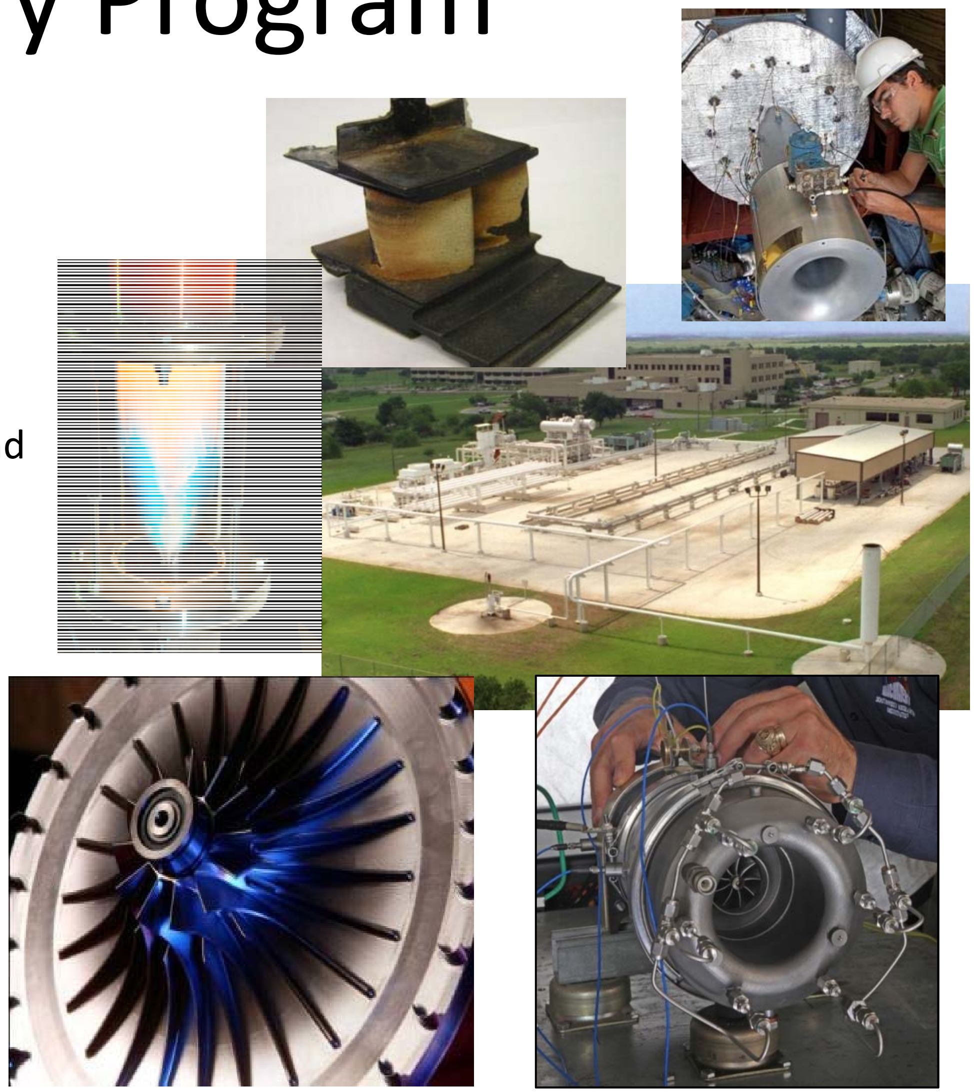
- Independent, nonprofit applied research and development organization founded in 1947
- Eleven technical divisions
  - Aerospace Electronics, Systems Engineering & Training
  - Applied Physics
  - Applied Power
  - Automation & Data Systems
  - Chemistry & Chemical Engineering
  - Engine, Emissions & Vehicle Research
  - Fuels & Lubricants Research
  - Geosciences & Engineering
  - Mechanical Engineering
  - Signal Exploitation & Geolocation
  - Space Science & Engineering
- Total 2013 revenue of $592 million
  - 38% Industry, 36% Govt., 26% Govt. Sub
  - $6.7 million was reinvested for internal research and development
- Over 2,800 staff
  - 275 PhD’s / 499 Master's / 762 Bachelor's

- Over 1,200 acres facility in San Antonio, Texas
  - 200+ buildings, 2.2 million sq. ft of laboratories & offices
  - Pressurized Closed Flow Loops
  - Subsea and High Altitude Test Chambers
  - Race Oval and Crash Test Track
  - Explosives and Ballistics Ranges
  - Radar and Antenna Ranges
  - Fire testing buildings
  - Turbomachinery labs

Benefiting government, industry and the public through innovative science and technology

Machinery Program

- Fluids & Machinery Engineering Department
  - Mechanical Engineering Division (18)
- Specialties
  - Turbomachinery component design and testing
  - Root cause failure analysis
  - Rotordynamic design/audit
  - Pipeline/plant simulation
  - CFD and FEA analysis
  - Test stand design
  - Performance testing



Thar companies:

TharEnergy — Systems for fuel production, power generation and geothermal heating and cooling

TharProcess — Supercritical fluid process design and toll extractions from organic feedstocks

***Core competencies*:**

- **25+ years commercializing "Green" supercritical fluid technologies (SCF)**
- **Designer and developer of supercritical fluid processes, systems & major components**
- **Industrial scale 24/7/365 installations, world wide:**
  - **Food**
  - **Chemicals**
  - **Nutraceutical**
  - **Pharmaceutical**
  - **Chemical**
- **Heat exchangers for high pressure, high temperature application**

Shown here:

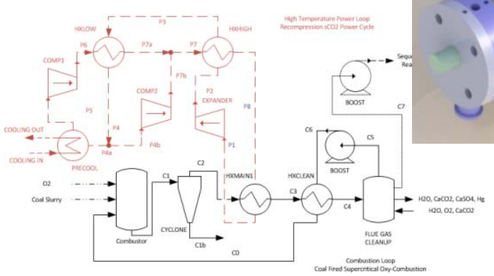
Pharmaceutical production system

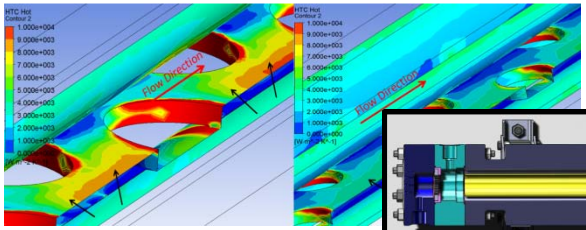
… Good Manufacturing Process

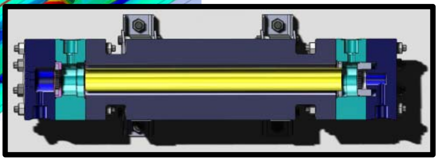
… Supercritical fluid extraction

Recent DOE Programs

- CO_2 Compression
  - CO_2 Compressor, NETL, Q1-15
- sCO_2 Cycles and Components
  - Sunshot Expander, NREL, Q4-15 (SwRI + Thar)
  - Oxyfuel, NETL, Q1-16 (SwRI + Thar)
  - sCO_2 Recuperator, NETL, Q1-16 (Thar + SwRI)
  - sCO_2 Heat Exchanger, NETL, Q1-16
  - sCO_2 Utility Scale, NETL, Q1-16
  - sCO_2 Heat Management - Focus, ARPA-E, Q3-16
  - CSP sCO_2 Seal Test, NREL, Q3-16
- Renewable Energy
  - Sunshot Combustor, NREL, Q4-15
  - Linear Motor Compressor, EERE, Q2-17
  - LNG Fracking, EERE, Q2-17







PROJECT AND TECHNOLOGY OVERVIEW

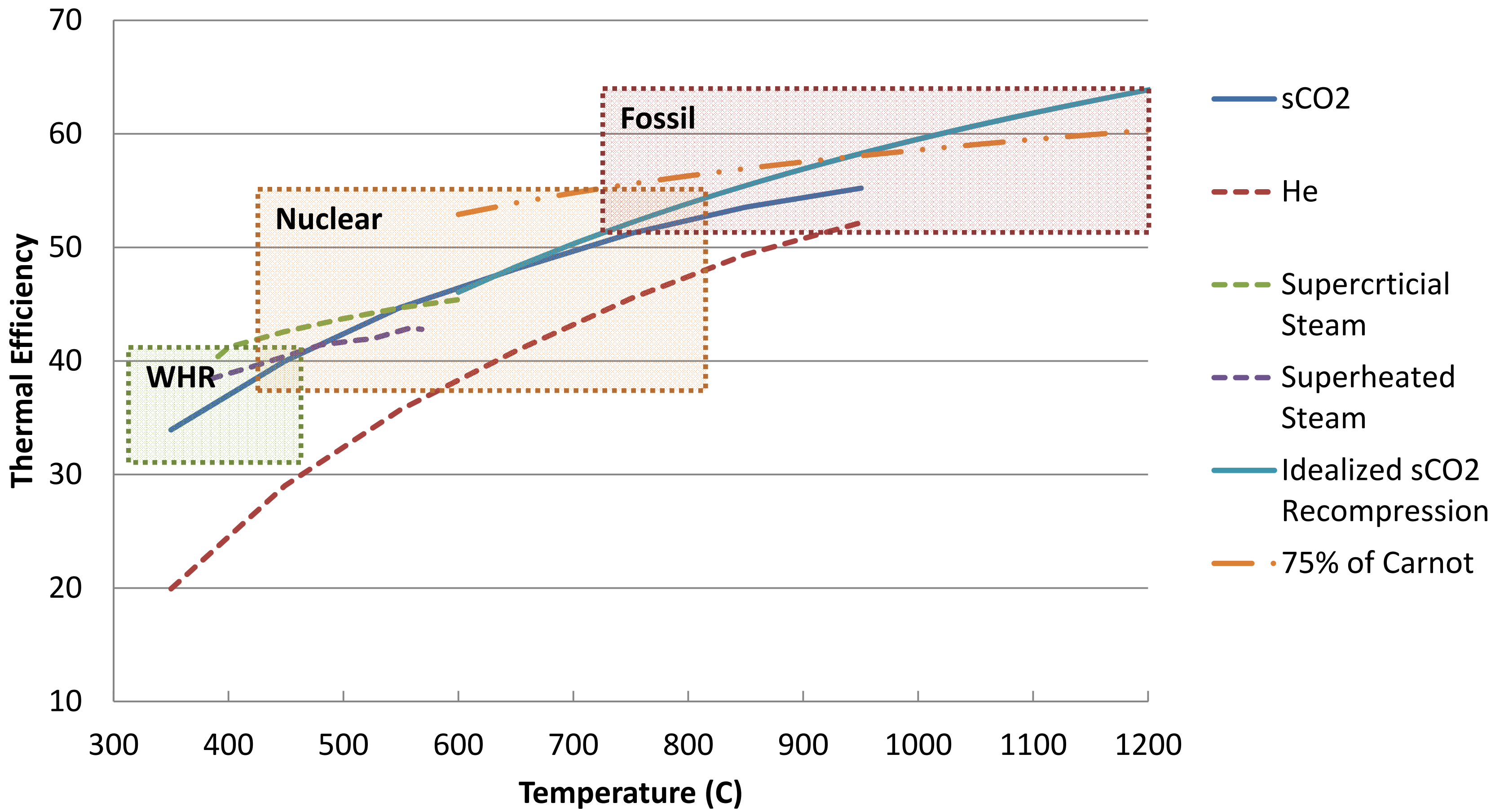
Project Objectives

- Identify technical challenges impacting the integration of fossil based thermal sources with highly recuperated closed Brayton sCO_2 power cycles
- Evaluate the impact of boiler design and sCO_2 cycle configuration on integrated plant performance, cost, and operability
- Evaluate technology readiness of the integrated system and identify specific technologies requiring development advance fossil based sCO_2 cycles.

Why sCO2 Power Cycles?

- Thermal efficiencies approaching 50% at 700°C, 65% at 1,200°C for the Recompression Cycle
- Offer +3 to +5 percentage points over supercritical steam for indirect coal fired applications
- High fluid densities lead to compact turbomachinery
- Efficient cycles require significant recuperation
- Compatible with dry cooling techniques

Representative Cycle Efficiencies



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

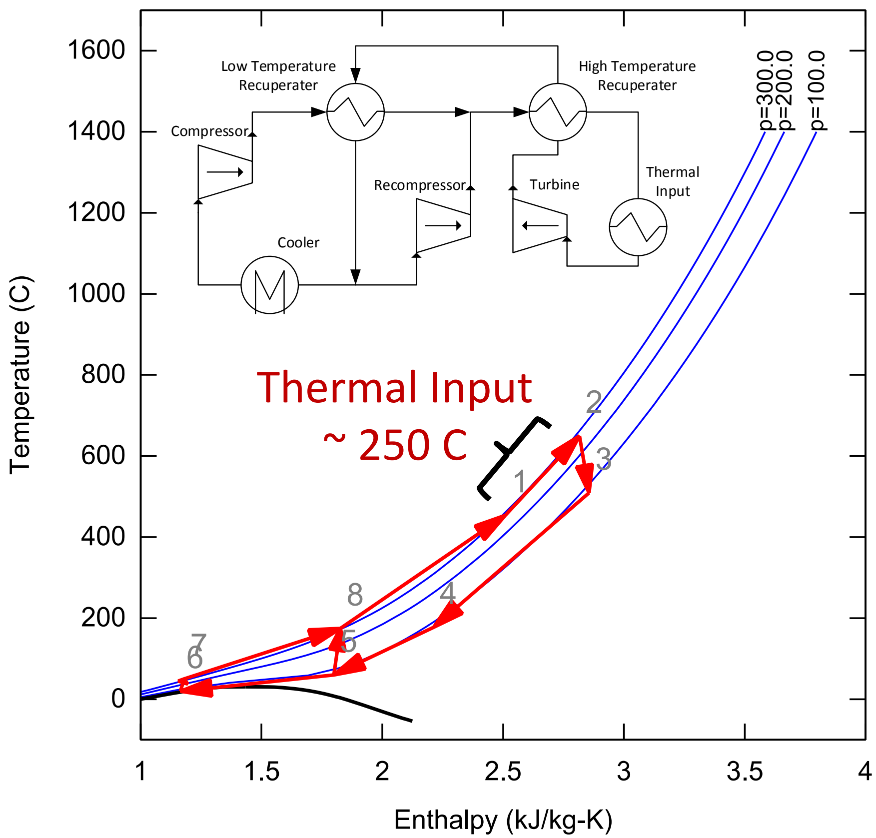
"Typical" sCO2 Cycle Conditions

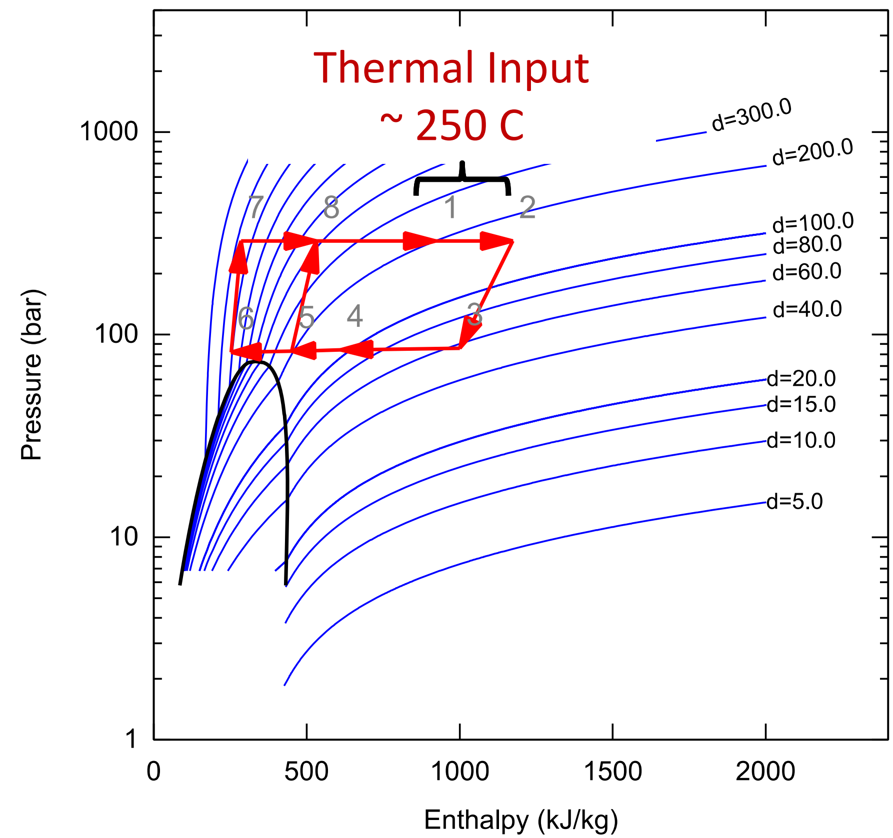
Application	Organization	Motivation	Size [MWe]	Temperature [C]	Pressure [bar]
Nuclear	DOE-NE	Efficiency, Size	300 - 1000	400 - 800	350
Fossil Fuel	DOE-FE	Efficiency, Water Reduction	500 - 1000	550 - 1200	150 - 350
Concentrated Solar Power	DOE-EE	Efficiency, Size, Water Reduction	10, 100	500 - 1000	350
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

Fossil Based sCO2 Power Cycles

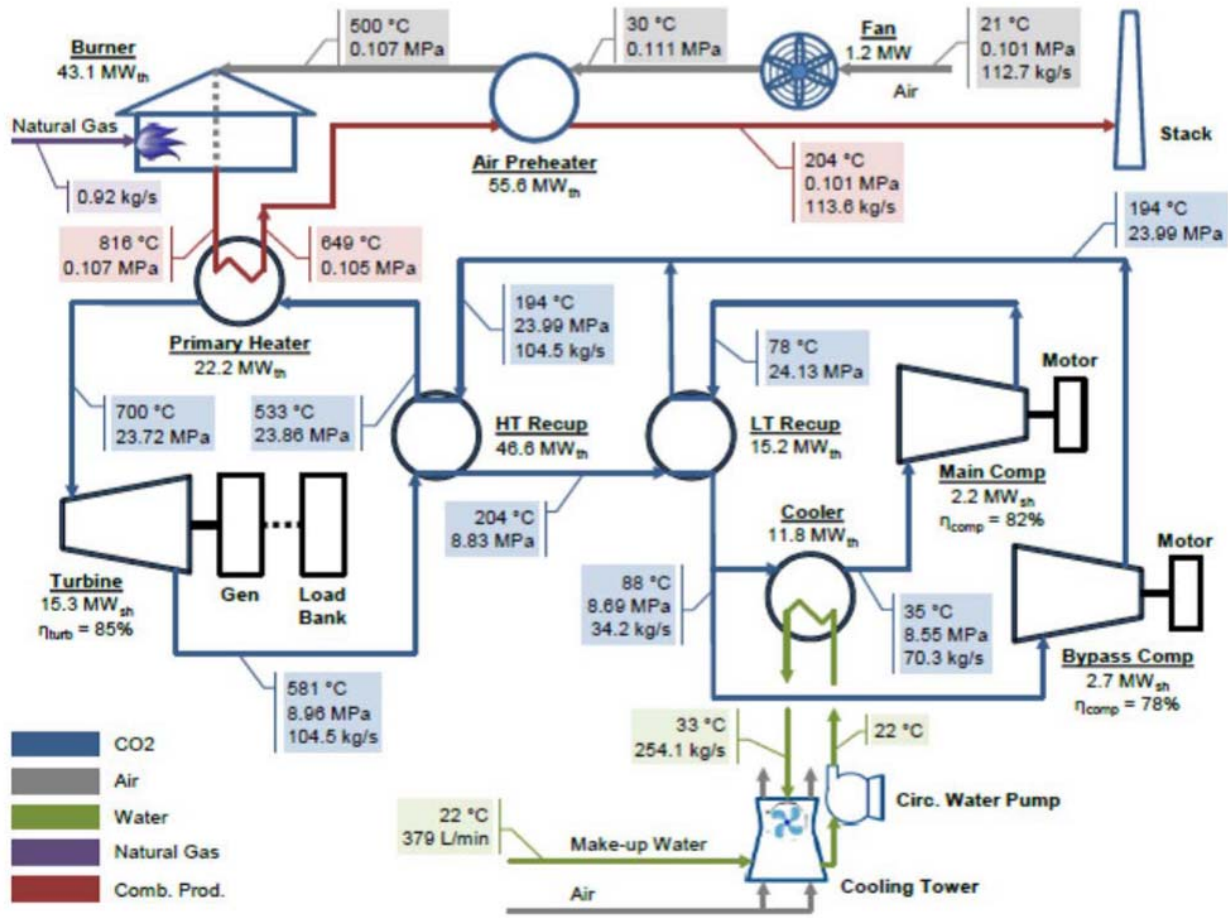
- Competition
  - Indirect: Supercritical Steam with CCS
  - Direct: Natural Gas Combined Cycle
- Advantages
  - High power efficiencies at "Moderate" temperatures
  - Oxy-combustion facilitates integrated carbon capture
  - Compact turbomachinery lead to compact power blocks
  - Partially offset by recuperation to achieve high cycle efficiencies
- Challenges
  - 250 C thermal input temperature widow (recompression cycle) is not ideal for combustion based systems
    - 400 C Combustor inlet for 650 C Turbine Inlet
    - 950 C Combustor inlet for 1200 C Turbine inlet
  - Flue gas cleanup for direct fired systems
  - Non-trivial efficiency losses for indirect cycles

Recompression Cycle





Nominal 10 MWe RCBC test facility

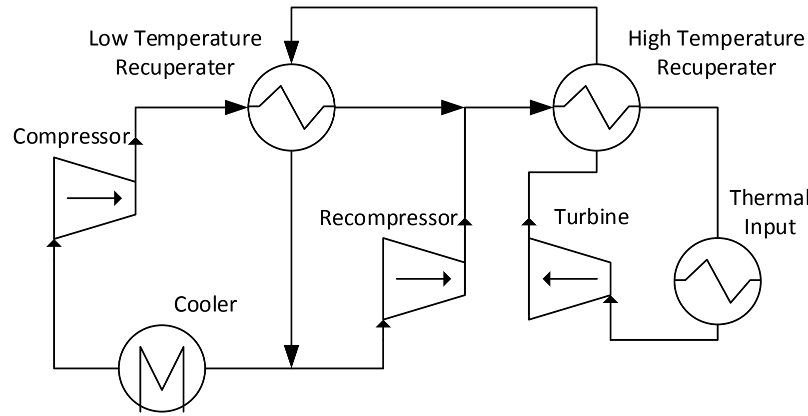


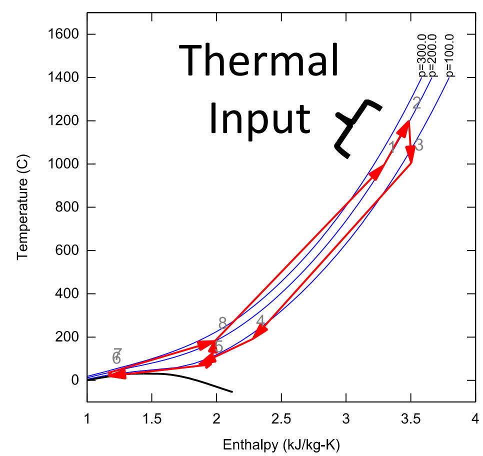
Integration Challenges

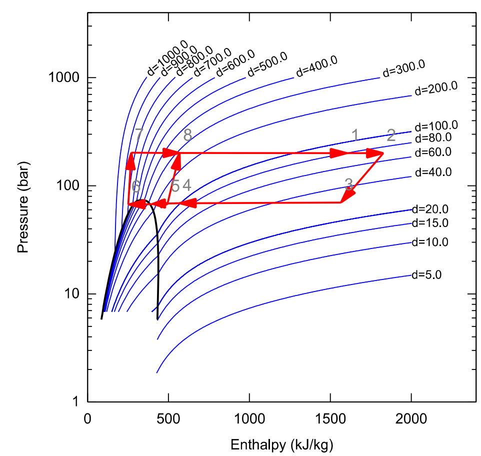
- Mismatched thermal input leads to inefficiencies in the boiler or heater
- Addressed by
  - Optimizing the power cycle to change thermal input characteristics
  - Adapting the thermal system to the power cycle
    - Recuperated thermal system
    - Direct fired configurations
- Impact of sCO2 interface heat exchanger design on system performance is unknown

Recompression Cycle

- Leverages recent SunShot and DOE-NE cycles development
- High efficiencies possible for the power block
  - 60% at 1100C
- High degree of recuperation drives a narrow thermal input window (~250C) and high mass flow requirements
- Combustor inlet temperatures
  - 400 C Combustor inlet for 650 C Turbine Inlet
  - 950 C Combustor inlet for 1200 C Turbine inlet

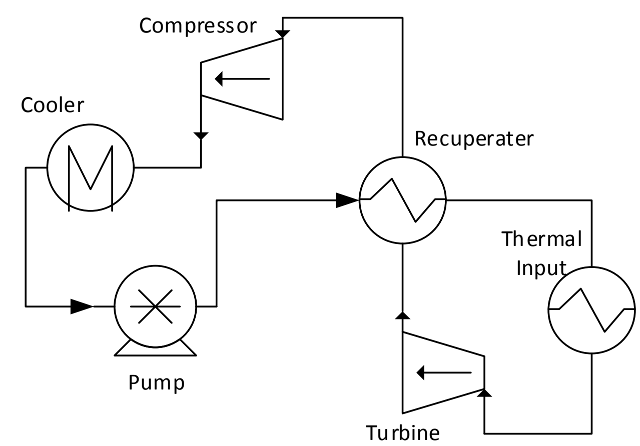


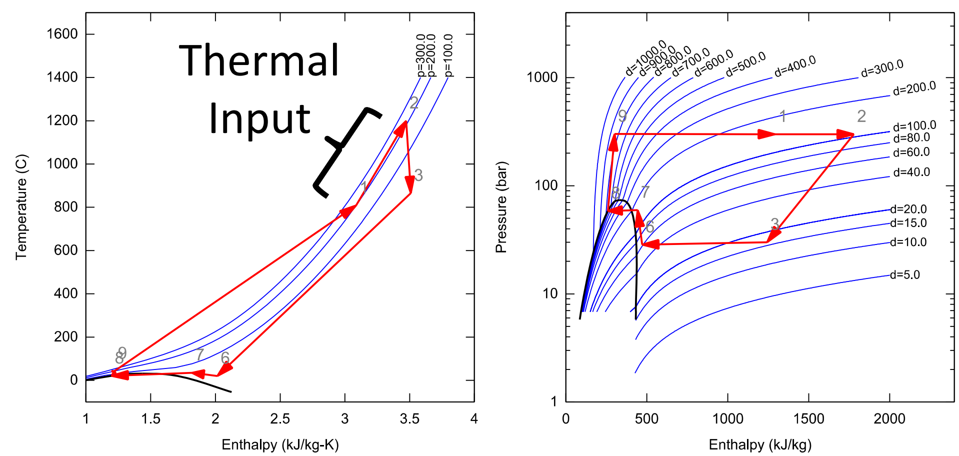




Partial Condensation Cycle

- Trans-critical cycle
- Optimization schedules the vapor phase compression, cooling for liquefaction, and liquid pumping to reduce compression power requirements





Cycle Comparison

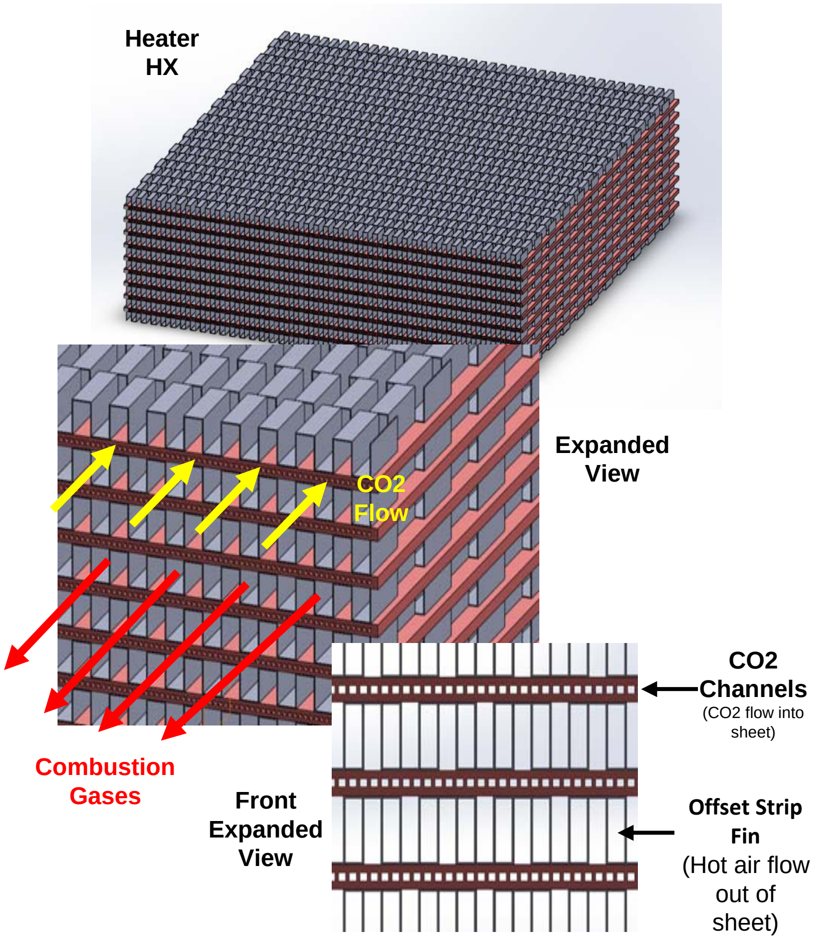
	Single Recouperator Condensation	Single Recouperator Condensation	Recompression	Recompression
Net fuel to bus bar plant efficiency	54.03%	51.60%	56.73%	53.44%
Total Recouperation (kW)	989.91	1078.16	1163.44	1205.34
HE Duty per Net Power Ratio (kW/kW)	2.48	3.21	4.34	6.55
Power per Mass Flow Ratio (kJ/kg)	399.06	335.38	268.08	183.92
Combustor Inlet Temp. (°C)	755.18	808.60	918.16	994.37
Combustor Inlet Pres. (bar)	300.00	200.00	300.00	200.00

** Cycles evaluated at 1200°C Turbine Inlet Temperature and 1 kg/s mass flow

sCO2 "Boiler"

- sCO2 Recuperators are being actively developed to address TRL for the power cycle
- Air fired sCO2 heaters are not an off the shelf component for integrated systems
- Challenges
  - Dis-similar fluid densities, heat capacities
  - High dP between air and sCO2 at high temperatures
  - Minimizing air side pressure drop with high volumetric flows
  - Managing air side fouling

Plate and Fin Heater Concept



- Easy to manufacture.
- Integrated manifold can handle CO2 pressure.
- Combustion gas side pressure drop is low.
- Staggered fin increases heat transfer.
- Lower probability of plugging on combustion gas side.

Absorption/Desorption

- Utilize Absorption/Desorption of a binary mixture to minimize compression work
  - CO_2 (R744)
  - Acetone or Ethanol
- Previously evaluated for increasing Coefficient of Power for refrigeration cycles
- Initial Aspen models indicate a 60% reduction in compression work is possible
  - Provides a 5% to 10% gain in cycle thermal efficiency

Challenges

- Verification of fluid properties at conditions of interest
  - Test for a dense phase compressibility doublet
- Adaptation of sCO2 cycles
  - Evaluate Absorption/Desorption process and applicable range of temperatures and pressures
- Optimization of the cycle

PROPOSED SCOPE

Project Objectives

- Identify technical challenges impacting the integration of fossil based thermal sources with highly recuperated closed Brayton sCO2 power cycles
- Evaluate the impact of boiler design and sCO2 cycle configuration on integrated plant performance, cost, and operability
- Evaluate technology readiness of the integrated system and identify specific technologies requiring development advance fossil based sCO2 cycles.

SOPO Tasks

- Task 1.0 – Project Management and Planning
- Task 2.0 – Evaluation of Fossil Fired sCO2 Power Plants
- Task 3.0 – Critical Component and Technology Identification for sCO2 based Power Plants
- Task 4.0 – Component and Boiler Technology Assessment
- Task 5.0 – Evaluation of Novel sCO2 Absorption/Desorption Cycles

Task 2.0 – Evaluation of Fossil Fired sCO2 Power Plants

- Evaluate sCO2 cycle configurations to establish operating requirements for an indirect fossil based power plant
  - Recompression and Partial Condensation cycles
  - Review work of Angelino and Dostal for additional cycle configurations of interest
- Baseline component performance requirements for thermal sub-systems

Task 3.0 – Critical Component and Technology Identification for sCO2 based Power Plants

- Identify critical components and determine their impact on a fossil based sCO2 plant using
  - Design space exploration
  - Sensitivity studies of the integrated power plant
- Down select and optimize cycle configurations for overall efficiency
  - Focus is on indirect cycles

Task 4.0 – Component and Boiler Technology Assessment

- Assess boiler integration issues for sCO2 power cycles
  - Technical gap assessment to identify of critical components and development needs
  - Evaluate feasibility of existing boiler configurations to meet needs of sCO2 cycles
  - Evaluate the sCO2/Air heat exchanger
    - Analysis, prototyping, and bench scale evaluation

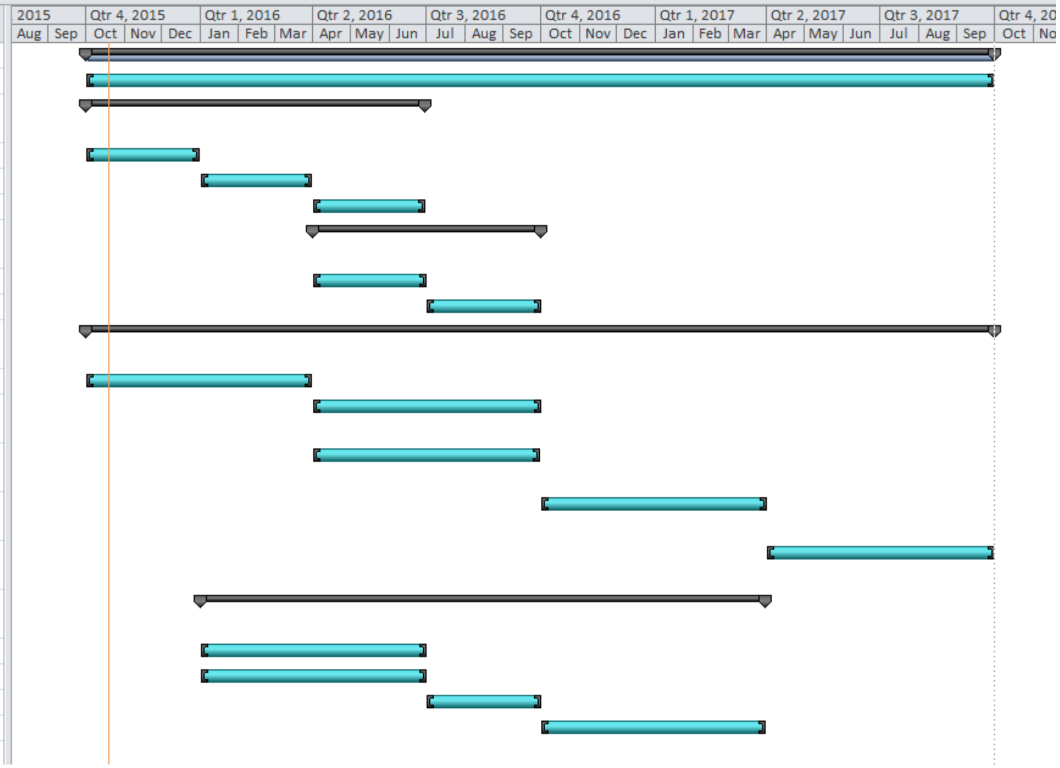
Task 5.0 – Evaluation of Novel sCO2 Absorption/Desorption Cycles

- Evaluate the application of Absorption/Desorption to power generation
  - Utilize absorption of CO2 into Acetone or Ethanol to minimize compression work
- Fluid properties verification at conditions at high P and T than is available in literature
  - Physical properties testing
  - Desorption and separation
- Materials compatibility review
- Cycle definition, evaluation, and optimization

PROGRAM MANAGEMENT

Schedule

	Task Name	Start	Finish
1	**Task 1.0 – Project Management and Planning**	**Thu 10/1/15**	**Sat 9/30/17**
2	Participant Coordination	Thu 10/1/15	Sat 9/30/17
3	**Task 2.0 – Evaluation of Fossil Fired sCO2 Power Plants**	**Thu 10/1/15**	**Wed 6/29/16**
4	Thermal System Requirements	Thu 10/1/15	Wed 12/30/15
5	Cycle Evaluation	Fri 1/1/16	Wed 3/30/16
6	Critical Component Identification	Fri 4/1/16	Wed 6/29/16
7	**Task 3.0 – Critical Component and Technology Identification for sCO2 based Power Plants**	**Fri 4/1/16**	**Fri 9/30/16**
8	Design space exploration and sensitivity studie	Fri 4/1/16	Thu 6/30/16
9	Cycle Optimization	Fri 7/1/16	Fri 9/30/16
10	**Task 4.0 – Component and Boiler Technology Assessment**	**Thu 10/1/15**	**Sat 9/30/17**
11	Technical Gap Assessment	Thu 10/1/15	Wed 3/30/16
12	sCO2 Cycle Layout Considerations and Boiler Integration	Fri 4/1/16	Fri 9/30/16
13	sCO2 /Air Heat Exchanger Technology Evaluation	Fri 4/1/16	Thu 9/29/16
14	Fabrication of a Bench Scale Air/sCO2 Heat Exchanger	Sat 10/1/16	Fri 3/31/17
15	Bench Scale Evaluation of a Representative Air/sCO2 Heat Exchanger	Sat 4/1/17	Sat 9/30/17
16	**Task 5.0 – Evaluation of Novel sCO2 Absorption/Desorption Cycles**	**Fri 1/1/16**	**Thu 3/30/17**
17	Physical Properties Testing	Fri 1/1/16	Thu 6/30/16
18	Dense Phase Separation Evaluation	Fri 1/1/16	Thu 6/30/16
19	Materials Compatability Review	Fri 7/1/16	Fri 9/30/16
20	Absorption/Desorption Cycle Evaluation	Sat 10/1/16	Thu 3/30/17



Budget Breakdown

Participant	Type	Project Budget	Cost Share	POC
Southwest Research Institute®	Not for Profit	$ 525,000.00	$ 50,000.00	Aaron McClung
Thar Energy LLC	For Profit	$ 600,000.00	$ 175,000.00	Lalit Chordia
Project Total		$ 1,125,000.00	$ 225,000.00	

THANK YOU FOR YOUR ATTENTION