

Technical and Economic Evaluation of Supercritical Oxy-combustion for Utility Scale Power Generation

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Outline

- Project Participants
- Fossil based sCO₂ systems
 - Typical characteristics
- Coal fired oxy-combustion
 - Cycle layouts
 - Predicted performance
 - Component Technology Readiness Levels
- Direct fired natural gas oxy-combustion
 - Cycle concepts
 - Anticipated challenges

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***

SwRI Machinery Program

- Fluids & Machinery Engineering Department
 - Mechanical Engineering Division (18)
- Capabilities
 - Root cause failure analysis
 - Rotordynamic design/audit
 - Pipeline/plant simulation
 - CFD and FEA analysis
 - Test rig design
 - Performance testing
- Recent Commercial Projects
 - Test stands for LNG and CNG process evaluation
 - Air Cycle Machine Design, Build, and Test
 - Numerical Propulsion System Simulation® (NPSS®) Consortium Management
- Recent DOE sCO₂ Programs
 - Physical Properties
 - High-Pressure Gas Property Measurements
 - CO₂ Pipeline and Compression
 - CO₂ Pipeline Pulsation Analysis and Mitigation
 - Novel Concepts for the Compression of Large Volumes of CO₂ (FC26-05NT42650)
 - sCO₂ Turbomachinery
 - Development of a High Efficiency Hot Gas Turbo-Expander and Low Cost Heat Exchangers for Optimized CSP Supercritical CO₂ Operation (DE-EE0005805)
 - Electrothermal Energy Storage with A Multiphase Transcritical CO₂ cycle (DE-AR0000467)
 - Physics-Based Reliability Models for Supercritical CO₂ Turbomachinery Components (DE-FOA-0000861, PREDICTS)
 - Utility-Scale sCO₂ Turbomachinery and Seal Test Rig Development (DE-FOA-0001107) Oxy-combustion
 - Novel Supercritical Carbon Dioxide Power Cycle Utilizing Pressurized Oxy-combustion In Conjunction With Cryogenic Compression (DE-FE0009395)
 - High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion (DE-FE0024041)
 - Heat Exchangers
 - High Temperature, High Pressure Compact Heat Exchanger Development (DE-FOA-0001095)
 - Development of a Thin Film Primary Surface Heat Exchanger for Advanced Power Cycles (DE-FOA-0001095)



Thar companies:

TharEnergy

TharProcess

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

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



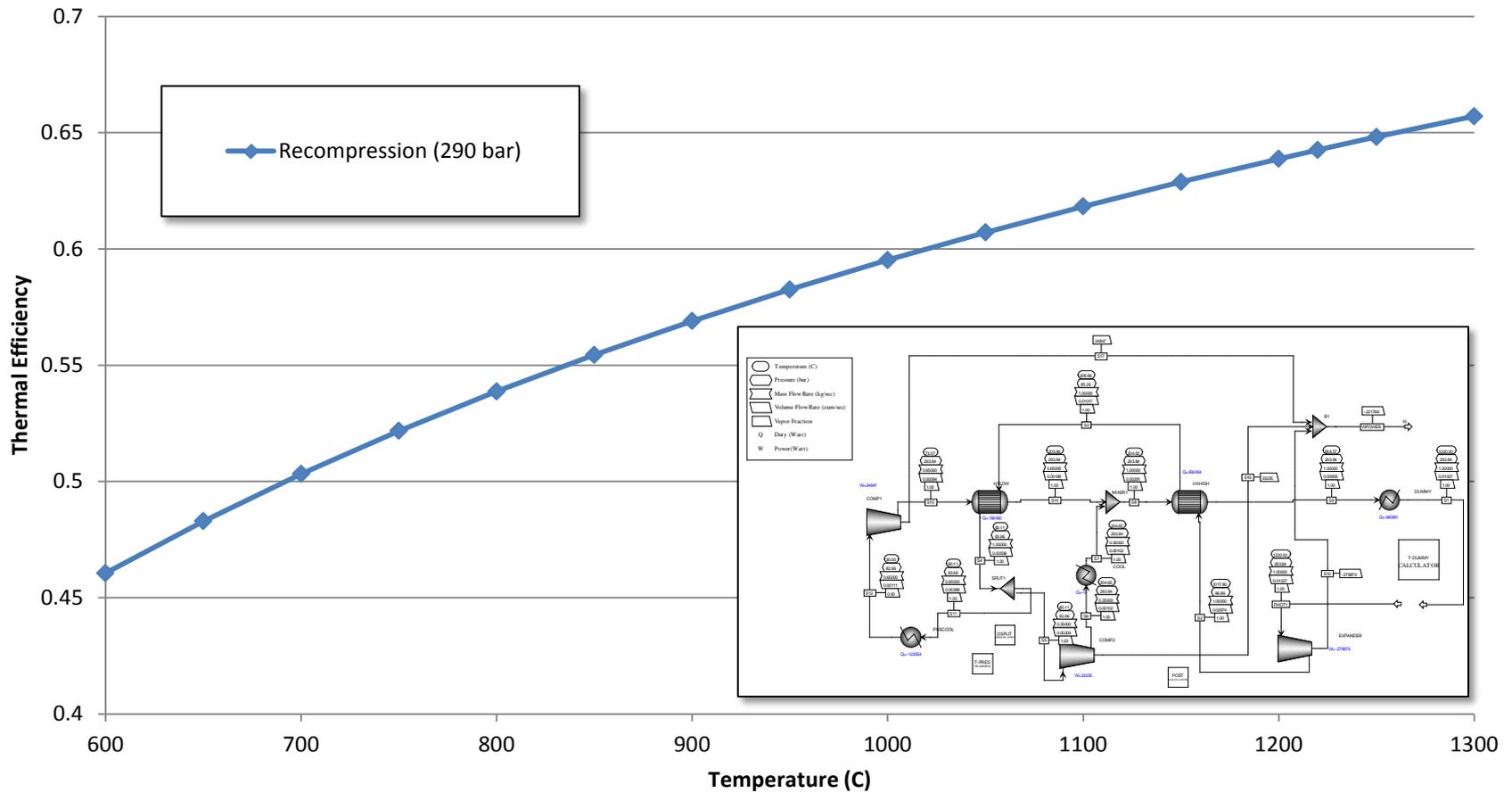
FOSSIL BASED SCO₂ SYSTEMS

“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

Cycle Efficiency

Recompression Cycle at 290 bar

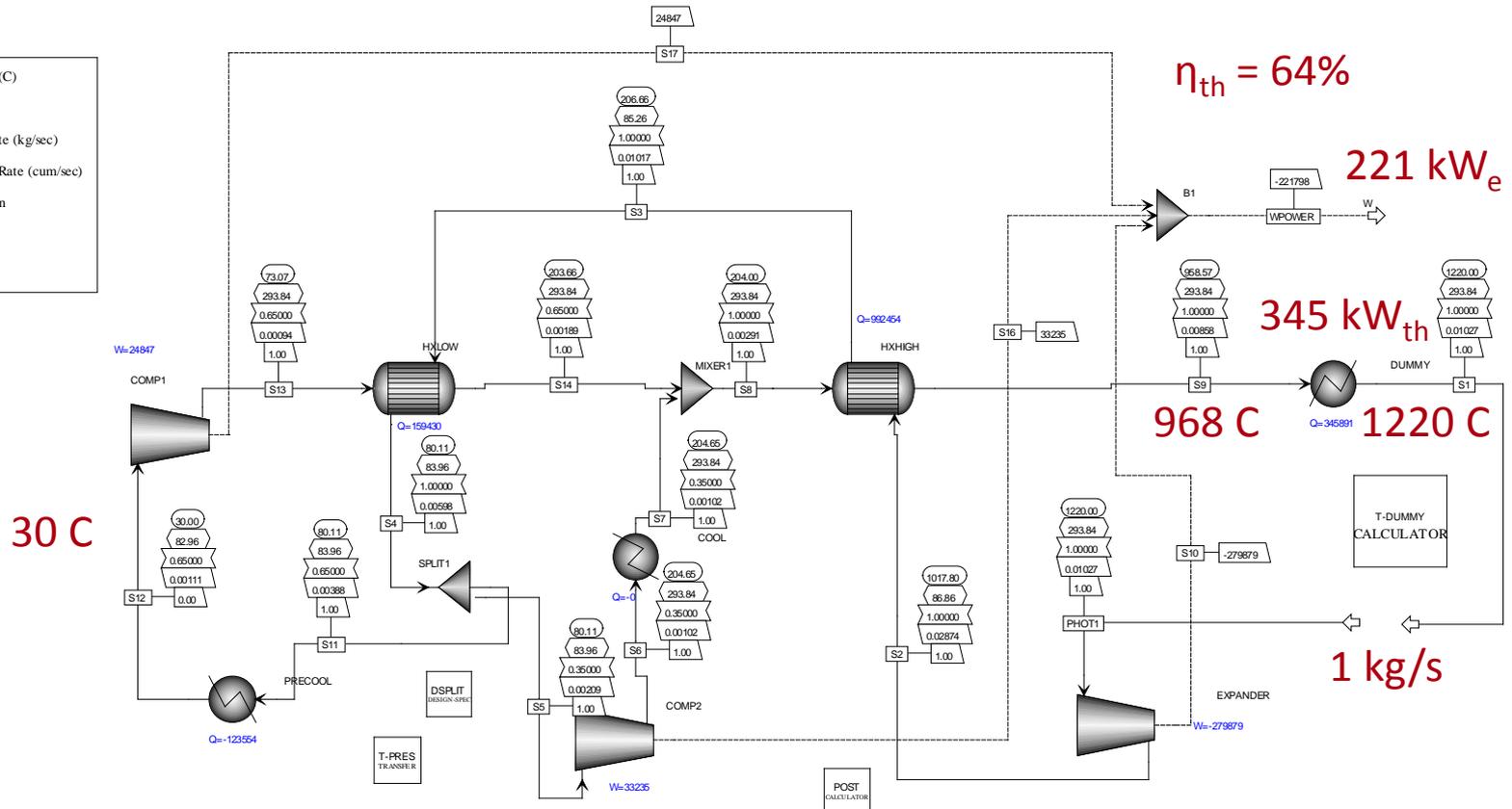


Fossil Based sCO₂ Power Cycles

- 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
 - Offset by recuperation to achieve high cycle efficiencies
- Challenges
 - 250 C thermal input temperature window 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
 - Efficiency losses for indirect cycles

High Temperature Recompression Cycle

- Temperature (C)
- Pressure (bar)
- Mass Flow Rate (kg/sec)
- Volume Flow Rate (cum/sec)
- Vapor Fraction
- Duty (Watt)
- Power (Watt)

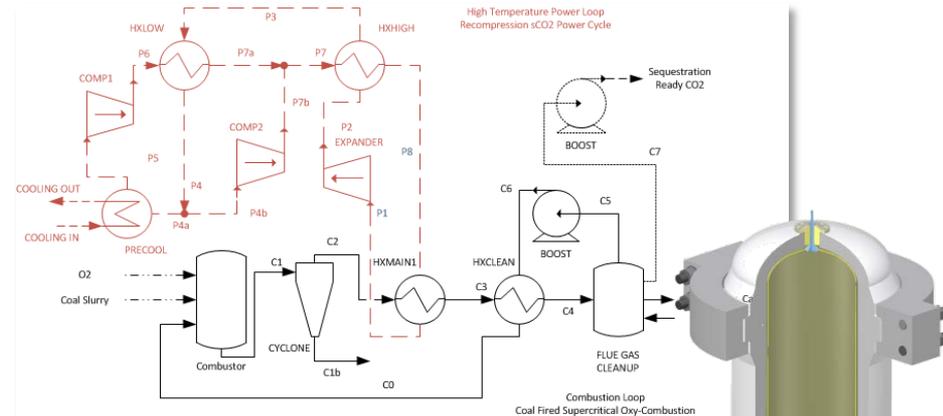


COAL FIRED OXY-COMBUSTION

Development of a Supercritical Oxy-combustion Power Cycle with 99% Carbon Capture

Southwest Research Institute® and Thar Energy L.L.C.

- Engineering development, technology assessment, and economic analysis used to evaluate technical risk and cost of a novel supercritical oxy-combustion power cycle
- Optimized cycle couples a coal-fired supercritical oxy-combustor with a supercritical CO₂ power cycle to achieve *40% efficiency at low firing temperature, 650 C*
 - Cycle is limited by TRL of critical components
- COE \$121/MWe with 99% carbon capture
 - 49% increase over Supercritical Steam Without Carbon Capture (\$81/MWe), *exceeding the 35% target*
 - 21% reduction in cost as compared to Supercritical Steam with 90% Carbon Capture (\$137/MWe).
- Phase 1 completed in September 2013
- Budget \$1.25 million
- Ready to demonstrate supercritical oxy-combustor and critical low TRL technologies

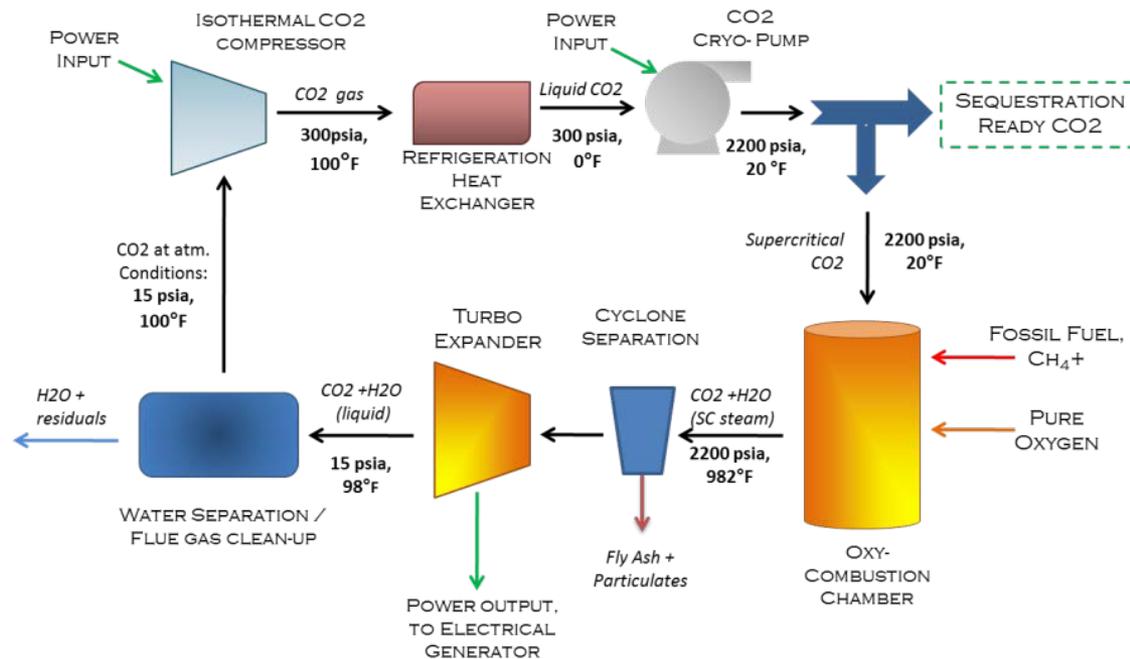
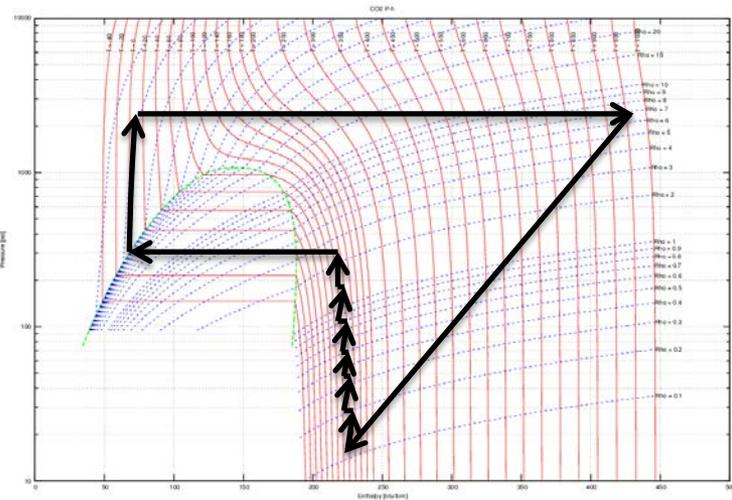


Project Scope

- Evaluate a novel supercritical oxy-combustion power cycle for meeting the DOE goals of:
 - Over 90% CO₂ removal for less than 35% increase in cost of electricity (COE) when compared to a Supercritical Pulverized Coal Plant without CO₂ capture
- Cycle evaluation based on:
 - Cycle and economic modeling to qualify cost and cycle performance
 - Technology gap assessment to identify critical low TRL components and technologies
 - Bench scale testing to back up cycle models and evaluate state of low TRL technologies
- Propose development path to address low TRL components

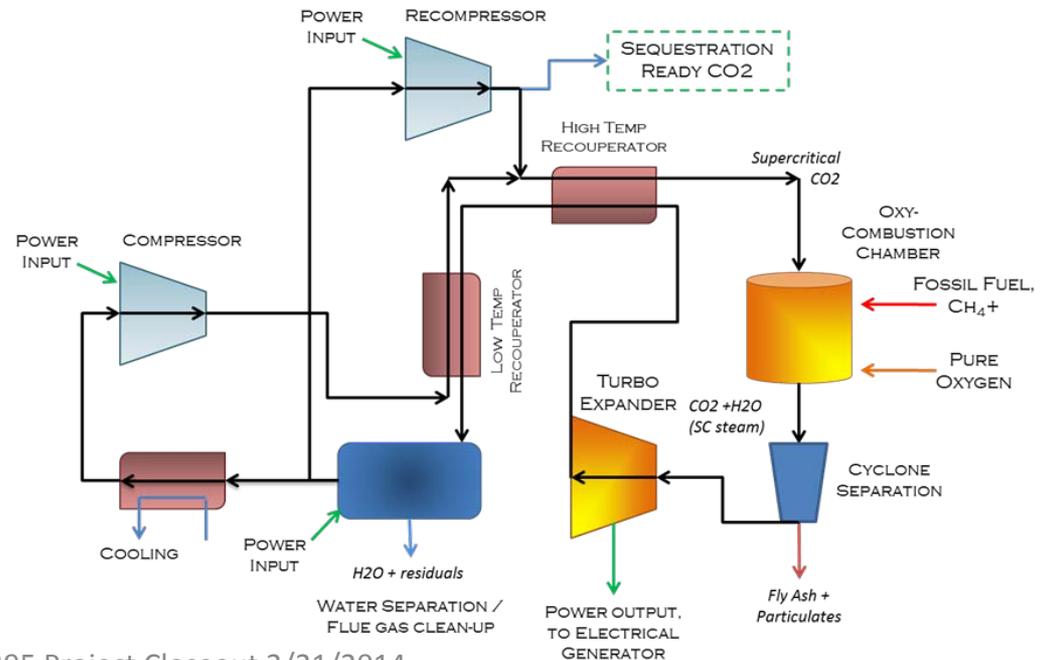
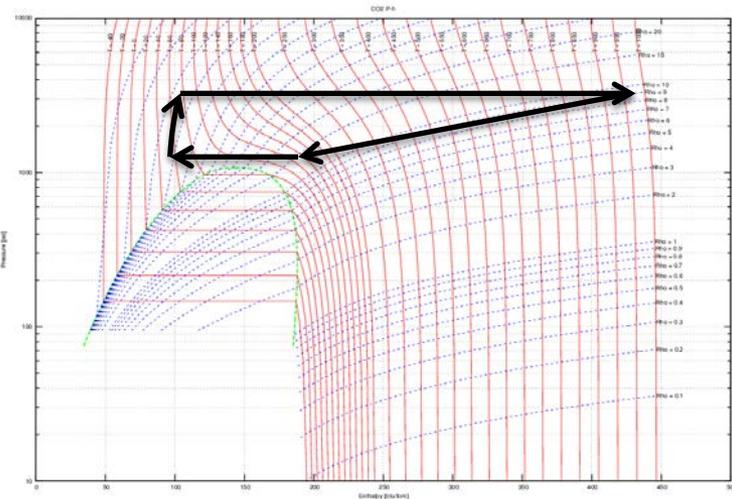
Proposed Cycle: Cryogenic Pressurized Oxy-combustion (CPOC)

- Transcritical cycle (gas, liquid, and supercritical states)
- Leverage iso-thermal compression to minimize compression work

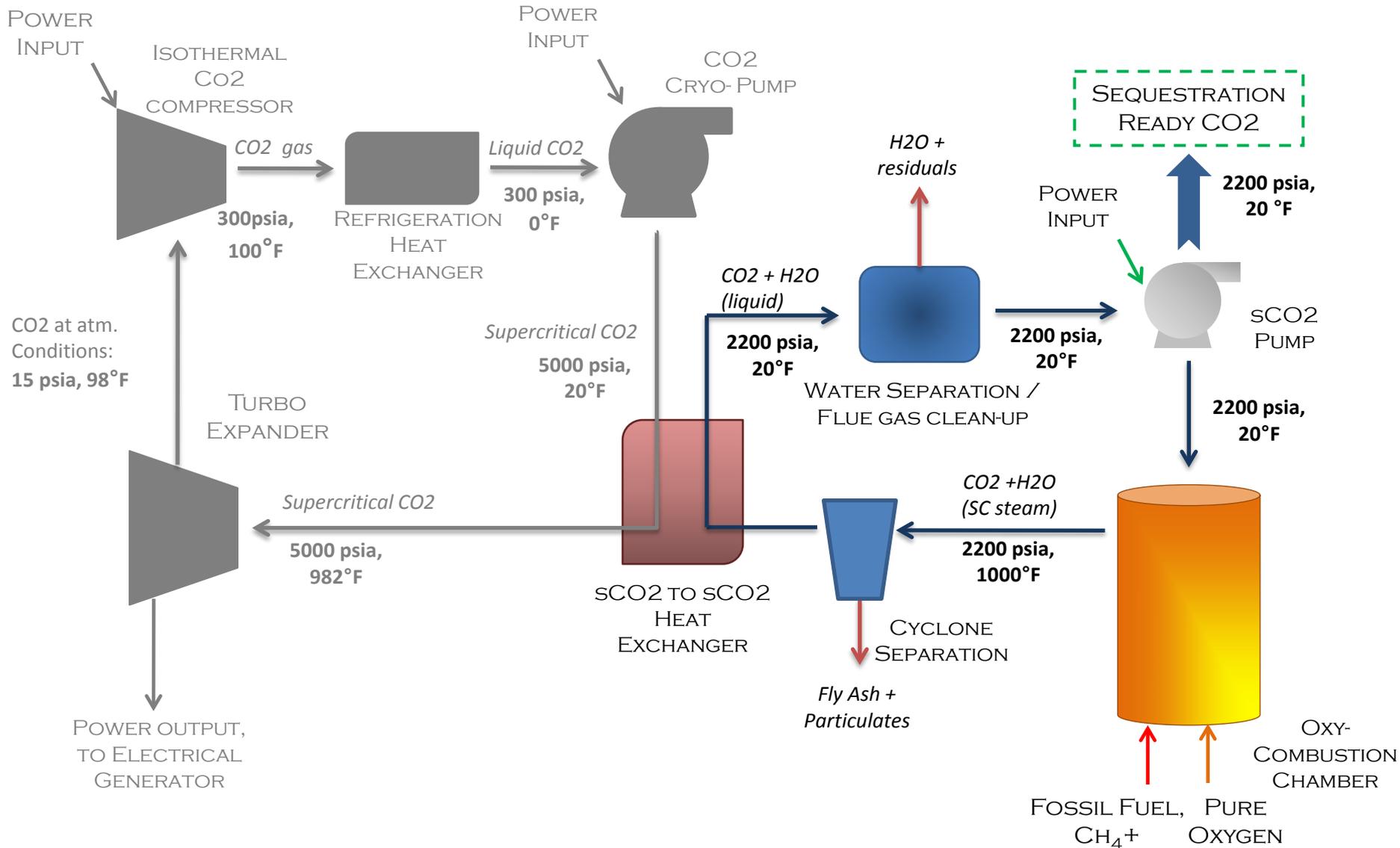


Proposed Cycle: Supercritical Oxy-combustion

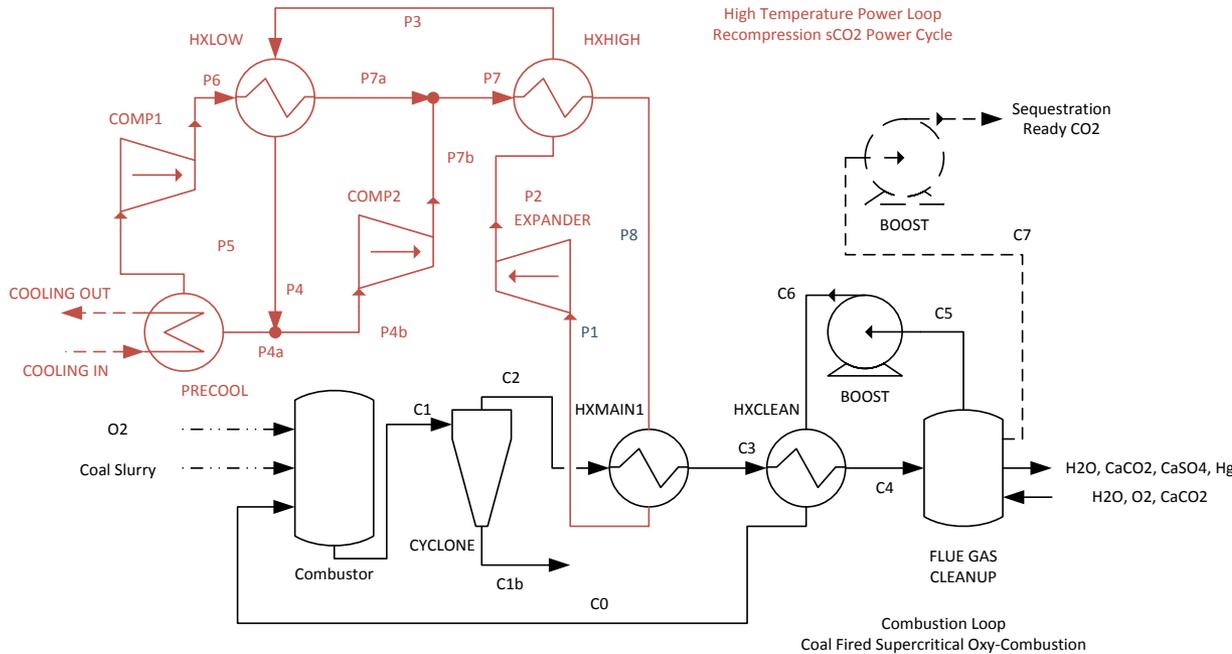
- Leverages recent SunShot and DOE-NE cycles development
- Efficiencies up to 60% possible for the power block



Indirect CPOC Layout

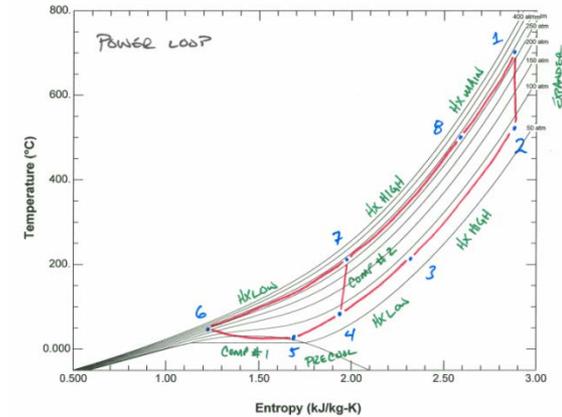


Coal Fired Indirect Supercritical Oxy-combustion Cycle Configuration

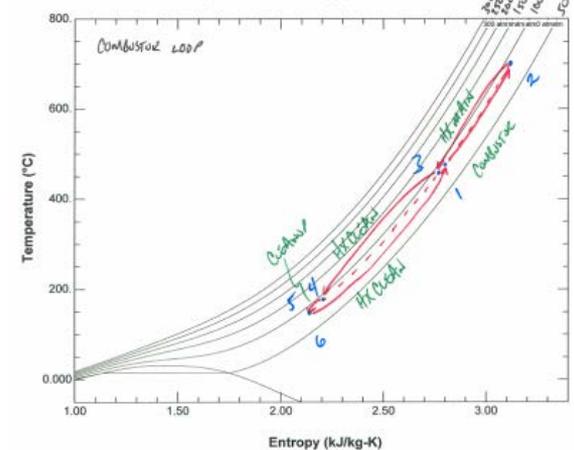


	Power Block	Thermal Loop	Overall
Efficiency [%]	48 Thermal	78.9 HHV / 81.8 LVH	37.9 HHV / 39.3 LHV
CO ₂ Flow [kg/s]	4887	4930 Recycle	
P high / P low [atm]	290 / 82	100 / 93	
T high / T low [C]	650 / 20	653 / 78	

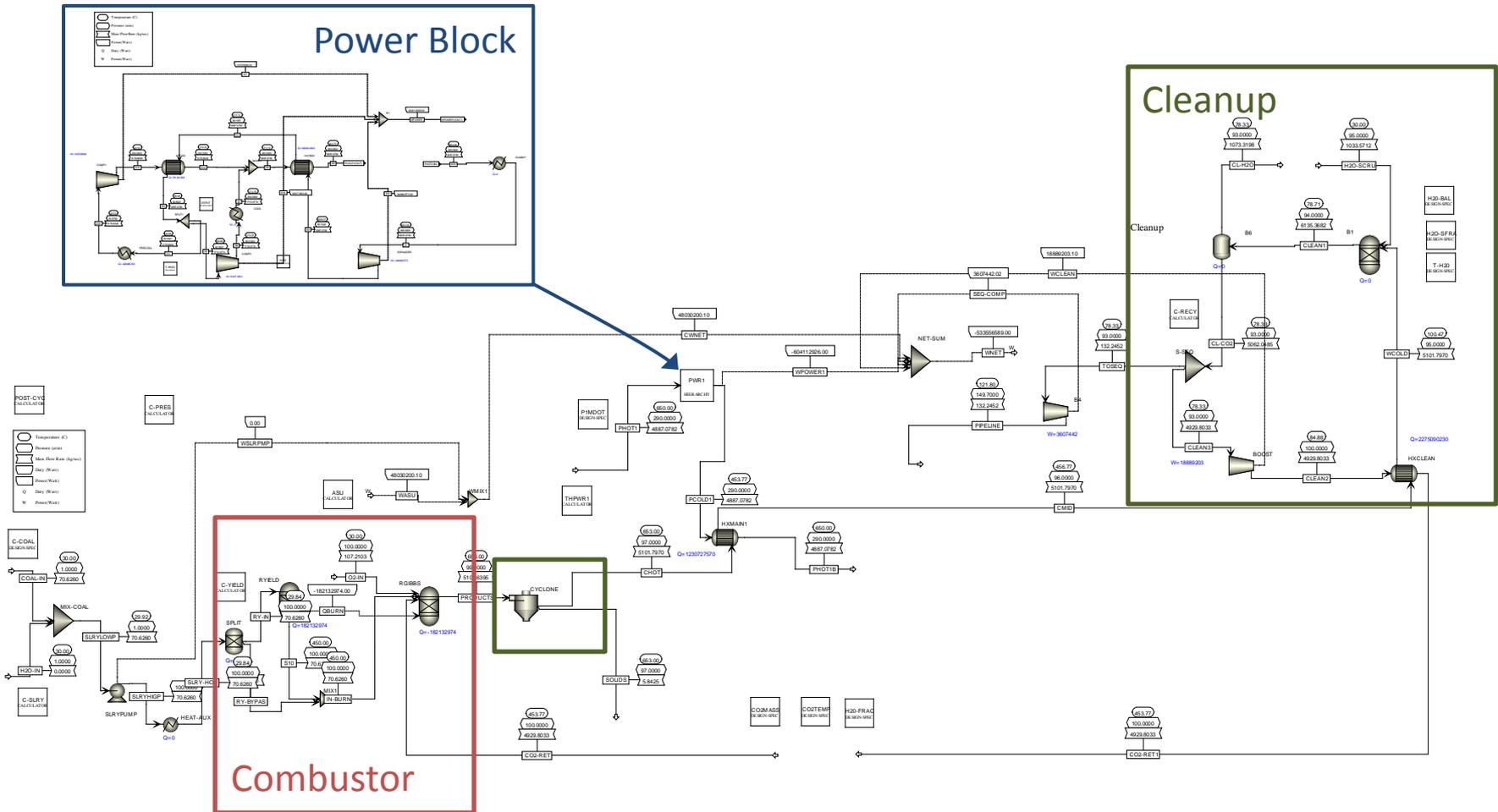
19: Temperature vs. Entropy plot: carbon dioxide



26: Temperature vs. Entropy plot: carbon dioxide



Indirect Cycle Model with Supercritical Oxy-Combustor



Combustion Loop TRL

Component/Sub-system	Technology Type	Operating Conditions				Assumed or Specified Performance Characteristics	Assumptions Regarding Anticipated Application Issues	Technology Readiness
		Inlet		Outlet				
		Temperature [C]	Pressure [atm]	Temperature [C]	Pressure [atm]			
Combustion Loop								
Coal Pulverizer	Generic	25	1	25	1	< 9 kw-h/ton		TRL 9
Slurry Pump	Generic	25	1	30	92.25	60% Efficiency		TRL 9
Supercritical oxy-combustor	New vertical flow swirl combustor	450	95	93	92.25	98+% combustion efficiency	Combustor to be demonstrated in Phase 2	TRL 6 at the completion of Phase 2 demonstration
Dry pulverized coal feed	Supercritical CO2 slurry	25	1	<450	110	Minimal added water content	Demonstrated systems can not achieve pressure ratio	TRL 2
Dry pulverized coal feed	Posimetric Pump	25	1	<450	110	Dry feed		TRL 4
Removal of solid products of combustion	Lock-hopper	703	92	80	1	Fluid and thermal losses, impact on efficiency unknown		TRL 4
Cyclone Separator	Generic	703	93	703	91	98% Removal 3 atm dP	Materials considerations and thermal insulation for hot gas cleanup	TRL 9
Recuperator (HXMAIN)	Compact micro-channel heat exchanger	703	91	460	88	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1
Pre-heater (HXCLEAN)	Compact micro-channel heat exchanger	460	88	162	85	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1
Sulfur Cleanup	Under evaluation for hot, high pressure cleanup	162	85	?	?	Under Evaluation to identify technologies compatible with loop conditions	High efficiency requirements drive the need for hot, high pressure cleanup	TRL 5 - 9 depending on cleanup conditions
Water Removal	Under evaluation for hot, high pressure cleanup	162	85	?	?	Under Evaluation to identify technologies compatible with loop conditions	High efficiency requirements drive the need for hot, high pressure cleanup	TRL 5 - 9 depending on cleanup conditions
Boost Pump	Generic	150	80	95			Seals and materials for supercritical CO2	TRL 9
Air Separation Unit	Cryogenic	30	1	450	93	140 kWh/t for 95% O2 based on literature		TRL 9

Note 1: TRL 7 at the completion of a compantion DOE SunShot Project in 2016 (DE-EE0005804)

Note 2: TRL 7 at the completion of a compantion DOE SunShot Project in 2013 (FC26-05NT42650)

Note 3: Materials and manufacturing assumptions for cost and performance

Note 4: Turbomachinery layout and design is being addressed in other DOE sponsored programs (DE-EE0005804)

Power Loop TRL

Component/Sub-system	Technology Type	Operating Conditions				Assumed or Specified Performance Characteristics	Assumptions Regarding Anticipated Application Issues	Technology Readiness
		Inlet		Outlet				
		Temperature [C]	Pressure [atm]	Temperature [C]	Pressure [atm]			
Power Loop	Supercritical CO2 Recompression Cycle							TRL 7, See Note 1
sCO2 Turbo-expander		650	290	509	86	90+% efficiency	See Note 4	TRL 7, See Note 1
Recuperator (HXHIGH)	Compact micro-channel heat exchanger	509	86	213	84	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1
Recuperator (HXLOW)	Compact micro-channel heat exchanger	213	84	70	83	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1
sCO2 Pump/Compressor		70	83	190	290	05+% efficiency	See Note 4	TRL 7, See Note 2
sCO2 Pump/Compressor		25	82	60	290	05+% efficiency	See Note 4	TRL 7, See Note 2
Pre-cooler	Compact micro-channel heat exchanger	70	83	25	82	5 C Pinch Point 3 atm dP	See Note 3	TRL 7, See Note 1

Note 1: TRL 7 at the completion of a compantion DOE SunShot Project in 2016 (DE-EE0005804)

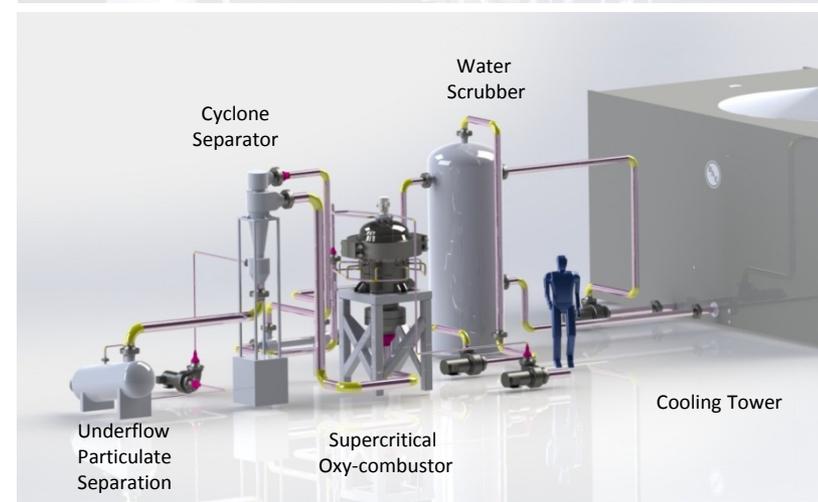
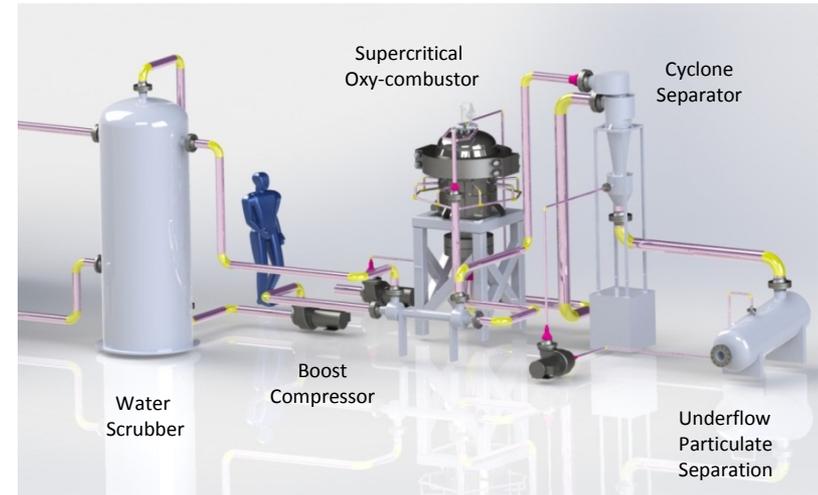
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Note 3: Materials and manufacturing assumptions for cost and performance

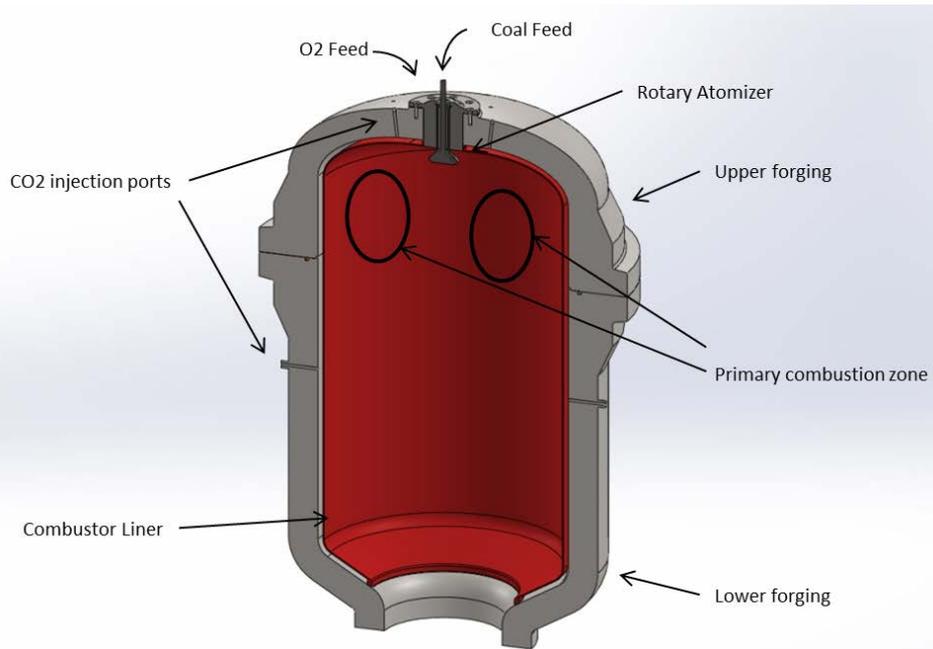
Note 4: Turbomachinery layout and design is being adressed in other DOE sponsored programs (DE-EE0005804)

Development Path

- 1 MWth Supercritical Oxy-combustor Demonstration
- Test bed for technology development
 - Supercritical oxy-combustor
 - Particulate cleaning of the compact microchannel heat exchanger
 - Solids injection at pressure
 - Solids removal at pressure
- Advance technologies from TRL 2, *Technology Concept*, to TRL 6, *Pilot Scale System Demonstrated in a Relevant Environment*
- Operate with coal water slurry, plan for dry feed or sCO₂ slurry extension



SwRI Oxy-Combustor Concept

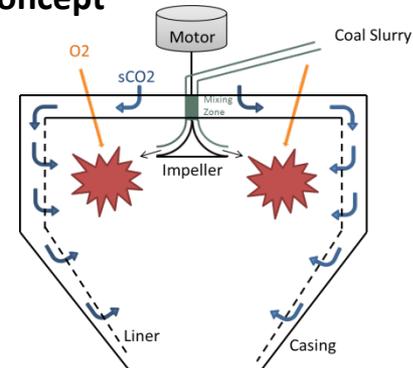


- Pulverized coal + water slurry
 - Recycle water from combustion loop cleanup
 - Water provides flame temperature control
- Rotating impeller fuel injector
 - Optimize shear-mixing of slurry, CO₂, and O₂
 - Controlled fuel injection rate through impeller, O₂ injection controls flame position
- CO₂ cooled liner
 - Flame position, diffusion, and dilution control
 - Flame centering
 - Wall temperature buffering

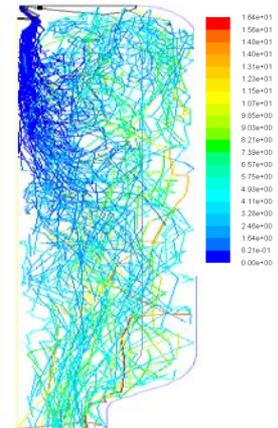
Combustor Design

- Designed to feed a coal-water slurry and O₂ into supercritical CO₂
 - Inlet Temperature 450 C (842 F)
 - Inlet Pressure 96.5 bar (1400 psi)
 - Firing Temperature 700 C (1292 F)
- Limited data on coal combustion at elevated pressures
- Combustor design through simulation, augmented with coal combustion properties testing
- Flow rates at 550 MWe
 - Coal 50 kg/s
 - O₂ 80 kg/s
 - H₂O 50 kg/s
 - CO₂ 4000+ kg/s

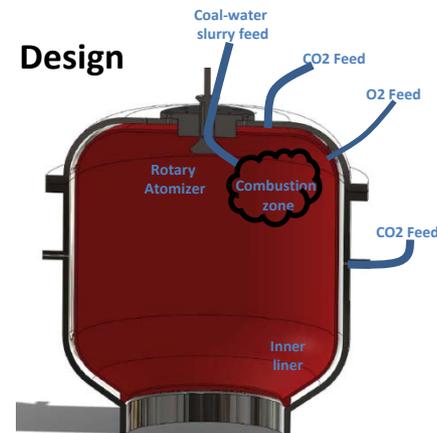
Concept



Analysis

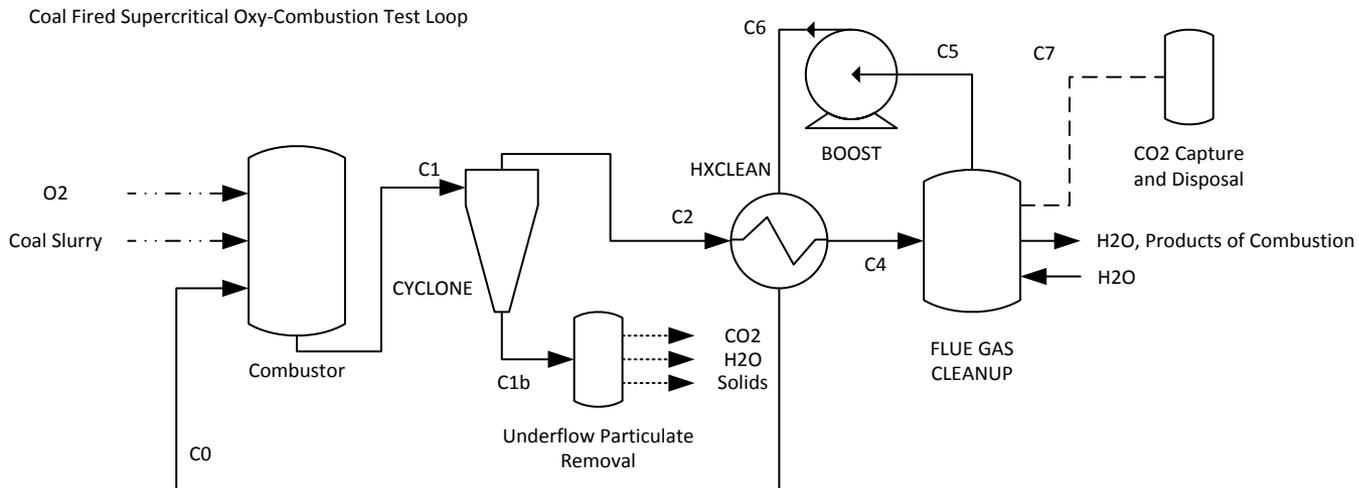


Design



Oxy-Combustion Test Loop

- Major components
 - Charge Compressor or Pressurized CO₂ Feed
 - Combustor
 - Oxygen feed
 - Coal slurry feed
 - Cyclone separator
 - Solids removal and handling
 - Recuperater
 - Water scrubber and cleanup
 - Liquid removal and handling
 - CO₂ removal and handling
 - Cooling Tower
 - Boost Compressor
- Operating Conditions
 - 450 – 650 C (800 – 1200 F)
 - 102 atm (1500 psi)
- Flow Rates: 1 MWth
 - 3.4 kg/s Hot side flow rate
 - 3.2 kg/s CO₂ recycle
 - 0.05 kg/s Coal feed
 - 0.08 kg/s O₂ Feed
 - 4.25 kg/s H₂O Recycle



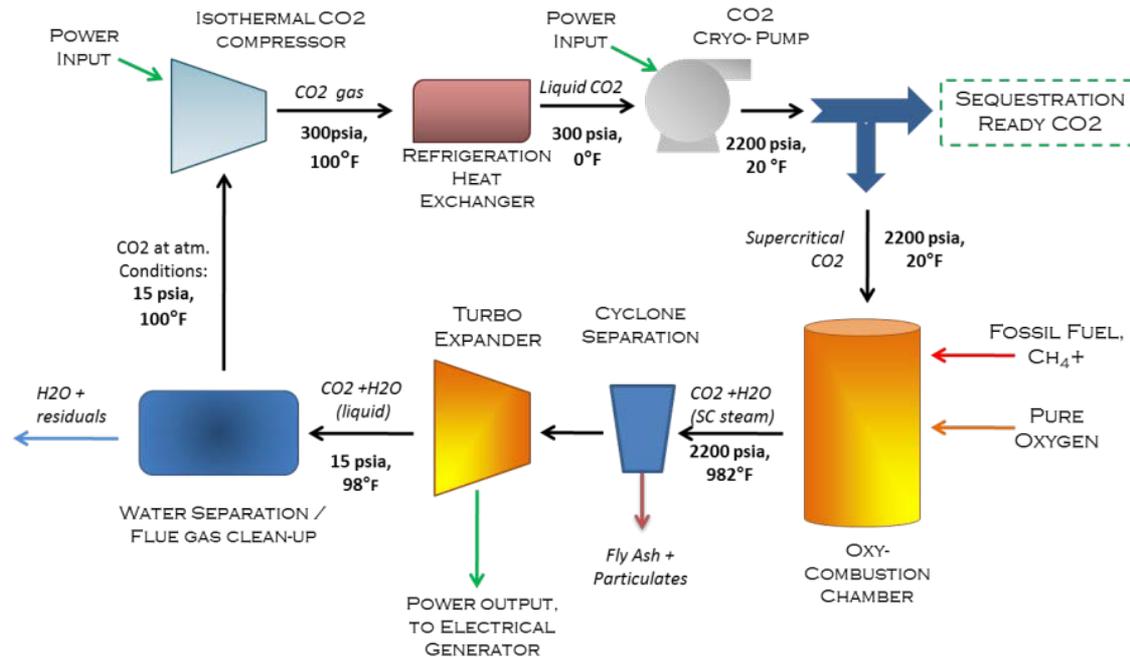
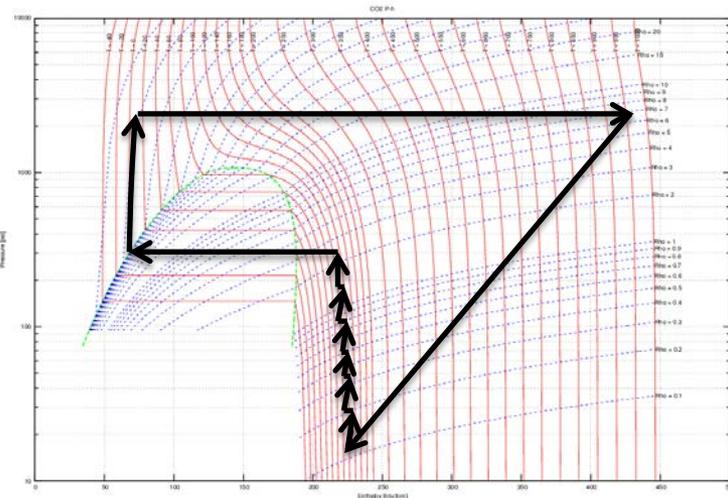
DIRECT NATURAL GAS FIRED OXY-COMBUSTION

High Inlet Temperature Combustor for Direct Fired Supercritical Oxy-Combustion Southwest Research Institute® and Thar Energy L.L.C.

- Cycle analysis and optimization for large scale, direct fired supercritical oxy-combustion for power generation
 - Based on engineering development and technology assessment
 - Target 52% plant efficiency to compete with NGCC
 - Requires 64% cycle efficiency
 - Turbine inlet 1220 C at 290 bar
- Evaluate technology readiness level of critical cycle components
 - Key known low TRL component: supercritical Oxy-combustor
 - Initial design of a high pressure, high temperature natural gas fired oxy-combustor
- Phase 1 award negotiations in progress

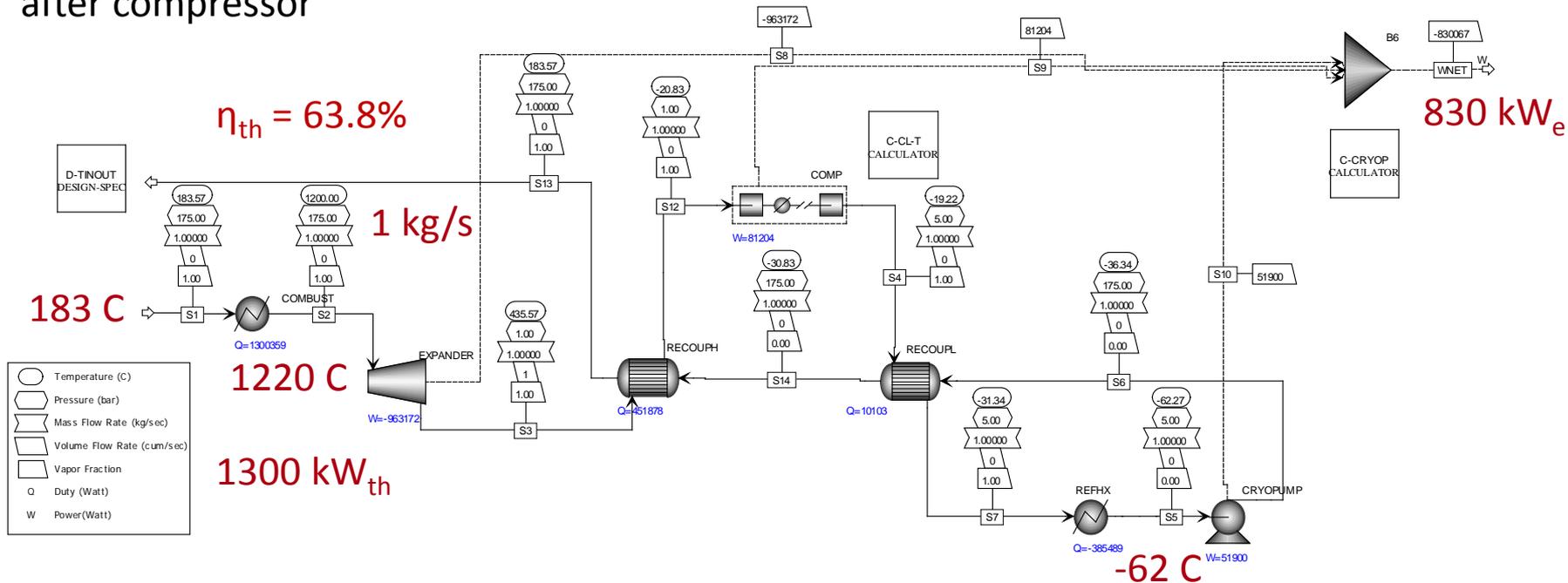
Initial Cycle: Cryogenic Pressurized Oxy-combustion (CPOC)

- Transcritical cycle (gas, liquid, and supercritical states)
- Leverage iso-thermal compression to minimize compression work



Recuperated CPOC

Add high temperature recuperator after expander, low temperature recuperator after compressor



High temperature recuperator

- Hot stream: Turbine outlet
- Cold stream: Low temperature recuperator
- Assume 10 C pinch point

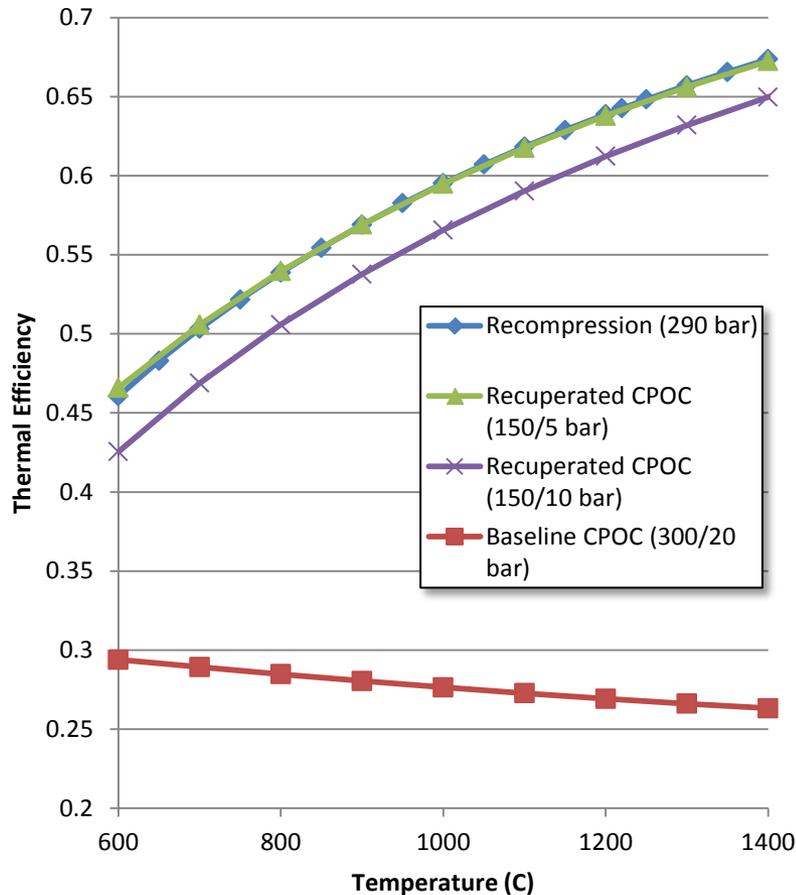
Low temperature recuperator

- Hot stream: Iso-thermal compressor outlet
- Cold stream: Dense phase pump
- Assume 5 C pinch point

Performance tweaks

- Iso-thermal compressor
 - Reduce pressure ratio (Increases refrigeration requirements)
 - Assume 20% of adiabatic temperature rise
- Turbine inlet pressure between 145 and 175 bar
- Assume 5C of sub-cooling for refrigeration

Efficiency Comparison



Recuperated CPOC performs on par with the recompression cycle, has larger thermal input window, higher power density, and requires less recuperation

	CPOC	Recompression
Efficiency	63.85%	64.00%
Turbine Inlet Temp (C)	1200	1200
Turbine Inlet Pressure (bar)	150	290
Turbine Outlet Pressure (bar)	1	100
Mass flow (kg/s)	1.00	1.00
W net (MW)	0.830	0.221
Q in (MW)	1.300	0.345
HX high (MW)	0.451	0.992
HX low (MW)	0.010	0.154
Total Recuperation (MW)	0.461	1.146

Scaled to 550 MWe plant, parasitic losses neglected

	CPOC	Recompression
Mass flow (kg/s)	662.65	2,488.69
W net (MW)	550.00	550.00
Q in (MW)	861.45	858.60
HX high (MW)	298.86	2,468.78
HX low (MW)	6.63	383.26
Total Recuperation (MW)	305.48	2,852.04

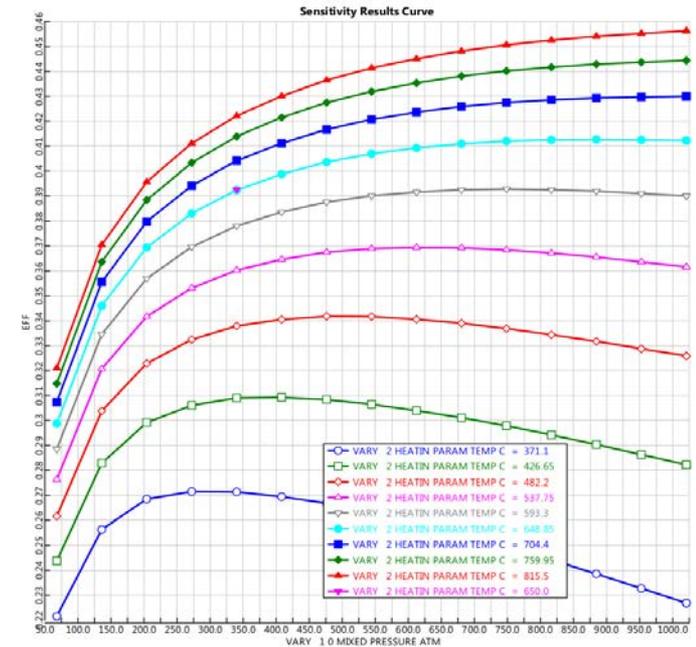
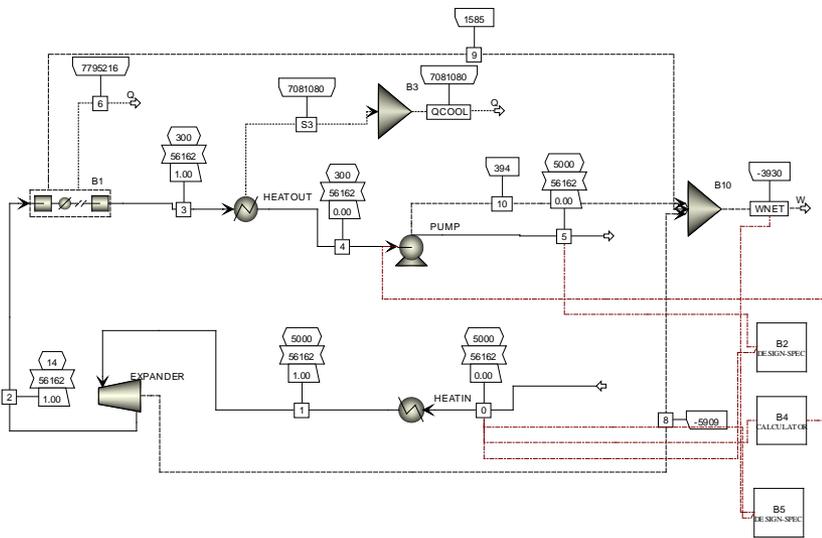
QUESTIONS

APPENDIX

Initial CPOC Power Block Analysis

CPOC w/out Combustion

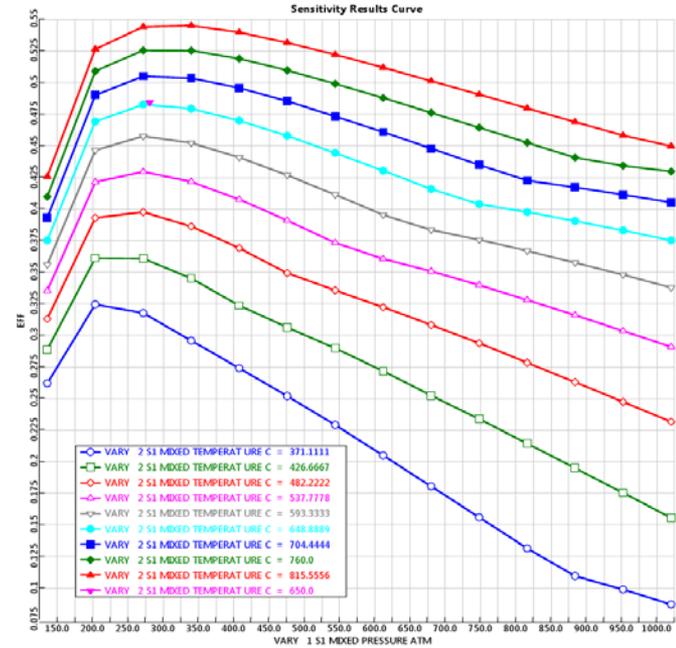
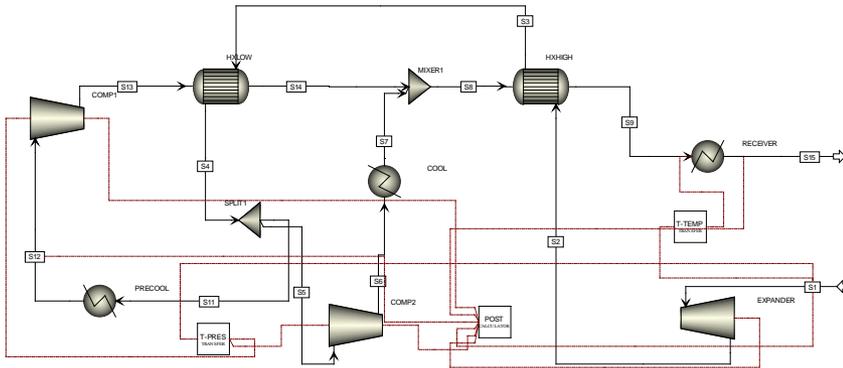
Thermal Efficiency



sCO₂ Recompression Power Block

sCO₂ w/out Combustion

Thermal Efficiency



Efficiency Comparison

