DE-FE0009395

Novel Supercritical Carbon Dioxide Power Cycle Utilizing Pressurized Oxy-combustion In Conjunction With Cryogenic Compression

Kickoff Meeting

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

Period of Performance: 10/01/2012 – 09/30/2013

Participants

Participant	Type	Project Budget	Cost Share	POC
Southwest Research Institute®	Not for Profit	$715,000	$0	Aaron McClung, Ph.D.
Thar Energy LLC.	For Profit	$535,000	$250,000	John Davis
Project Total		$1,250,000	$250,000	

Period of Performance: 10/01/2012 through 09/30/2013

Outline

- Project Overview
- Proposed Cycles
- Leveraged Programs
- Technology Gaps
- Analysis Methods
- Project Details

PROJECT OVERVIEW

Proposed Effort

- Evaluate a novel supercritical oxy-combustion power cycle for meeting the DOE goals of:
  - Achieve over 90% CO2 removal for less than 35% increase in cost of electricity (COE)
  - High overall plant efficiencies with 90% CO2 capture and compression to 2,200 psi
- Identify technologies requiring development in order to demonstrate a pressurized oxy-combustion cycle

Evaluation

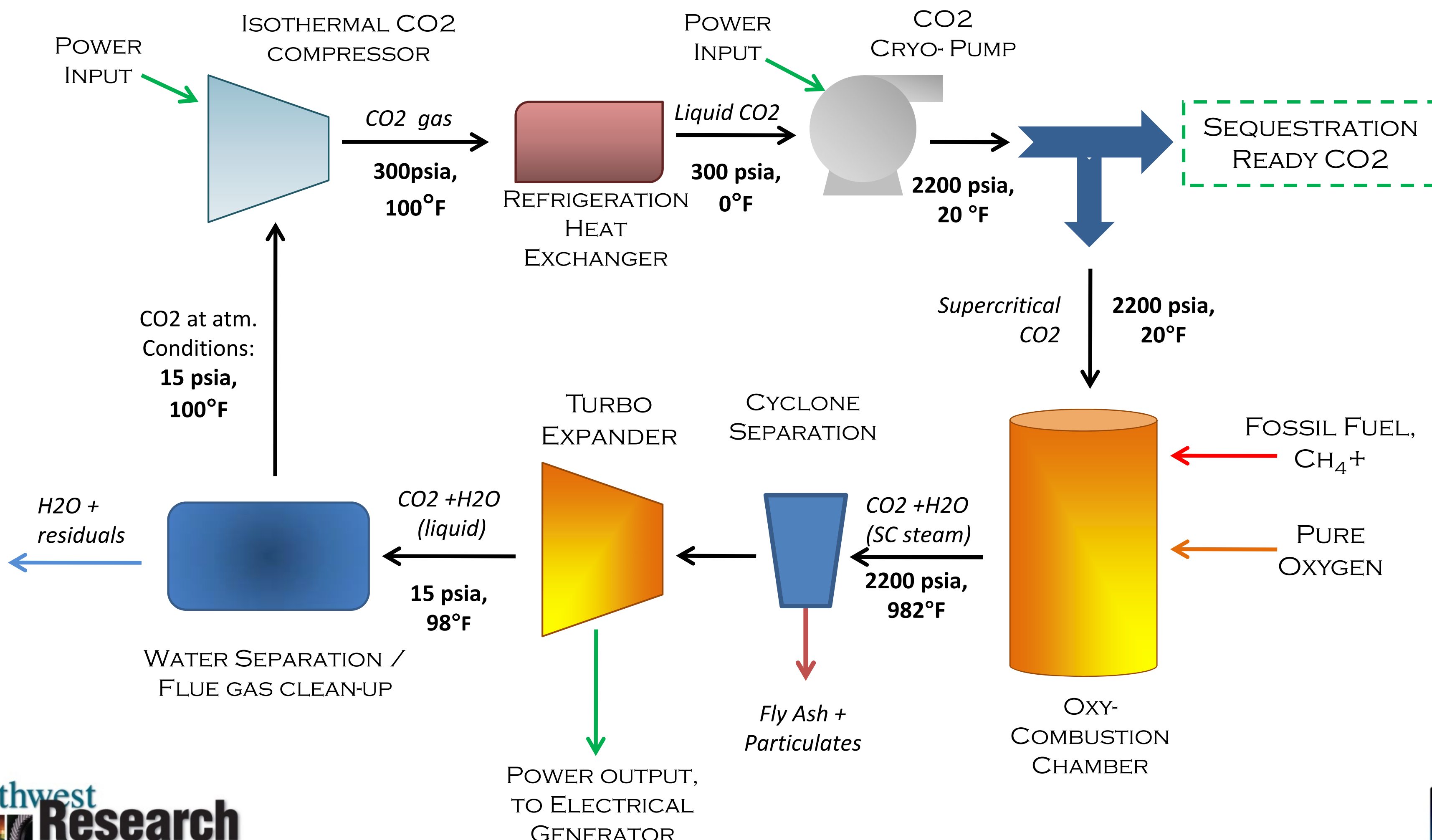
- Cycle evaluation based on:
  - Cycle and economic modeling to qualify cost and cycle performance
  - Technology gap assessment to identify critical low TRL components and technologies
  - Bench scale testing to back up cycle models and evaluate state of low TRL technologies

Project Technology Focus

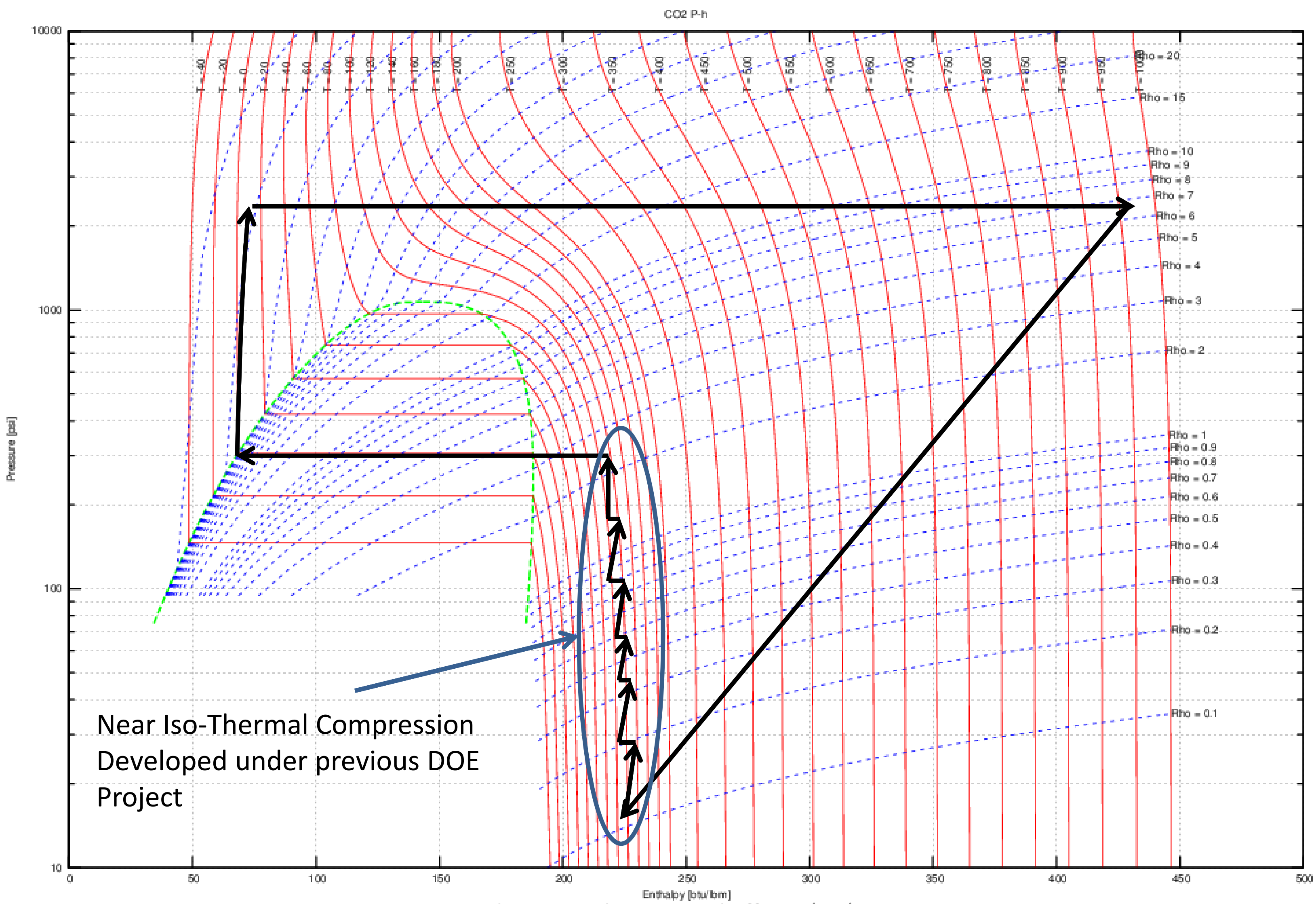
- Primary
  - Pressurized oxy-combustion
    - Negate need for CO_2 recompression
    - Increase combustion and cycle efficiencies
- Secondary
  - High-pressure and high-temperature cleanup technologies
    - Required to commercialize a sCO_2 oxy-combustion cycle
- Tertiary
  - High efficiency power cycle
    - Must be cost effective to be a viable commercial project

PROPOSED CYCLES

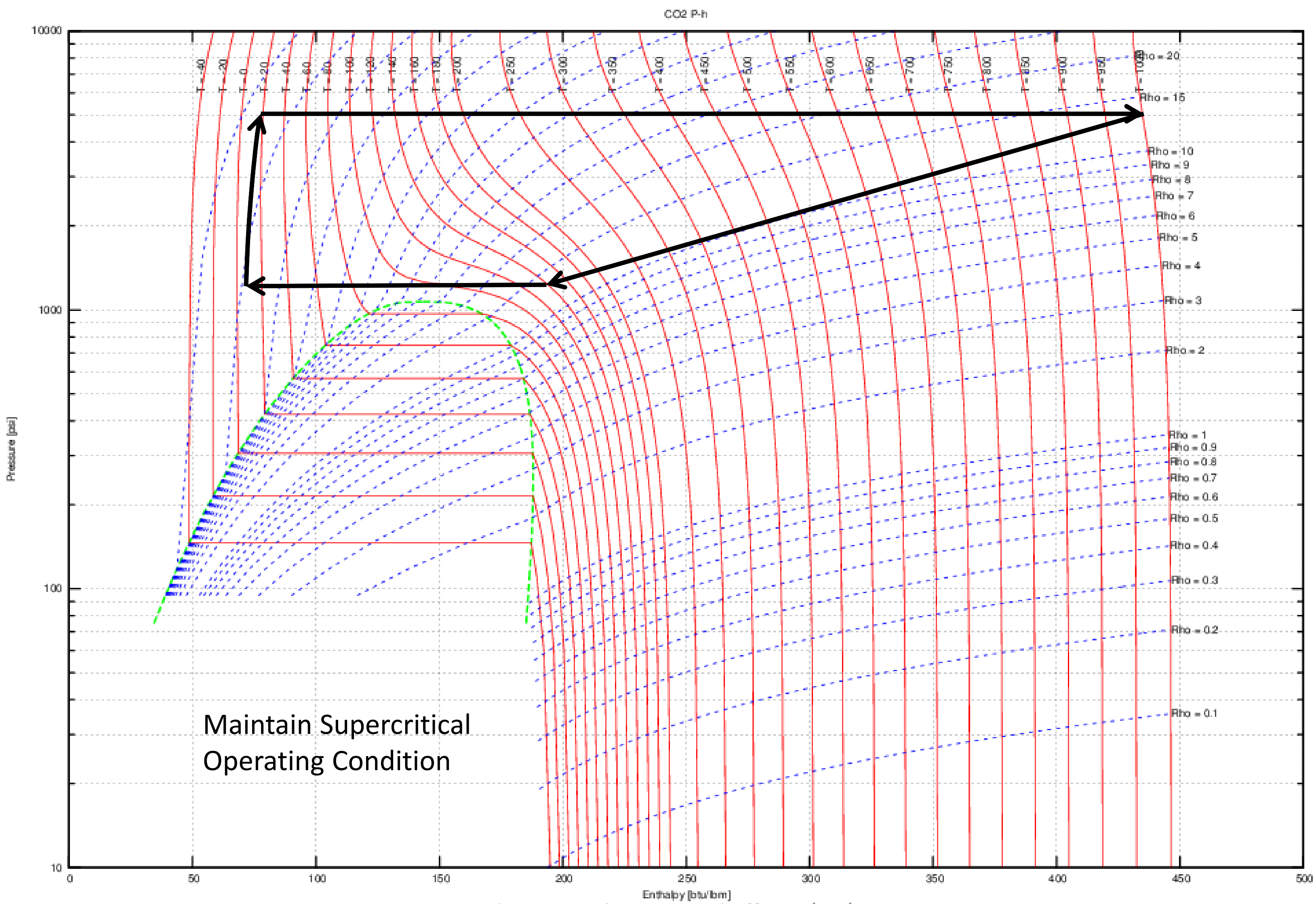
Original Concept:
Cryogenic Pressurized Oxy-Combustion Cycle (CPOC)



Original Concept: Single Loop CPOC



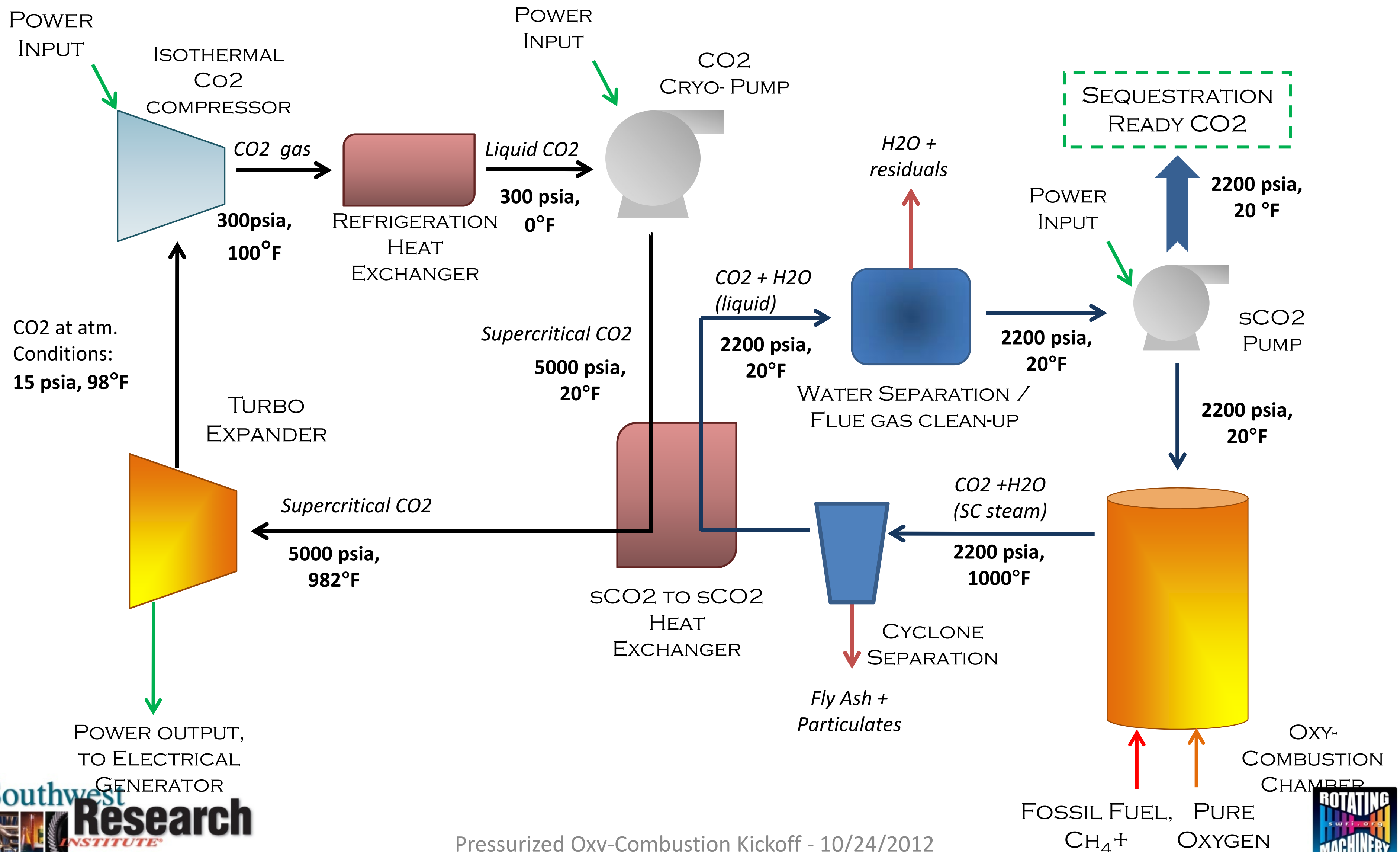
Original Concept: Variation



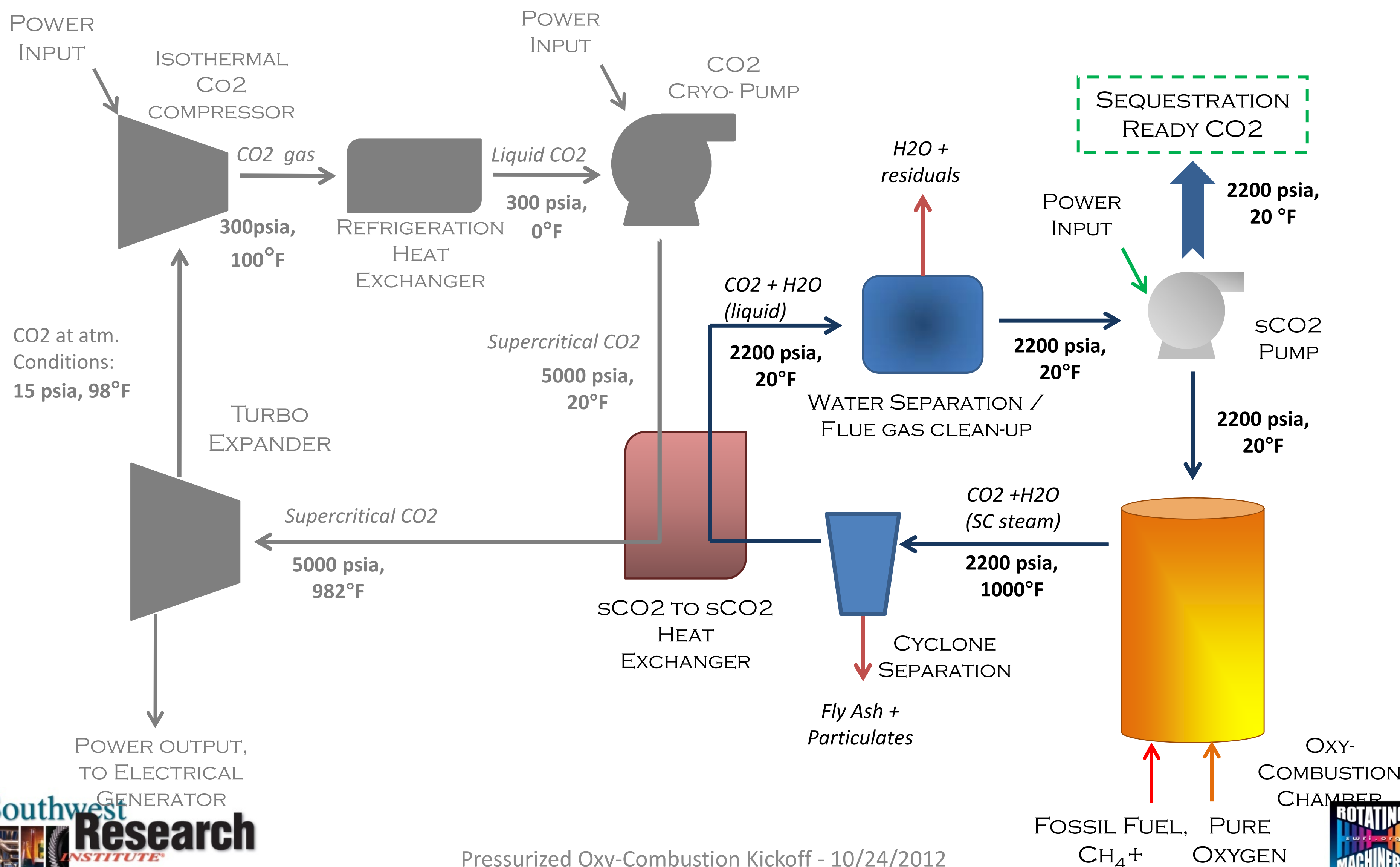
Challenges with the Original CPOC Concept

- Managing contaminants
  - Fly ash and particulates (erosion, clogging)
  - Heavy metals (corrosion)
  - Water (corrosion)
  - Gasses (expander performance, corrosion)
- Gas quality
  - Gas composition will vary with fuel and cleanup technology, equipment condition

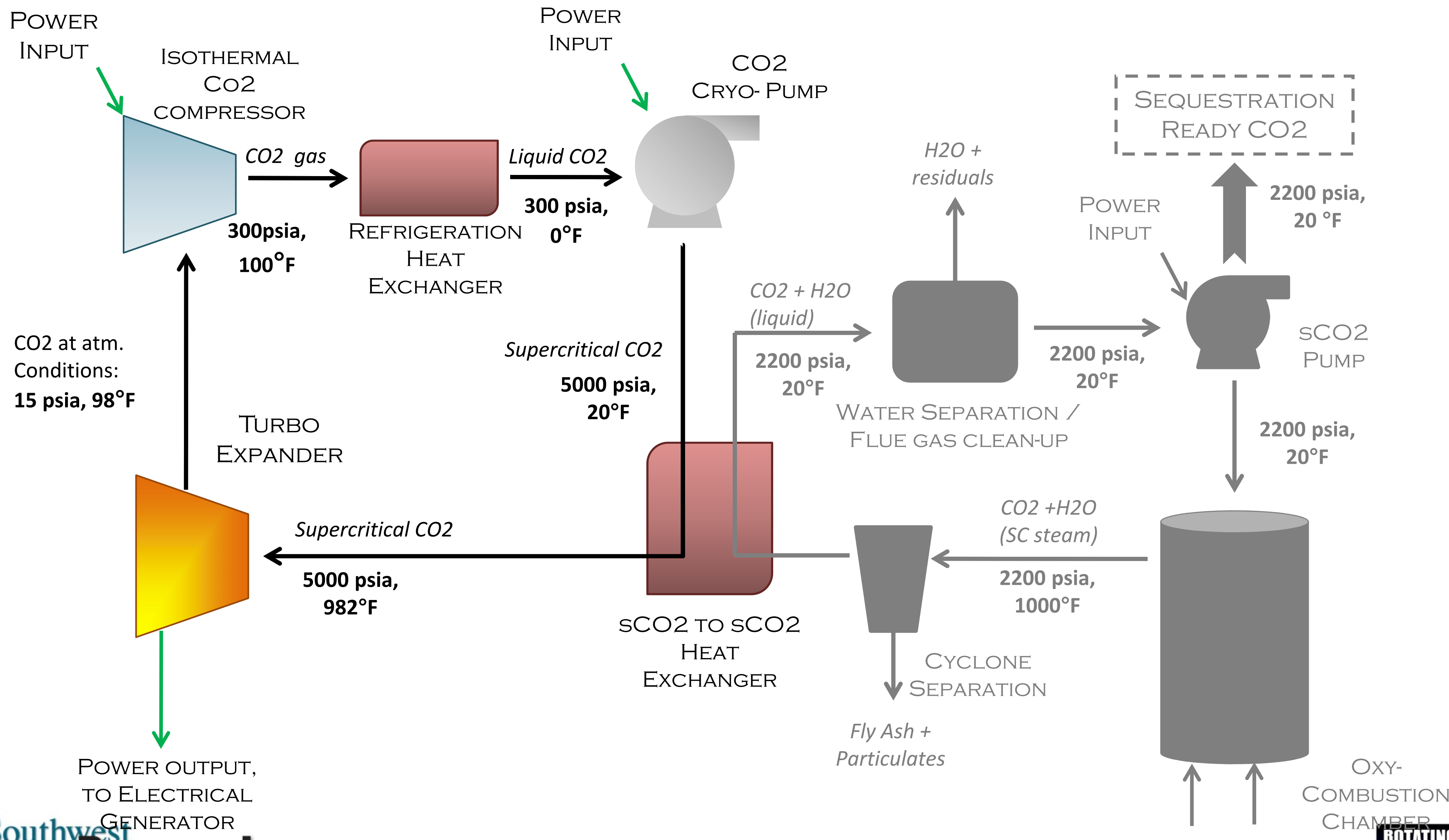
Dual Loop CPOC Concept



Combustion Loop



Power Loop



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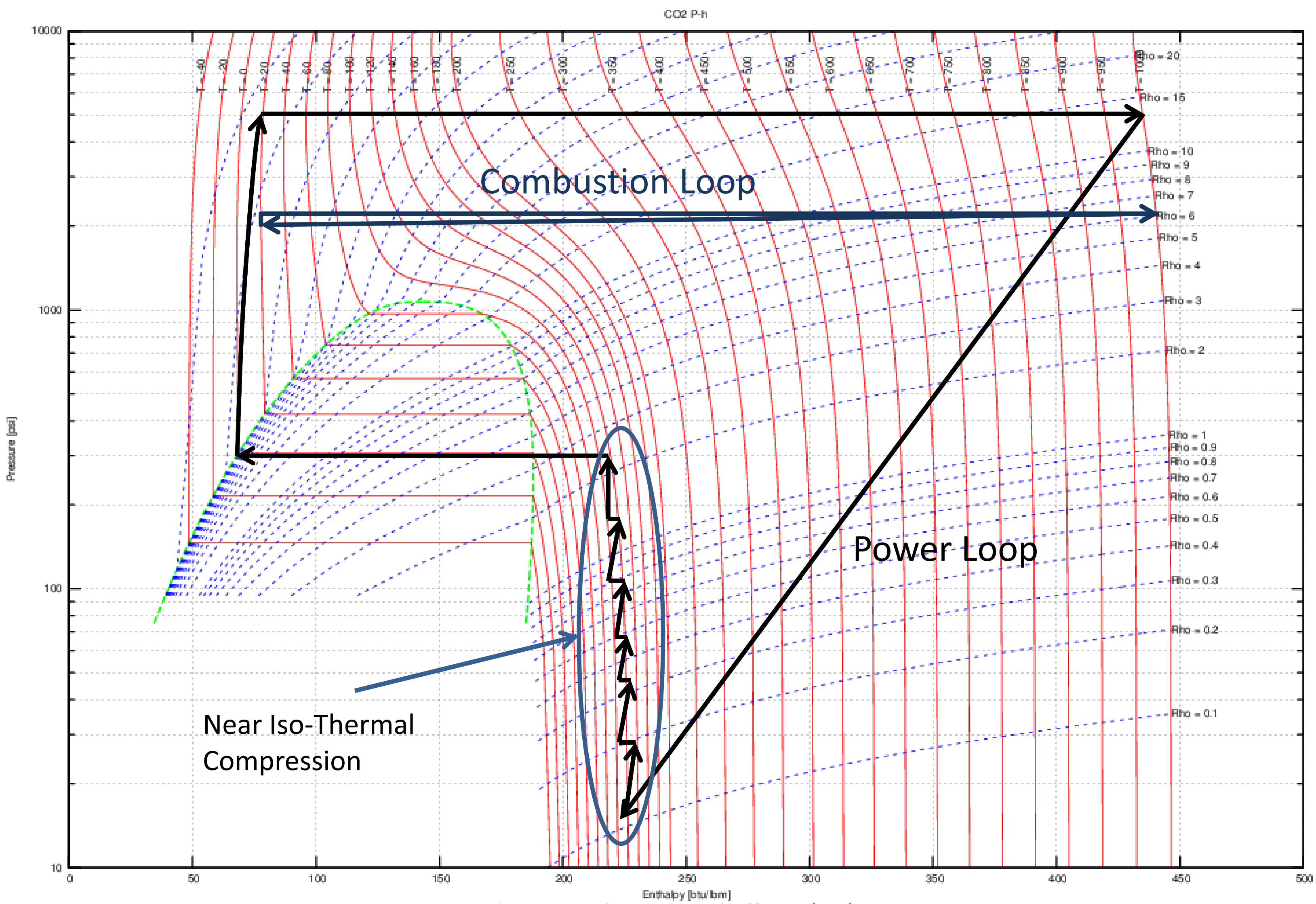
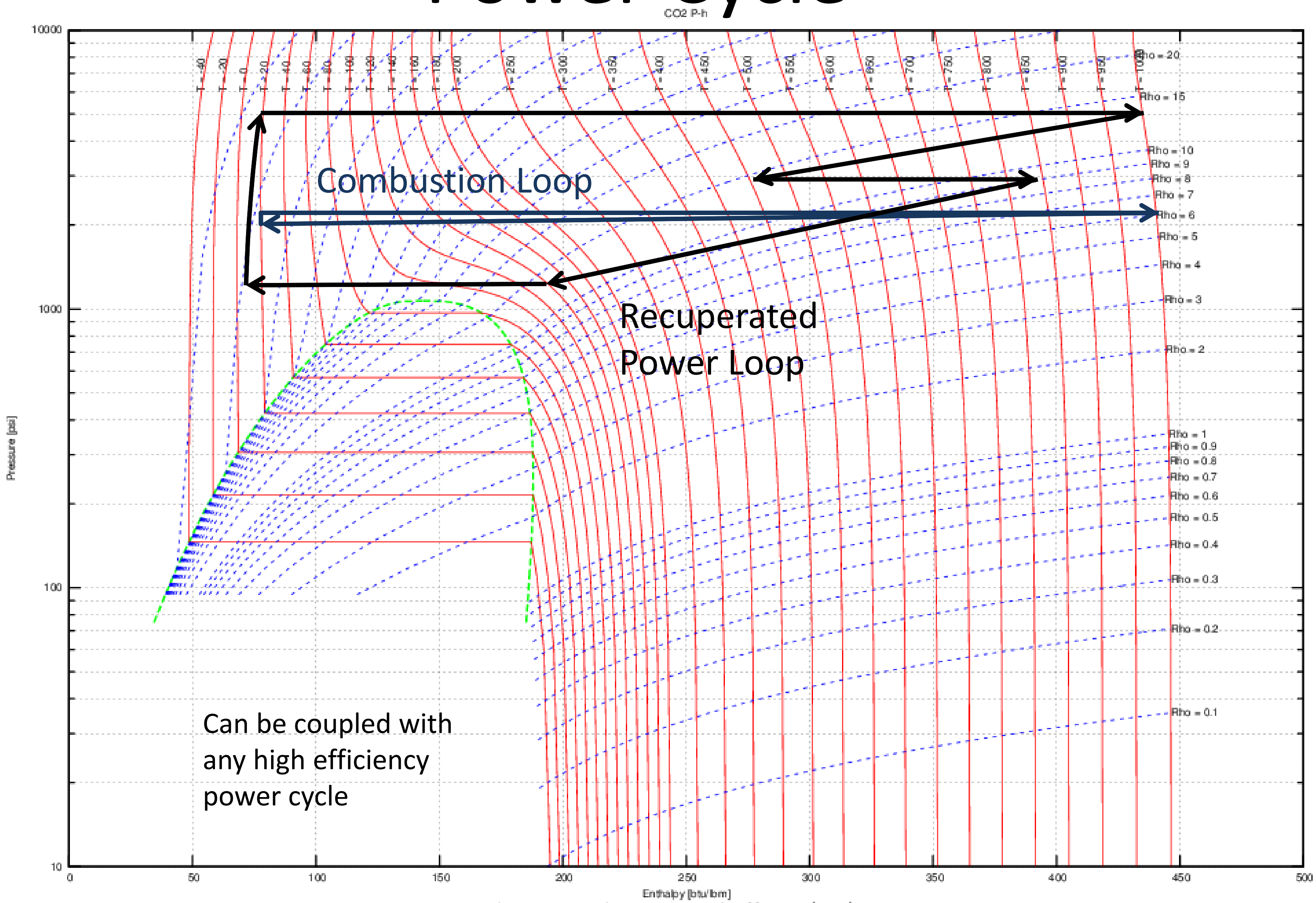
Rotating Machinery

Dual Loop CPOC Concept



Compatible with any High Efficiency Power Cycle



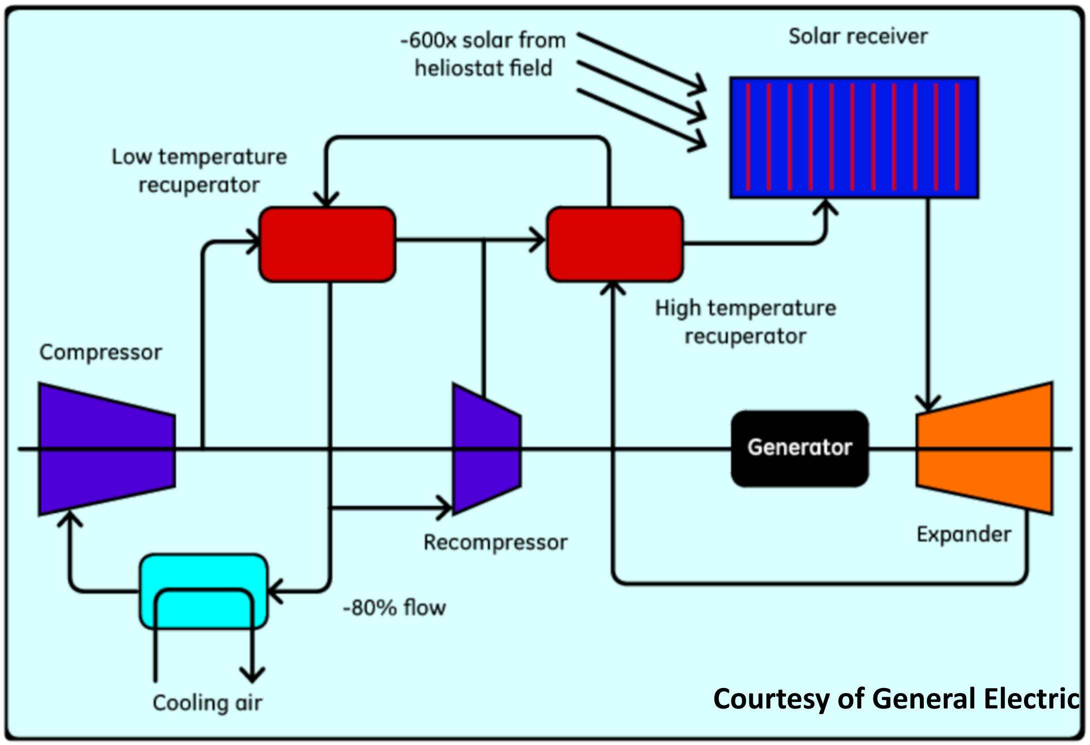
Advantage of Dual Loop Configuration

- Anticipated technology developments contained in the combustion loop
  - High pressure oxy-combustor
  - Cleanup (Fly-ash, Metals, Water, Gases) of supercritical CO2
- Power cycle is *tertiary* for this project
  - Any power cycle can be integrated into dual loop configuration with minimal modification
  - Technology enhancements can be re-integrated into a single loop configuration down the line

Configuration can utilize *any* advanced power cycle

Example: High Efficiency sCO2 Power Cycle

GE double recuperated sCO2 power cycle developed for solar applications, greater than 50% efficiency for 650°C receiver temperature

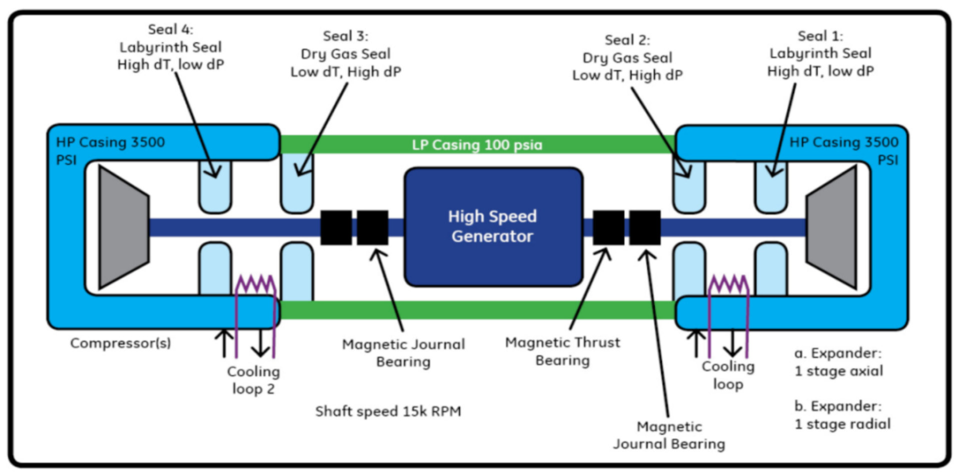


Leverage DOE SunShot sCO2 power cycle investment

LEVERAGED PROGRAMS

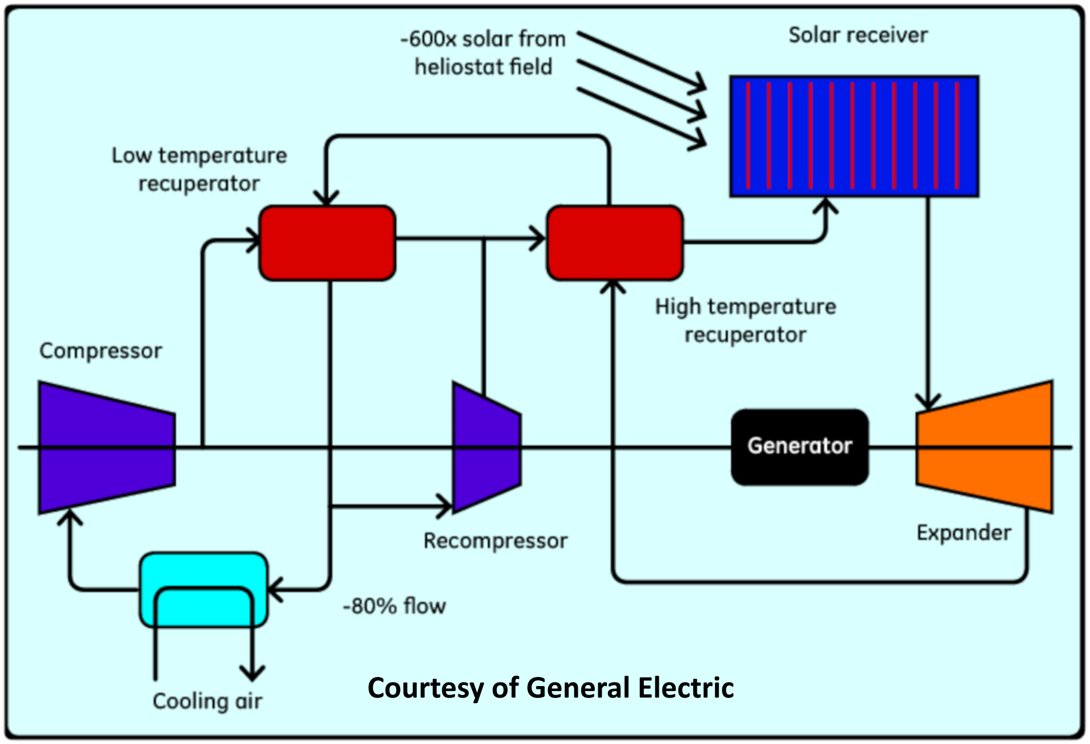
SunShot DE-EE0005804: Supercritical Carbon Dioxide Turbo-Expander and Heat Exchangers

- Supercritical CO2 power cycle for a modular solar power block
- Develop and demonstrate
  - 1-MWe high efficiency sCO2 turbo-expander
  - A novel high efficiency, low cost heat exchanger technology



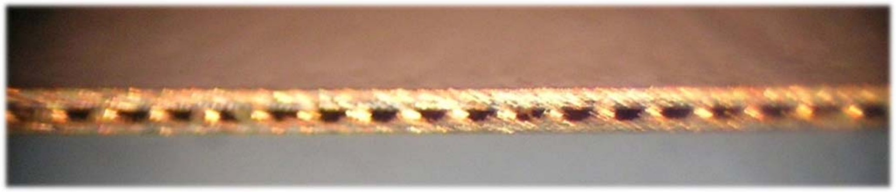
SunShot DE-EE0005804: High Efficiency sCO2 Power Cycle

- Focused on turbo-expander development
- To meet DOE performance target of greater than 50% efficiency, the turbo-expander must operate near or above 280 bar (4061 psi) and 685°C (1265°F) and have low mechanical/aero losses.

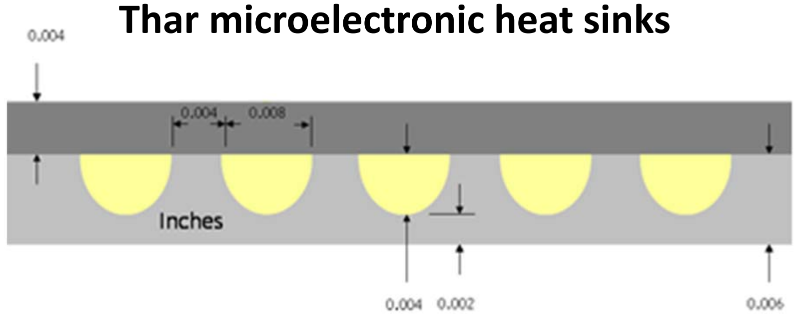


Courtesy of General Electric

SunShot DE-EE0005804: Printed Circuit Heat Exchangers



Thar microelectronic heat sinks

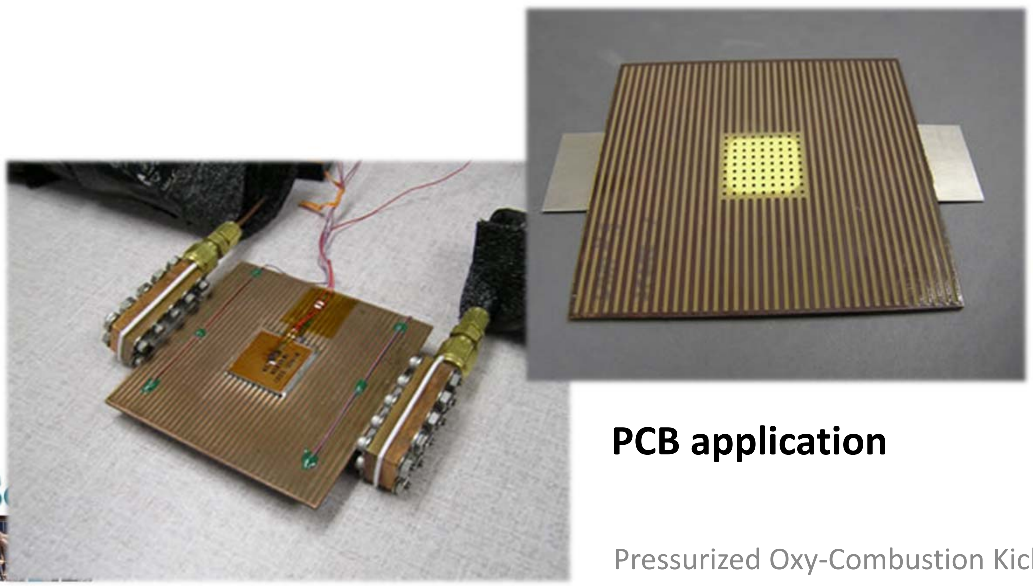


Process

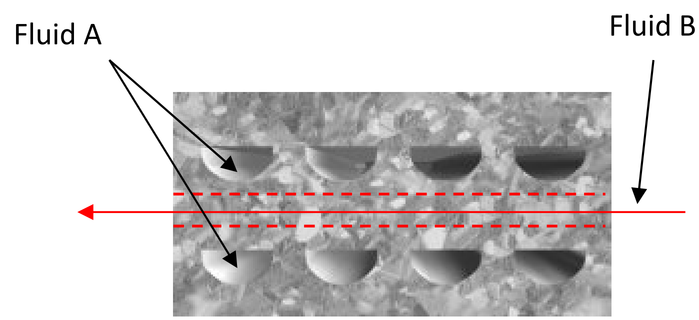
- Etch one layer
- Cover with unetched plate
- Diffusion bond stacked plates
  - Proven technique
  - Obey dimension rules to prevent channel flooding

Characteristics

- Channels as small as 100 microns
- Novel header design to achieve countercurrent flow



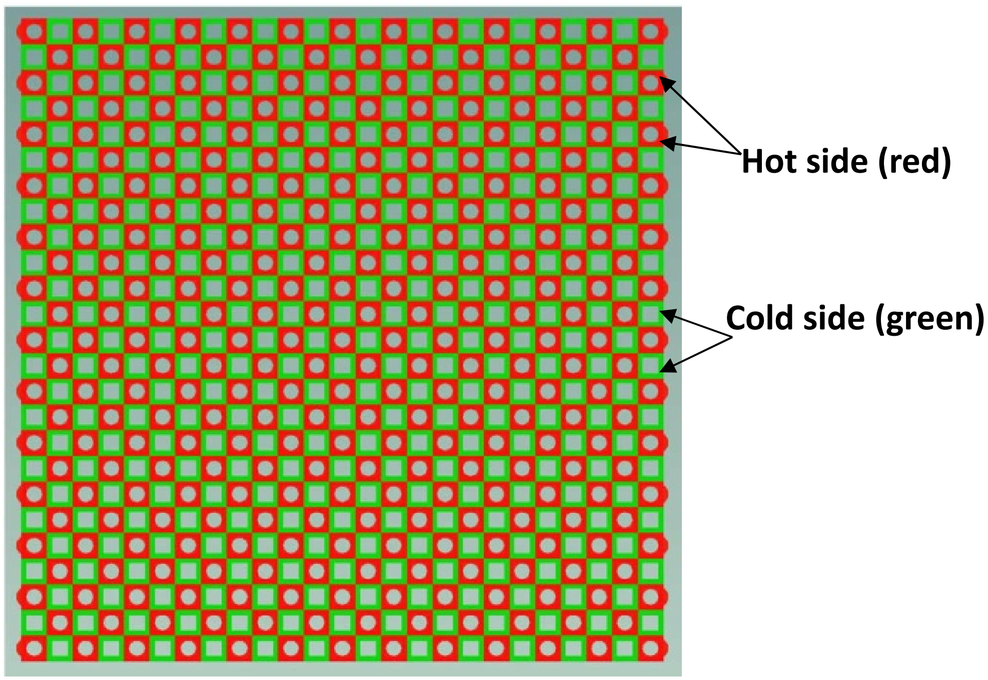
PCB application



Heatric – stacked layers, ***fluids in cross flow***

SunShot DE-EE0005804: Advanced Concepts: Built-Up Metal Powder Heat Exchangers

Checkerboard (alternating vertical & horizontal channels) concept



Process

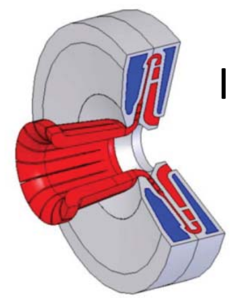
- Direct metal laser sintering
  …highly automated
- Inconel capable

Characteristics

- Walls as thin as 0.3 mm
- Suited to counter-flow
  …novel header design
- Can incorporate sealed chambers, curved contour, other unusual features

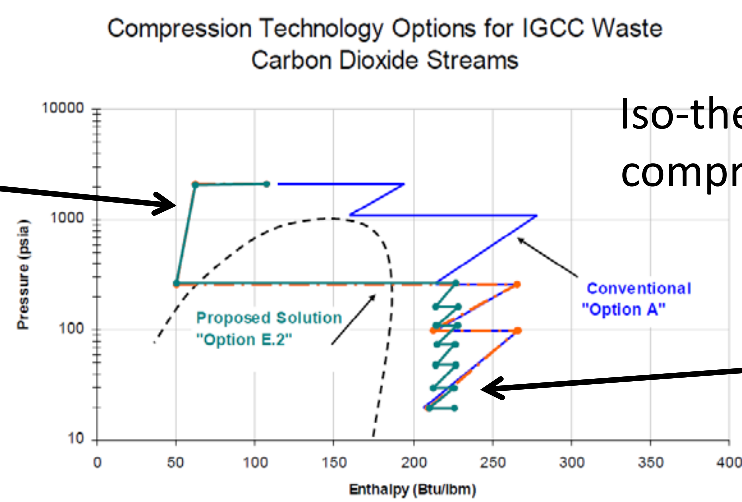
Novel Concepts for the Compression of Large Volumes of CO2

- Efficient compression of CO2 for capture and sequestration
  - Phase 1 – Evaluation
  - Phase 2 – Design and Pilot Test
  - Phase 3 – Demonstration

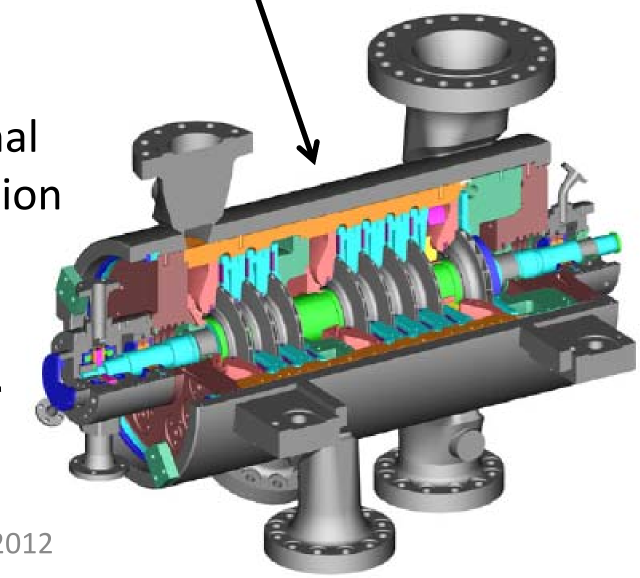


Internally cooled diaphragm

Cryogenic pumping



Iso-thermal compression



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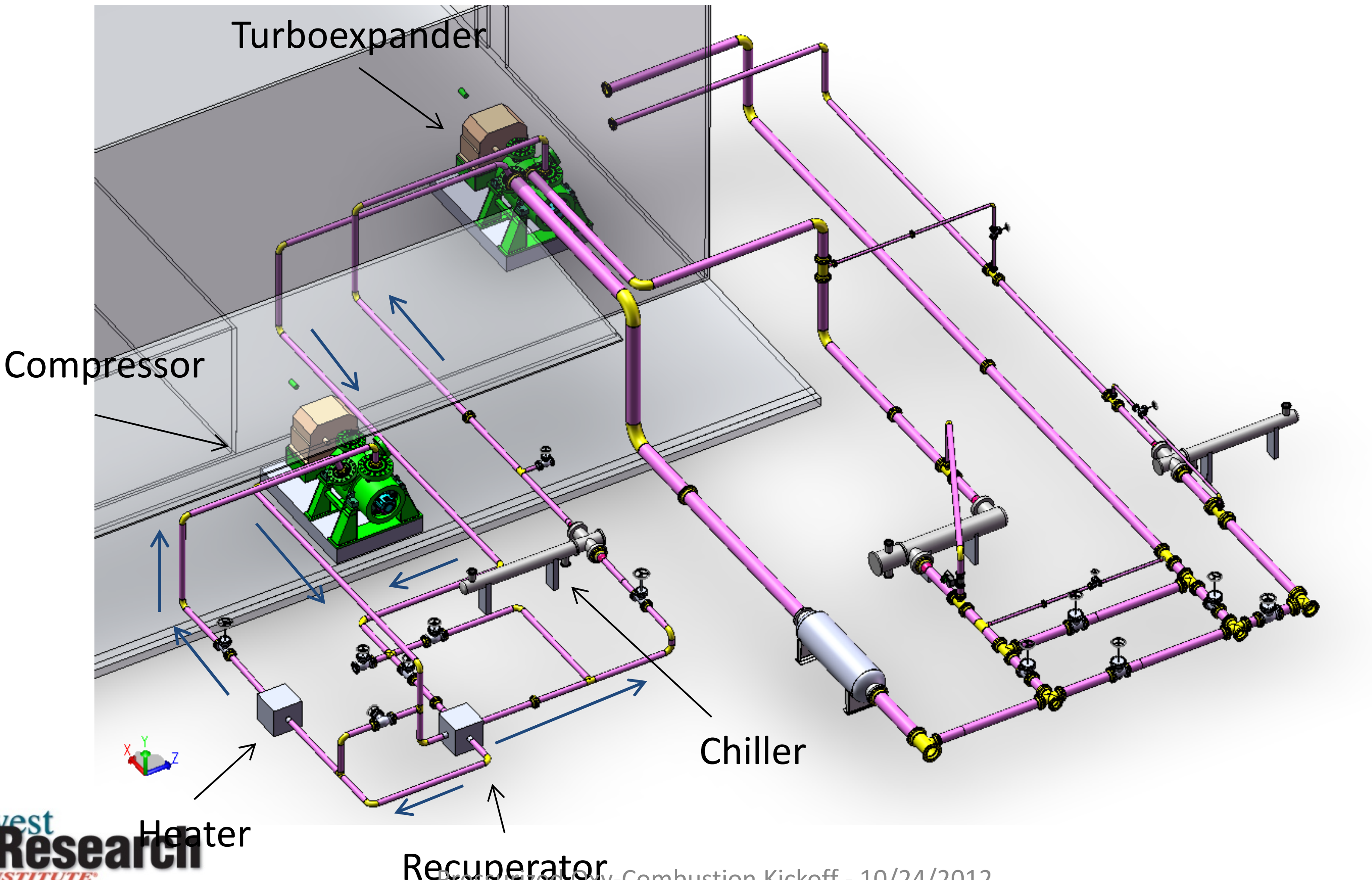
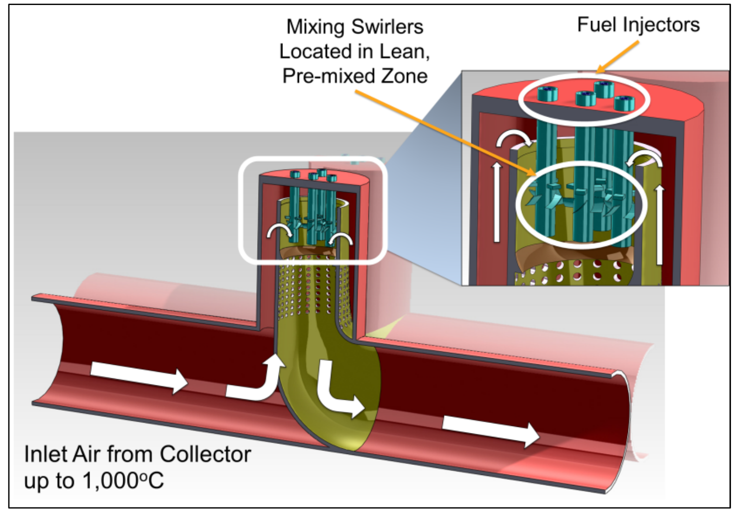
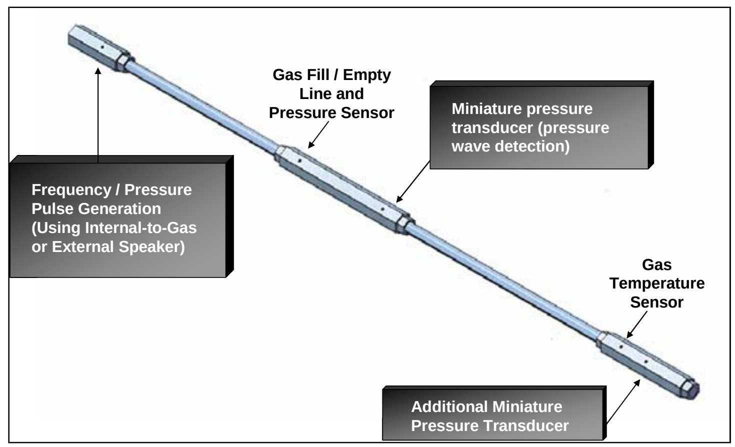
Pressurized Closed Loop CO2 Test Facility



Other programs

- CSP Tower Air Brayton Combustor, SunShot DE-EE0005805
  - High inlet temperature (1000°C) combustor development and demonstration
- Great Horned Owl (IARPA)
  - Combustion turbine for hybrid aerospace propulsion
- Fundamental Gas Property Testing (DOE, MHI, GE, Dresser-Rand)
  - Fundamental gas property tests for CO2 mixtures, falling outside of typical EOS model limits: speed of sound, specific heat, and density up to 15,000 psi, 400 degF

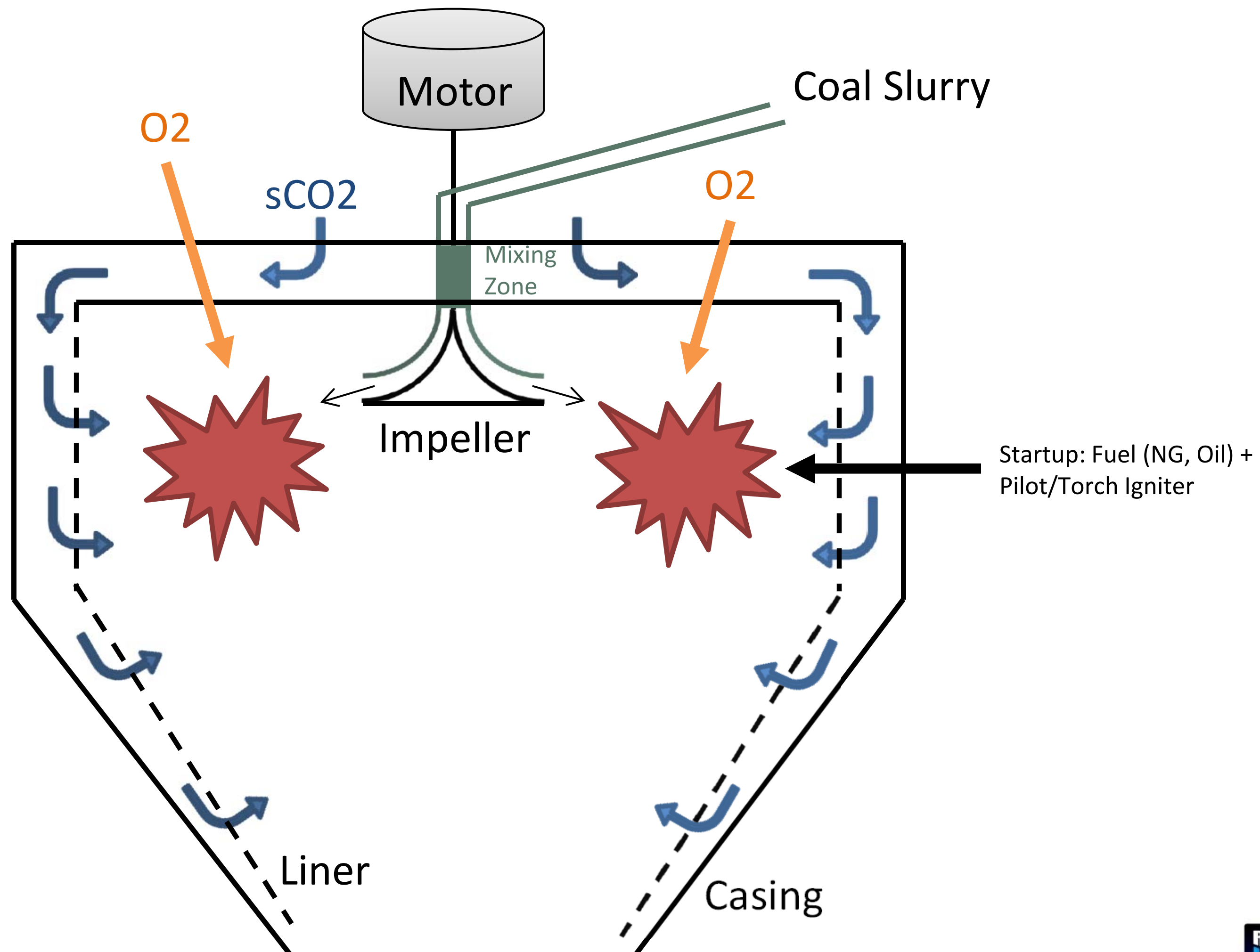




Previous SwRI Coal Combustion and Oxy-Combustor Efforts

- 1980s – Coal slurry development for combustion bombs and transportation fuel
- 2010 – Optimization of a novel oxy-combustion swirl burner
- 30+ industry projects related to IGCC, Gasification, and Coal Combustion

SwRI Oxy-Combustor Concept



Combustor Features

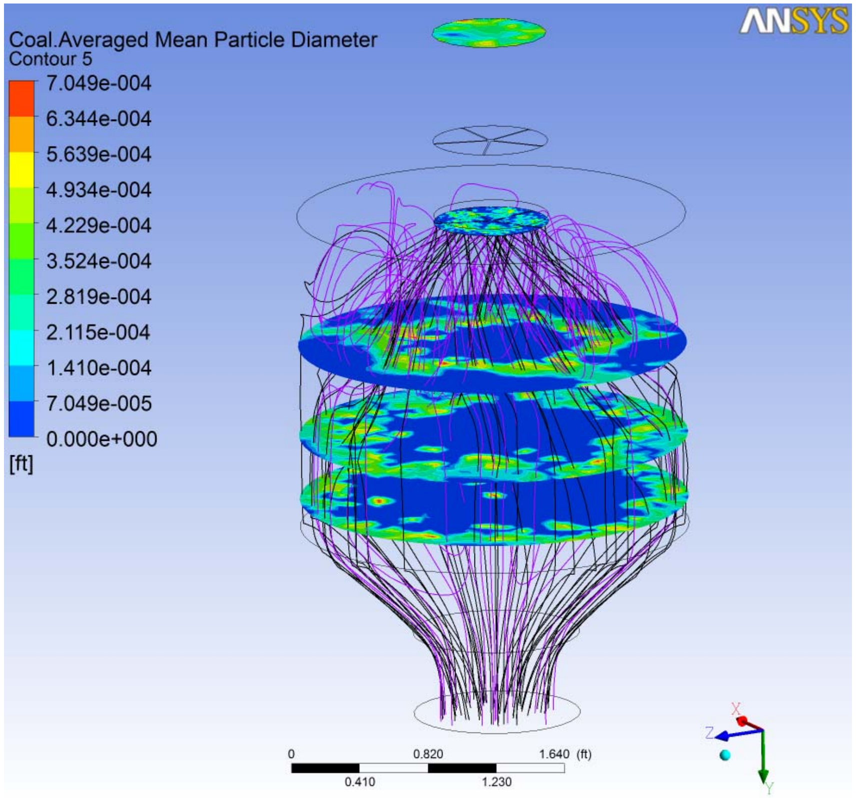
- Pulverized coal + water slurry
  - Recycle water from combustion loop cleanup
  - Water provides flame temperature control
- Rotating impeller fuel injector
  - Optimize shear-mixing of slurry, CO_2, and O_2
  - Controlled fuel injection rate through impeller, O_2 injection controls flame position
- CO_2 cooled liner
  - Flame position, diffusion, and dilution control
  - Flame centering
  - Wall temperature buffering

Fundamental Challenge: Combustor Temperature Control

- Oxy-coal stoichiometric flame temperature exceeds 3000^{o}C, well above acceptable material limits
- Must operate bulk stoichiometric in closed loop mode to maintain constituent balance
- Should keep flame temperature below 1000^{o}C to avoid slag formation and fouling
- Flame temperature control can utilize:
  - Slurry water fraction
  - Premixing of oxygen with CO2 as a diluent
  - Direct injection of CO2 jet into flame for further dilution

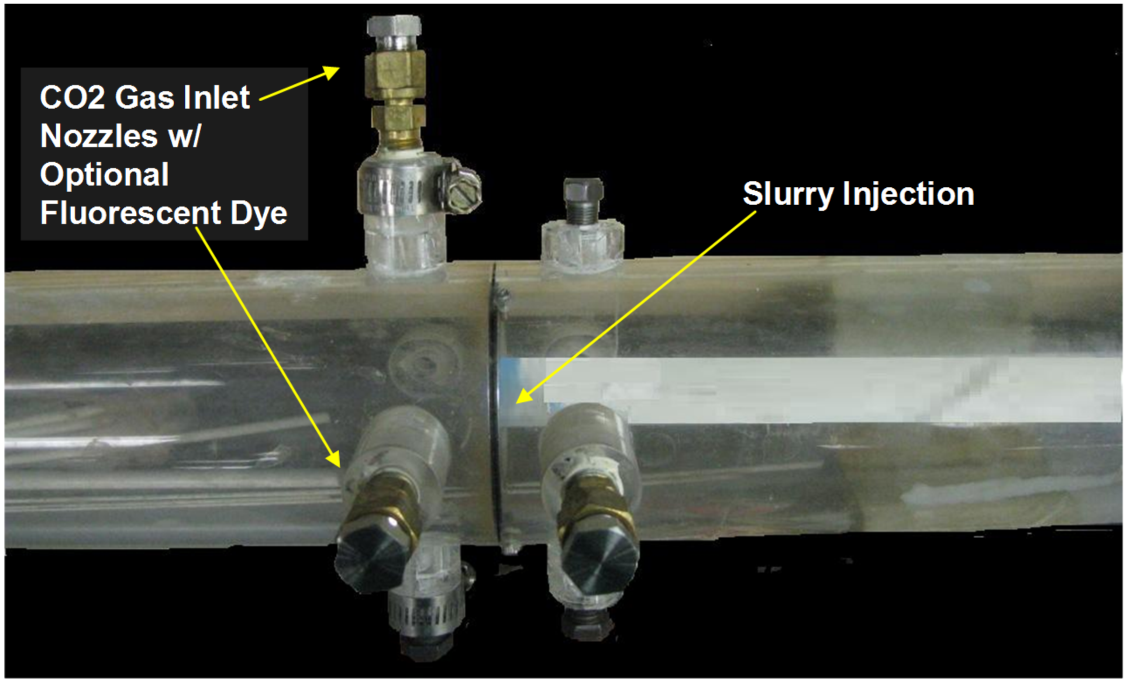
Previous Work: Swirl Oxy-Combustor Optimization

- Particulate mixing
  - Bench Test
- Combustion properties
  - Bench Test
- Combustion chamber optimization w/ inlet swirler
  - CFD
- Materials
  - Stainless Casing + liner
  - Ceramic liner/Refractory bricks
  - Hi Ni-alloy injector



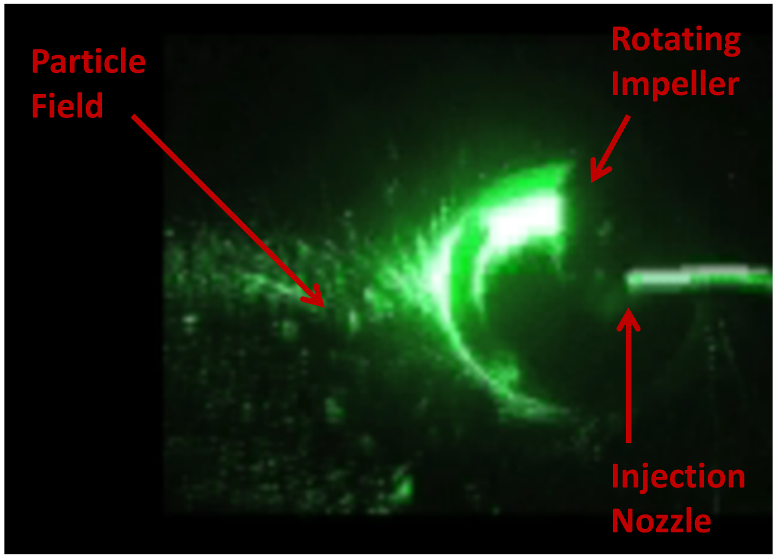
Previous Work: Slurry Mixing

- Flow visualization of coal particle injection and mixing



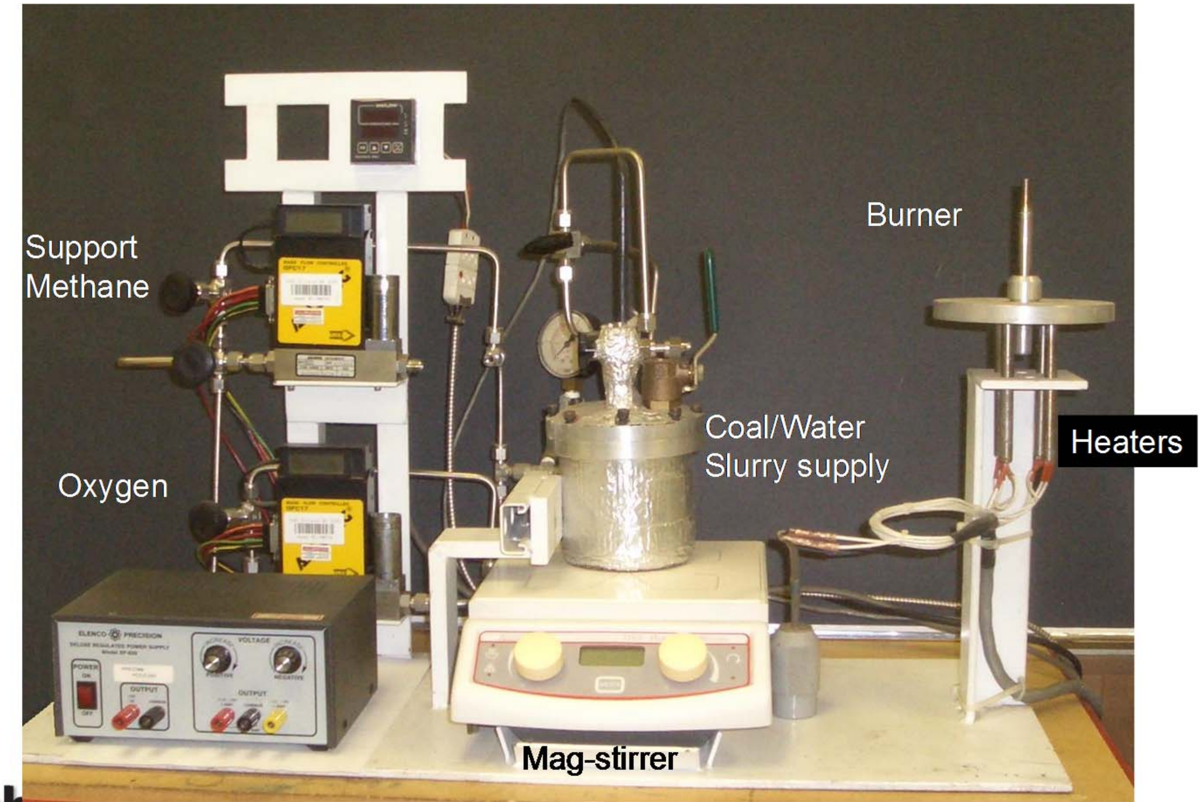
Previous Work:
Swirler Visualization

- Examine particle trajectories for coal particles and slurry for different impeller configurations and speeds

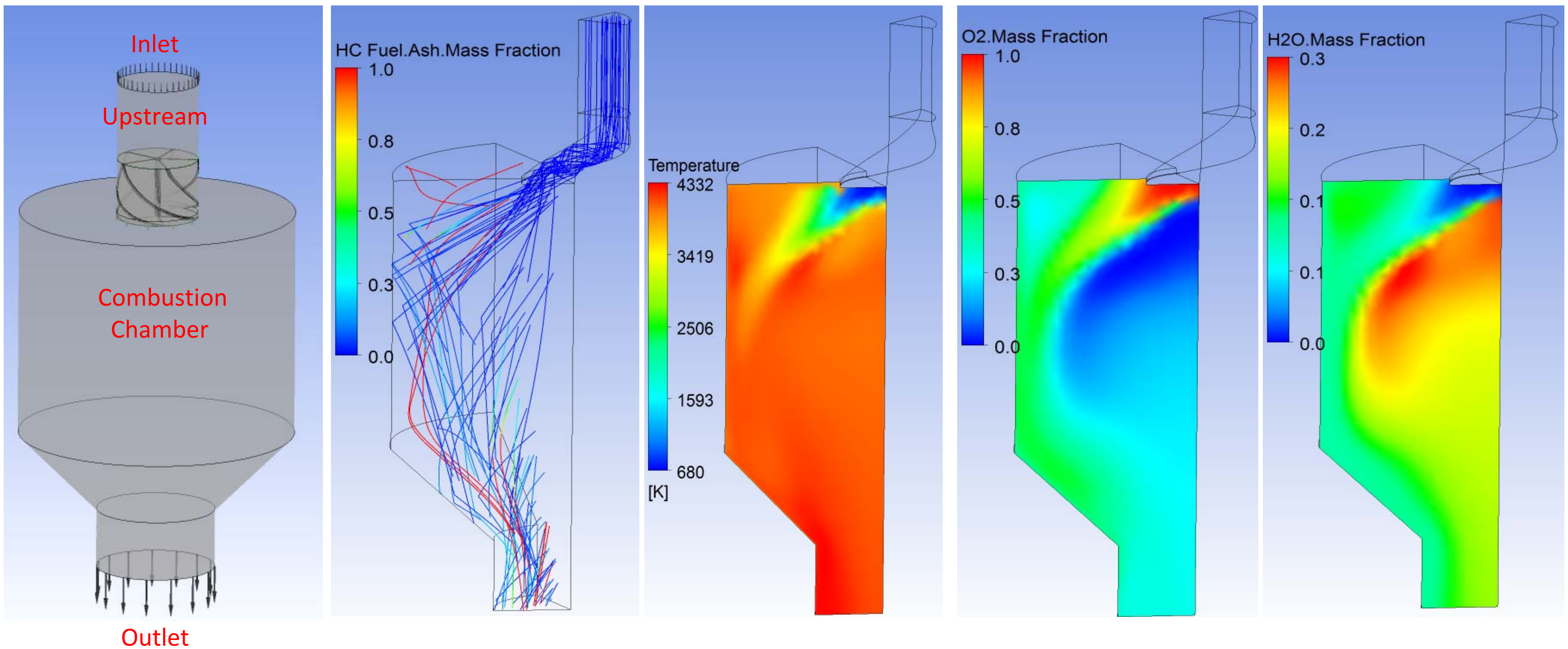


Previous Work: Bench-Top Oxy-Combustion Burner

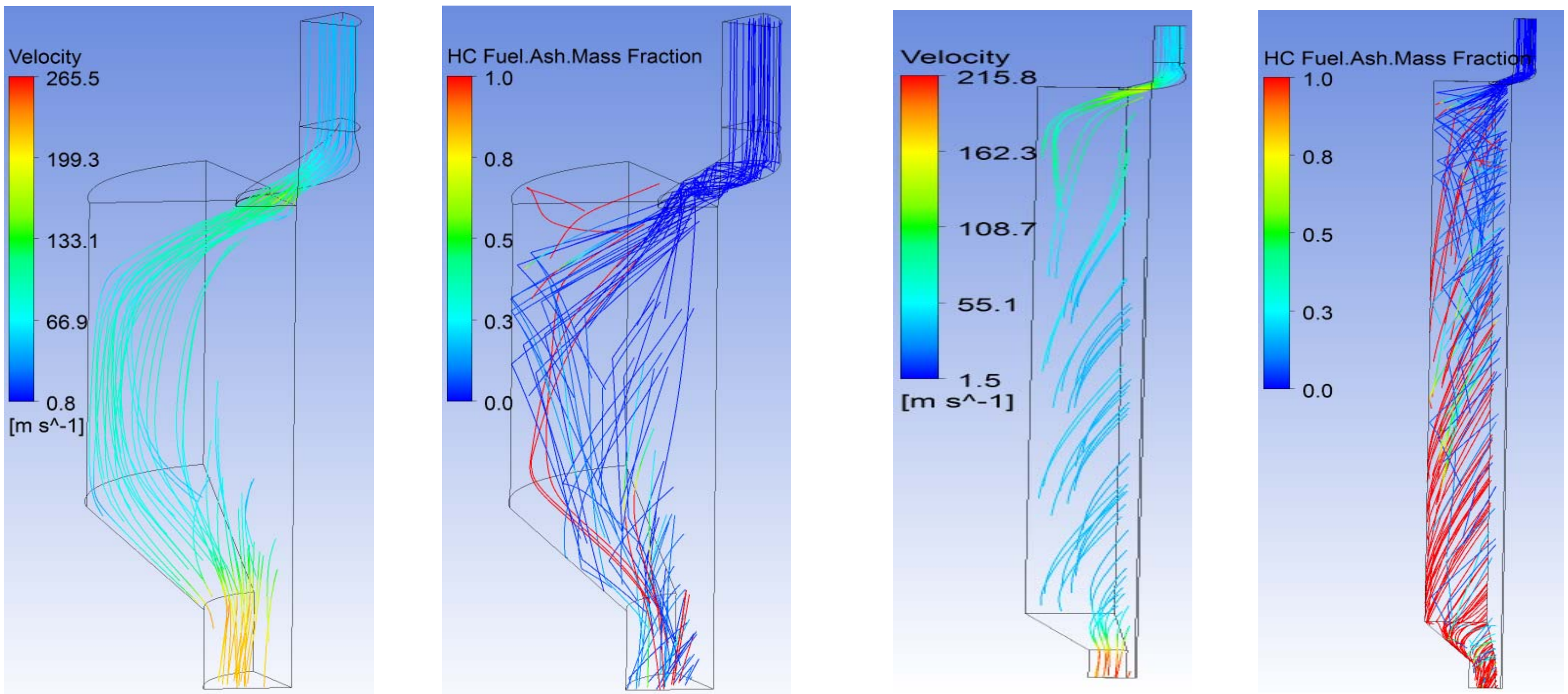
- Combustion property testing of slurry mixtures



Previous Work:
Combustor Optimization



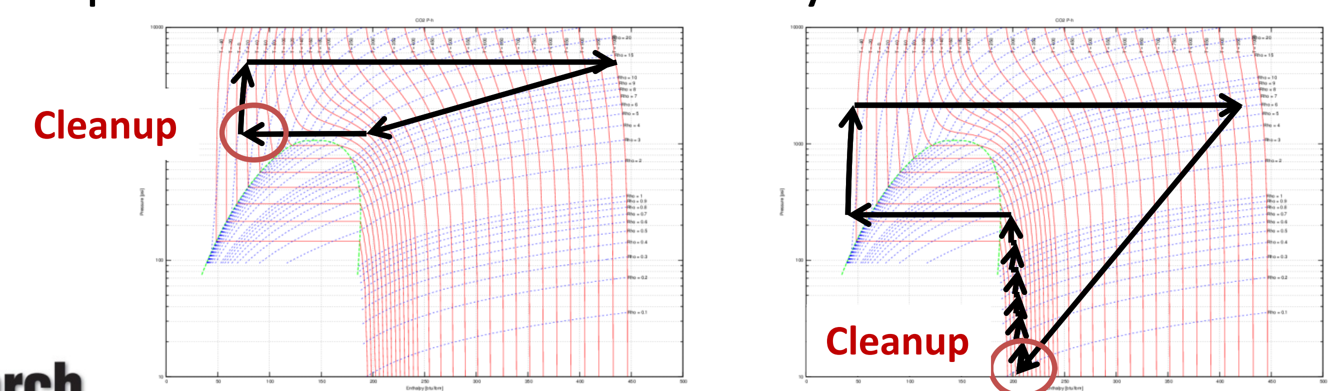
Previous Work: Change in Residence Time with Change in Geometry



TECHNOLOGY GAPS AND CHALLENGES

Technology Focus Areas

- High Pressure Oxy-combustor
  - Stable and complete combustion
  - Flame temperature control
  - Secondary systems (fuel injection and mixing)
- Clean up and separation technologies for supercritical CO_2
  - Cleanup technologies will likely constrain pressure and temperature conditions in the cycle



Proposed Pressurized Oxy-Combustor Developments

- Combustor type selection
  - Swirl, fluidized bed
  - Fuel/air mixing
  - Flame front control
  - Stoichiometric flame temperature control
  - Combustion stability
  - Fuel residence for complete combustion
- Fuel Injection at high Pressure
  - Dry vs. Slurry
  - Slurry mixing
  - Slurry stabilization
  - Injector design
- Combustor Materials Selection
  - Moderate Temperature
  - High Pressure
  - Corrosion Resistant
  - Cooling Stream

Proposed Cleanup Developments

- Fly-ash
  - Upstream of expander or heat exchanger
  - Withstand high Pressure and Temperature
  - Minimize heat loss
  - Minimize slagging
- Water separation
  - Water solubility in sCO2?
  - Influence of Temperature (fall out in HX or expander)
- Metals removal (Ar, Hg, …)
  - Can it be done at high T and P?
- Gas removal (SO2, …)
  - Removal of gas vapor at high T and P (state, solubility)

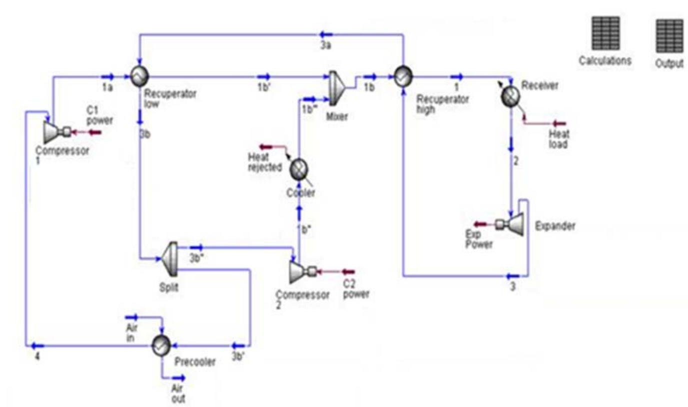
Proposed Bench Scale Testing

- Focus on component technologies
  - Fuel injection
  - Fuel mixing
  - Water solubility in CO_2
- Small scale combustion
  - Combustion properties at Pressure
- Evaluate separation techniques as available
  - Cyclone separation at elevated Pressure

ECONOMIC AND CYCLE ANALYSIS

Method: Cycle Model

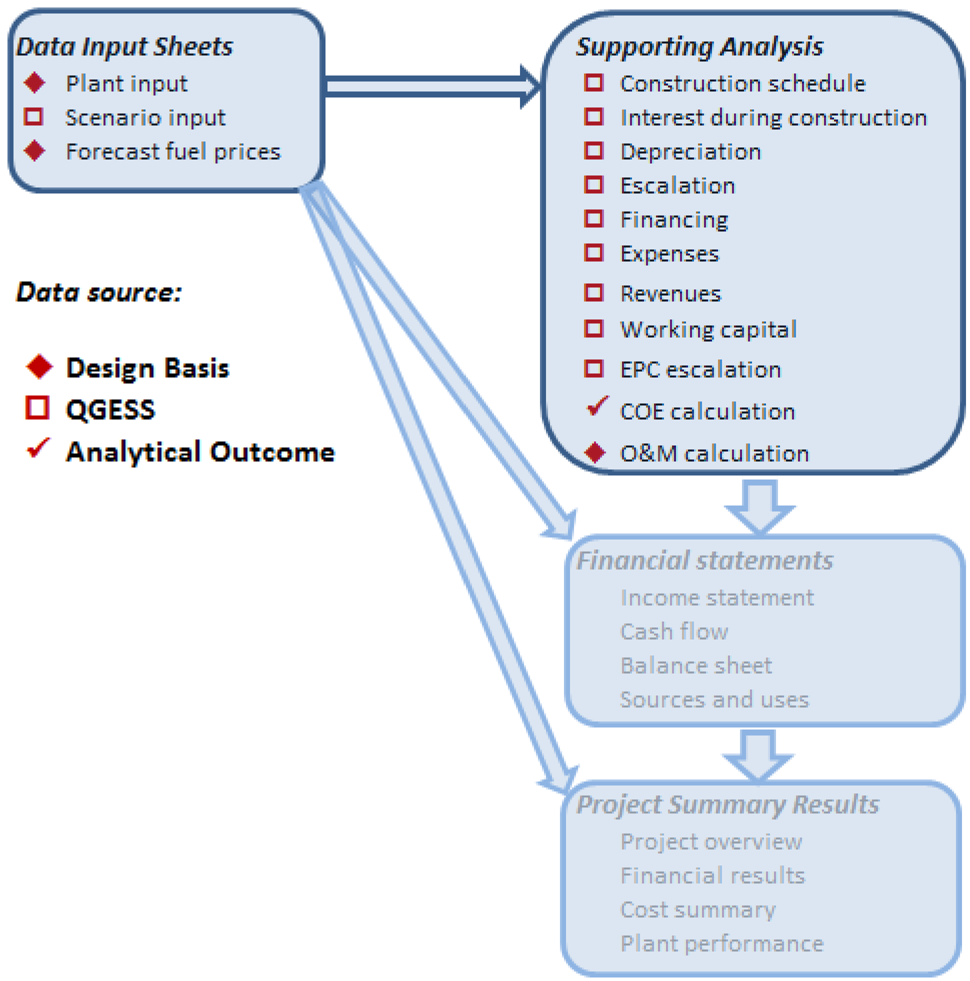
- Full Cycle Model using Aspen HYSYS
  - Mature component specifications from vendor or QGESS Process Modeling Design Parameters
  - Low TRL component data from bench test or literature



Courtesy of General Electric

Method: Economic Model

Process Systems Financial Model



Method: Economic Model

- Items set by Design Basis
  - Plant location and ambient conditions
  - Plant capacity, op rate and sparing assumptions
  - Labor rates and policies
  - Fuel type (one of three choices)
    - Illinois No. 6 bituminous
    - Rosebud sub-bituminous
    - Texas lignite

Method: Economic Model

Relative amounts of contaminants

Property	Illinois No. 6 Bituminous	Rosebud PRS Sub-bituminous	Texas lignite Low Na lignite
Ash	Moderate	Moderate	High
Sulfur	High	Low	Low
Moisture	Low	Moderate	High
Nitrogen	Moderate	Low	Low
Chlorine	Low	Nil	Nil
Heavy Metals	Moderate	Low	Moderate

For detail see Exhibit 1-2, QGESS Specifications for Selected Feedstocks

Method: Economic Model

- Other Design Basis Requirements
  - Financial structure in accordance with *high-risk Investor-Owned Utility (IOU)*
  - Five-year capital expenditure period
  - Adherence to guidelines in *Quality Guidelines for Energy Systems Studies*:
    - Estimated owner's costs from Table 3
    - Estimated global economic assumptions from Table 4

Method: Technology Gap Assessment

- Set cycle conditions and flow scheme, then
  - Spec components
  - Investigate available equipment and assess capability and cost
    - Identify technology gaps
  - Literature/patent screening of gap technologies
    - Assess freedom-to-operate
    - Assess IP opportunities
  - Propose innovative remedies

Method: Technology Gap Assessment

- Assess Tech Readiness Levels
  - Needed for Phase 2 planning
  - Document developmental needs for any technology not meeting at least TRL 3 (Critical Function or Proof-of- Concept established)
- Benchmark against NETL CO_2 Capture Roadmap
  - Feasibility of meeting 2016 target (0.5-5 MW plant)
  - Feasibility of meeting 2020 target (~25 MW demo)

PROJECT PROGRAMMATIC DETAILS

Status of Participants

- SwRI
  - DOE Contract in place
  - Finalizing sub-contract with Thar
  - Preparing Engineering Design Basis Report
  - Revising PMP and Risk Management Plan
- Thar
  - Finalizing sub-contract with SwRI
  - Contributing to Engineering Design Basis Report

Personnel

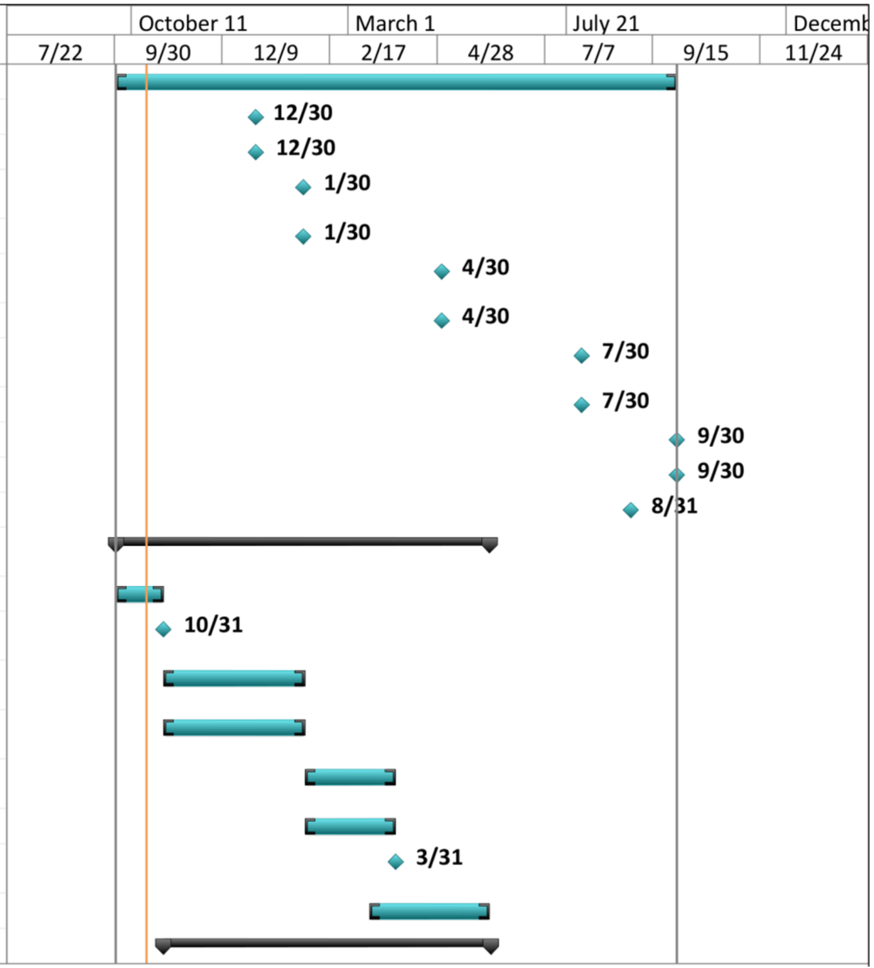
- SwRI
  - Aaron McClung , Ph.D. (PM)
  - Klaus Brun , Ph.D.
  - Thomas Chirathadam, Ph.D.
  - Shane Coogan
- Thar
  - Lalit Chordia, Ph.D.
  - John Davis

Project Tasks

Tasks	SwRI	Thar
Engineering design and economic analysis		
Cycle model definition	40%	60%
Economic model	0%	100%
Revised cycle model	75%	25%
Cycle optimization	76%	24%
Technology gap analysis		
Critical component ID	38%	63%
Critical component TRL	13%	88%
Development requirements	17%	83%
Bench Scale Testing		
Critical component ID and Testing	100%	0%

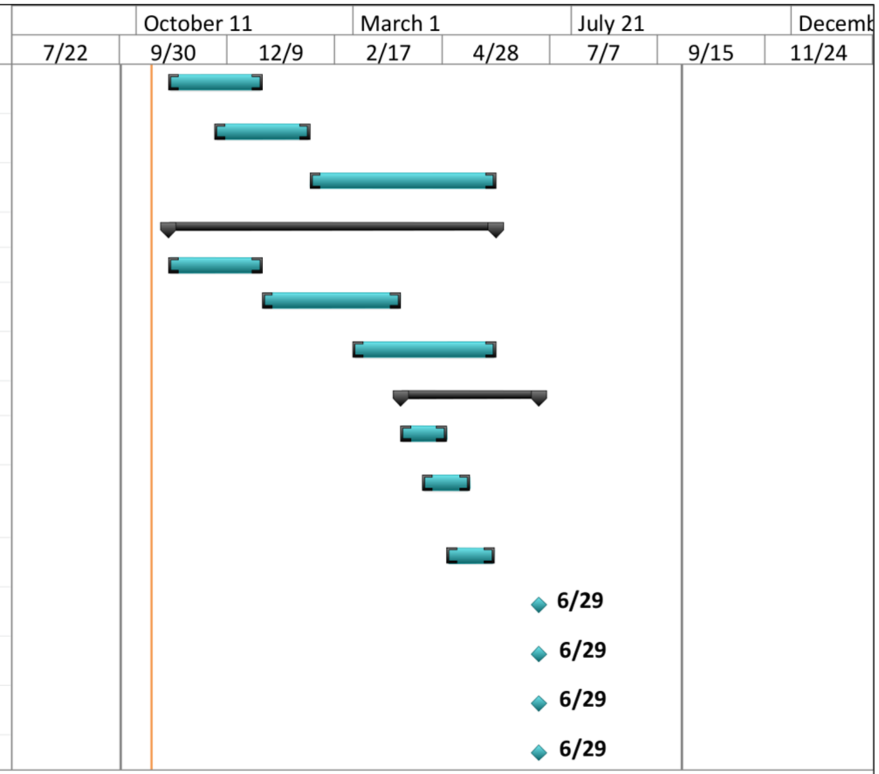
Project Schedule

ID	Task Name	Start	Finish
1	Project Management	Mon 10/1/12	Mon 9/30/13
2	Revised Project Management Plan	Sun 12/30/12	Sun 12/30/12
3	Revised Risk Management Plan	Sun 12/30/12	Sun 12/30/12
4	Research Performance Progress Report (RPPR) #1	Wed 1/30/13	Wed 1/30/13
5	SF-425 Federal Financial Report	Wed 1/30/13	Wed 1/30/13
6	Research Performance Progress Report (RPPR) #2	Tue 4/30/13	Tue 4/30/13
7	SF-425 Federal Financial Report	Tue 4/30/13	Tue 4/30/13
8	Research Performance Progress Report (RPPR) #3	Tue 7/30/13	Tue 7/30/13
9	SF-425 Federal Financial Report	Tue 7/30/13	Tue 7/30/13
10	Final Scientific/Technical Report	Mon 9/30/13	Mon 9/30/13
11	Final SF-425 Federal Financial Report	Mon 9/30/13	Mon 9/30/13
12	Annual Indirect Cost Proposal	Sat 8/31/13	Sat 8/31/13
13	**Technology Engineering Design and Economic Analysis**	**Mon 10/1/12**	**Fri 5/31/13**
14	Cycle Model Definition	Mon 10/1/12	Wed 10/31/12
15	Phase I Engineering Design Basis Report	Wed 10/31/12	Wed 10/31/12
16	Base Cycle Model Implementation and Analysis	Thu 11/1/12	Thu 1/31/13
17	Economic Model Implementation and Analysis	Thu 11/1/12	Thu 1/31/13
18	Revised Cycle Model Implementaion and Analysis	Fri 2/1/13	Sun 3/31/13
19	Revised Economic Analysis Analysis	Fri 2/1/13	Sun 3/31/13
20	Phase I Engineering Design Interim Report	Sun 3/31/13	Sun 3/31/13
21	Cycle Optimization	Fri 3/15/13	Fri 5/31/13
22	**Bench Scale Testing**	**Thu 11/1/12**	**Sat 6/1/13**

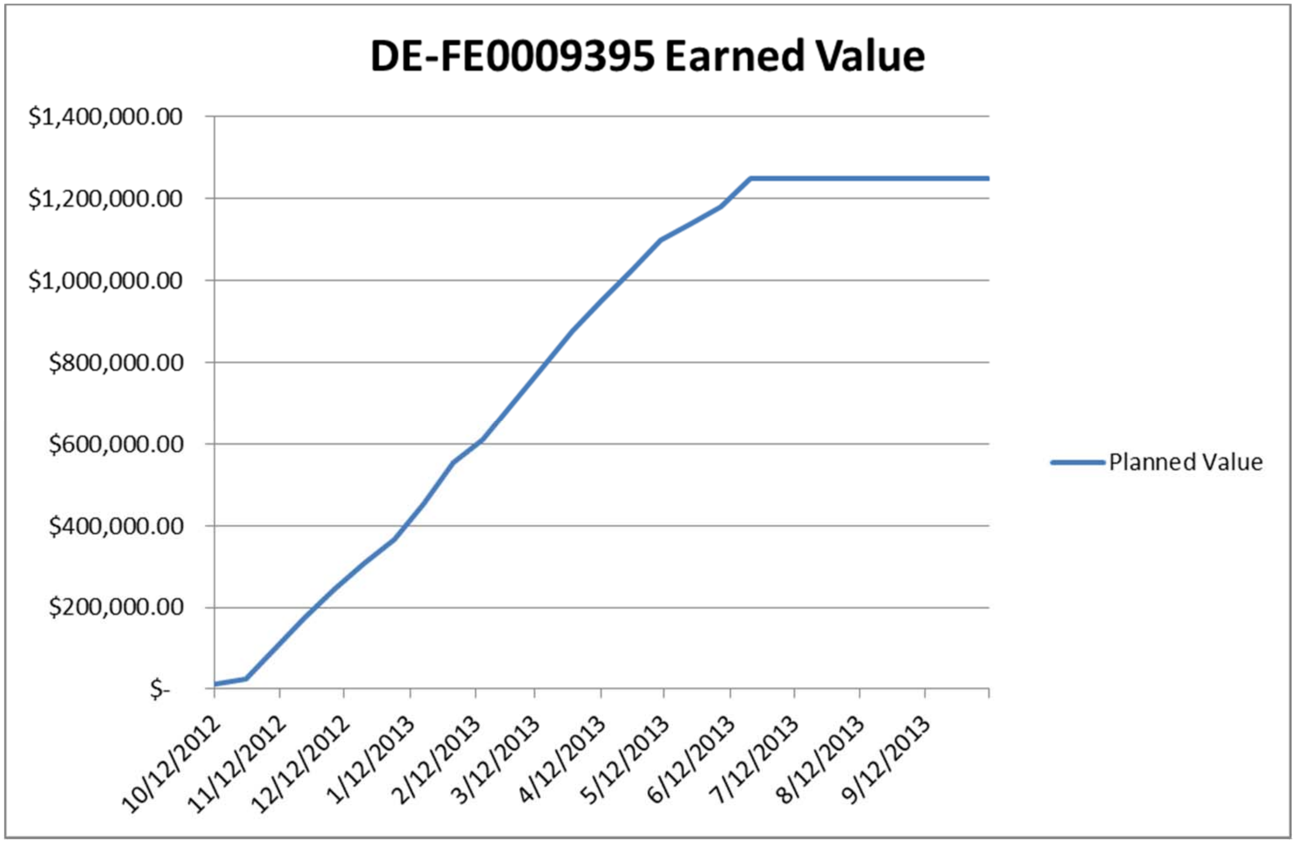


Project Schedule

ID	Task Name	Start	Finish
23	Identification of critical component technologies	Thu 11/1/12	Mon 12/31/12
24	Definition of bench scale component tests	Sat 12/1/12	Thu 1/31/13
25	Execution of bench scale component tests	Fri 2/1/13	Sat 6/1/13
26	**Technology Gap Analysis**	**Thu 11/1/12**	**Sat 6/1/13**
27	Critical Component Identification	Thu 11/1/12	Mon 12/31/12
28	Review of Critical Component Technology Levels	Tue 1/1/13	Sun 3/31/13
29	Document Critical Component Development Requirements	Fri 3/1/13	Sat 6/1/13
30	**Phase II Application**	**Mon 4/1/13**	**Sat 6/29/13**
31	Select optimal cycle to demonstrate cycle and economic performance	Mon 4/1/13	Tue 4/30/13
32	Down-select low TRL critical technologies for Phase II Development	Mon 4/15/13	Wed 5/15/13
33	Select advantagous cycle layout for Phase II technology demonstration	Wed 5/1/13	Fri 5/31/13
34	Phase I Technology Engineering Design and Economic Analysis Report	Sat 6/29/13	Sat 6/29/13
35	Phase I Topical Technology Engineering Report	Sat 6/29/13	Sat 6/29/13
36	Phase I Technology Gap Analysis Report	Sat 6/29/13	Sat 6/29/13
37	Phase II Application	Sat 6/29/13	Sat 6/29/13



Budget



Period of performance, 10/01/2012 through 09/30/2013
Phase II Application due 06/29/2013

QUESTIONS