power generation group

Commercialization of an Atmospheric Iron-Based Coal Direct Chemical Looping Process for Power Generation

Project Kick-Off Meeting
DE-FE0009761
October 29, 2012

Outline

- Introduction
- Technology Review
- Project Objectives
- Phase I Activities and Budget
- Phase II Activities and Budget

Project Participants

Government Agencies:

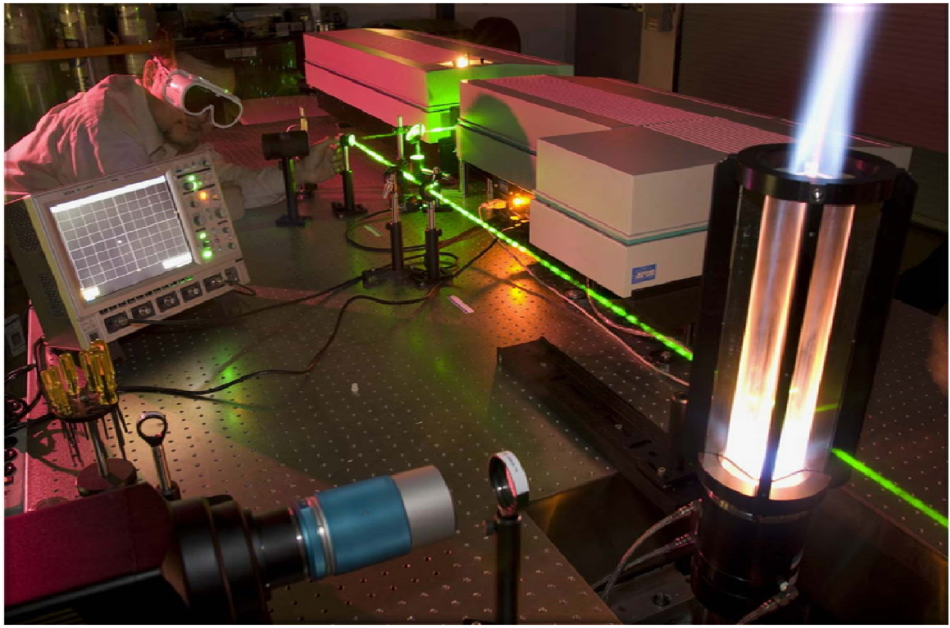
- DOE/NETL
- ODOD

Industrial participants:

- The Babcock & Wilcox, PGG
- The Ohio State University
- Clear Skies Consulting

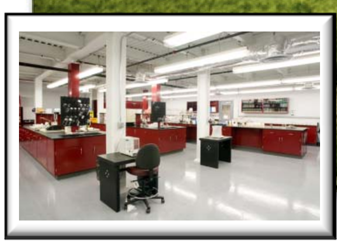
Babcock & Wilcox Research Center

- **Relocated to Barberton in November 2006**
- **Facility inaugurated in August 2007**
- **Modern laboratories for basic research on clean fuel utilization**
- **Pilot plants for combustion, oxy-firing, emissions control, and post-combustion CO_2 capture**
- **Research collaborations with universities, National labs, and industry**

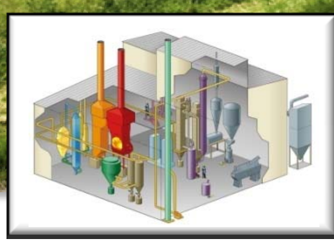


Babcock & Wilcox Research Center

Focused by Technology Roadmaps



Fundamental Research



Advanced Environmental

Oxy Combustion

CO_2 Scrubbing

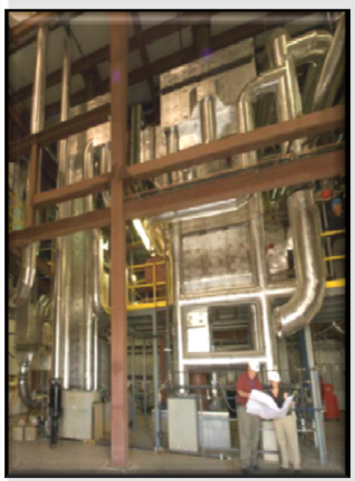
Advanced Ultra-Supercritical

Babcock & Wilcox Research Center

Progressive Facilities

- ***Fundamental Research***
- ***Lab Scale***
- ***Pilot scale***

Modern laboratories with advanced instruments



Small Boiler Simulator
(6 MBtu/hr – 1.8 MW$_{th}$)

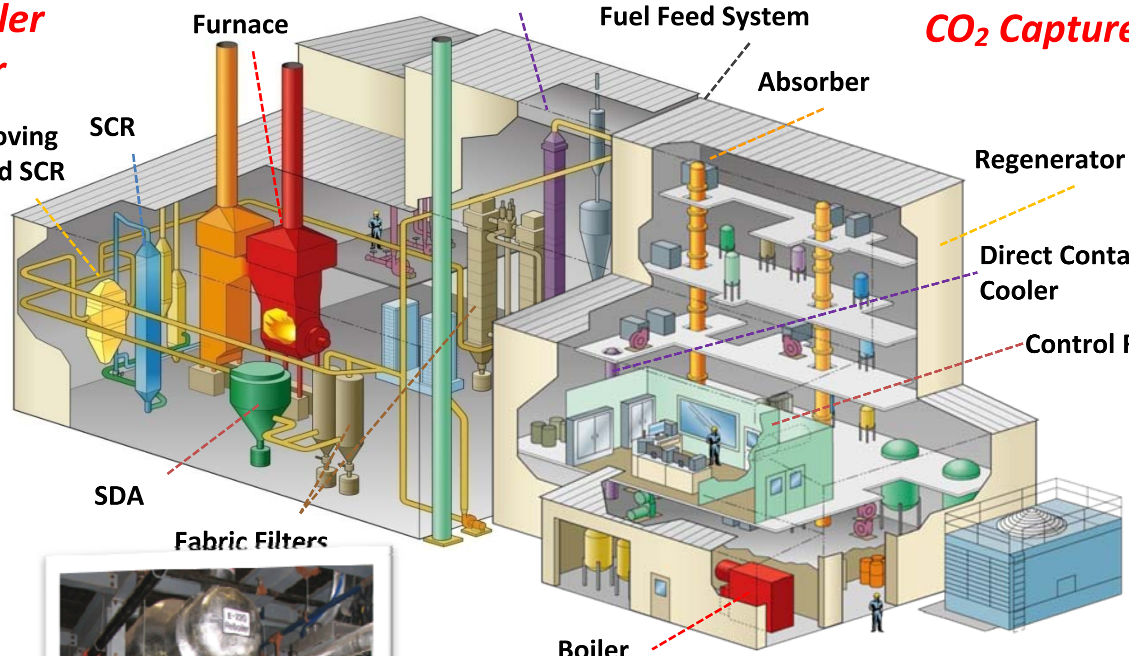
RSAT™ post-combustion CO_2 capture pilot
(~7 tons CO_2/day)

Babcock & Wilcox Research Center

SBS + RSAT™ Pilot Plant *(7 tons CO_2 capture/day)*

Key Features:

- **High quality, representative data**
- **Coal flue gas source**
- **Designed for R&D studies**



Applications:

- **Performance data**
- **Process optimization**
- **Accurate mass and energy balances**
- **Simulation model validation**

The Ohio State University: Clean Coal Research Laboratory

Coal-Direct Chemical Looping

Sub-Pilot Scale Unit

Pilot Scale Unit
w/ B&W

Syngas Chemical Looping

Sub-Pilot Scale Unit

250-kW_{th} Pilot Scale Unit
Projected in 2013

Calcium Looping Process

Sub-Pilot Unit

CCR Process

120kW_{th} Demonstration Unit

Other Research

- Process/Reactor Simulation
- Quantum Calculation
- Particle Technology
- Reaction Engineering
- ECVT

Research in various aspects of engineering and science to support demonstration work

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  - Concept
  - Bench and Sup-pilot Scale Demonstrations
  - Techno-economic analysis
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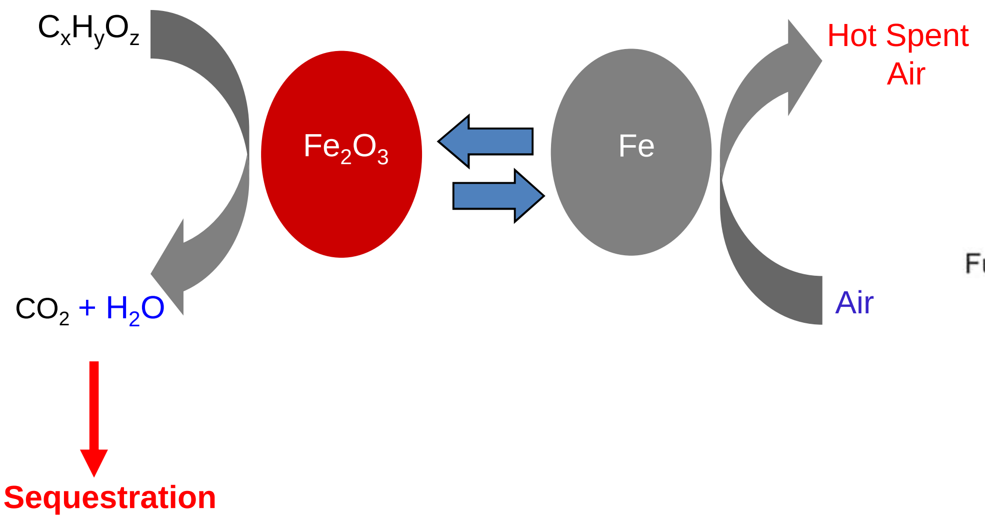
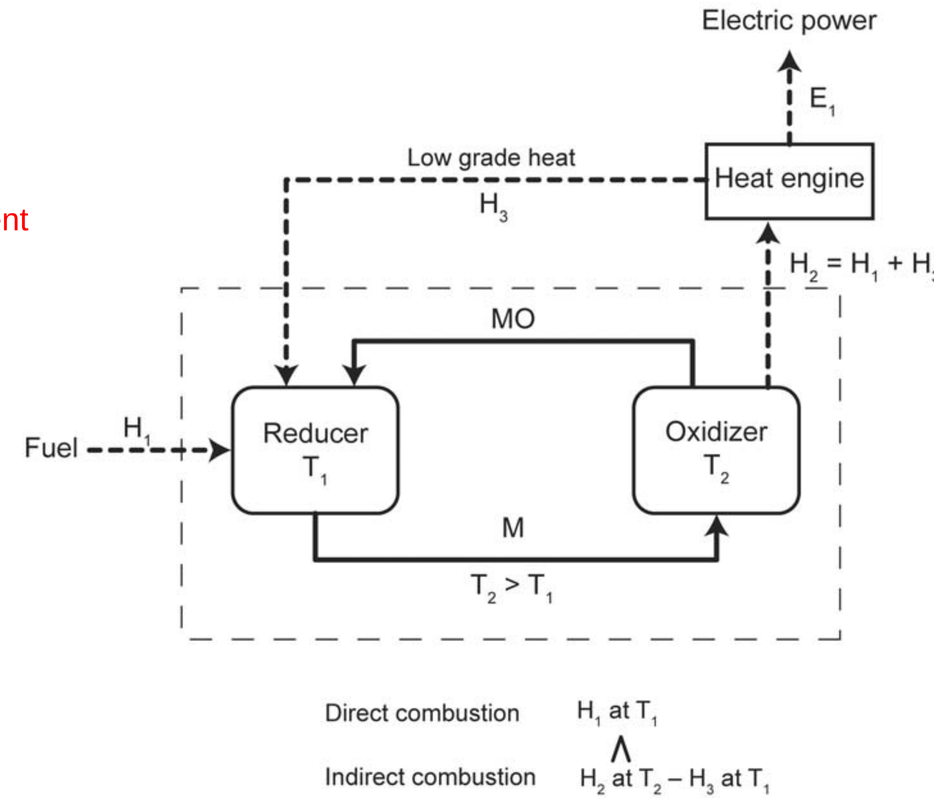
Process Concept

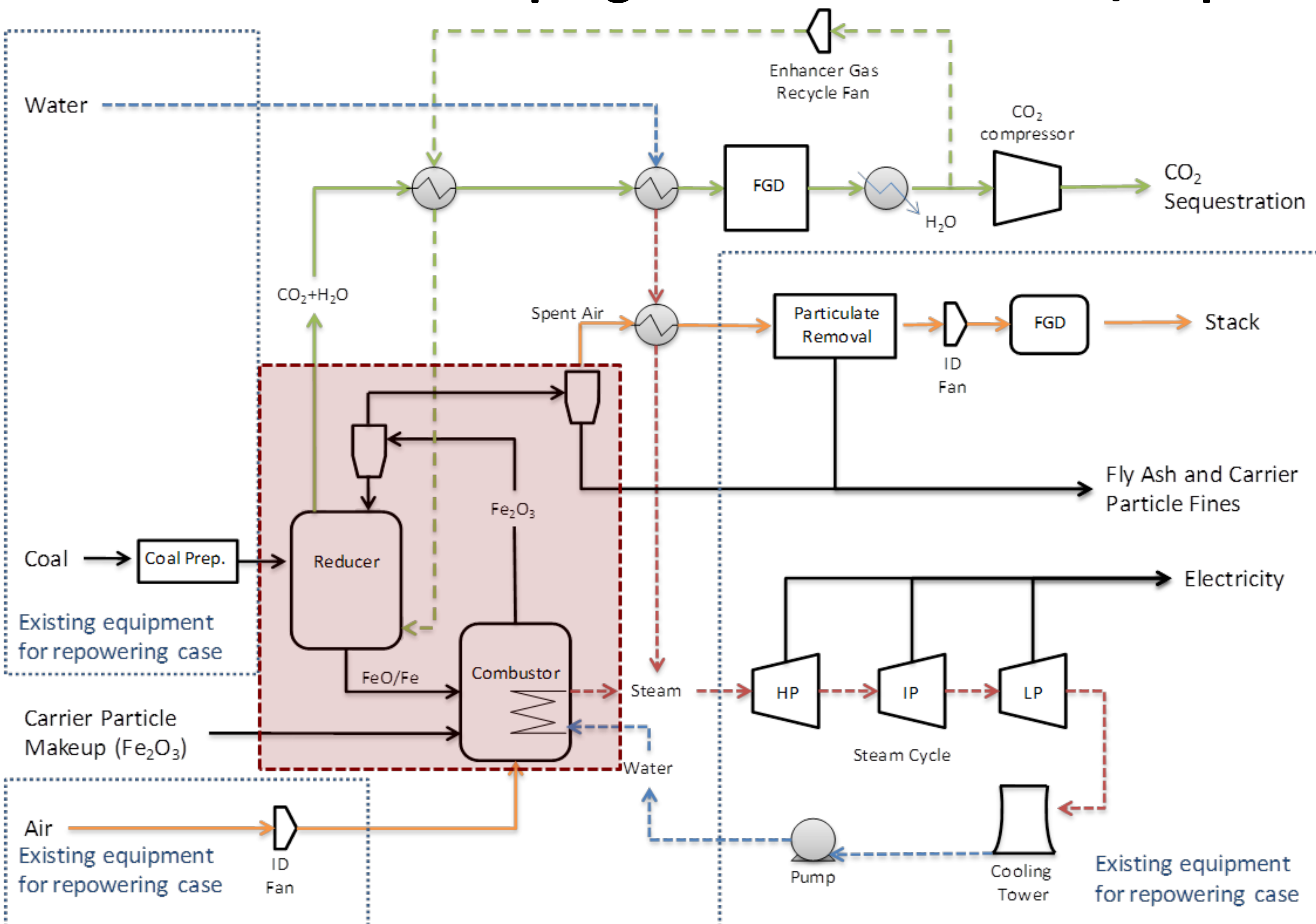




Reducer:	Coal + Fe_2O_3 → Fe/FeO + CO_2 + H_2O	(endothermic)
Oxidizer:	Air + Fe/FeO → Fe_2O_3 + Spent Air	(exothermic)
Overall:	Coal + Air → CO_2 + H_2O + Spent Air	(exothermic)

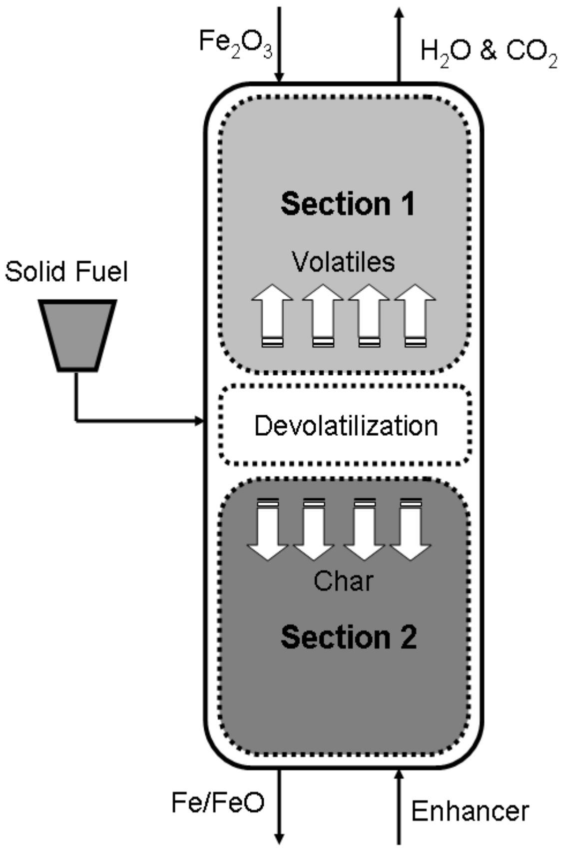
CL Process reduces exergy loss by recuperating the low grade heat while producing a larger amount of high grade heat

Coal-Direct Chemical Looping Process for Retrofit/Repower



Thomas, T., L.-S. Fan, P. Gupta, and L. G. Velazquez-Vargas, "Combustion Looping Using Composite Oxygen Carriers" U.S. Patent No. 7,767,191 (2010, priority date 2003)

CDCL OSU Moving Bed Reactor Configuration



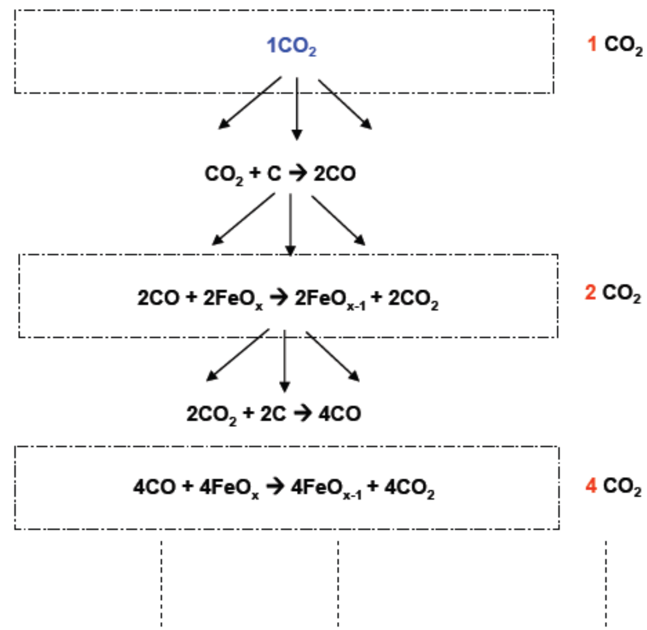
Enhancer Gas

Particle reduction :
$CH_4 + Fe_2O_3 \rightarrow CO_2 + H_2O + FeO$

Coal devolatilisation:
$Coal \rightarrow C + C_xH_y$

Char gasification and particle reduction:
$FeO + H_2 \rightarrow Fe + H_2O$
$FeO + CO \rightarrow Fe + CO_2$
$CO_2 + C \rightarrow 2CO$

Reaction Initiation:
$H_2 + FeO \rightarrow Fe + H_2O$
$H_2O + C \rightarrow CO + H_2$



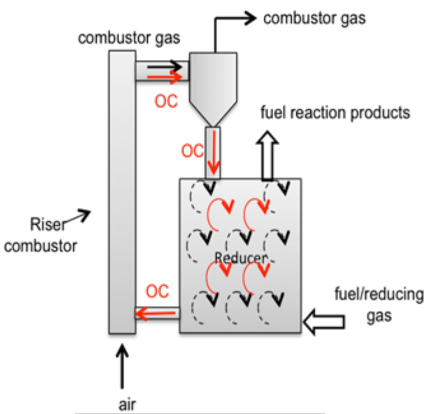
Two-stage moving bed

- Stage I for gaseous volatiles
- Stage II for coal char

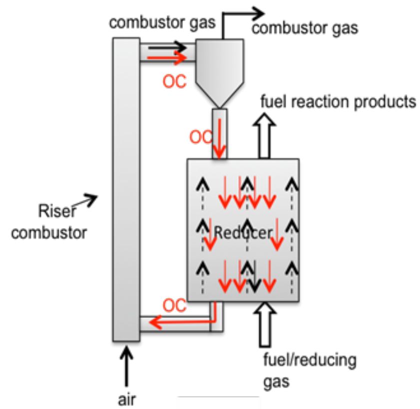
Thomas, T., L.-S. Fan, P. Gupta, and L. G. Velazquez-Vargas, "Combustion Looping Using Composite Oxygen Carriers" U.S. Patent No. 7,767,191 (2010, priority date 2003)

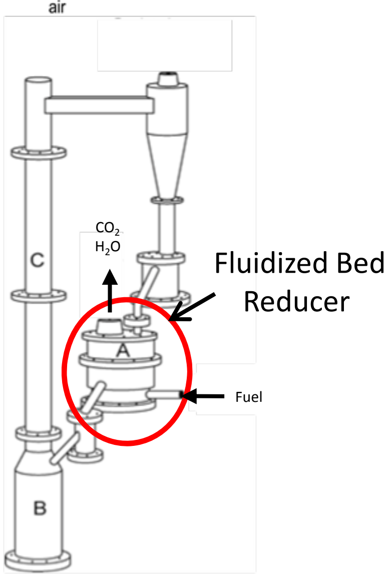
Modes of CFB Chemical Looping Reactor Systems

Mode 1- reducer: fluidized bed or co-current gas-solid (OC) flows

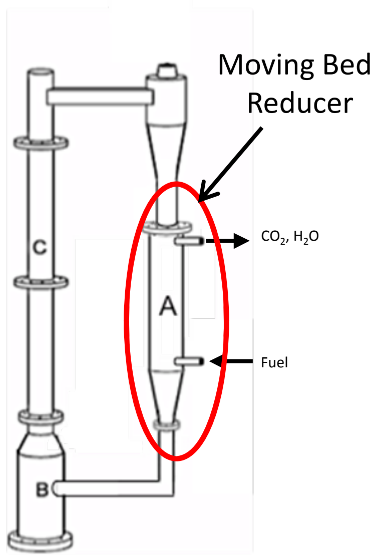


Mode 2 - reducer: gas-solid (OC) counter-current dense phase/moving bed flows





Chalmers University CLC System



OSU CLC System

Reducer	Mode 1	Mode 2
Operation Regime	Bubbling, turbulent, fast fluidized, or spouted bed	Moving packed, or multistage fluidized bed
Gas Solid Contacting Pattern	Mixed/Cocurrent	Countercurrent
Controllability on Fuel and OC Conversions	Poor, due to back mixing and gas channeling	High
Maximum Iron oxide Conversion	11.1% (to Fe_3O_4)	>50% (to Fe & FeO)
Solids circulation rate	High	Low
Ash Separation Technique	Separate Step	In-Situ
Subsequent Hydrogen Production	No	Yes
Particle size, µm	100-600	1000-3000
Reducer gas velocity*, m/s	<0.4	>1.0
Reactor size for the same fuel processing capacity	Large	Small
Hydrodynamics effects on scaling up	Large	Small

*Reducer gas velocity calculated at 900 °C, 1 atm

Modes of CFB Chemical Looping Reactor Systems

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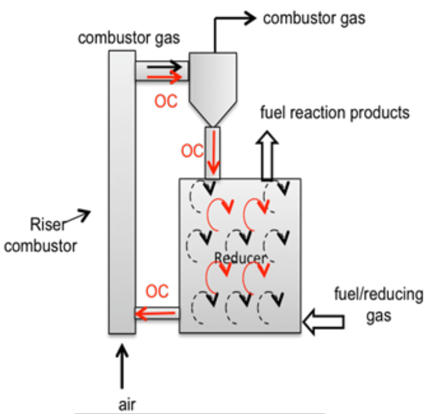
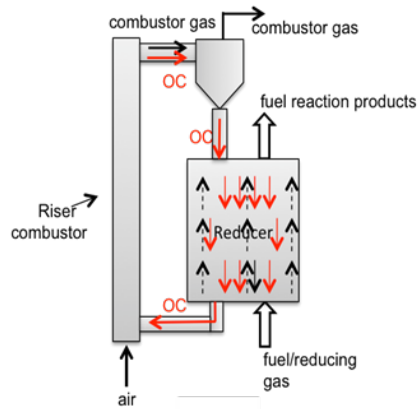
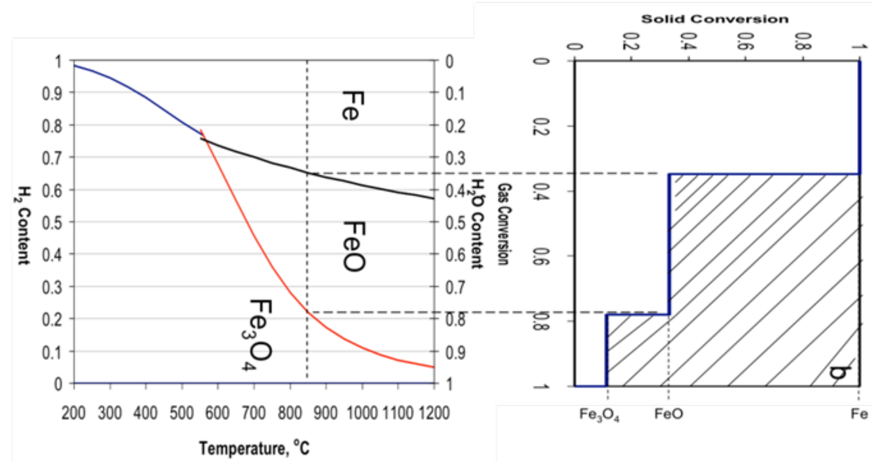
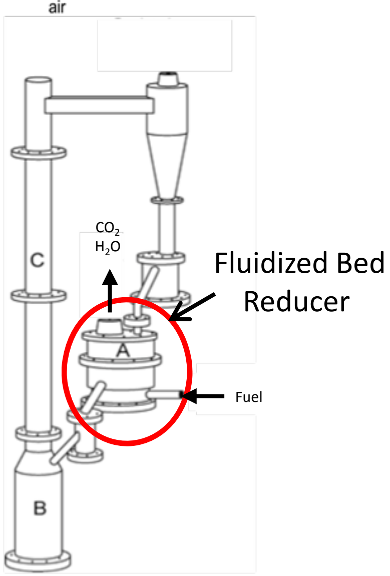


Mode 2 - reducer: gas-solid (OC) counter-current dense phase/moving bed flows



Phase Diagram – Thermodynamic Restrictions





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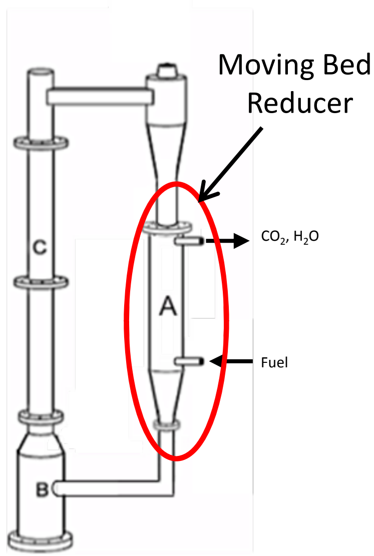


OSU CLC System

Operating Equation for Moving Bed Reducer

Fixed solid molar flowrate n_{Fe},

Oxygen content for solid $y = \frac{3n_{Fe_2O_3} + 4n_{Fe_3O_4} + n_{FeO}}{n_{Fe}}$

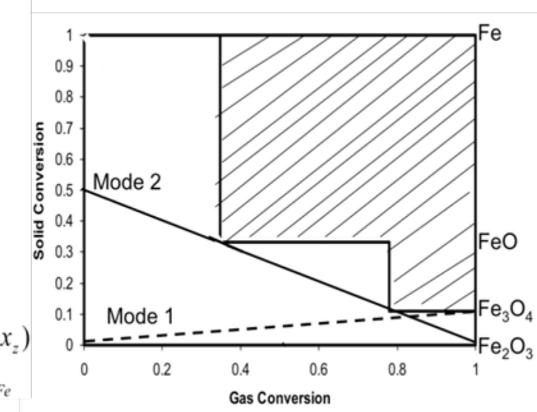
Fixed gas molar flowrate $n_{H2} + n_{H2O}$,

Oxygen content for gas $x = \frac{n_{H_2O}}{n_{H_2} + n_{H_2O}}$

Oxygen Balance

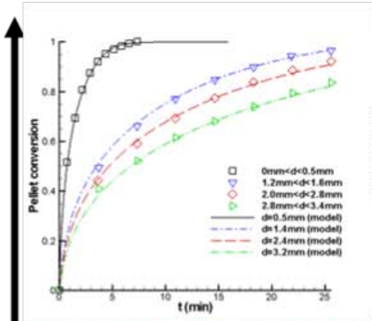
$$n_{Fe}(y_{z+\Delta z} - y_z) = (n_{H_2} + n_{H_2O})(x_{z+\Delta z} - x_z)$$

$$\Delta z \to 0 \Rightarrow dy/dx = (n_{H_2} + n_{H_2O})/n_{Fe}$$

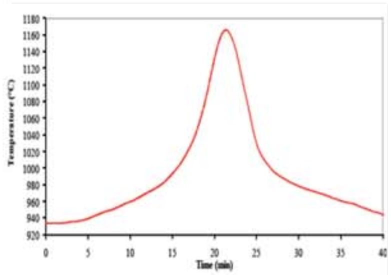


OSU Chemical Looping Process Development

Scale



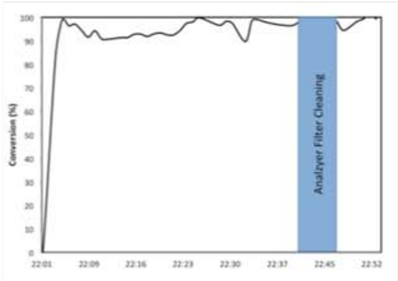
More than **300** types of particle tested. A low cost, robust, highly reactive, and O^{2-} conductive composite particle is obtained.



Determined operating maximum operating temperature of oxygen carrier for sustained reactivity and recyclability

Fuel Type	Fuel Conversion (%)	CO_2 Purity (%)
CO, H_2	99.9	99.9
CH_4	99.8	98.8
Lignite Char	94.9	99.23
Bituminous Char	95.2	99.1
PRB	>97	-
Bituminous	>95	-
Anthracite	95.5	97.3

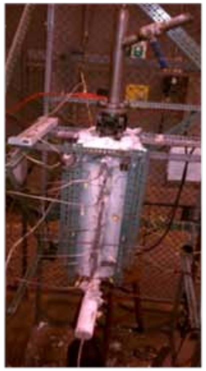
>300 hours operation with ***>99%*** volatile conversion, ***>95%*** char conversion



>800 hours operation with ***>99%*** coal/syngas conversion with nearly 100% carbon capture

TGA

Fixed Bed Tests



Bench Scale Tests

25 kW_{th} Sub-Pilot Scale Tests

Time

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Fuel Feedstock Studied

Fuel Feedstock	Type	Fuel Flow (lb/hr)	Enhancer
Syngas	CO/H_2	0.1-1.71	N/A
Coal volatile/ Natural Gas	CH_4	0.1-0.4	N/A
Coal char	Lignite	0.7-2.0	CO_2/H_2O
	Metallurgical Coke	0.05-3	CO_2/H_2O
Coal	Sub-Bituminous	0.05-7.38 **(25kW_{th})**	CO_2/H_2O
	Bituminous	0.05-3	CO_2/H_2O
	Anthracite	0.2-0.7	CO_2/H_2O
	Lignite	2.84-6.15 (**20 kW_{th}**)	CO_2
Biomass	Wood pellets	0.1	CO_2

- Combined >800 hours of sub-pilot SCL and CDCL operational experience
- Successful results for all coal/coal derived feedstock tested

25 kW_{th} Sub-Pilot Demonstration

- Fully assembled and operational
- 500+ hours of operational experience
- 200+ hours continuous successful operation
- Smooth solid circulation
- Confirmed non-mechanical gas sealing under reactive conditions
- 13 test campaigns completed

200 hour Sub-Pilot Continuous Demonstration

Purpose of long run:

- Determine the feasibility of long-term coal injection on the flowability and reactivity of the oxygen carrier particles in the system.
- More accurately understand the dynamics of the system in hot condition
- Further ability to troubleshoot potential problems and how/why they occur

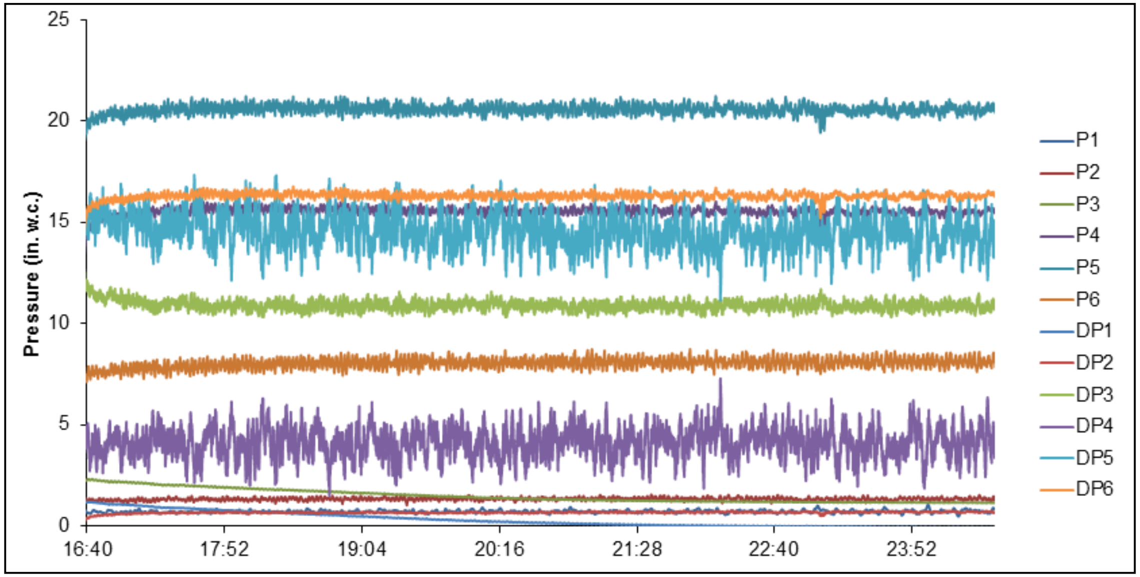
	Fuel Feed (lb/hr)	Energy Value (kW_{th})
Metallurgical Coke	1.3 – 2.9	5.3 – 15.3
Powder River Basin	1.3 – 7.4	4.5 – 25
North Dakota Lignite	2.9 – 6.1	9.3 – 19.7

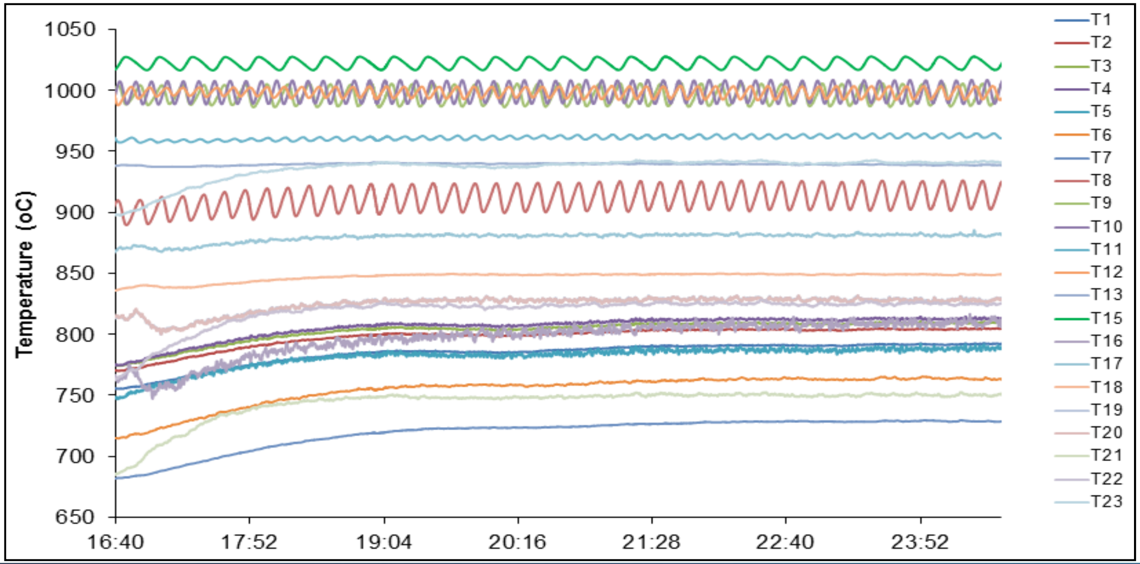
Results:

- System able to sustain 200 hours of circulation with no major issues
- Reactivity of the oxygen carrier particle maintained over hundreds of cycles

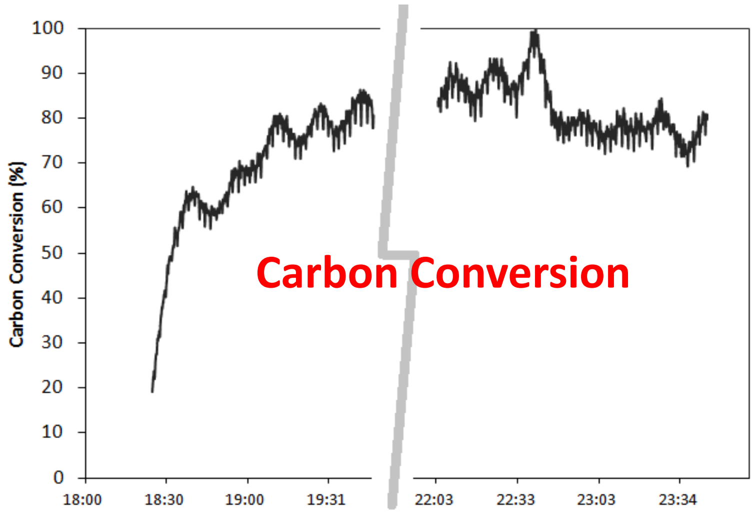
25 kW_{th} Sub-Pilot Demonstration – Sample Data

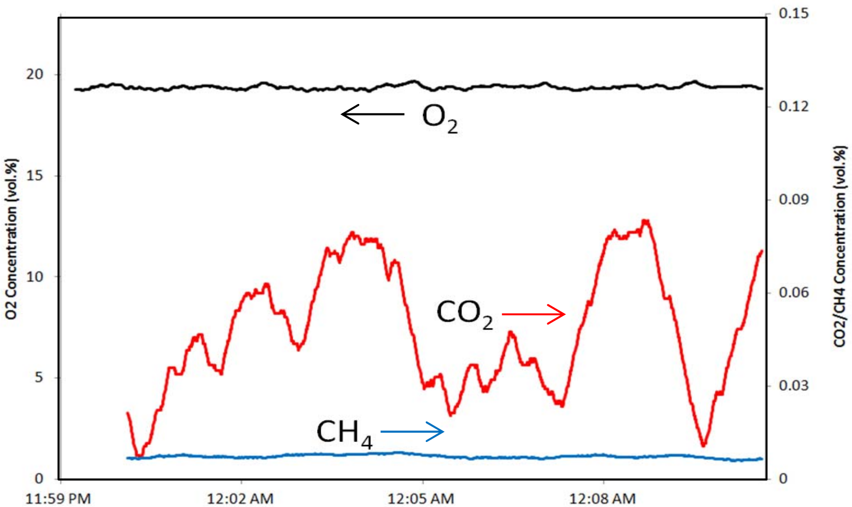
200-hour Continuous Demonstration

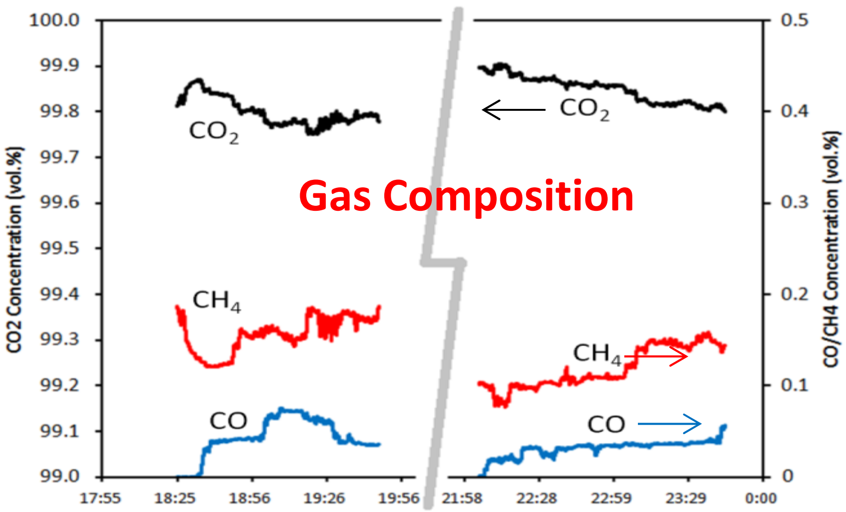




Metallurgical Coke Performance - *Sample Data*



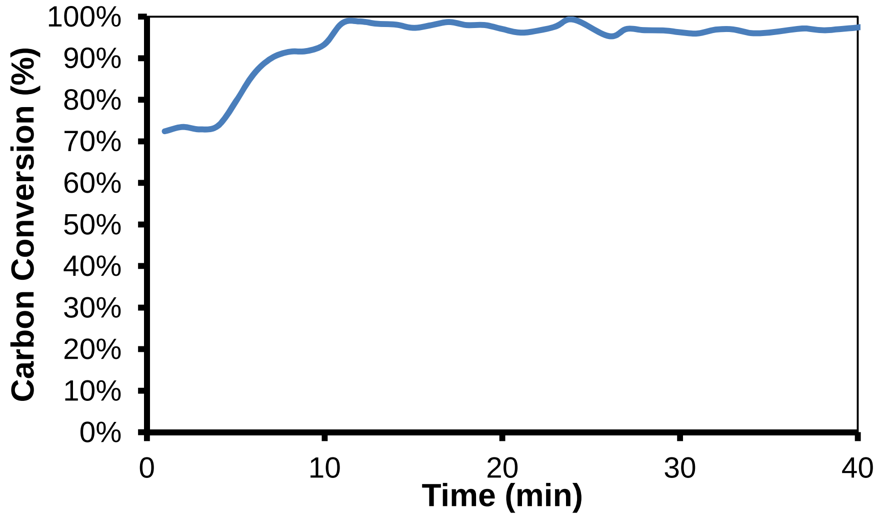




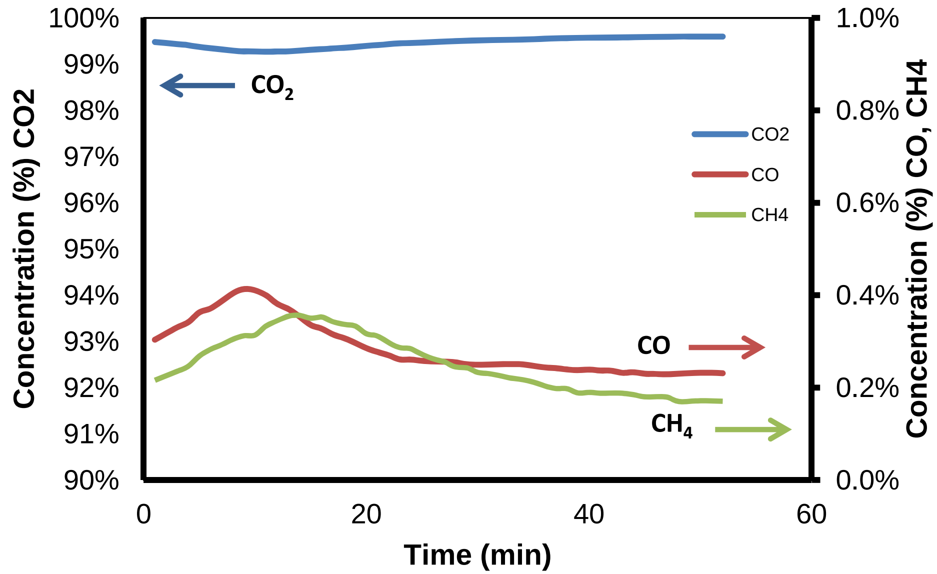
- Low volatile and high carbon contents
- ~20-hour operation
- Avg. 80% carbon conversion in reducer
- High Purity CO_2 concentration
  - Negligible CO and CH_4 observed
- Low CO/CH_4 Concentration in Combustor outlet
  - No carbon carry-over from reducer

200+ Sub-Pilot Continuous Run - Sample Results Lignite

Once-Through Reducer Carbon Conversion Profile

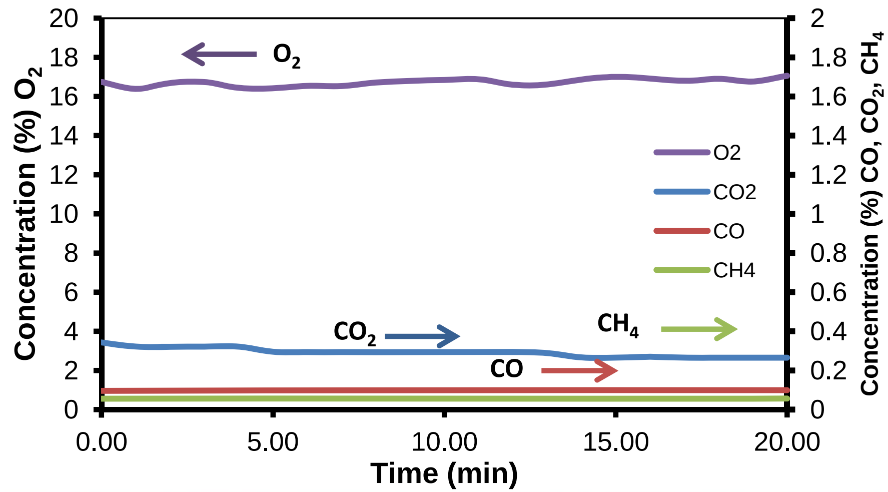


Reducer Gas Concentration Profile



- **Continuous steady carbon conversion from reducer throughout all solid fuel loading (5- 25kW$_{th}$)**
- **<0.25% CO and CH_4 in reducer outlet = full fuel conversion to CO_2/H_2O**
- **<0.3% CO, CO_2, and CH_4 in combustor = negligible carbon carry over, nearly 100% carbon capture**

Combustor Gas Concentration Profile



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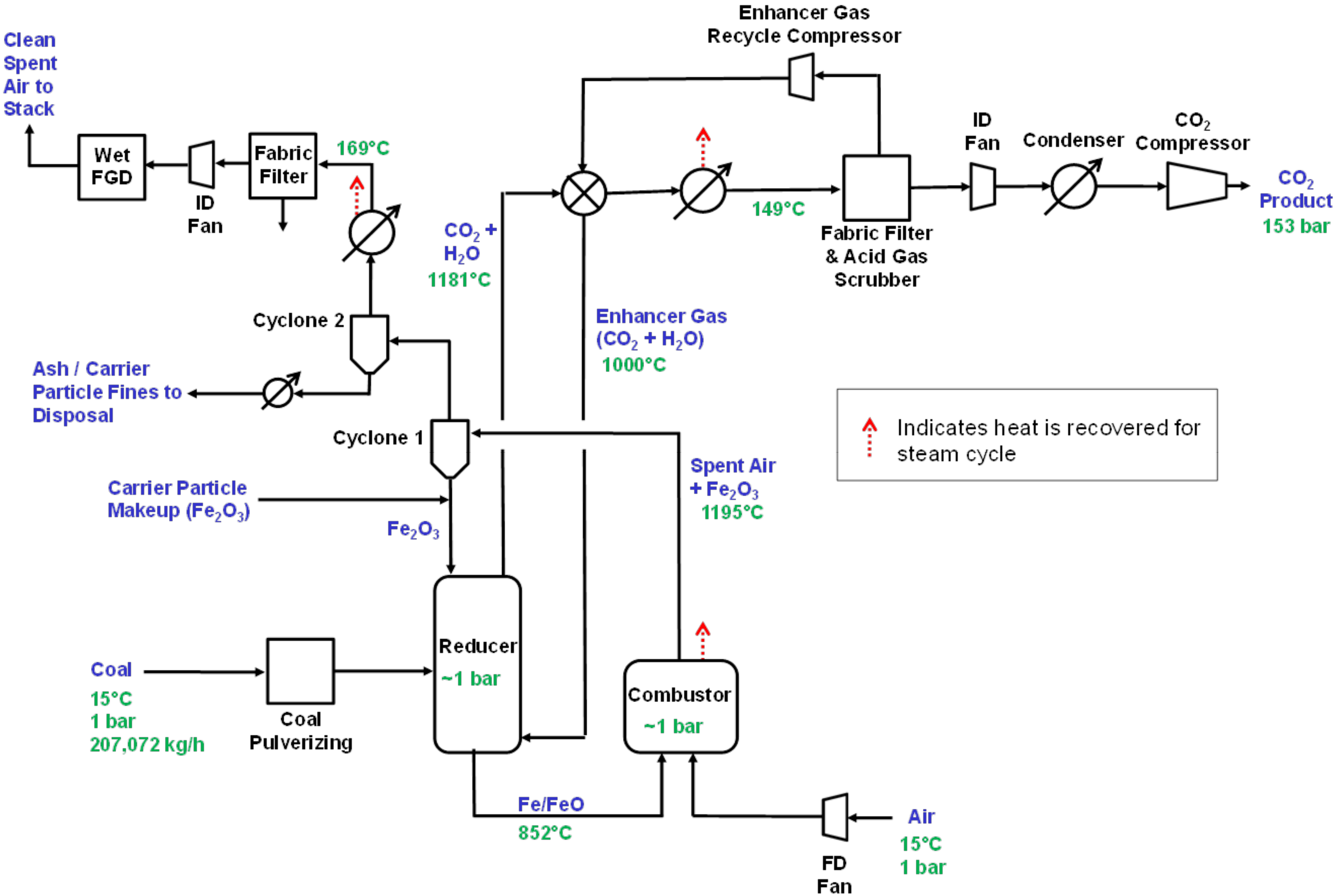
Process Simulation and Analysis

Systems Analysis Methodology

- Performance of CDCL plant modeled using Aspen Plus® software
- Results compared with performance of conventional pulverized coal (PC) power plants with and without CO_2 capture
  - U.S. Department of Energy, National Energy Technology Laboratory; *Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity* (November 2010)
    - Case 11 – Supercritical PC plant without CO_2 capture ("Base Plant")
    - Case 12 – Supercritical PC plant with MEA scrubbing system for post-combustion CO_2 capture ("MEA Plant")
- All plants evaluated using a common design basis
  - 550 MW_e net electric output
  - Illinois No. 6 coal: 27,113 kJ/kg (11,666 Btu/lb) HHV, 2.5% sulfur, 11.1% moisture as received
  - Supercritical steam cycle: 242 bar/593°C/593°C (3,500 psig/1,100°F/1,100°F)
  - ≥ 90% CO_2 capture efficiency (MEA and CDCL Plants)
  - CO_2 compressed to 153 bar (2,215 psia)
- Results are preliminary, will be used to guide further design improvements

Process Simulation and Analysis



Aspen Plus® Modeling Results

	Base Plant	MEA Plant	CDCL Plant
Coal Feed, kg/h	185,759	256,652	207,072
CO_2 Emissions, kg/MWh_{net}	802	111	28
CO_2 Capture Efficiency, %	0	90.2	97.0
Solid Waste,[a] kg/MWh_{net}	33	45	43
Net Power Output, MW_e	550	550	548
Net Plant HHV Heat Rate, kJ/kWh (Btu/kWh)	9,165 (8,687)	12,663 (12,002)	10,248 (9,713)
Net Plant HHV Efficiency, %	39.3	28.5	35.2
Energy Penalty,[b] %	-	27.6	10.6

[a]Excludes gypsum from wet FGD. [b]Relative to Base Plant; includes energy for CO_2 compression.

First-Year Cost of Electricity

	Base Plant	MEA Plant	CDCL Plant
First-Year Capital ($/MWh)	31.7	59.6	44.2
Fixed O&M ($/MWh)	8.0	13.0	9.6
Coal ($/MWh)	14.2	19.6	15.9
Variable O&M ($/MWh)	5.0	8.7	8.7
TOTAL FIRST-YEAR COE ($/MWh)	**58.9**	**100.9**	**78.4**

Δ = +71%

Δ = +33%

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Project Objectives

- To evaluate the commercial viability of the CDCL Technology
  - Conduct minimal testing to support the commercial design
  - Develop a commercial plant design concept
  - Perform a techno-economic evaluation of the CDCL process
  - Identify technology gaps
  - Develop a preliminary design and budget estimate for a phase II pilot plant experimental facility
  - Submit Phase II application and final report

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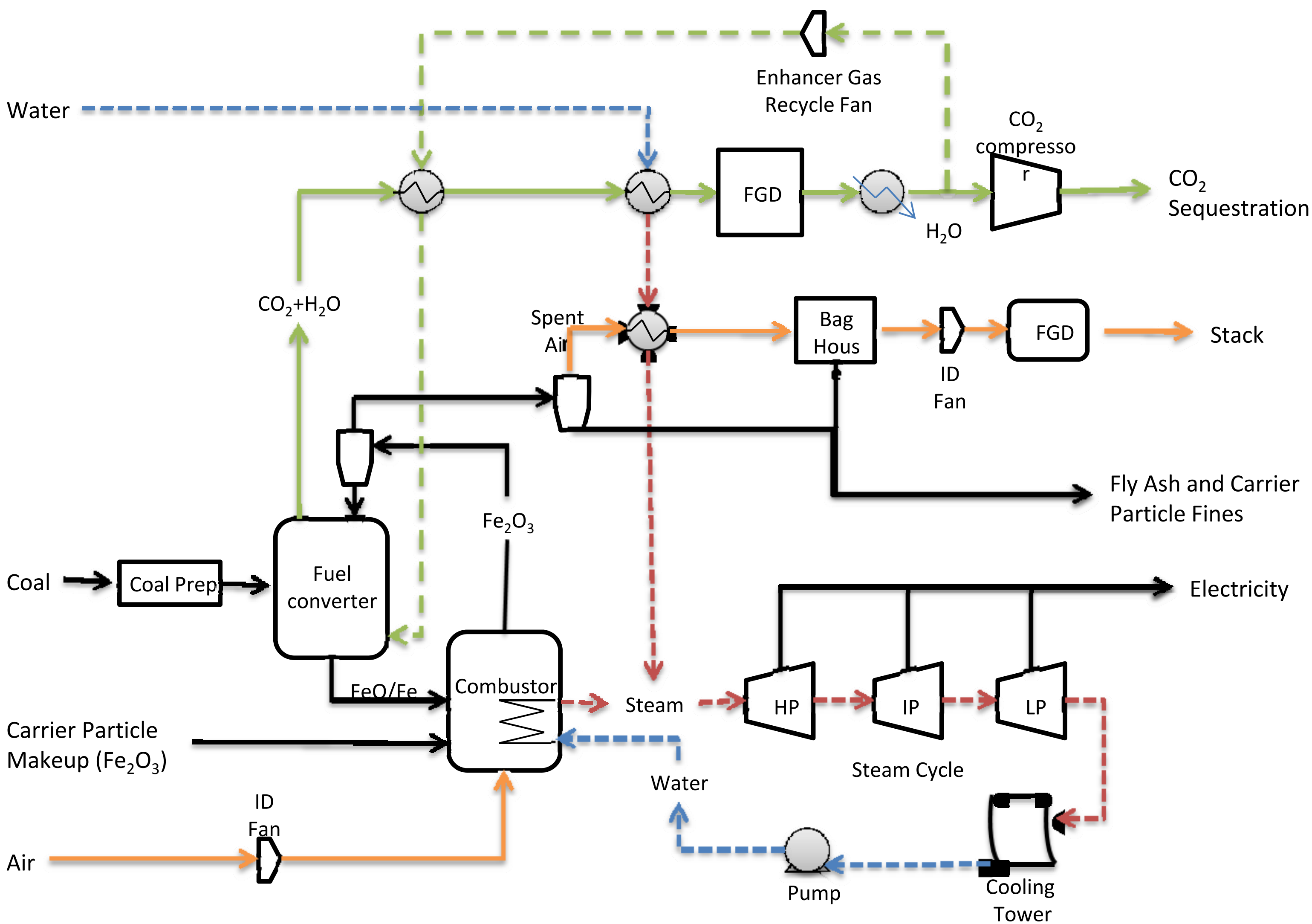
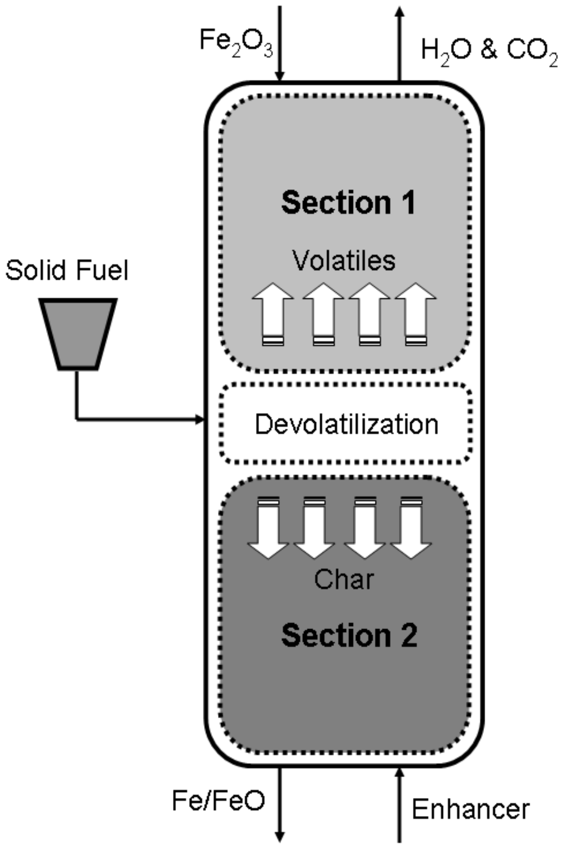
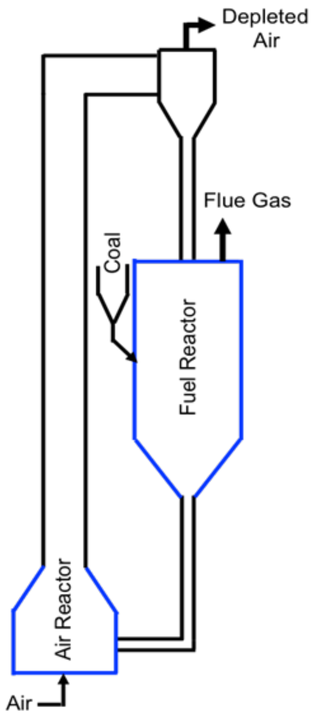
Commercial Plant Design: 550 MW_e



Proposed Concept



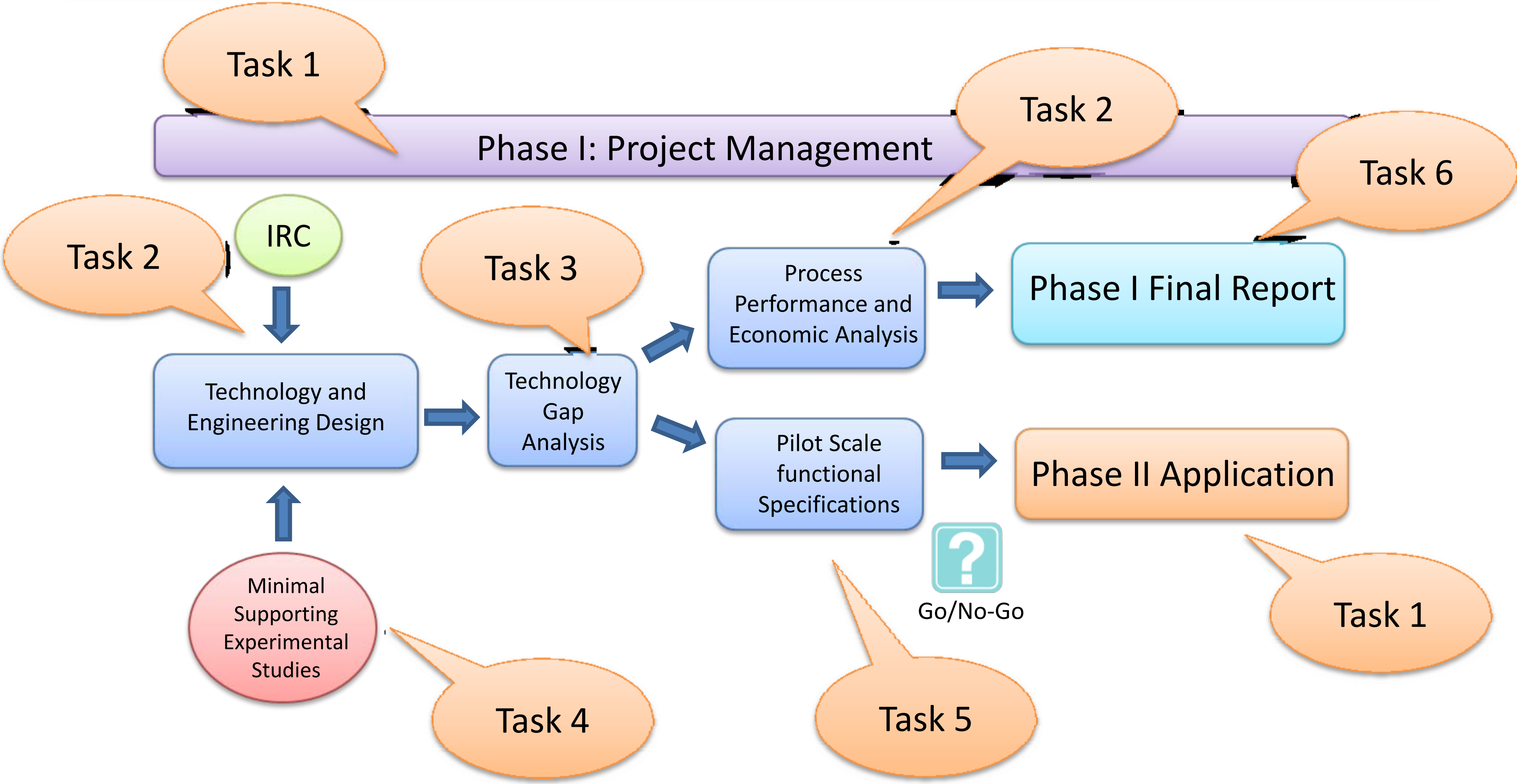


Two-stage moving bed

- Stage I for gaseous volatiles
- Stage II for coal char

- No internal mechanical moving parts
- Packed moving bed design increases oxygen carrier conversion reducing solid flow rate
- In-situ ash separation
- Scalable reactor design
- Simple design – no loop seals/carbon strippers

Approach


Task 1
Phase I: Project Management
Task 2
Task 6
Task 2
IRC
Task 3
Process Performance and Economic Analysis
Phase I Final Report
Technology and Engineering Design
Technology Gap Analysis
Pilot Scale functional Specifications
Phase II Application
Go/No-Go
Minimal Supporting Experimental Studies
Task 1
Task 4
Task 5

Phase I Schedule

Phase I: Technical and Economic Evaluation	2012			2013								
	10	11	12	1	2	3	4	5	6	7	8	9
Task 1 Project Management and Planning												
1.1 Project Management	x	x	x	x	x	x	x	x	x	x	x	x
1.2 Management Plan	x											
1.3 Phase II Application								x	x			
Task 2 Technology and Engineering Design Evaluation Analysis												
2.1 Technology Engineering Design Basis	x											
2.2 Develop Reference Conceptual Plant Design	x	x	x	x	x	x						
2.3 Perform Final TechnoEconomic Analysis							x	x	x			
Task 3 Technology Gap Analysis												
3.1 Identify Process Technology Gaps					x	x	x					
3.2 Identify Mechanical Technology Gaps					x	x	x					
Task 4 Support Testing and Analysis												
4.1 Char Conversion Kinetics and Residence time	x	x	x									
4.2 Determine Coal Distribution Requirement		x	x	x								
4.3 Study and Quantify Particle Attrition			x	x	x							
4.4 Determine Particle Cost			x	x	x	x						
Task 5 Pilot-Scale Facility Design												
5.1 Develop Functional Specifications							x	x				
5.2 Develop Budgetary Cost							x	x				
5.3 Support for Phase II Review											x	x
Task 6 Final Report												
6.1 Prepare Topical/Final Report								x	x			
6.2 In case project is not selected to Phase II											x	x

Phase I Milestone Log

Phase I: Technical and Economic Evaluation	Start Date	End Date	2012			2013									Verification Method
			10	11	12	1	2	3	4	5	6	7	8	9	
Task 1 Project Management and Planning															
Kick-Off Meeting	10/1/2012	10/29/2012	x												Presentation File
Phase I Closeout Meeting	8/1/2013	9/30/2012											x	x	Presentation File
Periodic Reports	12/1/2013	9/30/2012			x			x			x			x	Periodic Report Documents
Closeout Documentation	8/1/2013	9/30/2012											x	x	Closeout Documents
NETL's CO2 Capture Meeting	7/2/2012	8/31/2012										x	x		Presentation File
Upadted Phase I Management Plan	10/1/2012	11/30/2012	x	x											Project Management Plant Document
Phase II Application	6/1/2013	6/29/2013									x				Phase II application Documentation
Task 2 Technology and Engineering Design Evaluation Analysis															
Technology Engineering Design Basis Report	10/1/2012	10/31/2012	x	x											Design Basis Report Document
Technology Engineering Design Interm Report	3/1/2013	3/31/2013						x							Design Interim Report Document
Final Phase I technology Engineering Design and Economic Analysis Report	6/1/2013	6/29/2013									x				Design and Economic Analysis Report Document
Task 3 Technology Gap Analysis															
Go/no Go Descision to continue to Phase II	6/2/2013	6/29/2013									x				Issue a go/no-go decision
Final Phase I Technology Gap Analysis	6/2/2013	6/29/2013									x				Technology Gap Analysis Report Document
Task 4 Support Testing and Analysis															
Complete Minimum Required Laboratory Testing	3/1/2013	3/29/2013						x							Issue an experimental status report
Task 5 Pilot-Scale Facility Design															
Response to questions resulting from NETL review of Phase II application	9/1/2013	9/30/2013												x	Issue a reply to reviewers comments/suggestions
Task 6 Final Report															
Phase I Topical Report (Draft)	6/3/2013	6/29/2013									x				Topical Report Document
Updating Phase I topical report into Final Report	9/2/2013	9/30/2013												x	Final Report Document

Role of Participants: B&W

1. Project management and reporting
2. Translate experimental data into a commercial design
3. Estimate the cost for the commercial plant and auxiliary components
4. Perform an economic evaluation of the technology
5. Make the go/no-go decision to continue forward
6. Commercialize the technology
   - Carry the commercial risks and guaranties
   - Stand behind the final commercial design

Role of Participants: OSU

1. Support B&W on the commercial design
   - Provide process performance data
   - Perform data analysis and interpretation of experimental results
   - Provide know-how on the operation of the system
2. Perform process simulations to support economic analysis
3. Review final report and provide comments on the economic results

Role of Participants: Clear Skies

1. Coordinate IRC Committee
2. Determine particle manufacturing cost and explore cost reduction strategies
3. Ensure that the commercial plant design meets DOE targets and addresses IRC concerns.
4. Review and provide feedback on design documentation
5. Support B&W by providing feedback on quarterly reports and deliverables

Phase I Budget

BP1 10/1/2012 - 9/30/2013				
Participant	**Federal Share**	**State Share**	**Cost-share**	**Total**
B&W	$408,416	$400,000	$198,574	$1,006,990
OSU	$285,014		$27,796	$312,810
Clear Skies	$68,170		$12,030	$80,200
Total	**$761,600**	**$400,000**	**$238,400**	**$1,400,000**

Total Project Cost Share of 45.6 %

Thank you

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