Coal Direct Chemical Looping (CDCL) Retrofit to Pulverized Coal Power Plants for In-Situ CO_2 Capture

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PI: Liang-Shih Fan

Department of Chemical and Biomolecular Engineering
The Ohio State University

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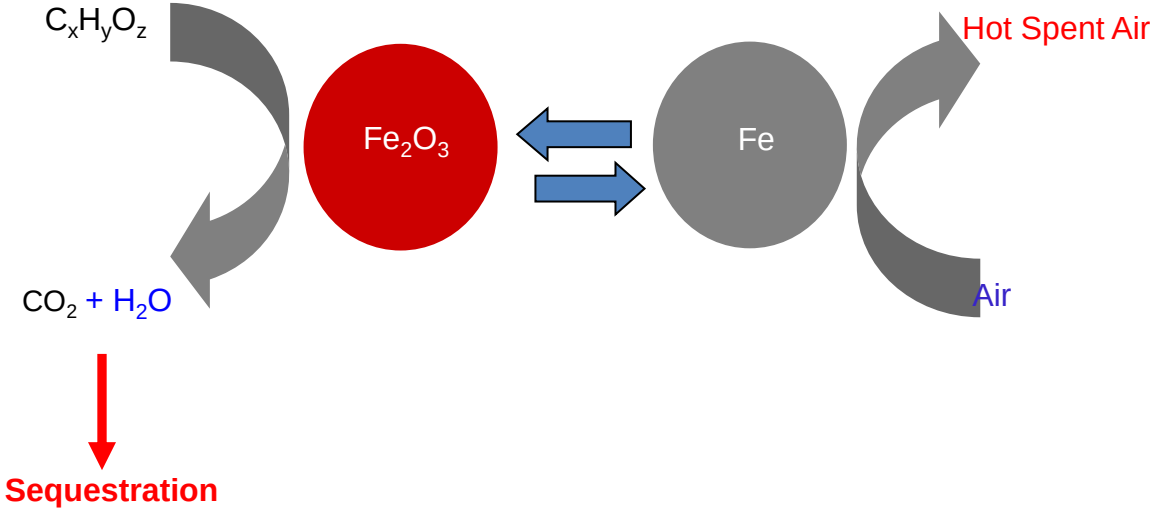
THE OHIO STATE UNIVERSITY
WILLIAM G. LOWRIE
DEPARTMENT OF CHEMICAL AND BIOMOLECULAR ENGINEERING

Outline

- Introduction to the Technology
- Project Objectives
- Project Review
  - Phase I: Oxygen Carrier Selection
  - Phase II: Bench Test and Cold Flow Model Study
  - Phase III: Integrated Subpilot Unit Demonstration and Techno-Economic Analysis

Coal Direct Chemical Looping 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)

Project Objectives

Further advance the novel Coal Direct Chemical Looping process technology to sub-pilot scale (25 kWt)

1. Improve the oxygen carrying capacity as well as the sulfur/ash tolerance of the particle developed for gaseous fuels;
2. Demonstrate continuous CDCL operations in an integrated mode with > 99% coal (bituminous, sub-bituminous, and lignite) conversion as well as the production of high temperature exhaust gas stream that is suitable for steam generation in PC boilers;
3. Identify, via demonstrations, the fate of sulfur and NO_x;
4. Conduct thorough techno-economic analysis that validates the technical and economical attractiveness of the CDCL system.

Coal Direct Chemical Looping Retrofit to Pulverized Coal Power Plants for In-Situ CO_2 Capture

Key Tasks

Task 1: Project Management and Planning
Task 2: Particle Improvement
Task 3: Identification of Optimum Reducer Reactor Operating Conditions
Task 4: Design and Construction of the Bench Scale Unit
Task 5: Particle Finalization
Task 6: Bench Scale Demonstrations and Fates of Sulfur and NO_x
Task 7: Ash Separation and Particle Attrition
Task 8: Design and construction of Sub-Pilot scale CDCL system
Task 9: Integrated System Performance
Task 10: Techno-Economic Analysis

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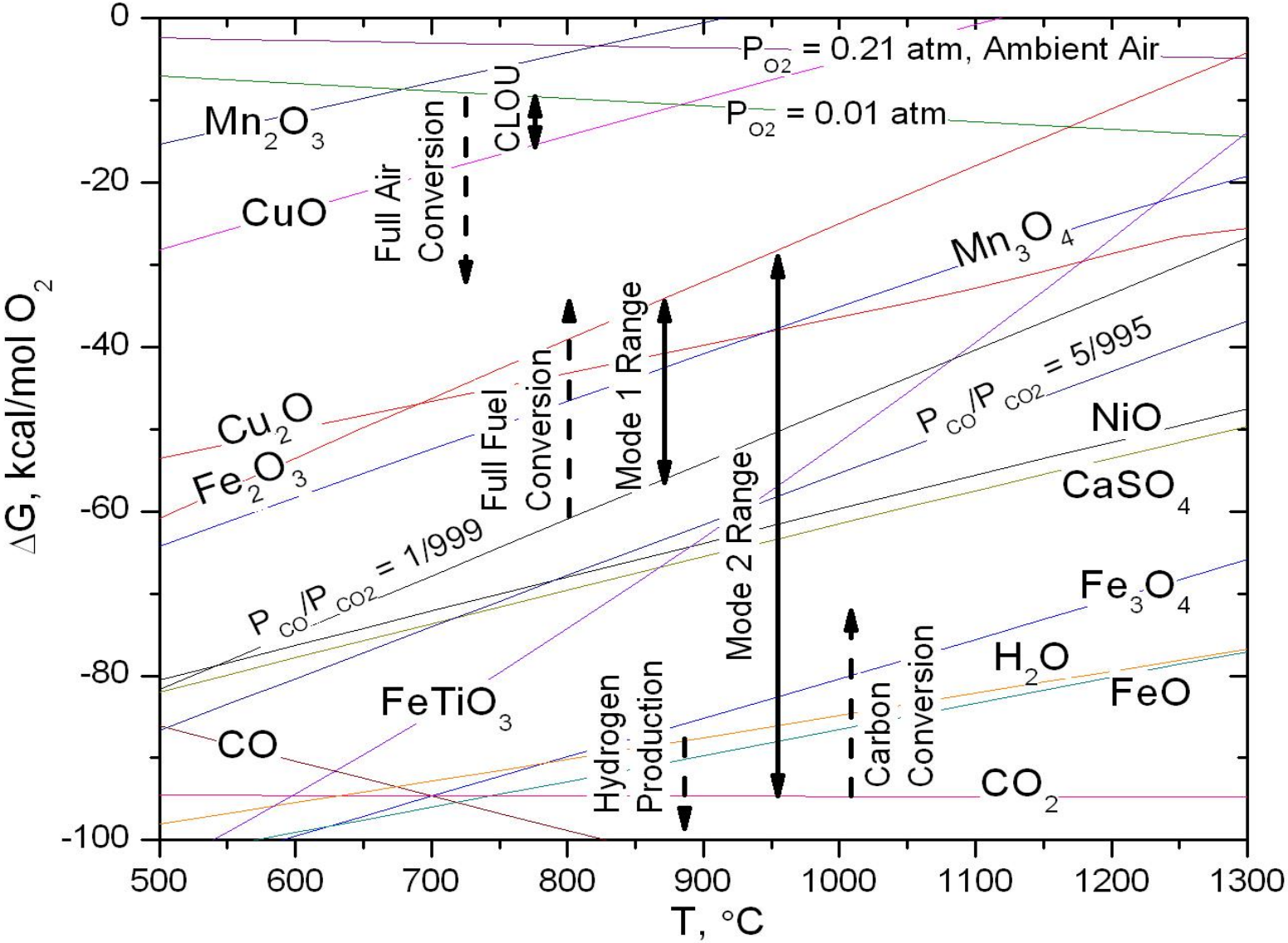
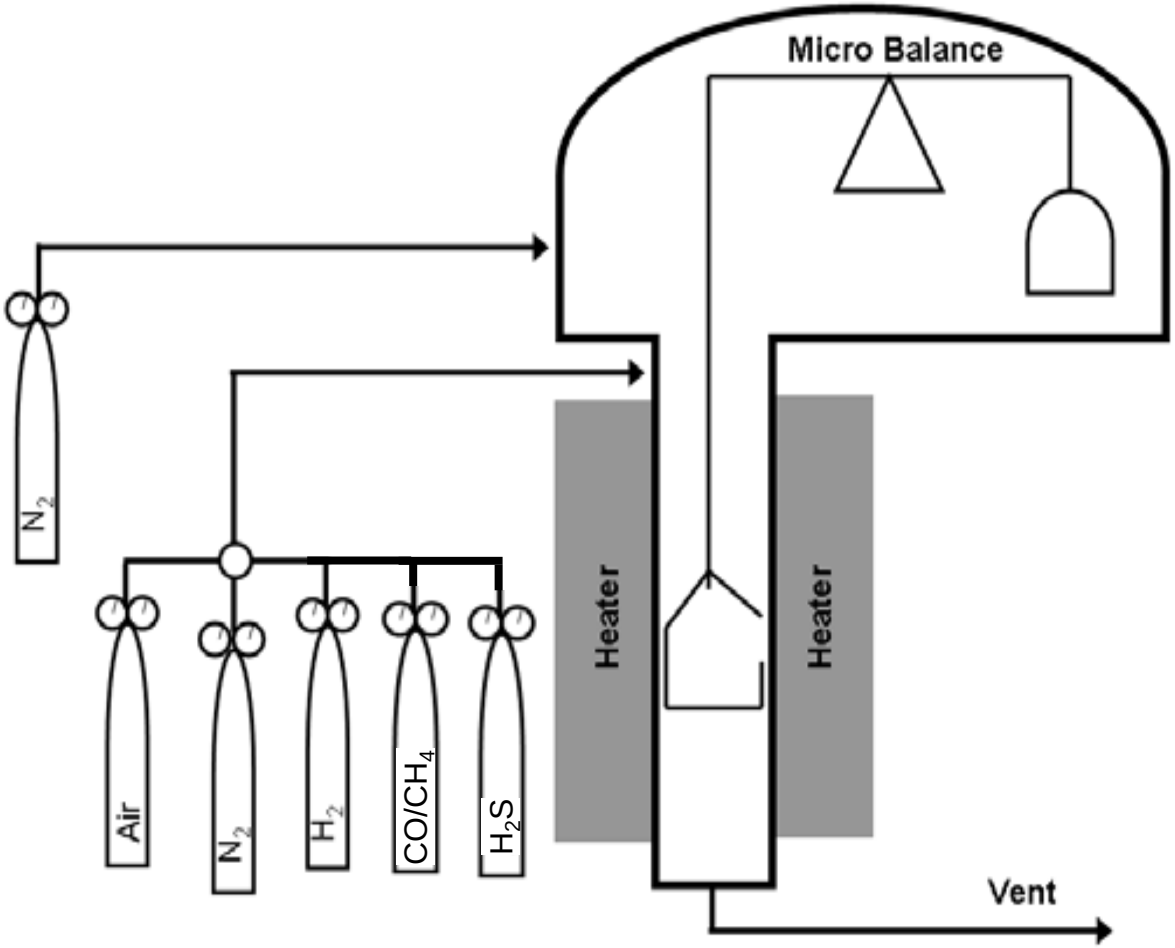
Phase 1:Oxygen Carrier Particle Development

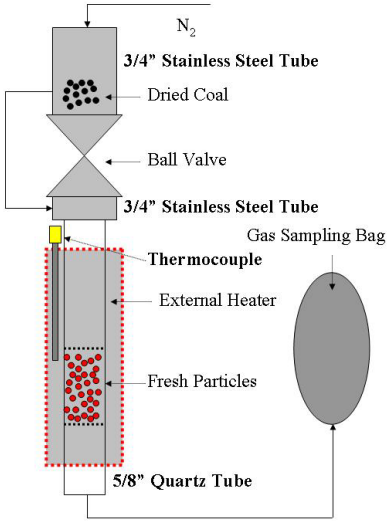
Ellingham Diagram: Selection of Primary Metal

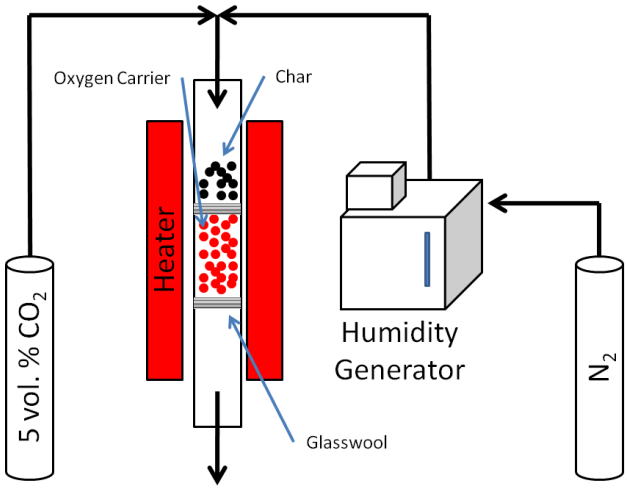


TGA studies with oxygen carriers

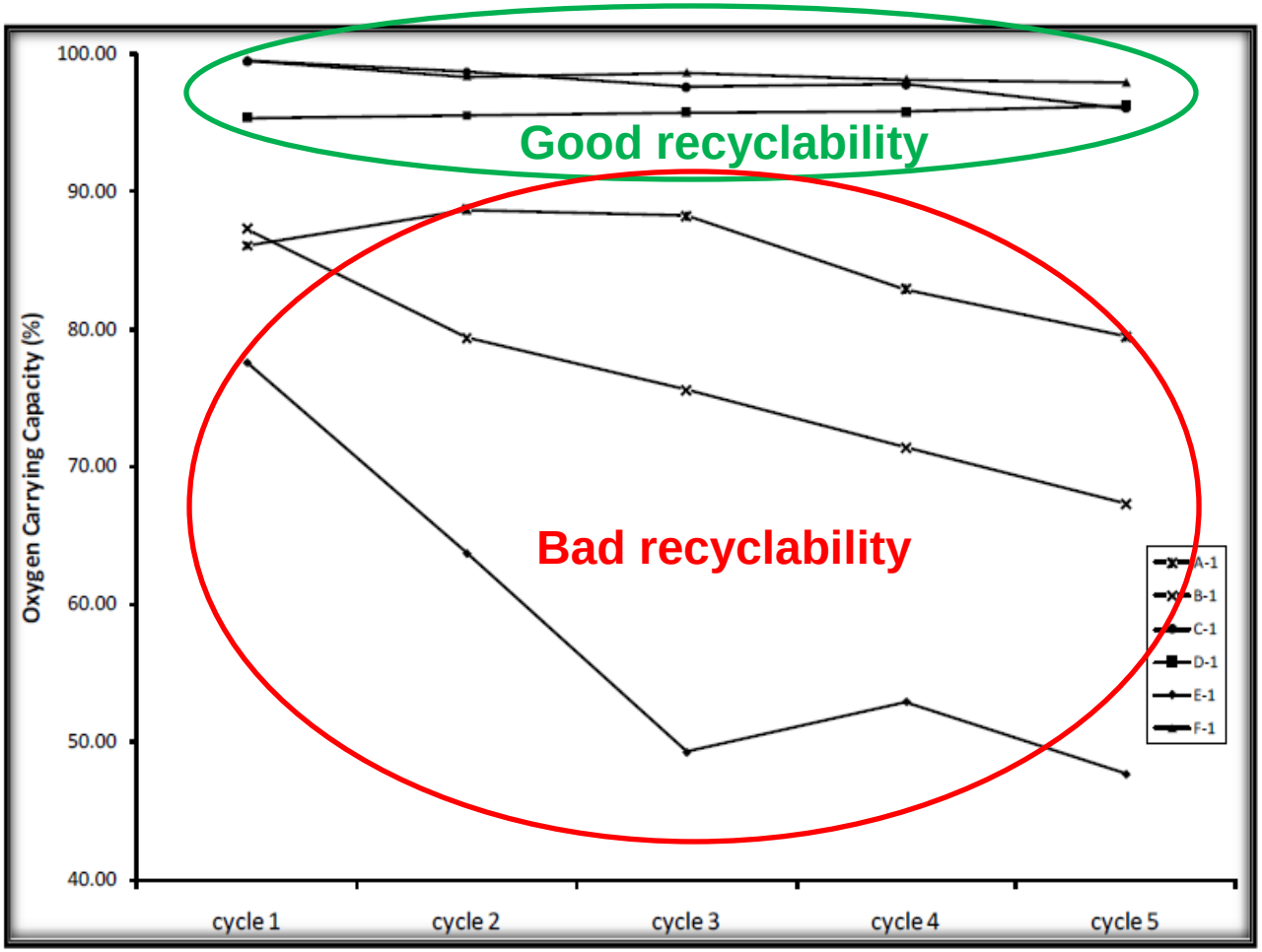


Fixed Bed Studies with Oxygen Carriers





Oxygen Carrier Particle Selection – Recyclability Test



- Oxygen Carrying Capacity = Ratio of Actual Carried Oxygen and Theoretical Value
- Oxygen Carrying Capacity vs. # of Cycles of Various OC

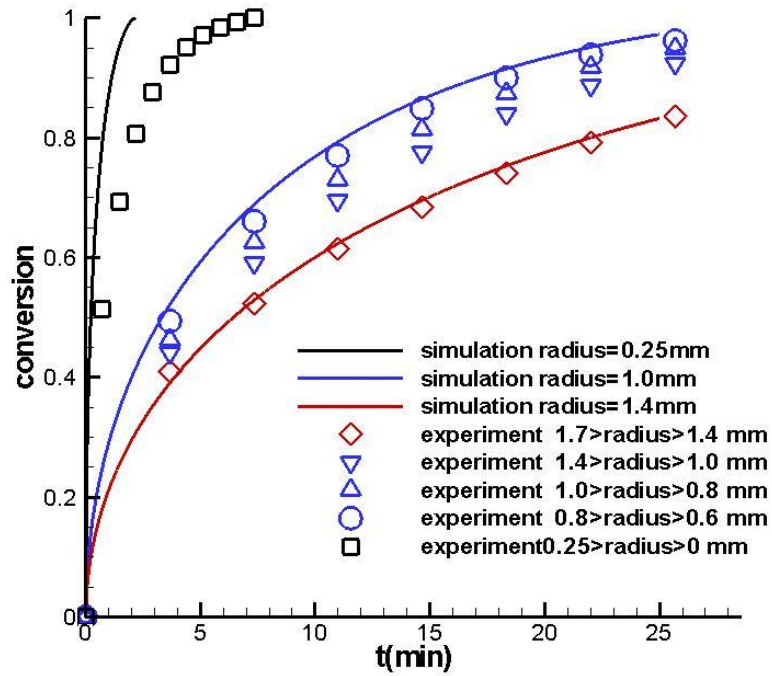
TGA - Oxygen Carrier Particle Reduction Kinetics

Three-interface unreacted shrinking core model (USCM) *

- Isothermal and isobaric conditions
- The pellet volume is unchanged
- First order reversible reaction

Three factors that affect the overall reaction rate

- **Diffusion through the gas film**
- **Intraparticle diffusion**
- **Chemical reaction at reaction interface**



Reaction rates at each reaction step:

$$r_1 = \frac{P}{\tilde{R}T\omega}\left\{\begin{array}{l} A_3(A_2+B_2+B_3+F)+(A_2+B_2)(B_3+F)(y-y_1^*) \\ -[A_3(B_2+B_3+F)+B_2(B_3+F)](y-y_2^*)-A_2(B_3+F)(y-y_3^*) \end{array}\right\}$$

$$r_2 = \frac{P}{\tilde{R}T\omega}\left\{\begin{array}{l} [(A_1+B_1+B_2)(A_3+B_3+F)+A_3(B_3+F)](y-y_2^*) \\ -[B_2(A_3+B_3+F)+A_3(B_3+F)](y-y_1^*)-(A_1+B_1)(B_3+F)(y-y_3^*) \end{array}\right\}$$

$$r_3 = \frac{P}{\tilde{R}T\omega}\left\{\begin{array}{l} [(A_1+B_1)(A_2+B_2+B_3+F)+A_2(B_2+B_3+F)](y-y_3^*) \\ -A_2(B_3+F)](y-y_1^*)-(A_1+B_1)(B_3+F)(y-y_2^*) \end{array}\right\}$$

$$A_i = \frac{1}{(1-R_i)^{2/3}}\frac{1}{k_i(1+1/K_i)} \qquad B_1 = \frac{(1-R_2)^{1/3}-(1-R_1)^{1/3}}{(1-R_1)^{1/3}(1-R_2)^{1/3}}\frac{d_p}{2D_1}$$

$$B_2 = \frac{(1-R_3)^{1/3}-(1-R_2)^{1/3}}{(1-R_2)^{1/3}(1-R_3)^{1/3}}\frac{d_p}{2D_2} \qquad B_3 = \frac{1-(1-R_3)^{1/3}}{(1-R_3)^{1/3}}\frac{d_p}{2D_3}$$

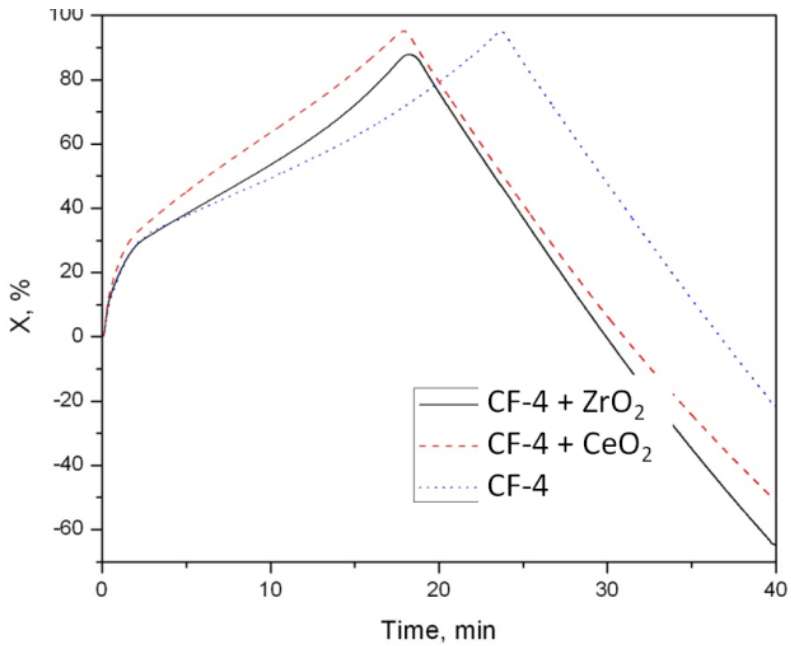
$$F = 1/k_f$$

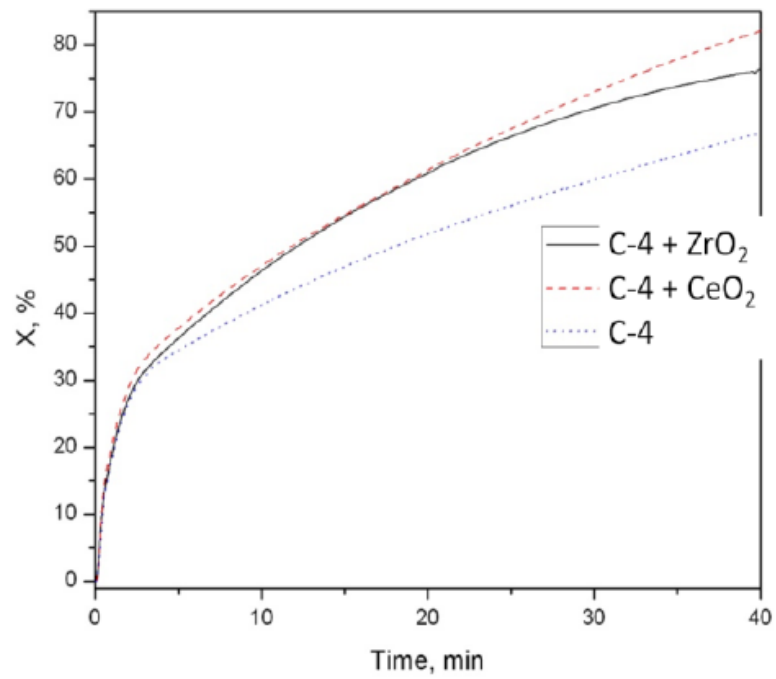
$$\omega = (A_1+B_1)[A_3(A_2+B_2+B_3+F)+(A_2+B_2)(B_3+F)]+A_2[A_3(B_2+B_3+F)+B_2(B_3+F)]$$

Yanagiya T., Yagi J., Omori Y. 1979 reduction of iron oxide pellets in moving bed. Ironmaking and steelmaking, No.3 93-100

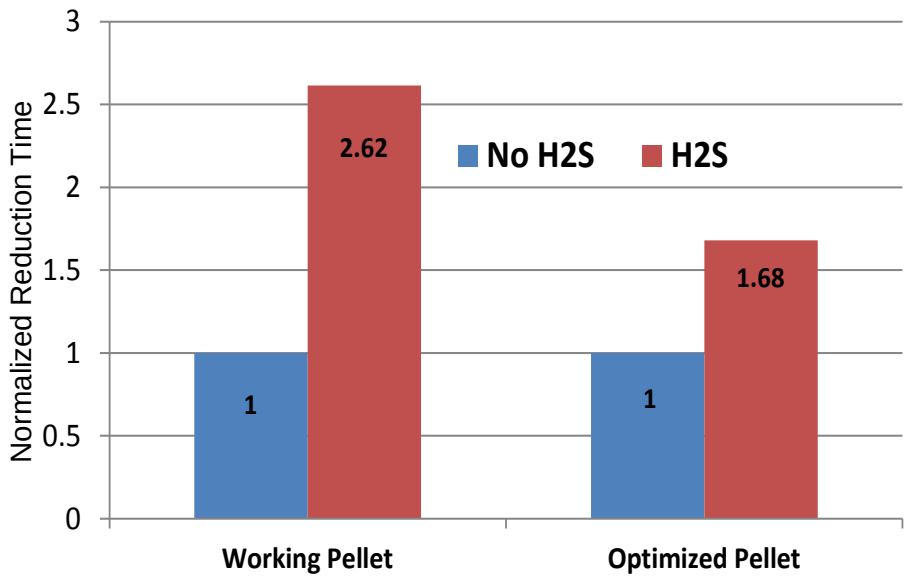
Oxygen Carrier Particle Selection – Carbon Deposition

- Dopant Addition: CeO_2 and ZrO_2 Increases Maximum Reduction Rate
- Increases Carbon Deposition Tolerance

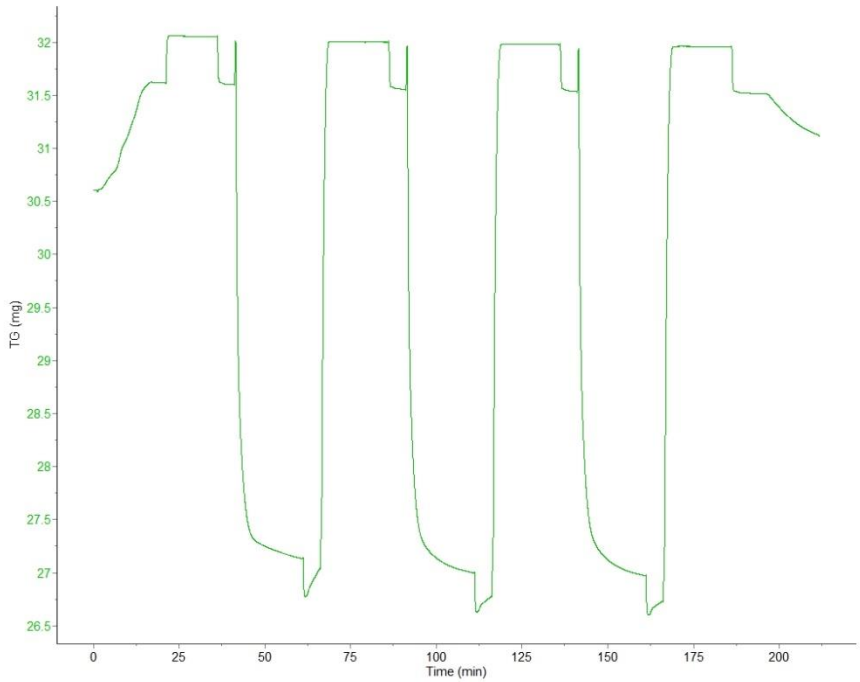




Oxygen Carrier Particle Selection – Effect of Sulfur

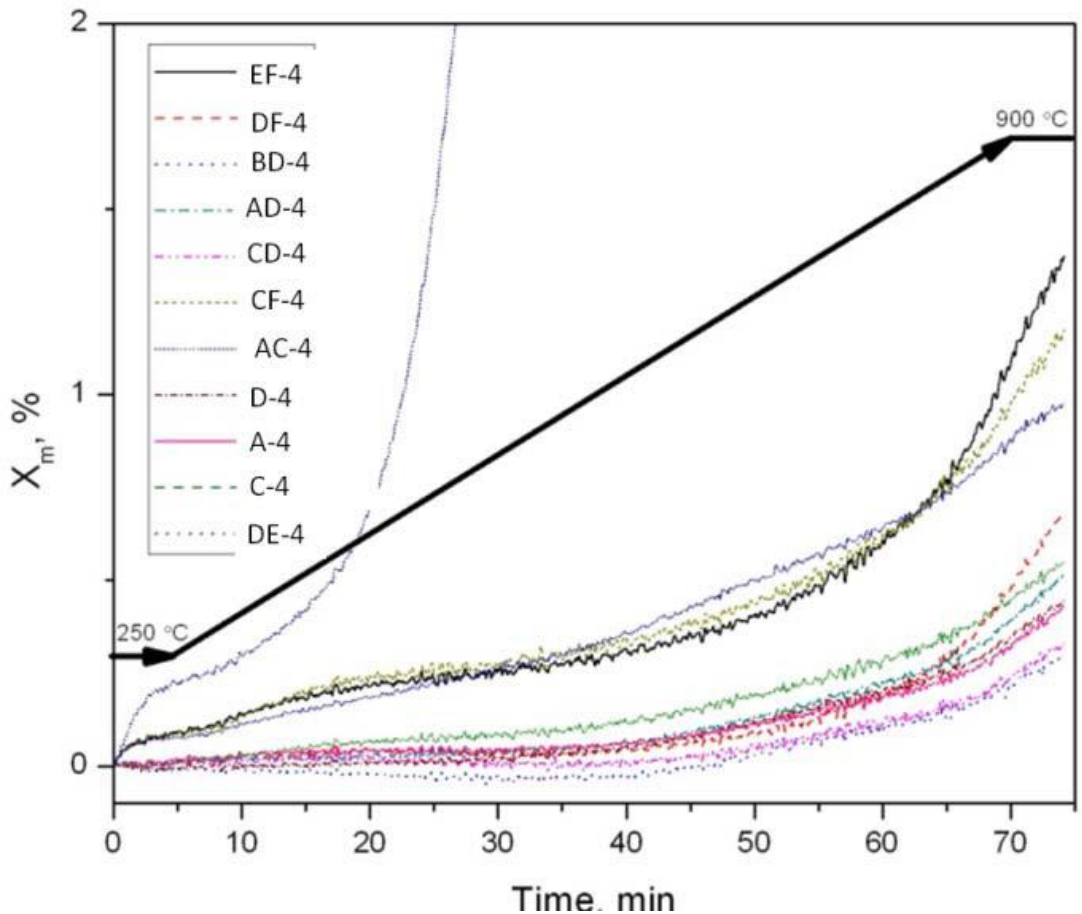


Effect of sulfur on the time of reduction for oxygen carrier particles; XRD results shows the formation of $Fe_{0.877}S$ after reduction



Reactivity and recyclability of sulfur poisoned oxygen carriers particle after air regeneration

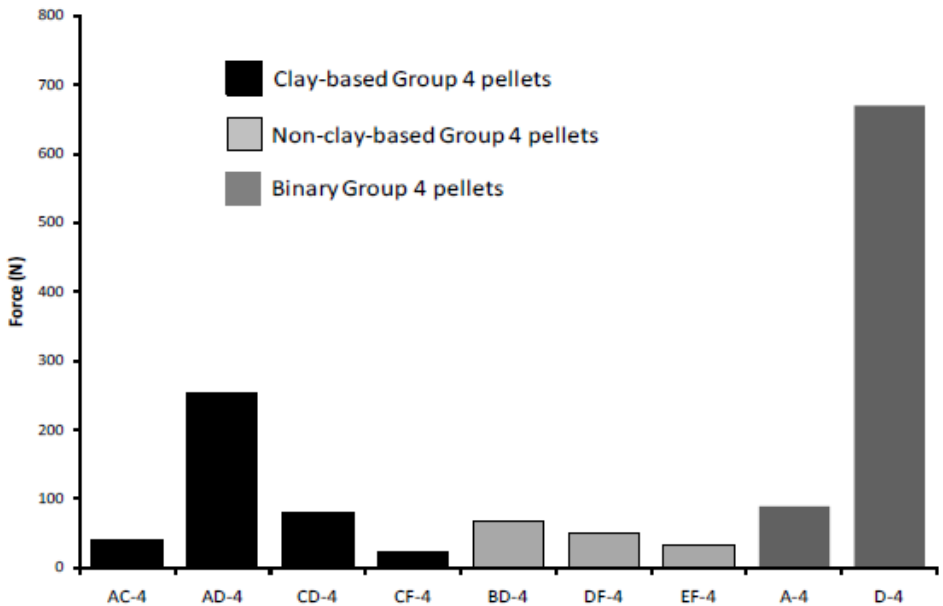
Oxygen Carrier Particle Selection – Reaction with Char

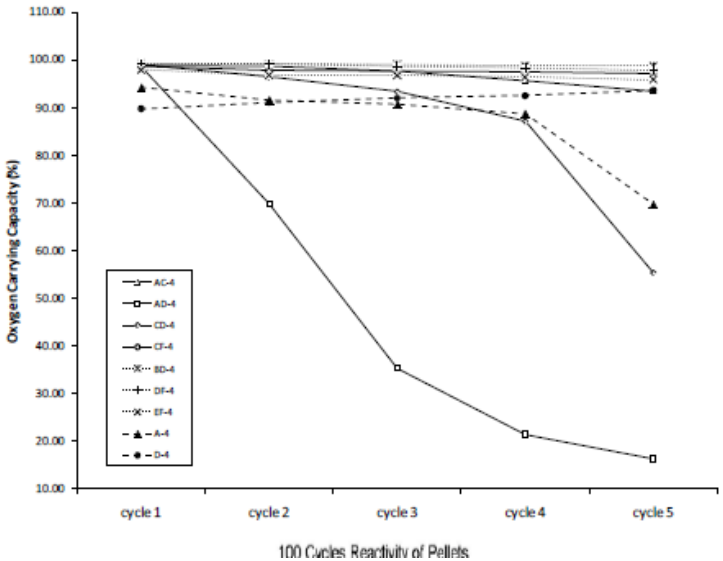


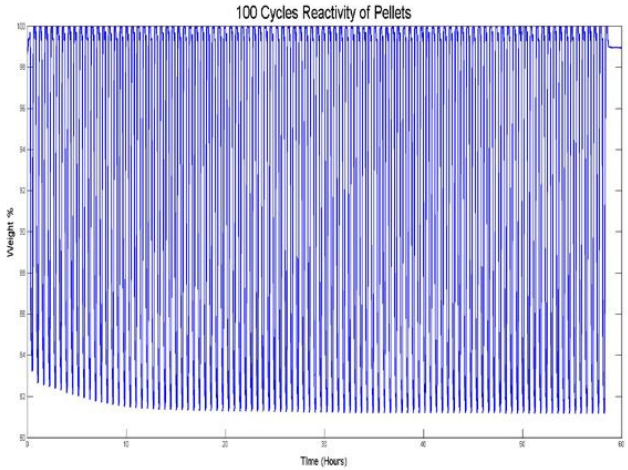
- OC/Char = 5-10
- Temperature
  - 25°C to 250°C
  - 250°C for Drying
  - 250°C to 900°C
- Less than 2 wt.% Loss

Solid-solid reaction between OC and char is slow.

Oxygen Carrier Particle Selection – Pelletization







Pellet Strength

- Support affects pellet strength
- Bentonite and kaolinite

Pellet Reactivity

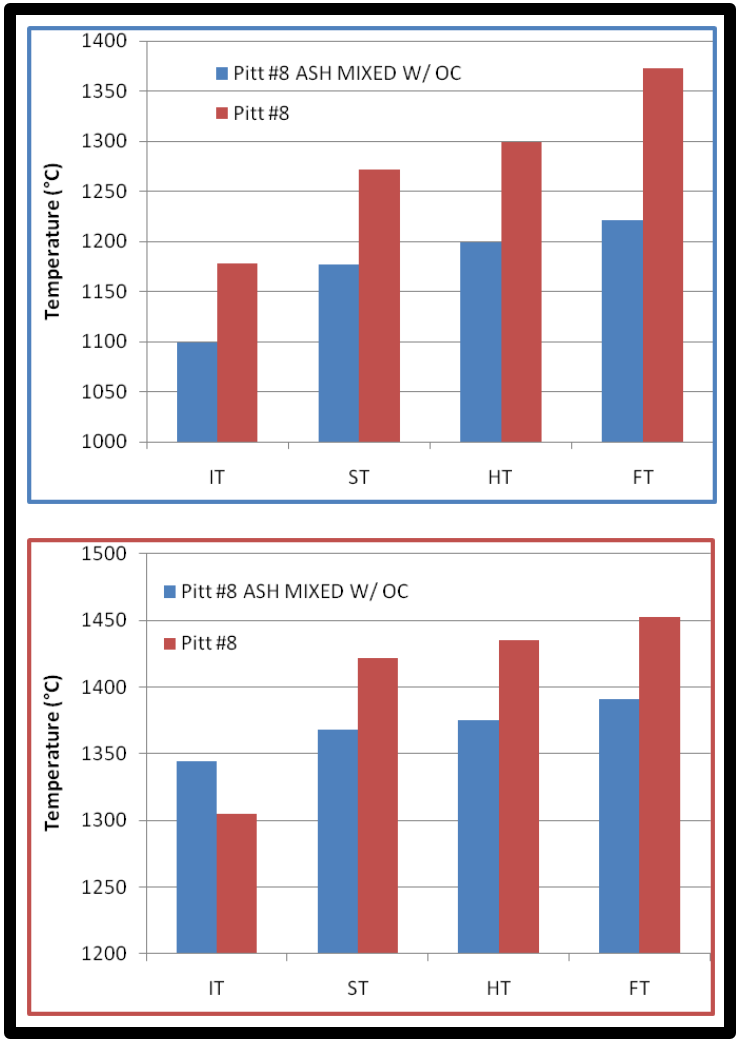
- Needs to maintain the reactivity of fine powder form

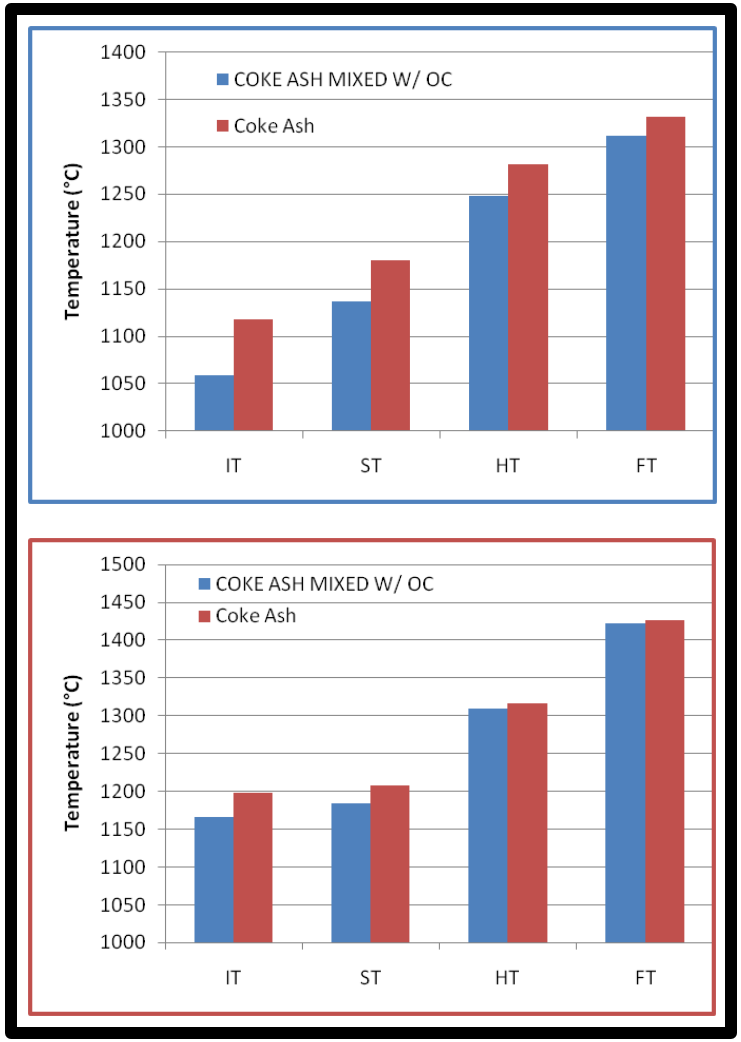
100-Cycle test achieved with a pellet.

Ash Study

Reducing Environment

Oxidizing Environment

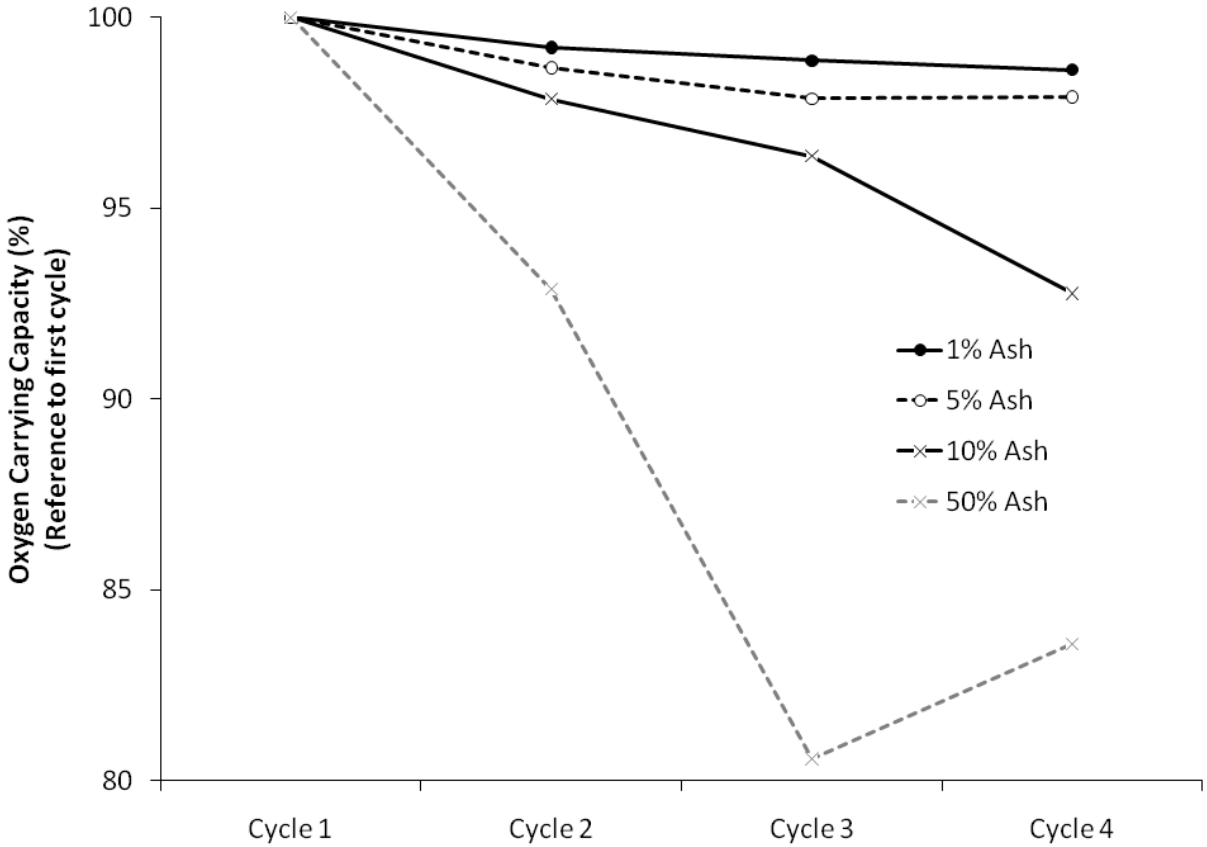




Effect of OC on ash deforming temperature is minimal.

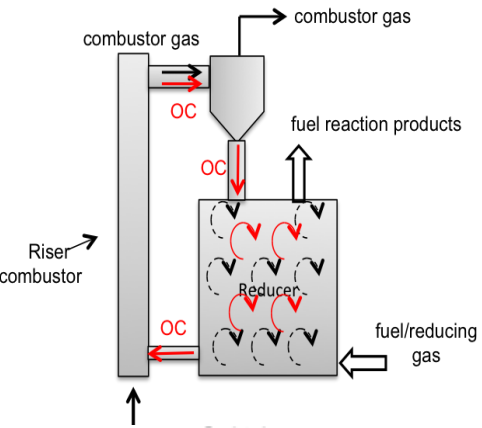
Useful Data for combustor operation & Ash separation

Effect of ash on the reactivity and recyclability of oxygen carriers

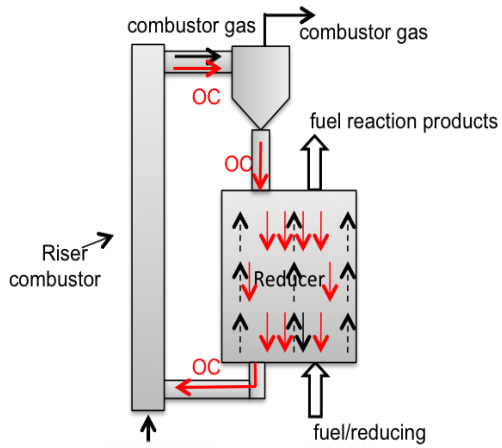


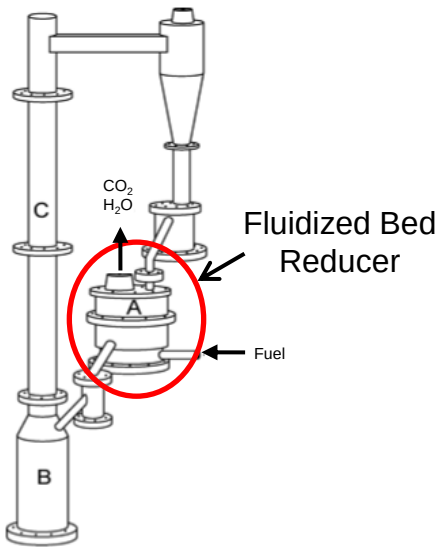
Modes of CFB Chemical Looping Reactor Systems

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

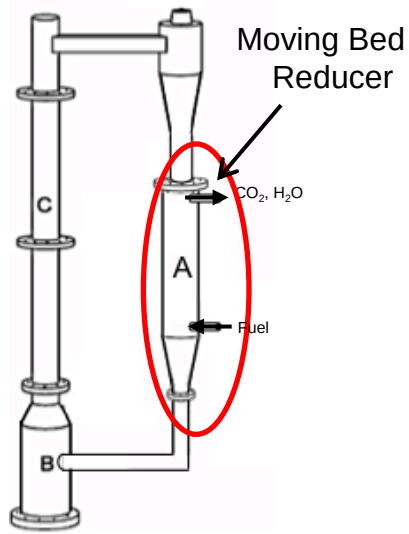


Mode 2 - reducer: gas-solid (OC) counter-current dense phase/moving bed flows





Chalmers University CLC System



OSU CLC System

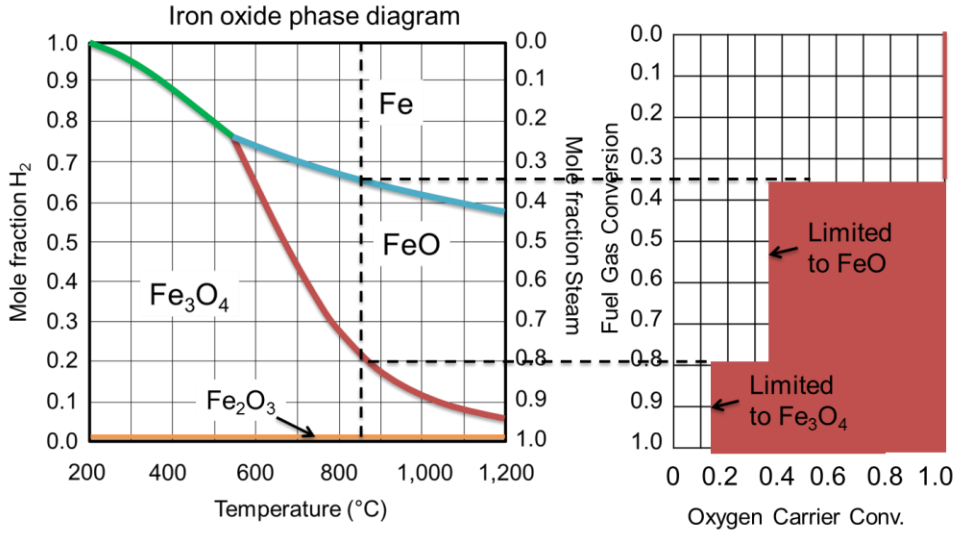
Reducer	Mode 1	Mode 2
Operation Regime	Bubbling, turbulent, fast fluidized, or spouted bed	Moving packed, or multistage fluidized bed
Gas Solid Contacting Pattern	Mixed/Cocurrent	Countercurrent
Controllability on Fuel and OC Conversions	Poor, due to back mixing and gas channeling	High
Maximum Iron oxide 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

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)

Phase II: Reducer Reactor Design and Testing

Phase Diagram – Thermodynamic Restrictions



Shaded area is not reducer operation zone

Operating Equation for Moving Bed Reducer

Fixed solid molar flowrate n_{Fe},

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

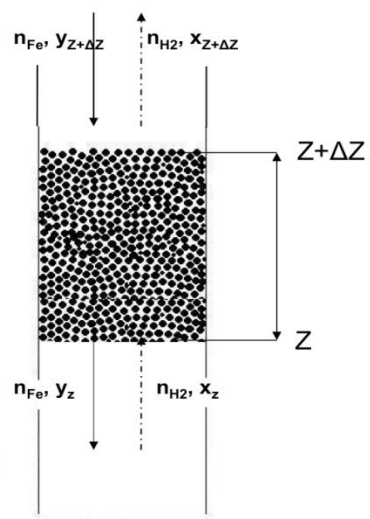
Fixed gas molar flowrate $n_{H2} + n_{H2O}$,

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

Oxygen Balance

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

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

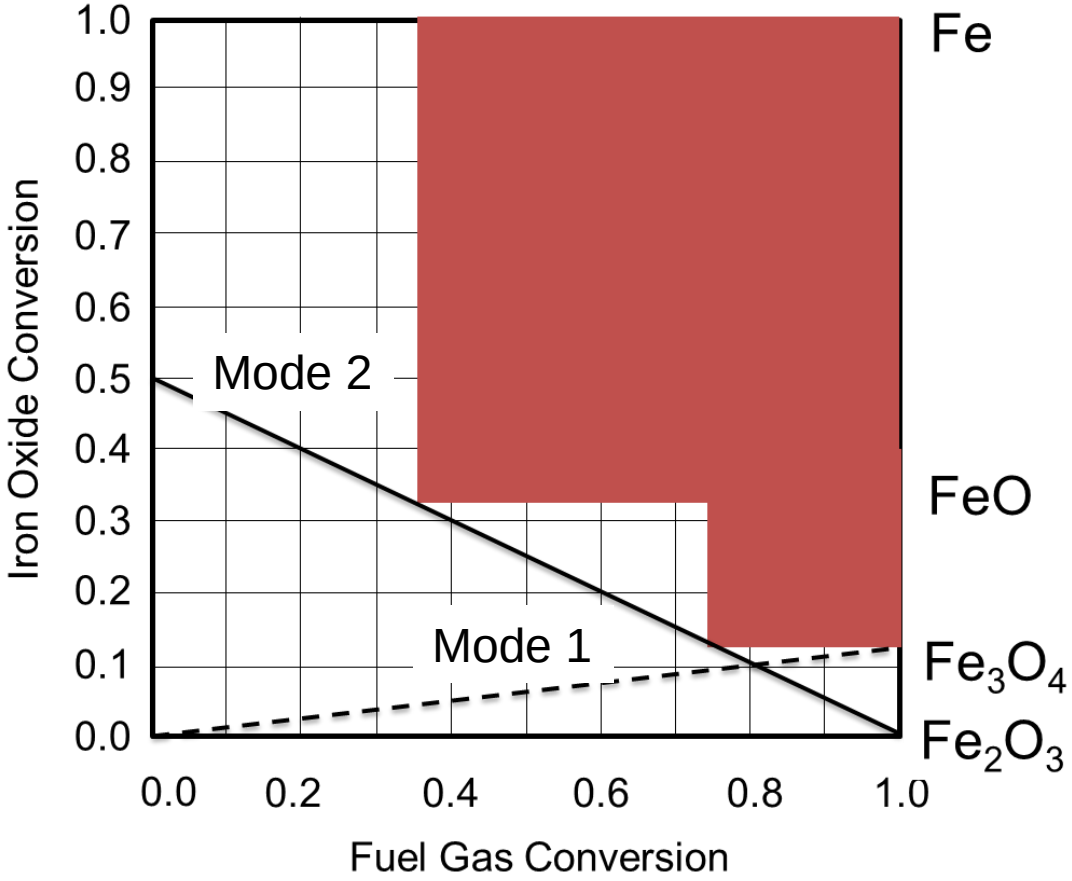


Countercurrent moving bed: straight operation line with negative slope

Similarly, Concurrent fluidized bed: straight operation with positive slope

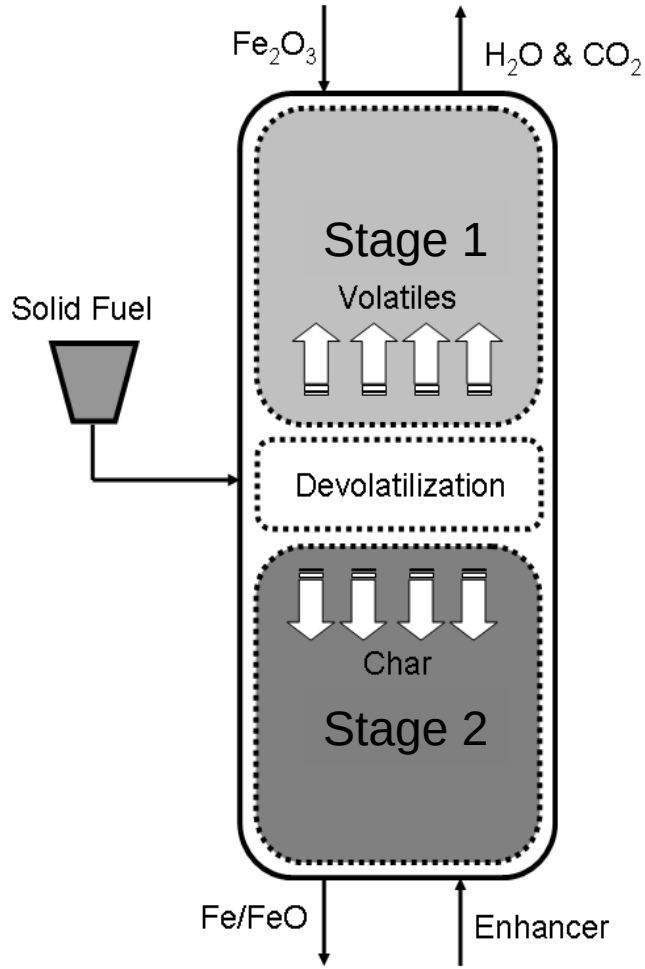
Phase II: Reducer Reactor Design and Testing

Operation Diagram



The operating line is straight when feeding ratio is fixed: solid line represents countercurrent moving bed operation, dash line represents co-current fluidized bed operation

Reducer Reactor Design



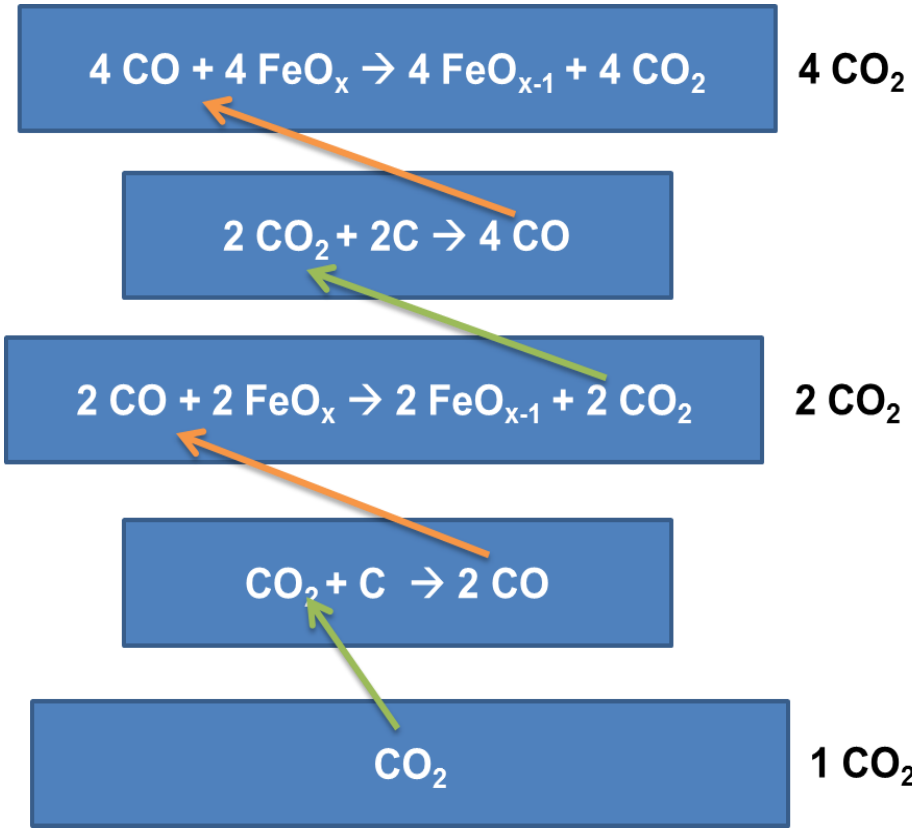
Particle reduction :
$CH_4 + Fe_2O_3 \rightarrow CO_2 + H_2O + FeO$

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

Enhancer Gas



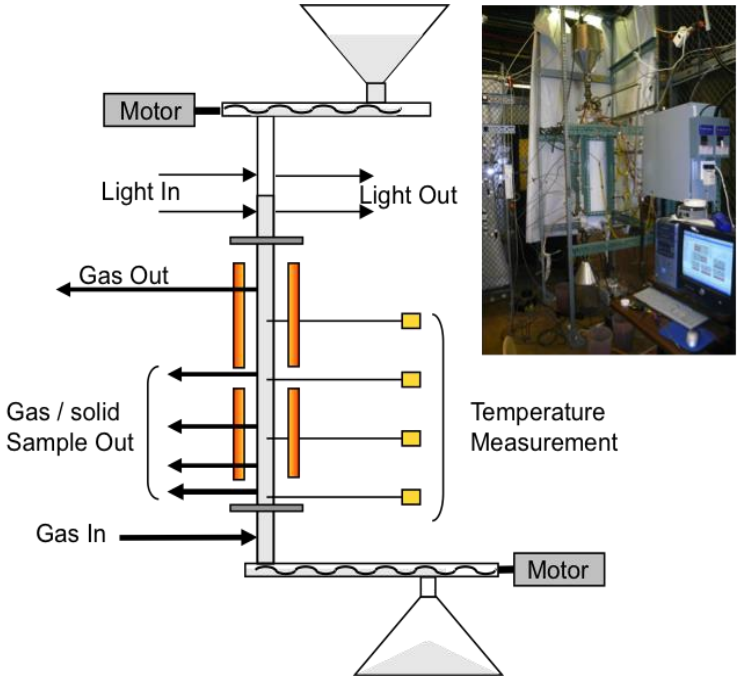
Two-stage moving bed

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

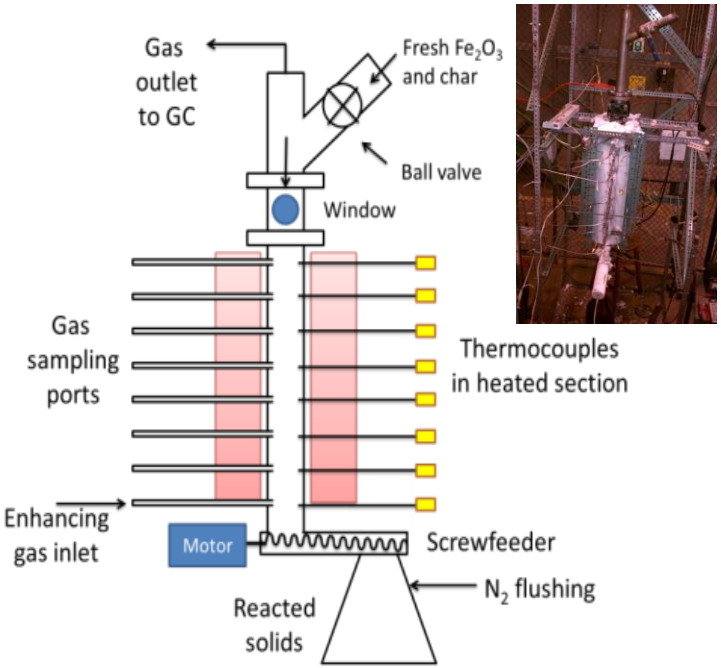
Thomas, T., L.-S. Fan, P. Gupta, and L. G. Velazquez-Vargas, "Combustion Looping Using Composite Oxygen Carriers" U.S. Patent No. 7,767,191 (2010, priority date 2003)

Phase II: Reducer Reactor Design and Testing

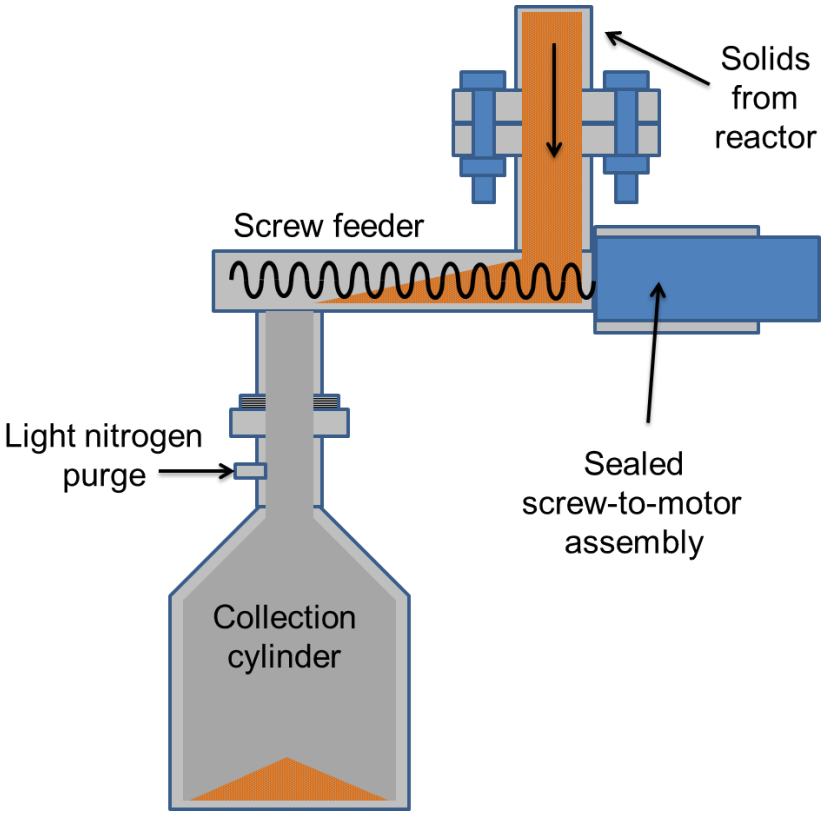
Stage I – Volatile Conversion (Previous Experimental Setup)



Stage II – Char Conversion (Modified Experiment Setup)



Solids Conveyance

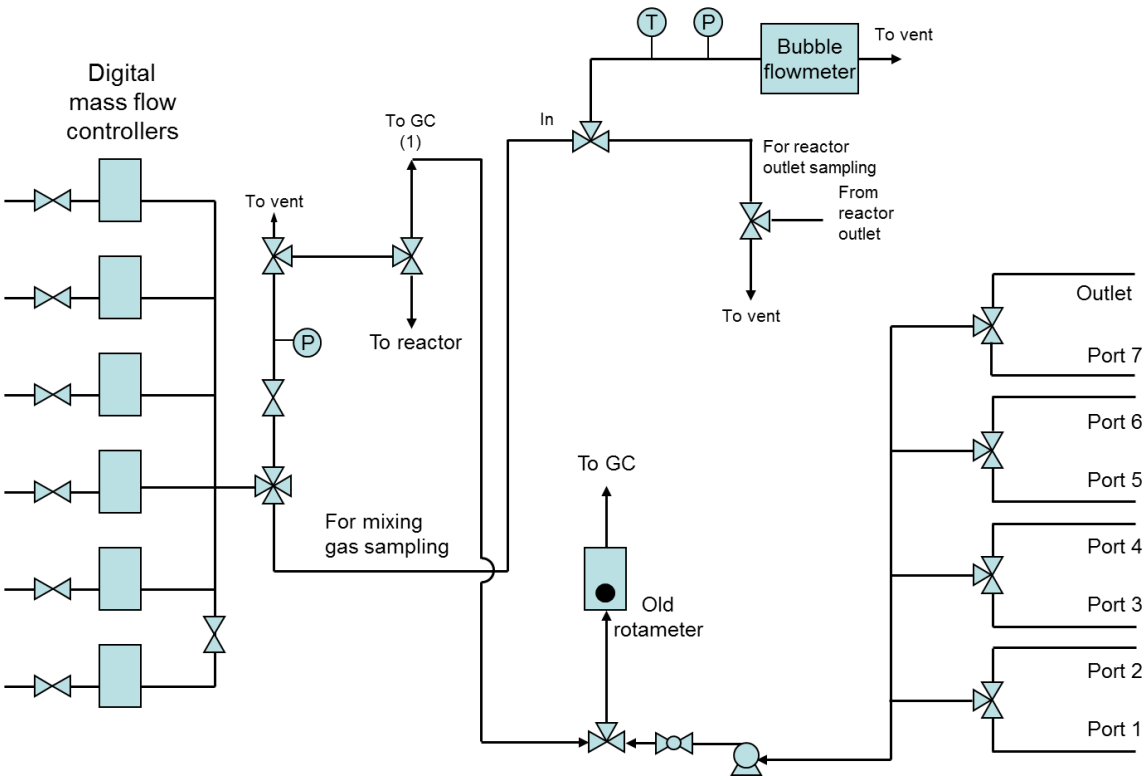


- Sealed screw feeder design
- Solids exit into sealed collection cylinder
- Screw controlled by 24 V DC motor
- Flow calibration before and after tests

Gas Mixing Panel

New Gas Mixing Panel built to serve these purposes:

- Controlled flow rates of nitrogen and CO_2
- Sample port selection to GC
- Gases for calibration of GC
- Measure alternate flow rate with bubble flowmeter



Fuel Feedstock Studied in both Bench and Subpilot Units

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 **(25 kW_{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
Coke	Petroleum Coke	1.98-5.95	CO_2/H_2O

Successful results for all coal/coal derived feedstock tested

Experiment Design-Sample Case

- Sample Fuel: Bituminous coal char (Metallurgical coke breeze)

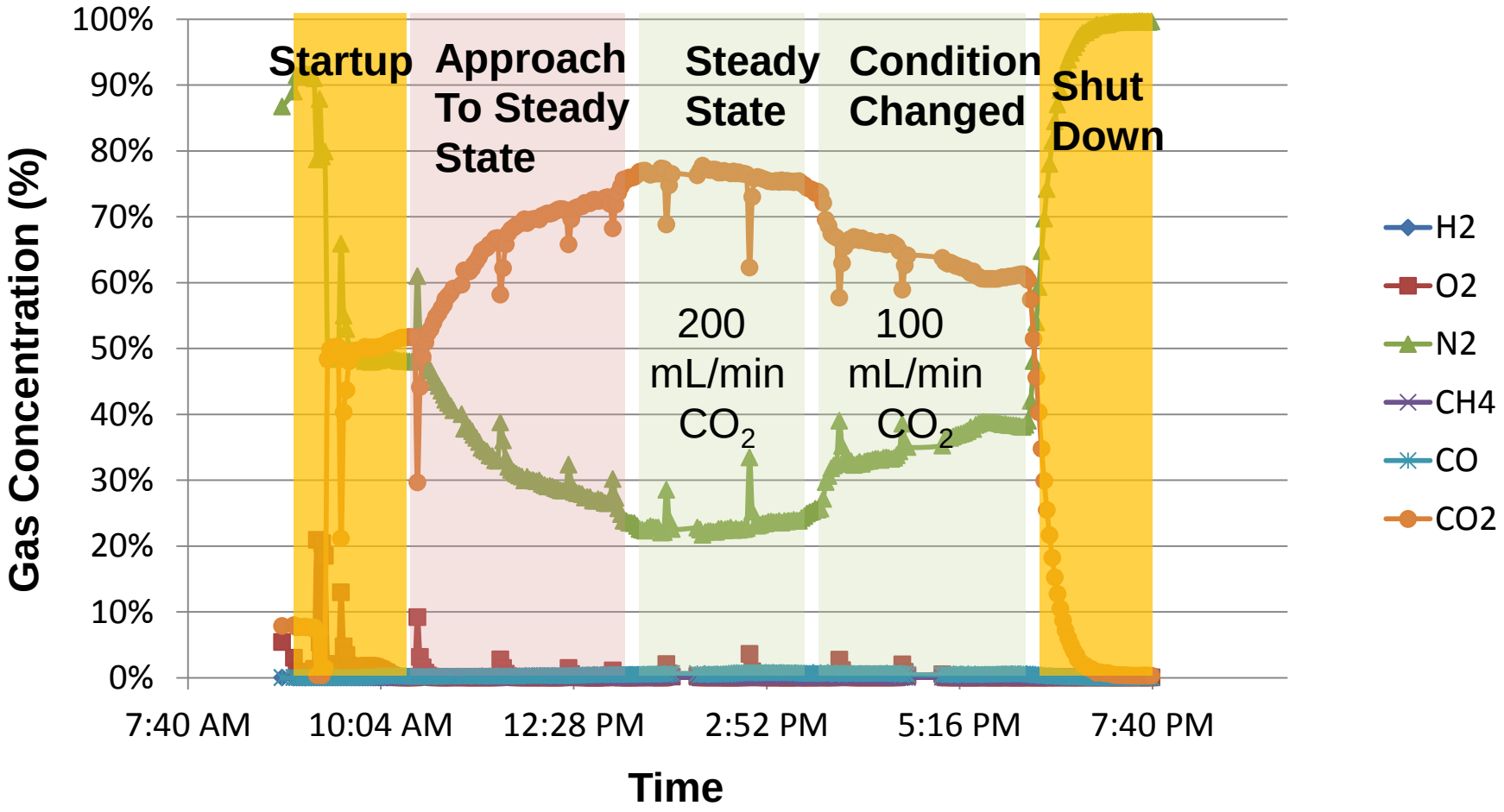
Ultimate Analysis	**Moist**	**Ash**	**Vol**	**Carbon**	**Sulfur**
Weight%	0.18	12.66	2.89	84.44	0.7047
Size Analysis (mesh)	**100**	**200**	**325**	**400**	**PAN**
Size%	0.12	3.25	16.13	9.27	71.23

- Oxygen Carrier: Fe_2O_3
  - Particle size: 5 mm diameter cylinder
- Manipulated Variables:
  - Temperature
  - Solids (Oxygen carrier) flow rate
  - Iron oxide to char ratio
  - Effect of the enhancing gas (CO_2, H_2O)
  - Flowrate of the enhancing gas

Key Variables to Measure

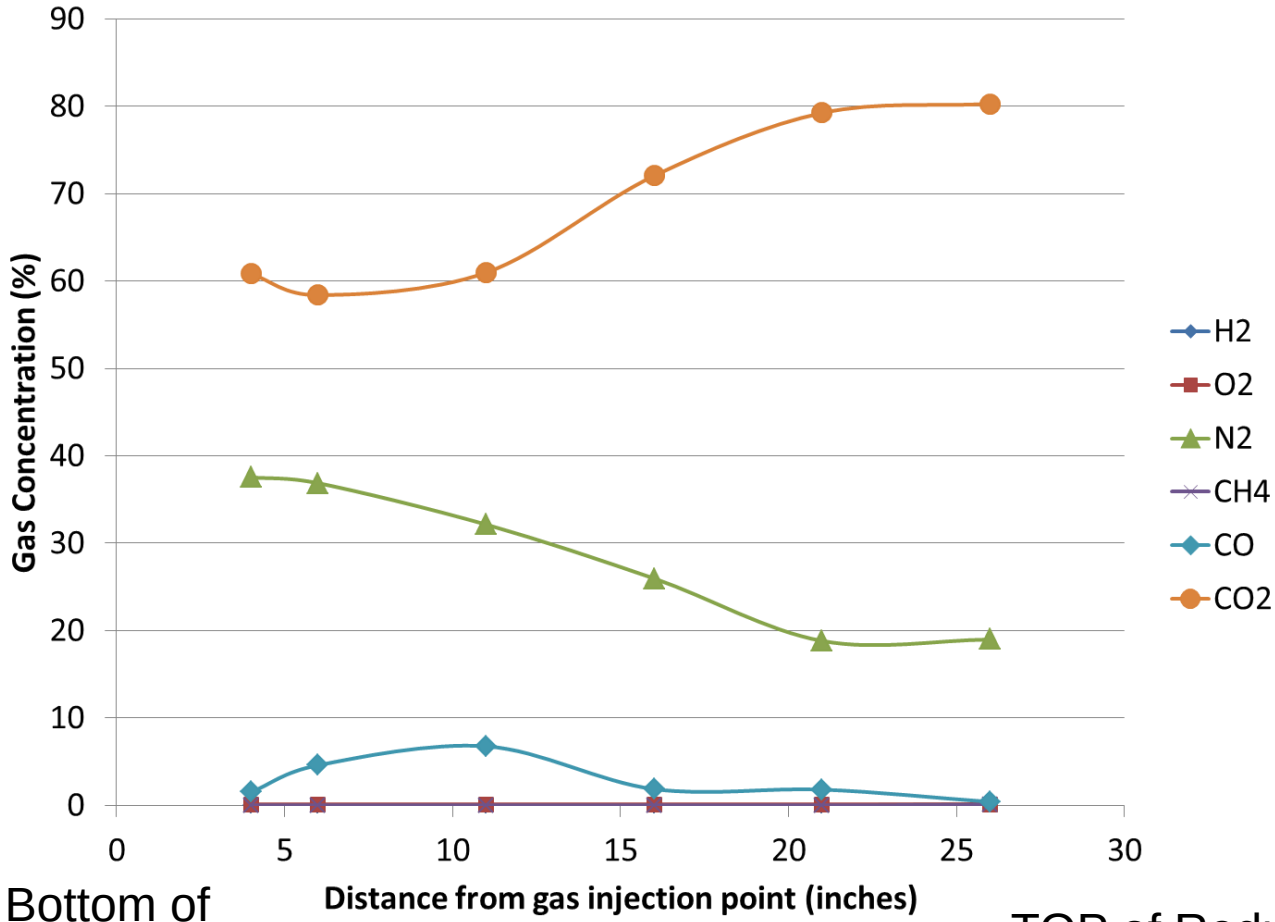
- Fuel conversion
  - Volatile and char conversion profile
  - Using mass balance and micro-GC
- Oxygen carrier conversion
  - Iron oxide conversion profile
  - Using TGA and/or Carbon Analyzer Sampler
- Carbon deposition on particles

Typical Conversion Profile



200 and 100 mL/min CO_2,
200 mL/min N_2,
10 g/min oxygen carrier, Oxygen carrier to char ratio of 30:1.

Species Distribution Along Reducer

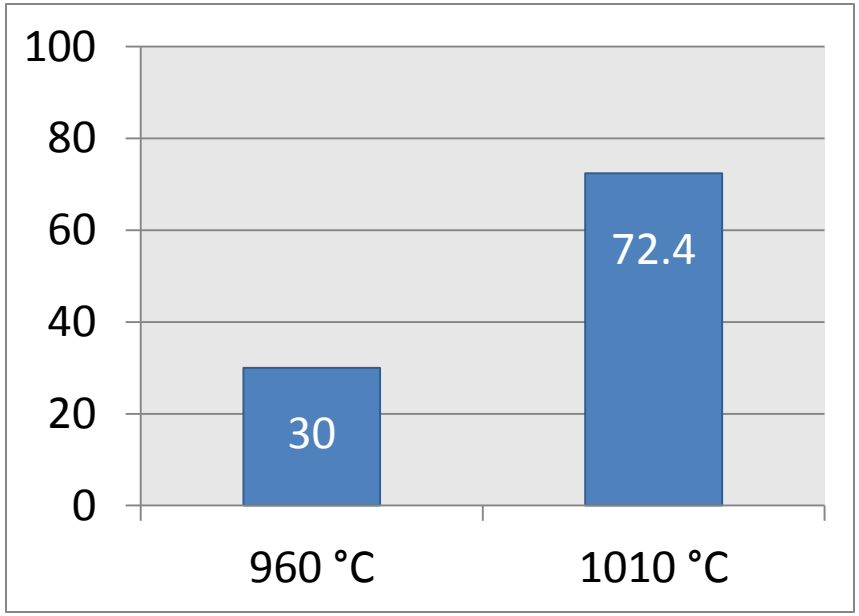


Bottom of Reducer

TOP of Reducer

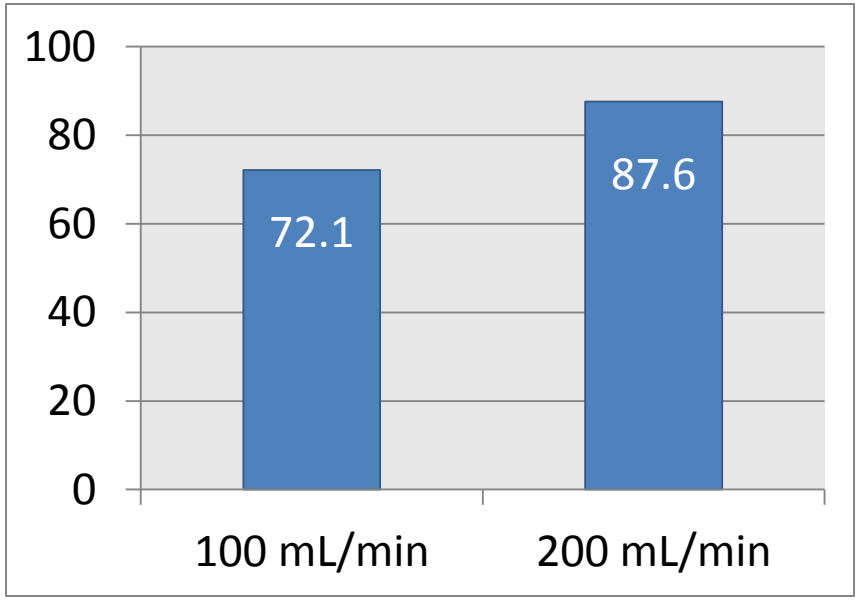
Conditions:
250 mL/min steam,
200 mL/min N_2,
9.6 g/min oxygen carrier,
Oxygen carrier to char ratio of 30:1.

Fuel Conversion with Temperature



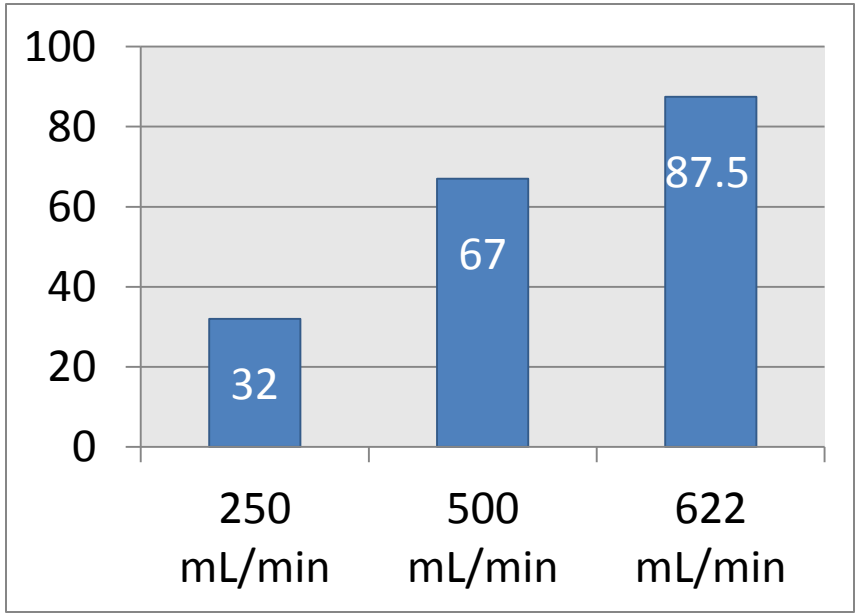
- Oxygen Carrier Flowrate: 20.2 g/min
- O.C./Fuel Weight Ratio: 30.0
- CO_2 Flowrate: 600 mL/min
- N_2 Flowrate: 200 mL/min
- Fuel: Bituminous Char

Fuel Conversion with CO_2 Flowrate



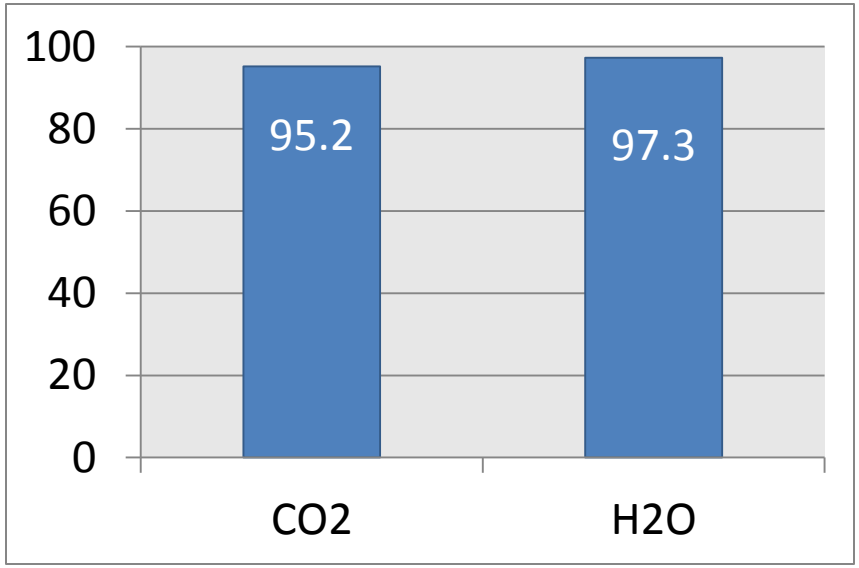
- Enhancing Gas: CO_2
- Oxygen Carrier Flowrate: 9.6 g/min
- O.C./Fuel Weight Ratio: 30.0
- N2 Flowrate: 200 mL/min
- Fuel: Bituminous Char
- Temperature: 1020 °C

Fuel Conversion with Steam Flowrate



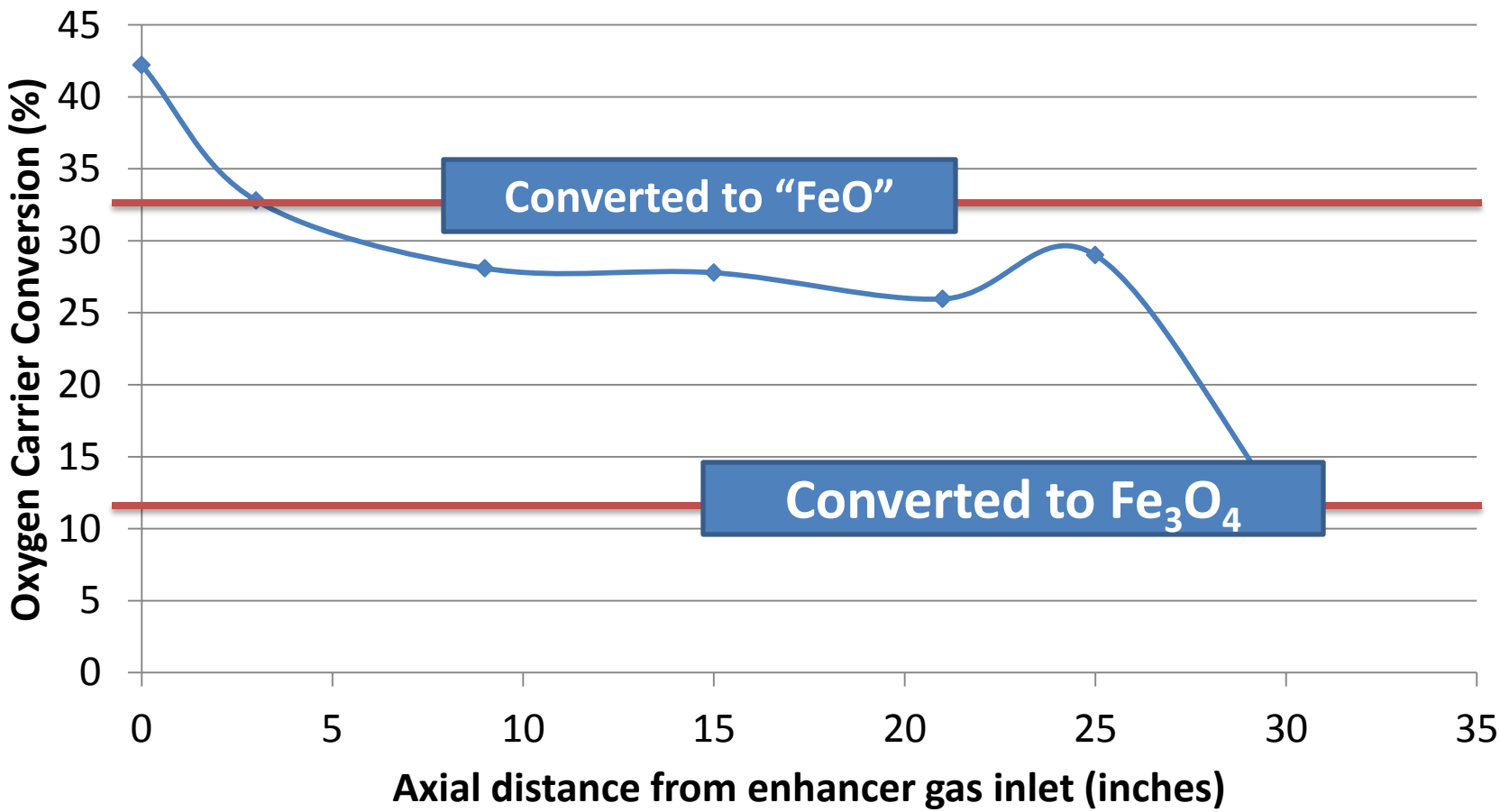
- Enhancing Gas: H_2O
- Oxygen Carrier Flowrate: 9.9 g/min
- O.C./Fuel Weight Ratio: 30.0
- N2 Flowrate: 200 mL/min
- Fuel: Bituminous Char
- Temperature: 1010 °C

Conversion with CO_2 or H_2O



- Oxygen Carrier Flowrate: 10 g/min
- O.C./Fuel Weight Ratio: 36.0
- Temperature: 1055 °C
- N_2 Flowrate: 200 mL/min
- Fuel: Bituminous Char

Iron Oxide Conversion Profile



Run 2: Oxygen Carrier Flowrate: 10 g/min, OC/Fuel Ratio: 36, Enhancing Gas Flowrate : H_2O at 200 mL/min, N_2 flowrate: 200 mL/min, Max. Temp.: 1055°C

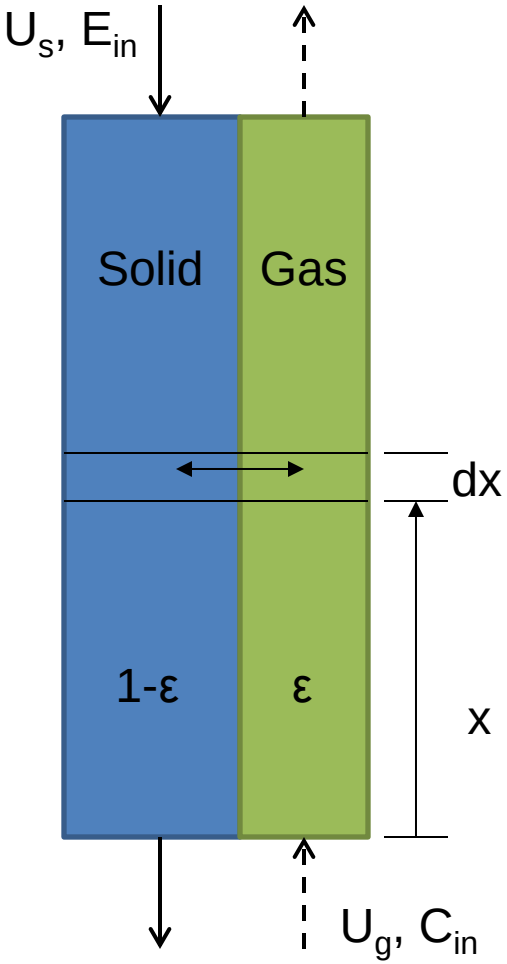
1-D Reducer Modeling

- Assumptions:
  - Both gas and solid streams are in plug flow.
  - Three-interface USCM for representing the overall reaction rate of the pellet.
  - Negligible temperature difference between gas and solid.
- Governing Equations
  - Gas Phase
  - Solid Phase

$$\frac{\partial \varepsilon C_i}{\partial t} = -Ug_i \frac{\partial \varepsilon C_i}{\partial x_i} + \sum_l \upsilon_{li} \frac{6(1-\varepsilon) r_l}{d_p}$$

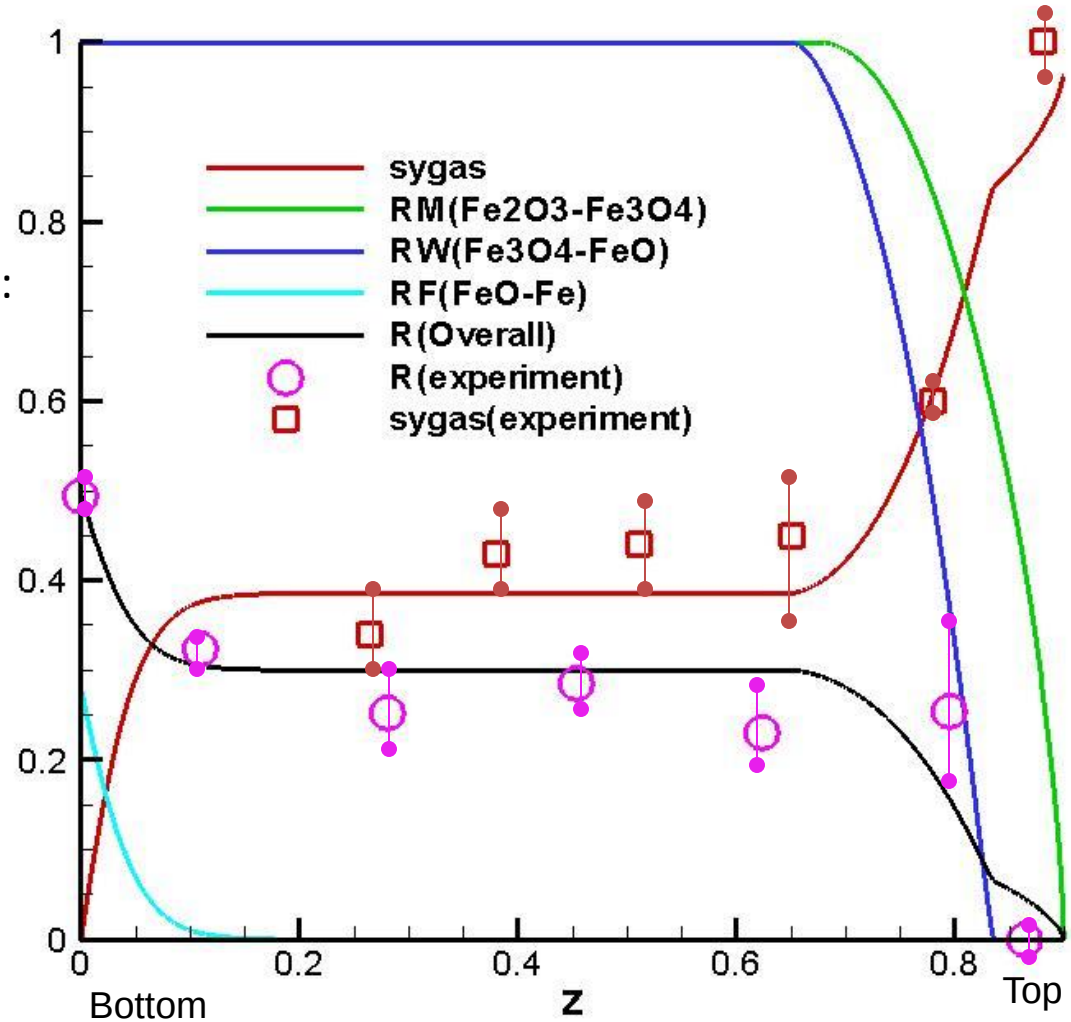
$$\frac{\partial E_i}{\partial t} = -Us_i \frac{\partial E_i}{\partial x_i} + \sum_l \upsilon_{li} \frac{6(1-\varepsilon) r_l}{d_p}$$

- Numerical Methods
  - Temporal terms are discretized by third order Runge-Kutta schemes
  - Spatial terms are discretized by fifth order schemes



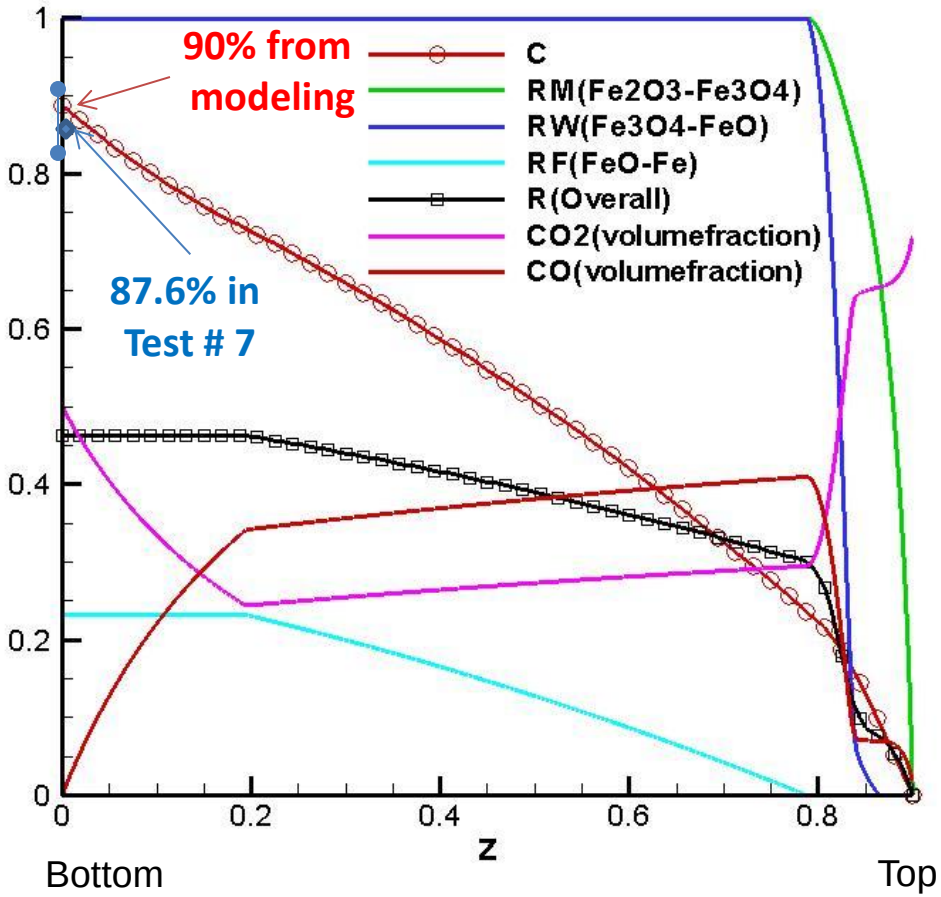
Stage I Modeling: Volatile Conversion

- Reactor modeling validated by previous bench scale syngas test results
  - Reaction： Iron Oxide reduced by sygas:
  - Initial mole fraction of sygas in gas: 72.9%
  - Mass fraction of Iron Oxide in particle： 60%
  - Solid feedrate: 12.87g/min
  - Diameter of the reducer: 4.06 cm
  - Density of solids： 2500 g/cm^3
  - Voidage of reducer 0.40g
  - Diameter of solid: 4mm
  - Gas feedrate: 1.683 mol/s
  - Temperature: T=1273K
  - Pressure: P=1 atm



Stage II Modeling: Char Conversion

Stage II Modeling Results



Stage II Bench Test Results

#	OC flowrate (g/min)	CO_2 flowrate (mL/min)	N_2, flowrate (mL/min)	T, (°C)	X_C (%)
7	WP-5mm, 9.6	200	200	1000	87.6
17	OP-1.5mm, 10.9	200	200	1000	95.2

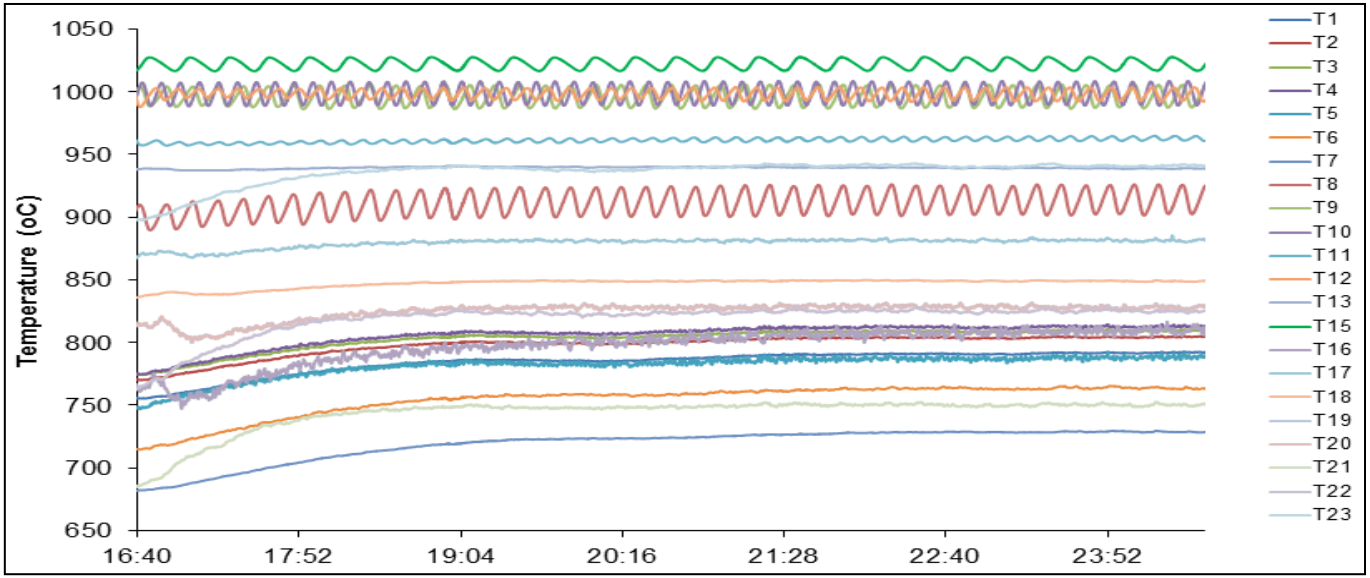
Both individual particle kinetics model and moving bed reactor model have been developed and validated by experimental results, and helped the reducer design and operation optimization.

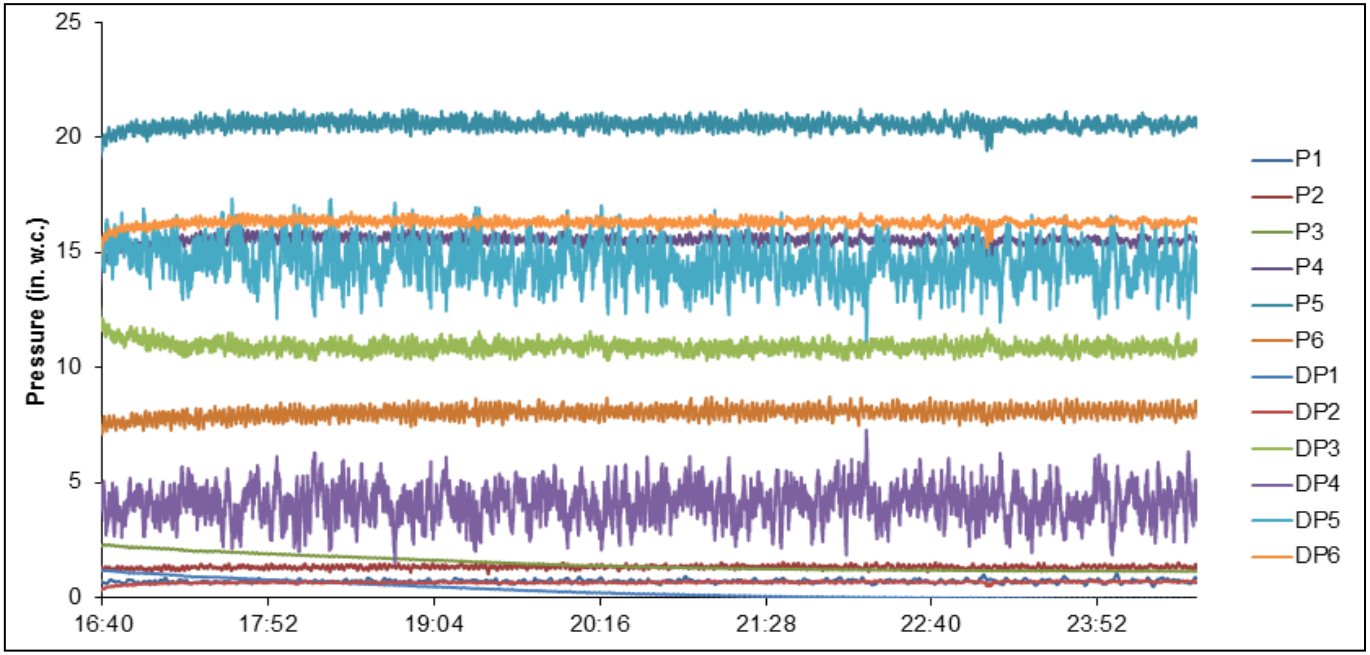
25 kW_{th} Sub-Pilot Demonstration

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

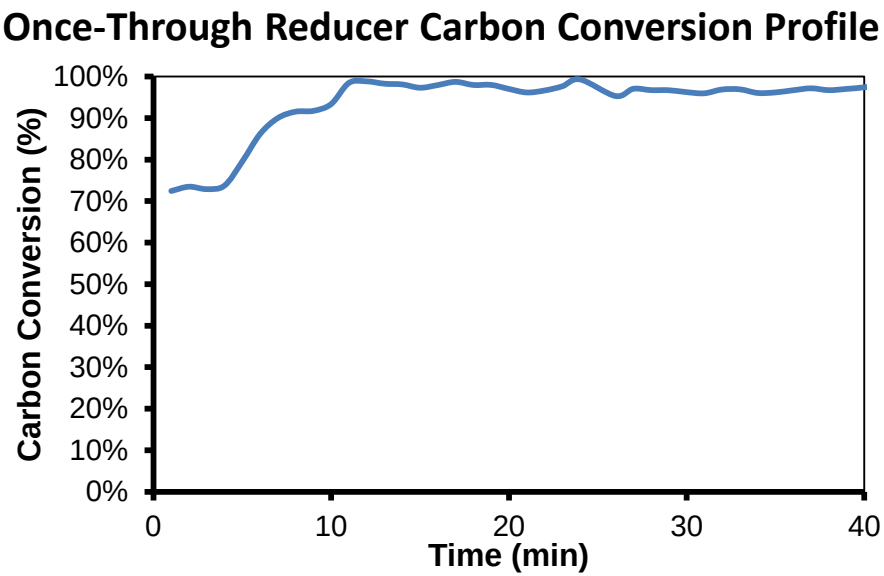
Phase III: Integrated CDCL System Testing

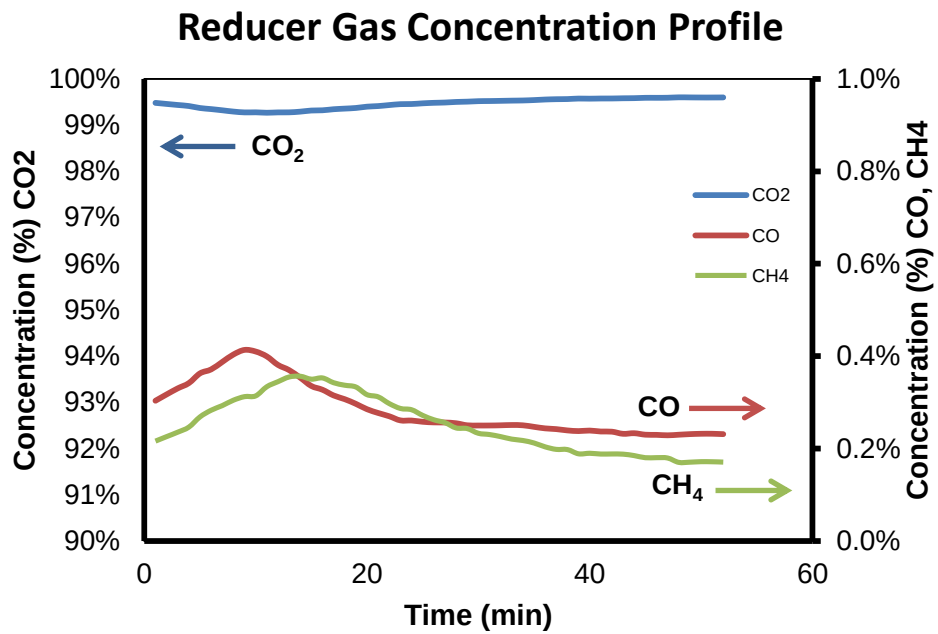
200+ Sub-Pilot Continuous Run Results



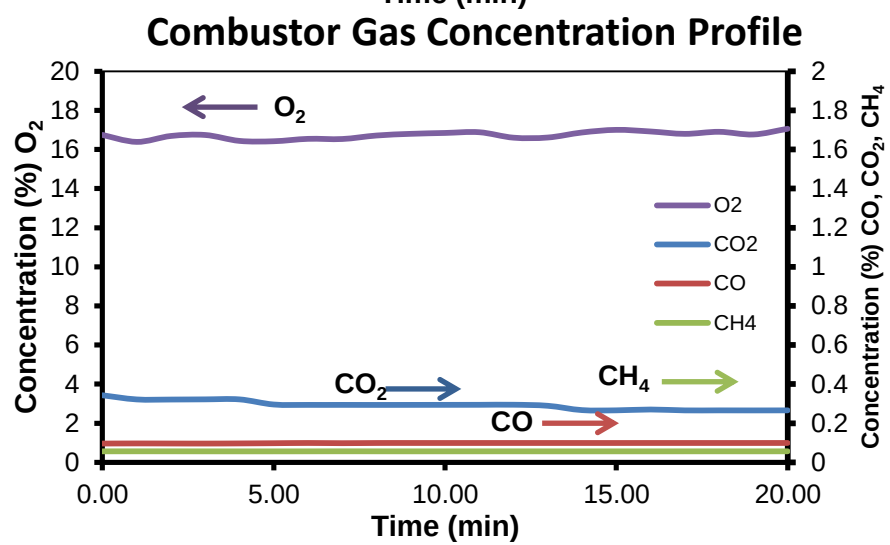


200+ Sub-Pilot Continuous Run - Sample Results Lignite



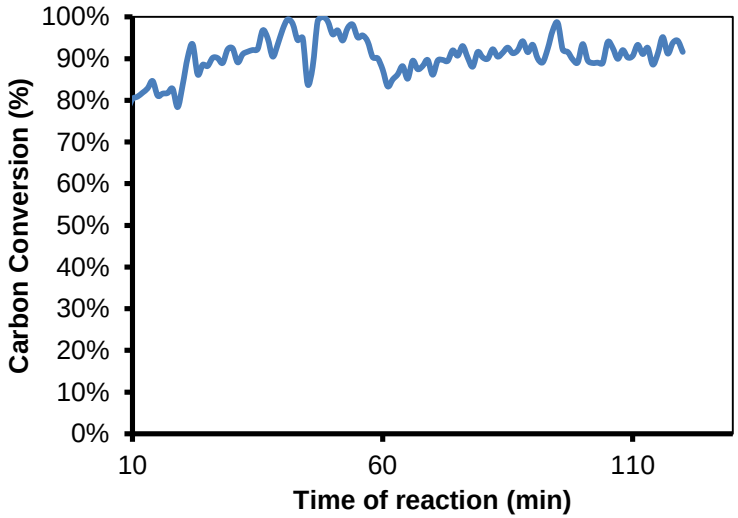


- Continuous steady carbon conversion from reducer throughout all solid fuel loading (5- 25kW$_{th}$)
- <0.25% CO and CH_4 in reducer outlet = full fuel conversion to CO_2/H_2O
- <0.3% CO, CO_2, and CH_4 in combustor = negligible carbon carry over, nearly 100% carbon capture

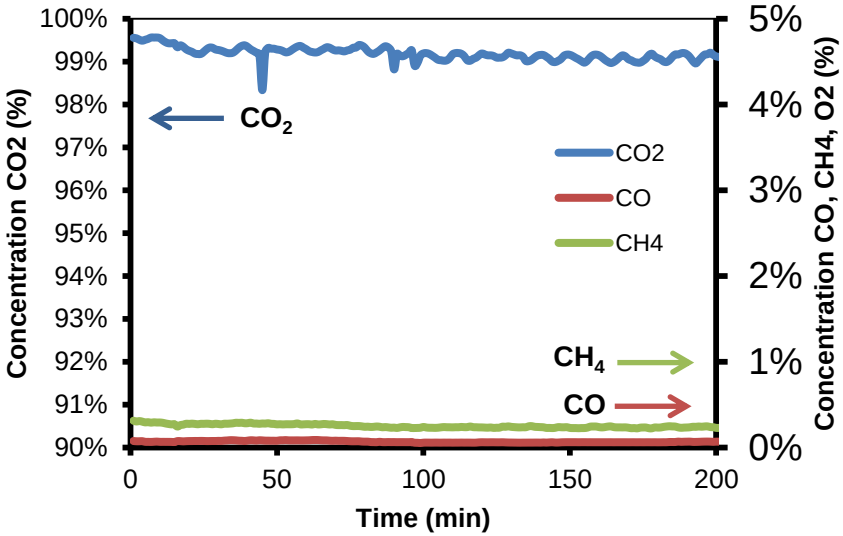


200+ Sub-Pilot Continuous Run - Sample Results PRB

Once-Through Reducer Carbon Conversion Profile

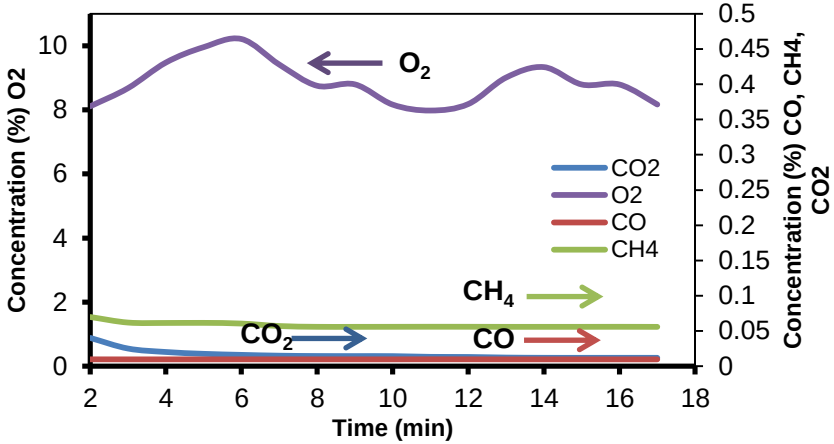


Reducer Gas Concentration Profile



- **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**
- **<0.1% CO, CO_2, and CH_4 in combustor = negligible carbon carry over, nearly 100% carbon capture**

Combustor Gas Concentration Profile

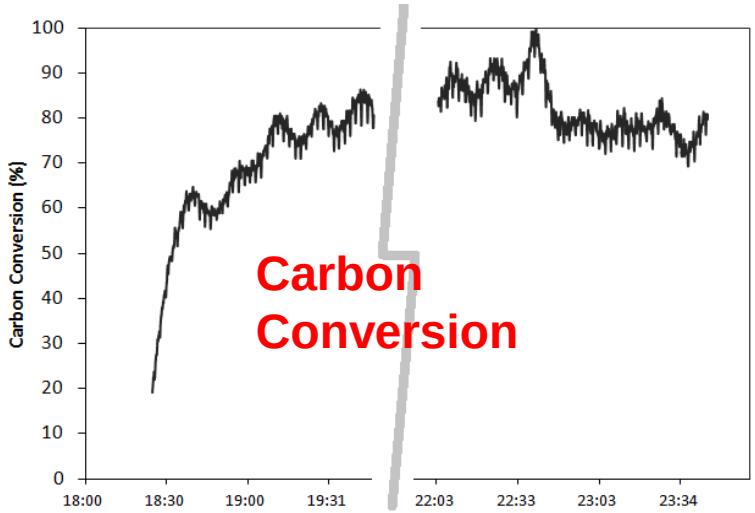


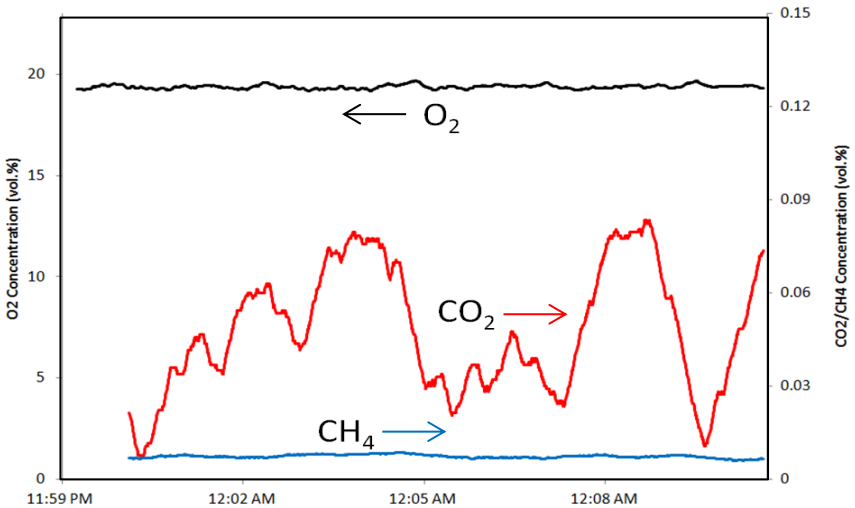
CDCL NO_x/SO_x Analysis

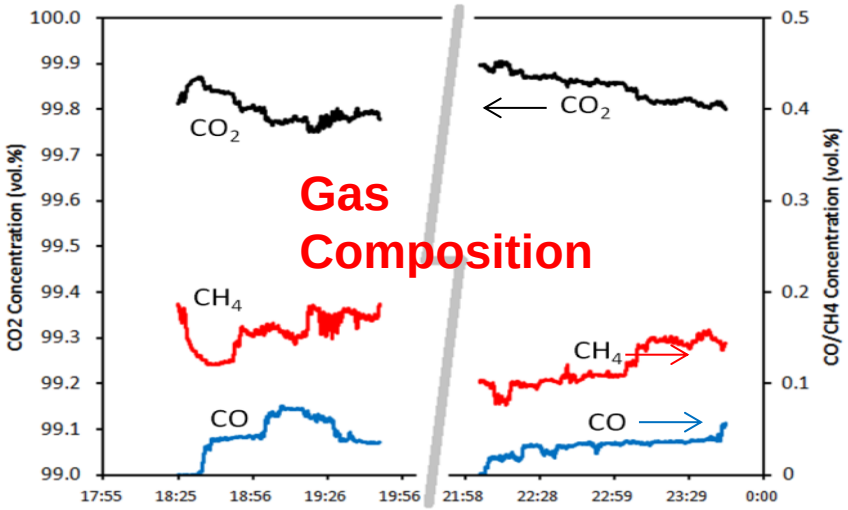
	Reducer	Combustor
SO_x (ppm)	190-1170	0 - 70
NO_X (lb/MMBTU)	0.100 – 0.200*	~ 0

*Conventional PC Boiler NO_x Generation = 0.2 – 0.5 lb/MMBTU[1]

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 hour Sub-Pilot Continuous Demonstration

Purpose of long run:

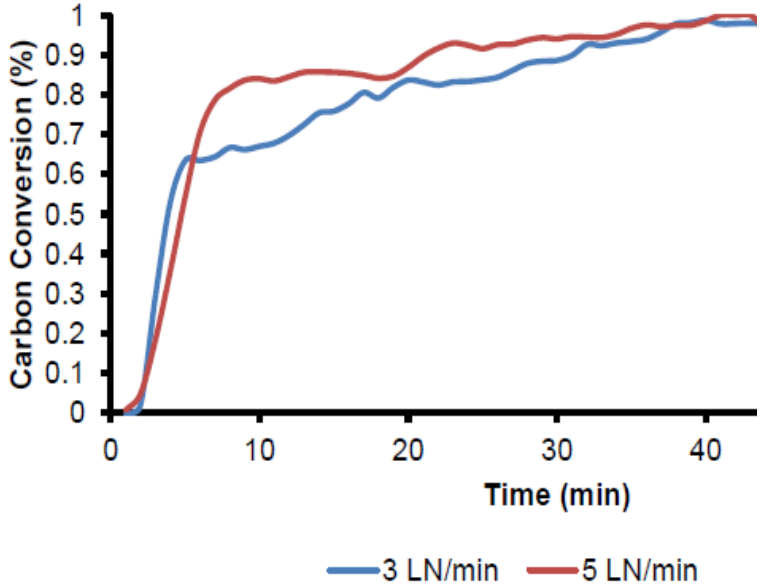
- Determine the feasibility of long-term coal injection on the flow and reactivity of the oxygen carrier particles in the system.
- More accurately understand the dynamics of the system in hot condition
- Further ability to troubleshoot potential problems and how/why they occur

	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

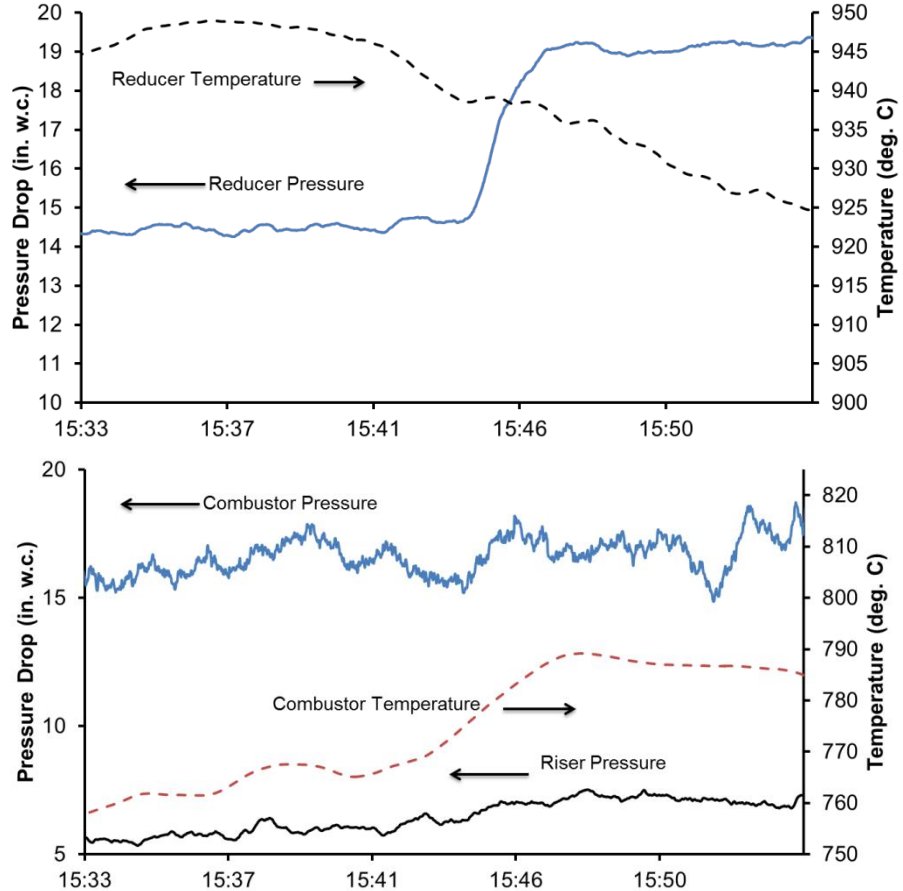
Results:

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

Sensitivity Testing – Parametric Unsteady State Studies of Integrated CDCL System



Effect of enhancing gas on approach to steady state



Effect of coal injection on system temperatures and pressures

CDCL Moving Bed Reducer Model

Reactions

Reduction of Iron oxide

$$Fe_2O_3 + H_2 / CO / CH_4 \leftrightarrow H_2O + CO_2 + Fe_3O_4$$

$$Fe_3O_4 + H_2 / CO / CH_4 \leftrightarrow H_2O + CO_2 + Fe_xO$$

$$Fe_xO + H_2 / CO / CH_4 \leftrightarrow H_2O + CO_2 + Fe$$

Coal gasification

$$C_{5.4}H_{4.4}O \rightarrow 0.926H_2 + CO + 0.637CH_4 + 3.763C$$

$$C + H_2O \leftrightarrow CO + H_2$$

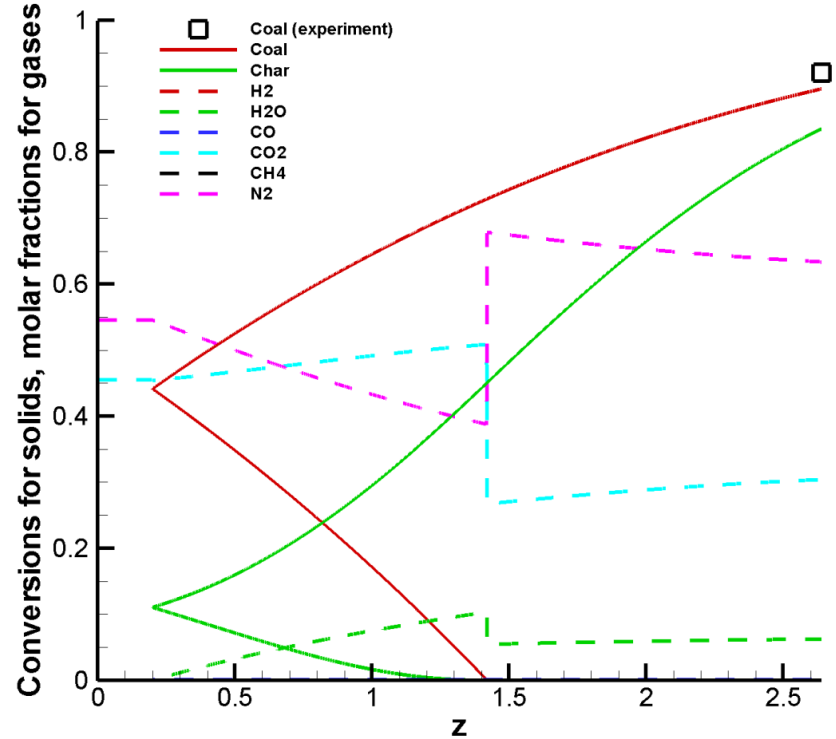
$$C + CO_2 \leftrightarrow 2CO$$

Water-gas shift

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

Methane reforming

$$CH_4 + 2H_2O \leftrightarrow 4H_2 + CO_2$$



Iron oxide flow rate (Top-> bottom) : ***2.5kg/min (d=1.5mm)***

Coal flow rate: ***9.5g/min (d=30um)***

Gases flow rate (bottom->top): ***22 L/min***

Molar fraction of co2: 45%

Molar fraction of N2: 55%

Temperature, fixed at 1025 °C

Background

- CONSOL Energy completed a comprehensive techno-economic evaluation of the Coal Direct Chemical Looping (CDCL) process as a subcontractor to The Ohio State University (OSU) under DOE Cooperative Agreement No. DE-NT0005289

- Several process configurations studied:
  - New construction of a 550 MW_e (net) supercritical power plant firing Illinois No. 6 coal ("New ILB Case")
  - New construction of a 550 MW_e (net) supercritical power plant firing Powder River Basin coal ("New PRB Case")
  - Retrofit application to an existing, fully-depreciated, 550 MW_e (net), supercritical pulverized coal (PC) power plant firing Illinois No. 6 coal ("Retrofit ILB Case")

- Objective: Guide OSU's research toward development of commercially viable technology

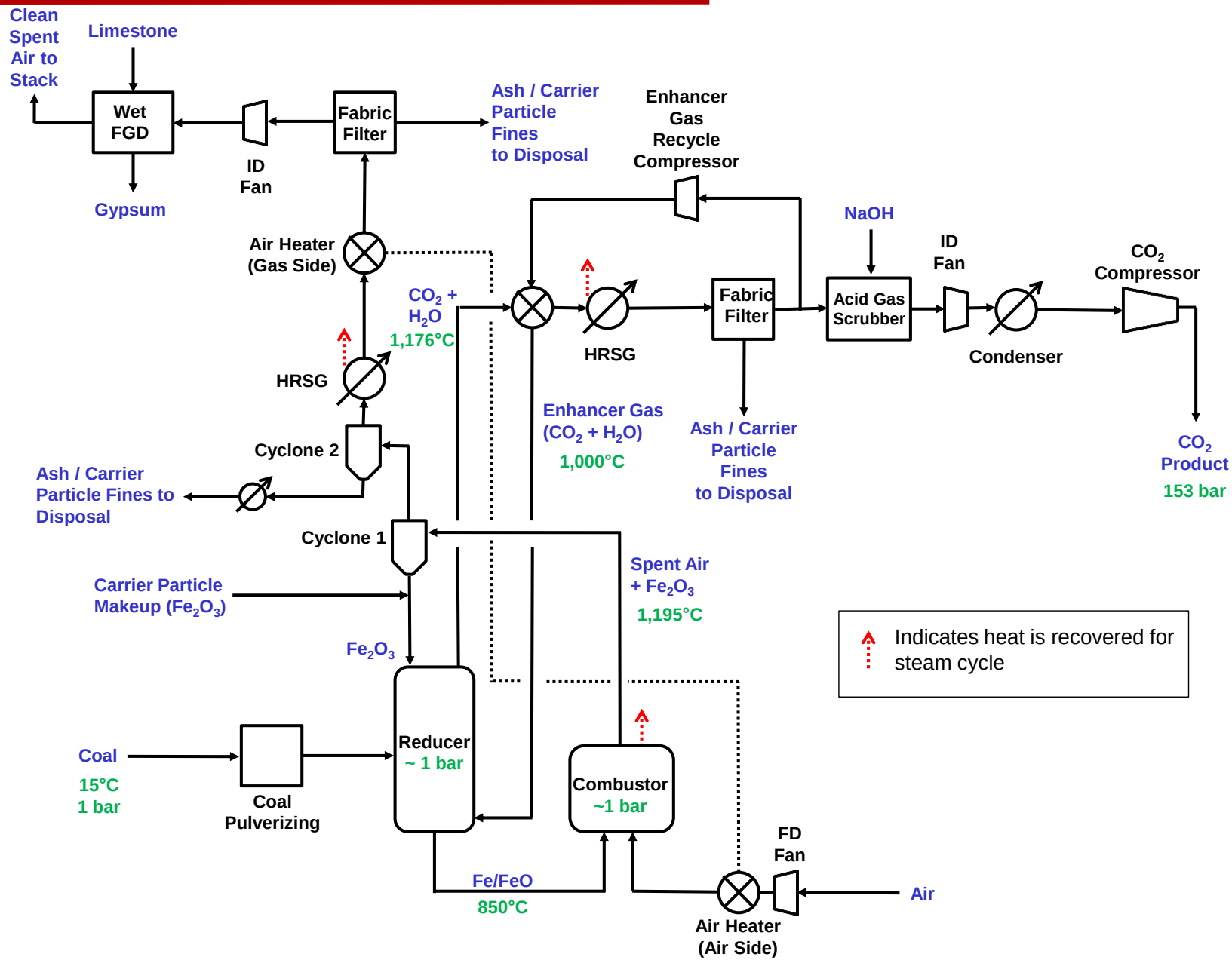
Systems Analysis Methodology – New ILB Case

- Performance of CDCL plant modeled using Aspen Plus® software, with key assumptions chosen to comport with OSU's experimental program and performance targets

- Results compared with performance of conventional 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
  - 300-acre Midwestern U.S. site; ambient conditions: 59°F (15°C), 14.696 psia (1.01325 bar)
  - 550 MW_e net electric output
  - Illinois No. 6 coal: 11,666 Btu/lb HHV (27,113 kJ/kg), 2.5% sulfur, 11.1% moisture as received
  - Supercritical steam cycle: 3,500 psig/1,100°F/1,100°F (242 bar/593°C/593°C)
  - ≥ 90% CO_2 capture efficiency (MEA and CDCL Plants)
  - CO_2 compressed to 2,215 psia (153 bar), transported 62 mi (100 km), injected in saline formation

Process Flow Diagram – New ILB Case



Aspen Plus® Modeling Results – New ILB Case

	Base Plant	MEA Plant	CDCL Plant
Coal Feed, lb/h (kg/h)	409,528 (185,759)	565,820 (256,652)	462,107 (209,608)
CO_2 Emissions, lb/MWh$_{net}$ (kg/MWh$_{net}$)	1,764 (800)	238 (108)	87 (40)
CO_2 Capture Efficiency, %	0	90.2	95.5
Solid Waste,[a] lb/MWh$_{net}$ (kg/MWh$_{net}$)	72 (33)	99 (45)	96 (44)
Net Power Output, MW$_e$	550	550	550
Net Plant HHV Heat Rate, Btu/kWh (kJ/kWh)	8,687 (9,165)	12,002 (12,663)	9,795 (10,334)
Net Plant HHV Efficiency, %	39.3	28.5	34.9
Energy Penalty,[b] %	-	27.6	11.3

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

Economic Analysis Methodology – New ILB Case

- Economic performance compared on the basis of first-year cost of electricity (COE)
- 2011 U.S. Dollars
- Base and MEA Plant economics taken from *Updated Costs (June 2011 Basis) for Selected Bituminous Baseline Cases* (August 2012)
- CDCL Plant economics calculated using same methodology/assumptions
- Capital cost estimated as Total Overnight Cost (TOC), which is the sum of:
  - Bare Erected Cost (BEC): obtained by scaling from the Bituminous Baseline report, other DOE reports, vendor quotes, and engineering cost estimating equations
  - Engineering, Construction Management, and Home Office Costs: 8-10% of BEC
  - Process Contingency: 30% on reducer, L valves & zone seals; 20% on combustor
  - Project Contingency: 10-20%
  - Owner's Costs: preproduction costs, inventory capital, initial costs for catalysts and chemicals, land, financing costs, and other owner's costs
- First-year capital costs computed using the following capital charge factors:
  - 0.116 for the Base Plant (low-risk IOU, 5-yr construction period)
  - 0.124 for the MEA and CDCL Plants (high-risk IOU, 5-yr construction period)

First-Year Cost of Electricity – New ILB Case

	Base PC Plant without CO_2 Capture			CDCL Plant with CO_2 Capture		
Capital Charge Factor		0.116			0.124	
	Cost ($/y)	**Electricity Production (MWh)**	**COE ($/MWh)**	**Cost ($/y)**	**Electricity Production (MWh)**	**COE ($/MWh)**
Capital Cost	$156,427,160	4,095,226	$38.20	$220,784,327	4,098,003	$53.88
Fixed O&M Cost	$38,828,867	4,095,226	$9.48	$47,687,200	4,098,003	$11.64
Variable O&M Cost	$136,263,778	4,095,226	$33.27	$164,373,252	4,098,003	$40.11
TOTAL (without CO_2 TS&M)			**$80.95**			**$105.62**

ΔCOE = 30.5%

CO_2 TS&M Cost	$0	4,095,226	$0.00	$35,284,689	4,098,003	$8.61
TOTAL (with CO_2 TS&M)			**$80.95**			**$114.23**

ΔCOE = 41.1%

New PRB Case - Differences in Design/Economics

- Plant sited in Montana; ambient conditions: 42°F (5.6°C), 13.223 psia (0.90 bar)
- PRB coal: 8,564 Btu/lb HHV (19,920 kJ/kg), 0.73% sulfur, 25.77% moisture as received
- CDCL plant requires 28% greater carrier particle circulation rate than in New ILB Case because of coal moisture content
- Reducer assumed to achieve 98% char conversion; less residence time required than in New ILB Case
- No FGD needed for SO_2 removal from spent air stream in CDCL Plant; Base Plant uses lime spray dryer rather than wet limestone forced oxidation scrubber
- Activated carbon injection included for Hg control in CDCL and Base Plants
- Lower coal sulfur content enables use of lower air heater outlet exit gas temperature
- Air-cooled condenser provides half of cooling duty in CDCL and Base Plants
- Coal cost = $1.17/mmBtu ($19.96/ton) vs. $2.94/mmBtu in New ILB Case
- CO_2 TS&M cost = $19.96/ton vs. $9.07/ton in New ILB Case

Retrofit ILB Case - Differences in Design/Economics

- CDCL process applied to an existing, fully-depreciated 550 MW_e supercritical PC plant
- Net output of the CDCL Plant is less than 550 MW_e, because it is sized to enable the use of existing equipment items, to the greatest extent possible, from the existing base plant
- Convective pass and economizer sections of existing PC boiler are used as the spent air stream HRSG in the CDCL plant
- Zero capital cost incurred for base plant equipment items (e.g., steam turbine-generator, coal handling system, coal pulverizers, feedwater system, wet FGD, fabric filter, ID fan, stack, etc.) that are retained for use in CDCL Plant
- 30% project contingency applied to all new equipment items in CDCL Plant to account for retrofit difficulty

Comparison of New ILB, New PRB, and Retrofit ILB Results

	New ILB CDCL Plant	New PRB CDCL Plant	Retrofit ILB CDCL Plant
Net Electric Power Output (MWe)	**550.4**	**549.8**	**482.4**
Net Plant Efficiency (HHV, %)	**34.9**	**33.7**	**35.0**
CO_2 Capture Efficiency (%)	**95.5**	**97.6**	**95.5**
First-Year Cost of Electricity			
First-Year Capital Cost ($/MWh)	53.88	55.99	37.75
Fixed O&M Cost ($/MWh)	11.64	12.26	14.84
Fuel Cost ($/MWh)	28.80	11.62	28.68
CO_2 Emissions Credit ($/MWh)	-1.52	-2.16	-1.52
Variable O&M Cost ($/MWh)	12.83	12.78	13.82
TOTAL without CO_2 TS&M ($/MWh)	105.62	90.49	93.57
CO_2 TS&M ($/MWh)	8.61	21.47	8.58
TOTAL with CO_2 TS&M ($/MWh)	114.23	111.96	102.14

Conclusions

- The CDCL process has potential to significantly reduce the cost and energy penalty associated with capturing CO_2 from coal-fired power plants, when compared with today's best near-commercial CO_2 capture technology options
- Greenfield CDCL plants using bituminous and subbituminous coals are projected to meet DOE's performance target of ≥90% CO_2 capture with ≤35% increase in COE
- Additional cost savings (~$12/MWh) might be realized by retrofitting the CDCL process to existing PC power plants, but the feasibility of this approach must be evaluated on a plant-by-plant basis
- Additional R&D is required to resolve technical uncertainties related to the commercial application of the CDCL technology and to develop opportunities for additional cost and performance improvements. Key R&D needs include:
  - Demonstrate and optimize coal distribution in the reducer at larger scale
  - Demonstrate high-temperature circulation of carrier particles at larger scale

Accomplishments

- Synthesis/screening of oxygen carrier particles and selected particles with optimal performance for further testing
- 100 hrs of 2.5 kW_t bench-scale operations achieving coal high char conversions
- >680 hrs of integrated 25 kW_t sub-pilot scale operations achieving 90-99+% coal conversion
- The longest demonstration to date is >200 hours continuous with smooth operations and high fuel conversions.
- The CDCL process has the potential to meet DOE's goal of ≥90% CO_2 capture at no more than a 35% increase in cost of electricity

Thanks