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

**Award #: DE-NT0005289**

**Principal Investigator : Professor Liang-Shih Fan**
**The Ohio State University**
**Department of Chemical and Biomolecular Engineering**

Presented by Ray Kim

2010 NETL CO2 Capture Technology Meeting
September 15, 2010. 830AM-900AM
Pittsburgh, PA. USA

THE OHIO STATE UNIVERSITY

# Chemical Looping Research at OSU

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

**Syngas Chemical Looping for $H_2$**

25kW$_{th}$ Sub-Pilot Unit

Awarded by ARPA-E

Pilot Scale Plant proposed to be tested at NCCC

**120kW$_{th}$CCR Demonstration**

# Process Overview

# Overall CDCL Scheme

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

**Step I:** Coal + $Fe_2O_3$ (Hot) $\rightarrow$ Fe/FeO + $H_2O$ + $CO_2$

**Step II:** Air + Fe/FeO $\rightarrow$ $Fe_2O_3$ (Hot) + Spent Air (To boiler)

---

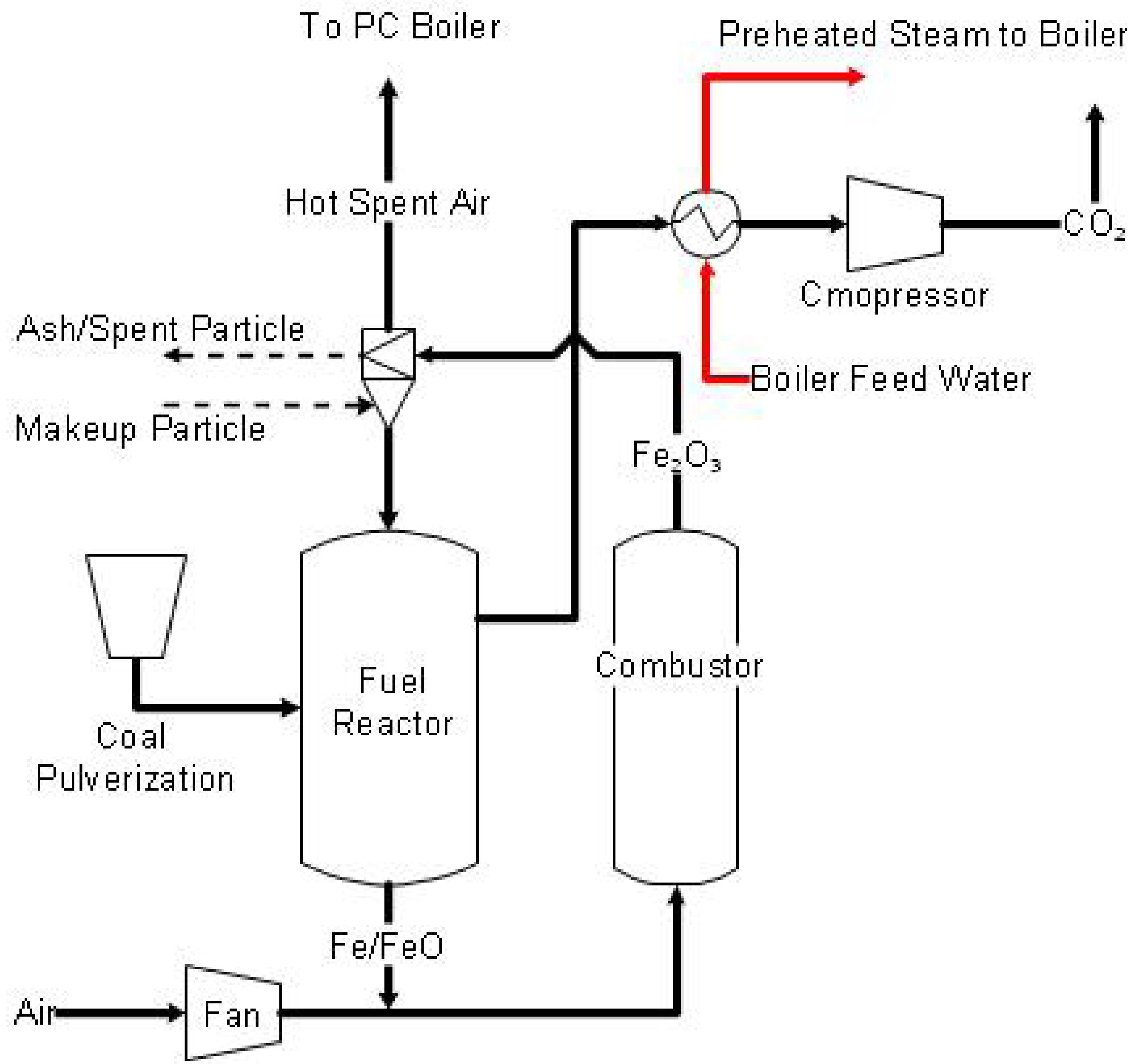
*Overall reaction*

**Coal + Air $\rightarrow$ $CO_2$ + $H_2O$ + Spent Air (Heat)**

THE OHIO STATE UNIVERSITY

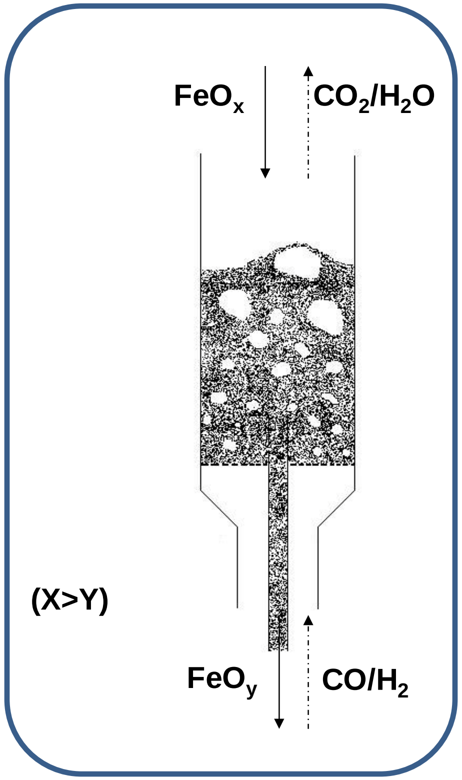
# Process Flow Diagram

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*



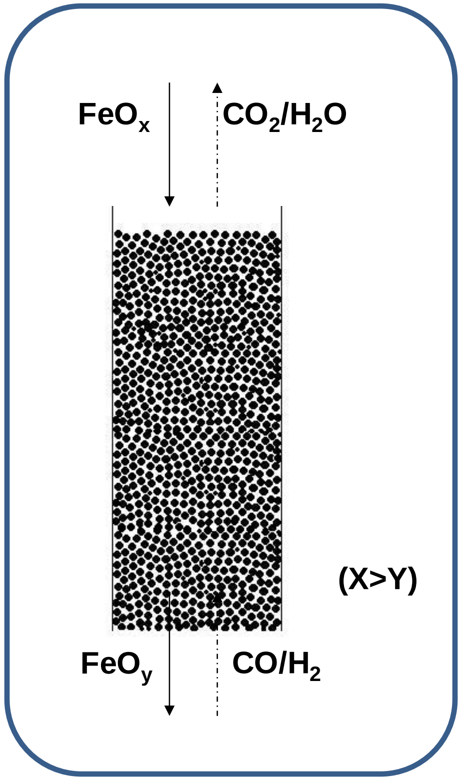
# Key I: Pelletization and Moving Bed

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*



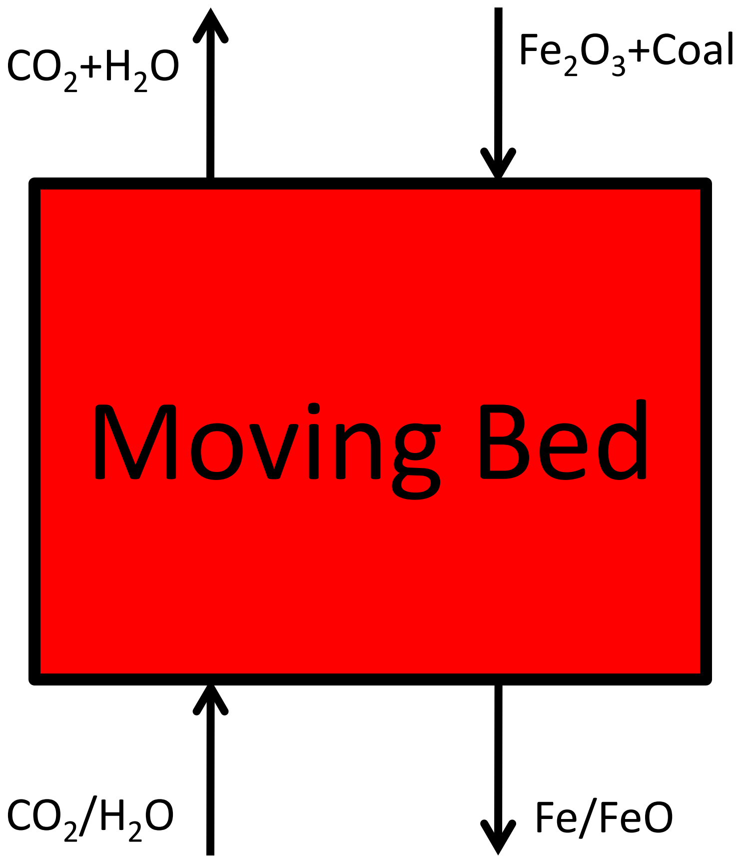

**Fluidized Bed *vs.* Moving Bed**

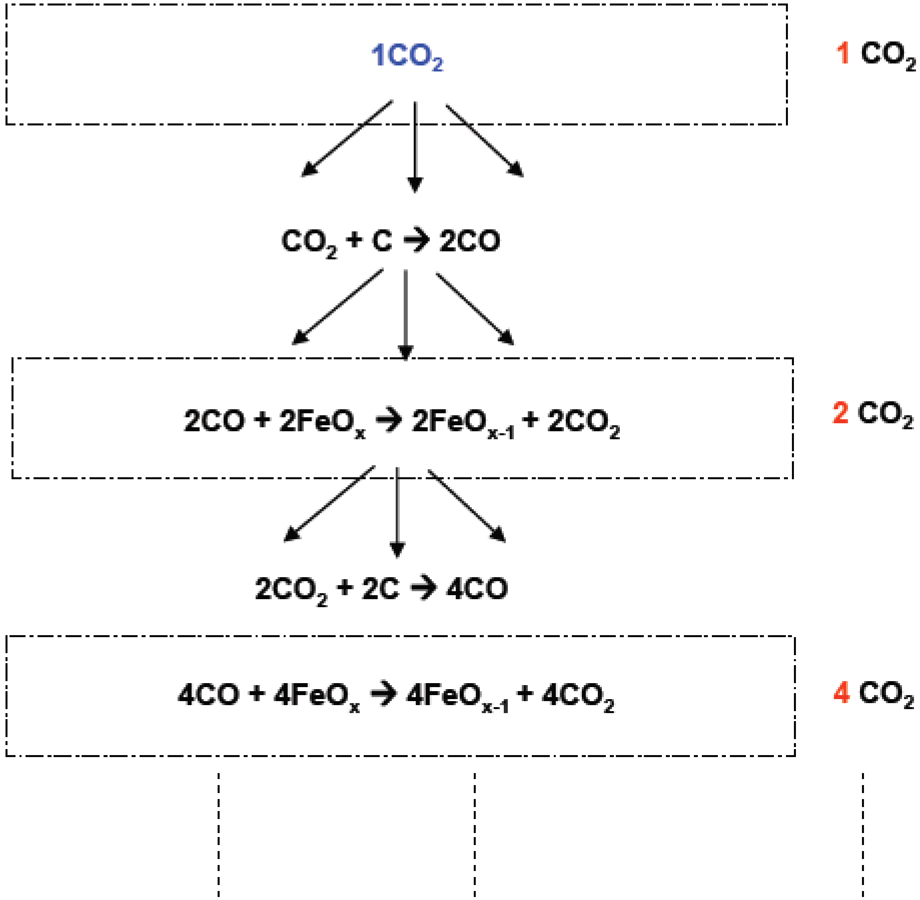
| Fluidized Bed | | Moving Bed |
|---|---|---|
| **11.1%** | Maximum OC Conversion | **50.0%** |
| **> $U_{mfv}$** | Gas Velocity | **< $U_{mfv}$** |
| **Small** | Particle Size | **Large** |



# Key II: Char Conversion Enhancement

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*



# Project Overview

# Project Funding

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

- Funding
  - January 1, 2009 through December 2011
  - $2.86 Million Supported by U.S. DOE
  - $1.12 Million Cost-Share from OSU, State Government and Industries

- Participants
  - Lead Applicant : The Ohio State University
    - Principal Investigator (PI) : Professor Liang-Shih Fan
    - Planning, Experiments and Demonstrations
  - Partners
    - Ohio Air Quality Development Authority (OAQDA)
      - $300,000 Sponsor
    - CONSOL Energy
      - Techno-Economic Study of the Overall CDCL System
    - Shell/CRI
      - Oxygen Carrier Particle Synthesis
    - Babcock & Wilcox Company
      - Engineering Consultation and Support on PC Retrofit Plan
    - Air Products
      - Gas Handling
    - ClearSkies Consulting
      - Organization and Coordination of Project

# Proposed Key Tasks

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ C02 Capture*

- Selection of Iron-Based Oxygen Carrier (*Year I and II*)
- Demonstration of Bench Scale (2.5kW$_{th}$) Coal Direct Chemical Looping (*Year II*)
  - Fuel Rector demonstration
  - Coal char and volatile conversion
- Demonstration of Sub-Pilot Scale (25kW$_{th}$) Coal Direct Chemical Looping (*Year III*)
  - Integration of Fuel Reactor and combustor with continuous solid circulation at reaction temperature
- Conduct Techno-Economic Study
  - Based on the demonstration results, ASPEN simulation will be conducted
  - Collaborated with CONSOL Energy R&D Center

# Project Progress (As of Year II)

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

- Selection of Optimum Oxygen Carrier Particle
  - Iron oxide based oxygen carrier
  - Selection of support
- Coal Conversion by Oxygen Carrier
  - Thermogravimetric analyzer (TGA) test with FTIR coupling
  - Fixed bed test
- Bench Scale Demonstration (2.5kW$_{th}$)
  - Coal char conversion
- Cold Model Reactor
  - Solid handling study for sub-pilot scale demonstration
- Construction of Sub-Pilot Scale (25kW$_{th}$) System

THE OHIO STATE UNIVERSITY

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

# Progress Review I

## Oxygen Carrier Particle Selection

# Oxygen Carrier Particle Selection

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ C02 Capture*

- Started with ~100 Fe-Based Particles

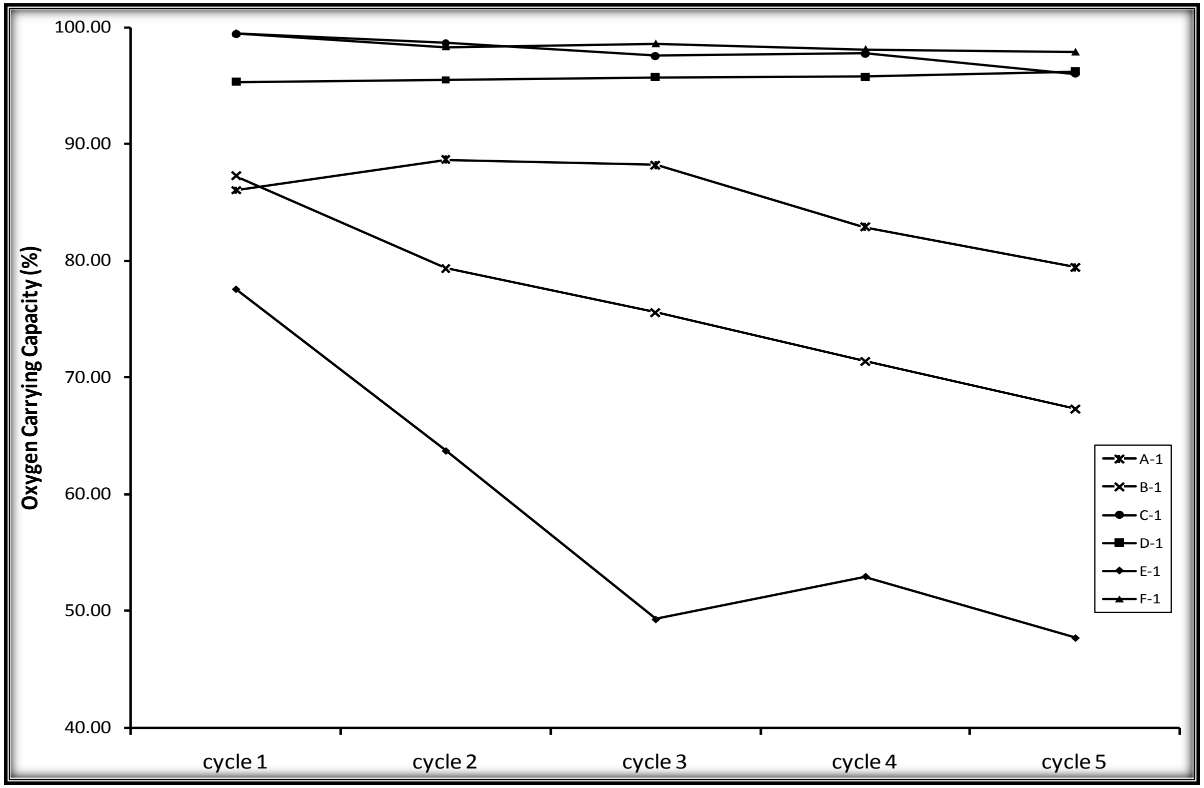
- Addition of Various Supporting Metals at Different Ratio

- Performed Experiments/Criteria
  - Recyclability
    - Regeneration
  - Carbon Deposition Tolerance
    - Deactivation of OC
  - Reaction with Coal Char
  - Pelletization and Its Strength and Reactivity
    - Attrition
    - Reaction: Pellet vs. Powder

# Oxygen Carrier Particle Selection – Recyclability Test

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

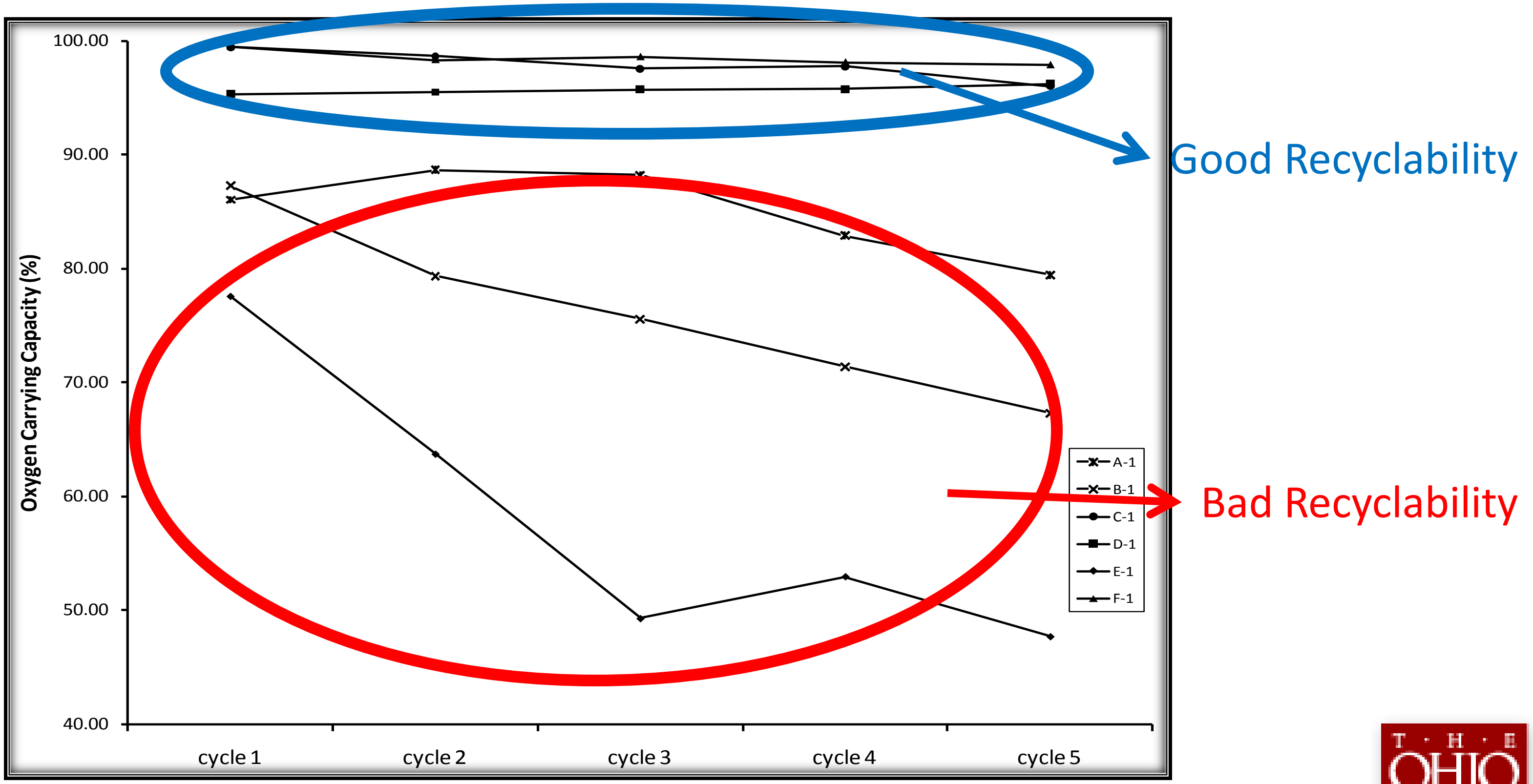
- Oxygen Carrying Capacity vs. # of Cycles of Various OC
- Oxygen Carrying Capacity = Ratio of Actual Carried Oxygen and Theoretical Value



# Oxygen Carrier Particle Selection – Recyclability Test

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

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

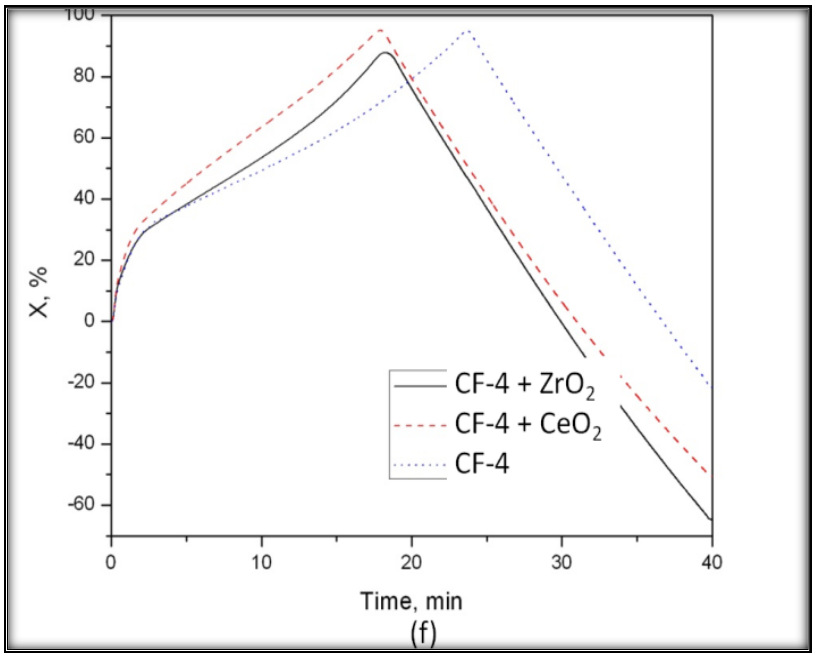


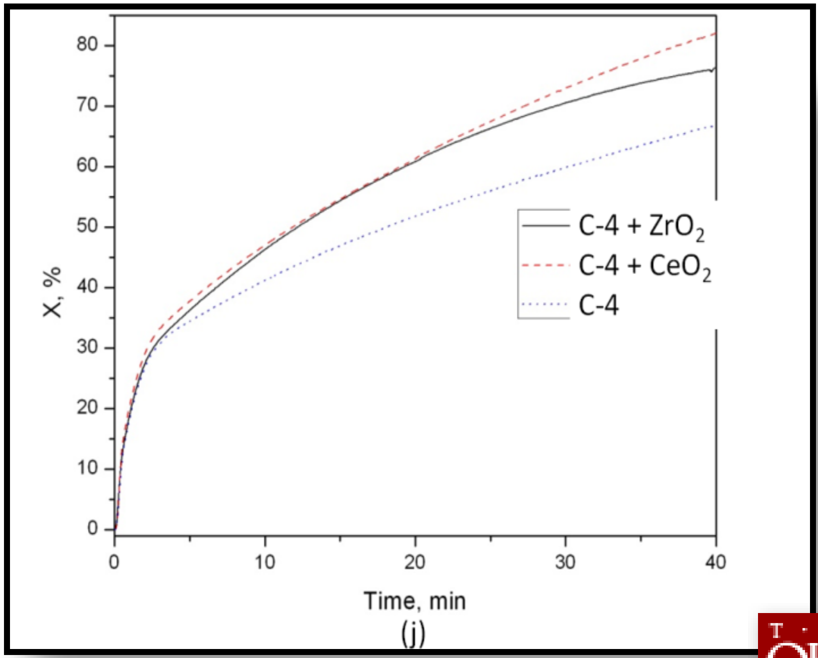

**OC's should be recyclable.**

# Oxygen Carrier Particle Selection – Carbon Deposition

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

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



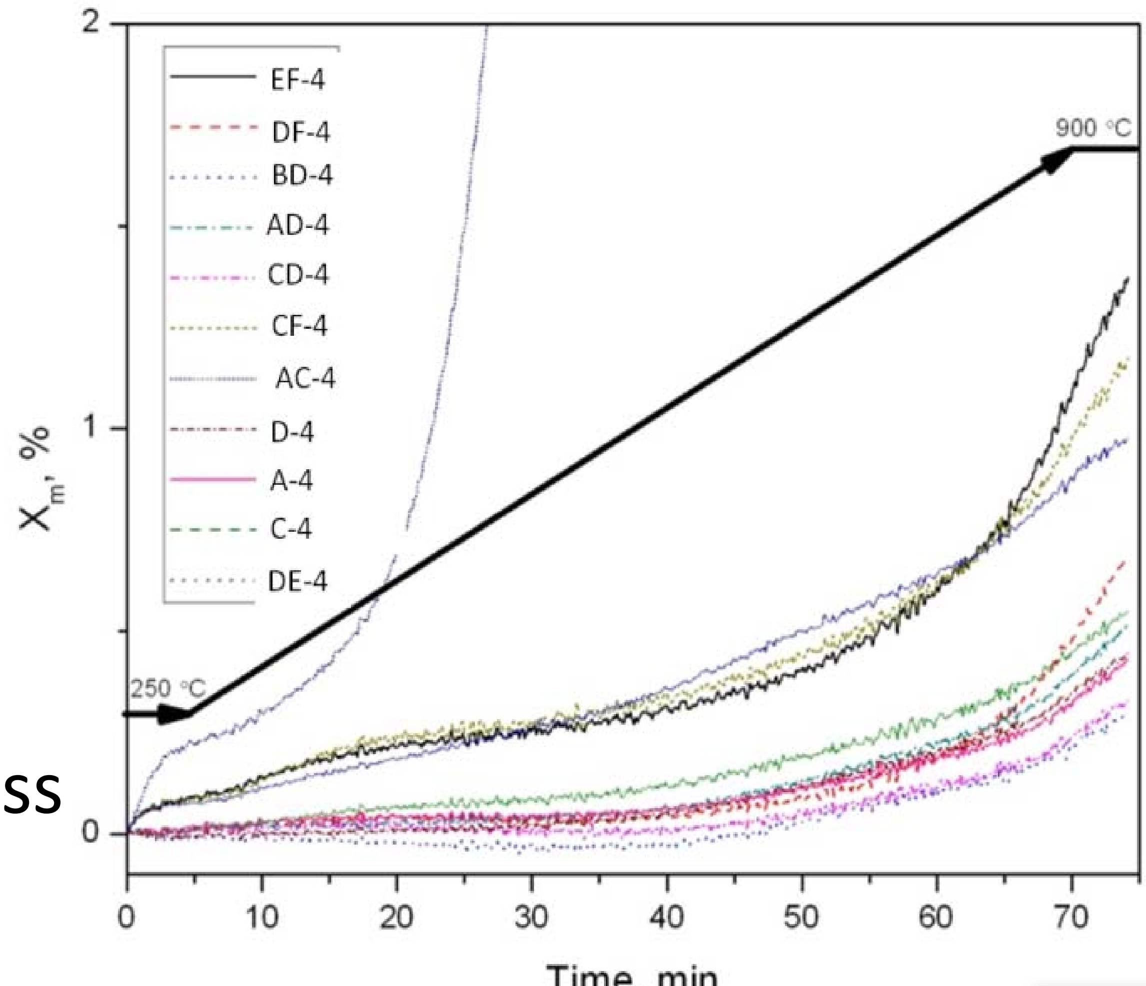




**Effect of carbon deposition can be reduced by dopants.**

# Oxygen Carrier Particle Selection – Reaction with Char

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

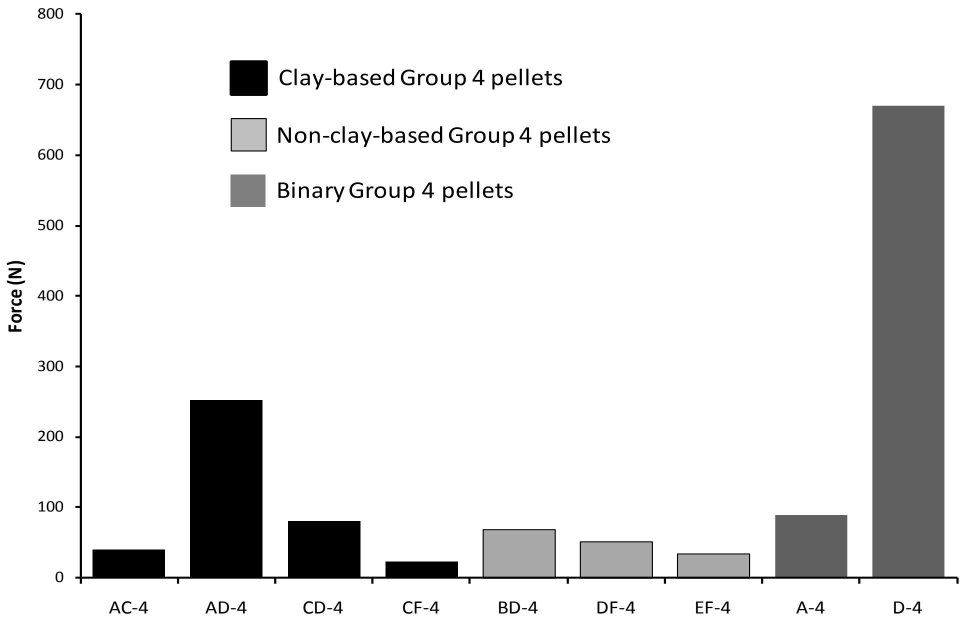
- OC/Char = 5~10
- Temperature
  - 25°C to 250°C
  - 250°C for Drying
  - 250°C to 900°C
- Less than 2 wt.% Loss

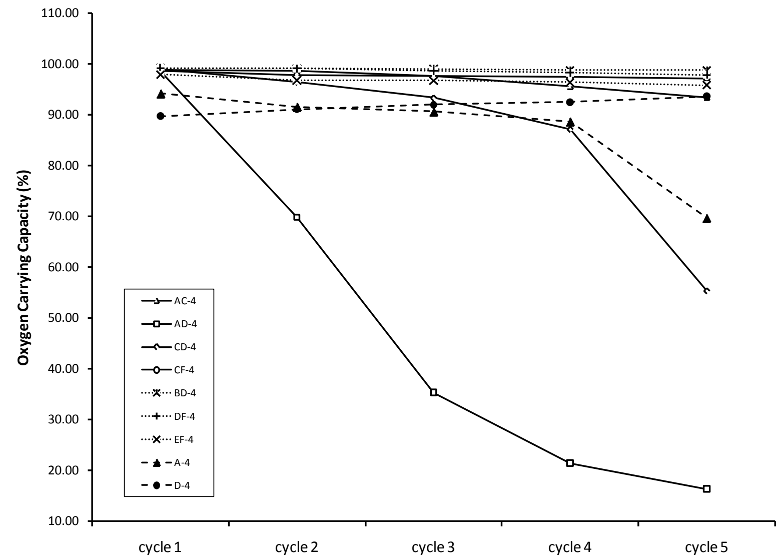


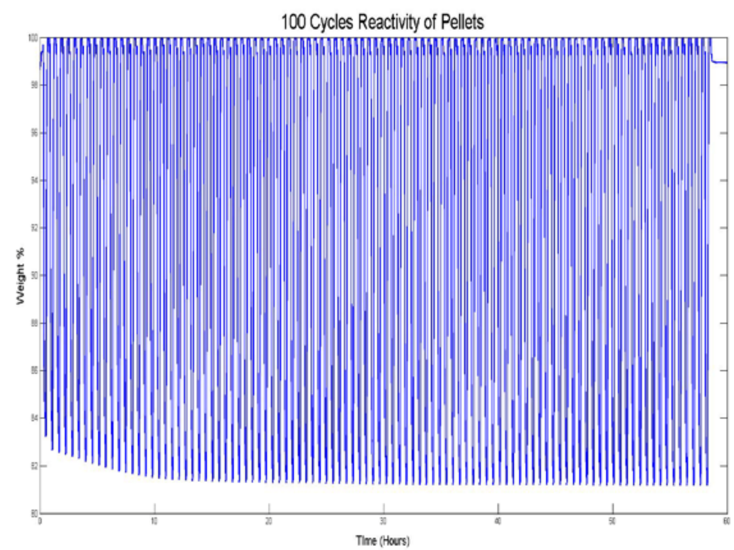

**Slow solid-solid reaction between OC and char is slow. Enhancement is needed.**

# Oxygen Carrier Particle Selection – Pelletization

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*




- Pellet Strength
  - Support affects pellet strength
- Pellet Reactivity
  - Needs to maintain the reactivity of fine powder form
  - Shows drastic changes

**100-Cycle test achieved with a pellet.**

# Oxygen Carrier Particle Selection – Final Selection

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

| Particle | Pellet Strength | Pellet Oxygen Carrying Capacity | Methane Reaction Kinetics | Coal Char Reaction Kinetics |
|---|---|---|---|---|
| **CF-4** | 5 | 3 | 2 | 2 |
| **BD-4** | 2 | 1 | 4 | 5 |
| **DF-4** | 3 | 2 | 3 | 3 |
| **EF-4** | 4 | 4 | 1 | 1 |
| **D-4** | 1 | 5 | 5 | 4 |

**5 Candidates for OC were selected.**

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

# Progress Review II

## Coal Conversion by Oxygen Carrier

# Coal Conversion by Oxygen Carrier

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ C02 Capture*

- Enhancement of Char Conversion
  - Initiate the Solid-Solid Reaction
  - Gasification Enhancer

$H_2O + C = H_2 + CO$

$CO + H_2 = Fe_2O_3 + CO_2 + H_2O$

$CO_2 + C = CO$

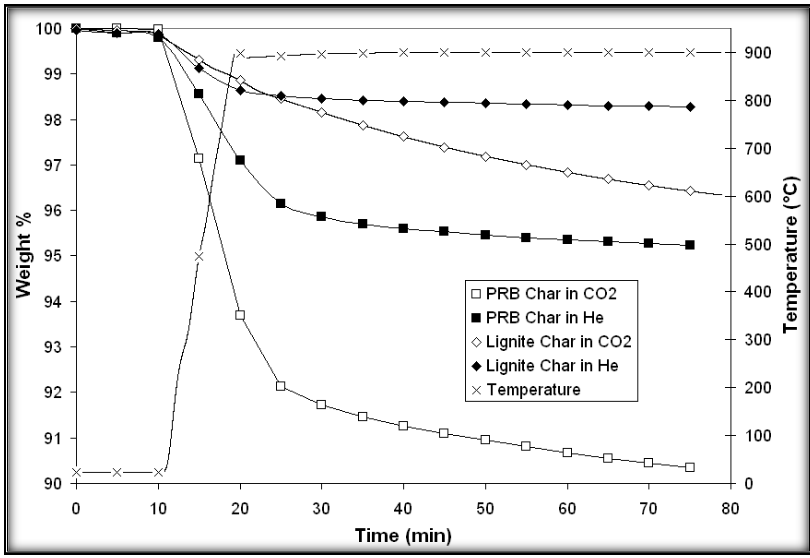
$CO + Fe_2O_3 = Fe + CO_2$

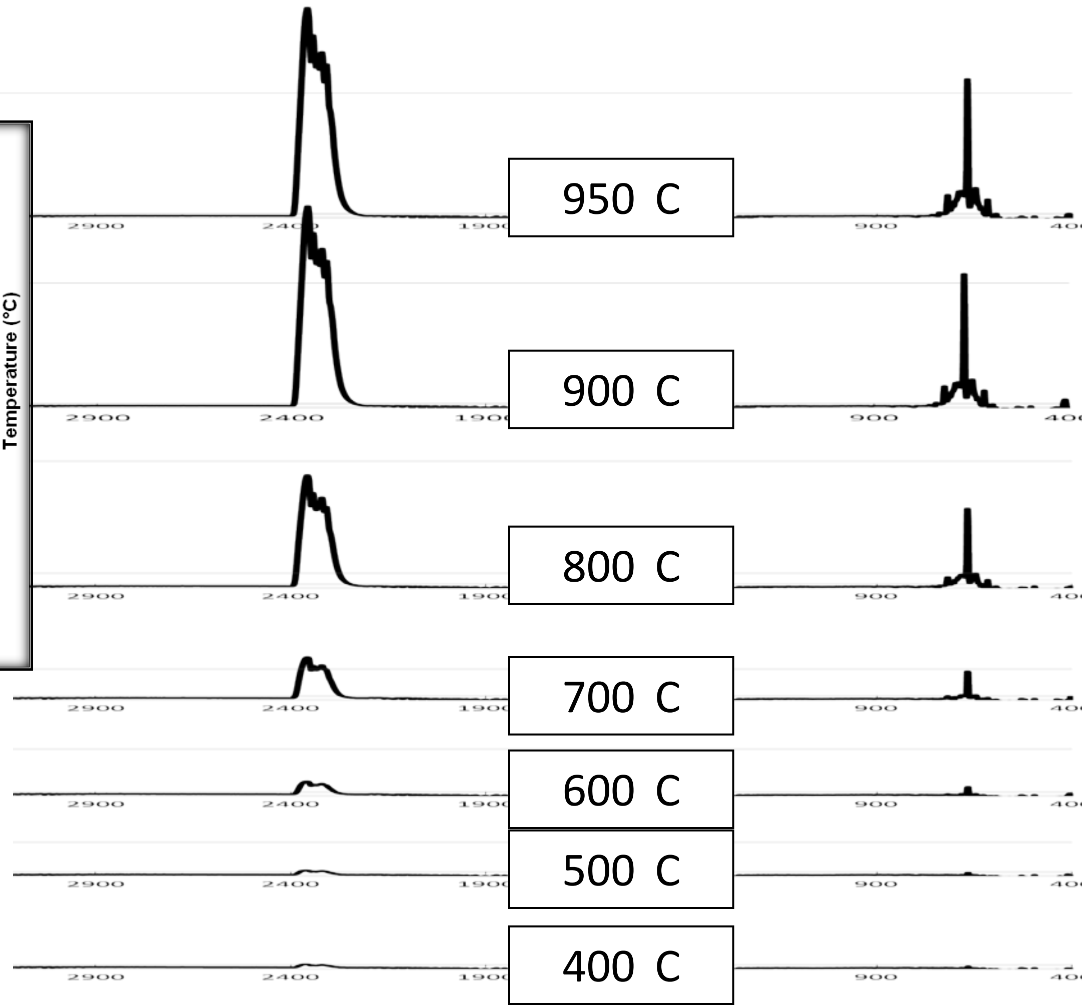
- Thermogravimetric Analysis (TGA) for Solid Analysis

- Fixed Bed Experiment for Gas Analysis

# FTIR-TGA Coupling

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

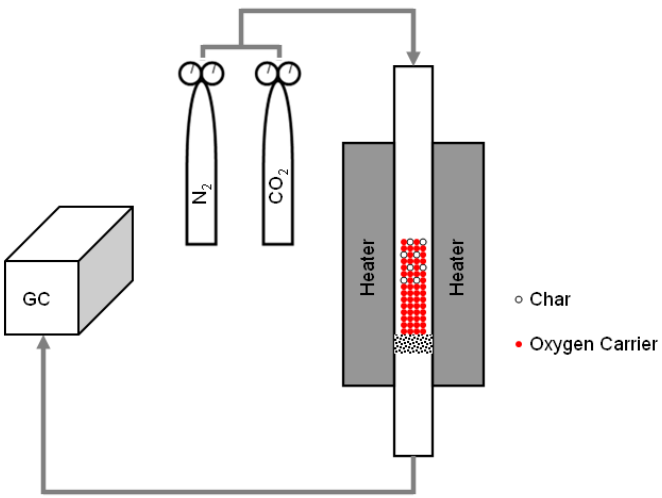


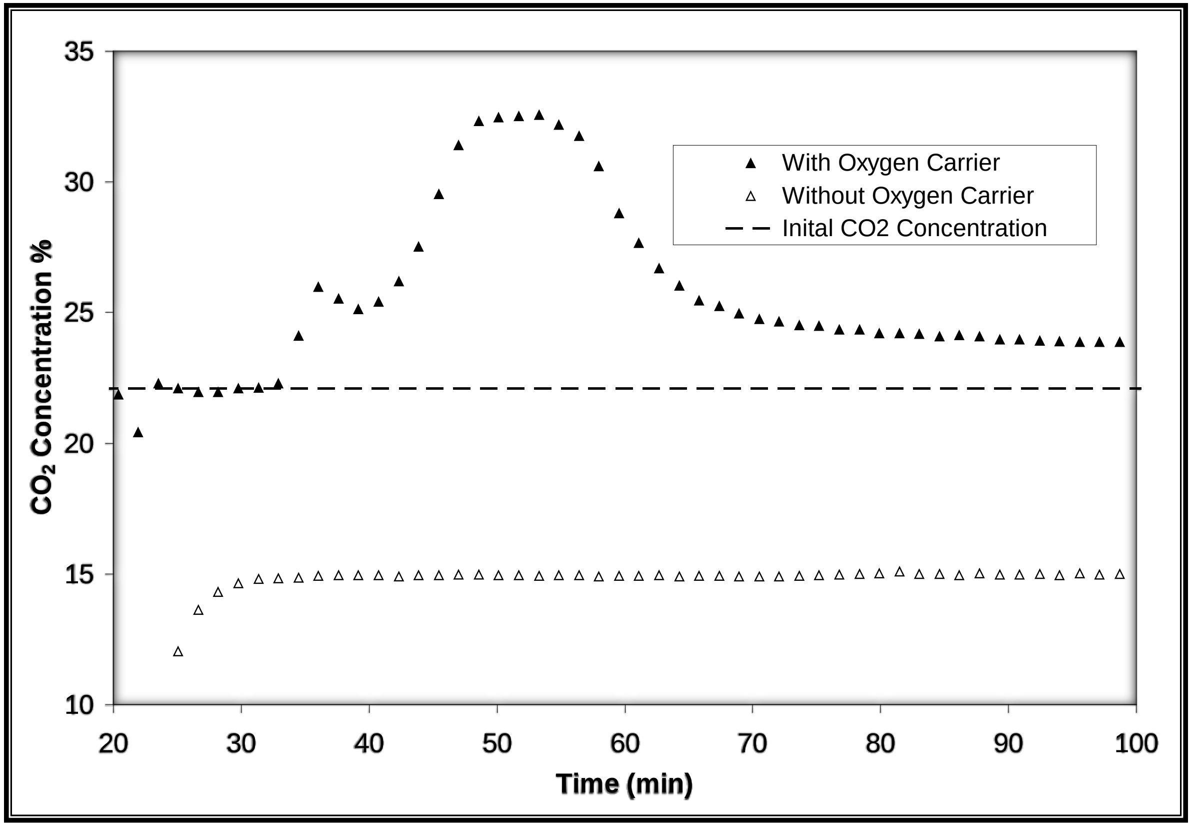




- Char and OC in He
- Reaction Initiated at 400-450 C
- Max. Intensity at 900 C
- $CO_2$ Formation Observation
- Enhanced Reaction at Higher T

# Fixed Bed Experiment

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*




- Gas Analysis
- ~22 vol.% Initial $CO_2$
- Slow Char Conversion w/o OC
- ~70 min. for Char Conversion

**$CO_2$ can enhance the char conversion with OC.**

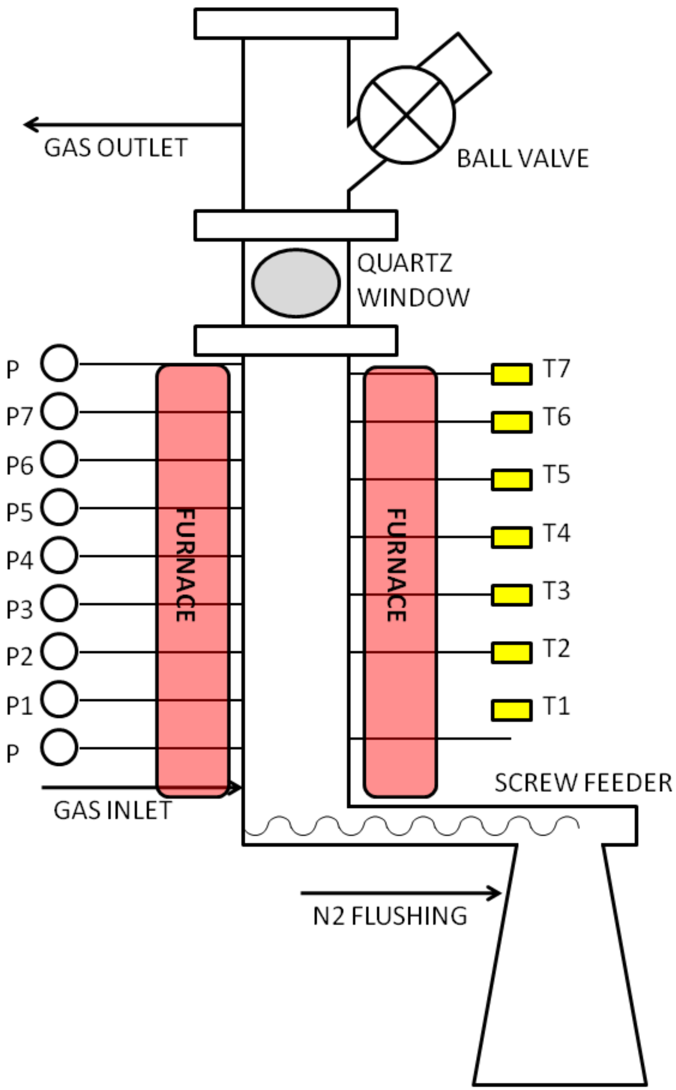
*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

# Progress Review III

## Bench Scale Demonstration

# Bench Scale Demonstration

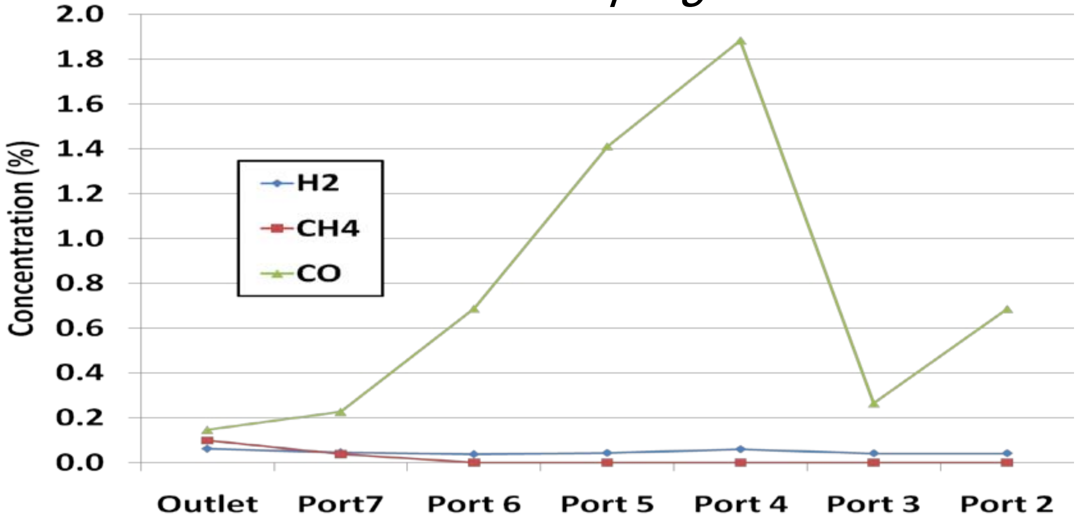
*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*



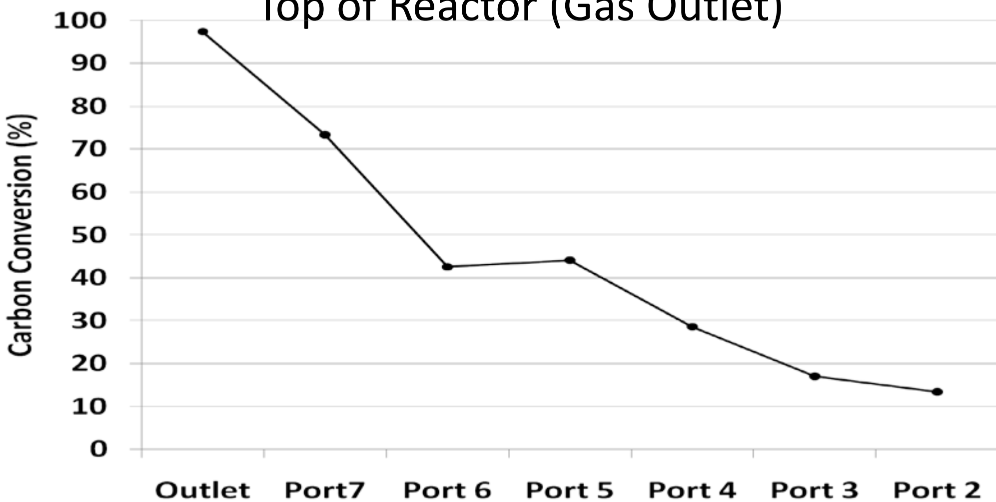

- 2.5kW$_{th}$ Capacity
- Coke Char Used
  - Low volatiles (2.89%)
  - High Carbon (84.4%)
- Gasification Enhancer
  - $CO_2$
  - $H_2O$
- Reaction Temperature Range: 950-1000°C
- Analysis Methods
  - Outlet Flowrate
    - C (Solid) → $CO_2$ + CO + $CH_4$(Gas)
    - Inlet Flow < Outlet Flow
  - Gas Chromatogram (GC)
    - Gas Sampling at Ports

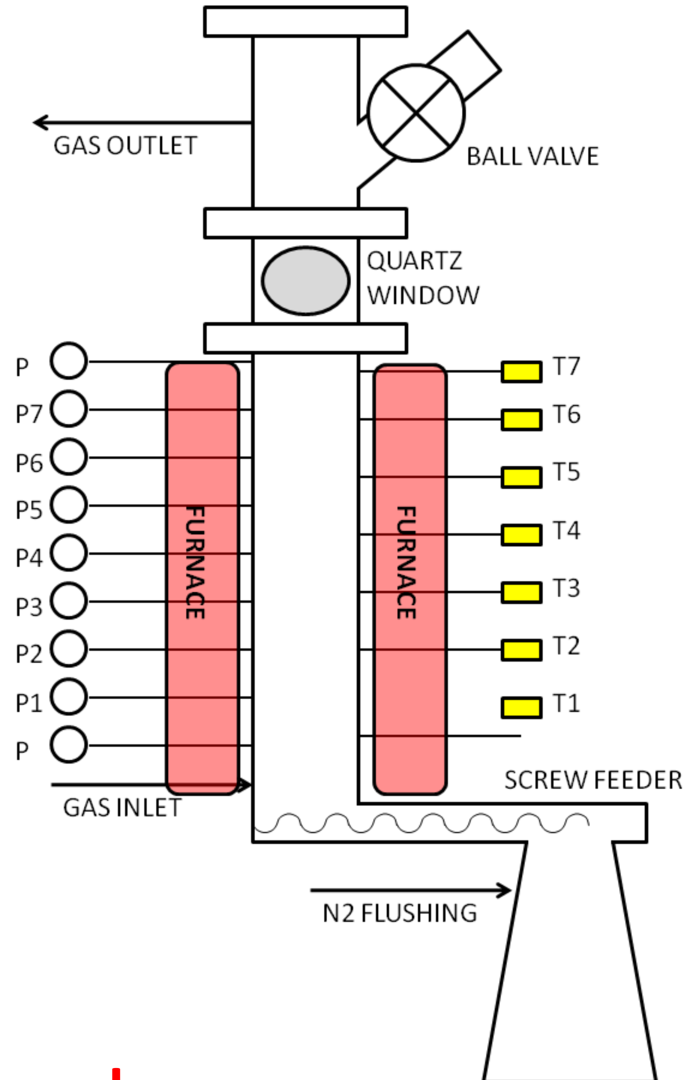
# Bench Scale Demonstration

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*




Top of Reactor (Gas Outlet)



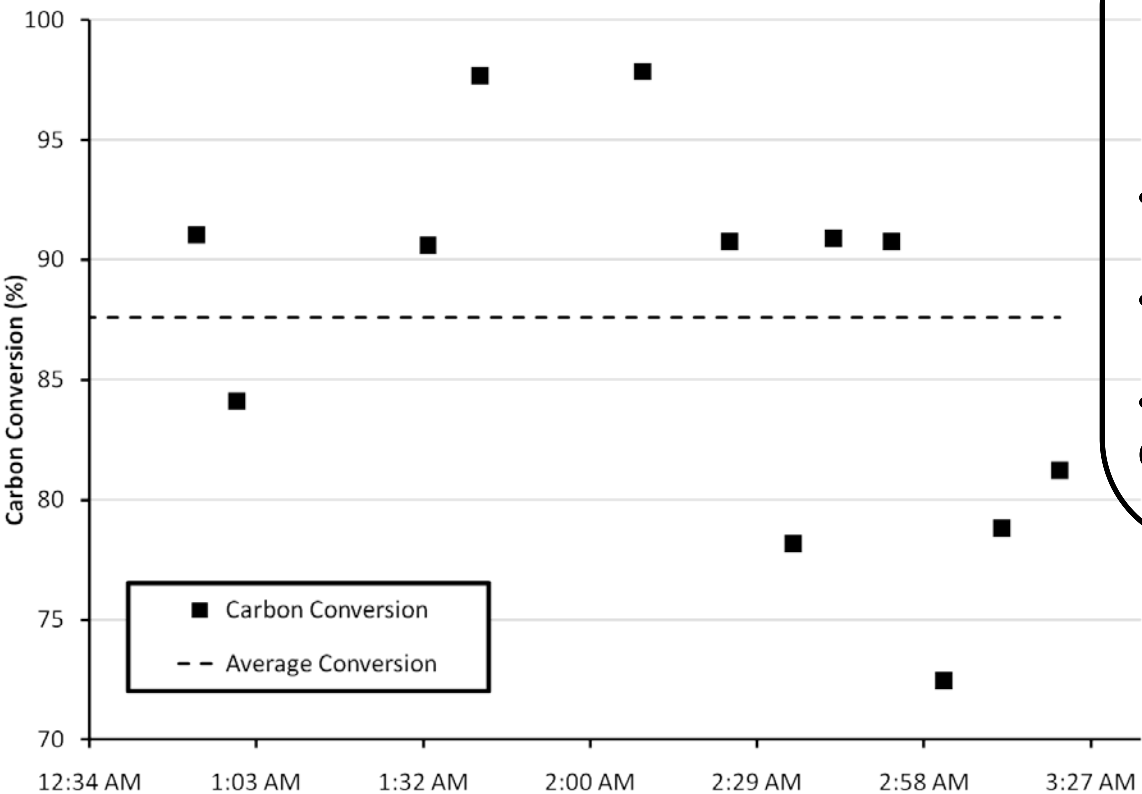




**97% Char conversion with $H_2O$ as gasification enhancer.**

# Bench Scale Demonstration

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

- **Flowrate Measurement at Outlet**
- **Assumes Gas Increment is due to char conversion**




$$X = \frac{V_{measured} - V_{in}}{V_{Carbon}}$$

- $V_{measured}$=Outlet Flowrate (Measured)
- $V_{in}$=Inlet Flowrate (Measured)
- $V_{carbon}$=Max. Flowrate Increment by Char Conversion

  Calculated based on Char Flowrate

**88% Char conversion with $CO_2$ as gasification enhancer.**

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

# Progress Review IV

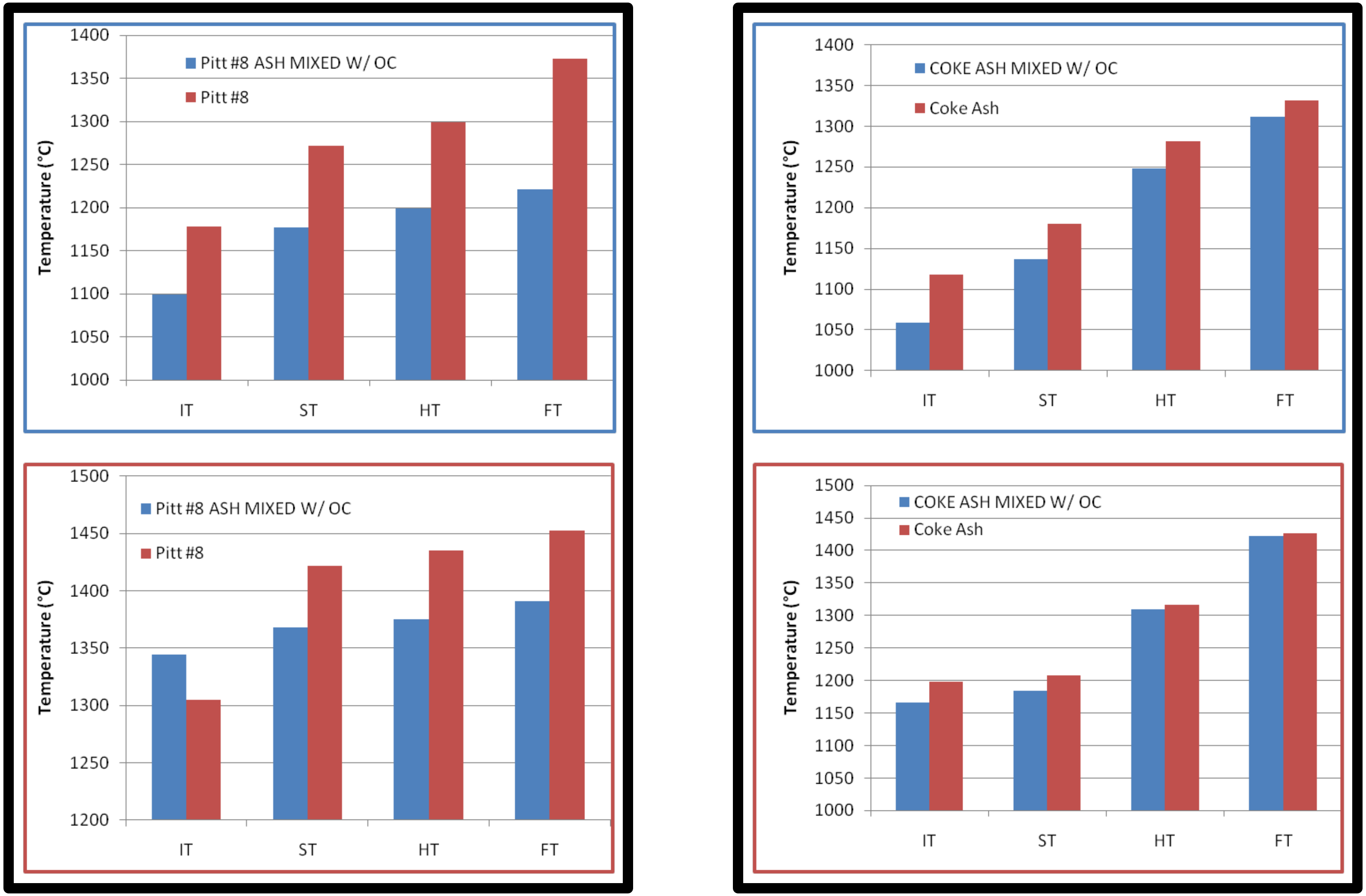
## Ash Study

# Ash Study

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ C02 Capture*

Reducing Environment

Oxidizing Environment




**Effect of OC on ash deforming temp. is minimal.**

**Useful Data for combustor operation & Ash separation**

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

# Progress Review V

## Cold Model/Sub-Pilot Scale Construction

# Cold Model/Sub-Pilot Scale Construction

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ C02 Capture*

- Cold Model - Purposes
  - Feasibility of Reactor Design
  - Hydrodynamic Study of OC, Coal and Ash
  - OC/Coal Residence Time
  - Coal Injection Study

- Sub-Pilot Scale
  - Preliminary Design Based on Cold Model
  - Site Preparation (Reactor Frame, Ventilation, Utilities)
  - Equipment Procurement (Gas Analyzer, Heaters, Control System)
  - Local Vendor Bid
  - Particle Procurement (~2 tons)

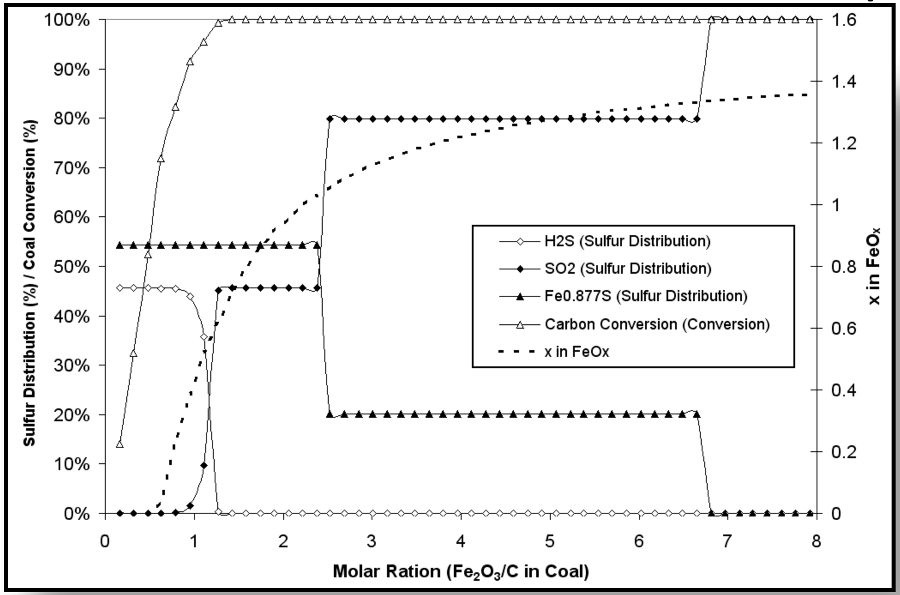
# Progress Review VI

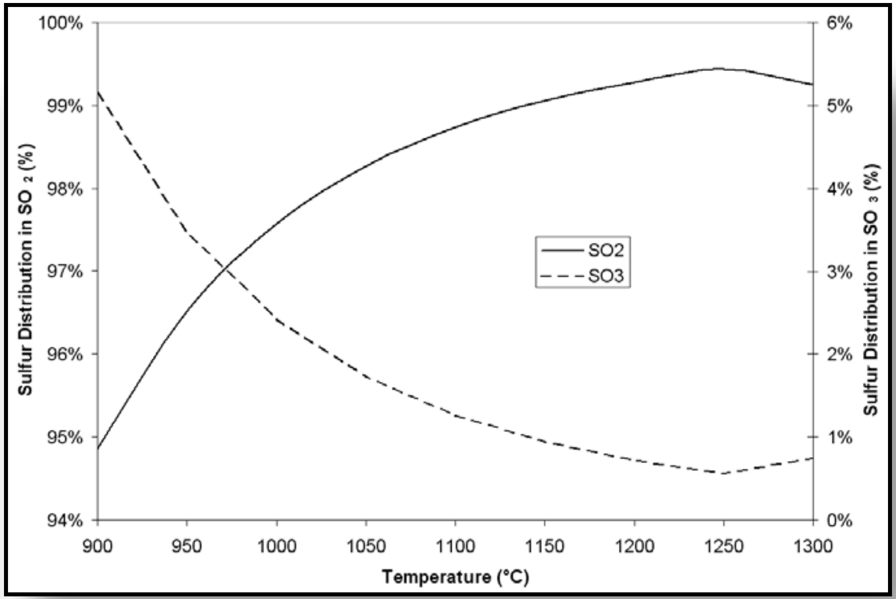
Other Studies

# Other Studies I

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

- ASPEN Simulation for Fate of Sulfur
  - To track down the sulfur contents in CDCL system
    - Reducer – mostly $SO_2$ and FeS, little $H_2S$ and $SO_3$
    - Combustor – mostly $SO_2$ (higher $SO_2$ at higher T) and little $SO_3$
    - Retrofit to PC Plant Set-up

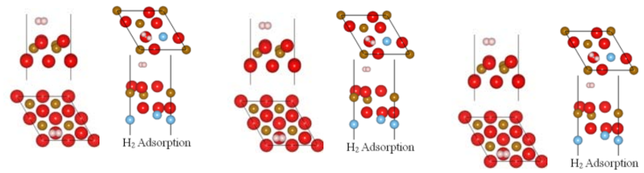


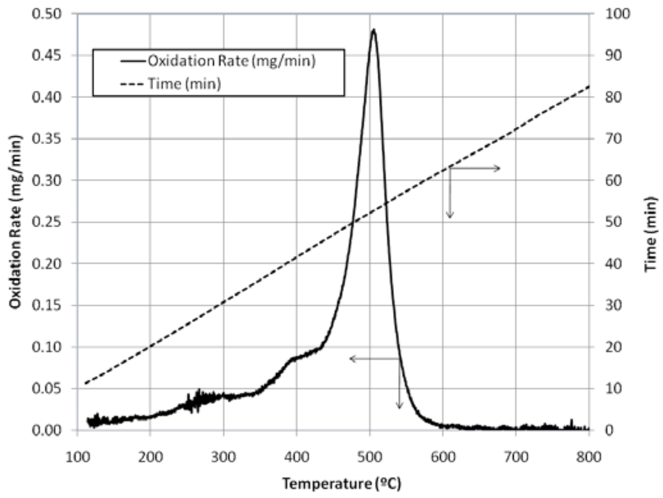
# Other Studies II

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*

- Oxygen Transfer Mechanism
  - To assist OC development




- Combustor Study
  - Operating temperature
  - Particle residence time




# Future Plan

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ C02 Capture*

- Sub-Pilot Scale Construction and Demonstration
- Techno-Economic Study
- Explore Further Development Options for Scale-up

# Team Work is Key

*Coal-Direct Chemical Looping Retrofit to PC Power Plants for In-Situ CO2 Capture*