CHEMICAL LOOPING COAL GASIFICATION
SUB-PILOT UNIT DEMONSTRATION AND ECONOMIC ASSESSMENT FOR IGCC APPLICATIONS

Award #: DE-FE0026185

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Department of Chemical and Biomolecular Engineering

Project Kickoff Meeting | December 7th, 2015
Outline

• Background
• Project Team
• Technical Approach
• Project Management
Metal Oxide as Oxygen Carrier:
Chemical Looping Redox Applications

Combustion: Complete Fuel Oxidation
Reducer: Fe₂O₃ + CH₄ → FeO/Fe + CO₂ + H₂O
   (oxidized) (reduced)
Oxidizer: FeO/Fe + Air (O₂) → Fe₂O₃

Gasification: Partial Fuel Oxidation
Reducer: Fe₂O₃ + CH₄ → FeO/Fe + CO + H₂
   (oxidized) (reduced)
Oxidizer: FeO/Fe + Air (O₂) → Fe₂O₃

Chemicals Production: Selective Oxidation
Reducer catalytic metal oxide reduction
Hydrocarbons
Reduced Metal Oxide
Oxidizer reduced catalytic metal oxide oxidation
Depleted Air
Solar Energy or Nuclear Energy
O₂
Reduced Metal Oxide
Oxidizer reduced metal oxide oxidation
H₂
H₂O

Chemicals (Olefins)

Evolution of OSU Chemical Looping Technology

- **Particle Synthesis**: 1993
- **Fixed Bed Tests**: 1998
- **Bench Scale Tests**: 2001
- **Sub-Pilot CDCL Process Tests**: 2007
- **Pilot Scale Demonstration**: 2010 to date

Evolution of OSU Chemical Looping Technology

- **TGA Tests**
- **CCR Process**
- **SCL Process**
- **STS Process**
Chemical Looping Reactor Design

Fluidized Bed

- Fe₂O₃
- Fe₃O₄
- FeO
- Fe
- CO, H₂
- Unconverted CH₄

Moving Bed

- Fe₂O₃
- Fuel (Coal, CH₄)
- CO, H₂ (Syngas)
- Fe/FeO

Fluidized Bed v.s. Moving Bed

- Large → Reactor Size for same fuel capacity → Small
- Low → Syngas purity → > 90%
- Poor → Controllability on syngas composition → Excellent

Graphs:

- CO₂/PCO vs. Temperature (C)
- Fe₂O₃ vs. Temperature (C)
- Fe₃O₄ vs. Temperature (C)
- FeO vs. Temperature (C)
- Fe vs. Temperature (C)
OSU Chemical Looping Platform Technology

Feedstock:
- Coal
- Natural Gas
- Oil
- Petcoke
- Biomass
- Waste
- Syngas
- F-T light hydrocarbon

Driver:
- Chemical Looping Combustion (CLC)
- Chemical Looping Gasification (CLG)
- Carbonation-Calcination Reaction (CCR)
- Calcium Looping Process (CLP)
- Direct Chemical Synthesis (with EcoCatalytic)

Applications and Products:
- CO₂ Capture/Emission Control
- Electricity/heat
  - Retrofit to PC
  - New Plant
  - Combined Cycle
  - SOFC
- Hydrogen
- CLG Syngas
- Liquid fuel
  - F-T Synthesis
  - CO₂ Hydrogenation
  - Olefins to Liquid Fuel
- Chemicals
  - Olefins
  - Ammonia

Metal Oxide Development

OSU Chemical Looping Platform Processes

Two Basic Modes

**Counter-current: Full Combustion**

- **Simplicity:** One Loop
- **Unique Reducer Configuration:** Moving Bed
- **Unique Flow Controller:** Non-Mechanical L-Valve

**Co-current: Full Gasification**

- **Depleted Air**
- **Syngas out**

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CLG Process Advantages

- Ease in syngas production and quality control
  - Mild operation condition (850-1,000 °C)
  - Advanced oxygen carrier particle can help achieve high syngas yield and selectivity (>90%, low in CH₄, H₂O, CO₂)

- Standalone and flexible energy management
  - No need for gasifier and air separation unit
  - Effective integration with IGCC process

- Efficiency improvement and cost reduction

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<tr>
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<th>GEE</th>
<th>OSU CLG</th>
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<tr>
<td><strong>Gasifier/Reducer Input</strong></td>
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<tr>
<td>H₂O (mol H₂O/mol C)</td>
<td>0.426</td>
<td>0.01 - 0.4</td>
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<tr>
<td><strong>Gasifier/Reducer Output</strong></td>
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<tr>
<td>H₂ (mol H₂/mol C)</td>
<td>0.678</td>
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<td>CO (mol CO/mol C)</td>
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<tr>
<td>CO₂ (mol CO₂/mol C)</td>
<td>0.270</td>
<td>0.09 - 0.06</td>
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*Carbon value based on as-received coal (Illinois #6)
Oxygen Carrier Selection

Modified Ellingham Diagram

Standard Gibbs Free Energy of Reactions (kJ/mol O₂)

Temperature (°C)

Reactivity and recyclability of selected particle confirmed
Classical Thermodynamics: CH$_4$ and Fe$_2$O$_3$

% CH$_4$ conversion – 99.80%

% Solid Conversion – 33.33%

H$_2$/CO = 1.97

Increasing Fe$_2$O$_3$/CH$_4$ ratio decreases syngas yield, which qualitatively agrees with ab initio thermodynamic calculation.

Conversion, Yield (%)

Fe$_2$O$_3$/CH$_4$ molar ratio

Oxygen Vacancy Rich

Oxygen Vacancy Lean

(0.38)

(1.38)
Classical Thermodynamics: 100% Coal

- 92.8% Carbon conversion – 100.0%
- Fuel input: 100% Illinois #6 Coal
- 0.90
- 0.3
- 5

% Conversion vs. \( \frac{Fe_2O_3}{C_{input}} \) (molar ratio)
CLG Bench Scale Studies

- Coal mixed with Oxygen Carrier particles
- Tests performed:
  - Methane to syngas
  - Sub-bituminous and bituminous coal to syngas
  - Co-injection of methane
  - Co-injection of methane and steam
CLG Bench Scale Studies

- Coal volatile tests: CH₄ to syngas
  - CH₄ conversion: >95%
  - Syngas purity: >88%
  - H₂:CO Ratio: 2:1

- Coal Tests: PRB
  - Coal conversion: >93%
  - Syngas purity: >88%
  - H₂:CO Ratio: 0.64:1

- H₂ rich syngas produced co-injecting CH₄ and H₂O co-injection with PRB coal
  - H₂:CO Ratio: ~1.8
  - Syngas purity: >85%

**Coal Volatile Tests**

- Temp.: 1000°C
- OC Flow: 20g/min
- CH₄ Flow: 1.8 SLPM
- N₂ Flow: 0.2 SLPM

**PRB Coal Tests**

- Temp.: 1000°C
- OC: 20g/min
- Coal: 0.9g/min
- CH₄: 1.2SLPM
- H₂O: 0.8g/min
- N₂: 1SLPM

Coal:CH₄:H₂O:Fe₂O₃≈4:6:5:7 (mole ratio)
CLG Bench Scale Studies

- Sub-bituminous coal (PRB) and bituminous coal (Illinois #6) tested with CH₄ co-injection
- High purity syngas generation achieved
- H₂:CO ratio of 1:1 achieved by adjusting CH₄ flow rate for both coals tested
- Syngas with variable CO:CO₂ ratio can be generated
  - Extreme case of CO:CO₂ = 0.1 shown below

High CO₂ Syngas Generation

- Temp.: 950°C
- OC Flow: 20g/min
- Coal: 0.75 g/min
- H₂O Flow: 0.56 g/min

Illinois #6 Coal Test

- Temp.: 1000°C
- OC Flow: 20g/min
- Coal: 2.8g/min
- CH₄ Flow: 0.75 SLPM
Experimental Studies – Coal Volatile Tests

- 100% Methane Conversion
- 90% Syngas Purity
- 2:1 Ratio – Suitable for Liquid Fuel Synthesis
Coal Gasification for Methanol Production: OSU Process

Coal

Steam

Ambient Air

OSU Reducer

OSU Oxidizer

N₂

Fe₂O₃

2FeO

Sour Syngas

Low Temp Cooling & Mercury Removal

Sour Water System

Sour Gas

Sour Water

Flash Gas

Stripped Water

CO₂ Compressor

CO₂ Product

Crude Methanol Product

Tail Gas from Methanol Synthesis to Steam Production

Methanol Synthesis

Sweet Syngas

Acid Gas Removal (Rectisol)

Acid Gas

Claus Plant

Sulfur Product

Sour Gas

Overall Techno-Economic Analysis Summary

- A lower methanol Required Selling Price by $0.37/gal, a 21% decrease
- Lower total plant capital costs by 28%
- Lower the capital cost for syngas generation equipment by over 50%
- Higher efficiency based 14% in coal consumption
- A methanol Required Selling Price lower than the reference non-capture case, which results in CO\(_2\) capture cost less than 0.

Performance modelling Results: 10,000 mtpd crude methanol system

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<th>Mass Flow lb/hr</th>
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<tr>
<td>Case</td>
<td></td>
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<tr>
<td>As Received Coal</td>
<td>DOE/NETL MBL-1, MBL-2 OSU-1 OSU-2</td>
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<tr>
<td>Natural Gas to OSU CLG</td>
<td>NA</td>
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<tr>
<td>Oxygen from Air Separation Unit</td>
<td>10,10,968 (95% (O_2))</td>
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<tr>
<td>Steam to gasifier, reformer, quench, OSU CLG</td>
<td>1,533,584</td>
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<tr>
<td>Clean syngas for methanol production</td>
<td>1,183,080</td>
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<tr>
<td>Captured CO(_2)</td>
<td>1,569,410 (MLB-2)</td>
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Cost Analysis: Total Plant Capital Cost for 10,000 ton/day Methanol Production from Coal

DOE baseline: $1,789 MM
OSU CTS: $1,419 MM

Sale Price ($/gal):
- DOE baseline: 1.78
- OSU CTS: 1.41

Gasification equipment capital cost ($/MM/10,000 tpd crude methanol):
- DOE baseline: $1,145 MM
- OSU CTS: $913 MM

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Project Team

Government Agencies
• DOE/NETL: Darryl Shockley
• Ohio Development Service Agency: Gregory Payne

Project Partners
• Ohio State University: Liang-Shih Fan (PI), Andrew Tong (Co-PI)
• WorleyParsons: James Simpson
• Clear Skies: Robert Statnick
Outline

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Technical Approach - Project Objectives

- Prepare Chemical Looping Gasification (CLG) technology for a commercially relevant demonstration by 2020.
- Design and construct an integrated CLG system at sub-pilot scale with coal as its feedstock:
  - Continuously operate the system and demonstrate syngas and $H_2$ production.
  - Investigate the fates of some important impurities, such as sulfur and nitrogen.
- Conduct techno-economic analysis and optimize the CLG process for efficient electricity generation with reduced carbon emission.
# Technical Approach – Tasks and Schedule

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<td>2.3 System Design Finalization and Costing</td>
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15 kW$_{th}$ Sub-Pilot Reactor Design

- Integrated 3-reactor system
  - Non-mechanical devices
  - Computerized data acquisition and process control

- Design, Construction, and Commissioning
  - Detailed design and safety review
  - Reactor fabrication
  - Installation on existing structure
  - Leak check, instrument calibration, functional checks, and final safety review
Cold Flow Model Studies

Fuel Reactor Design

- Co-Current Move Bed Arrangement
  - Top Gas/Solids In
  - Bottom Gas/Solids Out
- Dipleg for solids/gas inlet
- Pressure Drop
  - Gas-Solids Relative Velocity
  - Ergun Equation
  - Pressure Drop v.s. Velocity
15 kW$_{th}$ Sub-Pilot Reactor Operation

- **Parametric studies**
  - Coal:Fe$_2$O$_3$ ratio
  - Coal:H$_2$O ratio
  - Temperature
  - Residence time
  - Verify performance model

- **Performance Parameters**
  - Coal conversion
    \[ X_{coal} = \frac{n_{C,\text{reducer}} + n_{C,\text{combustor}} + n_{C,\text{oxidizer}}}{n_{C,\text{coal}}} \]
  - Carbon capture efficiency
    \[ \eta_C = \frac{n_{C,\text{reducer}} + n_{C,\text{oxidizer}}}{n_{C,\text{coal}}} \]
  - Syngas purity
    \[ S = x_{CO,\text{reducer}} + x_{H_2,\text{reducer}} \]
  - Gasification thermal efficiency
    \[ \eta_t = \frac{HHV_{\text{reducer}} + HHV_{\text{oxidizer}}}{HHV_{\text{coal}}} \]
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<td><strong>4.0 Integrated Sub-Pilot Unit Operations</strong></td>
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<td><strong>4.2 Continuous Operation of the System</strong></td>
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<td><strong>5.0 Techno-Economic Analysis of the CLG Process for IGCC Application</strong></td>
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<td><strong>5.1 Developing a CLG Performance Model and Technology Analysis Plan (TAP)</strong></td>
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<td>12/31/16</td>
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<td><strong>5.3 Techno-Economic Assessment for IGCC Applications and Final Reporting</strong></td>
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<td><strong>6.0 Final Report</strong></td>
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</table>
Leading professional services provider to the energy, resource, and complex process industries

Organized into Customer Sector Groups:

**Upstream Hydrocarbons**
- Fixed Offshore Facilities
- Floating Production Systems
- Deepwater Solutions
- Subsea Systems
- Offshore Pipelines
- Onshore Pipelines
- Onshore Oil & Gas Production Facilities
- Heavy Oil and Oil Sands
- LNG
- Terminals

**Downstream Hydrocarbons**
- Refining
- Petrochemicals
- Chemicals
- Polymers
- Gasification
- Sulphur Management

**Power**
- Coal-Fired Plants
- Advanced Coal
- Nuclear
- Gas Turbine/Combined Cycle
- Air Quality Control
- Integrated Gasification Combined Cycle (IGCC)
- Transmission Networks
- Operations & Maintenance
- Renewable Energy

**Minerals, Metals & Chemicals**
- Base Metals
- Coal
- Chemicals
- Ferrous Metals
- Alumina
- Aluminum
- Iron Ore
- Gas Cleaning

**Infrastructure & Environment**
- Resource Infrastructure
- Urban Infrastructure
- Coastal and Marine
- Water and Wastewater
- Transport
- Environment
Objectives:

1. Develop process models and configurations for and IGCC power generation facilities incorporating OSU CLG technology.
2. Develop economic comparison of facility designs incorporating OSU CLG technology to IGCC reference cases.

Activities:

- Develop process models of OSU CLG technology in Aspen
- Incorporate OSU CLG technology modules in Aspen IGCC process models.
- Estimate capital and operating costs based on Aspen modeling of processes
- Perform financial analysis to determine power production costs and cost of CO₂ captured.
- Compare costs to DOE/NETL reference cases
Options Considered

- **Reference IGCC Power Production:**
  - IGCC cases from Cost and Performance Baseline for Fossil Energy Plants Volume 1b: Bituminous Coal (IGCC) to Electricity Revision 2b.

- **OSU CLG Cases**
  - No capture with 2 reactor CLG configuration
  - CO$_2$ capture with 2 reactor CLG configuration
CTS SYSTEM #1 (No CCS)

- As Received Coal
  - Coal Preparation
  - Reducer
  - Combustor
  - Compressor
  - HRSG

- FeO/Fe
- FeO₂/Fe₂O₃

- BFW Heating & Knockout
- Mercury Removal
- Acid Gas Removal (H₂S)

- Sour Water
- Syngas

- Sour Water System
- Gas Cooling

- Stripped Water
- Spent-Air to Stack

- Syngas
- Reheat & Humidification

- Sulfur Product
- Gas Turbine Combustor
- HRSG

- Nitrogen Diluent
- Electricity Production

- Turbine Cooling Air
- 2X Advanced F CLASS GAS TURBINE
- Air

- Turbine Combustor
- HRSG
- Steam Turbine

- HRSG
- Gas Turbine Combustor

- Syngas
- Combustor
- FeO/Fe₂O₃

- Air
- Nitrogen Diluent
- Electricity Production

- 2X Advanced F CLASS GAS TURBINE
- Turbine Cooling Air

- The Ohio State University
2 Reactor Design:

As Received Coal → Coal Preparation → Reducer → Combustor → Quench, Scrubbing → Shift Reactors → Gas Cooling BFW Heating & Knockout → Mercury Removal → Acid Gas Removal (Selexol) → CO₂ Compressor → CO₂ Product

CO₂ free syngas → Sour Water System → Sour Gas → Claus Plant → Sulfur Product

Stripped Water → HRSG → Spent-Air to Stack

Nitrogen Diluent → Gas Turbine Combustor

2X Advanced F CLASS GAS TURBINE

Ambient Air → Turbine Cooling Air → Electricity Production

HRSG → Steam Turbine

CO₂ free syngas → HRSG

Coal → HRSG → Ash Removal

FeO/Fe → Fe₂O₃
Evaluation Basis

- Fuel: Bituminous Coal
- CO₂ Removal: >90% based on raw syngas carbon content
- CO₂ Product
  - CO₂ Purity: Enhanced Oil Recovery as listed in Exhibit 2-1 of the NETL QGESS titled “CO₂ Impurity Design Parameters”. *
  - CO₂ Delivery Pressure: 2,215 psia
  - Transport and Storage (T&S): $10/tonne
- Plant Size: Sufficient syngas to fill two advanced F class gas turbines, 500-550 MW.
- Power Block: 2x1 Configuration, advanced F class gas turbines
- Ambient Conditions: Greenfield, Midwestern USA
- Capacity Factor: 80%
- Financial Structure: High risk IOU, capital charge factor = 0.124
Capital and Operating Costs

Reference Case

- Capital and O&M cost will be determined from costs presented in DOE/NETL Cost and Performance Baseline Studies for coal-fired power.

OSU CLG System

- Sizing information of reactors and consumption rates for consumables will be developed from Aspen modeling and guidance from OSU.
- ICARUS, from Aspen Tech., and in-house parametric models will be used for developing costs for reactor vessels, absorbers, and other specialized process equipment based on the equipment size, basic design, and materials of construction information.
- Factored estimates for equipment such as pumps
Capital Cost Breakdown

- Costs will be presented in 2011 dollars
- Factored estimates for equipment such as pumps
- Capital costs breakdown will be provided to illustrate the contribution of various accounts (such as Coal & Sorbent Handling and Instrumentation & Control) to the total plant costs.

- Breakdown of accounts will include:
  - Equipment
  - Material
  - Labor
  - Engineering, Construction
  - Management, Home Office and Fees
  - Process and Project Contingencies
Operation and maintenance cost breakdown will include:

**Fixed**
- Operating Labor
- Maintenance Labor
- Administrative & Support Labor
- Property Taxes and Insurance
- Maintenance Material

**Variable**
- Consumables
  - Water
  - Oxygen carrier
  - Solvents
- Waste Disposal
- Fuel
Purpose:

- Compare Cost of Electricity (COE) for systems including OSU CLC technology to reference case developed by DOE/NETL.
- Provide understanding of factors that impact COE

Activities:

- Determine COE and LCOE and cost of CO₂ captured using DOE/NETL Power Systems Financial Model or similar in house models.
- Explore sensitivity of metrics on input parameters to economic model including:
  - process efficiency
  - capital costs
  - operating costs

Deliverables

- Design basis report
- Quarterly updates
- Final techno-economic report
Outline

• Background
• Project Team
• Technical Approach
• Project Management
Project Management

- **NETL/DOE**
  - **Prof. Fan** (PI)
  - **Prof. Tong** (Co-PI)

- **Project Management and Planning** (Task 1)
  - **Detailed Design** (Task 2)
    - **Construction and Commissioning** (Task 3)
      - **Integrated Unit Operations** (Task 4)

- **2 Postdoctoral Research Associates**
  - **4 Graduate Research Associates**
  - **WorleyParsons**
    - **Postdoctoral Research Associate**
      - **Clear Skies Consulting**

- **Tasks**
  - Task 1: Project Management and Planning
  - Task 2: Detailed Design
  - Task 3: Construction and Commissioning
  - Task 4: Integrated Unit Operations
  - Task 5: Techno-Economic Analysis
## Project Budget

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Thanks