THE OHIO STATE UNIVERSITY

CHEMICAL LOOPING COAL GASIFICATION

SUB-PILOT UNIT DEMONSTRATION AND ECONOMIC ASSESSMENT FOR IGCC APPLICATIONS

Award #: DE-FE0026185

Liang-Shih Fan

Department of Chemical and Biomolecular Engineering

Project Kickoff Meeting | December 7th, 2015

Outline

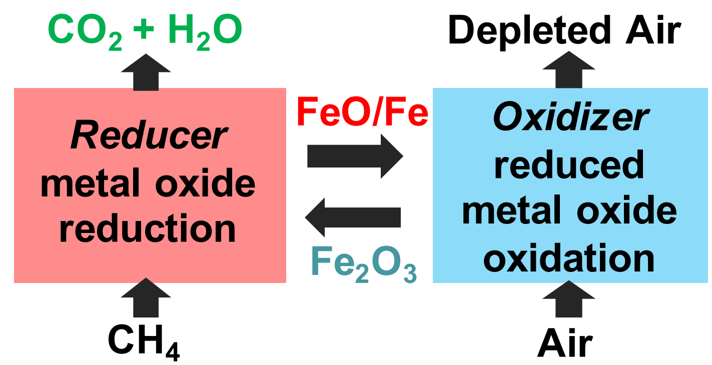
- **Background**
- Project Team
- Technical Approach
- Project Management

Metal Oxide as Oxygen Carrier:
Chemical Looping Redox Applications

Combustion: Complete Fuel Oxidation

Reducer: Fe_2O_3 + CH_4 → **FeO/Fe** + **CO_2 + H_2O**
(oxidized) (reduced)

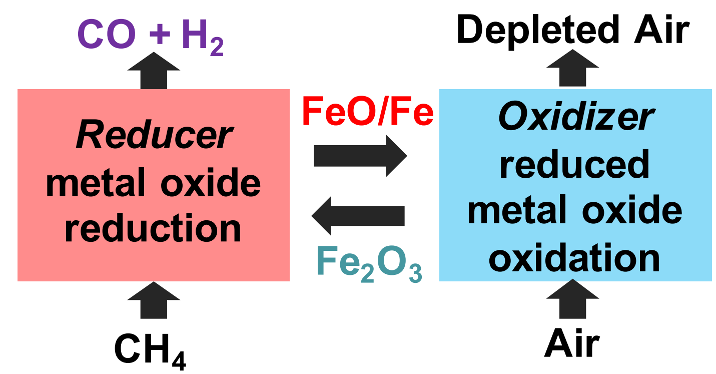
Oxidizer: **FeO/Fe** + Air (O_2) → **Fe_2O_3**

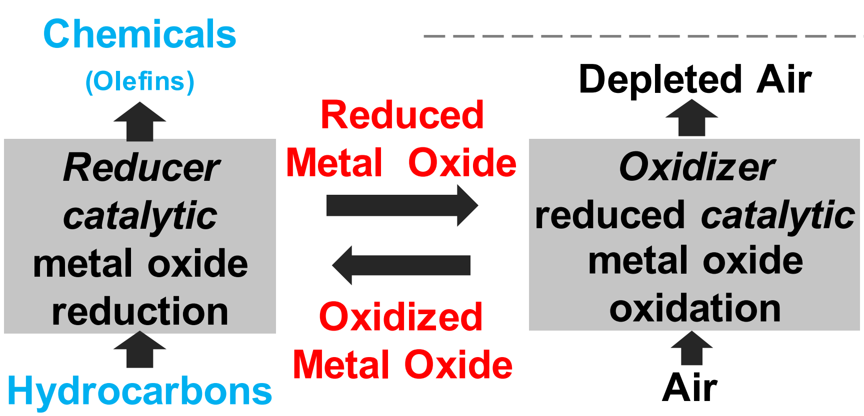


Gasification: Partial Fuel Oxidation

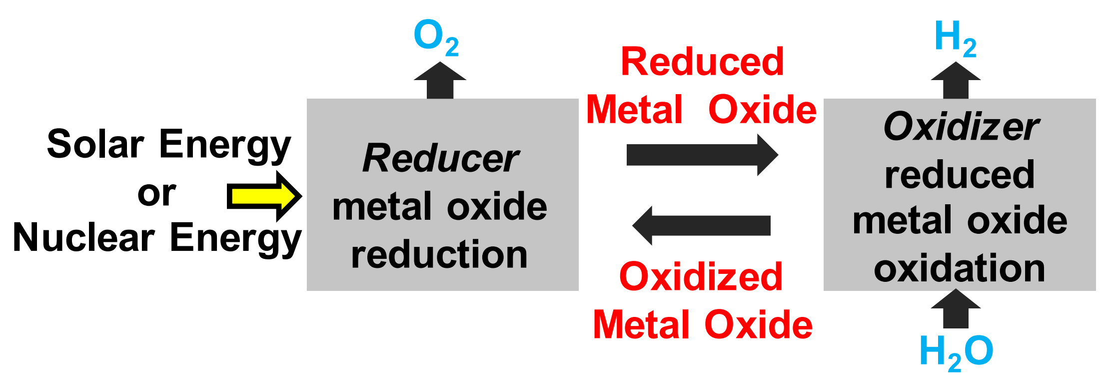
Reducer: Fe_2O_3 + CH_4 → **FeO/Fe** + **CO + H_2**
(oxidized) (reduced)

Oxidizer: **FeO/Fe** + Air (O_2) → **Fe_2O_3**





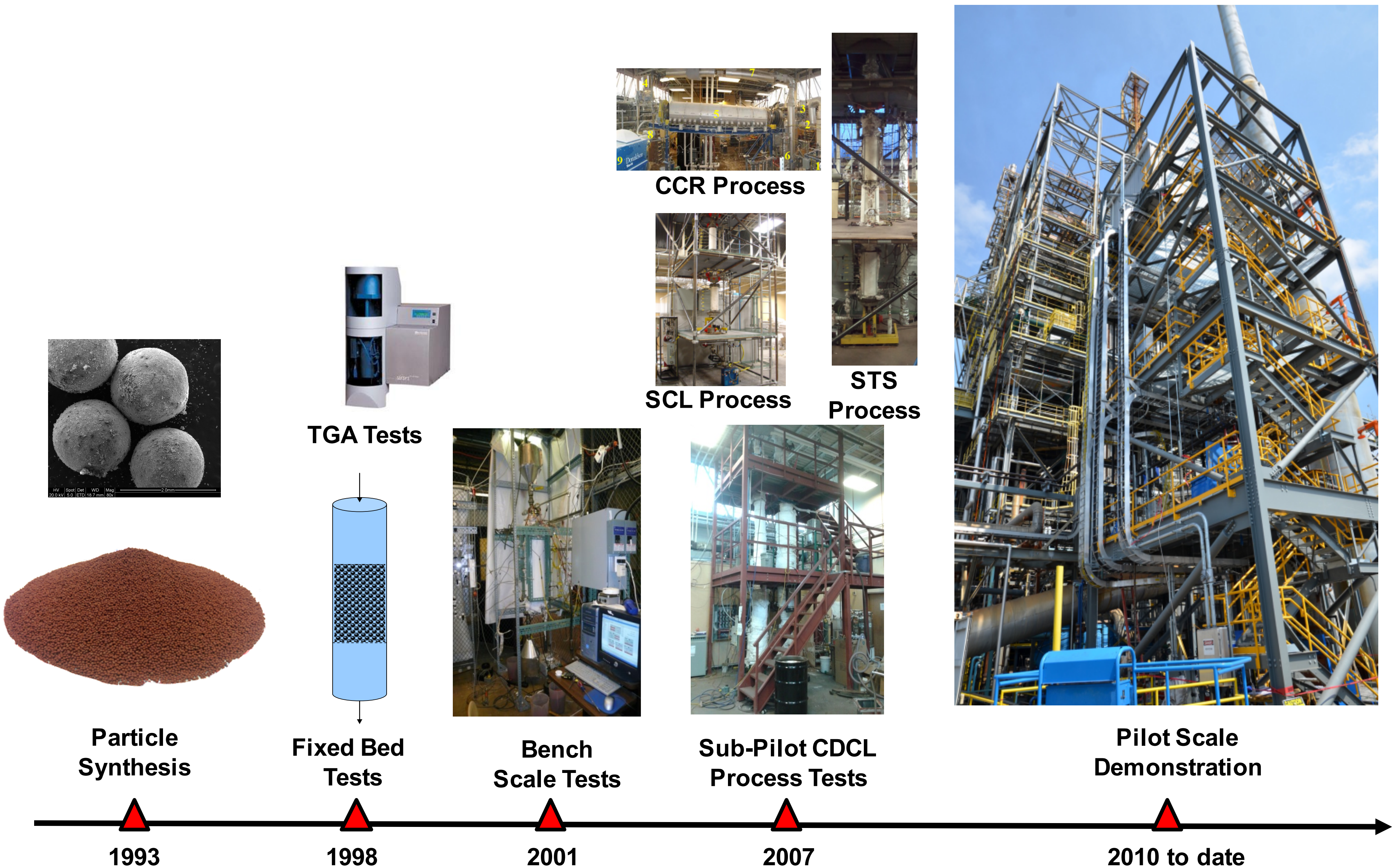
Chemicals Production: Selective Oxidation



Solar/Nuclear Chemical Looping: Water Splitting

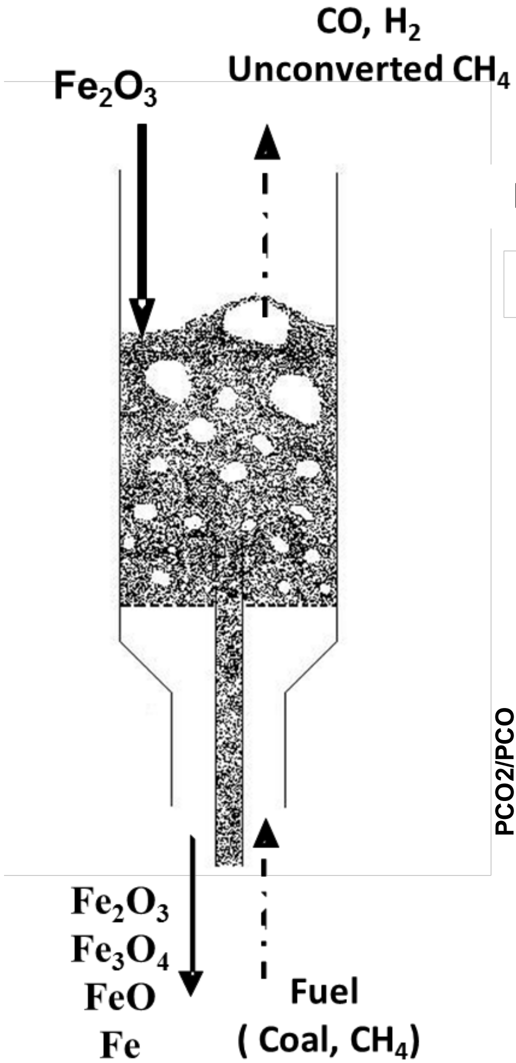
Luo, S., Zeng, L., Fan, L.-S., *Annual Review of Chemical and Biomolecular Engineering*. July 2015.
Chung, E.Y., Wang, W.K., Alkhatib, H., Nadgouda, S., Jindra, M.A., Sofranko, J.A., Fan, L.-S. 2015 AIChE Spring Meeting. April 2015.
Chueh, W. C., Falter, C., Abbott, M., Scipio, D., Furler, P., Haile, S.M., Steinfeld, A. *Science*. 2010.

Evolution of OSU Chemical Looping Technology



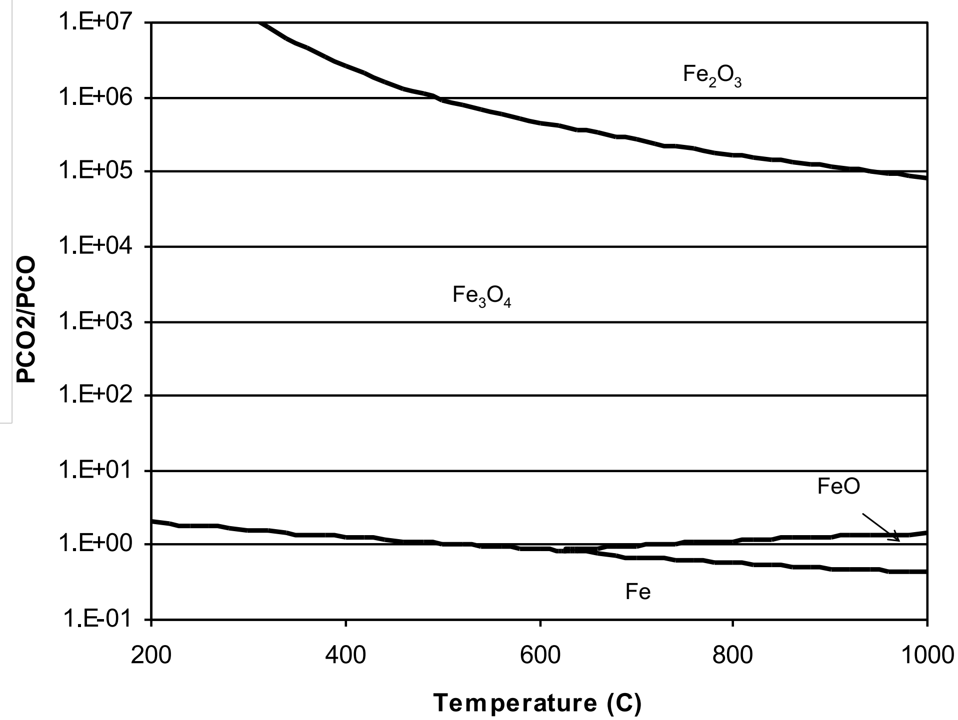
Fan, L.-S., Zeng, L., Luo, S. *AIChE Journal*. 2015.

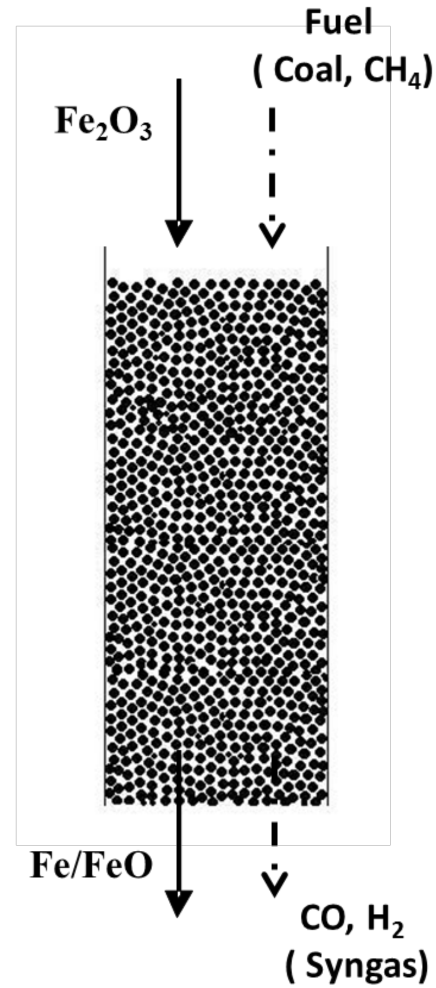
Chemical Looping Reactor Design



Fluidized Bed *v.s.* **Moving Bed**

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





Fluidized Bed

Moving Bed

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

- CO_2 Capture/Emission Control
- Electricity/heat
  - Retrofit to PC
  - New Plant
  - Combined Cycle
  - SOFC
- Hydrogen
- CLG Syngas
- Liquid fuel
  - F-T Synthesis
  - CO_2 Hydrogenation
  - Olefins to Liquid Fuel
- Chemicals
  - Olefins
  - Ammonia

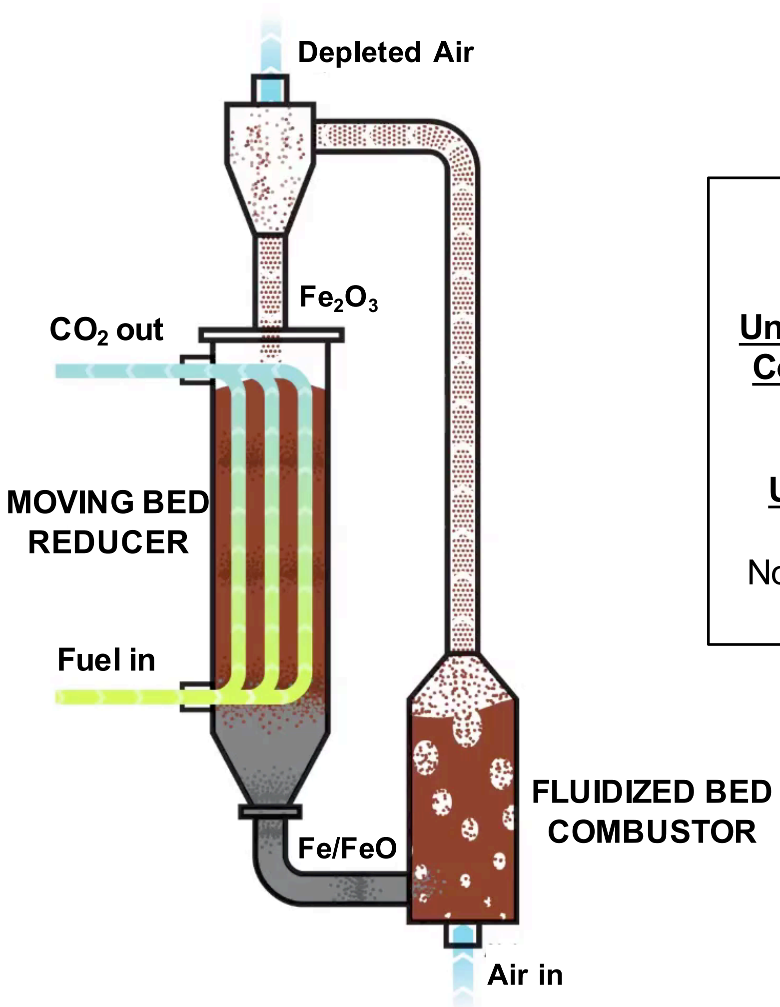
Metal Oxide Development

Thomas, T. J., Fan, L.-S., Gupta, P., Velazquez-Vargas, L.G. U.S. Patent 7,767,191.

OSU Chemical Looping Platform Processes

Two Basic Modes

Counter-current: Full Combustion

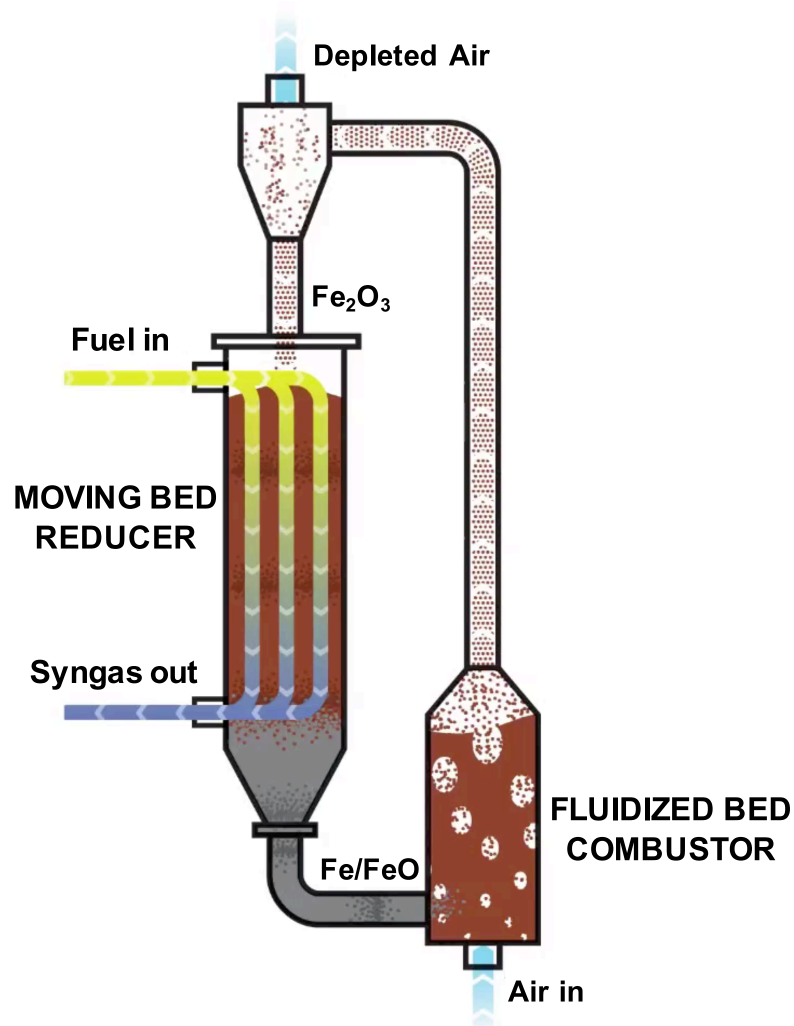


Simplicity:
One Loop

Unique Reducer Configuration:
Moving Bed

Unique Flow Controller:
Non-Mechanical L-Valve

Co-current: Full Gasification



Fan, L.-S., Zeng, L., Luo, S. *AIChE Journal*. 2015.

CLG Process Advantages

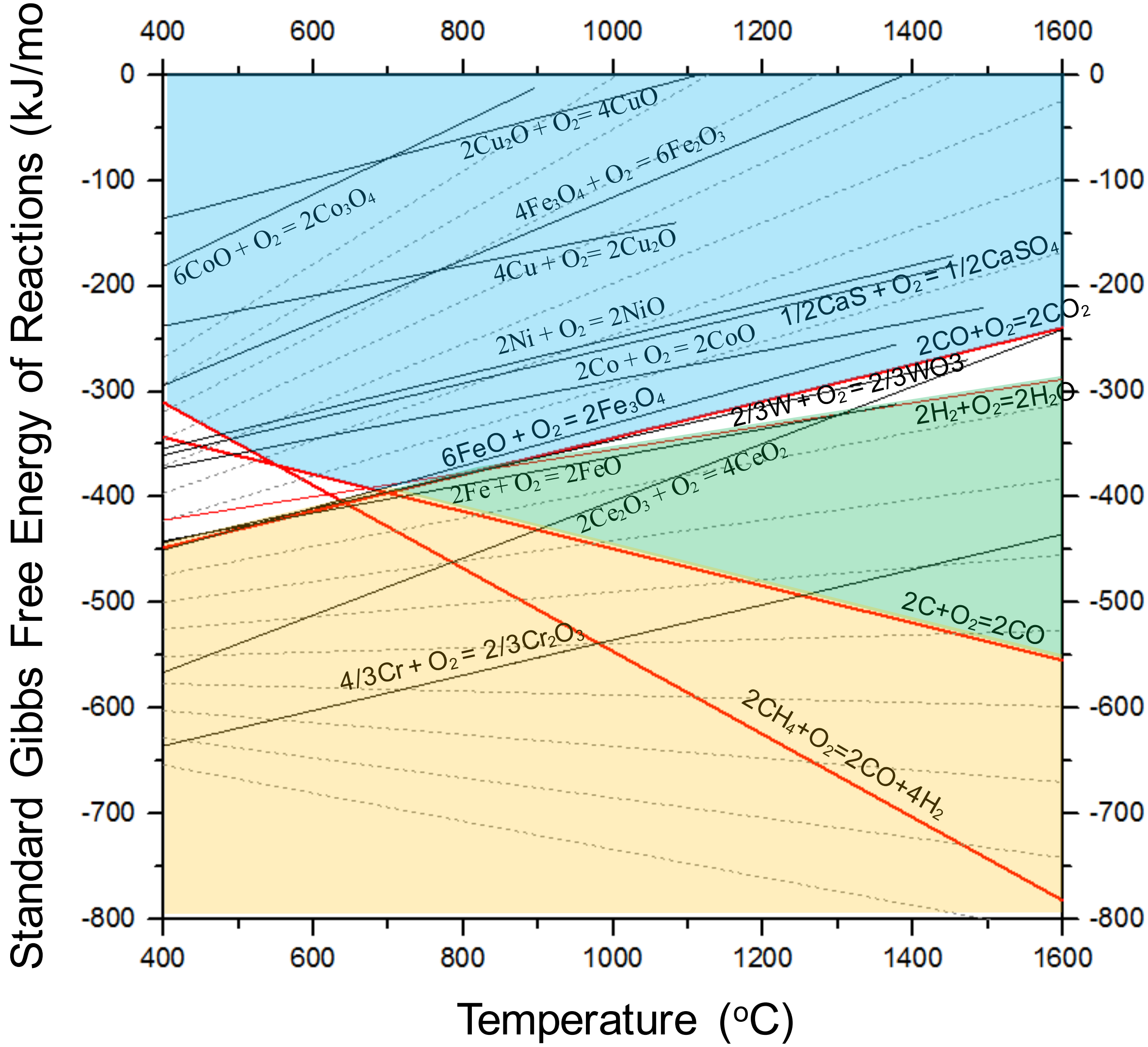
- Ease in syngas production and quality control
  - Mild operation condition (850-1,000 ℃)
  - Advanced oxygen carrier particle can help achieve high syngas yield and selectivity (>90%, low in CH_4, H_2O, CO_2)
- Standalone and flexible energy management
  - No need for gasifier and air separation unit
  - Effective integration with IGCC process
- Efficiency improvement and cost reduction

	GEE	OSU CLG
Gasifier/Reducer Input		
H_2O (mol H_2O/mol C)	**0.426**	**0.01 - 0.4**
Gasifier/Reducer Output		
H_2 (mol H_2/mol C)	**0.678**	**0.48-0.70**
CO (mol CO/mol C)	**0.707**	**0.91-0.93**
CO_2 (mol CO_2/mol C)	**0.270**	**0.09 -0.06**

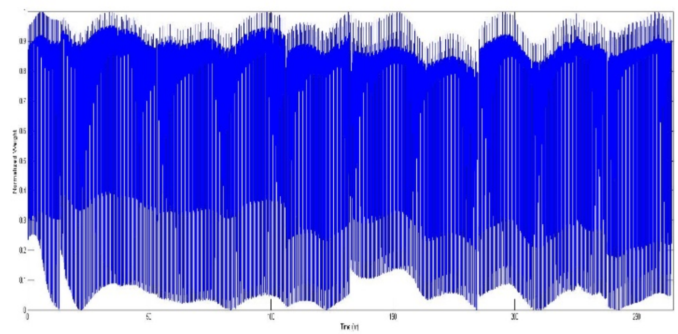
*Carbon value based on as-received coal (Illinois #6)

Oxygen Carrier Selection

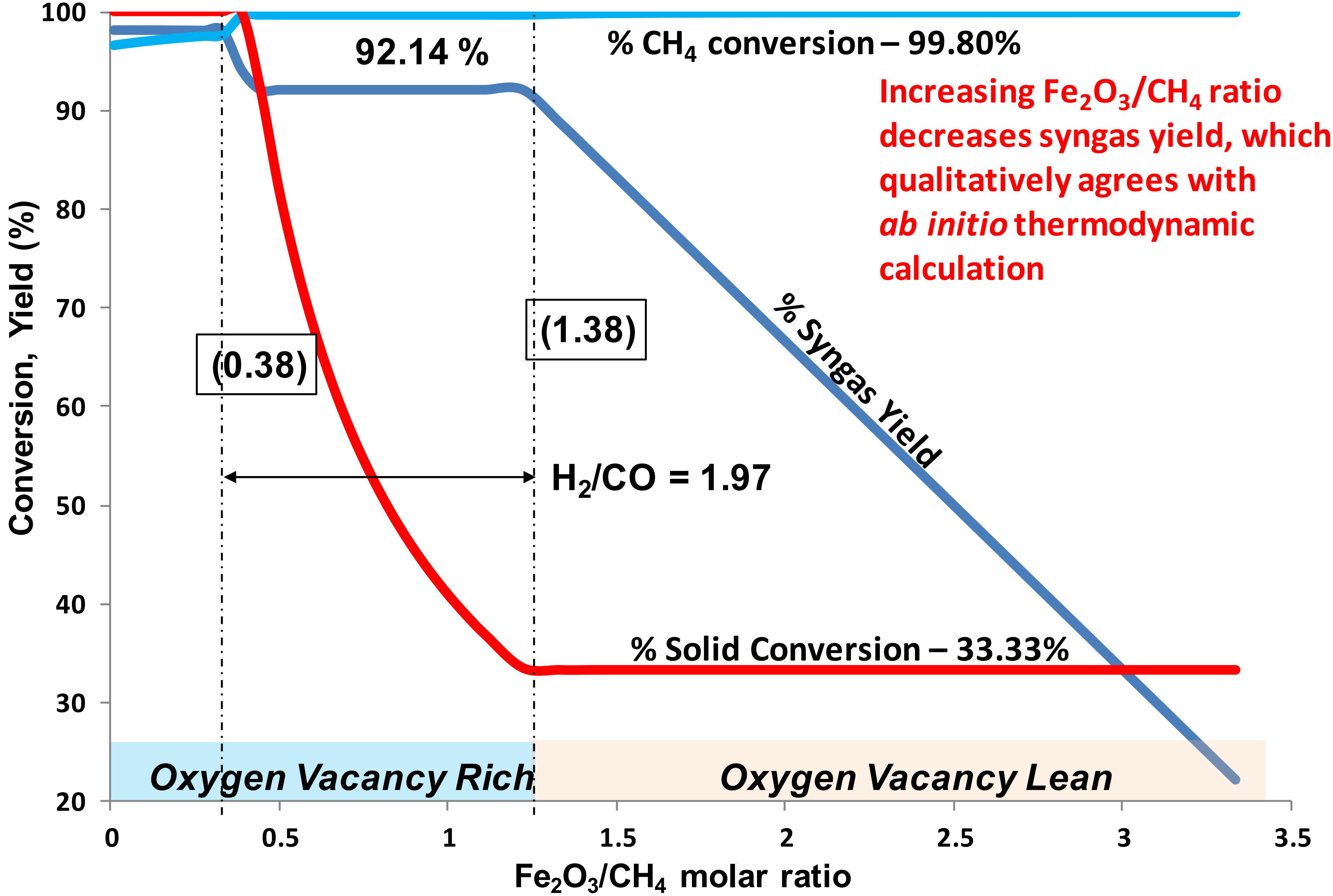
Modified Ellingham Diagram



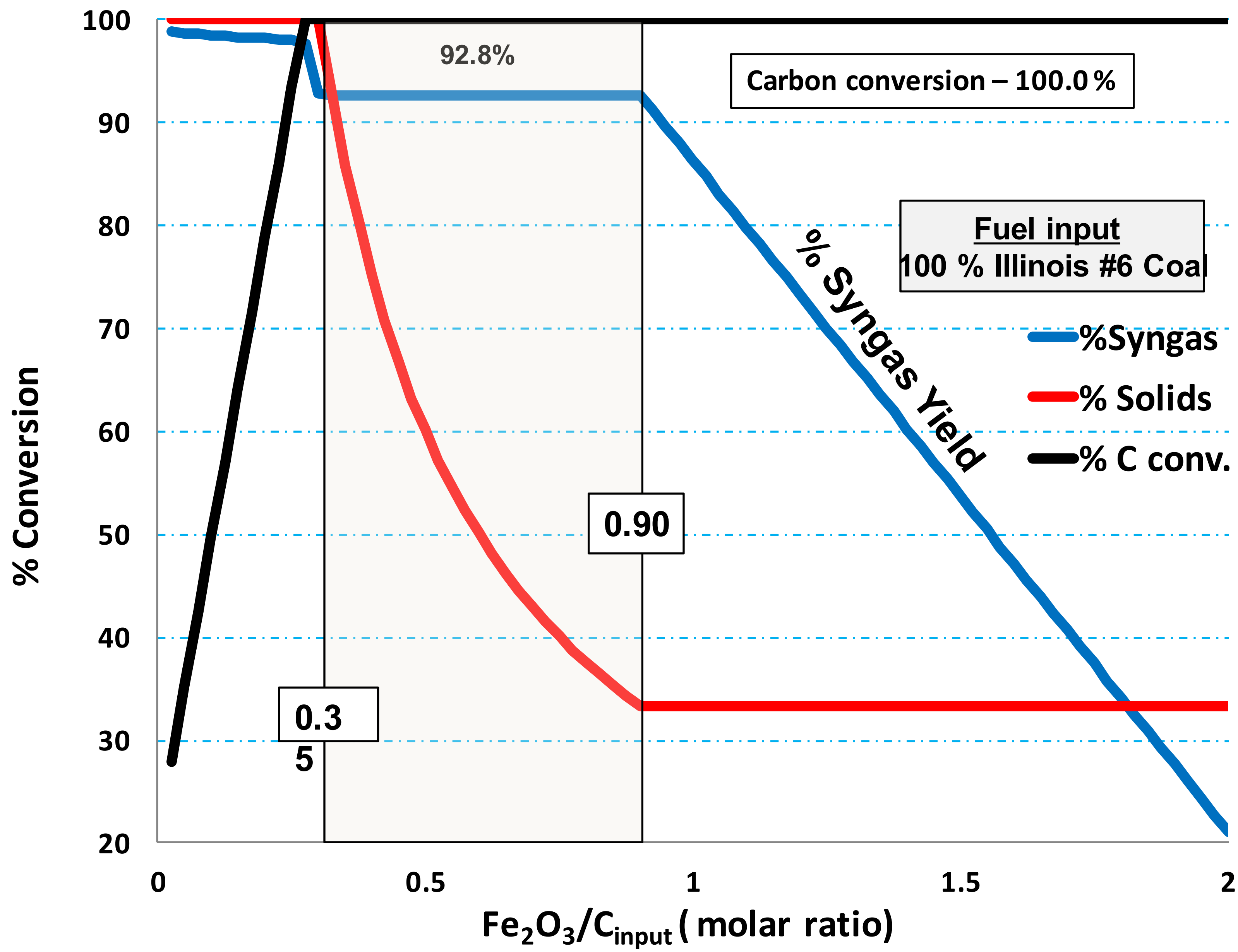
Reactivity and recyclability of selected particle confirmed



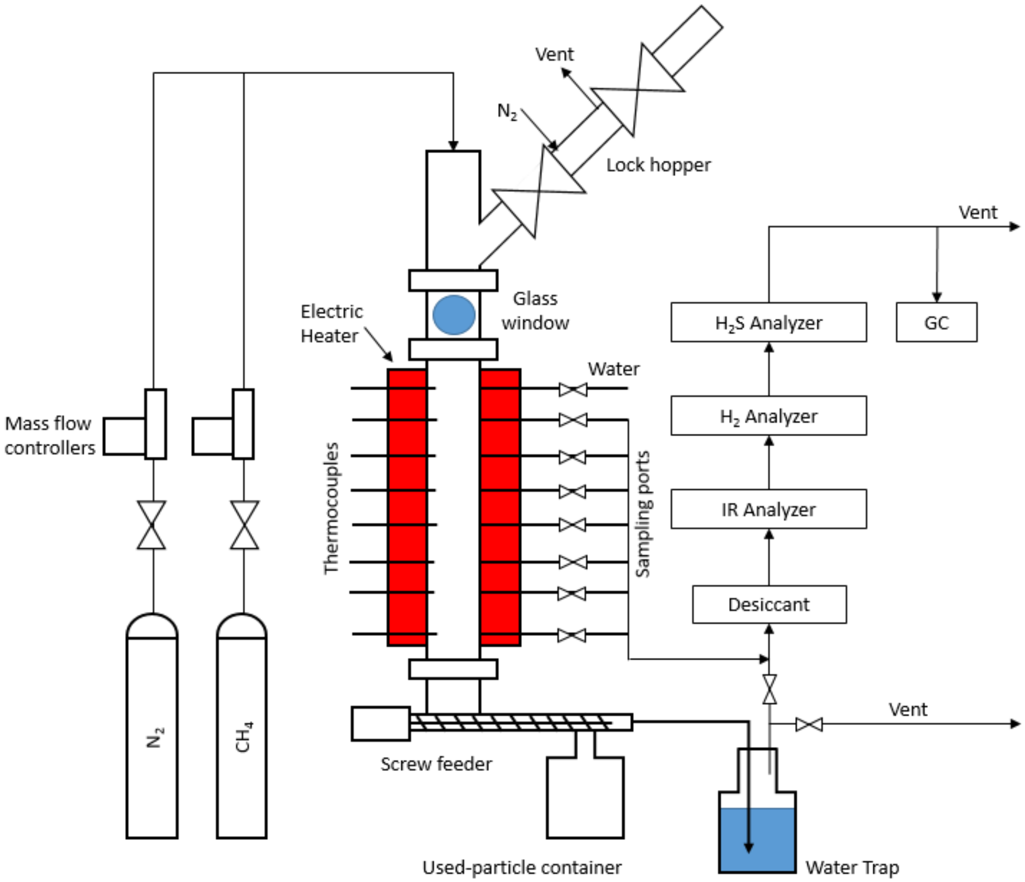
Classical Thermodynamics: CH_4 and Fe_2O_3

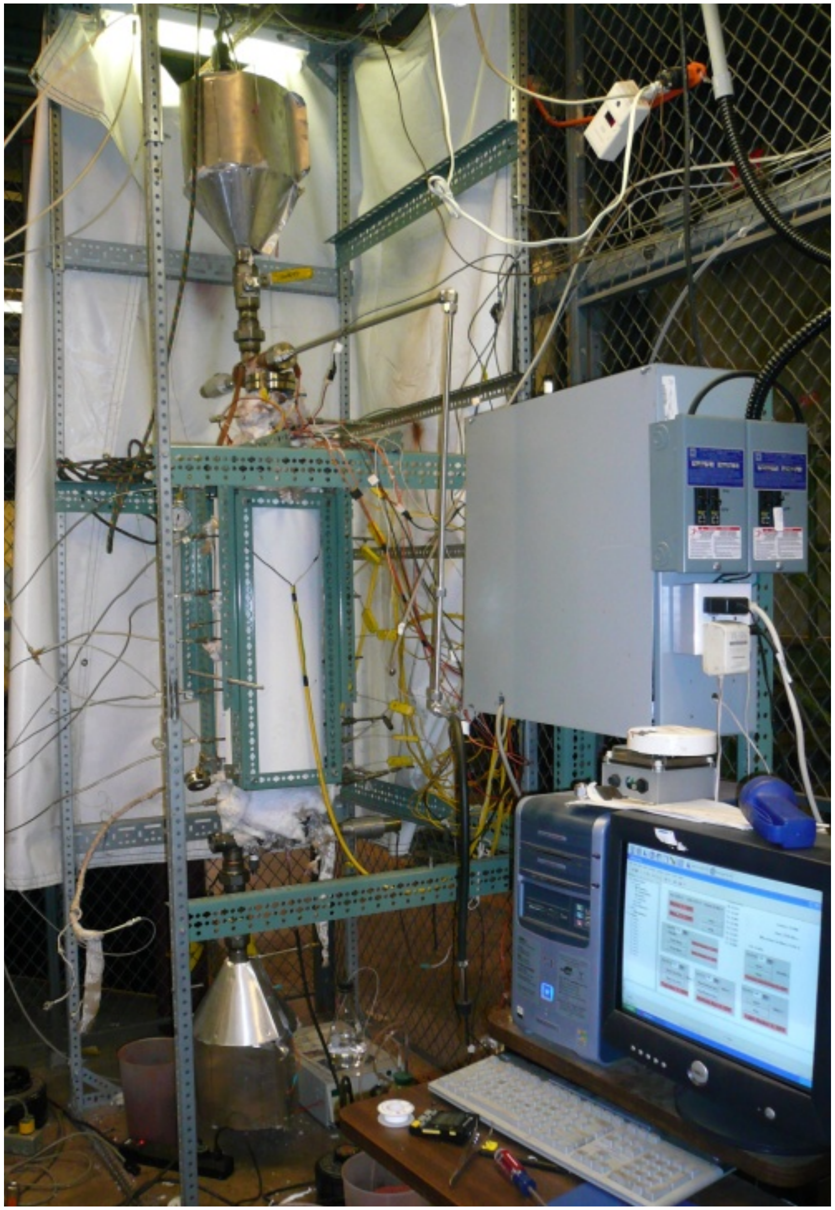


Classical Thermodynamics: 100% Coal



CLG Bench Scale Studies



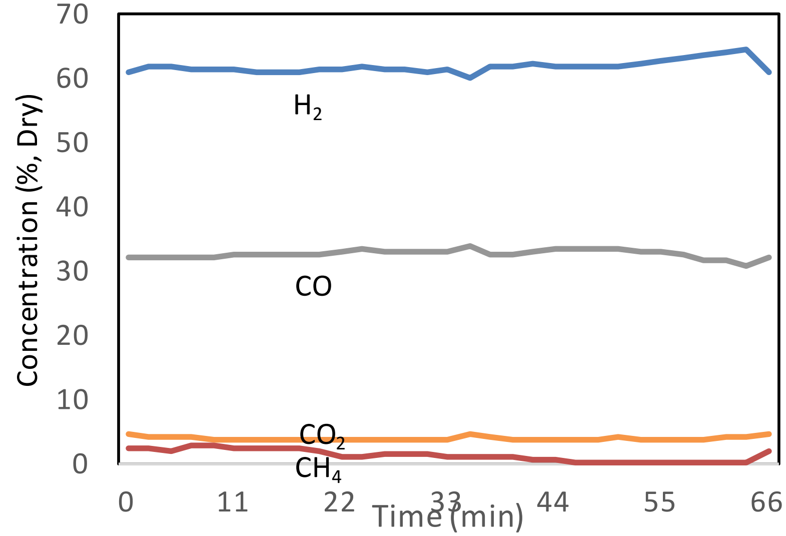


- Coal mixed with Oxygen Carrier particles
- Tests performed:
  - Methane to syngas
  - Sub-bituminous and bituminous coal to syngas
  - Co-injection of methane
  - Co-injection of methane and steam

CLG Bench Scale Studies

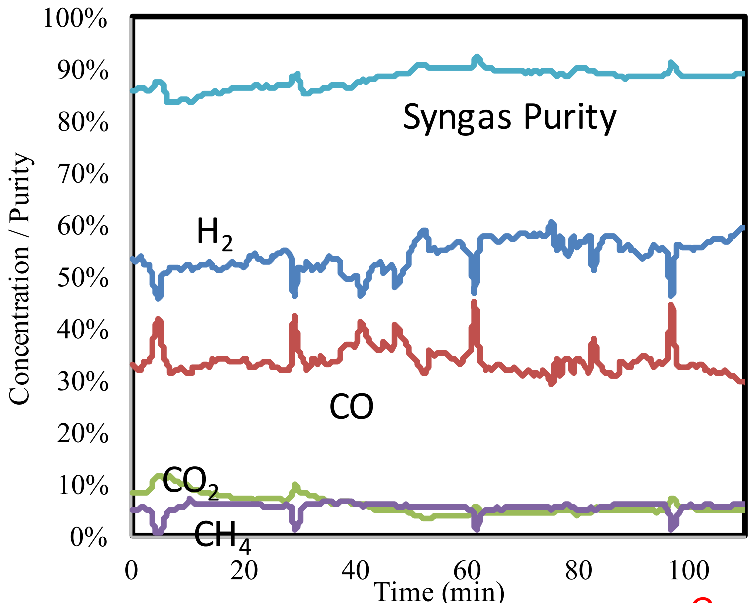
- Coal volatile tests: CH_4 to syngas
  - CH_4 conversion: >95%
  - Syngas purity: >88%
  - H_2:CO Ratio: 2:1
- Coal Tests: PRB
  - Coal conversion: >93%
  - Syngas purity: >88%
  - H_2:CO Ratio: 0.64:1
- H_2 rich syngas produced co-injecting CH_4 and H_2O co-injection with PRB coal
  - H2:CO Ratio: ~1.8
  - Syngas purity: >85%

Coal Volatile Tests



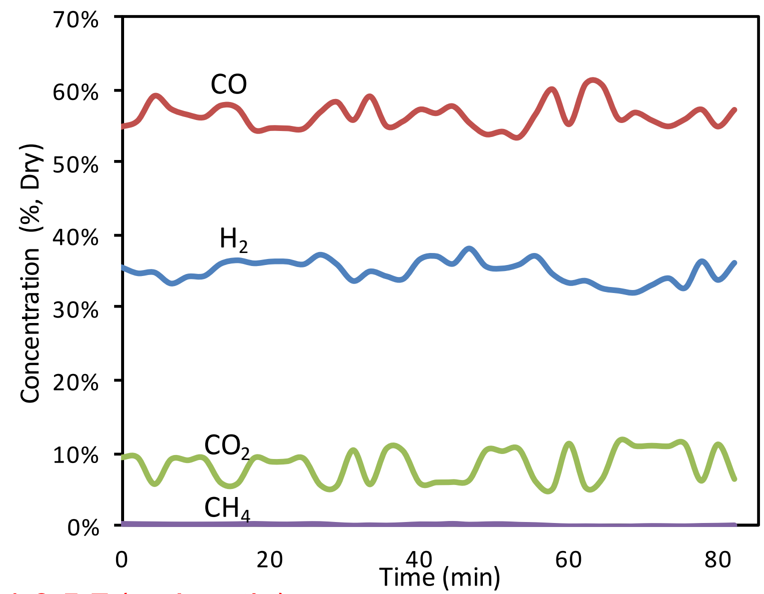
Temp.: 1000°C
OC Flow: 20g/min
CH_4 Flow: 1.8 SLPM
N_2 Flow: 0.2 SLPM

Co-Injection Test with PRB Coal



Temp.: 1000°C
OC: 20g/min
Coal: 0.9g/min
CH_4: 1.2SLPM
H_2O: 0.8g/min
N2: 1SLPM

PRB Coal Tests

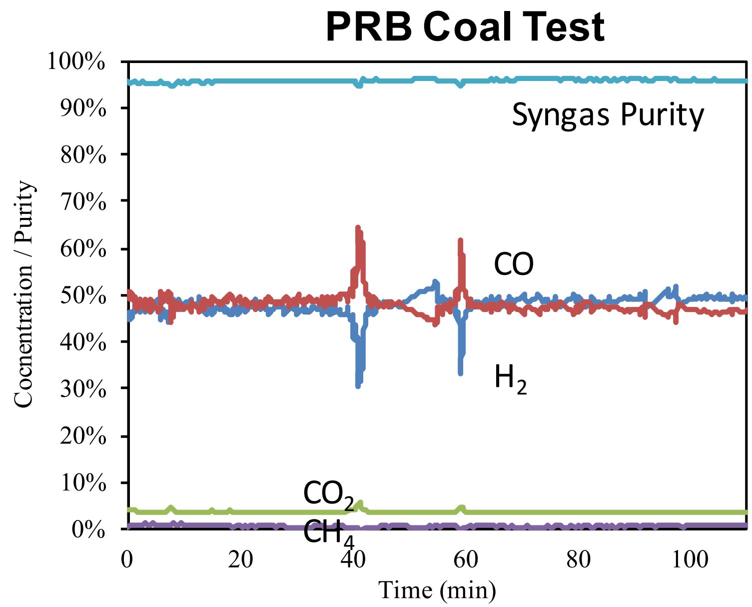


Temp.: 1000°C
OC: 20g/min
Coal: 4g/min
N_2: 1 SLPM

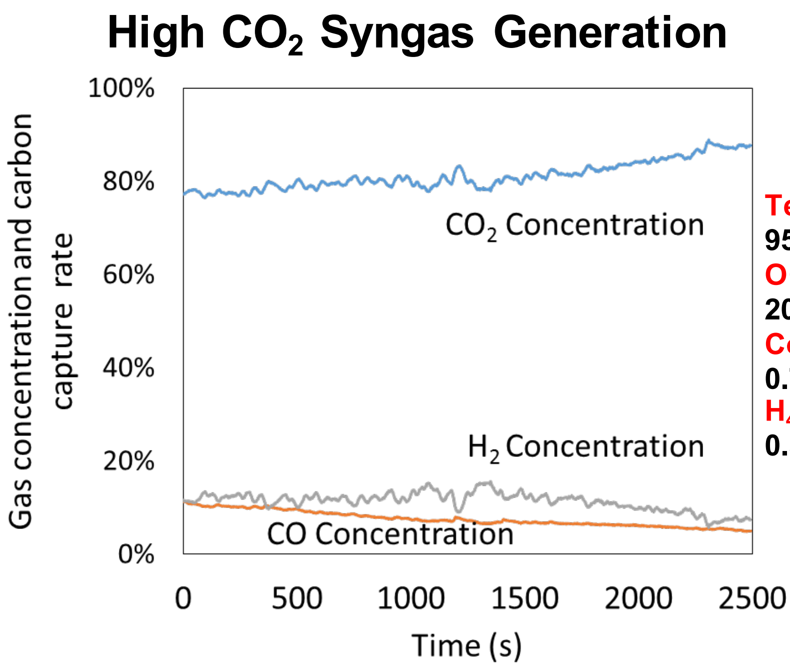
Coal:CH_4:H_2O:Fe_2O_3≈4:6:5:7 (mole ratio)

CLG Bench Scale Studies

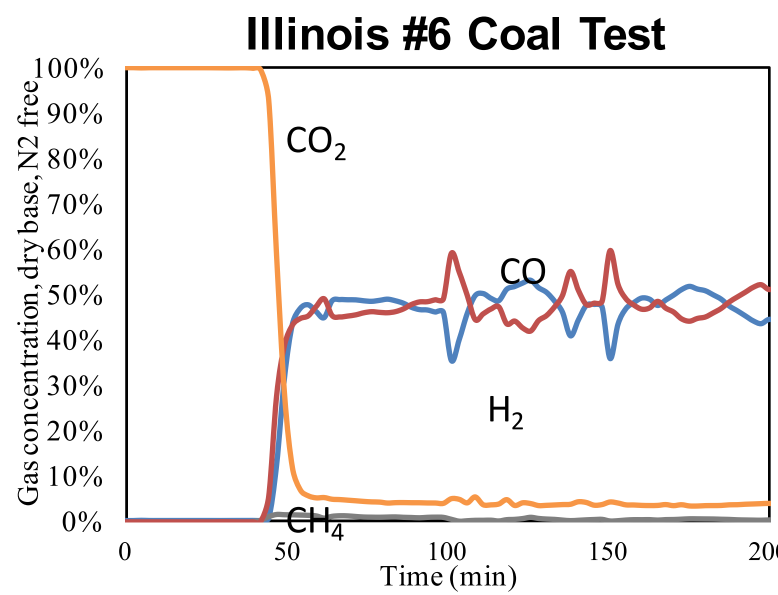
- Sub-bituminous coal (PRB) and bituminous coal (Illinois #6) tested with CH_4 co-injection
- High purity syngas generation achieved
- H_2:CO ratio of 1:1 achieved by adjusting CH_4 flow rate for both coals tested
- Syngas with variable CO:CO_2 ratio can be generated
  - Extreme case of CO:CO_2 = 0.1 shown below



Temp.: 1000°C
OC Flow: 23g/min
Coal: 3g/min
CH_4 Flow: 0.87 SLPM

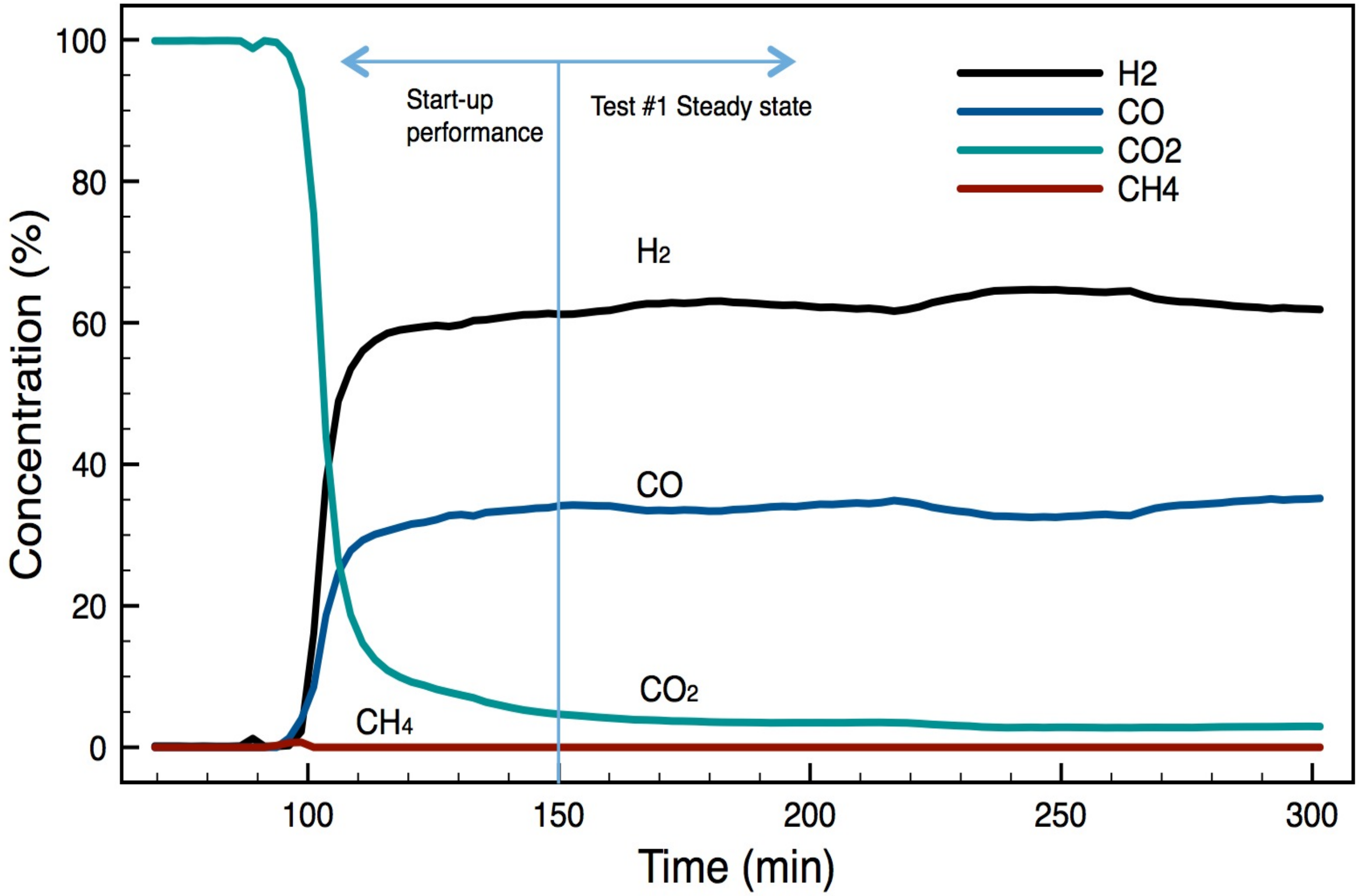


Temp.: 950°C
OC Flow: 20g/min
Coal: 0.75 g/min
H_2O Flow: 0.56 g/min



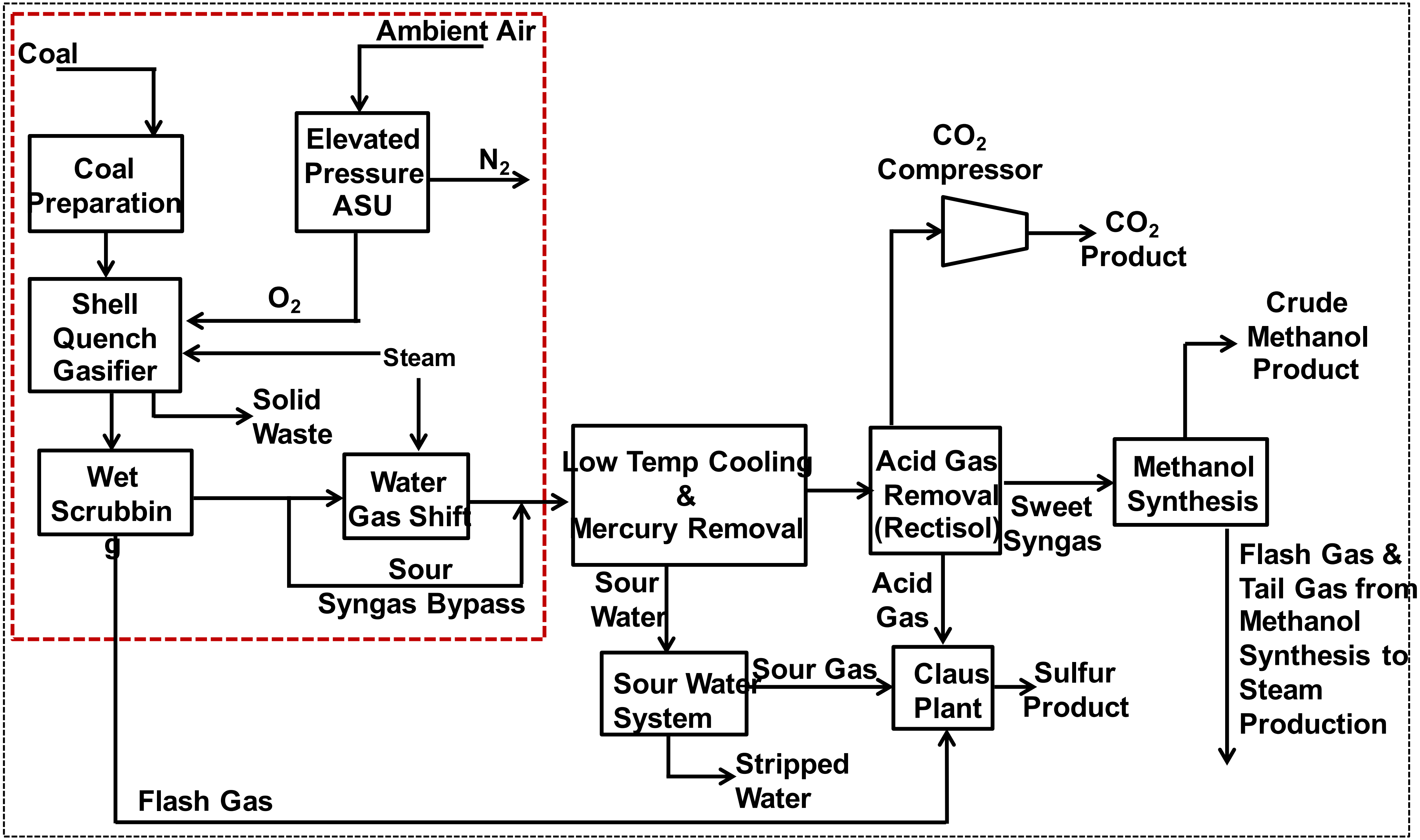
Temp.: 1000°C
OC Flow: 20g/min
Coal: 2.8g/min
CH_4 Flow: 0.75 SLPM

Experimental Studies – Coal Volatile Tests



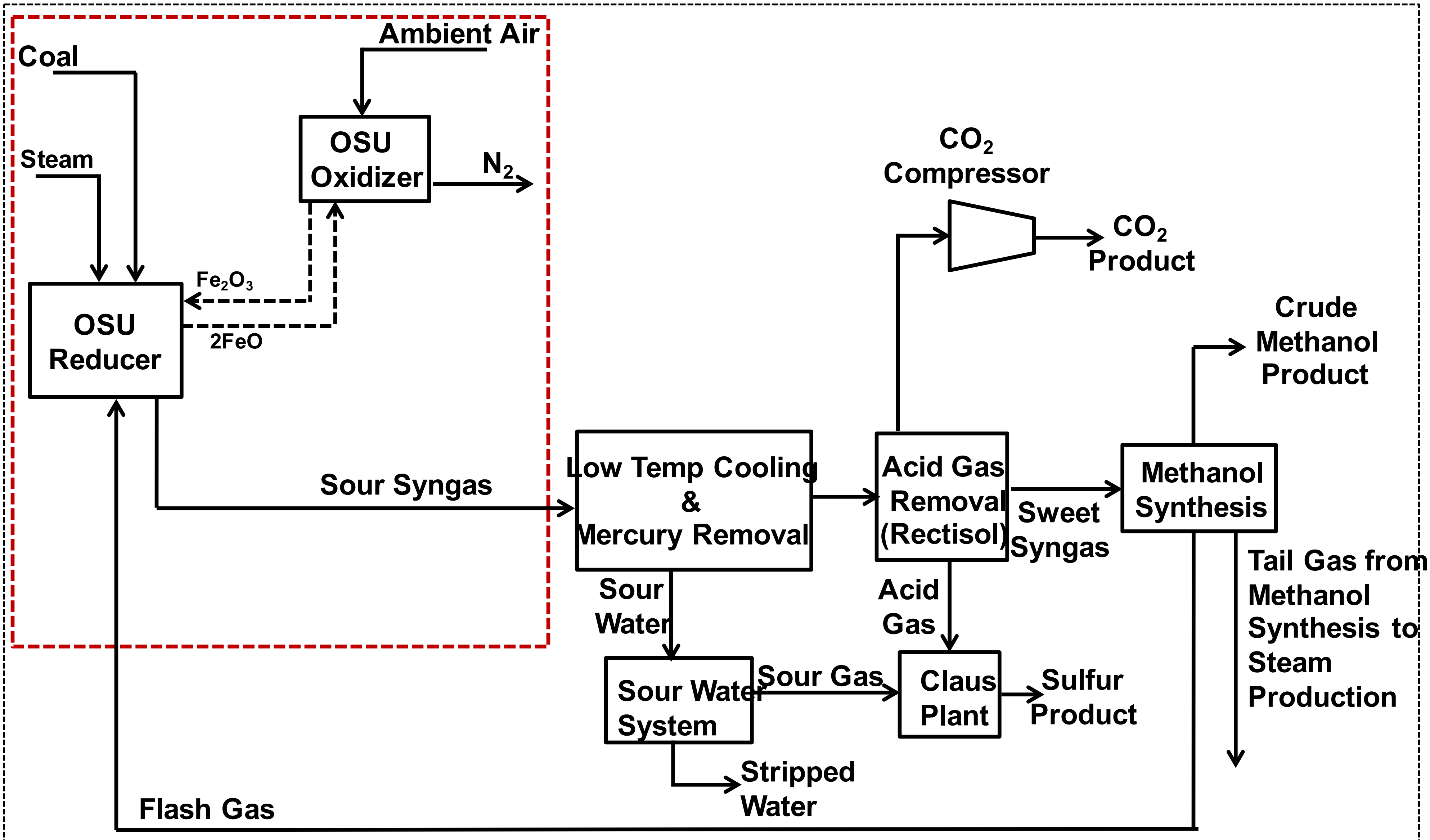
- **100% Methane Conversion**
- **90% Syngas Purity**
- **2:1 Ratio**
  - **Suitable for Liquid Fuel Synthesis**

Coal Gasification for Methanol Production: DOE Baseline (Traditional) Process



National Energy Technology Lab. U.S. DOE/NETL Report 341-101514, 2014.

Coal Gasification for Methanol Production: OSU Process



Kathe, M., Xu, D., Hsieh, T. L., Simpson, J., Statnick, R., Tong, A., Fan, L.-S. 2014. OSTI: 1185194.

Overall Techno-Economic Analysis Summary

WorleyParsons resources & energy

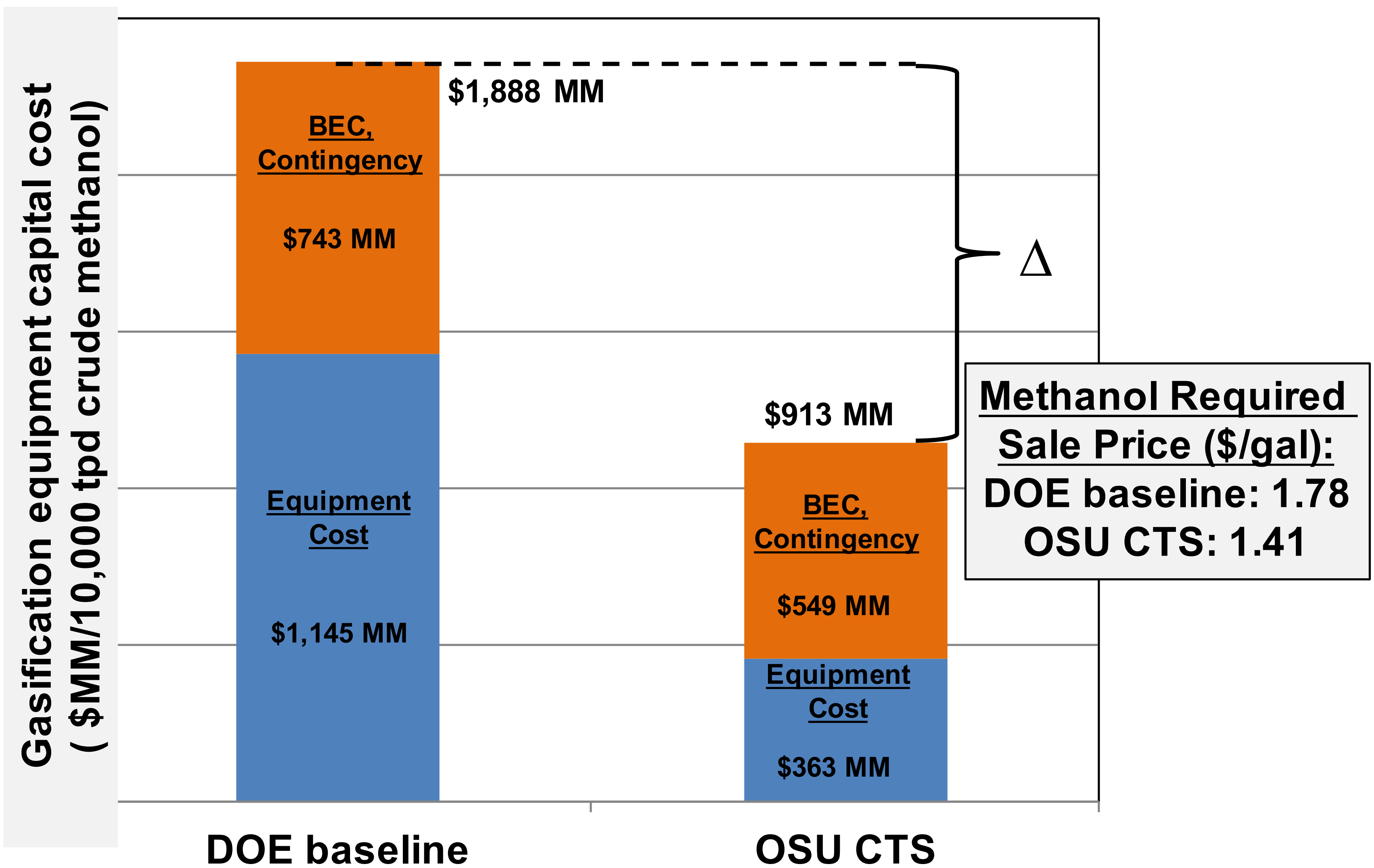
- A lower methanol Required Selling Price by $0.37/gal, a 21% decrease
- Lower total plant capital costs by 28%
- Lower the capital cost for syngas generation equipment by over 50%
- Higher efficiency based 14% in coal consumption
- A methanol Required Selling Price lower than the reference non-capture case, which results in CO_2 capture cost less than 0.

Performance modelling Results: 10,000 mtpd crude methanol system

Stream	Mass Flow lb/hr		
Case	DOE/NETL MBL-1, MBL-2	OSU-1	OSU-2
As Received Coal	1,618,190	1,395,457	718,631
Natural Gas to OSU CLG	NA	NA	272,290
Oxygen from Air Separation Unit	10,10,968 (95% O_2)	NA	NA
Steam to gasifier, reformer, quench, OSU CLG	1,533,584	1,624,318	693,587
Clean syngas for methanol production	1,183,080	1,025,106	1,039,864
Captured CO_2	1,569,410 (MLB-2)	1,302,138	663,393

Kathe, M., Xu, D., Hsieh, T. L., Simpson, J., Statnick, R., Tong, A., & Fan, L.-S. *Chemical Looping Gasification for Hydrogen Enhanced Syngas Production with In-Situ CO2 Capture*. 2014. OSTI: 1185194.

Cost Analysis: Total Plant Capital Cost for 10,000 ton/day Methanol Production from Coal



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Outline

- Background
- **Project Team**
- Technical Approach
- Project Management

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

- Background
- Project Team
- **Technical Approach**
- Project Management

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

	Tasks/Milestones			2015			2016												2017		
		Start	End	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
1.0	**Project Management and Planning**	**10/1/15**	**3/31/17**																		
2.0	**Detailed Design of Sub-Pilot Test Unit**	**10/1/15**	**3/31/16**																		
2.1	Detailed Design	10/1/15	12/31/15																		
2.2	Process Safety Review	1/1/16	2/29/16																		
2.3	System Design Finalization and Costing	2/1/16	3/31/16																		
	Milestone 1: Sub-pilot test unit design and quotes finalized		3/31/16						•												
3.0	**Construction and Commissioning of Sub-Pilot Test Unit**	**4/1/16**	**9/30/16**																		
3.1	Reactor Vessel Fabrication and Installation	4/1/16	6/30/16																		
3.2	Piping and Instrument Installation	6/1/16	7/31/16																		
3.3	Oxygen Carrier Particle Production	4/1/16	8/31/16																		
3.4	System Commissioning	7/1/16	9/30/16																		
	Milestone 2: Sub-pilot system installation and commissioning completed		9/30/16												•						
4.0	**Integrated Sub-Pilot Unit Operations**	**10/1/16**	**2/28/17**																		
4.1	Parametric System Operations with Sub-Bituminous Coal Feeding	10/1/16	12/31/16																		
4.2	Continuous Operation of the System	1/1/17	2/28/17																		
	Milestone 3: 100 hours of cumulative sub-pilot unit operation achieved		2/28/17																	•	
5	**Techno-Economic Analysis of the CLG Process for IGCC Application**	**10/1/15**	**3/31/17**																		
5.1	Developing a CLG Performance Model and Technology Analysis Plan (TAP)	10/1/15	6/30/16																		
5.2	CLG-IGCC Integrated Performance Model Development and Equipment Costing	7/1/16	12/31/16																		
5.3	Techno-Economic Assessment for IGCC Applications and Final Reporting	10/1/16	3/31/16																		
	Milestone 4: Design basis for CLG-IGCC defined		12/31/15			•															
	Milestone 5: Techno-economic assessment of CLG for IGCC application completed		3/31/17																		•
6	**Final Report**		**7/31/17**																		

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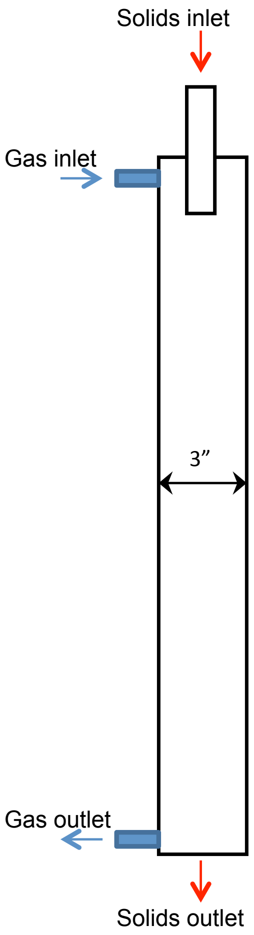
15 kW_{th} Sub-Pilot Reactor Design

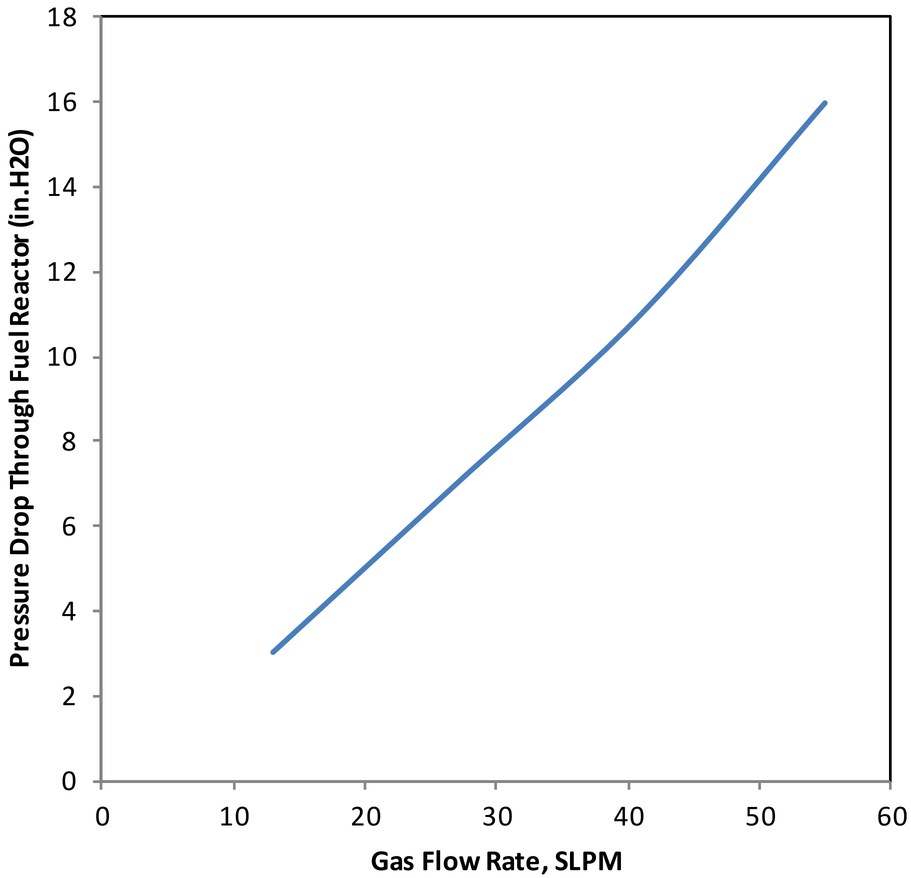
- Integrated 3-reactor system
  - Non-mechanical devices
  - Computerized data acquisition and process control
- Design, Construction, and Commissioning
  - Detailed design and safety review
  - Reactor fabrication
  - Installation on existing structure
  - Leak check, instrument calibration, functional checks, and final safety review

Existing Structure

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_2O_3 ratio
  - Coal:H_2O ratio
  - Temperature
  - Residence time
  - Verify performance model
- Performance Parameters
  - Coal conversion

$$X_{coal} = \frac{n_{C,reducer} + n_{C,combustor} + n_{C,oxidizer}}{n_{C,coal}}$$

  - Carbon capture efficiency

$$\eta_C = \frac{n_{C,reducer} + n_{C,oxidizer}}{n_{C,coal}}$$

  - Syngas purity

$$S = x_{CO,reducer} + x_{H_2,reducer}$$

  - Gasification thermal efficiency

$$\eta_t = \frac{HHV_{reducer} + HHV_{oxidizer}}{HHV_{coal}}$$

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4.0	**Integrated Sub-Pilot Unit Operations**	**10/1/16**	**2/28/17**																		
4.1	Parametric System Operations with Sub-Bituminous Coal Feeding	10/1/16	12/31/16																		
4.2	Continuous Operation of the System	1/1/17	2/28/17																		
	Milestone 3: 100 hours of cumulative sub-pilot unit operation achieved		2/28/17																	•	
5	**Techno-Economic Analysis of the CLG Process for IGCC Application**	**10/1/15**	**3/31/17**																		
5.1	Developing a CLG Performance Model and Technology Analysis Plan (TAP)	10/1/15	6/30/16																		
5.2	CLG-IGCC Integrated Performance Model Development and Equipment Costing	7/1/16	12/31/16																		
5.3	Techno-Economic Assessment for IGCC Applications and Final Reporting	10/1/16	3/31/16																		
	Milestone 4: Design basis for CLG-IGCC defined		12/31/15			•															
	Milestone 5: Techno-economic assessment of CLG for IGCC application completed		3/31/17																		•
6	**Final Report**		**7/31/17**																		

Company Overview

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- 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

Techno-Economic Assessment

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- 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 CO_2 captured.
  - Compare costs to DOE/NETL reference cases

Options Considered

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- 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)

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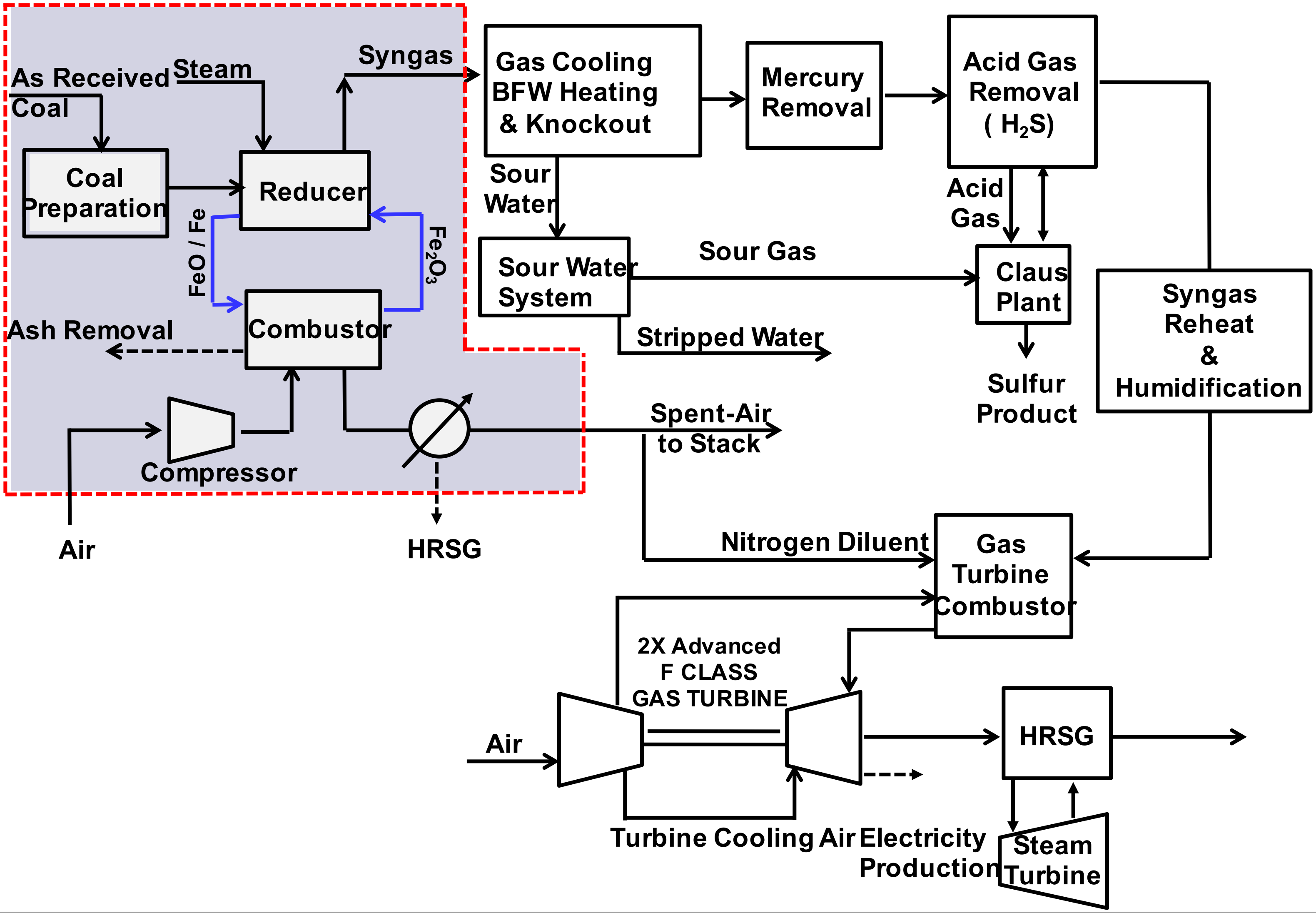

CTS SYSTEM #2 (90% CCS)

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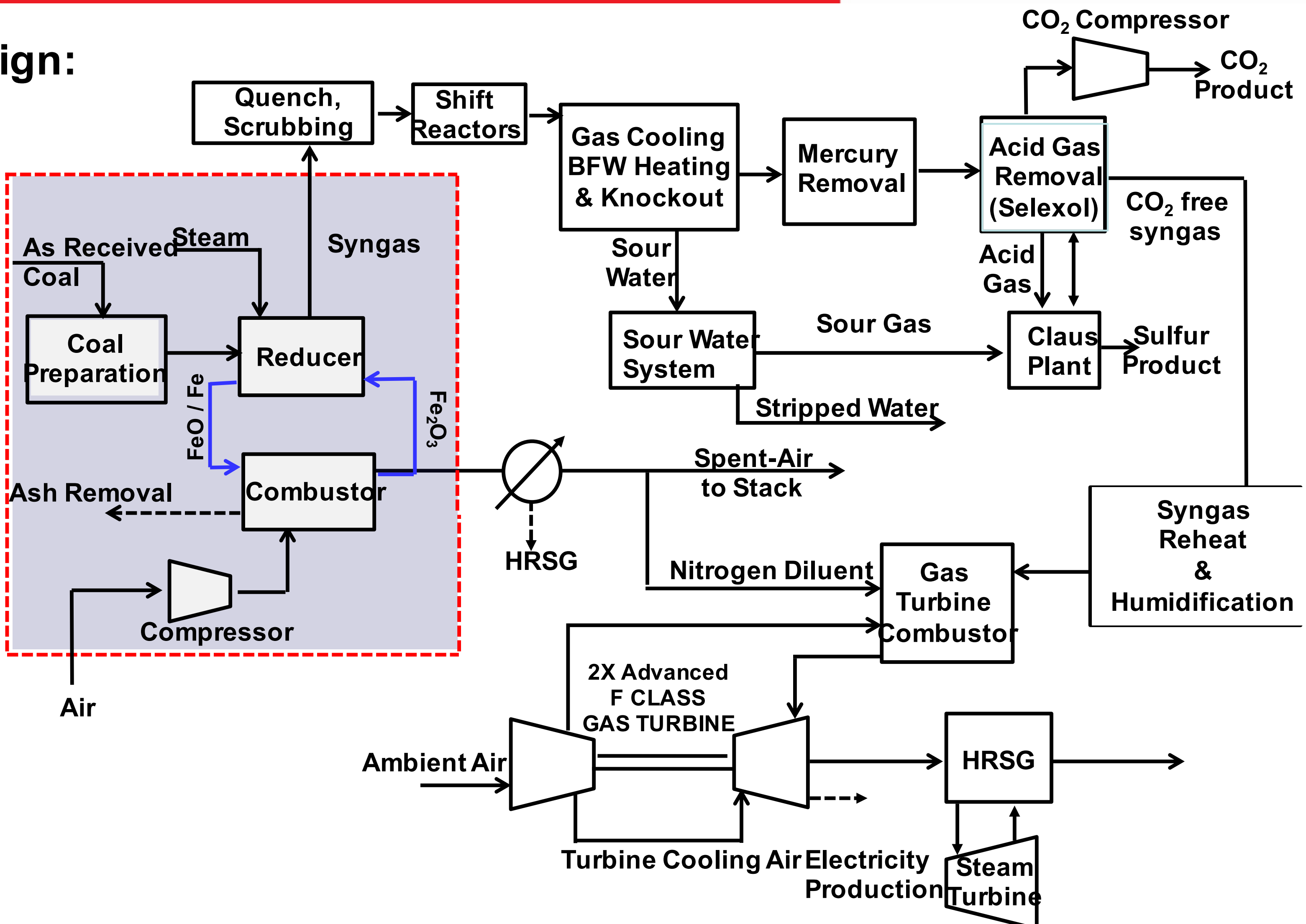
2 Reactor Design:



Evaluation Basis

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- Fuel: Bituminous Coal
- CO_2 Removal: >90% based on raw syngas carbon content
- CO_2 Product
  - CO_2 Purity: Enhanced Oil Recovery as listed in Exhibit 2-1 of the NETL QGESS titled "CO_2 Impurity Design Parameters". *
  - CO_2 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

http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=420

Capital and Operating Costs

- Reference Case
  - Capital and O&M cost will be determined from costs presented 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

Operating and Maintenance Costs Breakdown

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- 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

Economic Analysis

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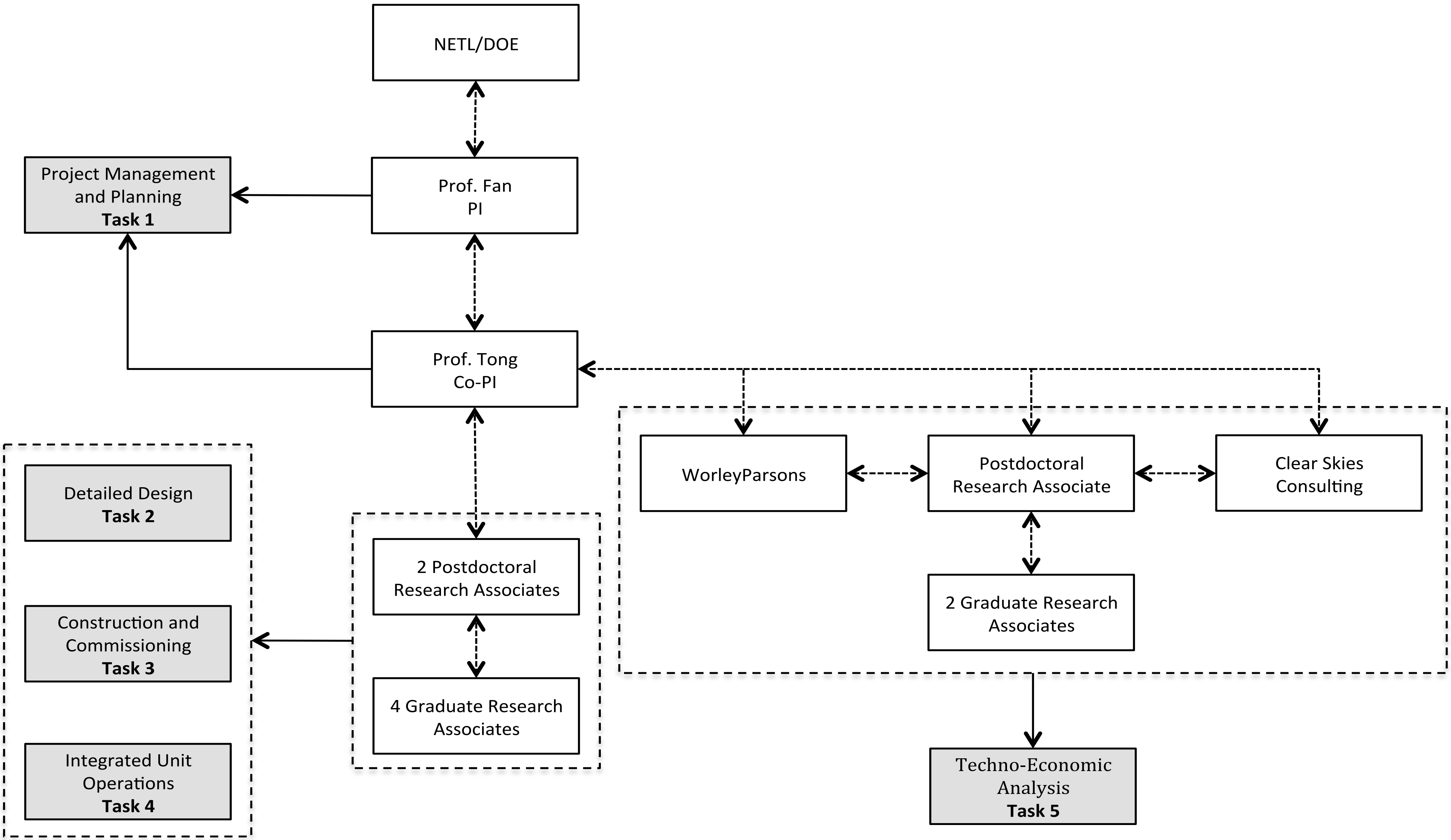
- Purpose:
  - Compare Cost of Electricity (COE) for systems including OSU CLC technology to reference case developed by DOE/NETL.
  - Provide understanding of factors that impact COE
- Activities:
  - Determine COE and LCOE and cost of CO_2 captured using DOE/NETL Power Systems Financial Model or similar 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



Project Budget

	Federal Funding	Cost Share
The Ohio State University	$1,274,516	$157,186
WorleyParsons	$195,484	-
Clear Skies Consulting	$30,000	$34,133
Ohio Development Services Agency		$500,000
Total	**$1,500,000**	**$686,000**

Category	Budget
Personnel	$649,976
Fringe Benefits	$152,252
Travel	$45,000
Equipment	$125,000
Supplies	$80,813
Contractual	$354,762
Other	$202,805
Total Direct Charges	$1,610,608
Indirect Charges	$575,392
Totals	**$2,186,000**

Milestone Log

Budget Period	Task Number	Milestone Title/Description	Planned Completion Date	Verification Method
1	2	Sub-pilot test unit design and quotes finalized and within budget	3/31/2016	Quarterly Report
1	3	Sub-pilot system installation and commissioning completed	9/30/2016	Quarterly Report
1	4	100 hours of cumulative sub-pilot unit operation achieved	2/28/2017	Final Report
1	5	Design basis for CLG-IGCC defined	12/31/2015	Quarterly Report
1	5	Techno-Economic assessment of CLG for IGCC Application Completed	3/31/2017	Final Report

Thanks