THE OHIO STATE UNIVERSITY

FE0023915: Pilot Scale Operation and Testing of Syngas Chemical Looping for Hydrogen Production
FE0026185: Chemical Looping Coal Gasification Sub-Pilot Unit Demonstration and Economic Assessment for IGCC applications

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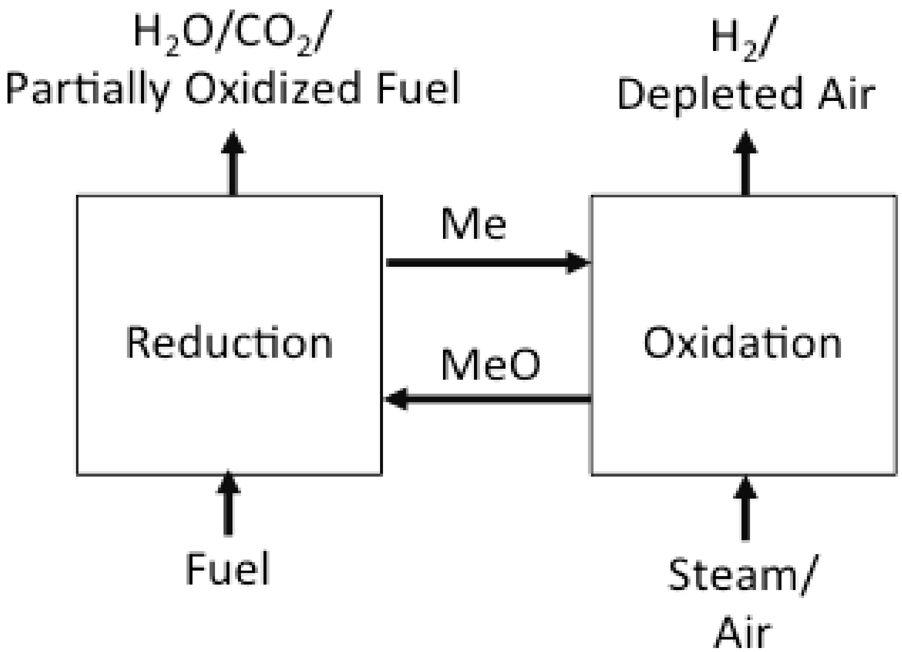
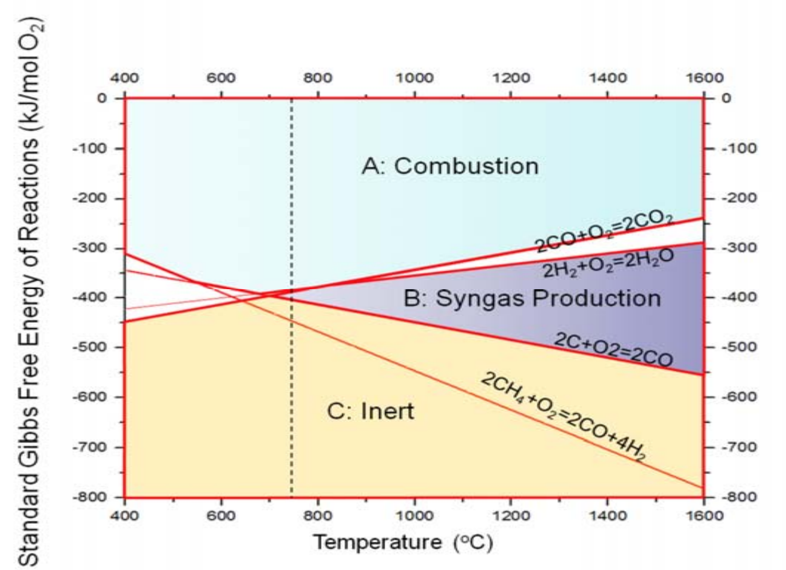
2017 Combined Project Portfolio Review| 20 March 2017

Chemical Looping Process with Oxygen Carriers



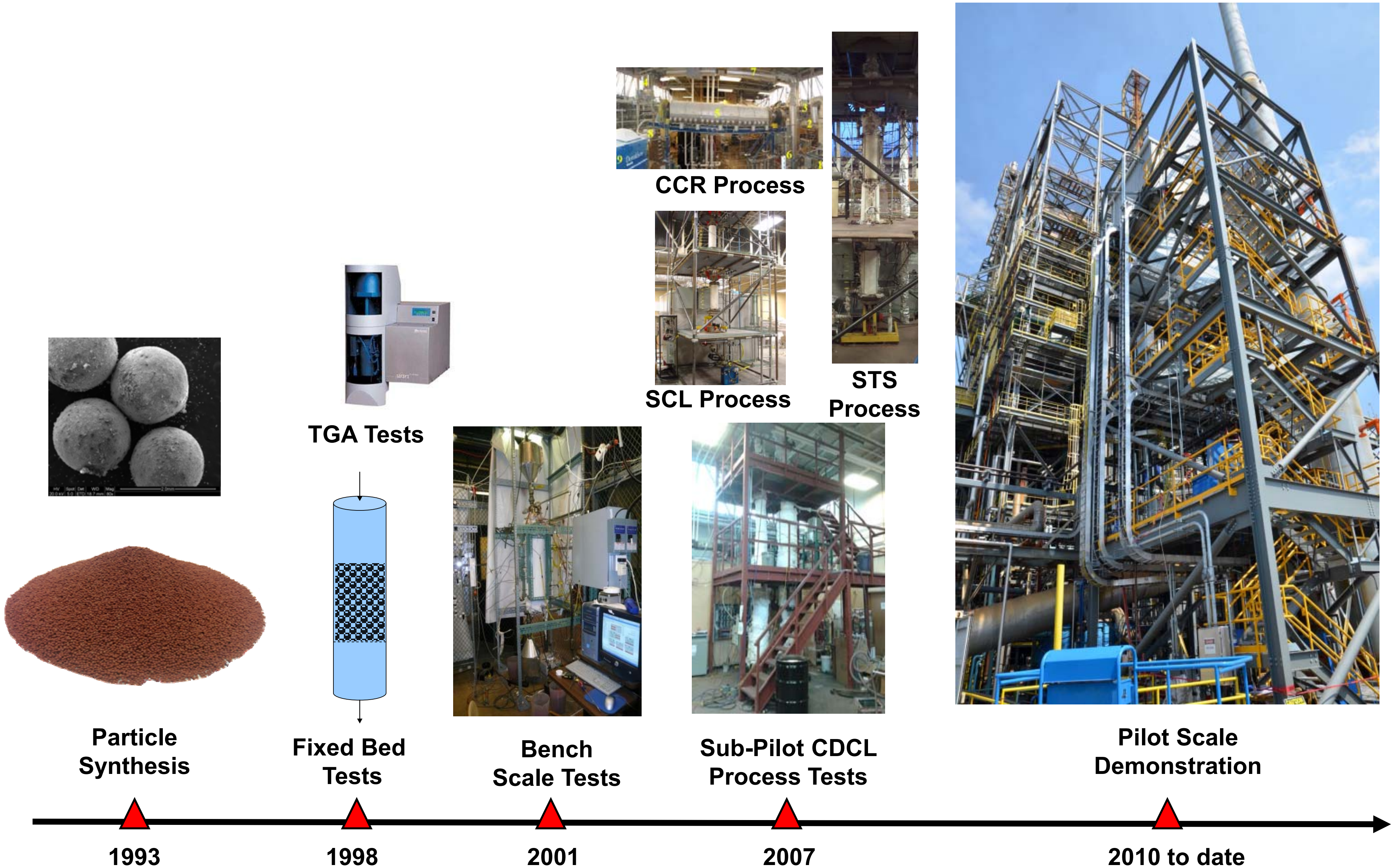
Ellingham Diagram



Net Reaction: $C_xH_yO_z + O_2 \rightarrow CO/H_2$ (or $CO_2 + H_2O$)

Chemical looping processes minimizes/eliminates the efficiency loss for gas separation

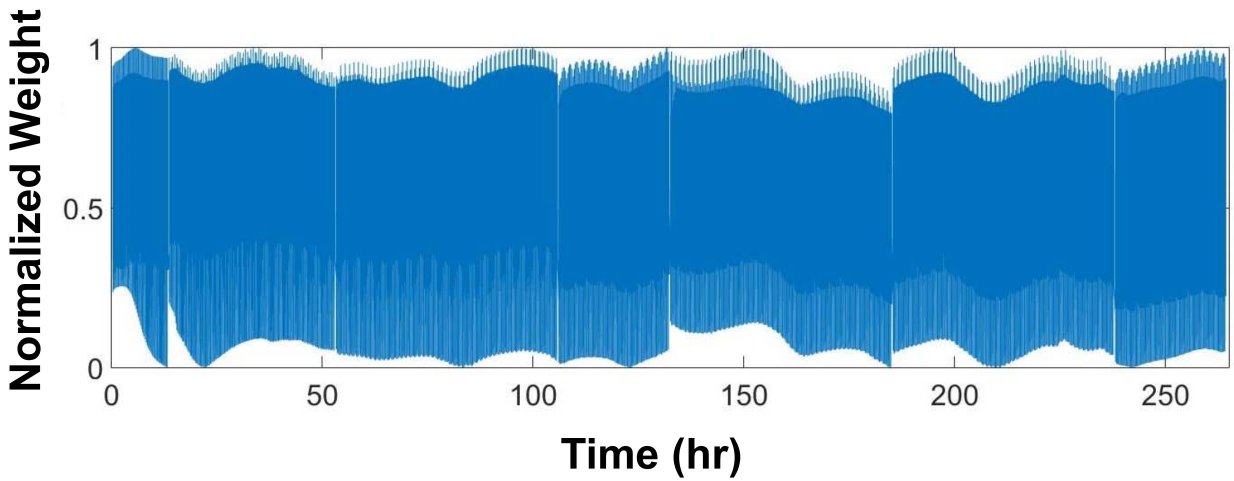
Evolution of OSU Chemical Looping Technology



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

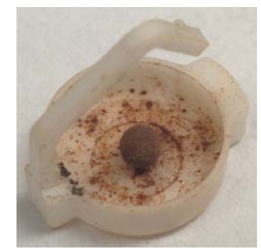
Oxygen Carrier Synthesis

Cyclic Redox of Composite Fe_2O_3

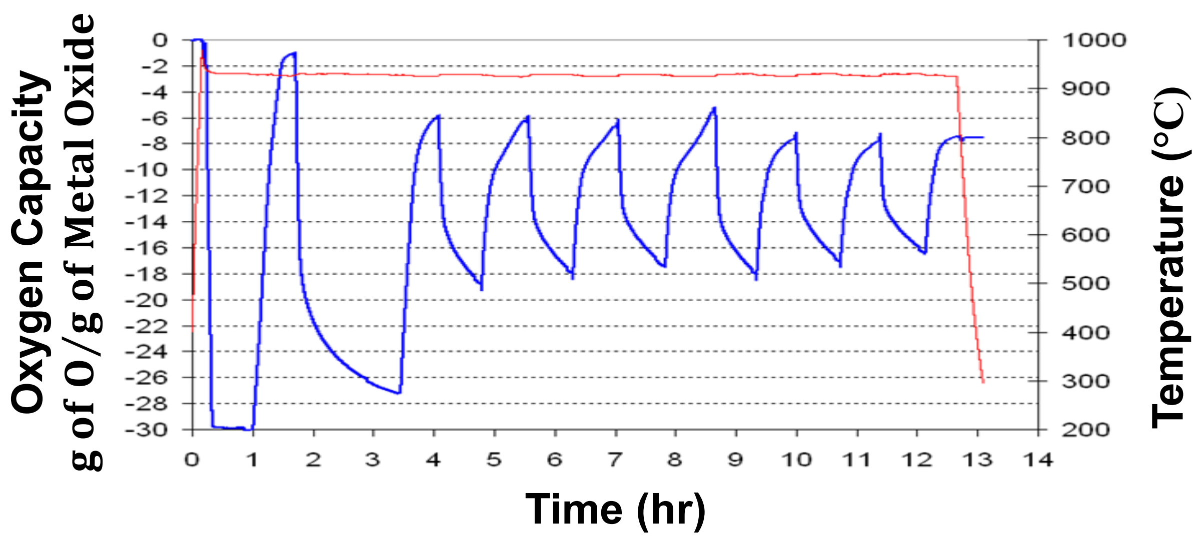


before

after



Cyclic Redox of Pure Fe_2O_3

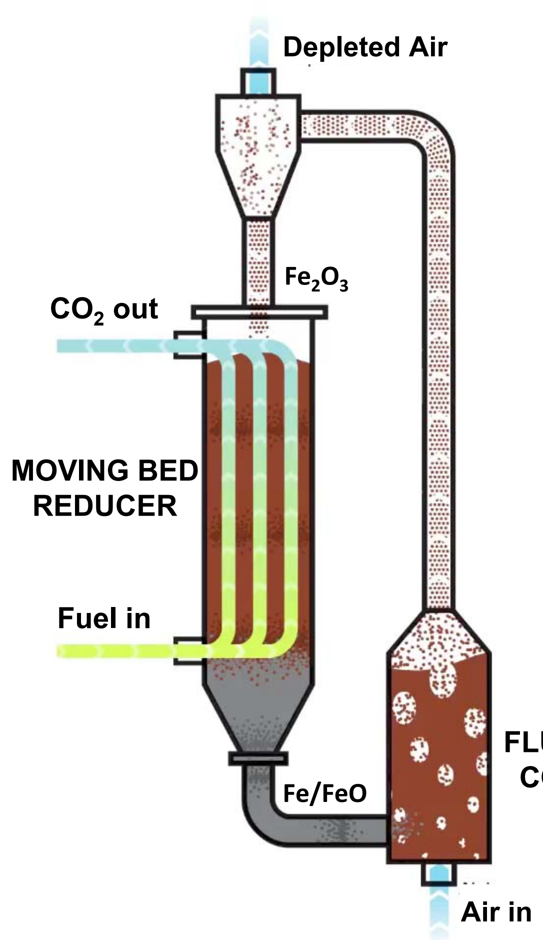


Fan, L.-S. Chemical Looping Systems for Fossil Energy Conversions. Wiley, 2010.
Li, F., Kim, H.R., Sridhar, D., Wang, F., Zeng, L., Fan, L.-S. *Energy & Fuels*. 2009.

OSU Chemical Looping Platform Processes

Two Basic Modes

Counter-current: Full Combustion

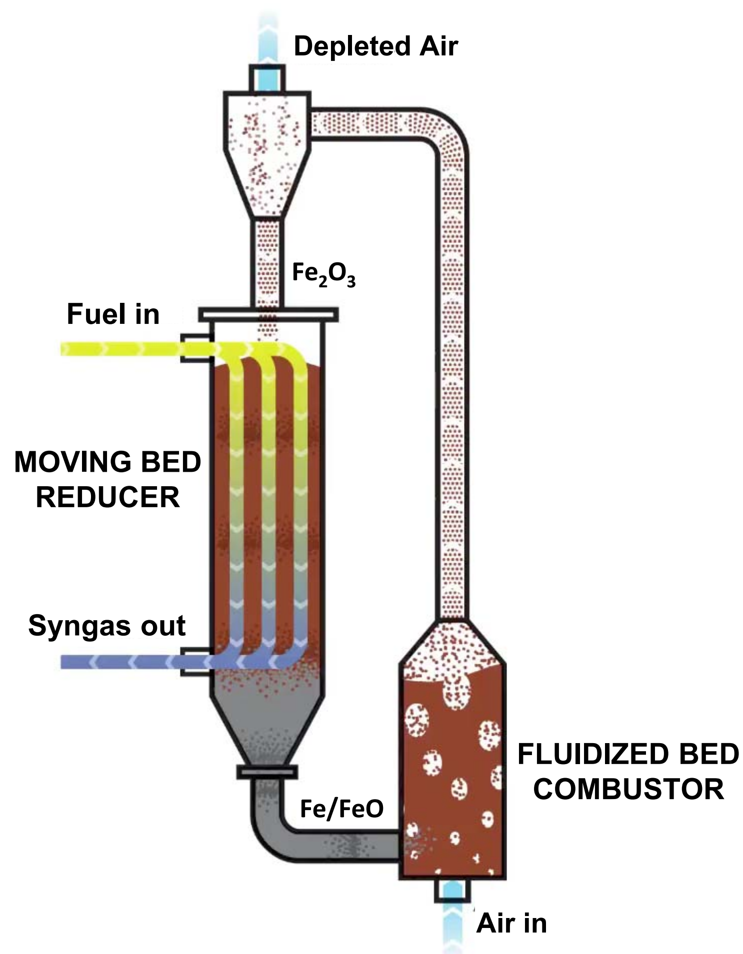


Simplicity:
One Loop

Unique Reducer Configuration:
Moving Bed

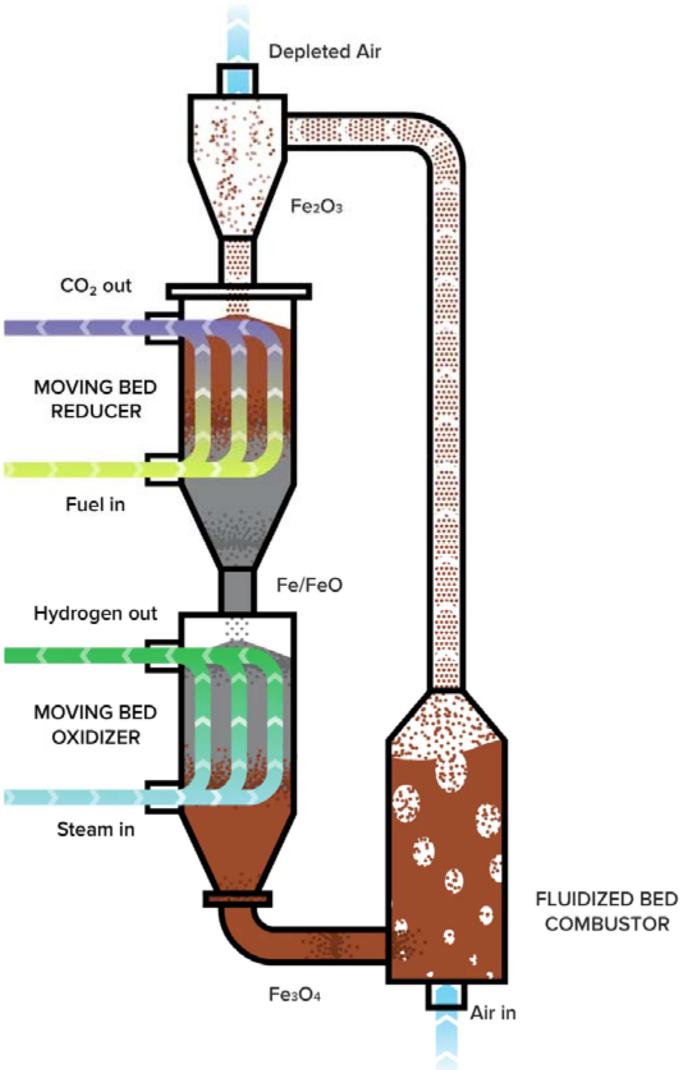
Unique Flow Controller:
Non-Mechanical L-Valve

Co-current: Full Gasification



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

Syngas Chemical Looping



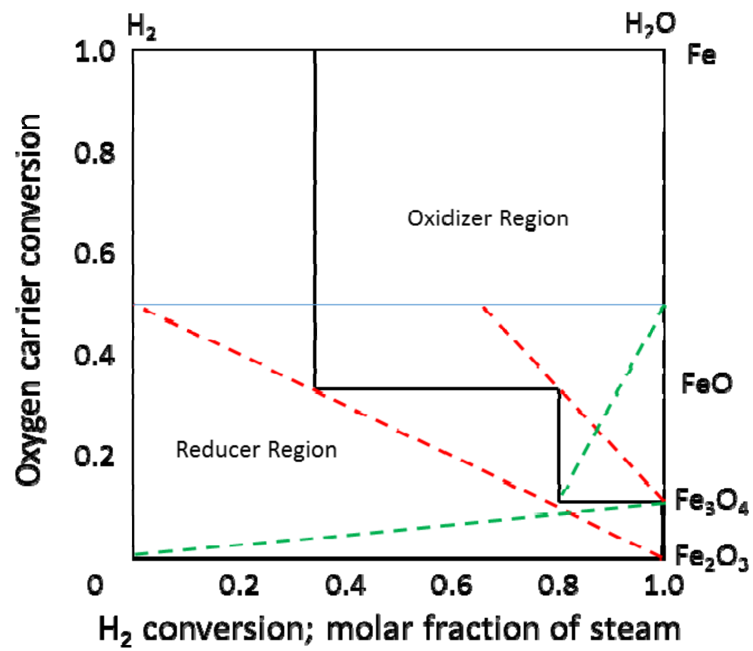
Main Reactions

Reducer: $C_xH_yO_z + Q + Fe_2O_3 \rightarrow CO_2 + H_2O + Fe$

Oxidizer: $Fe + H_2O \rightarrow Fe_3O_4 + H_2 + Q$

Combustor: $Fe_3O_4 + O_2 \rightarrow Fe_2O_3 + Q$

Total: $C_xH_yO_z + H_2O + O_2 \rightarrow CO_2 + H_2$



Coal to Syngas Chemical Looping Process

Main reactions:

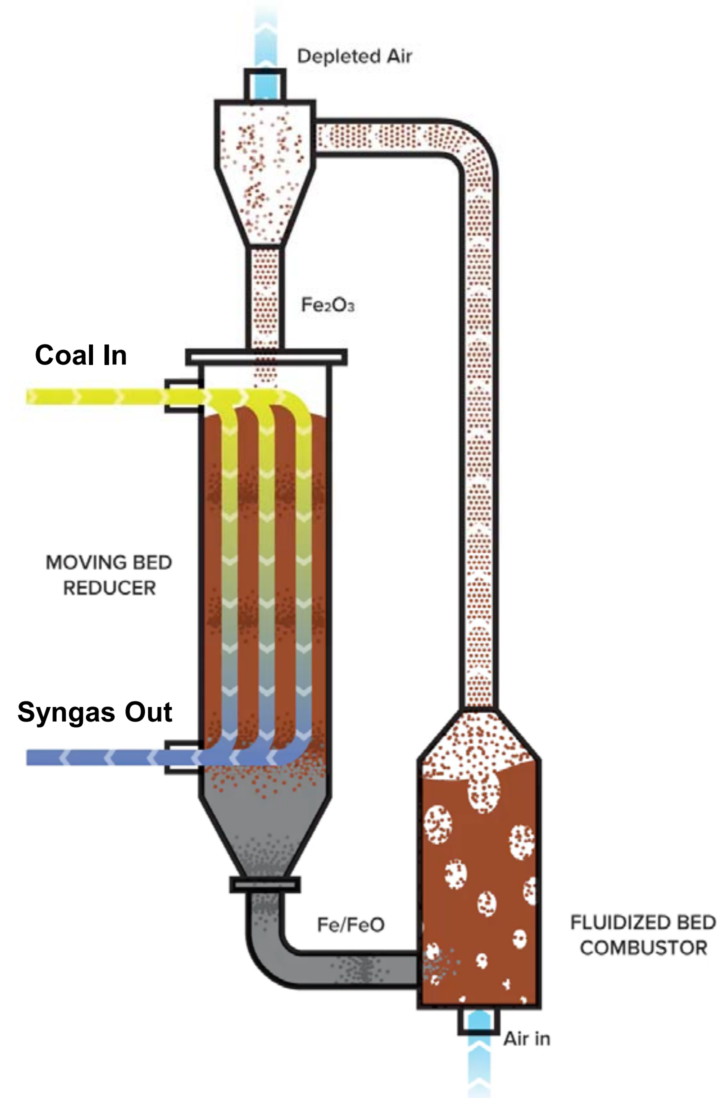
Reducer:	Coal + H_2O + Fe_2O_3 → CO + H_2 + Fe/FeO
Combustor:	Fe/FeO + O_2 (Air) → Fe_2O_3 + Q
Net:	Coal + H_2O + O_2 (Air) → CO + H_2 + Q

Unique Reactor Design:

- Co-current moving bed reducer design
  - Tight control of gas-solid flow
  - High fuel conversion to syngas
- Non-mechanical single loop system
  - Extensive experience with non-mechanical moving bed reactor design

Techno-Economic Assessment Support:

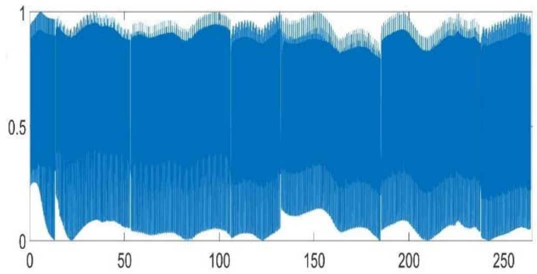
- Oxygen carrier selection: experimental and thermodynamic analysis
- Reactor design and hydrodynamic studies

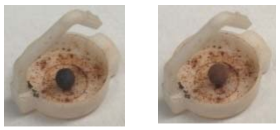


FE0023915: Syngas Chemical Looping (SCL) Pilot Unit

Syngas Chemical Looping Process Development

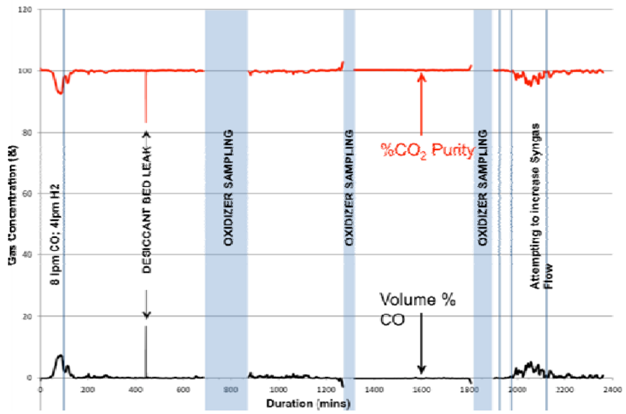
Oxygen Carrier Reactivity (TGA)



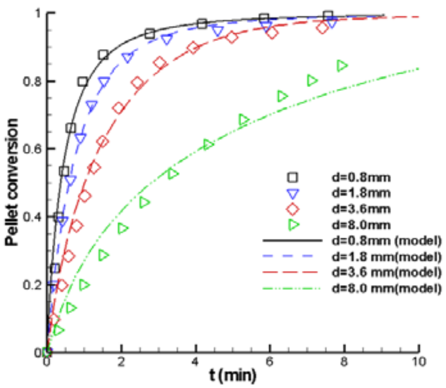


25 kW_{th} Sub-Pilot Unit

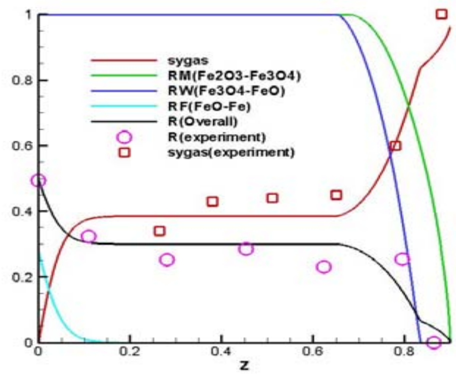
Reducer Gas Profile



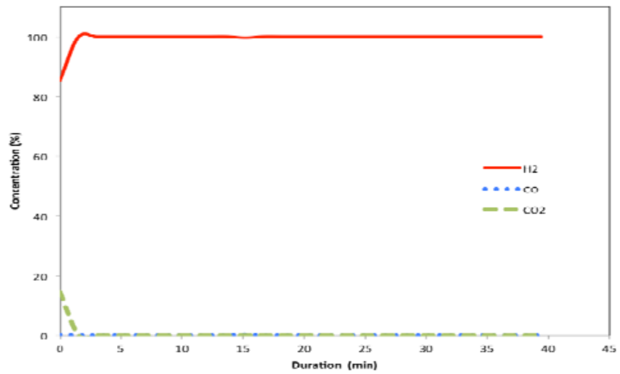
Reduction Kinetics



Counter-Current Moving Bed Reducer Model

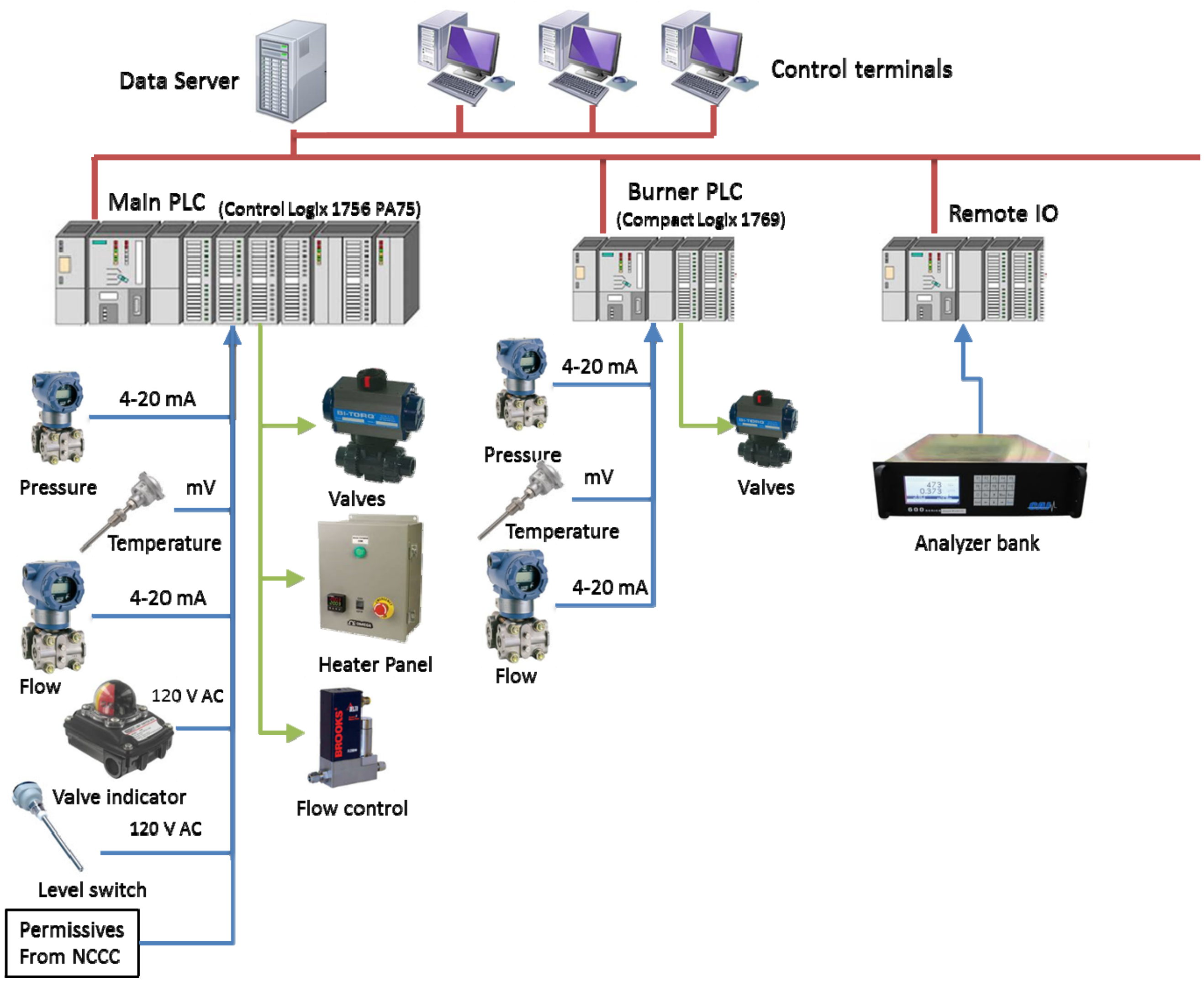


Oxidizer Gas Profile



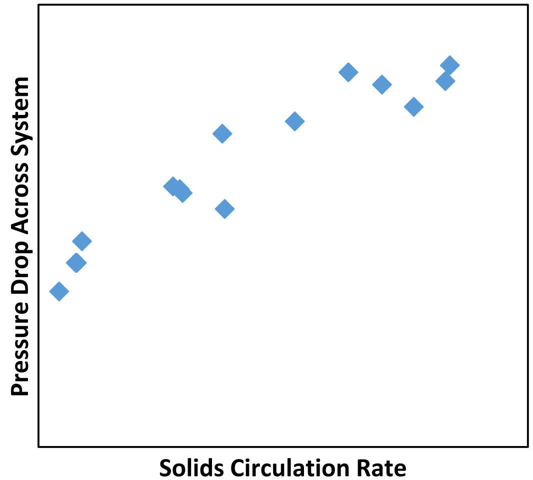
- Continuous ~99.99% syngas conversion throughout 3-day demonstration
- Continuous hydrogen production >99.99% purity
- >300hrs sub-pilot operations without operational issues

SCL Controls and Integration with DCS

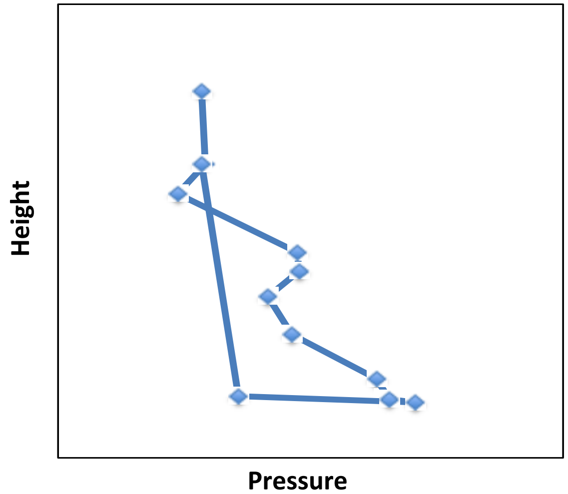


Initial Solid Circulation Tests

Solid Circulation Correlation to Pressure Drop



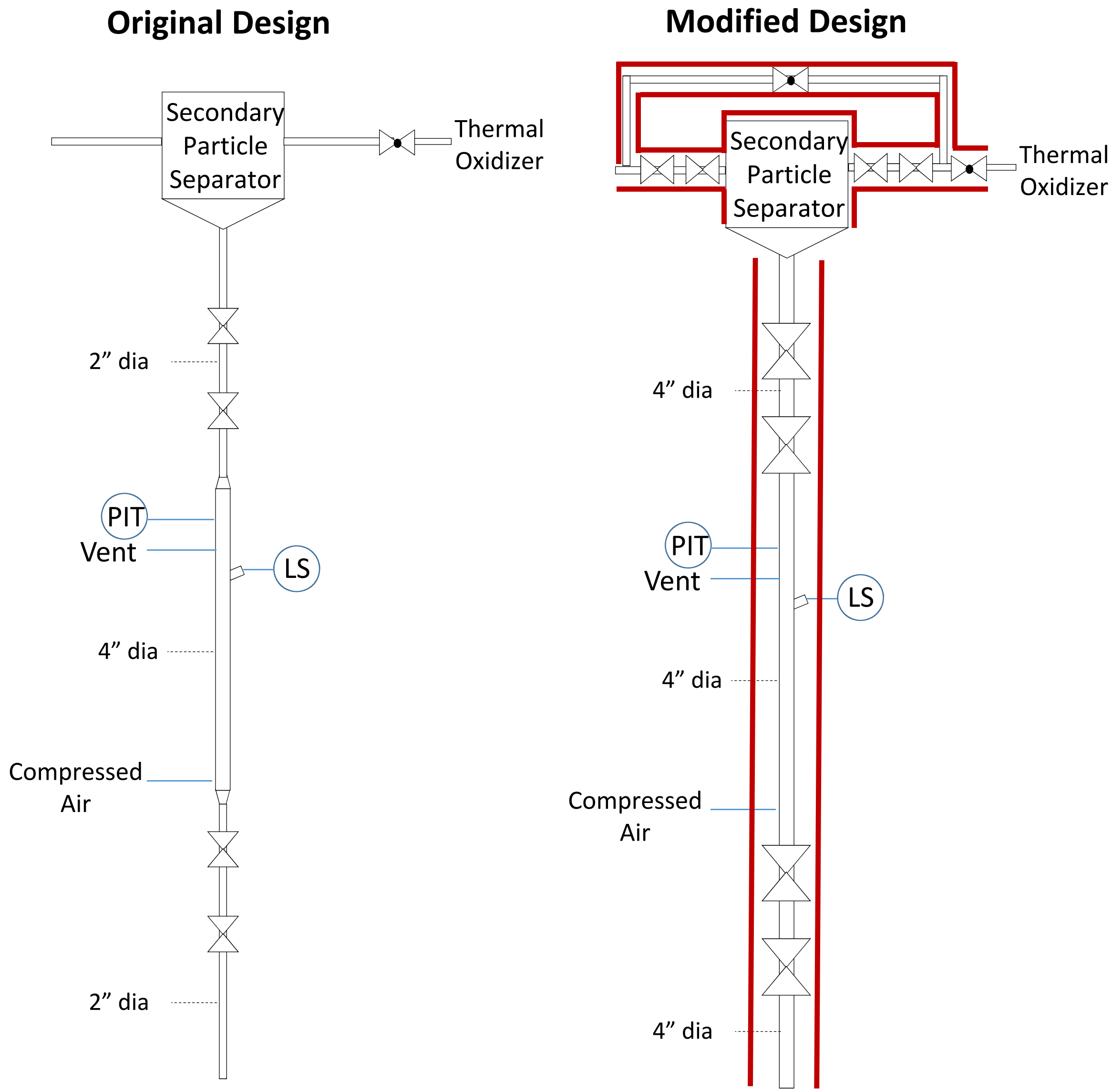
Pressure Profile Across SCL Reactor System



- >200 hours solid circulation studies completed
- Operating pressures: 1-10 atm
- Solid circulation Rate: 95 – 1900 kg/hr
- Demonstrated non-mechanical gas sealing between each reactor

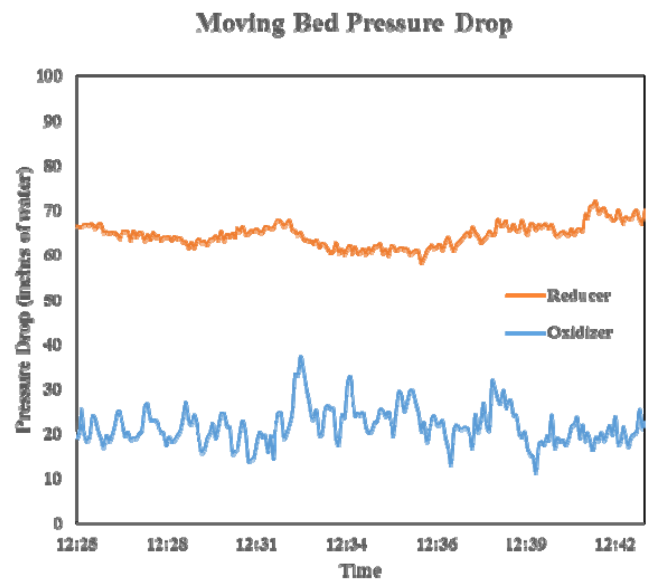
Preparation for April Gasifier Test

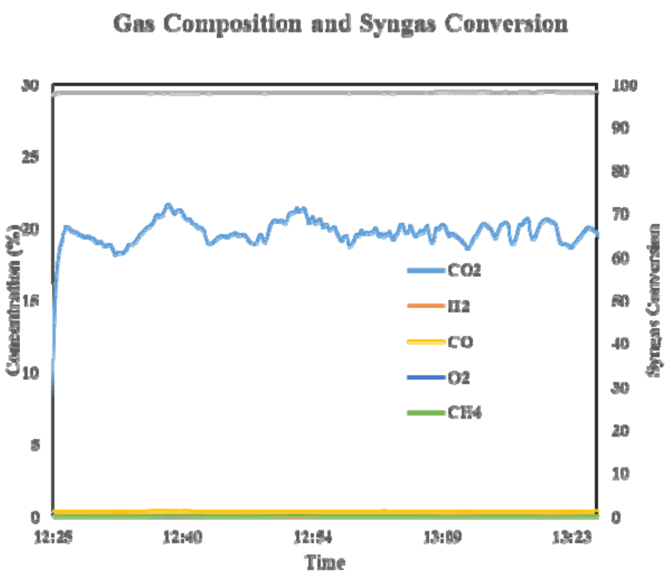
- Heat traced Secondary Particle Separator (SPS) and discharge piping
  - Eliminate moisture collection on filters and discharge piping
- Replaced sinter metal filters with Gore-Tex Filters
  - Operating temperature: 520F
  - Fabric filters – more effective back-pulse
- Enlarged discharge piping to 4”
  - Reduce plugging capability
  - Requires 4” metal seated ball valves
- Added bypass to SPS
  - Allow for maintained operations while servicing SPS
  - Allow flue gas to heat up prior to brining baghouse online

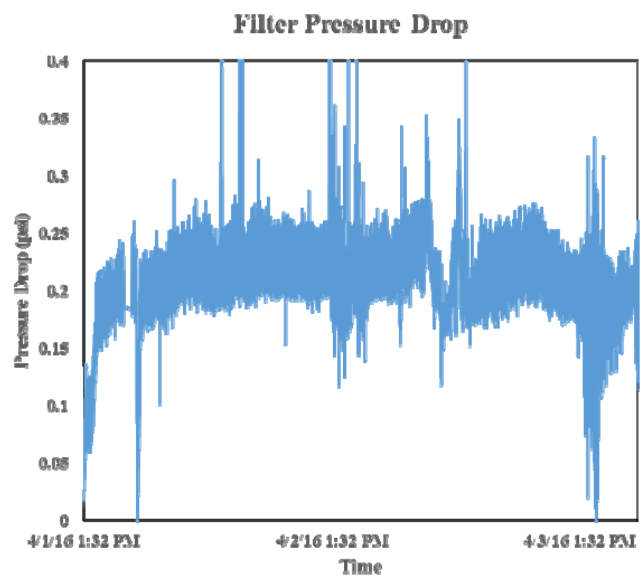


Pilot Plant Operations

- Syngas operation initiated
  - 350 lb/hr syngas processed
- Achieved >98% syngas conversion
- Pressure balance and gas sealing maintained
- Elevated combustor temperatures confirm redox reactions
- Achieved first large-scale demonstration of high pressure, high temperature chemical looping process







Future Work

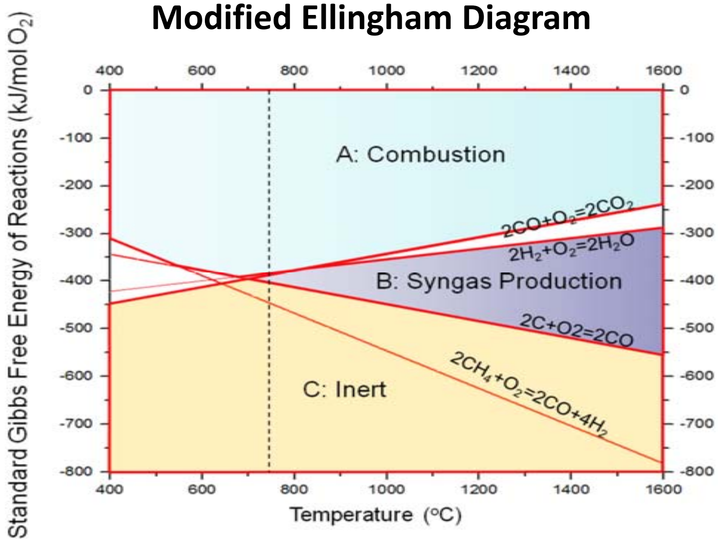
- Achievement
  - Resolved auxiliary equipment issues
  - Developed successful procedure for pilot unit heat up and pressurization while maintaining solid circulation
  - Achieved operating temperature and pressure for syngas conversion
- Continued work
  - Complete preparations for gasifier operation
  - Perform extended unit operations (600 hours) with >750 lb/hr syngas processed
  - Complete techno-economic analysis update

FE0026185: Coal to Syngas (CTS) Sub-Pilot Unit

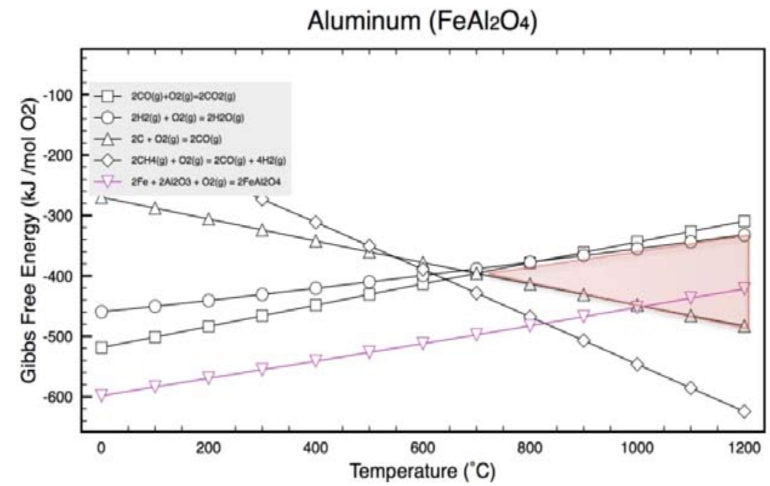
Oxygen Carrier Selection

Thermodynamic Assessment:

Modified Ellingham Diagram

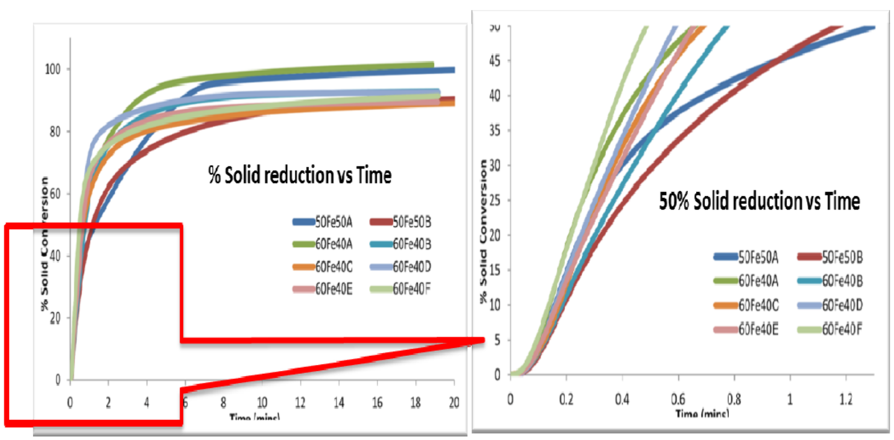


Modified Ellingham Diagram for $FeAl_2O_4$

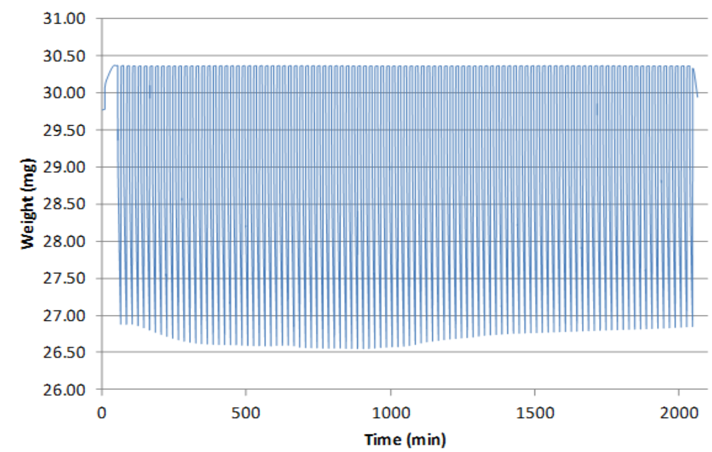


Experimental Screening:

TGA Studies for Oxygen Carrier Kinetics Using H_2



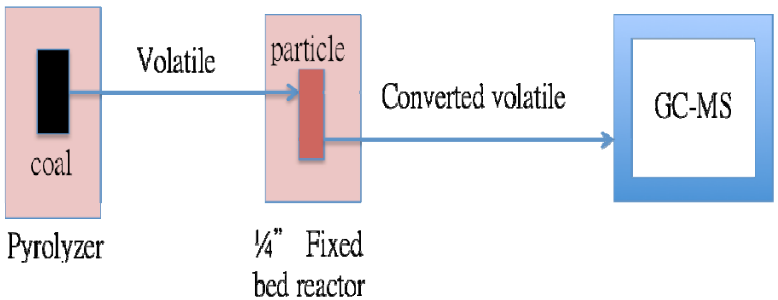
Selected Oxygen Carrier Recyclability

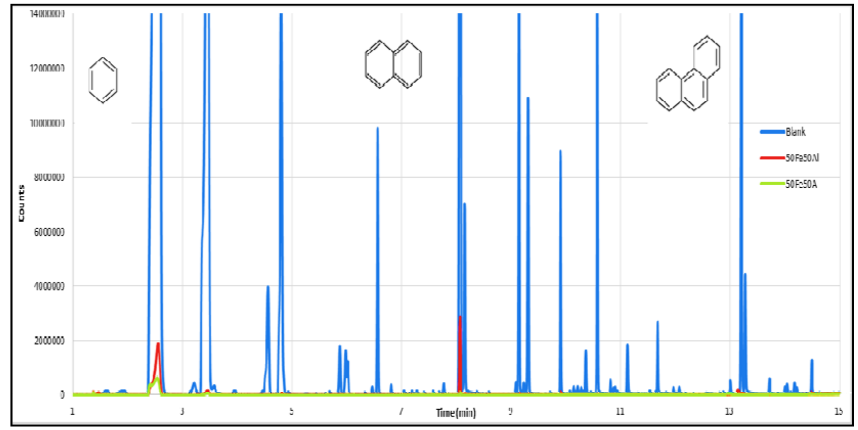


Experimental Studies: Coal Volatile and Moving Bed Reducer

Volatile Cracking Studies with and without OC

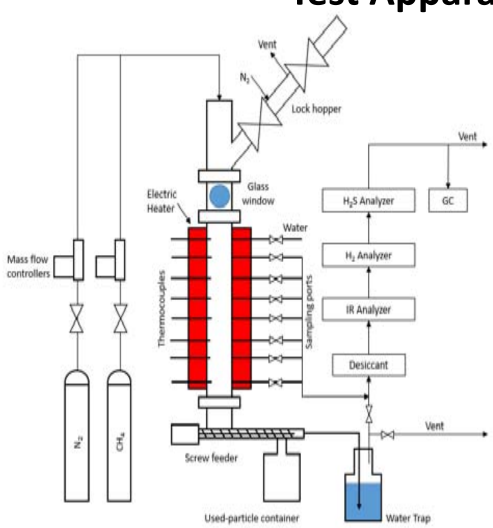
Test Apparatus



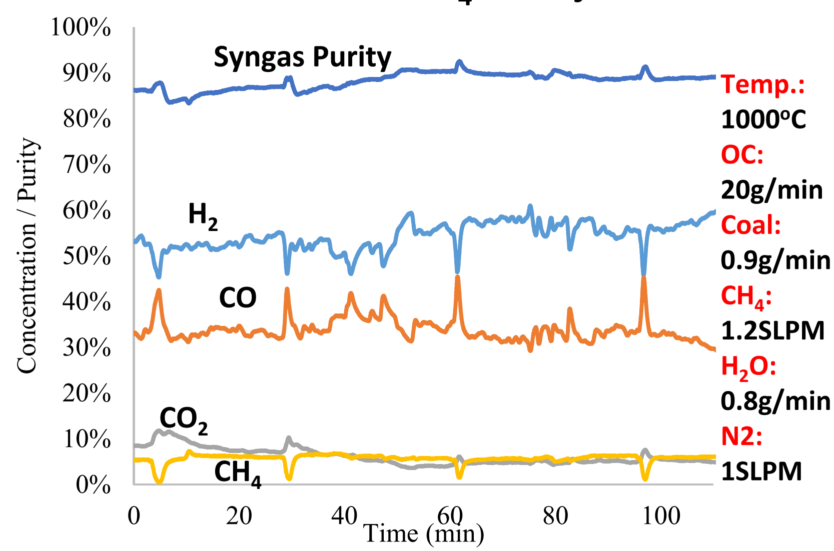


Bench Unit Co-Current Moving Reducer Testing

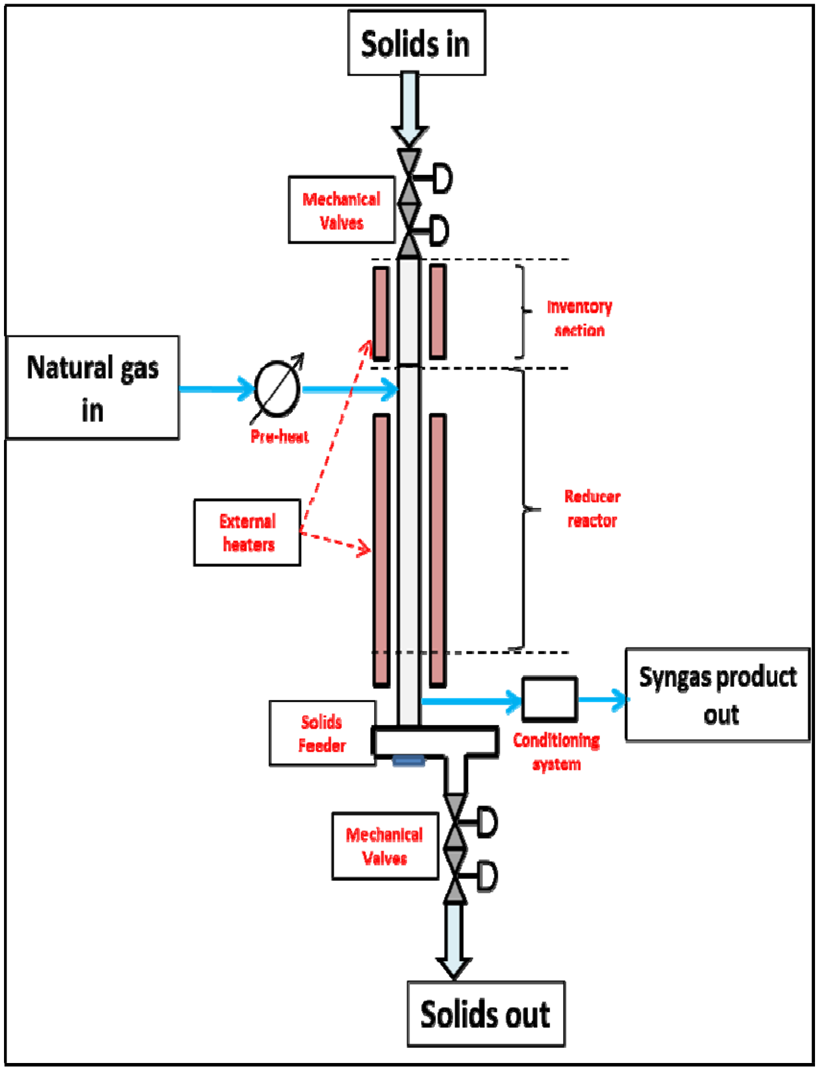
Test Apparatus

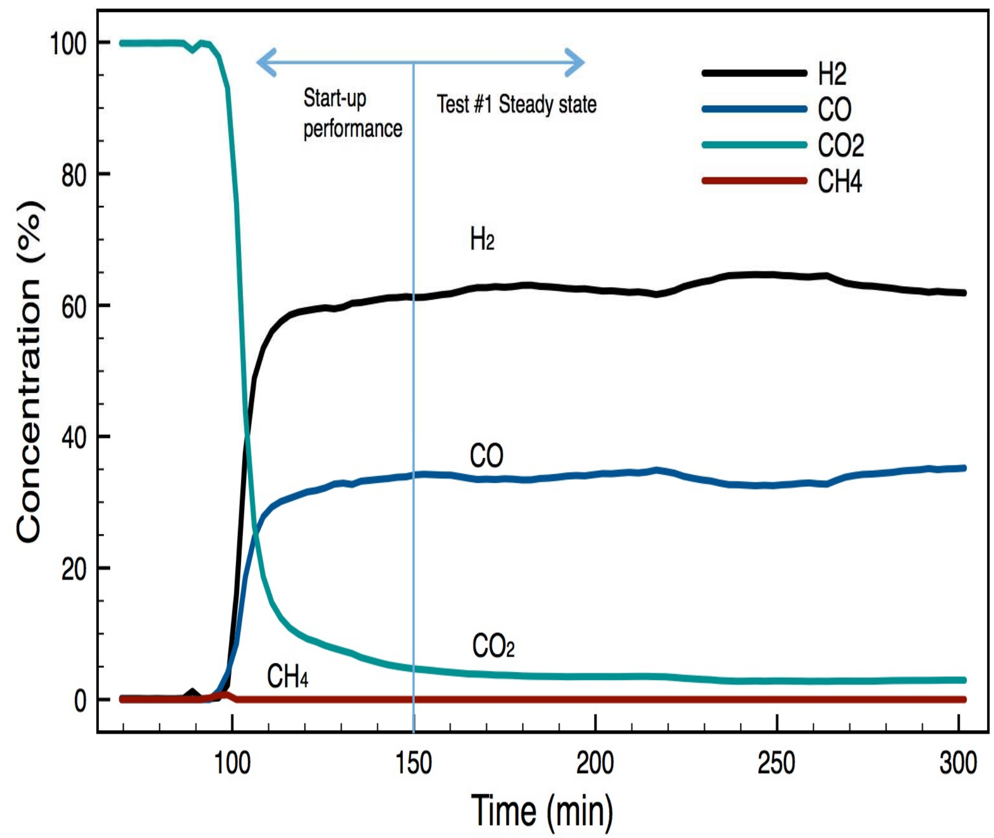


PRB Coal and CH_4 Co-Injection



Experimental Reducer Studies: Coal Volatiles

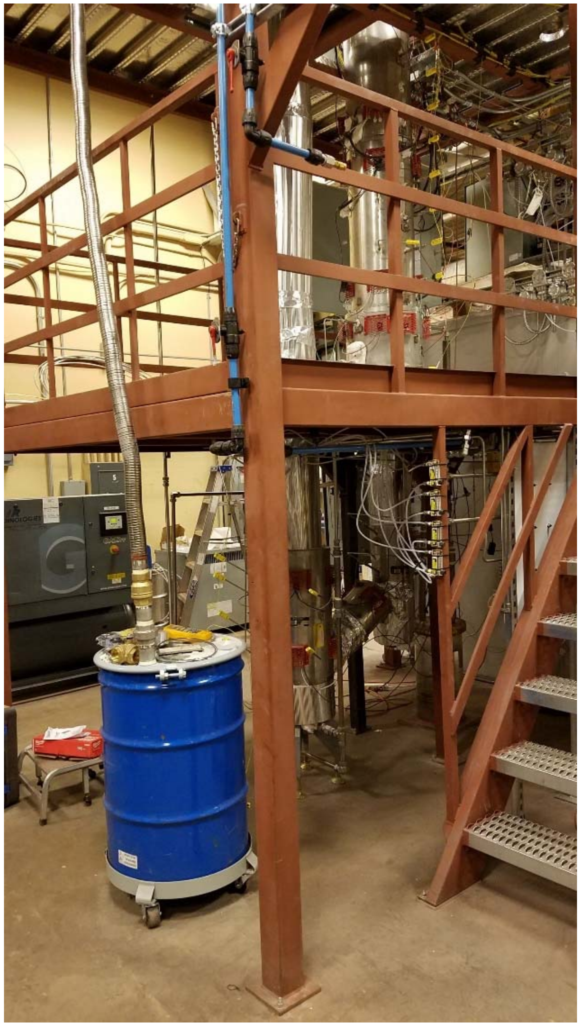


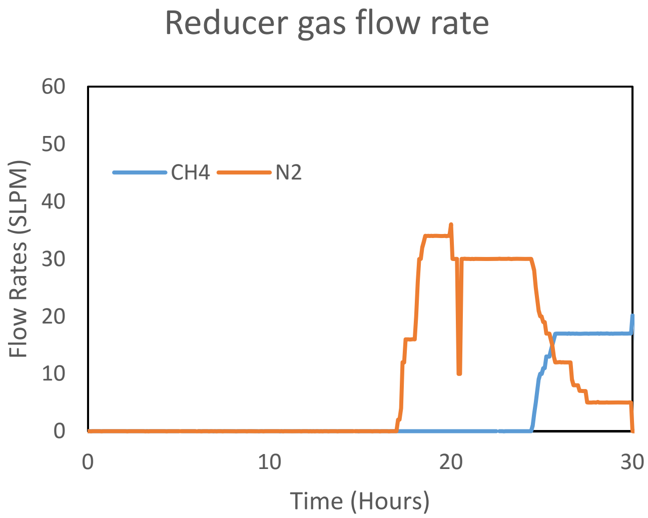


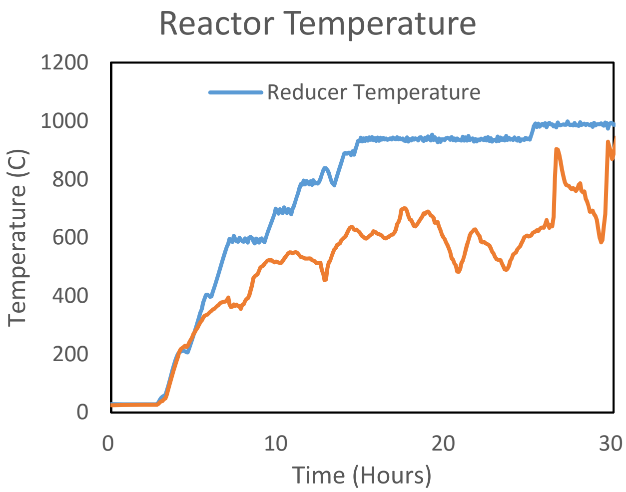
Project Overview

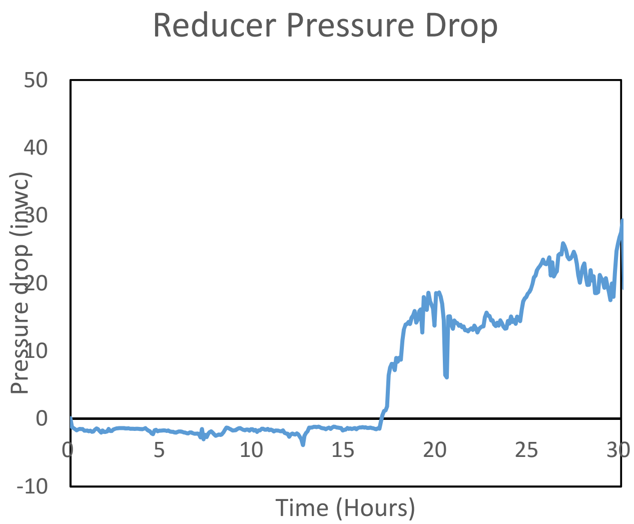
- Prepare Chemical Looping Gasification (CLG) technology for a commercially relevant demonstration by 2020
  - Design and construct an integrated CLG system at sub-pilot scale with coal as its feedstock
    - Continuously operate the system and demonstrate syngas production
    - Investigate the fates 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

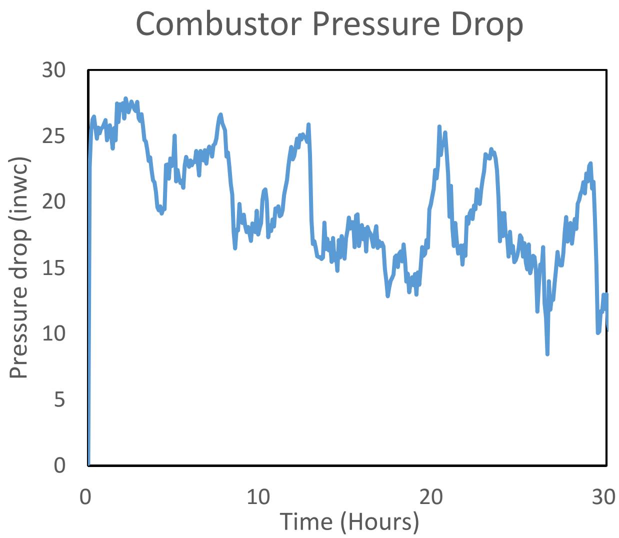
Sub-Pilot Commissioning and Startup









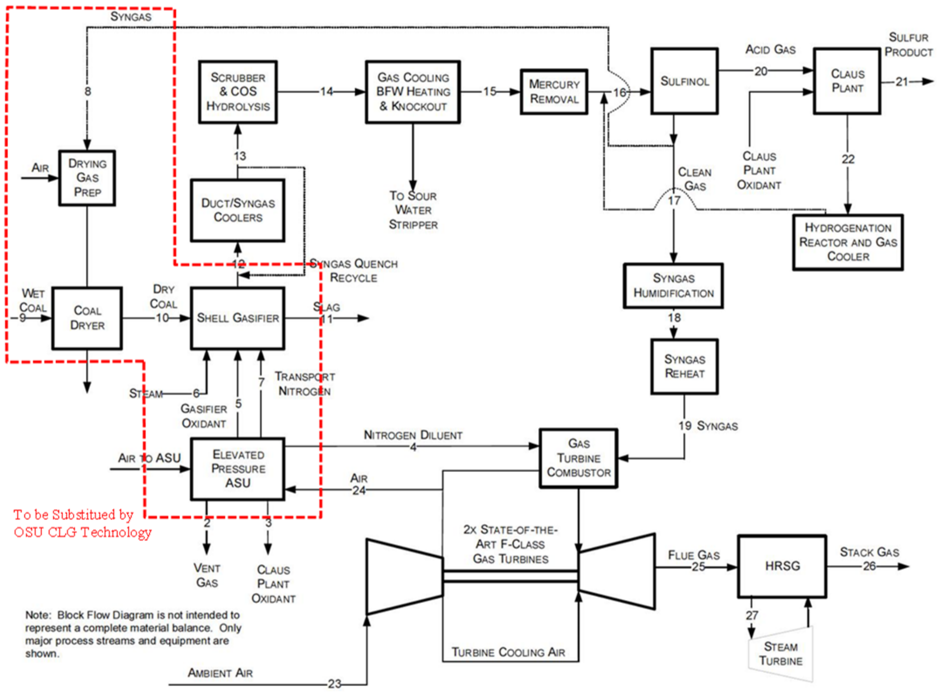


Purpose and Methodology of TEA

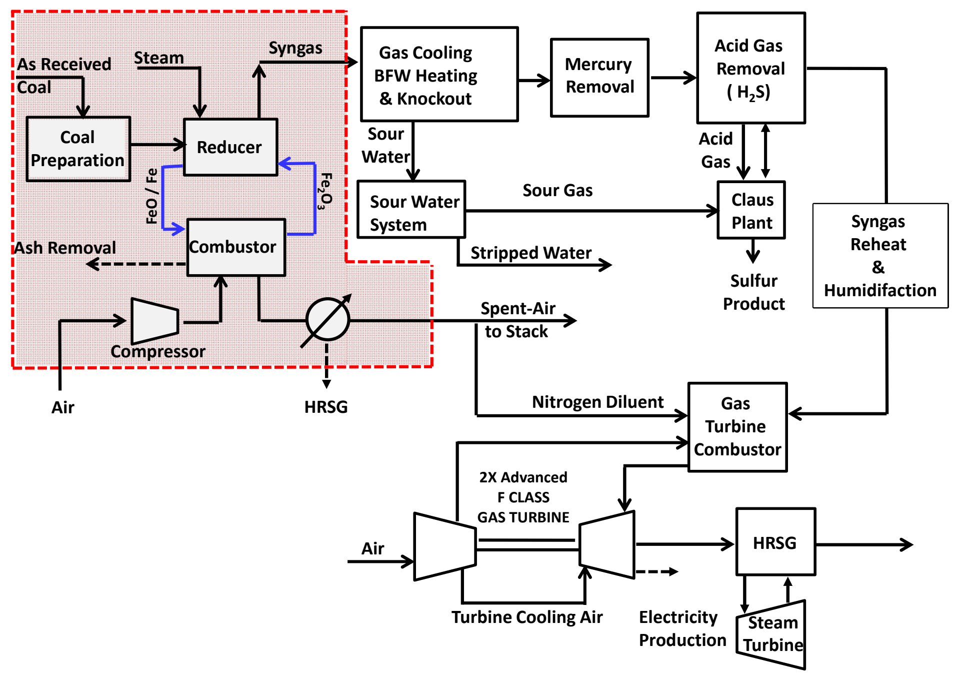
- Purpose
  - To compare capital and lifecycle costs to DOE reference power generation configurations
  - Develop process models and configurations for an IGCC power generation facilities incorporating OSU coal to syngas chemical looping technology.
  - Develop economic comparison of facility designs incorporating OSU CTS technology to IGCC reference cases.
- Methodology
  - Develop three process models of Coal to Syngas (CTS) technology in Aspen Plus
  - Incorporate OSU CTS technology into Aspen Plus IGCC process models.
  - Estimate capital and operating costs based on Aspen Plus modeling of processes
  - Perform financial analysis to determine power production costs and cost of CO_2 captured.
  - Compare costs to DOE/NETL reference cases
- OSU Coal to Syngas (CTS) Cases:
  - Baseline 0% CO_2 capture with 2 reactor CTS configuration
  - 90+% CO_2 capture with 2 reactor CTS configuration
  - 90+% CO_2 capture with 3 reactor CTS configuration

Case Comparison

Conventional Case (Shell Gasifier with no CO_2 Control)



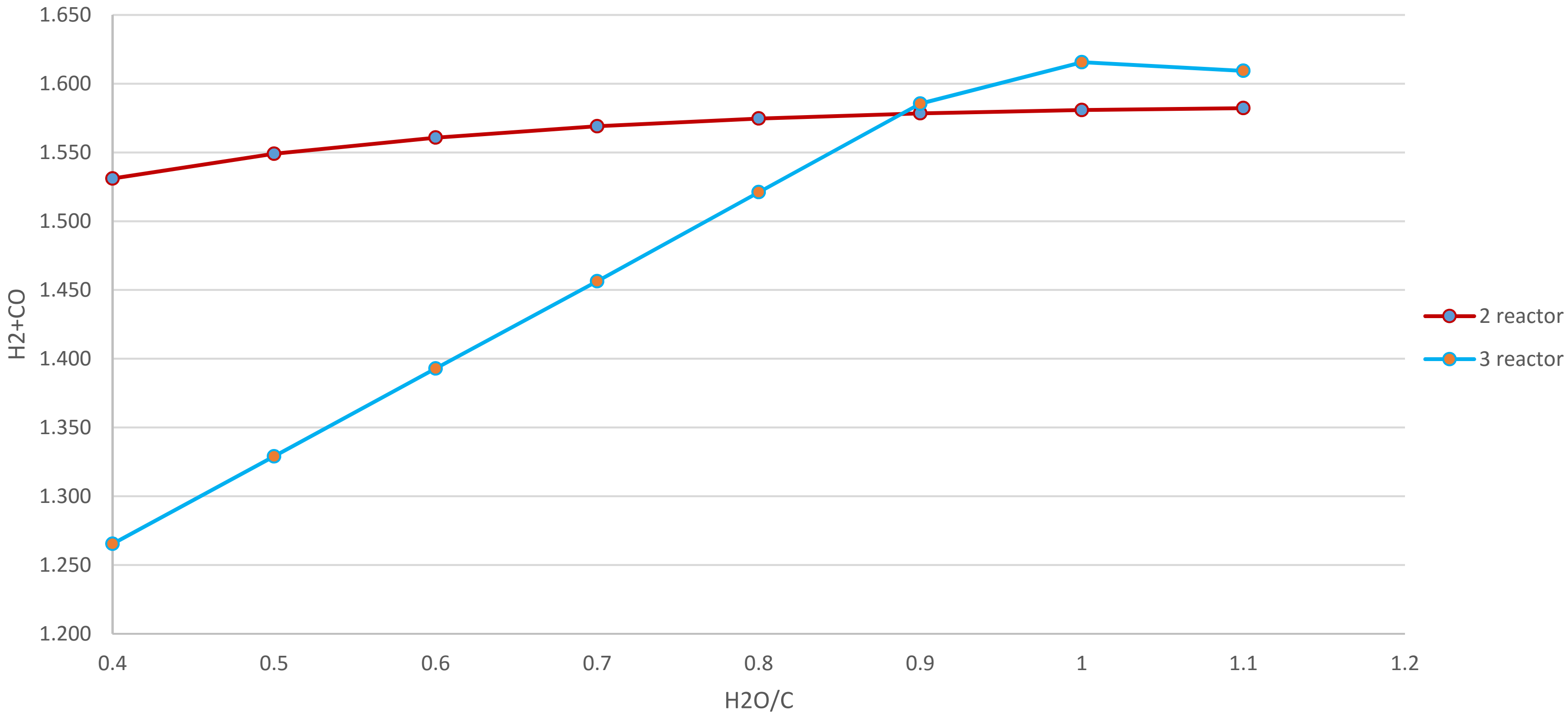
Coal to Syngas (CTS) Chemical Looping Gasification Process



IGCC Design Basis

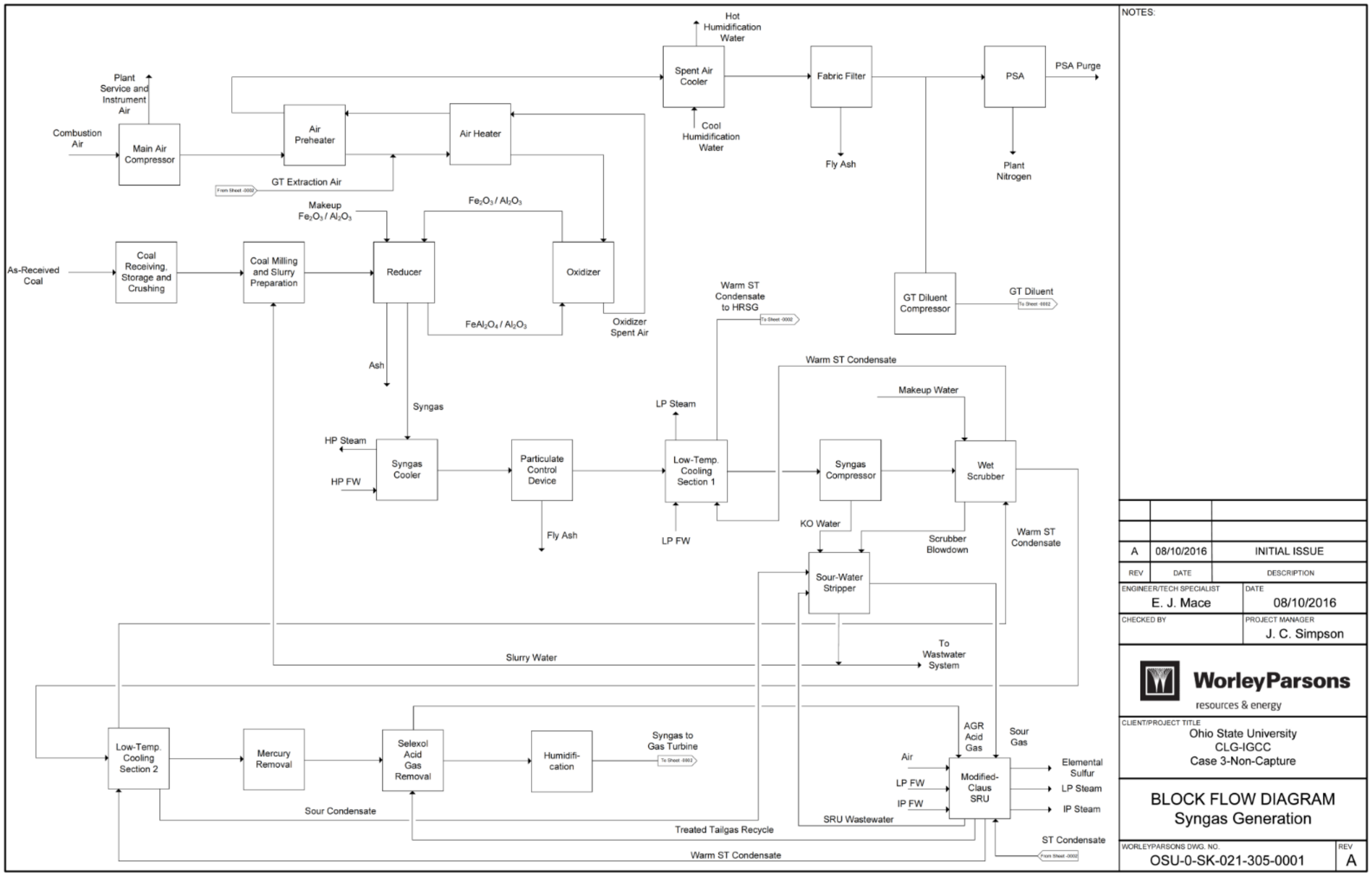
- Fuel: Illinois Bituminous Coal
- CO_2 Removal: O% or >90% based on raw syngas carbon content
- CO_2 Product
    - CO_2 Purity: Enhanced Oil Recovery as listed in Exhibit 2-1 of the NETL QGESS titled "CO_2 Impurity Design Parameters". *
    - CO_2 Delivery Pressure: 2,215 psia
    - Transport and Storage (T&S): $10/tonne
- Plant Size: Sufficient syngas to fire two advanced F-class gas turbines, generating capacity 500-550 MW_e net
- Ambient Conditions: Greenfield, Midwestern USA
- Capacity Factor: 80%
- Financial Structure: High risk IOU, capital charge factor = 0.124
- Reference IGCC Power Production:
    - IGCC cases from "Cost and Performance Baseline for Fossil Energy Plants Volume 1b: Bituminous Coal (IGCC) to Electricity Revision 2b."

CTS 2-Reactor vs 3-Reactor Performance Comparison



Syngas conversion of three reactor system reaches maximum at 1 and decreases dramatically with decreasing steam flow. (18% decrease from 1 to 0.5)
Syngas conversion of two reactor system does not change dramatically with decreasing steam flow. (2% decrease from 1 to 0.5)

2-Reactor CTS Block Diagram (No Capture)



IGCC Plant Integration:

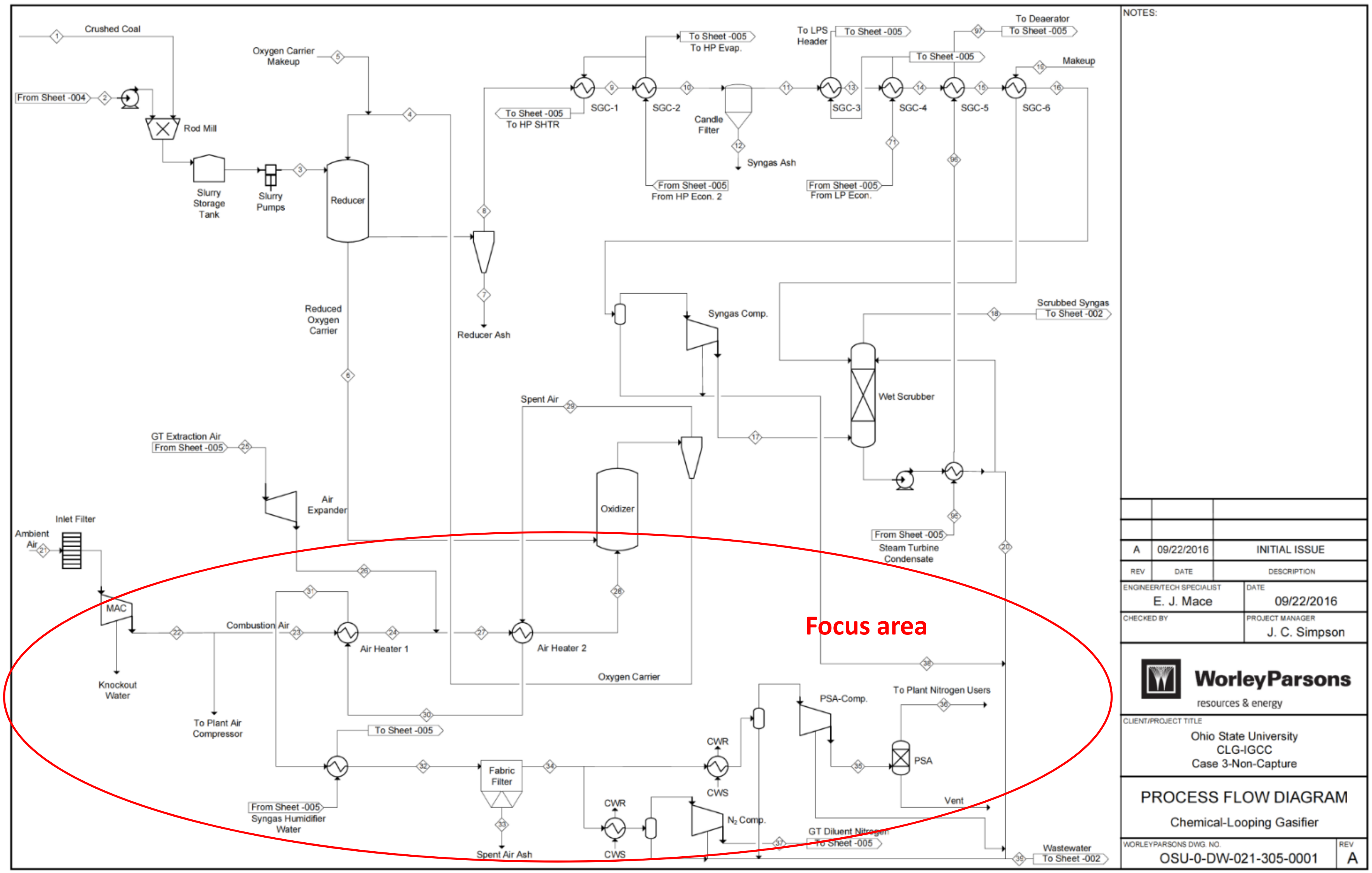
- Main air compressor
  - Supplemented by gas turbine extraction
- Syngas compressor
- Plant nitrogen production
  - HP gas turbine diluent
  - Plant purging and blanketing

2-Reactor Performance Summary – Slurry Feed

Gross Power, kW_e	
Gas Turbine Power	464,000
GT Extraction Expander	3,376
Steam Turbine Power	252,254
Total	719,631
Auxiliary Loads, kW_e	
Oxidizer Main Air Compressor	32,226
GT Diluent Nitrogen Compressor	26,386
Main Syngas Compressor	38,162
Selexol Acid Gas Removal	4,394
Balance of Plant	25,345
Total	126,513
Net Power, kW_e	
Net Power	593,117
Miscellaneous Performance Metrics	
HHV Net Plant Efficiency, %	39.4
HHV Net Plant Heat Rate, Btu/kWh	8,654
HHV Cold Gas Efficiency, %	83.7
HHV Gas Turbine Efficiency, %	37.6
LHV Net Plant Efficiency, %	40.9
LHV Net Plant Heat Rate, Btu/kWh	8,347
LHV Cold Gas Efficiency, %	80.3
LHV Gas Turbine Efficiency, %	40.6
Steam Cycle Efficiency, %	33.4
Steam Cycle Heat Rate, Btu/kWh	10,225
Condenser Duty, MMBtu/h	1,231
As-Received Coal Feed, lb/h	439,985
HHV Thermal Input, kWt	1,504,294
LHV Thermal Input, kWt	1,450,910
Raw Water Withdrawal, gpm/MW_{net}	7.3
Raw Water Consumption, gpm/MW_{net}	5.6

- CO_2 emissions
  - Close to new source EPA limit of 1,400 lb/MW_{gross} (1,429 lb/MW_{gross})
- Process heat recovery option
  - Oxidizer spent air (unique to CTS system)
    - High-quality heat is being used to heat air instead of making steam
- Potential Options to Lower CO_2 emissions: lower oxidation air temperature
  - More oxygen carrier
  - Higher syngas CO_2 yield
  - More nitrogen for gas turbine, less HP steam
  - Higher-quality spent air heat recovery

2-Reactor Performance Summary – Slurry Feed



Additional Work

- Sub-Pilot Demonstration
  - Complete Unit Startup Activities
  - Coal feed and parametric testing
  - Extended unit operations
- TEA Tasks
  - Optimization to other targets/goals
  - Improvement of efficiency (dry feed)
  - Meeting EPA CO_2 emissions target of 1,400 lb CO_2/MW_h gross
    - Expand to other feeds
    - Other coal types for regional applications
  - Understanding of markets and competition
  - Complete 3 TEA case studies of the CTS process

Acknowledgements

Government Agencies

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Project Participants

- Babcock & Wilcox: Christopher Poling, Thomas Flynn
- Clear Skies: Robert Statnick
- American Electric Power: Matthew Usher, Indrajit Bhattacharya
- Test Site Host: National Carbon Capture Center