# *Atmospheric Iron-Based Coal Direct Chemical Looping Process for Power Production*

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*FE-0009761*

# Project Objectives

**Phase I Project objectives: 2012 -2013**

- Evaluate commercial viability of OSU's coal-direct chemical looping process for power production with $CO_2$ capture.
- Perform a techno-economic evaluation of the commercial design.

**Phase II Project Objectives**

- Reduce technology gaps identified in Phase I by conducting laboratory testing and small pilot-scale testing.
- Re-evaluate the CDCL technology and identify development pathway for commercialization in year 2025.
- Update design and cost performance of the commercial 550 MWe CDCL power plant

# Project Participants

## Federal Agencies:

- DOE/NETL

## Project participants:

- The Babcock & Wilcox, PGG
- The Ohio State University
- Clear Skies Consulting

## Industrial Review Committee:

- Consol Energy
- First Energy
- Duke Energy
- Ohio Development Service Agency

# Outline

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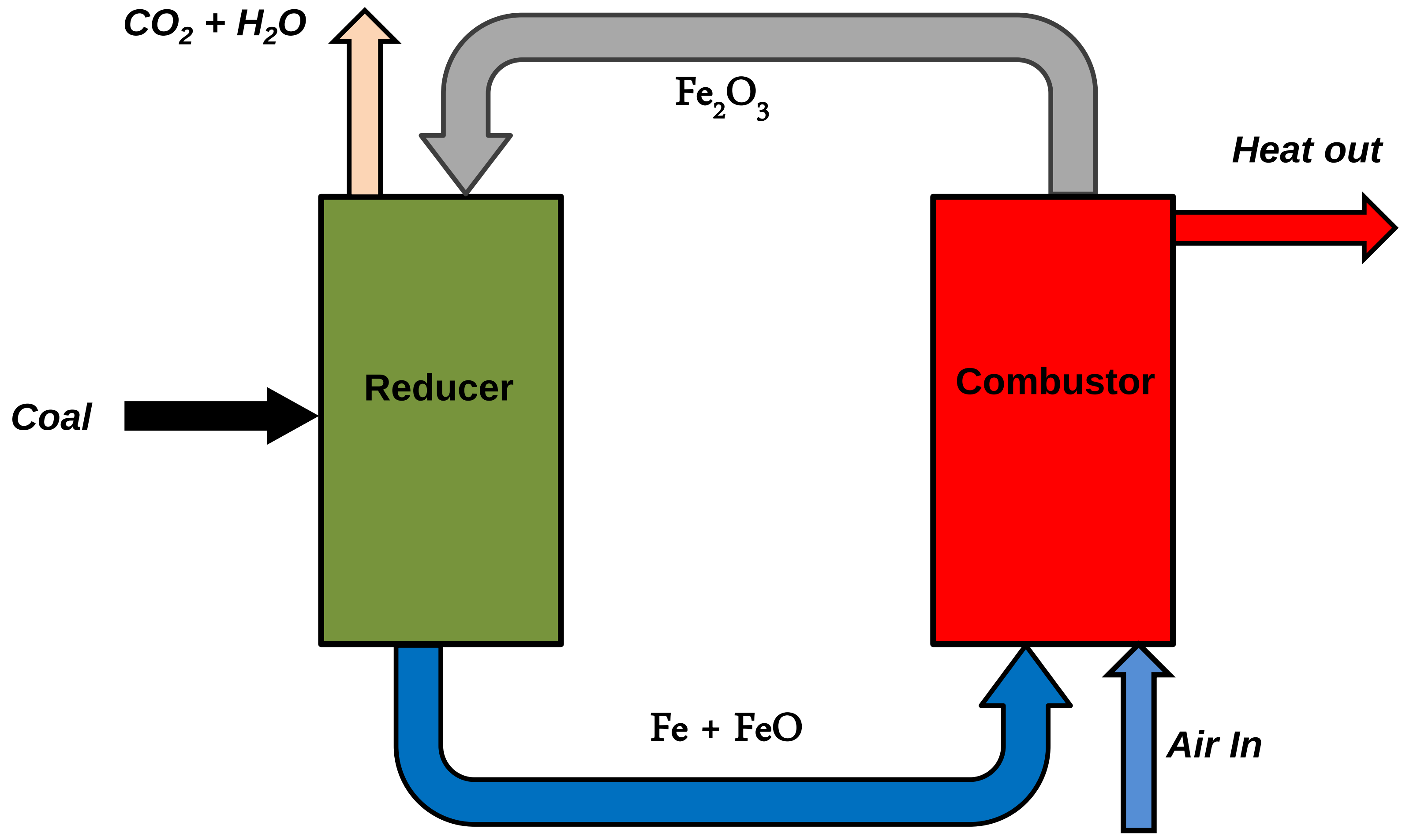
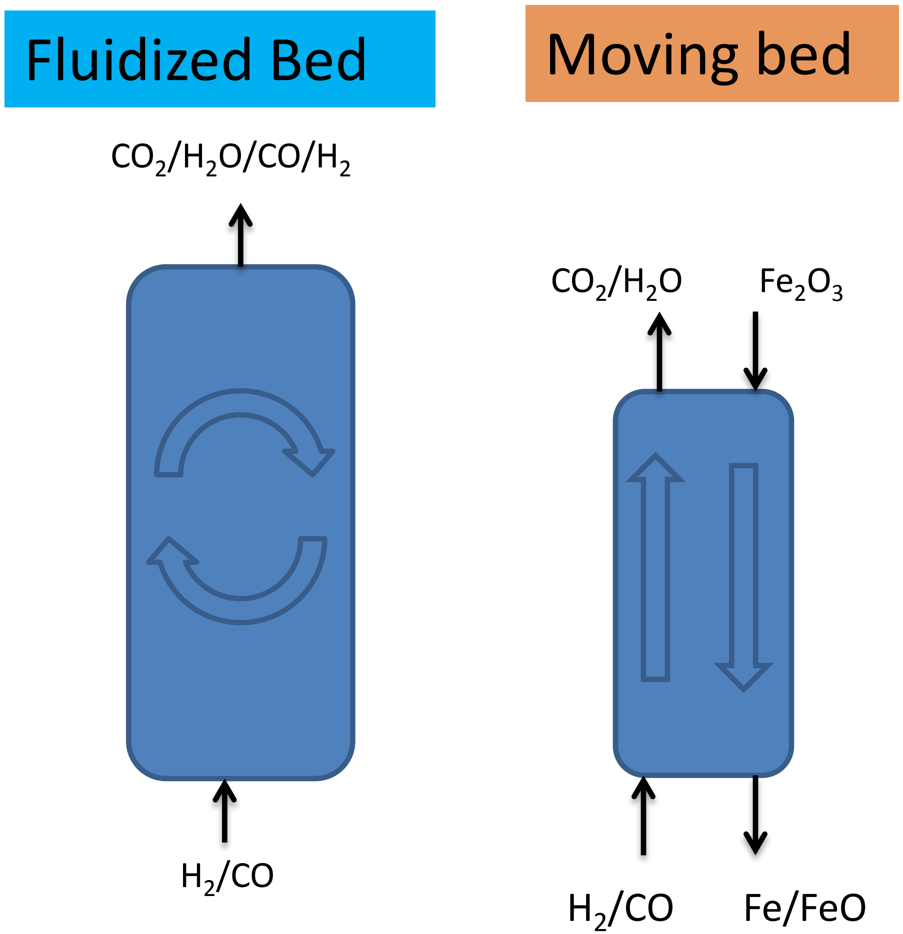
# Chemical Looping Concept

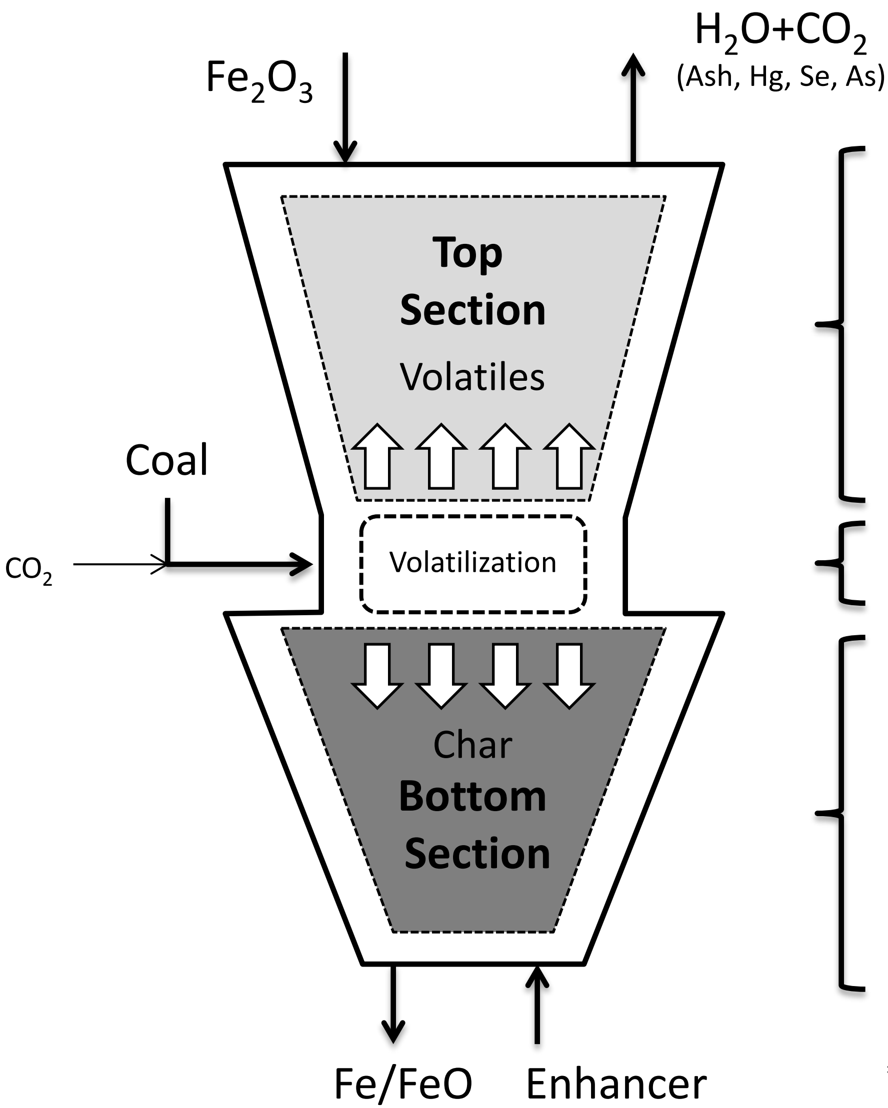


# Reducer Reactor Concept




| Reducer | Fluidized Bed | Moving Bed |
|---|---|---|
| Operation Regime | Bubbling, turbulent, fast fluidized, or spouted bed | Moving packed, or multistage fluidized bed |
| Gas Solid Contacting Pattern | Mixed/Cocurrent | Countercurrent |
| Particle Attrition | High | Low |
| 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 |

# CDCL Moving Bed Reactor Concept




**Top Section***

$C_xH_y + Fe_2O_3 \rightarrow Fe + FeO + CO_2 + H_2O$

$CO + Fe_2O_3 \rightarrow Fe + FeO + CO_2$

$H_2 + Fe_2O_3 \rightarrow Fe + FeO + H_2O$

**Coal Volatilization***

Coal $\rightarrow$ $C + C_xH_y$ (Volatiles)

**Bottom Section***

$C + CO_2 \rightarrow 2\ CO$

$2\ CO + Fe_2O_3 \rightarrow Fe + FeO + 2\ CO_2$

* Reactions not balanced

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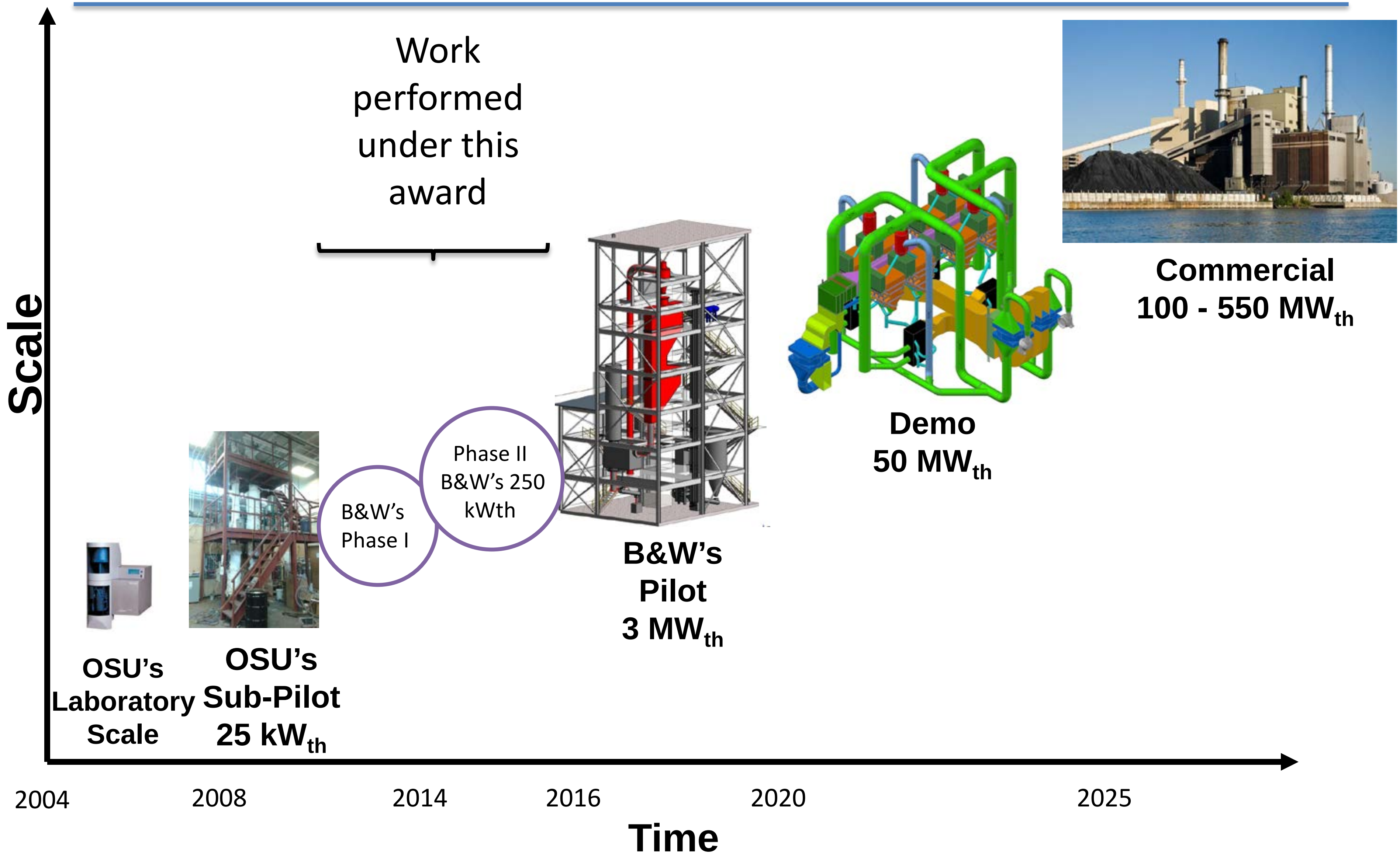
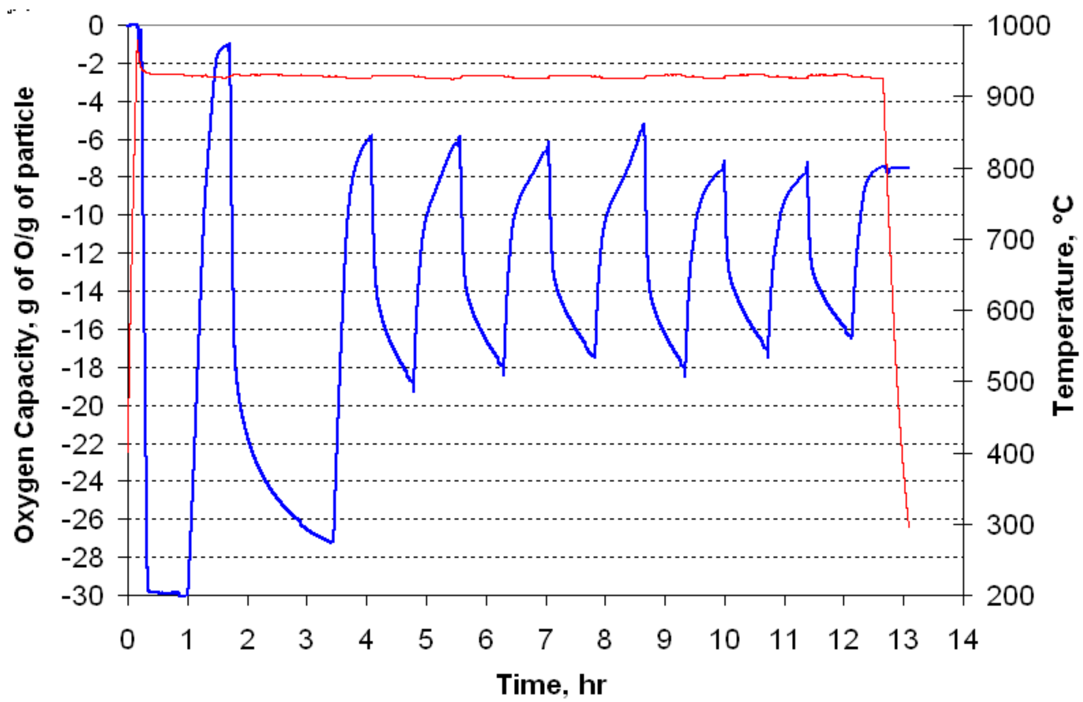
# Commercialization Path

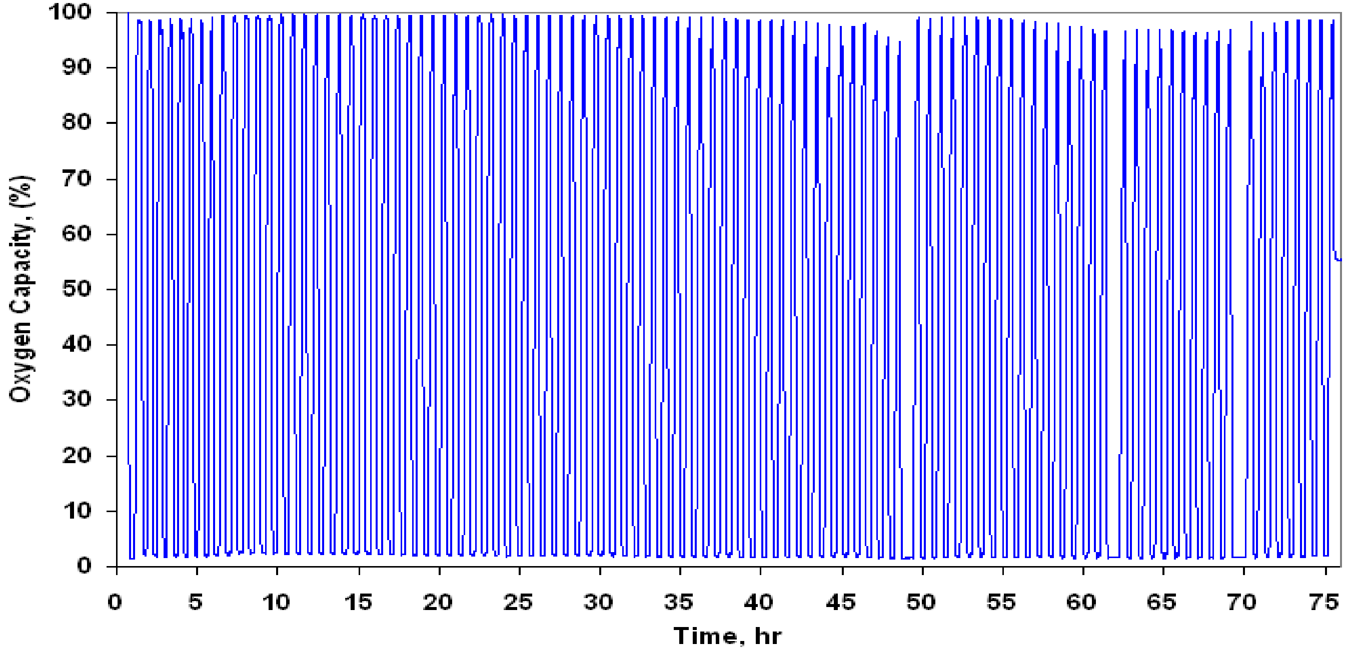


# Commercial $Fe_2O_3$ Oxygen Carrier Particles




Commercial $Fe_2O_3$ particles lose reactivity within a few cycles

# Composite $Fe_2O_3$ Oxygen Carrier Particles




Composite $Fe_2O_3$ particles sustain multiple redox cycles without significant loss in activity

# 25 $kW_{th}$ Sub-Pilot Demonstration

- **Fully assembled and operational**
- **>680 hours of operational experience**
- **>200 hours continuous successful operation**
- **Smooth solids circulation**
- **Confirmed non-mechanical gas sealing under reactive conditions**
- **17 test campaigns completed**

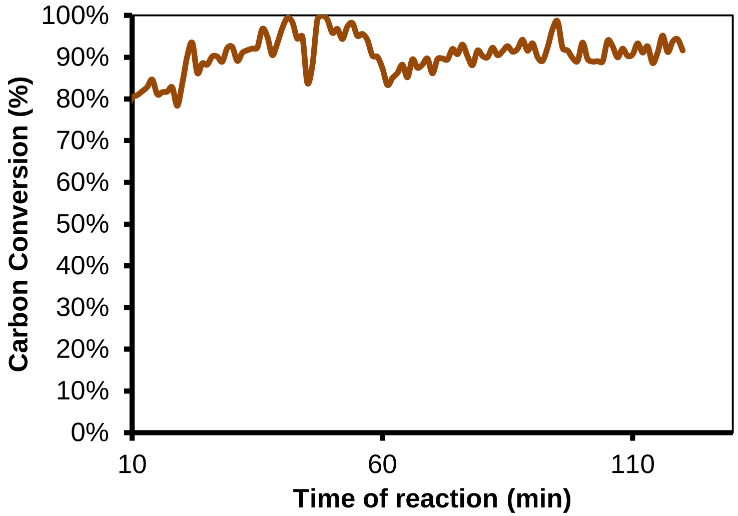
# Fuel Feedstock Study

| 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 | $CO_2/H_2O$ |

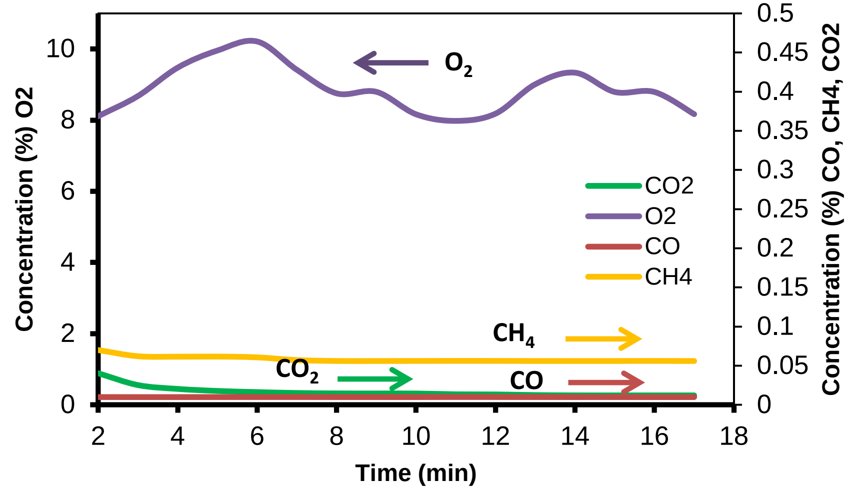
- **680 hours of sub-pilot CDCL operational experience**
- **Successful results for all coal / coal-derived feedstock tested**

# 200-hour Sub-Pilot Continuous CDCL Demonstration

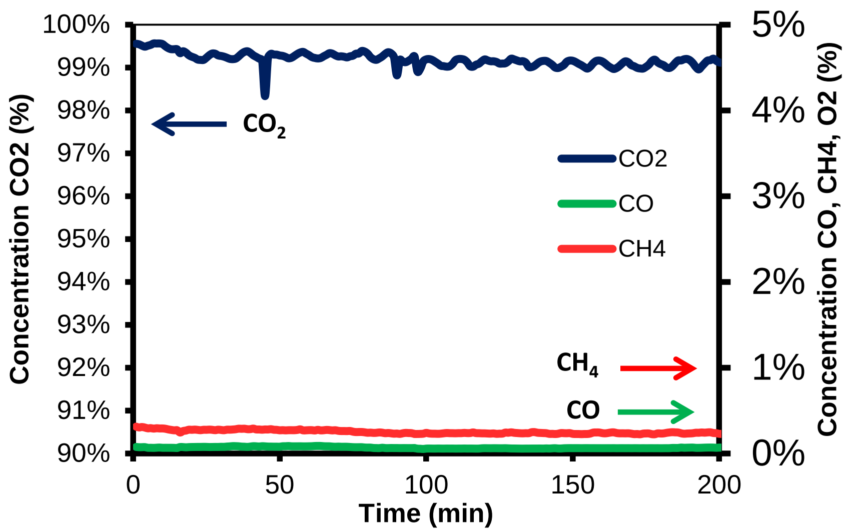
### Reducer Carbon Conversion Profile




### Combustor Gas Concentration Profile




### Reducer Gas Concentration Profile




### Sample Data: PRB Process Performance

- Continuous steady carbon conversion from reducer throughout all solid fuel loading (5- 25kWth)
- <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

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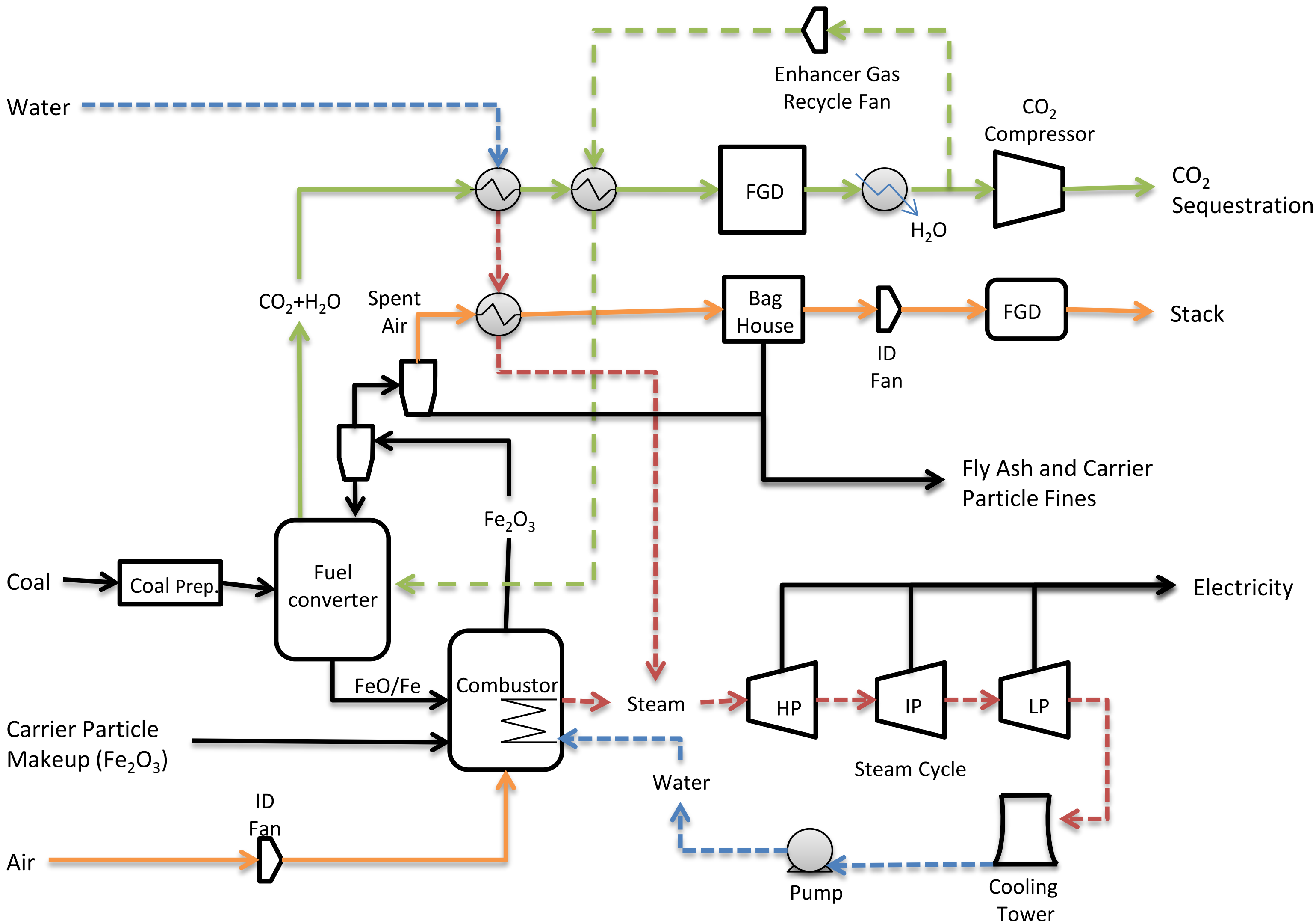
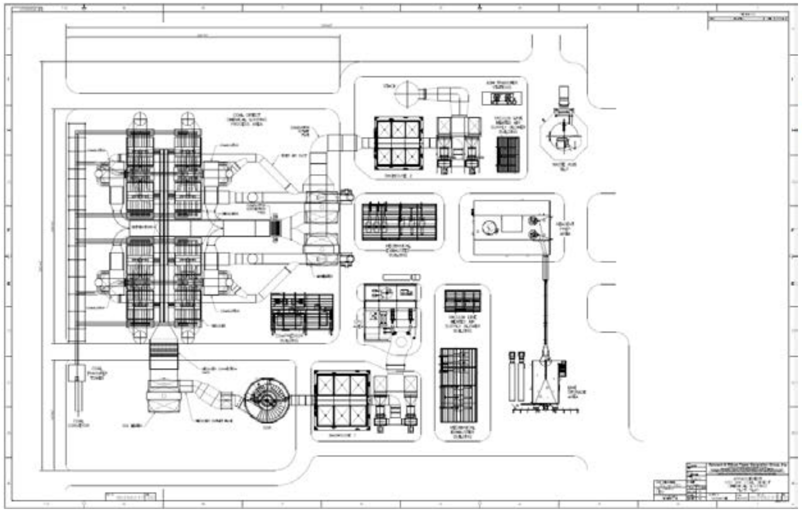
# Commercial Plant Design: 550 $MW_e$

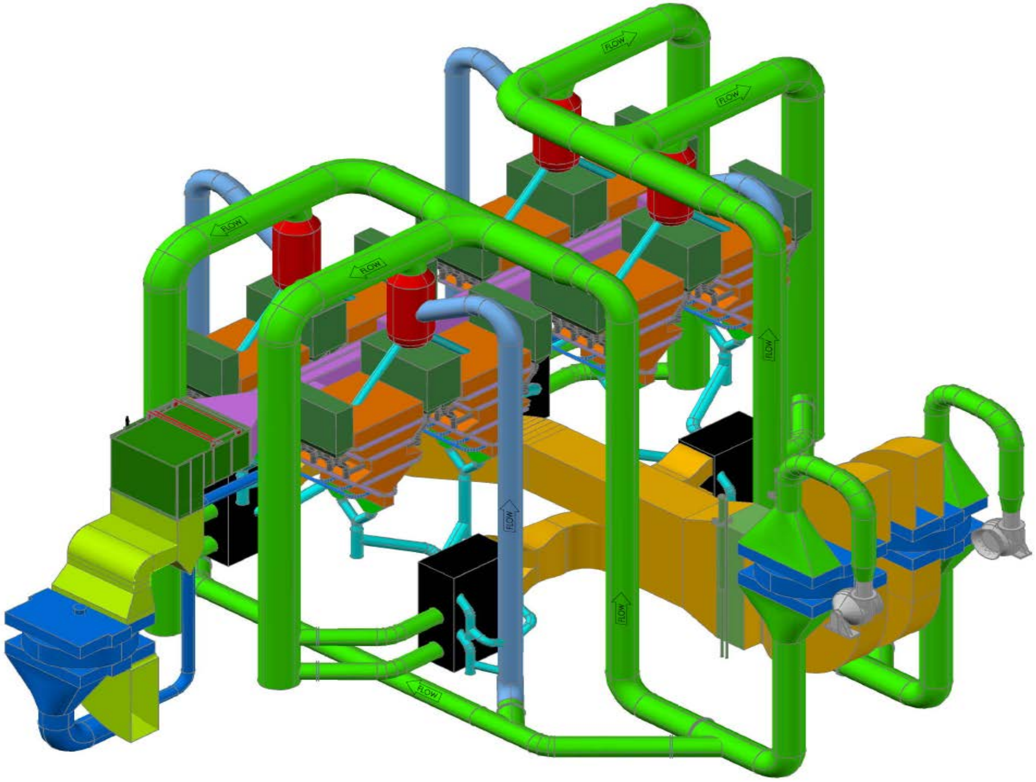


# CDCL Commercial Plant Design and Engineering

OSU's experimental data was converted into a commercial 550 MWe CDCL power plant.

- Material and Energy Balance
- Process Flow Diagrams
- Equipment Drawings
- Arrangement Drawings
- Plant layout Drawings
- 3-D Models





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# CDCL Technology Comparison

| | Base Plant | MEA Plant | CDCL Plant |
|---|---|---|---|
| Coal Feed, kg/h | 185,759 | 256,652 | 205,358 |
| $CO_2$ Emissions, kg/MWh$_{net}$ | 801 | 111 | 31 |
| $CO_2$ Capture Efficiency, % | 0 | 90 | 96.5 |
| Net Power Output, MW$_e$ | 550 | 550 | 550 |
| Net Plant HHV Heat Rate, kJ/kWh (Btu/kWh) | 9,165 (8,687) | 12,663 (12,002) | 10,084 (9,558) |
| Net Plant HHV Efficiency, % | 39.3 | 28.5 | 35.6 |
| Cost of Electricity, $/MWh | 80.96 | 132.56 | 102.67 |
| Increase in Cost of Electricity, % | - | 63.7 | 26.8 |

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# Total Plant Cost

| Acc. No. | Item Description | CDCL Cost, $k |
|---|---|---|
| 1 | Coal & Sorbent Handling | $ 45,930 |
| 2 | Coal & Sorbent Prep and Feed | $ 21,772 |
| 3 | Feedwater & Misc. BOP Systems | $ 95,364 |
| 4 | Boiler/CDCL Equipment | $ 554,053 |
| 5 | Flue Gas Cleanup | $ 154,402 |
| 5B | $CO_2$ Removal & Compression | $ 87,535 |
| 6 | Combustion Turbine/Accessories | - |
| 7 | HR, Ducting & Stack | $ 44,799 |
| 8 | Steam Turbine Generator | $ 146,288 |
| 9 | Cooling Water System | $ 44,951 |
| 10 | Ash/Spent Sorbent Handling System | $ 15,256 |
| 11 | Accessory Electric Plant | $ 61,392 |
| 12 | Instrumentation & Controls | $ 25,903 |
| 13 | Improvements to Site | $ 16,394 |
| 14 | Buildings & Structures | $ 66,362 |
| | Total Plant Cost | $1,380,401 |

# Cost of Electricity

| | Base Case, $k | CDCL, $k |
|---|---|---|
| Total Overnight Capital Cost | 1,348,350 | 1,725,172 |
| Fixed O&M | 38,829 | 48,769 |
| Variable O&M | 10,986 | 13,916 |
| Consumables | 20,742 | 13,743 |
| Fuel | 104,591 | 114,807 |
| Oxygen Carrier | - | 15,581 |
| Total Production Cost | 1,523,498 | 1,931,989 |
| Cost of Electricity, $/ MWh | 80.96 | 102.67 |
| **Increase in COE, %** | | **26.8%** |

# Sensitivity Analysis

| Technology Gap | Assumption | Target | Relative Increase in COE with respect to DOE's base plant |
|---|---|---|---|
| CDCL Designed Case | | | 26.8% |
| Residence Time | 100% | 33% reduction | 24.7% |
| $CO_2$ Credit | 0% Credit | 6.5% at $20/ton | 20.9% |
| $CO_2$ Credit | 0% Credit | 96.5% at $20/ton | 0.64 % |

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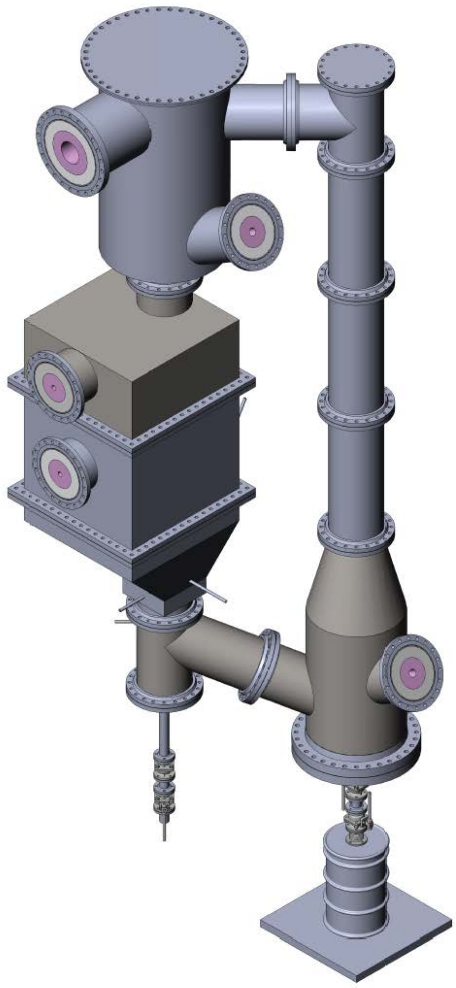
# Experimental CDCL Small-Pilot Design



**Objective:** Obtain representative reducer performance under autothermal system conditions.

- Thermal Input: 250 kWth.
- Height: 30’
- Footprint: 10’ x 10’
- Location: B&W’s Research Center. Barberton Ohio.

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# Conclusions

- Development of suitable oxygen carrier capable of >100 redox cycles

- Moving bed design enhances carbon and particle conversion and enhances process efficiency

- Continuous 200-hour feasibility demonstration of CDCL at 25 kWth scale
  - High coal conversions achieved in the reducer
  - High $CO_2$ purity with low carbon carryover to the combustor
  - Various types of coals successfully tested

- Techno-economic analysis shows that increase in COE is <27% for CDCL plant when compared to PC plant with no carbon capture

- Small Pilot unit designed to resolve technology gaps identified in Phase I with emphasis on autothermal system operation.

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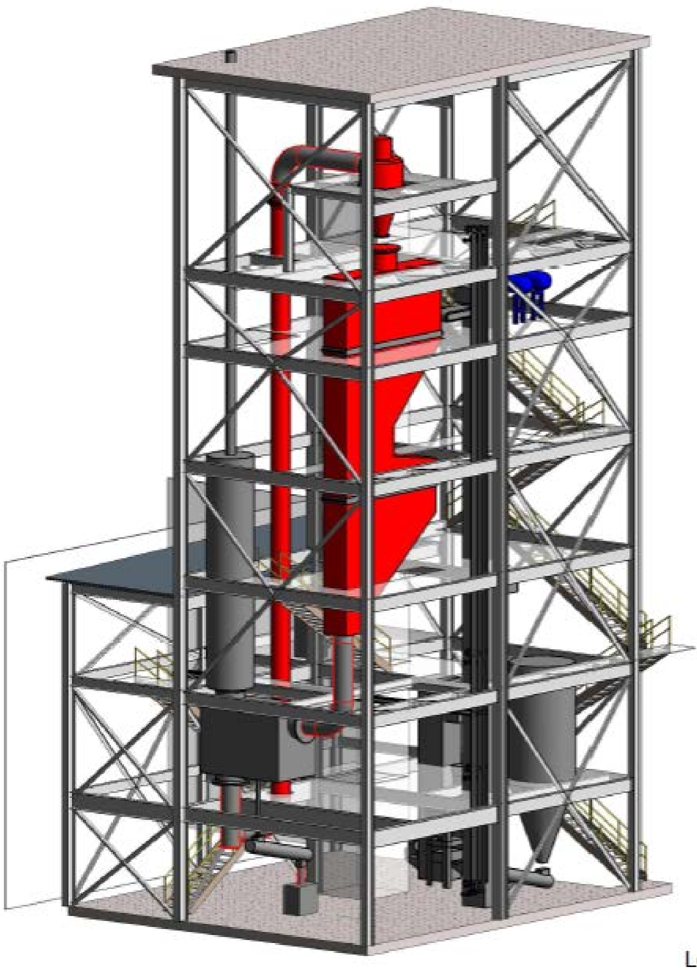
# Future Work: 3MWth Pilot Scale Demonstration



Looking Southwest

**Objective:** Investigate coal distribution and system performance at commercial-scale conditions.

- Thermal Input = 3 MW
- Height = 90 feet
- Footprint = 40’ x 40’
- Location: B&W’s Research Center. Barberton Ohio.

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# Acknowledgments

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