the Energy to Lead

Oxy-Combustion Pressurized Fluidized Bed with Carbon Dioxide Purification

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Agenda

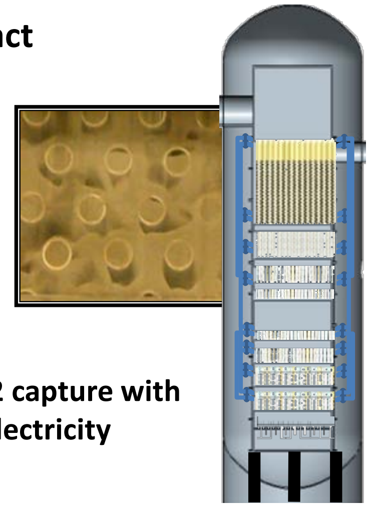
- Project Overview
- Background
- Technical Approach / Project Scope
- Progress and Current Status
- Future Plans
- Summary

Phase II Oxy-fired Pressurized Fluidized Bed Combustor (Oxy-PFBC) Overview

Description and Impact

Phase II Description

- Advance Oxy-PFBC technology to TRL 6 through pilot testing
- Budget: $19.1M ($12M DOE funding)
- Period of Performance: 33 months (7/1/2014 - 3/31/2017)
- Impact: Exceed DOE Goals of >90% CO2 capture with no more than 35% increase in cost of electricity



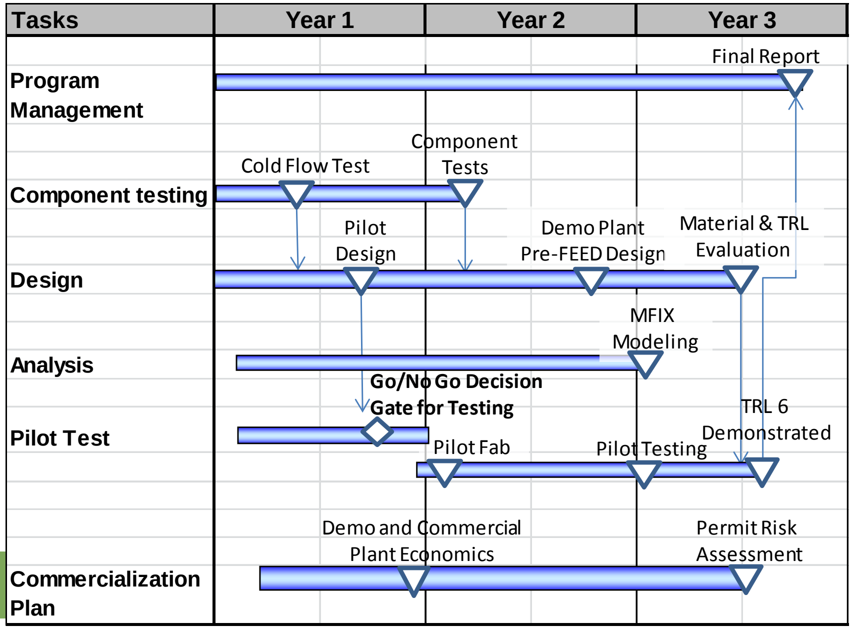
Team Members and Roles

- **Gas Technology Institute (GTI)** – Lead, PFBC technology
- **Linde, LLC** – Gas supply, CPU technology, HEX design
- **CanmetENERGY** – Pilot plant test facility and test support
- **Alstom** – PFBC design support and commercialization partner
- **Pennsylvania State University (PSU)** – Fuel & limestone testing, agglomeration model development
- **Electric Power Research Institute (EPRI)** – End user insight, review of process and cost modeling
- **Utility End User - TBD** – End user insight, demo plant site and demo plant design support

Project Objectives

- Assess the components of the system designed in Phase I to confirm scalability, performance, and cost
- Test the system at subscale pilot facility to evaluate system performance and operability
- Develop algorithms to model the components and system for scale-up
- Use the validated models to predict commercial scale cost of electricity
- Develop Phase III project plan, risk mitigation status and TRL advancement, and identify partners and sites for 30-50 MWth plant

Schedule



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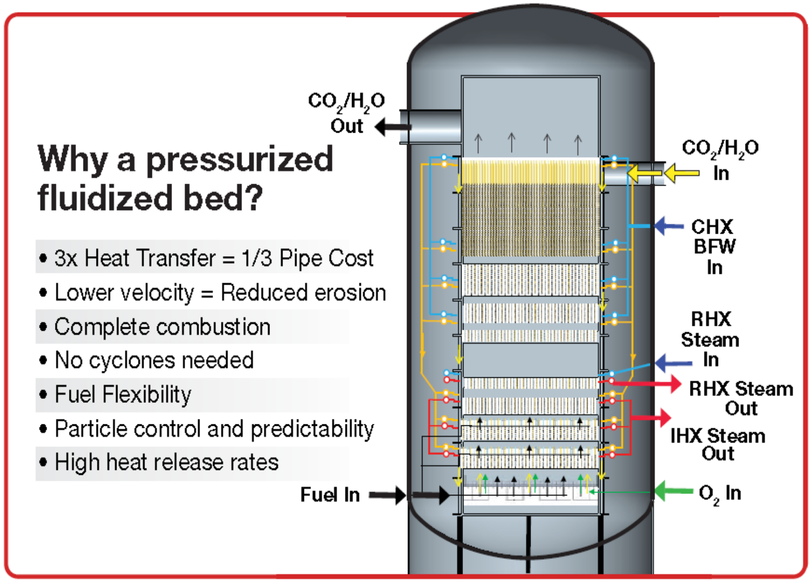
Oxy-PFBC Technology Overview

INNOVATION

- High power density reactor for coal-fired plants with CO2 capture
  - In-bed heat exchanger for ultra-compact combustor
  - Elutriated flow removes ash and sulfur prior to CO2 recycle
  - 1/3 the size and half the cost of traditional boiler

BENEFITS

- Produces affordable electric power with near zero emissions
- Produces steam for heavy oil recovery using low value feedstock (petcoke, coal, biomass)
- Produces pure CO_2 for Enhanced Oil Recovery (EOR)



Commercial Scale PFBC Concept

MARKETS

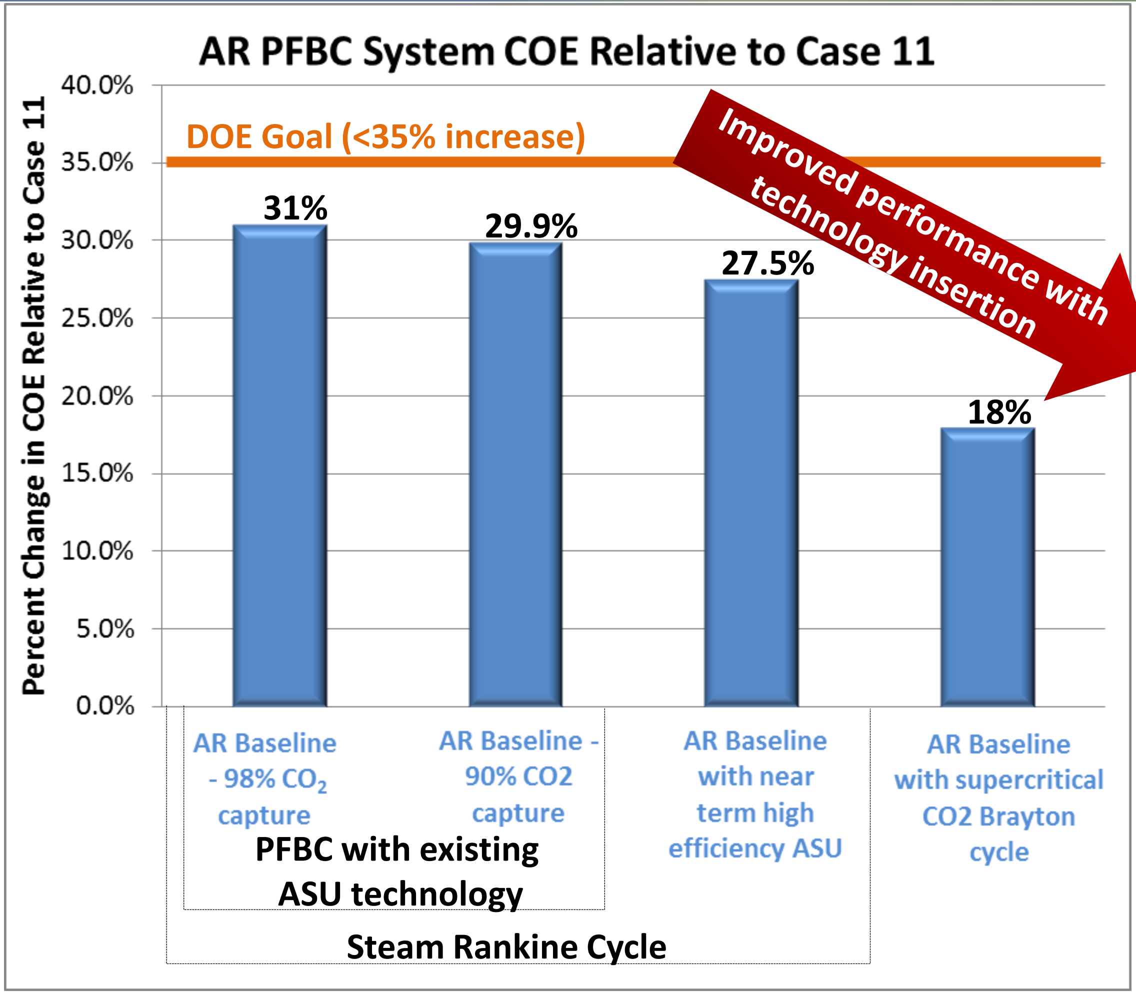
- Electric power generation with CO_2 capture, including CHP
- Heavy oil production (once-through steam)
- Light oil production (CO_2 floods)

Heritage Rocketdyne Test Facility that Demonstrated Long Life In-bed Heat Exchanger

STATUS

- Long-life, in-bed heat exchangers demonstrated in 1980s
- Two active DOE contracts
- Next step: TRL 6 by Spring 2017 with Pilot scale (1 MWth) testing

Phase 1 Economic Analysis Results



- **PFBC system provides affordable COE with additional upgrade paths**
- **No net increase in COE for CO2 prices/credit > $30/ton, or $18/ton with SCO2**

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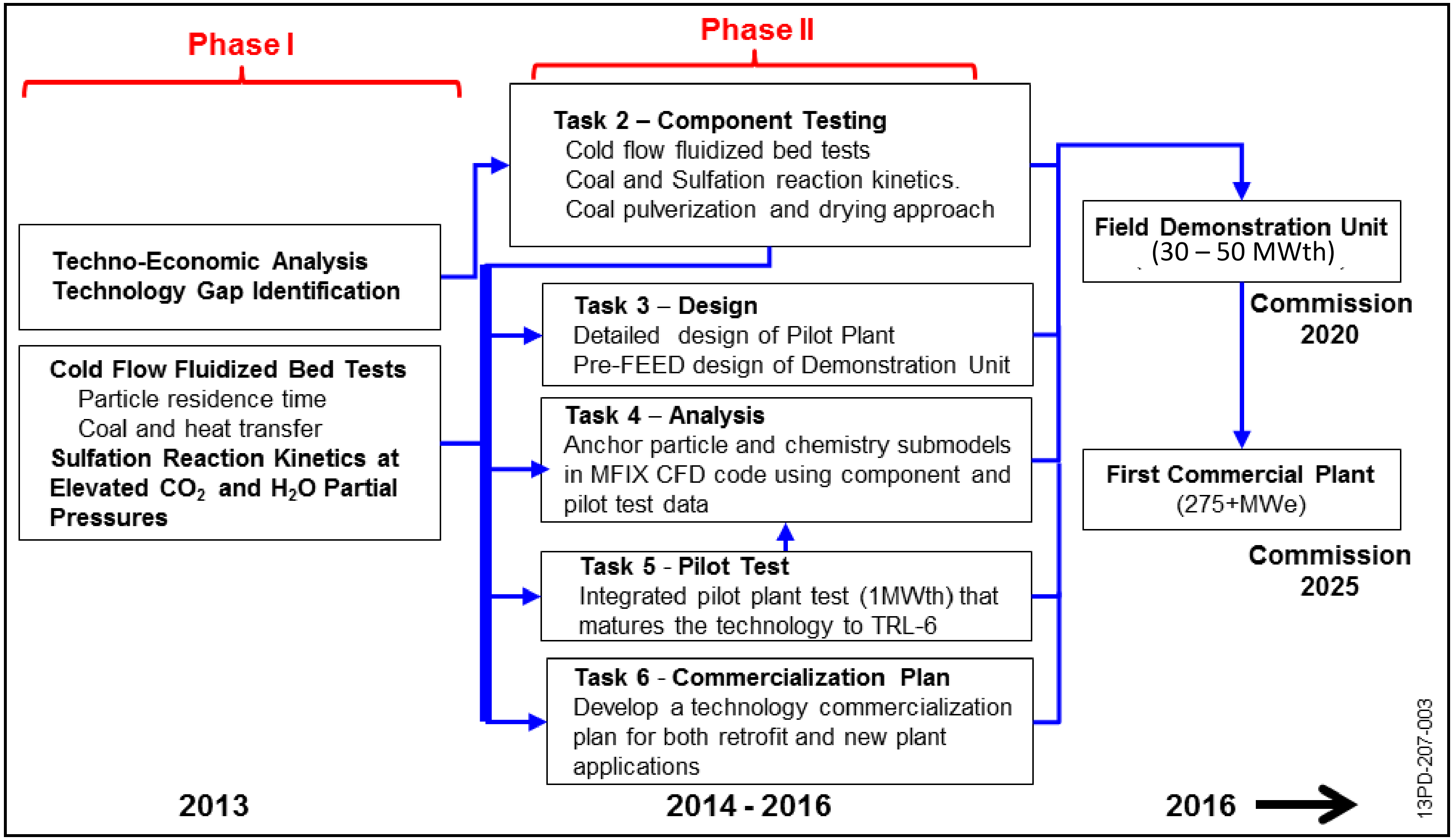
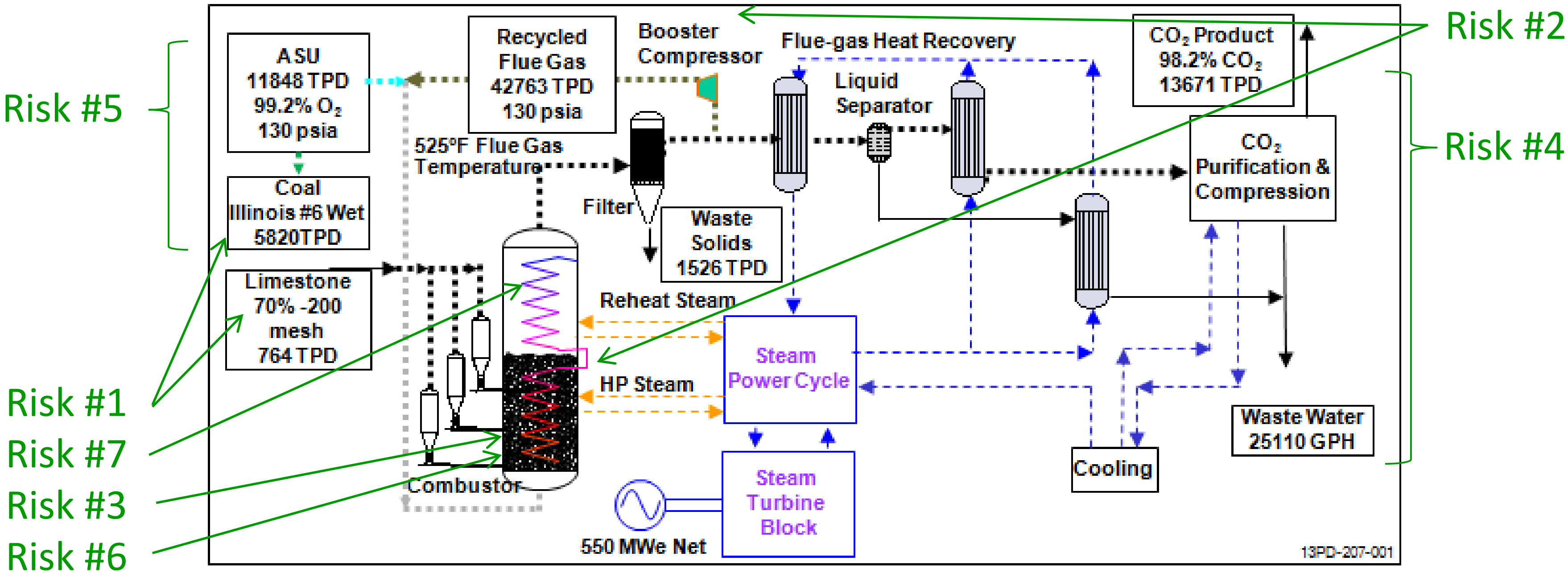
Technical Approach



- **Success Criteria:** Provide knowledge for target operating conditions and design features for the demonstration and commercial scale units. Examples:
  - Use test data to calibrate models for combustion, bed stability and heat removal, enabling a trade of bed height and staging strategy for commercial plants
  - Pressurized staged oxy-combustion system operation is characterized to develop operability criteria and scaled-up system requirements

Risks for Commercial System Development



Risks/mitigation

1) Reaction chemistry is too fast/slow
Mitigation: *Coal and sulfation reaction testing, Pilot plant testing*

2) Bubbling bed fluidizing velocity inappropriate or unstable
Mitigation: *Cold flow fluidized bed testing, Pilot plant testing*

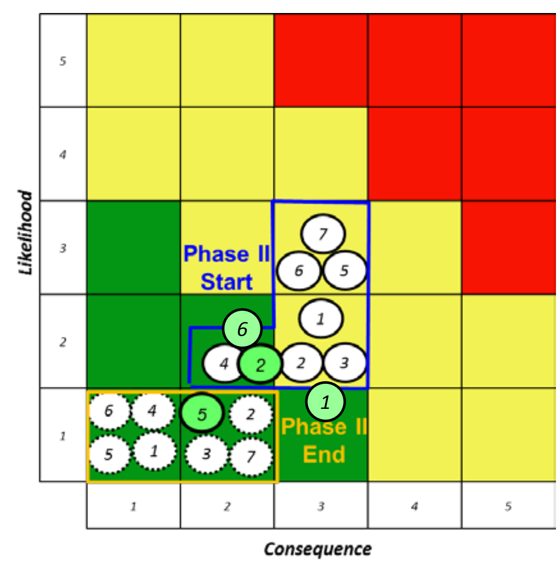
3) In-bed HEX erosion/corrosion shortens life
Mitigation: *Cold flow fluidized bed testing & CFD analysis, Pilot plant testing*

4) Flue Gas does not meet emissions or pipeline specs
Mitigation: *Pilot plant testing*

5) Pulverization and drying of coal lowers efficiency by using too much CO2 or heat
Mitigation: *Use waste heat for drying*

6) Inert particles change size over time leading to inoperable conditions
Mitigation: *Pilot plant testing and analysis*

7) Corrosion in convective HEX or recycle gas due to exceeding acid dewpoint limits
Mitigation: *Pilot plant testing and analysis*



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Significant Accomplishments

- Completed coal reactivity tests
  - Kinetics model validated, supports performance predictions
- Agglomeration model developed and validated
  - Predictions indicate minimal risk of agglomeration
- Completed pressurized elutriation testing
  - Quantified impact of elevated pressure on residence time; Sufficient time for complete carbon burnout
- Completed pre-FEED design
- 1 MWth pilot construction underway at CanmetENERGY
  - Major equipment installed
  - Gas cleanup skids design complete, fabrication underway
  - Component commissioning started

Testing and analysis results support performance predictions

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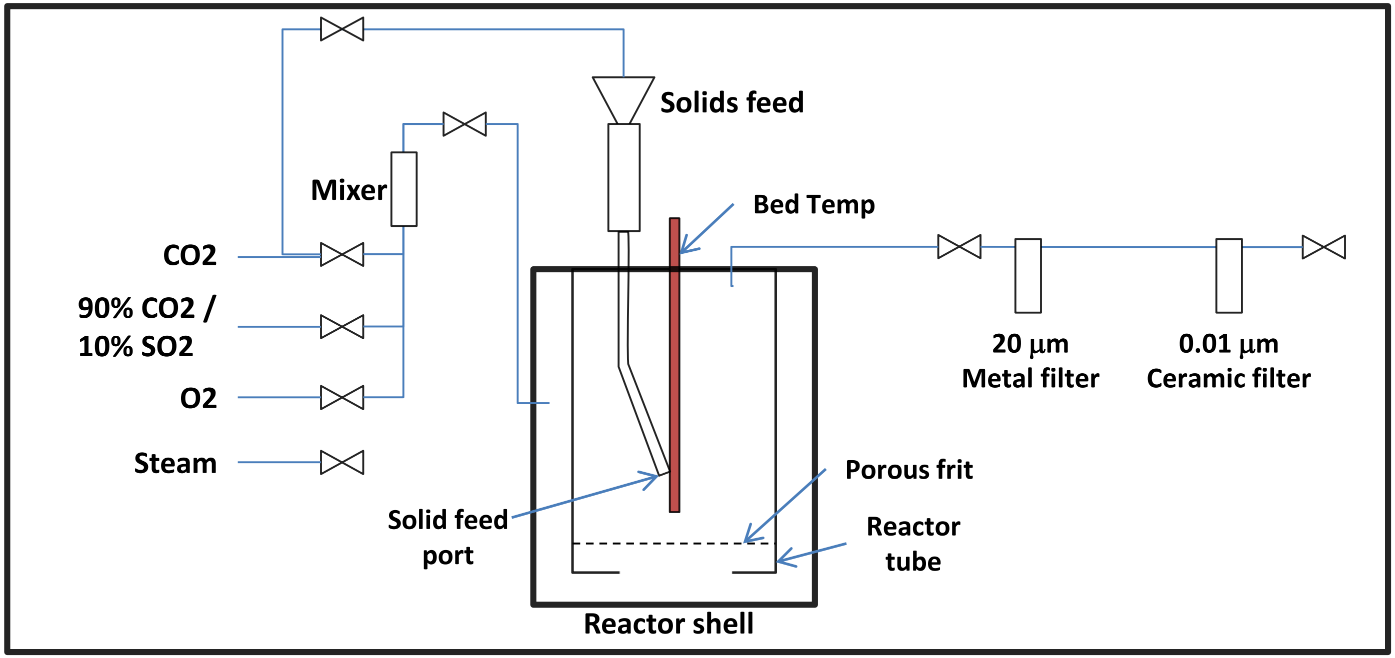
Coal Kinetics Testing Approach

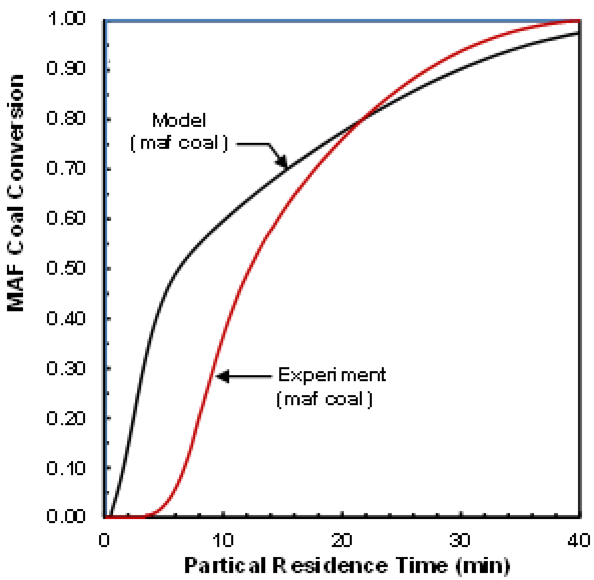
- Pressurized fluidized bed oxy-combustion coal reactions with gas evolution data
  - CO, CO_2, temperature
  - Flow CO_2 and O_2 in specified ratio
  - Measure time for gas to return to initial concentration
- Reaction rate determined from exit gas composition versus time

PSU Test Rig Schematic

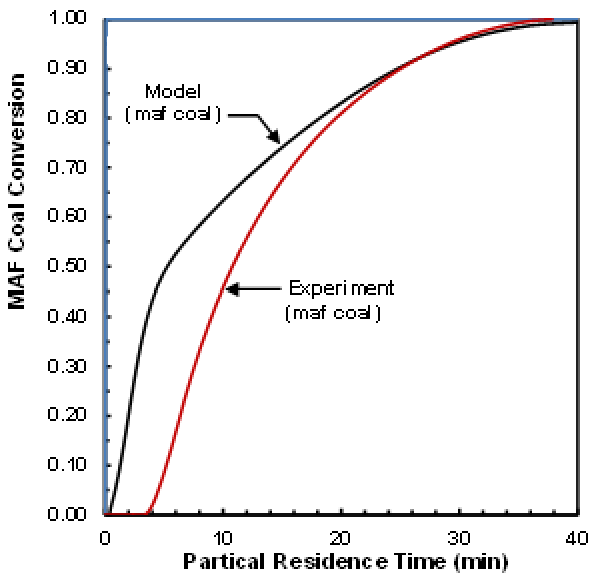


PSU Test Rig

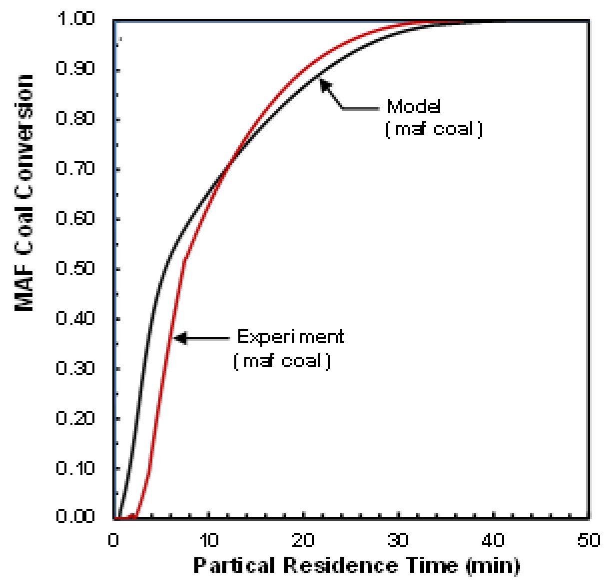
Coal Kinetics Testing Results



T=800C, P=8 bar, 7.2% O2



T=850C, P=8 bar, 7.5% O2

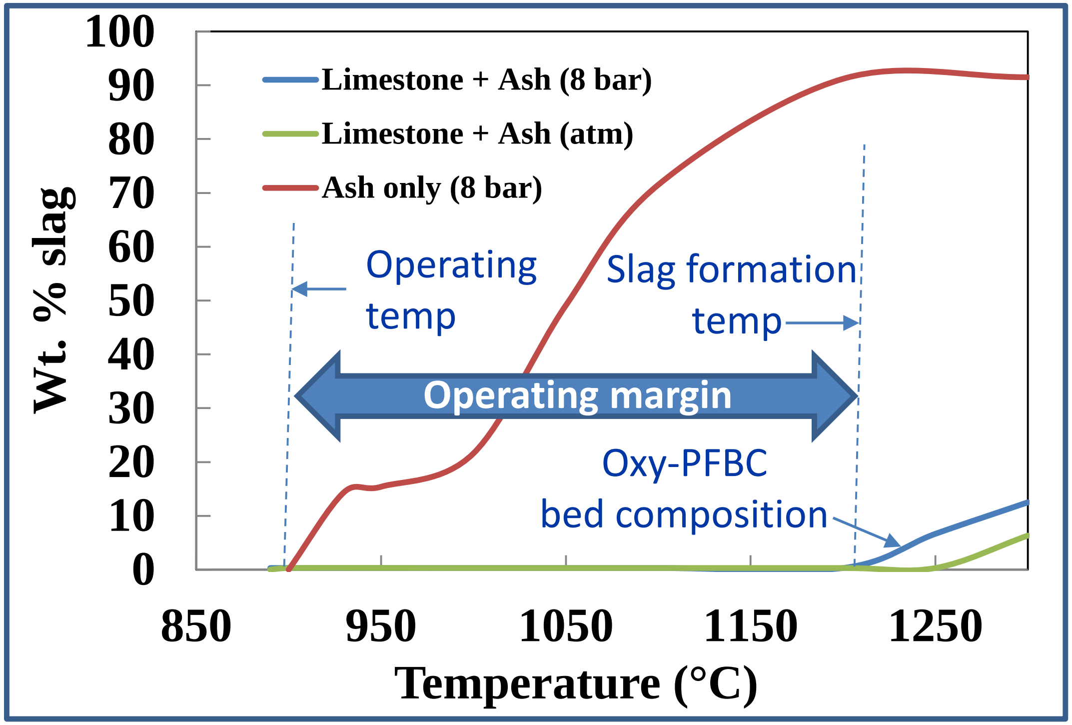


T=875C, P=8 bar, 16% O2

- GTI coal reactivity models anchored with PSU test results
  - Test results validate GTI coal kinetics models at expected pilot test operating conditions; Reasonable prediction of burnout time

Reduced the risk of reaction kinetics driving combustor temperatures outside of operational limits, and validated residence time requirements

Agglomeration Model Results



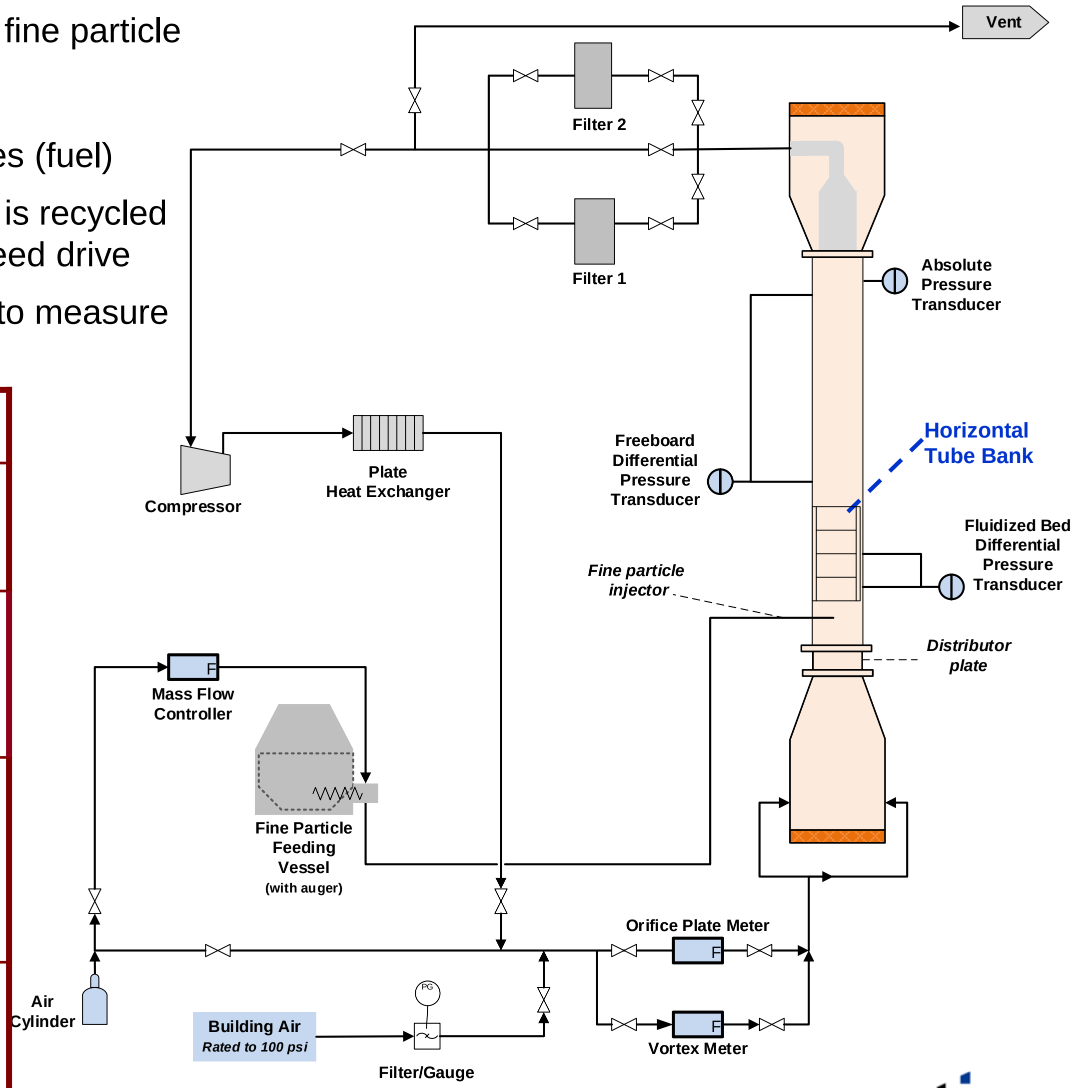
Validation Results - Model based on FactSage/MFIX				
Bed temperature (°C)	Superficial gas velocity (m/s)	Particle diameter (μm)	Defluidization time (h)	Defluidization time obtained from model (h)
800	0.25	425–500	15.36	13.9
850	0.25	425–500	7.23	8.0
900	0.25	330–355	7.22	6.9

Predictions indicate low risk of agglomeration at planned operating conditions

Pressurized Elutriation Testing

- **Objective**: Determine effect of pressurization on fine particle elutriation rates and residence time
- **Approach**
  - Continuous injection and capture of fine particles (fuel)
  - For operations at P > 1 bar, the fluidization gas is recycled via a centrifugal compressor with a variable speed drive
  - Each filter contains interchangeable filter bags to measure entrainment rate

Parameter	Value
Column Diameter	0.15 m (6 inch)
Fluidization Section Height	2.95 m
Column Material	Stainless Steel
Gas Type	**Air**
Gas Velocity Tested	**1.5-2.5 U_{mf}**
Gas Pressure Tested	**1, 6, 9, 12 bar**
Gas Temperature Tested	24± 1°C
Inert bed material surrogate	**Glass beads** (ρ = 2500 kg/m³)
Particle size distribution	0.8-1.2 mm
Coal surrogate (fines)	**Glass beads** (ρ = 2500 kg/m³)
Particle size distribution	30-158 μm
Fines feeding rate	5.9 kg/h
Inert Bed Static Height	0.50 m
L/D	3.3
Fluidization Time	28 minutes

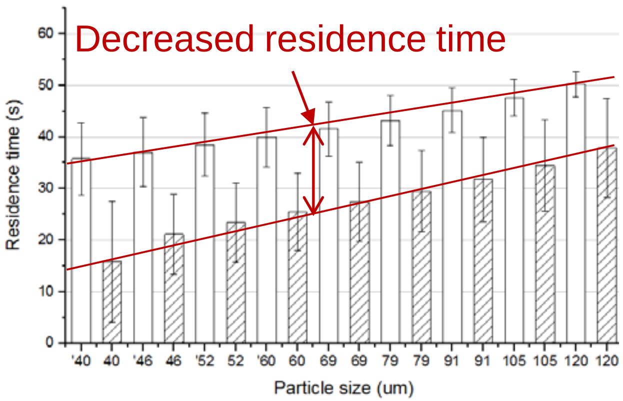


Pressurized Elutriation Test - Results

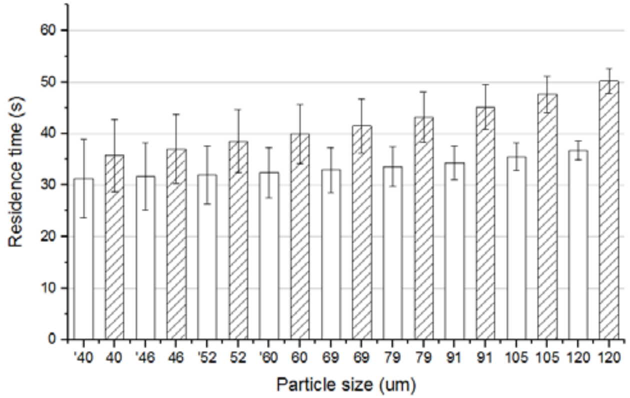
- Steady state entrainment is reached by approximately 8 min
- 3 entrainment rate measurements are done at 8, 18 & 28 min
- Mass of fines in the bed (m_{FB}) is measured by capturing the entrained fines for 5 min after shutting off the feeder
- Fines residence time in the bed: $\theta = m_{FB} / \dot{E}$ ($\dot{E}$ is the entrainment rate at steady state)

Conclusions

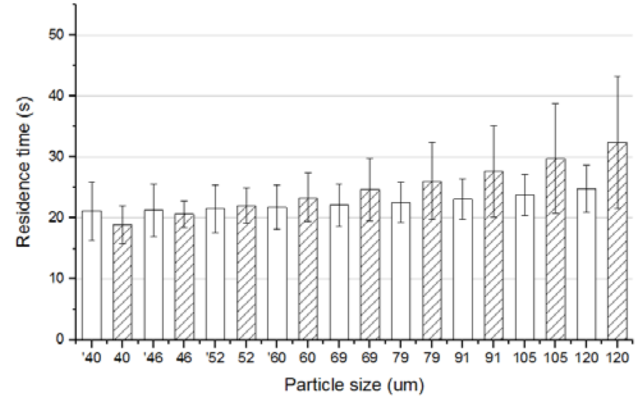
- Effect of gas velocity, operating pressure, and presence of a tube bank on the fines residence time in the bed was determined
    - **Increase in pressure decreased the fines residence time with tube bank present**
    - The presence of tube bundle only augmented residence time of the larger particle while that of smaller particles on average remained similar.
    - An increase in gas velocity decreased the fines residence time
    - Presently collecting data where effect of pressure is determined by keeping the *U-U_{mf}* constant.



1.9 U_{mf} – 5.9 kg/h – Tube Bank present
6 bar vs. 12 bar *(cross hatch)*



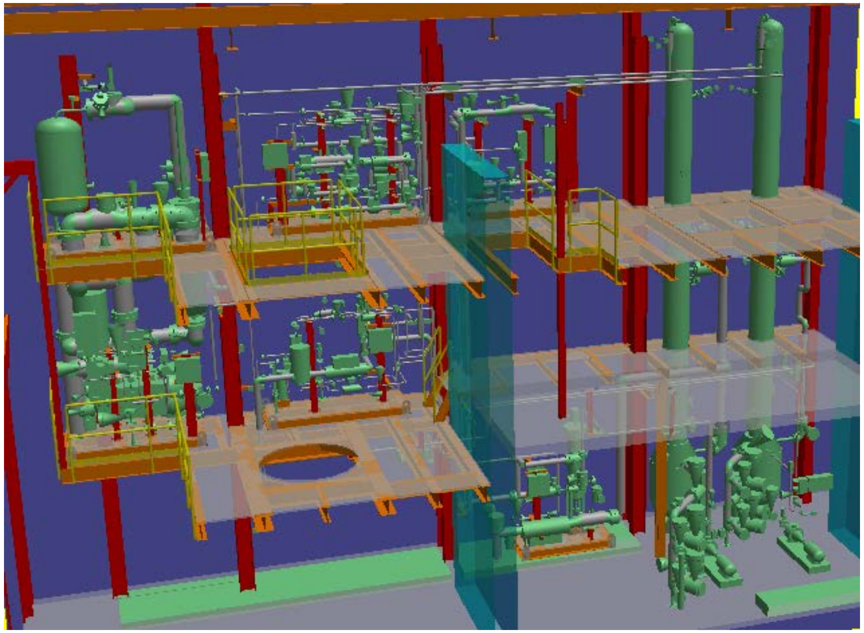
6 bar – 1.9 U_{mf} – 5.9 kg/h
With *(cross hatch)* vs. without tube bank



1 bar – 5.9 kg/h – No Tube Bank
1.5 U_{mf} *(cross hatch)* vs. 1.9 U_{mf}

CO2 Purification Unit (CPU) and Heat Recovery System

- Detailed engineering & procurement of CO2 purification unit for pilot completed
  - Process Description and PFD
  - P&IDs and equipment layout
  - 3-D model of CPU
  - Piping and structural design
  - Factory testing of distributed control system, control logic and display graphics
- Fabrication of skid sub-assemblies are in progress in Linde's Port of Catoosa facility
- DCC and LICONOX columns and other equipment shipped to Canmet in Ottawa. All skids expected to be shipped by Oct. 2016.



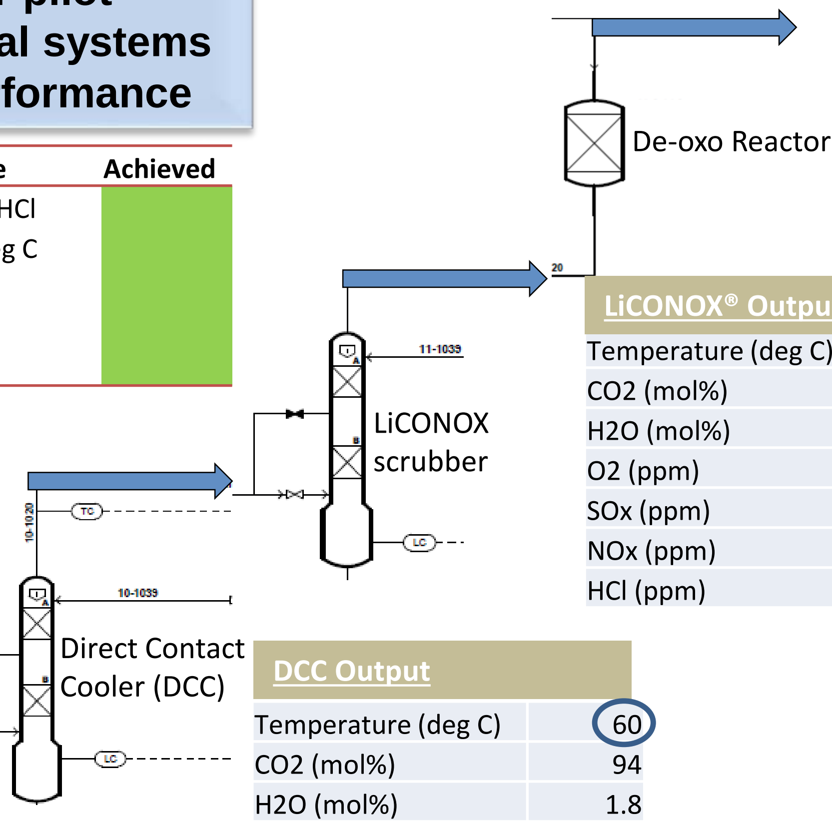
CPU equipment enables reduced cost relative to traditional cryogenic units

Engineering and procurement of CPU completed; Skid assembly is in progress

CPU Sub-systems

Process simulation for pilot confirms that all critical systems can achieve target performance

System	TRL	Target Performance	Achieved
DCC	6	Complete Removal HCl	
		Temperature <60deg C	
LiCONOX	5	> 90% Nox removal	
		>95% SOx removal	
De-OXO	5	<100 ppm O2	



Flue Gas Feed

Temperature (deg C)	230
CO2 (mol%)	66
H2O (mol%)	31
O2 (ppm)	20,000
SOx (ppm)	482
NOx (ppm)	1000
HCl (ppm)	1025

DCC Output

Temperature (deg C)	60
CO2 (mol%)	94
H2O (mol%)	1.8
O2 (ppm)	29,000
SOx (ppm)	683
NOx (ppm)	1505
HCl (ppm)	0

LiCONOX® Output

Temperature (deg C)	38
CO2 (mol%)	95.4
H2O (mol%)	0.6
O2 (ppm)	29,000
SOx (ppm)	29
NOx (ppm)	128
HCl (ppm)	0

CO_2 Product

Temperature (deg C)	118
CO2 (mol%)	98.4
H2O (mol%)	1.2
O2 (ppm)	100
SOx (ppm)	29
NOx (ppm)	128
HCl (ppm)	0

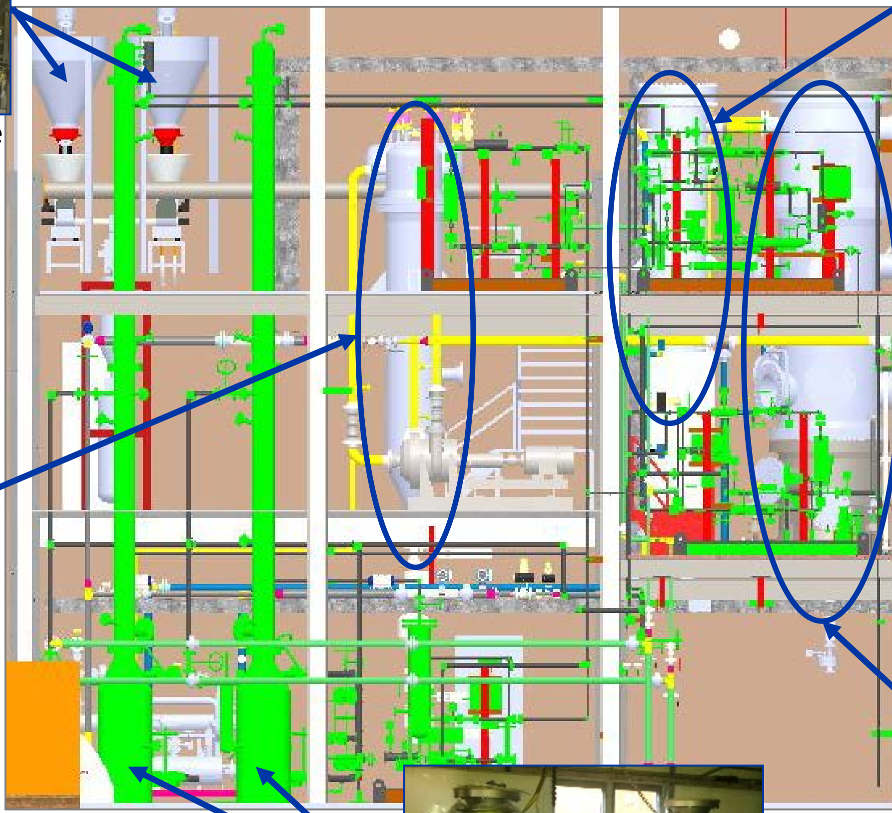
Pilot Plant Construction

- Enhancement of building utilities (structural, water, electrical, compressed air) complete. Canadian Federal government funding used for all building enhancements.
- All contracts for major equipment awarded
- Pilot plant equipment installation in progress (40% complete) including:
  - Bulk gas supply systems for O_2, N_2, CO_2, and NG
  - Bulk fuel and sorbent handling systems
  - GTI equipment including combustor and pressure vessel, particulate filter, convective heat exchanger
  - Linde direct contact cooler and Liconox™ columns

Pilot Plant Layout & Hardware Progress

Coal & limestone hoppers

Fly ash filter



PFBC Pressure Vessel

Combustor spool

Canada

Natural Resources Canada   Ressources naturelles Canada

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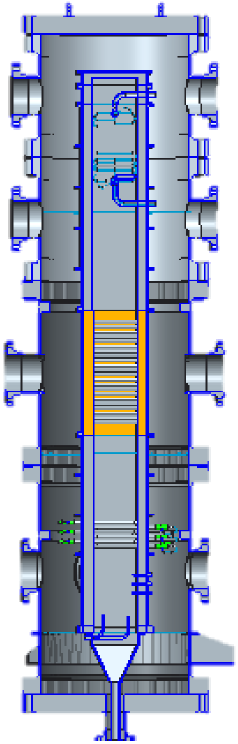
Future Plans

- Phase II plans
  - Fabrication and testing of the pilot scale rig
    - Update performance and technoeconomic analysis
    - Material and TRL evaluation
    - Anchor analysis codes
  - CFD modeling
  - Complete commercialization activities



1 MWth pilot scale Oxy-PFBC

Oxy- PFBC Commercialization Plan

Phase I – 2012 – 2013

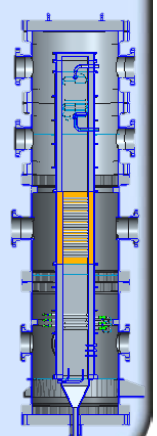
Cold Flow Testing & Bench Scale Kinetics (TRL 3)

Demonstrates:
- Coal & sulfation reaction rates at high CO_2 and H_2O partial pressure
- Heat transfer coefficients
- Bubble control
- Residence time

Phase II – 2014 – 2017

Pilot Plant (TRL 6)

Demonstrates:
- Pressurized system operation
- Elutriated bed operation and chemistry
- Flue gas clean-up
- Erosion risks



Duty ~1 MWth
Size ~1 foot scale

Phase III – 2017 – 2021

Large Pilot / Demo Plant

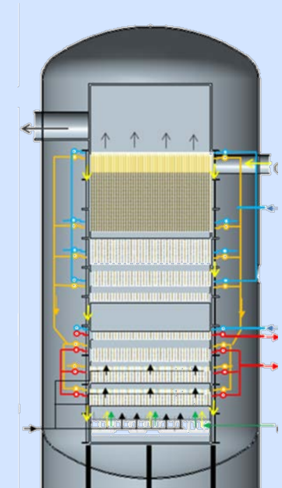
Demonstrates:
- Operation at scale
- Component life
- Operating parameters
- Maintenance approaches
- Erosion risks

~30-50 MWth
~3-4 foot scale

Phase IV – 2020 – 2025

Commercial Demonstration *5+ years*

Validates:
- System efficiency
- Capital costs
- O&M costs

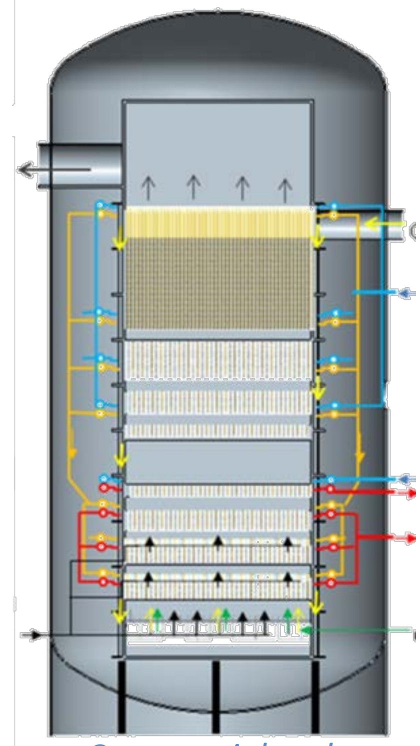


275+ MWe
~20+ foot scale

Plan for commercial scale demonstration by 2025

Summary

- Component testing completed and validates performance predictions
- Agglomeration model validated and indicates low agglomeration risk
- 1 MWth pilot plant construction well underway with major equipment installed
- Pilot testing expected to start late this year



Commercial scale Oxy-PFBC

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NETL Program Manager: Robin Ames

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