Oxy-Combustion
Pressurized Fluidized Bed
with Carbon Dioxide Purification

Presented by:

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Agenda

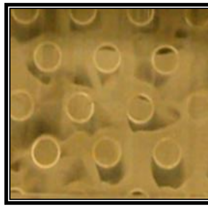
- Project Overview
- Background
- Technical Approach / Project Scope
- Progress and Current Status
- Future Plans

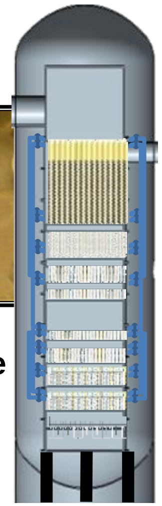
Phase II Oxy-fired Pressurized Fluidized Bed Combustor (Oxy-PFBC) Overview

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% CO_2 capture with no more than 35% increase in cost of electricity





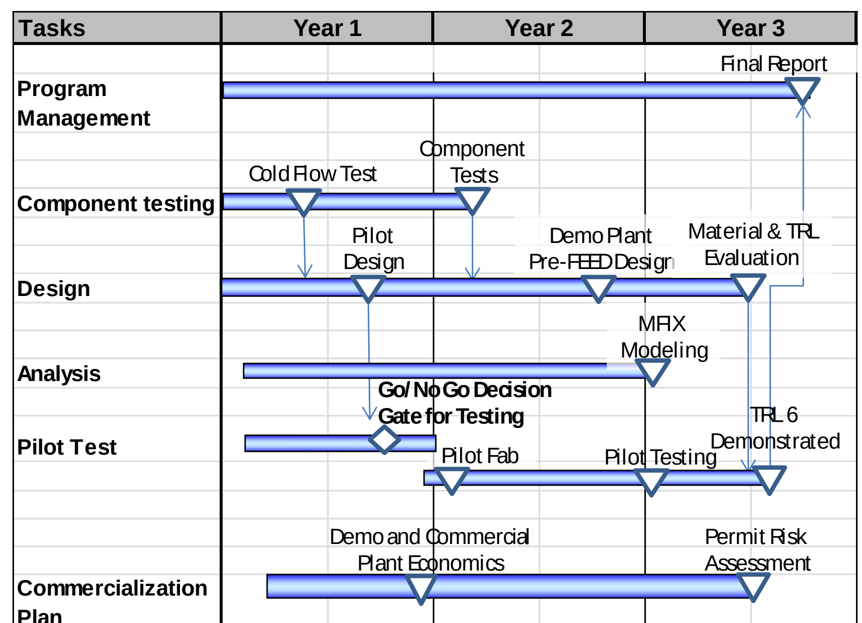
Team Members and Roles

- **Aerojet Rocketdyne (AR)** – 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, MFIX physics 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 (Demonstration at 20-40 MW) project plan, risk mitigation status and TRL advancement, and identify partners and sites

Schedule



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Oxy-Pressurized Fluidized Bed Combustor (PFBC)

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PRODUCT

- Oxy-fired, pressurized fluidized bed combustor equipment for coal-fired power plants
- Elutriated flow removes ash and sulfur prior to recycle

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)

MARKETS

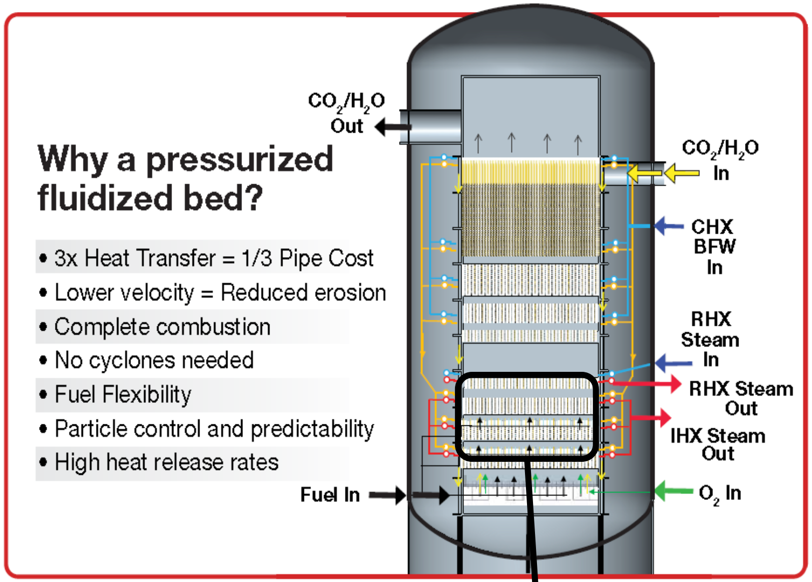
- Electric power generation with CO_2 capture
- Heavy oil production (once-through steam)
- Light oil production (CO_2 floods)

STATUS

- Long-life, in-bed heat exchangers demonstrated in 1980s
- Concept modified for oxygen-firing rather than air
- Technology development contracts with DOE

NEXT STEP

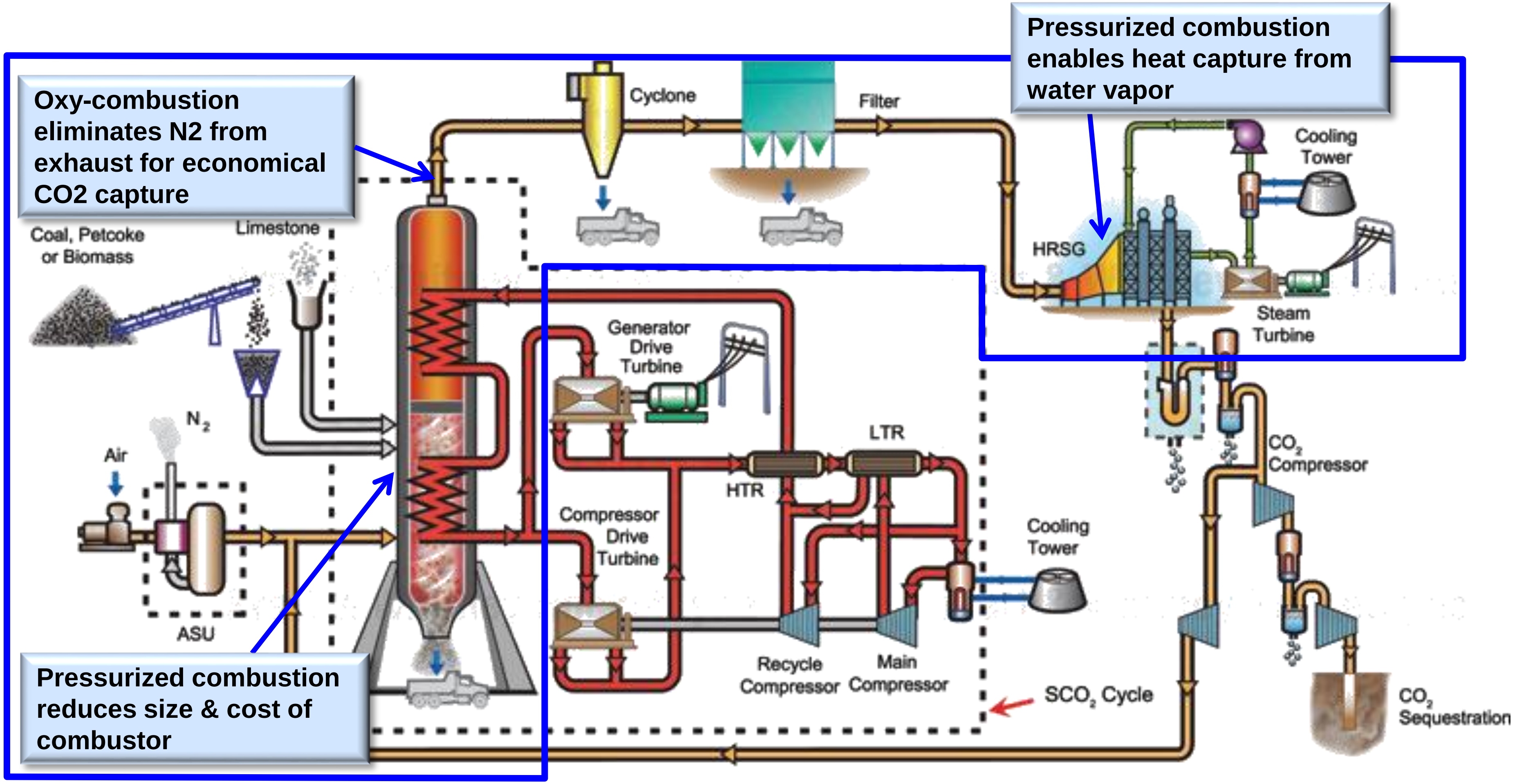
- Build & operate Pilot scale (1 MWth) plant



Commercial Scale PFBC Concept

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

ZEPS™ Powerplant Concept Vision



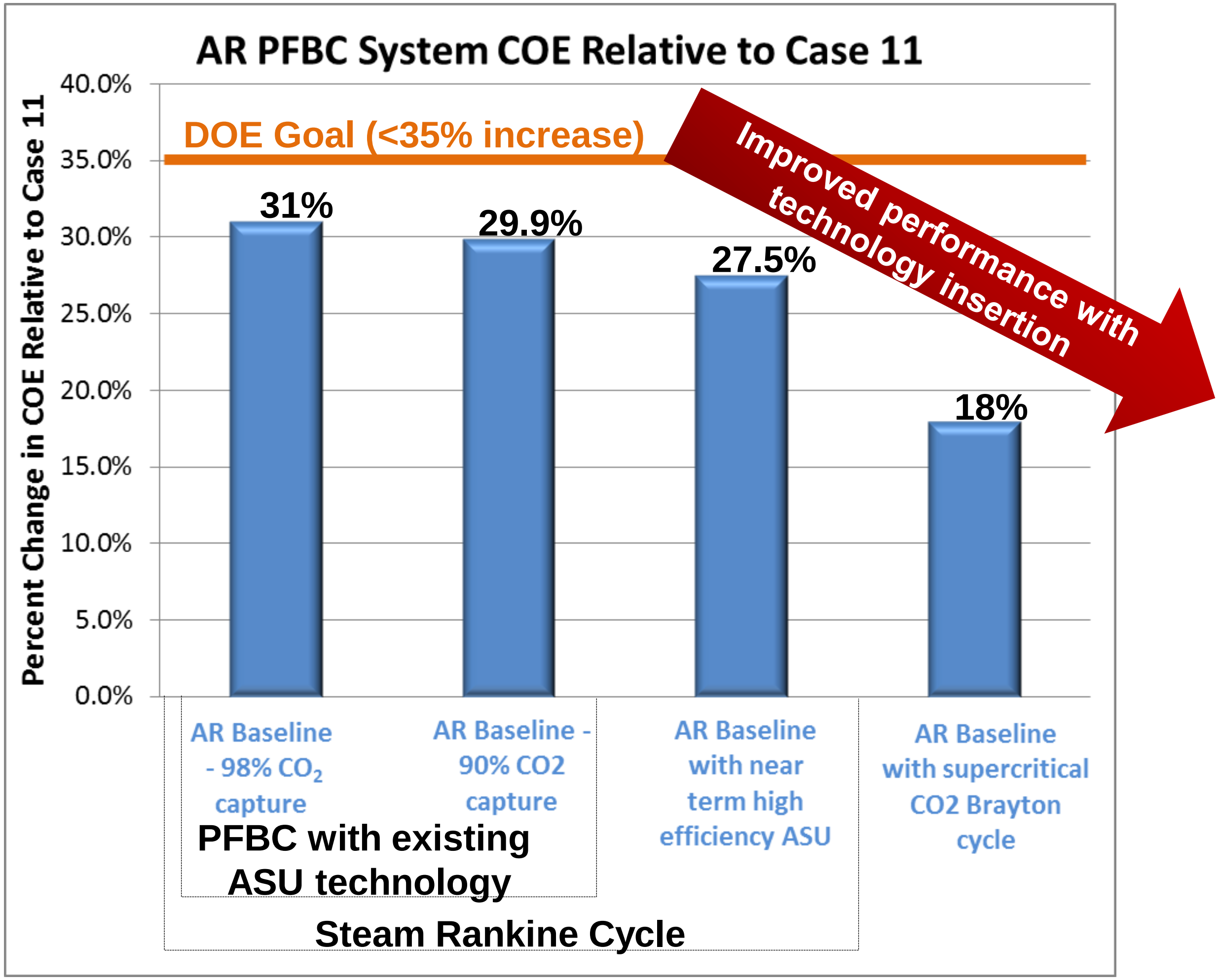
This program's focus

Enhanced efficiency and zero emissions

- **Program focused on Oxy-PFBC with steam-Rankine cycle**
- **Supercritical CO2 Brayton can be utilized for added efficiency**

ZEPS = Zero Emissions Power and Steam

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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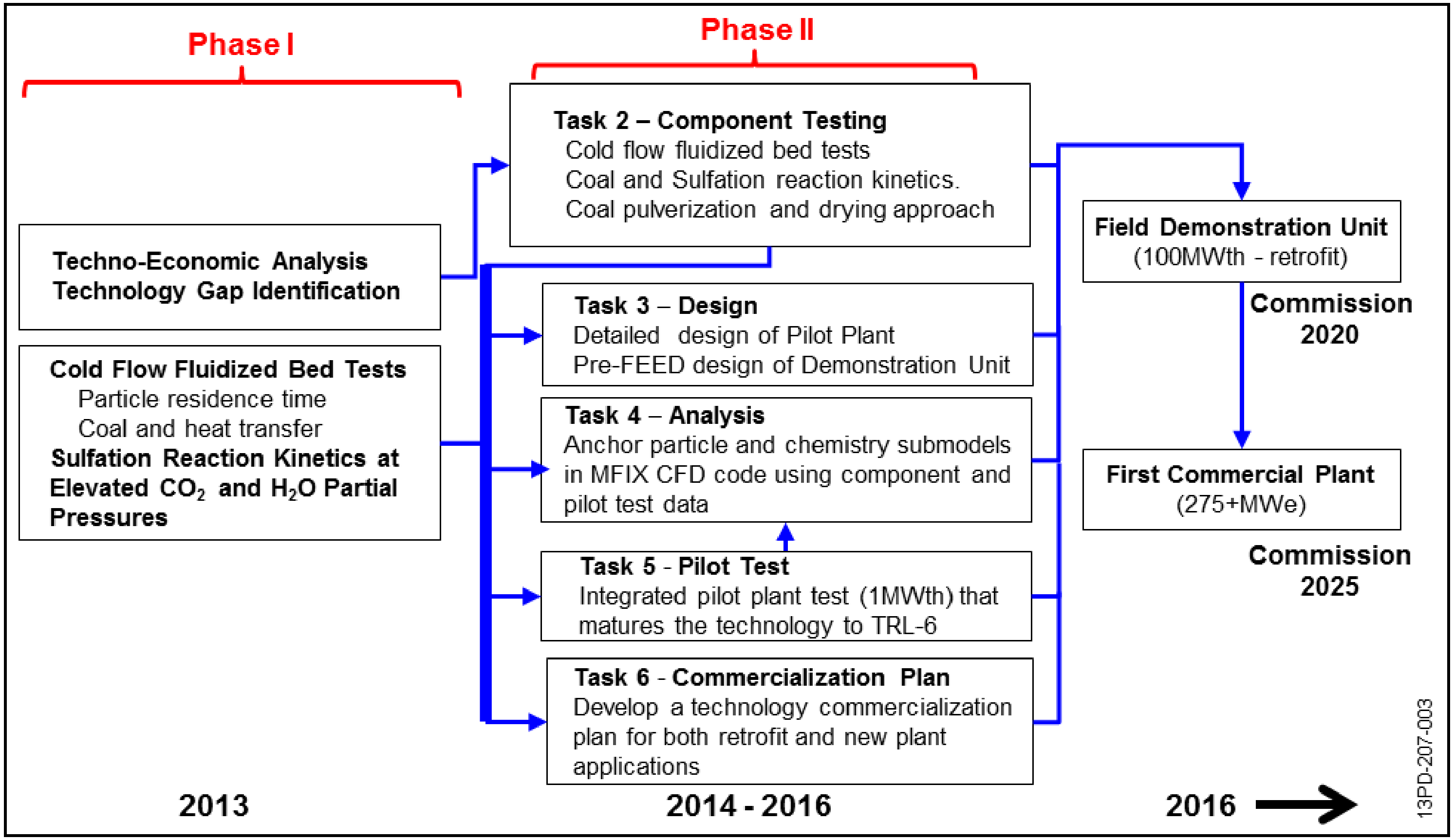
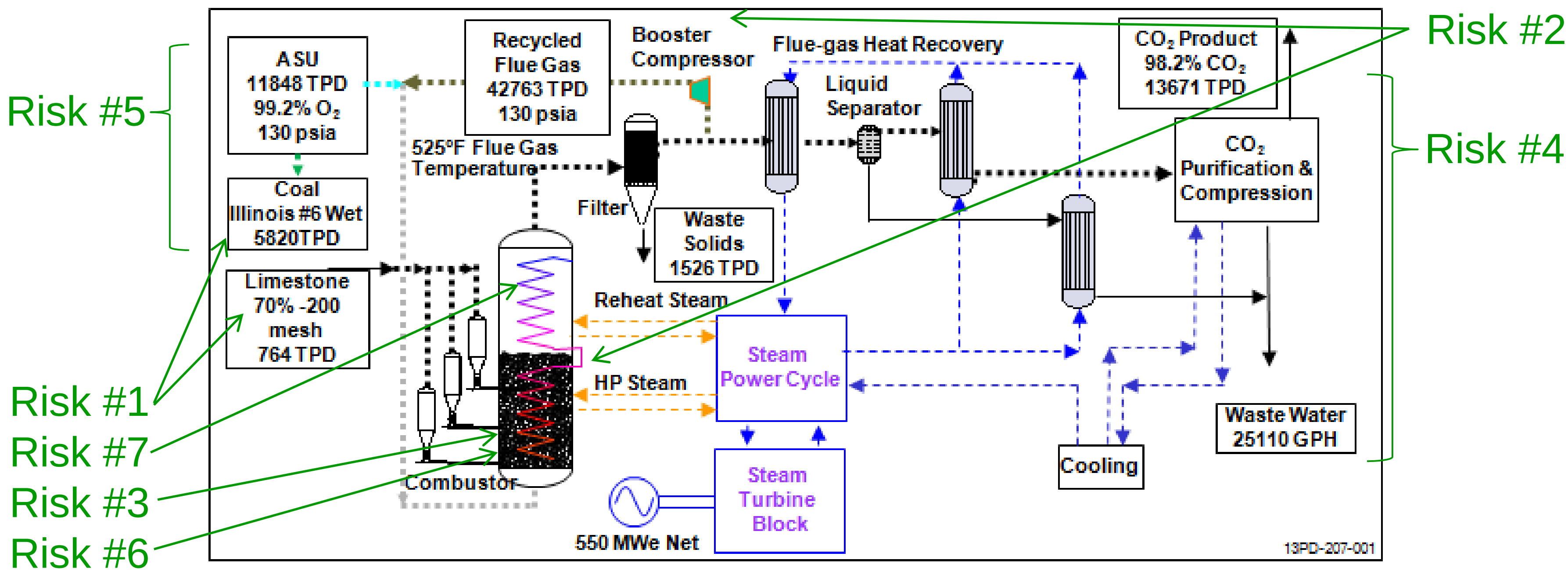
Technical Approach



- **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*

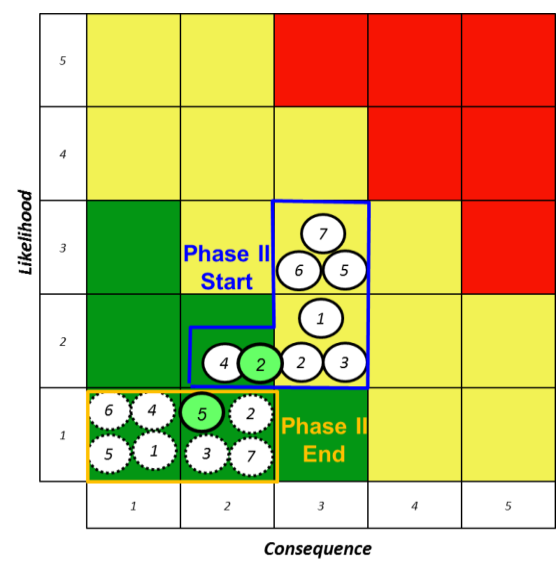
3) In-bed HEX erosion/corrosion shortens life
Mitigation: *Cold flow fluidized bed testing & CFD analysis, Pilot plant testing*

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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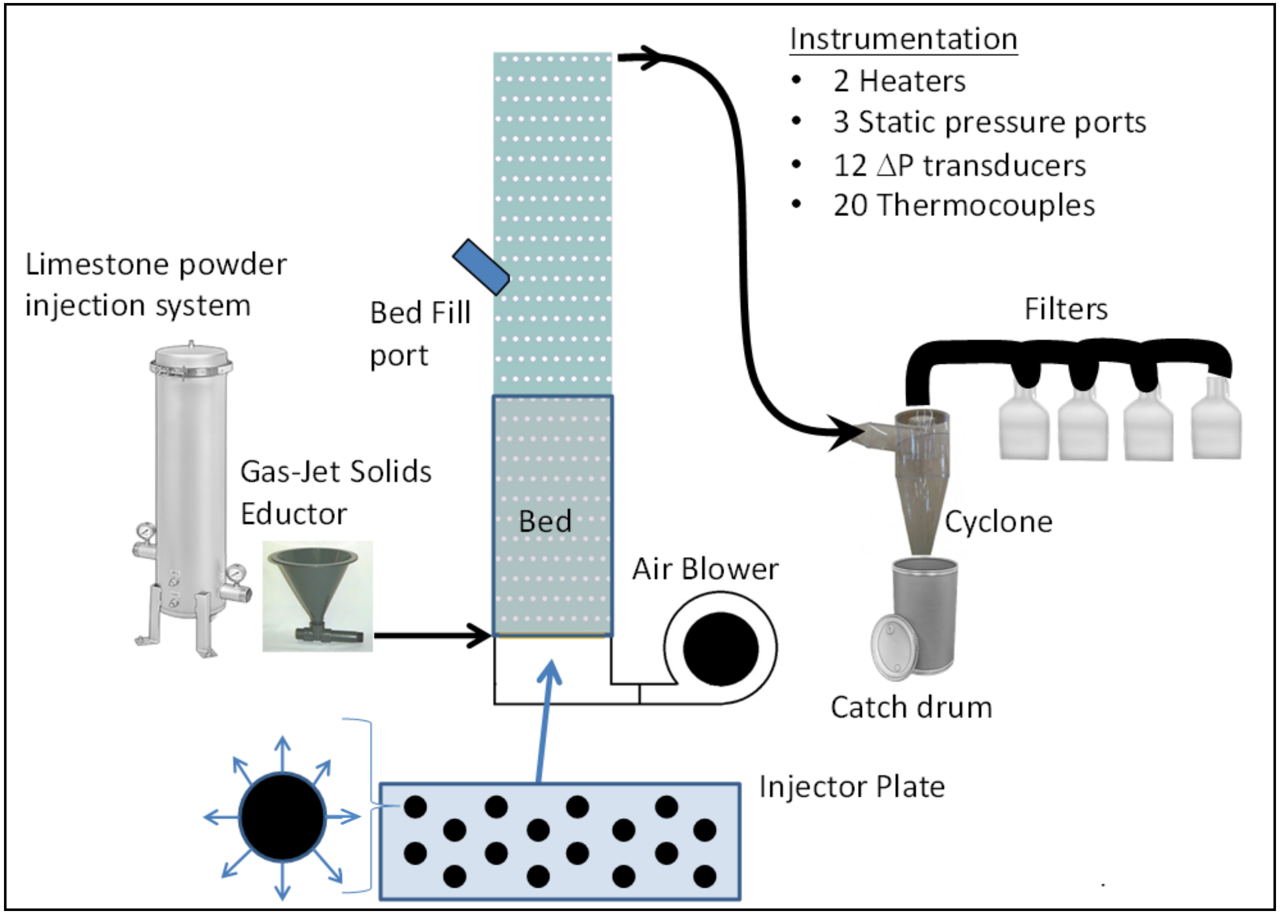
Significant Accomplishments

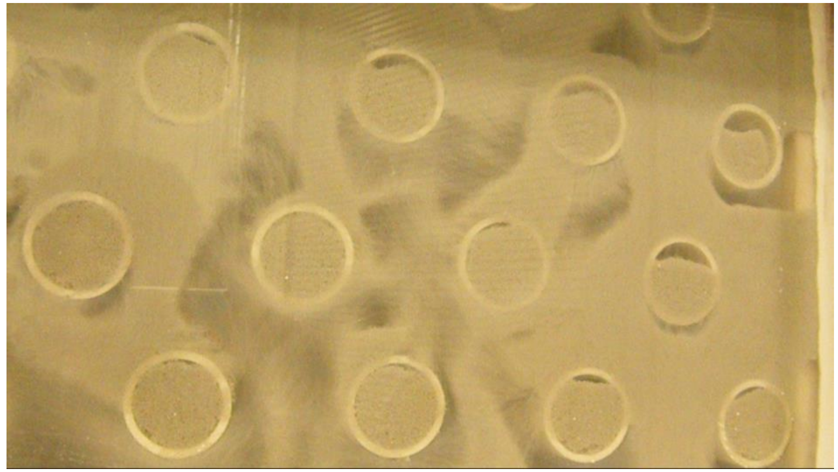
- **Cold flow testing completed**
  - Bed stability demonstrated
  - Heat transfer and elutriation rates characterized
- **9 limestone/dolomite and 7 coal reactivity tests completed at PSU**
  - Limestone & dolomite reactivity characterized for incorporation into AR models. Indicates need for larger particle sizes.
- **HAZOP events completed**
- **Completion of basic engineering at Linde and Canmet**
- **PFBC design/analysis tool automation - 2 order of magnitude improvement in cycle time for more thorough design assessment**
- **Parametric combustor design developed that enables:**
  - Multiple coolants simultaneously to tailor cooling
  - Change in in-bed HEX area during a run to enable more robust pilot operation and runtime flexibility
  - Future upgrade paths to SCO2 coolant or multiple fuel injection stages
- **Facility construction started at CanmetENERGY**
- **Pressurized elutriation testing started at U of Ottawa**
- **Fabrication started**

Cold Flow Test Setup

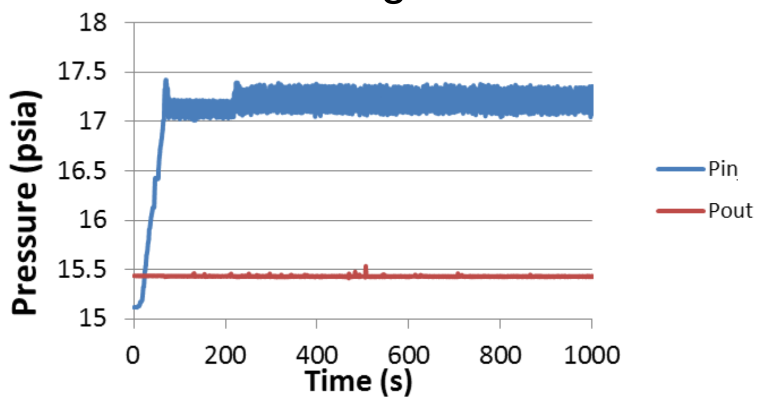


- **Testing designed to solve complex fluid bed interactions**
  - Data collected on heat transfer, elutriation rates and bed stability
  - Combustor section at full pilot scale, with heat exchanger tubes and spacing at full commercial scale

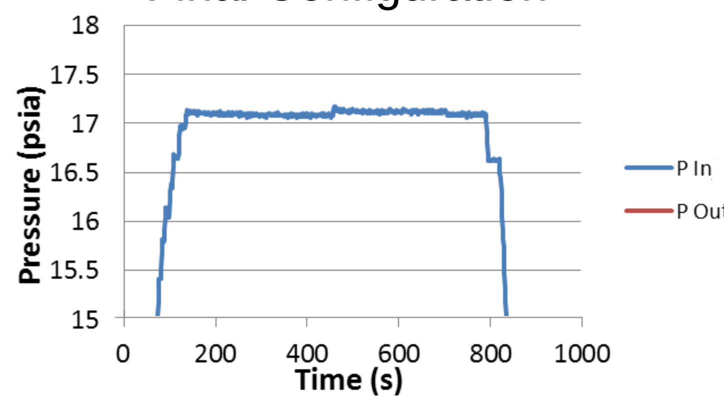
Cold Flow Test Results



First Configuration



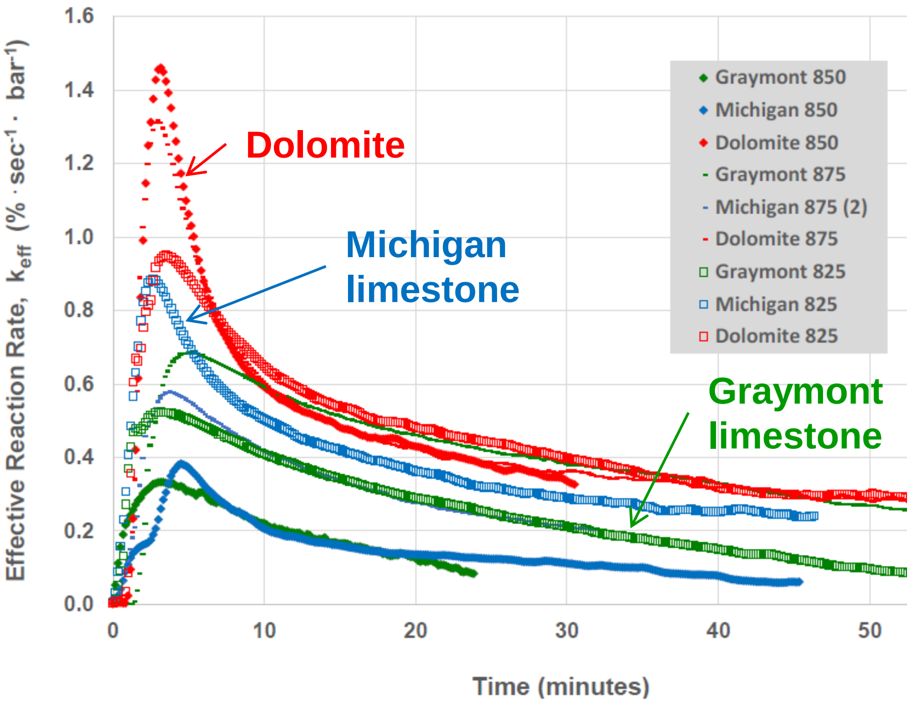
Final Configuration



Validated design approach by achieving stable bed operation, sufficient coal particle residence time, and enhanced heat transfer for reduced cost HEX

Limestone Sulfation Kinetics Test Results

- **Test objectives**
  - Measure limestone sulfation reaction rate in pressurized combustion conditions
  - Determine particle residence time requirements
- **Limestone particle testing**
  - Varied material, temperature
  - Measured calcium sulfation utility
  - Larger particle sizes are required, Dolomite performs best



Reduced the risk of sulfation kinetics providing insufficient sulfur capture, and refined particle size and residence time requirements

Linde CO_2 Purification Unit (CPU) and Heat Recovery System

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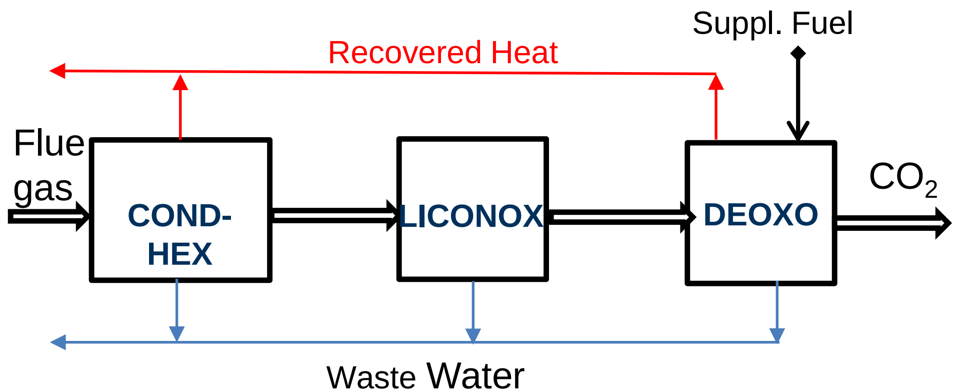
THE LINDE GROUP

Basis for CPU skid design - feed material streams –

	COND-HEX	LICONOX	DEOXO
Flow (kg/hr)	383	325	322
Temp. (C)	230	60	38
Press. (Bara)	12.0	11.8	11.4
Composition			
CO2 (mol%)	66.0%	94.0%	95.4%
H2O (mol%)	31.0%	1.8%	0.6%
Ar (mol%)	0.3%	0.5%	0.5%
N2 (mol%)	0.5%	0.6%	0.7%
O2 (mol%)	2.0%	2.9%	2.9%
NOx (ppm)	1,000	1,505	128
SOx (ppm)	482	683	29
HCl (ppm)	1,025		



Performance Targets:

COND. HEX:
- Complete HCl removal
- Water cond. heat recovery

LICONOX:
- 90% NO_x + 95% SO_x removal

DEOXO:
- < 100 ppm O_2 in CO_2 product
- Heat of Deoxo reaction recovery

Linde CPU provides reduced CapEx and OpEx costs for CO_2 purification and heat recovery compared to traditional cryogenic CO_2 purification units

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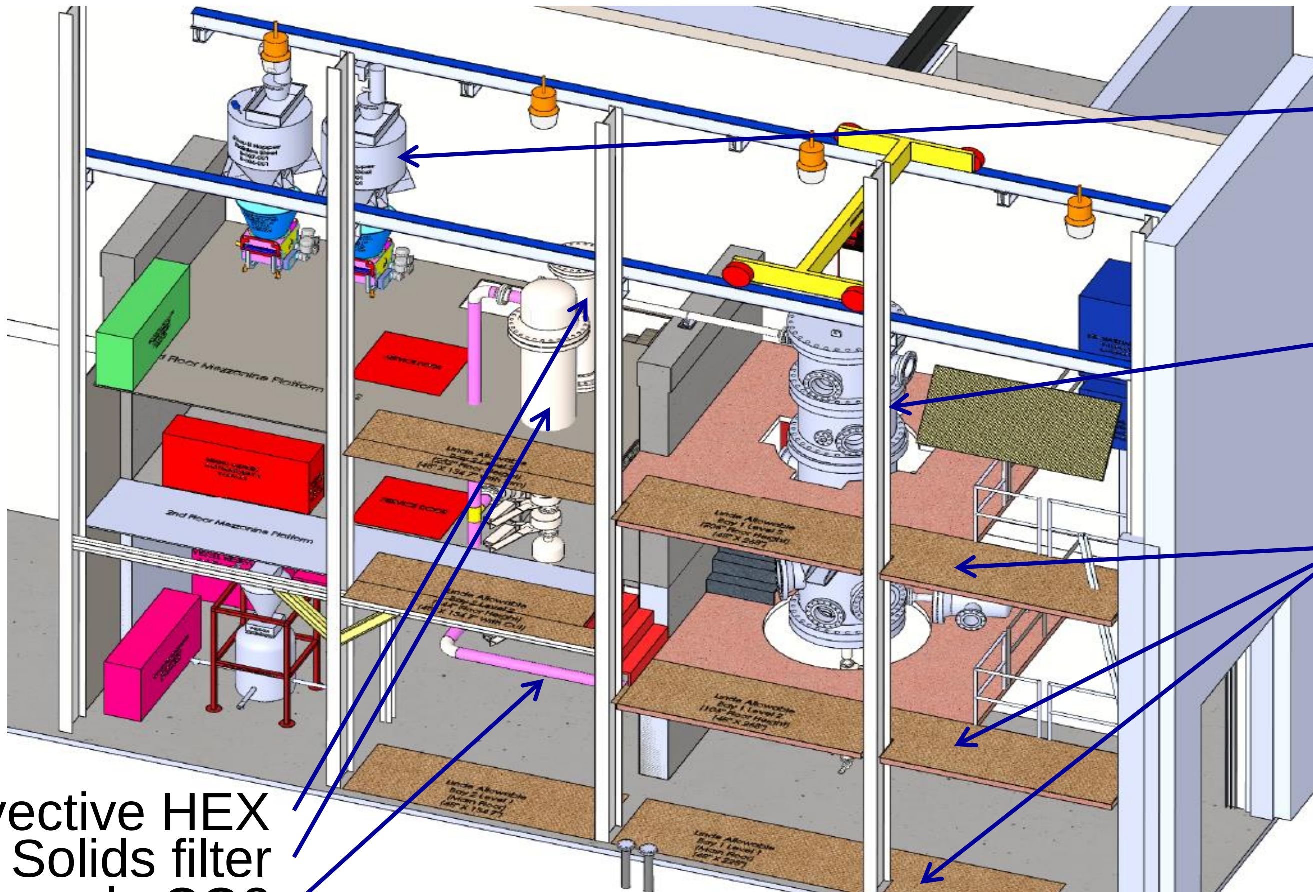
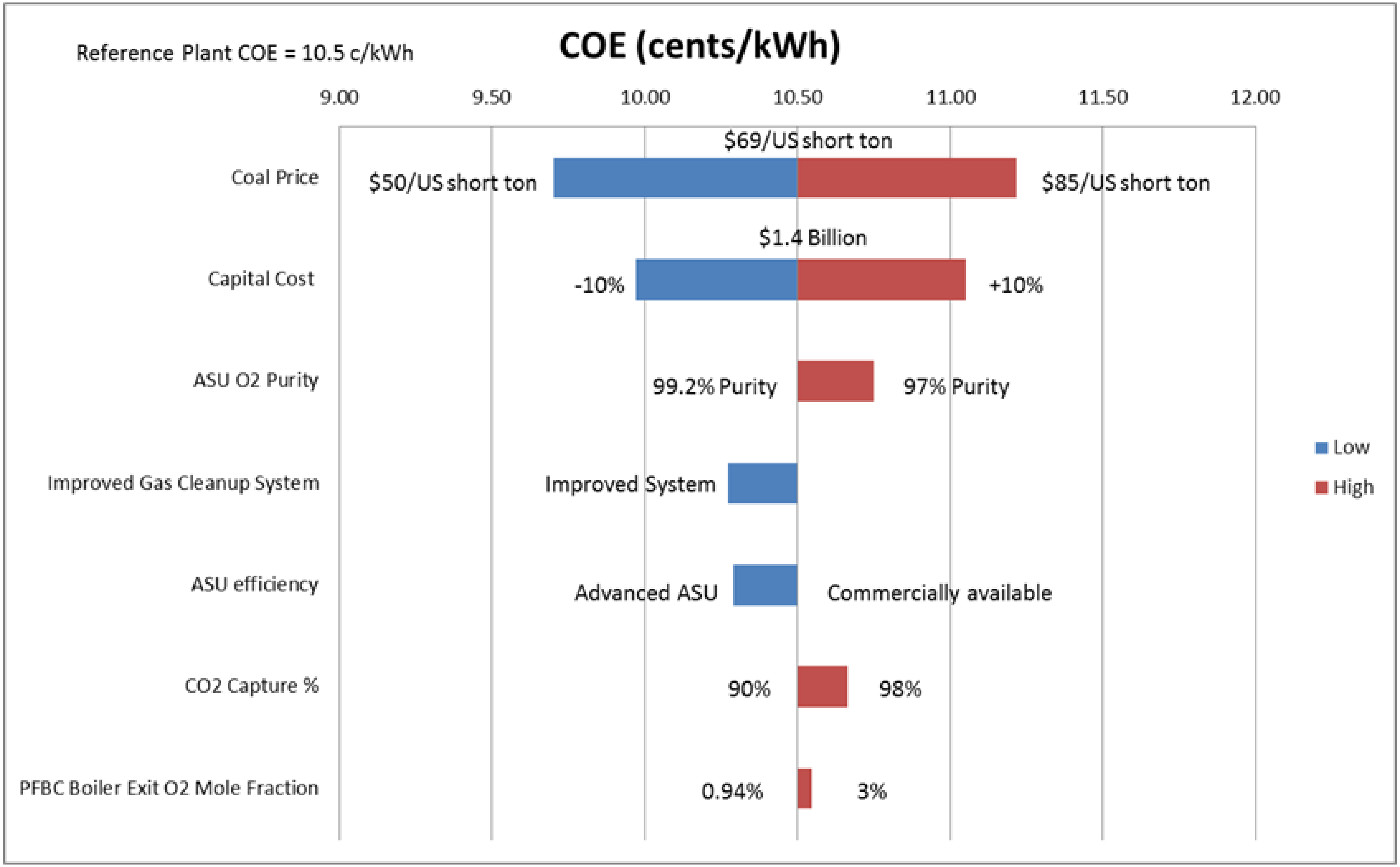
CanmetENERGY Test Facility Modifications Underway

- **Preliminary plant layout complete**
- **Equipment structural support design started**
- **Facility construction started**



Commercial Plant Sensitivity Analysis



Design options continue to be evaluated to drive the COE lower

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Future Plans

- **Phase II plans**
  - Completion of the coal and limestone reactivity testing
  - Completion of the pressurized cold flow elutriation testing
  - Pre-FEED of the demo scale plant
  - Fabrication and testing of the pilot scale rig
    - Update performance and technoeconomic analysis
    - Material and TRL evaluation
    - Anchor analysis codes

PFBC Commercialization Plan

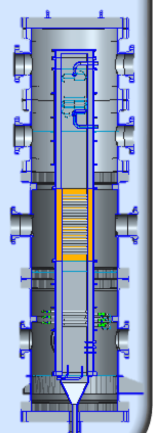
Phase I – 2012 – 2013	Phase II – 2014 – 2017	Phase III – 2017 – 2021	Phase IV – 2020 – 2025

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

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

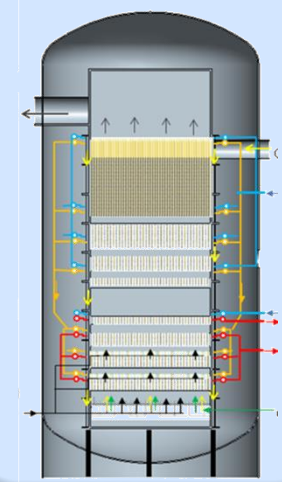
Large Pilot / Demo Plant

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

~50 MWth
~5 foot scale

Commercial Demonstration *5+ years*

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



275+ MWe
~20+ foot scale

Commercialization Plan leads to commercial scale demonstration by 2025

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