Oxy-Combustion
Pressurized Fluidized Bed
with Carbon Dioxide Purification

Presented by:
William Follett
Program Manager

June 26, 2015
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% CO₂ capture with no more than 35% increase in cost of electricity

**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

**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

**Schedule**

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
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<tr>
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<td>Final Report</td>
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<td>Cold Flow Test</td>
<td>Component Tests</td>
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<td>Design</td>
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<td>Pilot Design</td>
<td>Demo Plant Pre-FEED Design</td>
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<td>Analysis</td>
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<td>Go/No Go Decision</td>
<td>TRL 6 Demonstrated</td>
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<td>Pilot Test</td>
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<td>Pilot Fab</td>
<td>Pilot Testing</td>
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<tr>
<td>Commercialization Plan</td>
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<td>Demo and Commercial Plant Economics</td>
<td>Permit Risk Assessment</td>
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**Overview**

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- **Linde, LLC** – Gas supply, CPU technology, HEX design
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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 (pet coke, coal, biomass)
• Produces pure CO₂ for Enhanced Oil Recovery (EOR)

Markets:
• Electric power generation with CO₂ capture
• Heavy oil production (once-through steam)
• Light oil production (CO₂ 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
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™ Powerplant Concept Vision

Oxy-combustion eliminates N2 from exhaust for economical CO2 capture

Pressurized combustion reduces size & cost of combustor

Pressurized combustion enables heat capture from water vapor

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

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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**Risks/mitigation table**

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<th>3</th>
<th>4</th>
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<td>Phase I</td>
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<td>3</td>
<td>4</td>
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<td>Phase II</td>
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<td>Phase III</td>
<td>4</td>
<td>5</td>
<td>6</td>
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<td>1</td>
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</tbody>
</table>

**Legend**

- Green: Low Risk
- Yellow: Medium Risk
- Red: High Risk
- Blue: Phase I Start
- Orange: Phase I End
- White: Phase II Start
- Grey: Phase II End
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**Diagram notes**

- ASU 11848 TPD 99.2% O₂ 130 psia
- Coal Illinois #6 Wet 5820 TPD
- Limestone 70% - 200 mesh 764 TPD
- Recycled Flue Gas 42763 TPD 130 psia
- 525°F Flue Gas Temperature
- Filter
- Waste Solids 1526 TPD
- Reheat Steam
- HP Steam
- Combustor
- Steam Power Cycle
- Steam Turbine Block
- Booster Compressor
- Flue-gas Heat Recovery
- Liquid Separator
- CO₂ Product 98.2% CO₂ 13671 TPD
- CO₂ Purification & Compression
- Waste Water 25110 GPH
- Cooling
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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

![Diagram of Cold Flow Test Setup]

- Instrumentation
  - 2 Heaters
  - 3 Static pressure ports
  - 12 $\Delta P$ transducers
  - 20 Thermocouples
Cold Flow Test Results

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 CO₂ Purification Unit (CPU) and Heat Recovery System**

### Basis for CPU skid design - feed material streams –

<table>
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<th>COND-HEX</th>
<th>LICONOX</th>
<th>DEOXO</th>
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<tr>
<td>Flow (kg/hr)</td>
<td>383</td>
<td>325</td>
<td>322</td>
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<td>Temp. (°C)</td>
<td>230</td>
<td>60</td>
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<td>Press. (Bara)</td>
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<td>CO₂ (mol%)</td>
<td>66.0%</td>
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<td>H₂O (mol%)</td>
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<td>Ar (mol%)</td>
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<td>SOx (ppm)</td>
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<tr>
<td>HCl (ppm)</td>
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**Performance Targets:**

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

**LICONOX:**
- 90% NOₓ + 95% SOₓ removal

**DEOXO:**
- < 100 ppm O₂ in CO₂ product
- Heat of Deoxo reaction recovery

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Linde CPU provides reduced CapEx and OpEx costs for CO₂ purification and heat recovery compared to traditional cryogenic CO₂ purification units.
CanmetENERGY Test Facility
Modifications Underway

- Preliminary plant layout complete
- Equipment structural support design started
- Facility construction started
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
Cold Flow Testing & Bench Scale Kinetics (TRL 3)
Demonstrates:
- Coal & sulfation reaction rates at high CO2 and H2O partial pressure
- Heat transfer coefficients
- Bubble control
- Residence time

Duty
Size
~1 MWth
~1 foot scale

Phase II – 2014 – 2017
Pilot Plant (TRL 6)
Demonstrates:
- Pressurized system operation
- Elutriated bed operation and chemistry
- Flue gas clean-up
- Erosion risks

Phase III – 2017 – 2021
Large Pilot / Demo Plant
Demonstrates:
- Operation at scale
- Component life
- Operating parameters
- Maintenance approaches
- Erosion risks

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

Phase IV – 2020 – 2025
Commercial Demonstration 5+ years

275+ MWe
~20+ foot scale

Commercialization Plan leads to commercial scale demonstration by 2025
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