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

Commercial scale
Oxy-PFBC
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: 39 months (7/1/2014 - 9/30/2017)
- 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 project plan, risk mitigation status and TRL advancement, and identify partners and sites for 30-50 MWth plant

**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
- GE – 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

**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 CO2 for Enhanced Oil Recovery (EOR)

**MARKETS**
- Electric power generation with CO2 capture, including CHP
- Heavy oil production (once-through steam)
- Light oil production (CO2 floods)

**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
TEA updated to reflect component testing results
  • Component testing validated design assumptions – no change to performance

Primary contributors to reduced cost include significantly reduced CapEx from lower cost combustor and gas cleanup equipment
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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, 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

[Diagram of coal conversion process]
Commissioning Approach

- **Commissioning Phase 1: Leak and Gas Distribution Flow Tests**
  - **Objectives**: Cold flow of fluids through all gas and fluid systems. Testing of flow and pressure loops including startup / shutdown sequences and power loss scenario.
  - **Status**: Complete

- **Commissioning Phase 2: Solids Flow Systems**
  - **Objectives**: Cold flow operation of all solid material systems, including filters and solids removal. Bed behavior characterized at elevated pressure.
  - **Status**: Complete

- **Commissioning Phase 3: Warm-up Systems**
  - **Objectives**: Characterize operation of startup burner/heater and heat tracing. Test startup/shutdown procedures, bed behavior at elevated temp and pressure.
  - **Status**: Complete

- **Commissioning Phase 4: Coal Start-up and Shut-Down**
  - **Objectives**: Characterize operation of system with coal ignition and burning. Test startup/shutdown procedures, gas cleanup equipment at elevated temp and pressure.
  - **Status**: Complete

Performance checks of safety equipment and procedures conducted during each phase
Performance Test Objectives

- Validate assumptions for sulfur capture and flue gas purification
- Explore the effect of oxygen mole % on carbon burnout and particle agglomeration.
- Explore the effect of bed depth on carbon burnout
- Validate particle reaction rates and residence time requirements
- Validate thermal models for system level heat integration
- Validate operational procedures
  - Natural gas warm up to coal ignition temperatures
  - Transition to oxy-Combustion at pressure
  - Control recycle gas flow rates and temperatures
  - Control bed depth
  - Solids injection and removal systems
**CO₂ Purification Unit (CPU) Test Approach**

- **CPU includes 3 components**
  - **Direct Contact Cooler (DCC)** – Cools flue gas, condenses water, recovers heat, removes ash and HCl
  - **LICONOX** – Removes NOx and residual SOx
  - **DEOXO** – Removes O₂ and recovers heat

- **Commissioning includes 2 phases**
  - **Operational tests** – Demonstrates that all pipes, valves and instrumentation are properly installed, and all control and safety systems operate as designed
  - **Efficiency tests** – Demonstrate efficiencies of temperature and condensate flowrate control systems for DCC and LICONOX columns
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Significant Accomplishments

1 MWth pilot plant construction completed at CanmetENERGY

Commissioning tests demonstrated:

- Coal ignition and burning in combustor
- CO\textsubscript{2} Purification Unit operation
  - Direct contact cooler operation with combustor flue gas
  - Liconox and DeOxo in standalone tests

Initial performance testing also demonstrated:

- Air and oxy-combustion ignition / operation
- Pure oxy-combustion operation at full pressure (120 psia)
- Validated sulfur capture method in bed with 95-99% capture
Pilot Plant Overview

- Coal & dolomite hoppers
- Fly ash filter
- DeOxo Reactor
- CHX2 pressure vessel
- DCC & LiCONOX bases
- PFBC Pressure Vessel
- Combustor
Oxy-PFBC Commissioning Results

- Plant was successfully commissioned, including component and system testing
- Successful ignition and sustained burning demonstrated
  - Ignition was robust and repeatable as parameters varied
  - Varied bed mass and mass flow for: coal, natural gas, oxidizer, recycle gas
Oxy-PFBC Test Results

- Initial testing demonstrated successful oxy-combustion at full operating pressure
  - Demonstrated ignition and burning in both oxy-fired and air-fired modes
  - Ignition at 300 kPag, then ramped up to over 700 kPag
  - Temperature variation in bed of ~125-175 °C
  - Fuel feed at ~0.7 MWth
Oxy-PFBC Test Results

- Demonstrated average sulfur capture of 95% in the fluidized bed
- Sulfur capture downstream of filter estimated at >99% prior to entering CO₂ purification unit
## CO₂ Purification Unit Test Results

<table>
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<th>Parameter or Relationship</th>
<th>How achieved</th>
<th>Implications of Test</th>
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<tr>
<td>DCC Temp &amp; Condensate Flow control</td>
<td>Test performed with heated air and flue gas of natural gas combusted with air</td>
<td>Systems working</td>
</tr>
<tr>
<td>DCC Level &amp; Temp Trips</td>
<td>Test performed with water</td>
<td>Systems working</td>
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<tr>
<td>LICONOX® Temp &amp; Condensate Flow control</td>
<td>Test performed with heated air</td>
<td>Systems working</td>
</tr>
<tr>
<td>LICONOX® Level, Condensate Flow and Acidity (pH) control</td>
<td>Test performed with water and caustic solution</td>
<td>Systems working</td>
</tr>
<tr>
<td>DeOxo start up heater &amp; HEX</td>
<td>Test performed with air and CO₂</td>
<td>Systems working</td>
</tr>
<tr>
<td>DeOxo O₂ conversion, along with Temp and Composition (HC &amp; O₂) trips</td>
<td>Test performed with synthetic flue gas</td>
<td>Systems working</td>
</tr>
</tbody>
</table>

- CPU successfully commissioned and ready for performance testing with flue gas from oxy-coal PFBC
- Limited DCC tests so far performed with low pressure flue gas from air fired natural gas (P<1.5 Bara, H₂O conc. < 10%) confirmed efficient water condensation under controlled conditions
**CO₂ Purification Unit Test Results**

- **Encouraging initial DEOXO test**
  - Achieved performance targets using synthetic flue gas
  - O₂ Conversion > 99%
  - CH₄ Slip < 0.1 %

- **Operating conditions**
  - Feed to DEOXO Reactor: 0.7% O₂, 2.6% N₂, 0.4% CH₄, 96.3% CO₂
  - P=6 Bara
  - Inlet T=410 °C

- **Future testing planned with Oxy-PFBC flue gas**
Oxy-PFBC Lessons Learned

- Promising initial results with no significant issues or showstoppers identified
- Early tests provided significant learning on how to start and control the system
- Initial tests had more bed expansion than anticipated – bed particles too small
  - Bed covered more active heat exchanger tubes than expected
  - Result was overcooling of the bed and poor carbon conversion
- Test ended prematurely due to erosion of coal feed line
  - Erosion due to tight radius bends and excessive velocity
- Issues being corrected with next test scheduled for mid-September
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Future Plans

Phase II plans

- Complete pilot scale testing
  - Update performance and technoeconomic analysis
  - Material and TRL evaluation
  - Anchor analysis codes
- Complete commercialization activities
Oxy-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

Duty
Size

~30-50 MWth
~3-4 foot scale

Phase III – 2018 – 2022

Large Pilot / Demo Plant

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

Duty
Size

275+ MWe
~20+ foot scale

Phase IV – 2021 – 2026

Commercial Demonstration 5+ years

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

Plan for commercial scale demonstration by 2026
Summary

- Commissioning and initial tests completed
  - Combustor demonstrated robust ignition, oxy-combustion at full pressure
  - Demonstrated excellent in-bed sulfur capture
  - DeOxo achieved performance goals with synthetic flue gas

- TEA update
  - Exceeds DOE goals, with >50% reduction in CO₂ capture penalty relative to DOE Case 12

- Next test planned for September
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