Oxy-fired Pressurized Fluidized Bed Combustor (Oxy-PFBC) DE-FE0009448 Kickoff Meeting

Morgantown, WV
October 22, 2012

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<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Presenter</th>
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<tbody>
<tr>
<td>1:00</td>
<td>Introductions by NETL</td>
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<tr>
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<td>Project Overview</td>
<td>Subbaraman</td>
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Oxy-fired Pressurized Fluidized Bed Combustor (Oxy-PFBC) Overview

Description and Impacts

1. **Phase 1 Description**
   - Validate the Oxy-PFBC process with specific process performance and economic models developed by NETL.
   - Budget: $1.267M ($1.0M DOE funding)

2. **Impacts**
   - Enable production of electricity from coal with near zero emissions.
   - Captured CO\(_2\) may be sequestered at dedicated sites or oilfields for enhanced oil recovery.

Commercialization path

- Proof of concept testing / studies (~2 years)
- Pilot plant (~2 years)
- Demo Plant (~4 years)
- Commercial Plant Demo (5-10 years)

Novel Technologies - Pressurized combustion with O\(_2\) enables:

- High efficiency through staged combustion and reduced O\(_2\) use.
- Heat recovery from exhaust H\(_2\)O vapor for higher efficiency.
- Economical carbon capture due to pure pressurized CO\(_2\) exhaust stream ready for sequestration.

Team members & roles

- Pratt & Whitney Rocketdyne – Lead, PFBC technology
- Linde, LLC – Gas supply, CPU technology, HEX design, EPC
- Pennsylvania State University – Sorbent reaction risk mitigation, fluidized bed design support
- Electric Power Research Institute – End user insight, technology gap assessment, cost modeling
- Jamestown Board of Public Utilities – End user insight, demo site

Goals and Objective

1. **Goals**
   - Capture >90% of CO\(_2\) with no more than 35% increase in cost of electricity.

2. **Overall Objectives**
   - Enable direct capture of all emissions, including CO\(_2\).
   - Verify economic feasibility of Oxy-PFBC.
   - Mature to TRL 6.

3. **Phase I Objectives**
   - Validate performance and plant economics with NETL guidelines.
   - Identify technology gaps that need to be closed to reach TRL 6.

Schedule

<table>
<thead>
<tr>
<th>Tasks</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Program Mgt</td>
<td>ATP</td>
<td>Interim Brfg</td>
<td>Final report</td>
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<tr>
<td>System Design and Analysis</td>
<td>Design Interim Report</td>
<td>Tech Gaps Identified</td>
<td>Mitigations Defined</td>
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<tr>
<td>Technology Gap Analysis</td>
<td></td>
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<td>Application Complete</td>
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<tr>
<td>Phase II Application Prep</td>
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</table>
**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

*Pratt & Whitney Rocketdyne PROPRIETARY*
Oxy-PFBC Layout

- **Steam Headers**
- **O2/Recycle CO2 Inlet**
- **Flue Gas Outlet**
- **Convective HEX**
- **Combustion Wall HEX**
- **In-Bed HEX**
- **In-Bed HX**
- **Bed Fill**
- **Coal/Limestone Injection Stages**
- **Bed Drain**

**In-Bed Heat Exchanger**

External manifolding for maintainability
## Oxy-PFBC Predicted Performance

<table>
<thead>
<tr>
<th></th>
<th>Air-Fired SCPC without CO₂ Capture</th>
<th>Oxy-Fired Atmospheric SCPC</th>
<th>PWR Oxy-PFBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Input, MWth</td>
<td>1,396</td>
<td>1,878</td>
<td>1,662</td>
</tr>
<tr>
<td>Gross Power, Steam Turbine, MW</td>
<td>580</td>
<td>787</td>
<td>739</td>
</tr>
<tr>
<td>Total Auxiliary Loads, MWe</td>
<td>30</td>
<td>232</td>
<td>189</td>
</tr>
<tr>
<td>Net Power Output, MWe</td>
<td>550</td>
<td>555</td>
<td>550</td>
</tr>
<tr>
<td>Net HHV Efficiency, %</td>
<td>39.4</td>
<td>29.5</td>
<td>33.1</td>
</tr>
<tr>
<td>Carbon capture (&gt;90% is DOE Objective)</td>
<td>0%</td>
<td>90%</td>
<td>98%</td>
</tr>
<tr>
<td>Increase in COE relative to SCPC w/o carbon capture (&lt;35% is DOE Objective)</td>
<td>Baseline</td>
<td>50%</td>
<td>30%</td>
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<tr>
<td>Case 1</td>
<td>Case 5a</td>
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- **PWR Oxy-PFBC preliminary performance predicted to exceed DOE objectives**
  - Provides 98% carbon capture (goal of >90%)
  - LCOE increased by less than 30% (goal of <35%)

- **Phase I objective includes validation with NETL guidelines**
Oxy-PFBC Key Features

Efficiency Enhancement
- Staged combustion with elutriation – Reduces O2 consumption, with high sulfur capture
- Oxy combustion – Reduces energy required for CO2 purification
- Pressurized – Reduces CO2 compression required for sequestration

Cost Reductions
- PFBC – More compact combustor with lower Capex
- Simpler, lower-cost CPU
- Elimination of FGD (Potentially)
Changes Since Proposal

- Pilot Size reduced from 4-6 MWth to 1MWth
- Specific testing identified for Penn State
  - Address new risk item (below) with testing and analysis
- New Risk Identified
- Re-evaluated In-bed Heat Exchanger (IHX) risk
- Initiated discussions with additional partners for Phase II
  - Consol (Pilot Testing)
  - Tata Power (Commercialization)
  - Others
**Commercialization Plan**

Duty

- 1 MWth
- 100 MWth
- 275 MWe

Size

- 1.2’ Ø
- 10’ Ø
- 24’ Ø

**Cold Flow Tests**
- Lateral Mixing
- Bubble Control
- Elutriated Flow Hindering
- Superficial Velocity Range

**Materials Tests**
- Corrosion/Erosion in Rel. Environment for >1000 hrs
- Orientation effects
- Studding effects
- Shielding effects

**Pilot Plant**
- 2000 hrs

**DemoPlant**
- 3+ years

**BOP Systems**

**Efficiency & Cost Improvements**

**Commercial Demonstration**
- 5-10 years

**Demonstrates:**
- Staged Combustion
- Combustion/Sulfur Capture
- Heat transfer
- Lateral Mixing
- Injection Component Performance
- Corrosion/Erosion
- Klinker/deposit formation
- Upset Condition effects

**Demonstrates:**
- Operation at scale
- Component Life estimates
- Develop Operating Parameters
- Overall System Experience
- Maintenance Issues

**Demonstrates:**
- System Efficiency
- O&M Costs
- Establish Life Warranties
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- Flue Gas Outlet
- Convective HEX
- In-Bed HEX
- Combustion Wall HEX
- In-Bed HX
- Bed Fill
- Bed Drain
- Steam Headers

In-Bed Heat Exchanger

External manifolding for maintainability
Phase 1 Objectives

- Validate System Performance of Oxy-PFBC with steam-Rankine system using standardized tools (ASPEN) and specified guidelines
  - Baseline Performance – DOE/NETL-2010/1397, Rev 2
  - Process Simulation – DOE/NETL-341/081911
  - Feedstock Baseline – DOE/NETL-341/011812
  - CO2 Impurity Baseline – DOE/NETL-341/011212
- Validate plant economics of Oxy-PFBC system using standardized tools and compare with established baseline
  - Baseline Costs – DOE/NETL-2010/1397, Rev 2 & 341/082312
  - Cost Methodology – DOE/NETL-2011/1455
- Perform Technology Risk Assessment per Attachment E of DE-FE0000636
  - Identify Technology Gaps
  - Plan/execute near term risk mitigation
- Finalize business agreements with team members
- Complete Phase II application
## Phase 1 Tasks

<table>
<thead>
<tr>
<th>WBS #</th>
<th>WBS Level</th>
<th>WBS Title</th>
<th>Phase 1 Deliverables</th>
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<tbody>
<tr>
<td>1.0</td>
<td>Task</td>
<td>Project Management and Planning</td>
<td>Project Management Plan (and updates)</td>
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<td>Phase 1 Topical Report</td>
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<td>1.1</td>
<td>Subtask</td>
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<td>1.2</td>
<td>Subtask</td>
<td>NEPA Documentation</td>
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<td>1.3</td>
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<td>2.0</td>
<td>Task</td>
<td>System Design and Analysis</td>
<td>Technology Engineering Design Basis Report</td>
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<td>Technology Engineering Design Interim Report</td>
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<td>Final Phase 1 Technology Engineering Design and Economic Analysis Report</td>
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<td>2.1</td>
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<td>Design Basis Definition</td>
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<td>Economic Performance Analysis</td>
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<td>3.0</td>
<td>Task</td>
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<td>Subtask</td>
<td>Risk Mitigation and Pilot Plant Planning</td>
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<tr>
<td>4.0</td>
<td>Task</td>
<td>Phase II Application Preparation</td>
<td>Phase II Application</td>
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<td>4.1</td>
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Task 1.0 – Project Mgt and Planning

- Ensure coordination and planning of the project with DOE/NETL and other project participants, including the monitoring and controlling of project scope, cost, schedule, and risk, and the submission and approval of required NEPA documentation.
- Maintain and revise the Project Management Plan, and provide periodic reports on activities in accordance with the Federal Assistance reporting Checklist attached to the plan.
- Prepare detailed briefings for presentation to the Project Officer at the Project Officer’s facility located in Pittsburgh, PA or Morgantown, WV
- Project kick-off meeting held within 45 days of project start date
- Project status briefing held no more than 30 days before submittal of the final report
- Provide Interim Report 6 months after award
- Complete one presentation at a National Conference - TBD
Task 2.0 – System Design and Analysis

- Develop a Design Basis Document that describes the approach to be taken to perform the system study, including definition of the cases to be studied and the assumptions to be made for the process and economic performance analyses. Two cases are included in the proposal baseline - 275MWe New Supercritical Steam plant, and a >275MWe steam plant retrofit.


Due End of October

Due 6/29/13
Task 3.0 – Technology Gap Analysis

Due 6/29/13

• Complete an analysis of the current state of development of all the major/critical process components for the proposed technology, identify the research needs required to fully develop the technology to commercialization, and show how the proposed Phase II efforts along with any research and development efforts required (or ongoing) outside of the Phase II proposal will aid in the development of the proposed technology.
Task 4.0 – Phase II Application Preparation

- Deliver a Phase II project application per the requirements of DE-FE0000636 Attachment F that proposes efforts focused on the development and testing of:
  - Novel process components at the laboratory/bench/pilot scale prior to scale up to a fully integrated system
  - Bench/pilot scale integrated systems
Agenda

1:00  Introductions by NETL  Fout
1:15  Project Overview  Subbaraman
1:30  Phase I Objectives & Tasks  Mays
1:50  **Team Members & Responsibilities**  Mays (Lead)
2:10  Risks & Mitigation  Mays
2:25  Phase I Schedule & Deliverables  Follett
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## Team Members & Responsibilities

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<th>Role/Responsibility</th>
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<tbody>
<tr>
<td>Pratt &amp; Whitney Rocketdyne</td>
<td>Project lead &amp; PFBC technology, Process &amp; system engineering, Risk mitigation &amp; pilot test planning</td>
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<tr>
<td>Linde</td>
<td>Gas supply and clean-up systems, PFBC Heat exchanger design support</td>
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<tr>
<td>Penn State University</td>
<td>Fluidized bed design support, Sorbent reaction risk mitigation</td>
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<tr>
<td>EPRI</td>
<td>Field demonstration unit site, Engineering support &amp; review, Voice of the end-user, Review of process and cost modeling</td>
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### WBS # | WBS Title | Scope Summary |
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<tr>
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<td>Project Management and Planning</td>
<td>Ensure project coordination and planning with DOE/NETL and participants (project scope, cost, schedule, and risk).</td>
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<tr>
<td>1.1</td>
<td>Project Monitoring and Control</td>
<td>Submission and approval of any NEPA documentation required for Phase II testing.</td>
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<tr>
<td>1.2</td>
<td>NEPA Documentation</td>
<td>Provide periodic reports, detailed briefings, a project status briefing, and submittal of the final report on activities.</td>
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<tr>
<td>1.3</td>
<td>Briefings, Periodic Reports and Conference Attendance</td>
<td>Complete one conference presentation.</td>
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<tr>
<td>2.0</td>
<td>System Design and Analysis</td>
<td>Define the cases to be studied and the assumptions to be made for process and economic performance analyses. Two cases for the proposal baseline one - 550 MWe New Supercritical Steam plant, &gt;275 MWe plant retrofit.</td>
</tr>
<tr>
<td>2.1</td>
<td>Design Basis Definition (DBD)</td>
<td>Complete system performance analyses for the cases identified in the DBD.</td>
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<tr>
<td>2.2</td>
<td>System Performance Analysis</td>
<td>Complete economic performance analysis for the cases identified in the DBD using AspenPlus per NETL report, “GCESS: Process Modeling Design Parameters”.</td>
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**Lead - x**
• Roles and Responsibilities
  • Overall project lead
  • PFBC technology provider
  • Lead for System Design and Analysis, Phase II Application
• Previous Experience
  • Operational H₂ generator field demonstration unit (Current)
    • Fluidized bed and chemical looping operating above atmospheric pressure, and experience with oxy-fired systems
  • PWR’s Compact Gasifier System, and the Dry Solids Pump programs supported by PWR, federal and state/provincial governments and private sectors (Current)
  • Fluidized bed design, analyses, and qualifying components (e.g., In-bed Heat Exchangers) for commercial operation through a DOE-sponsored test program (1980 -1989)
• Strategic Fit
  • The Oxy-PFBC fits within PWR’s 50 year legacy of advanced energy production systems and supports PWR’s continued thrust in the clean fossil energy sector
• Unique qualifications
  • 50 years experience in advanced technology development for energy and propulsion
  • Relevant core capabilities: Advanced combustion with oxygen, fluidized beds, coal combustion, heat exchangers, sophisticated analysis and design, advanced technology development
The Linde Group

• **Roles and Responsibilities**
  - Jointly define design basis of the proposed oxyfuel system
  - Lead economic analysis and support the integrated system performance, with a focus on:
    - Flue gas processing (with Linde’s LiCONOx® technology)
    - Heat exchanger (HEX) design support (i.e. condensing HEX based on Linde’s Coil Wound technology)
    - Oxygen supply and optimization/integration of air separation unit (ASU)
  - Critically review technical gaps based on EPC experiences
  - Jointly prepare for Phase II pilot project application

• **Previous Experience**
  - Commercial scale aMDEA based CO2 capture from natural gas, Hammerfest, Norway
  - Pilot scale CO2 processing and DeNOx system for Oxyfuel, Schwarze Pumpe, DE
  - Pilot scale advanced solvent based PCC demo, Niederaussem, DE
  - Ongoing DOE sponsored pilot scale PCC demo, Wilsonville, AL
  - Development of novel integrated oxygen supply technology for oxyfuel (DOE funded project)

• **Strategic Fit**
  - Leading industrial gas supplier and engineering firm with global footprint
  - Strong corporate commitment to Clean Energy technology development and commercialization

• **Unique qualifications**
  - Over 130 years of experiences in engineering and technology innovation
  - Unique combination of industrial gas supply business and engineering capability
The Pennsylvania State University

• **Roles and Responsibilities**
  - Sorbent reaction risk mitigation
    - Review literature and identify technology gaps
    - Develop a technology maturation roadmap to close identified gaps.
    - Conduct necessary early analyses and/or tests, if feasible during Phase I that may be further refined during Phase 2.
  - Support in Fluidized bed Design

• **Previous Experience**
  - PSU conducted the largest and most extensive study in a laboratory and at a full scale operating CFB boiler in identifying factors that control sulfur capture characteristics of limestones and dolostones in 1990s and worked with several industries in this area.
  - Produced more than half a dozen theses (PH.D. and M.S.) in the area of sulfur capture and attrition mechanisms of limestones in CFB boilers including a study on sulfur capture by limestones at high pressures.

• **Strategic Fit**
  - Sorbent performance is a key component in the demonstration and development of Pratt & Whitney Rocketdyne's (PWR's) Pressurized Fluidized bed Combustor (PFBC) concept.

• **Unique qualifications**
  - With PSU's proven record with several scientific papers in this area and current activity understanding of the mechanisms and models, it is uniquely positioned in this partnership.
• **Roles and Responsibilities**
  - Voice of the end-user
  - Review of process and cost modeling
  - Technology gap analysis

• **Previous Experience**
  - Extensive utility-scale fluidized bed boiler field monitoring experience – bubbling and circulating beds.
  - Monitoring and operations of a pressurized coal combustor/gasifier at the US Department of Energy-funded Pressurized Systems Development Facility (PSDF) in Wilsonville, Alabama.
  - Numerous engineering and economic evaluations of utility power plant efficiency improvement technologies.
  - EPRI and PWR have ongoing projects since 2010 on ZEPS related R&D

• **Strategic Fit**
  - EPRI has routine dealings with electric utilities who are candidates for deploying pressurized oxy-coal technology and can bring the technology to these utilities.
  - EPRI personnel bring unique field experience with utility-scale fluidized bed combustion at both atmospheric pressure and elevated pressure.

• **Unique qualifications**
  - Significant direct experience in coal-fired power plant operations and maintenance.
  - On-going access to domestic US and worldwide coal-burning electric utilities and those contemplating coal-fired power plants.
  - Operations and monitoring at the AEP Tidd PFBC project in the 1990s; experience directly relevant to PWR’s pressurized oxy-FBC technology.
Jamestown BPU

• **Roles and Responsibilities**
  • Planned host site for the Pratt & Whitney Rocketdyne PFBC technology
  • Predict the economic feasibility of the project as it relates to a power producer

• **Previous Experience**
  • Have operated coal-fired power plants for nearly 100 years
  • Have operated natural gas combined cycle power plant for nearly 15 years
  • Participated in CCP I-3 in pursuing a 50MWe Oxy-Coal CFB Project

• **Strategic Fit**
  • The Oxy-Fired PFBC fits within Jamestown Board of Public Utilities needs as an alternative 15-25 MW power producing facility
  • Plan for initiating 15-25 MWe retrofit by 2015 with operation beginning no later than 2019

• **Unique qualifications**
  • Local Business Foundation, Political, and Customer support for advanced clean coal technology project to be implemented within its community

  • Municipal Utility with electric generation experience; coal and natural gas power plant currently in operation
**Agenda**

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<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Presenter</th>
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<tr>
<td>1:00</td>
<td>Introductions by NETL</td>
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Risk Mitigation - Relevant Experience

Materials Tests
- Baseline Corrosion rates in relevant environments

Battelle Columbus Labs

Rocketdyne

18”x18” Combustor (IR&D)
Demonstrated:
- Injector Layout
- Start Transient IHX Load Following

24”x24” Combustor
- 3-250 hr tests
- Identified Corrosion mechanism and material susceptibility
- Optimized Injection

Proved Heat Exchanger Design, Hanger & Supports Design and Heat Transfer

Bed Design, Bubble Control, injection Layout

Identified Corrosion mechanism and material susceptibility

AFB and BOP System Design, Construction

Material Evaluation: Heat exchanger, supports, cooled/uncooled, ox-rich/lean environments

Demonstrates:
- Corrosion/Erosion
- Bed Operation
- Heat Transfer
- IHX manifolding & Support
- No Klinker/Deposits

6’x6’ Combustor
- 1980 hrs

Atmospheric Fluidized Bed (AFB) Project Provided Evaluation of IHX materials & Fluidized Bed Combustor Design
Risk Mitigation - Relevant Experience

Proof of Concept Tests

2002 2003 2004 2005 2006 2007 2008 2009 2010 2011

Hot Fixed Bed Test
Demonstrated Chemistry

Demonstrated elutriated solids
hydrodynamic characteristics
and baffle design

Cold Flow Test

Pilot Tests

Pilot Plant

Hydrogen Generator Broke Ground on Elutriated Bubbling Bed Operation and Identified Design Parameters
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### Phase 1 Schedule

#### Project Milestones

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<tr>
<th>Task</th>
<th>Start Date</th>
<th>End Date</th>
<th>Total Cost</th>
<th>Predecessor Tasks</th>
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#### Phase 1 Deliverables

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### Future Phases

- Phase II Application
- NEPA Approval
- Pilot Plant Commissioned
Phase 1 Deliverables

• Technology Engineering Design Basis Report (due October 31, 2012)
• Technology Engineering Design Interim Report (due March 31, 2013)
• Final Phase I Technology Engineering Design and Economic Analysis Report (due with Phase II application by June 29, 2013)
• Final Phase I Technology Gap Analysis (due with Phase II application by June 29, 2013)
• Quarterly Progress reports (December 31, 2012; March 31, 2013; June 30, 2013)
• Final report (9/30/2013)
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3:00  Adjourn
Budget

Spend Plan

Cum Spending (\$ - millions)

## Cost Share Plan

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<th>Quarter</th>
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<th>Total</th>
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**Cost share funding**
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Summary

• Power generation based on Oxy-PFBC technology shows significant potential to meet DOE goals for CO2 capture and LCOE
  • CO2 Capture: 98% (vs. 90% DOE goal)
  • LCOE increase: <30% (vs. <35% DOE goal)

• PWR Team has the breadth of capabilities to assess and mature technology during Phase 1 and beyond
  • Multiple commercialization opportunities being defined

• Team has initiated Phase 1 work with updates to technology and gaps based on insights from operating air-fired PFBC plants
  • Discussions initiated with Consol towards Phase 2 efforts

• Team looks forward to continued partnership with DOE upon validating Oxy-PFBC performance and economics
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