the Energy to Lead

Enabling Technologies for Oxy-fired Pressurized Fluidized Bed Combustor Development

Kickoff Briefing

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October 23, 2015

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Enabling Technologies for Oxy-fired Pressurized Fluidized Bed Combustor (Oxy-PFBC) Development

- **Agenda**
  - Project Overview
  - Objectives and Tasks
  - Team Members and Responsibilities
  - Risks and Mitigation
  - Schedule and Deliverables
  - Budget and Spend Plan
  - Summary

Enabling Technologies for Oxy-PFBC Development

Overview

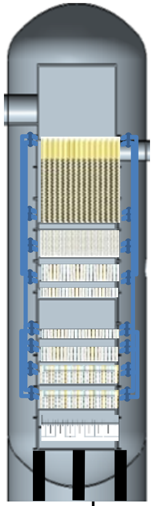
Description and Impacts

Program Description

- Demonstrate technologies at pilot scale that will improve Oxy-PFBC economics and reduce scale-up risk
- Budget: $2.6M ($2.0M DOE funding)

Impacts

- Supports path to exceed DOE's cost goal of $106.4/MWh
- SCO2 and improved gas cleanup technologies improve Oxy-PFBC COE from $107 to $82/MWh
- Closes key technology gaps and validates at pilot scale



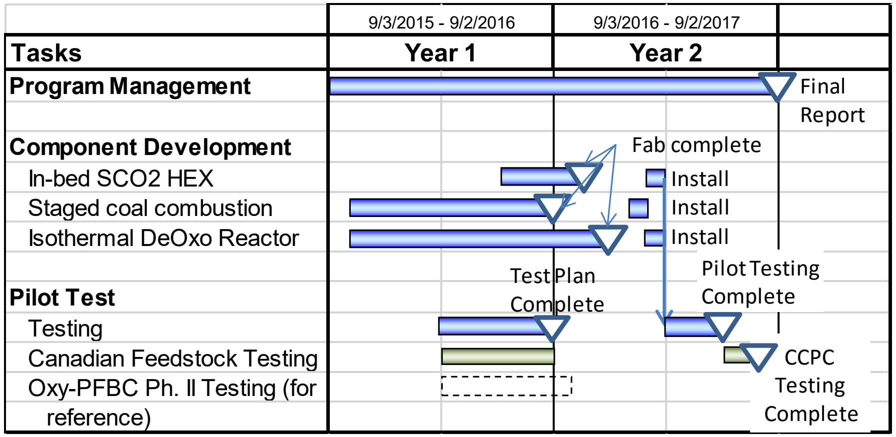
Team Members and Roles

- **GTI (Gas Technology Institute)** – Lead, PFBC technology
- **Linde, LLC** – Isothermal DeOxo Reactor technology and integration with SCO2 cycle
- **CANMET–** Pilot plant test facility and test support
- **CCPC (Canadian Clean Power Coalition)** – Funding for Canadian feedstock testing

Technology Objectives

- Supercritical CO2 (SCO2) Heat Exchanger – Quantify SCO2 heat transfer coefficients and pressure drop in an Oxy-PFBC environment to anchor design rules for scale-up
- Staged Coal Combustion – Develop design rules for injector placement for robust operation that maintains an oxidizing environment and avoids slagging
- Isothermal Deoxidation Reactor (IDR) – Define operational limits on flue gas O2 concentration for an isothermal catalyst bed and demonstrate heat recovery

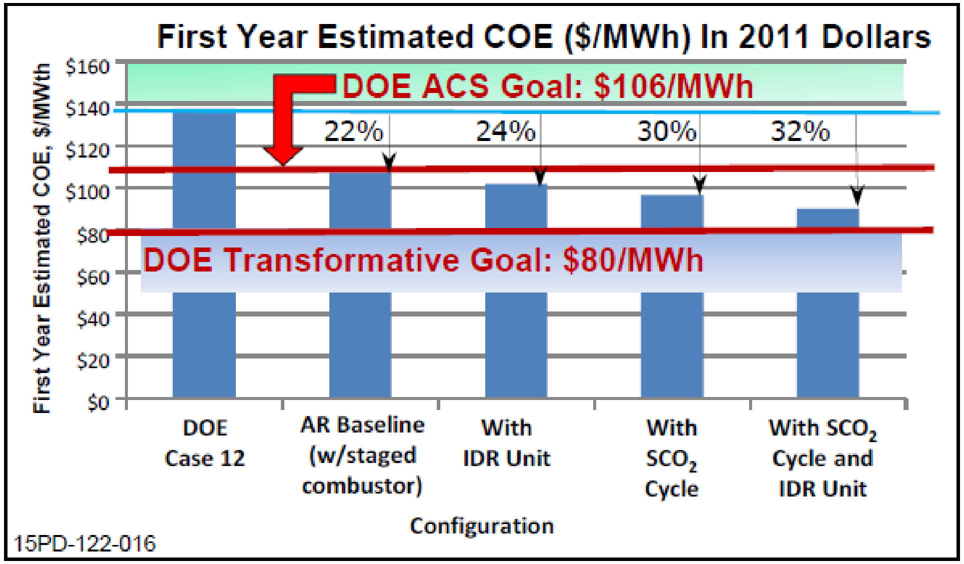
Schedule



Project Background and Benefits

- GTI (formerly Aerojet Rocketdyne, Advanced Energy group) has ongoing efforts in Oxy-PFBC and Supercritical CO2 Brayton cycle technologies
  - This effort is the first to test the two technologies together
  - The payoff is expected to be significant reductions in the cost of electricity (COE) for systems with CO2 capture

- Linde provides an improved gas cleanup system to further improve performance



Projected performance exceeds the DOE Advanced Combustion Goal and approaches the DOE Transformative Goal

Oxy-PFBC Technology Overview

PRODUCT

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

BENEFITS

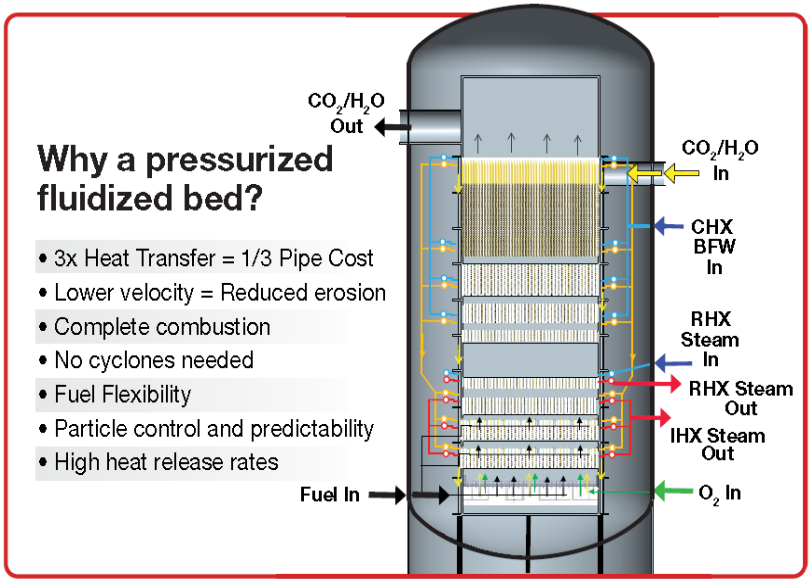
- Produces affordable electric power with near zero emissions
- Produces steam for heavy oil recovery using low value feedstock (petcoke, coal, biomass)
- Produces pure CO_2 for Enhanced Oil Recovery (EOR)

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

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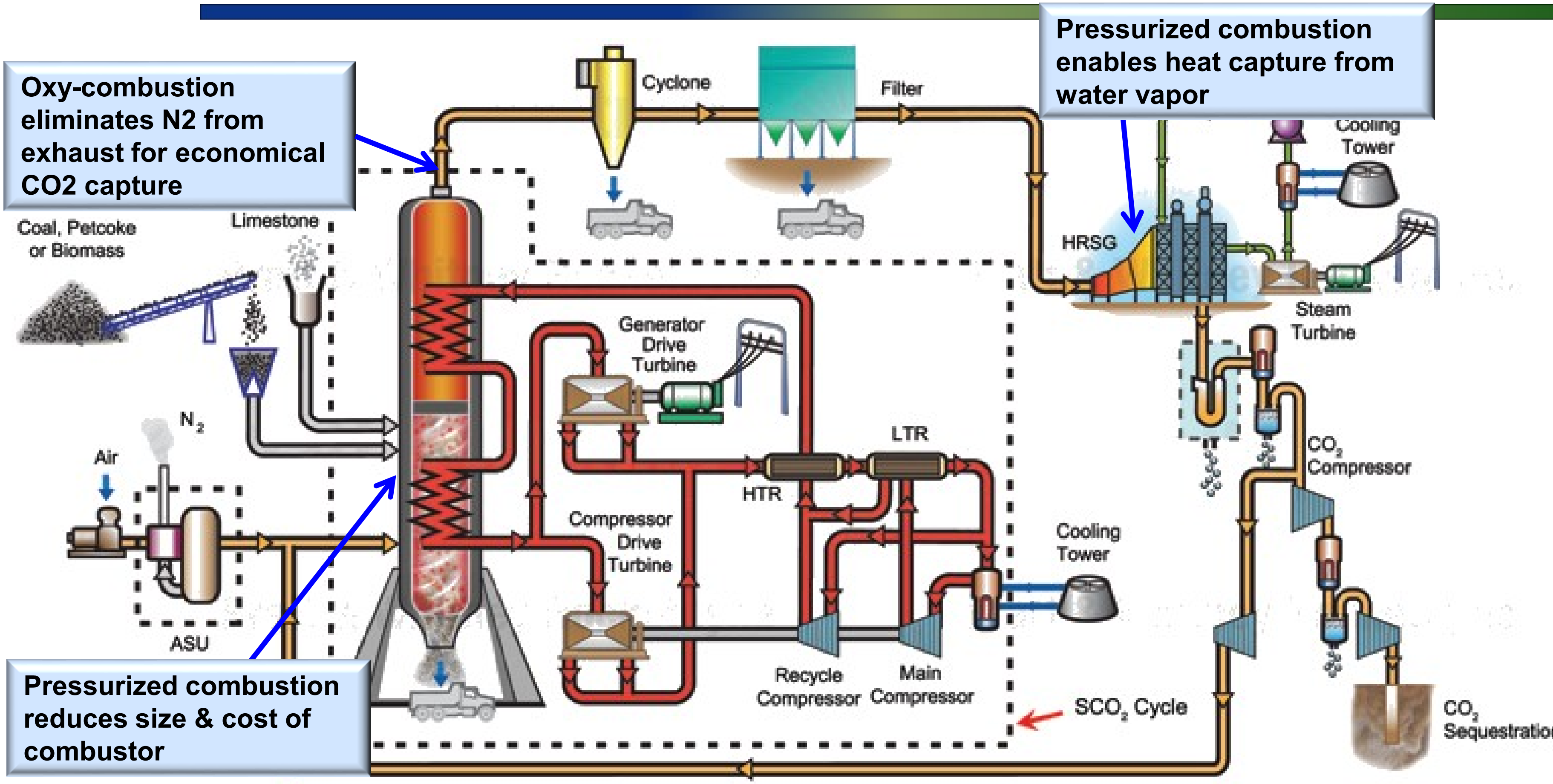
ZEPS™ Powerplant Concept Vision



- Enhanced efficiency and near zero emissions
- Enabling Technologies program focused on SCO2 HEX, staged fuel injection, improved gas cleanup

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ZEPS = Zero Emissions Power and Steam

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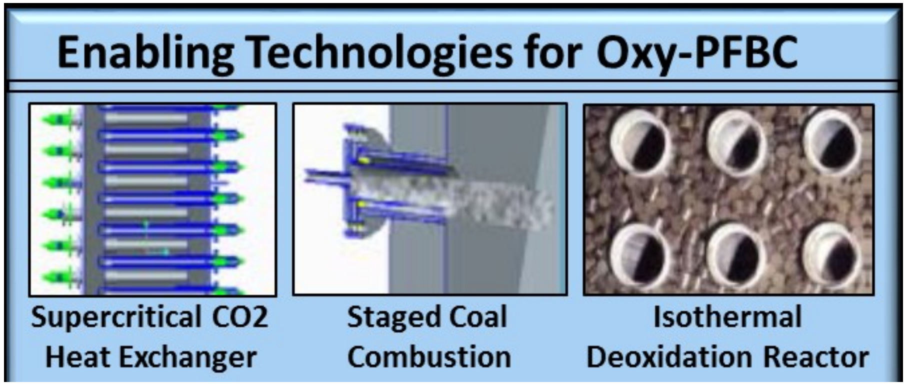
Objectives

- Project Objectives:
  - Develop technologies at the pilot-scale that will significantly improve the economics of our current oxy-combustion pathway
  - Directly address technology gaps associated with scale-up and system performance for both atmospheric- and pressurized oxy-combustion technology pathways in the DOE NETL program portfolio
  - Mature the advanced supercritical CO2 Brayton cycle technology at the combustor level
- Technology Objectives
  - Supercritical CO2 (SCO2) Heat Exchanger – Quantify SCO2 heat transfer coefficients and pressure drop in an Oxy-PFBC environment to anchor design rules for scale-up
  - Staged Coal Combustion – Develop design rules for injector placement for robust operation that maintains an oxidizing environment and avoids slagging
  - Isothermal Deoxidation Reactor (IDR) – Define operational limits on flue gas O2 concentration for an isothermal catalyst bed and demonstrate heat recovery



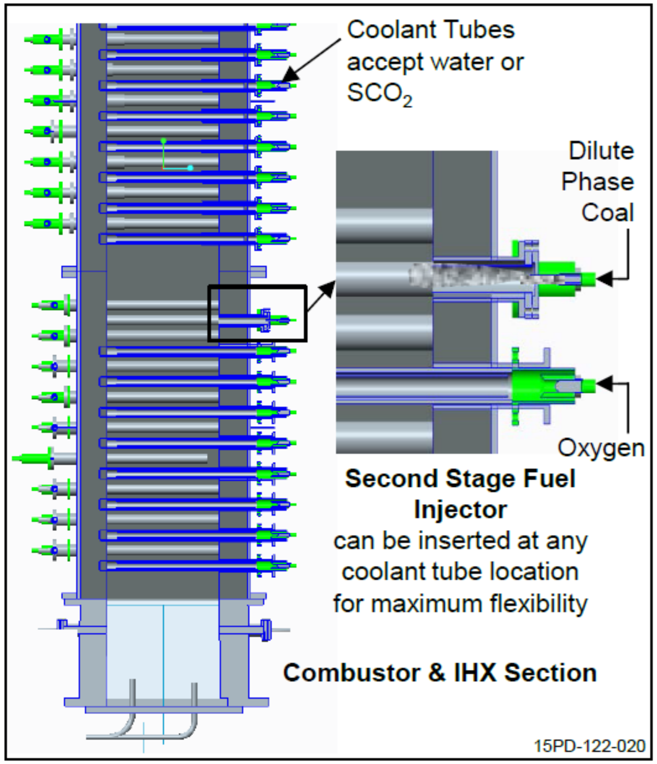
Success Criteria

- In-bed SCO2 Heat Exchanger
  - Demonstrate that the measured heat transfer coefficients and pressure drop support significant improvement in projected cost of electricity (COE) for a commercial scale application for the SCO2 Brayton cycle relative to a steam Rankine cycle
  - A significant improvement in COE is defined as a reduction of five percent or more based on the use of scaled test data
- Staged Coal Combustion
  - Demonstrate that second stage coal injection can be achieved while maintaining an oxidizing environment without slagging
- Isothermal Deoxidation Reactor
  - Demonstrate performance, including heat recovery, that supports reduced cost of electricity at commercial scale

In-bed SCO_2 Heat Exchanger

Technology Overview and Approach

- Background
  - One technology gap for SCO2 is integration with the heat source, including use of SCO2 as the working fluid in the in-bed heat exchangers
- Approach
  - Operating conditions
    - SCO2 system will be a closed loop system running at 2500 psia and between 400F and 700F
    - Operating conditions were chosen so the heat exchanger tube Reynolds and Prandtl numbers enable scaling to the predicted commercial operating conditions (3000 psia and 1000-1300F)
    - Conditions avoid potential condensation on the bed-side surface of the tubes, and allow use of steel alloys with demonstrated compatibility with SCO2
  - Determine hot and cold-side heat transfer coefficients, and coolant pressure drop, to enable scaling
  - Coolant conditioning (heating and cooling) in the SCO_2 supply system will establish design performance for heat exchangers
  - Scaling risk is minimized by running at similar coolant tube Reynolds number as in a commercial plant, and by using full scale in-bed heat exchanger tubes, particle sizes and velocities in the pilot



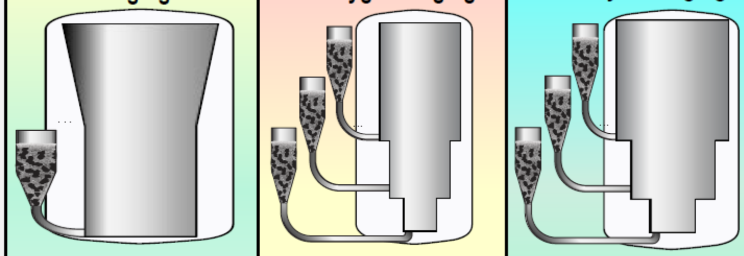
Modular pilot design enables retrofit of SCO2 coolant and fuel / oxygen injectors

Staged Coal Combustion

Technology Overview and Approach

- **Background**
  - Staged combustion is planed for the commercial scale Oxy-PFBC design to maximize power/volume and maintain uniform bed temps below ash slagging conditions
  - The GTI Oxy-PFBC is expected to have a different thermal profile than previous fluidized beds due to the fine coal and pressurized conditions

- **Approach**
  - Characterize the single stage thermal profile during Oxy-PFBC Phase II testing, then select the 2nd stage injection point
  - Demonstrate and characterize operation of the second stage injectors
    - Fuel for two-stage tests will be Illinois #6. Additional tests will be conducted with Canadian fuels in Subtask 3.4
    - Specific tradable features that drive performance will be characterized: flue gas recycle rate, fuel particle size and ash content, and coolant flow control
    - Oxygen / fuel flow rates and bed cooling will be varied to study bed injection point temperatures and ash behavior (burnout percentage, particle temperature, agglomeration potential)
  - Develop performance curves for multiple fuels for scale-up to commercial size power plants
    - Knowledge is required to balance the power cycle (steam or SCO2) with the coal combustion cycle, optimize compression requirements, and generate the most commercially viable design →



	No staging	Stage coal and recycle No oxygen staging	Stage coal and oxygen No recycle staging
Pros	Least Expensive Simple Design	Possible High Efficiency	Best Compromise Moderate Efficiency
Cons	Lowest Efficiency Possible Agglomeration	High Agglomeration Risk More Expensive	Stage Size Depends on Coolant

15PD-122-008

Isothermal Deoxidation Reactor (IDR)

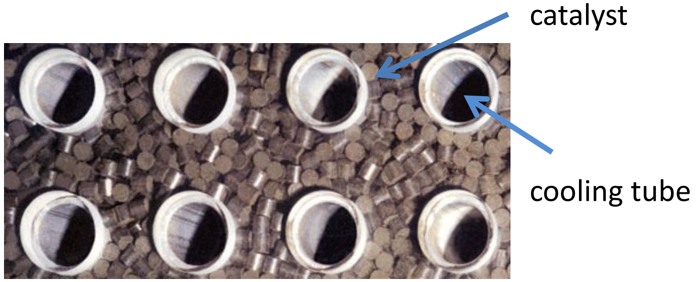
Technology Overview and Approach

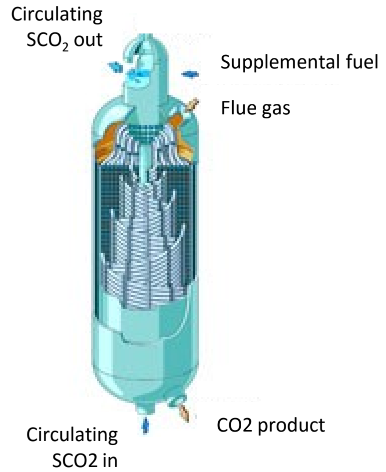
Background

- The Linde isothermal reactor is a fixed bed reactor with indirect heat exchange suitable for endothermic and exothermic catalytic reactions.
- The IDR will reduce the oxygen content in the flue gas below 100 ppm level making the final CO_2 suitable for EOR.
- This project will also test the benefits of integrating the heat of oxidation reactions of supplemental fuel and/or CO_2 impurities into the SCO2 Brayton Cycle

Approach

- The isothermal reactor will be fabricated as a single piece to replace the existing deoxidation catalytic reactor in the CO_2 purification unit from the Oxy-PFBC Phase II project. The existing DCC and LiCONOX will be used.
- The IDR uses an internal heat exchanger with supercritical steam or CO_2 working fluid to maintain a near constant temperature throughout the catalyst bed
- Characterize and define operational limits, in terms of flue gas O_2 content and heat recovery for the retrofits to the CO_2 purification unit.
  - O_2 residual content in the flue gas is managed by altering the fuel/oxygen ratio in the PFBC. The quantity of oxygen removed is controlled by the fuel flow rate into the catalytic reactor.
  - Temperature of the catalyst bed is controlled by matching catalytic deoxidizer fuel flow rate with catalyst heat exchanger coolant flow
  - Performance of the heat exchanger and balance between reaction and heat removal are to be measured in multiple locations to allow design of full scale cooled reactors
  - Fuel for the catalytic deoxidizer is to be natural gas, with hydrogen as a fallback option





Task 1.0 - Project Management and Planning

- Manage and direct the project in accordance with a Project Management Plan
  - Meet all technical, schedule and budget objectives and requirements
  - Ensure that project plans, results, and decisions are appropriately documented and project reporting and briefing requirements are satisfied.

- The Recipient shall update the Project Management Plan 30 days after award and as necessary throughout the project to accurately reflect current status of the project.
  - PMP was updated and approved

- Project risk management
  - Follow risk management methodology in the Project Management Plan
  - Identify, assess, monitor and mitigate technical uncertainties as well as schedule, budgetary and environmental risks associated with all aspects of the project
  - Results and status shall be presented during project reviews and in Progress Reports with emphasis placed on the medium- and high-risk items

Task 2.0 – Component Development

- Task 2.0 - Design, fabricate and install the technologies into the pilot plant, and conduct facility integration tasks to update Piping and Instrumentation Diagrams (P&IDs) and control narratives

  - Subtask 2.1 – In-bed SCO_2 Heat Exchanger
    - Design, acquire, fabricate and assemble SCO2 system components for the oxy-fired coal pilot plant, including the coolant loop CO_2 compressor and CO_2 temperature conditioning components.
  - Subtask 2.2 – Staged Coal Combustion
    - Design, acquire, fabricate and assemble the second stage injection system
    - The system should be designed for retrofit compatibility with the previously designed pilot scale combustor hardware.
  - *Subtask 2.3 – Isothermal Deoxidation Reactor (IDR)*
    - An IDR system with heat recovery shall be fabricated and installed at the PFBC pilot plant.

Task 3.0 – Pilot Plant Testing
(Subtasks 3.1 and 3.2)

- Subtask 3.1 – Test Planning
  - Integrated pilot plant test plans shall be developed and Hazardous Operations (HAZOPS) assessments completed
  - Refine cost projections to complete pilot testing in Budget Period 2

- Subtask 3.2 – Commissioning
  - Pilot plant commissioning tests shall be conducted under this task to make it operational and ready for testing
  - Subsystem testing of new hardware prior to full plant operation
    - Leak tests at pressure, flow tests, and, where applicable, heat-up transients of fluid thermal conditioning units.

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Task 3.0 – Pilot Plant Testing
(Subtask 3.3)

Subtask 3.3 – Testing

- Up to two weeks of testing shall be completed over a two month period with Illinois #6 fuel to achieve the following objectives:
  - Demonstrate operation of in-bed heat exchangers with SCO_2, including validation of heat transfer coefficients
    - Determine hot and cold-side heat transfer coefficients, and coolant pressure drop, to enable scaling
    - Coolant conditioning (heating and cooling) in the SCO_2 supply system will establish design performance for heat exchangers, which is an important metric for Brayton cycle power systems.
  - Demonstrate and characterize operation of the second stage injectors.
    - Oxygen flow rates, fuel flow rates and bed cooling will be varied in such a way as to allow a study of bed injection point temperatures and ash behavior (burnout percentage, particle temperature, agglomeration potential)
  - Characterize and define operational limits, in terms of flue gas O_2 content and heat recovery
    - Oxygen residual content in the flue gas is managed by altering the fuel/oxygen ratio in the PFBC. The quantity of oxygen removed is controlled by the fuel flow rate into the catalytic reactor.
    - Performance of the heat exchanger and balance between reaction and heat removal are to be measured in multiple locations to allow design of full scale cooled reactors

Task 3.0 – Pilot Plant Testing
(Subtask 3.4)

Subtask 3.4 – Canadian Feedstock Testing

- Under this subtask, two Canadian coals, Genesee and Saskatchewan lignite, shall be tested to demonstrate operation with different feedstock
- Up to two weeks of testing is targeted over a 3-month period
- Importance of Genesee and Saskatchewan lignite
  - The objective is to test two coals that are of interest to Canadian power producers and have potential performance benefits in the Oxy-PFBC system
  - The two primary coal producing and using regions in Canada are Alberta and Saskatchewan
    - Genesee (Alberta subbit #1) is of interest because of its high calcium and low sulfur content, which should reduce the need for limestone for sulfur capture
    - Saskatchewan lignite (similar to North Dakota lignite) is of interest because of its current use in the Boundary Dam CCS plant, its lower energy content and its lower ash fusion temperature relative to Illinois #6
  - The test experience with these two coals will span the likely range for agglomeration propensity and help expand the operating envelope of the Oxy-PFBC unit

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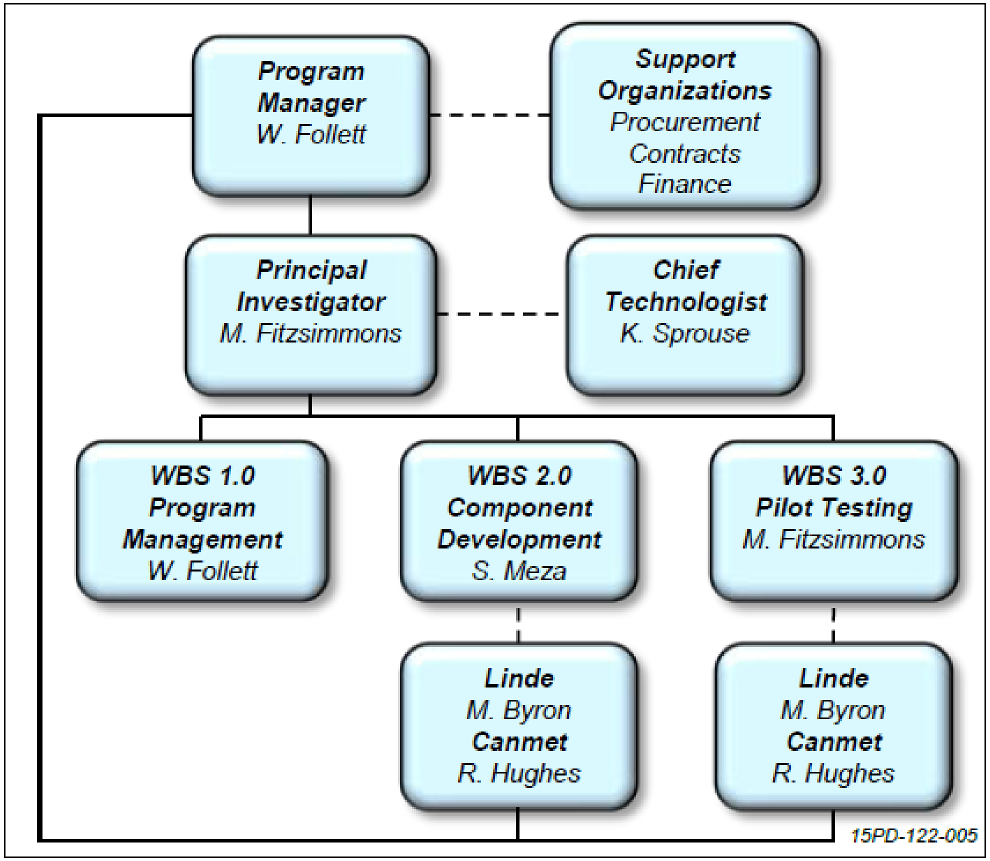
Team Members and Responsibilities



Organization Chart

Team Members and Responsibilities

Organization	Role/Responsibility
gti	• Project lead & PFBC technology • Process & system engineering • Risk mitigation & pilot test planning
Linde	• Gas supply and clean-up systems • PFBC Heat exchanger design support
CanmetENERGY	• Fluidized Bed Pilot Test Facility • Plant operating personnel

Roles are aligned to team member capabilities

	AR	Linde	Canmet
WBS 1.0 – Program Management	Lead	Support	Support
WBS 2.0 – Component Testing	Lead		
WBS 2.1 – In-bed SCO2 HEX	Lead		Support
WBS 2.2 – Staged coal combustion	Lead		Support
WBS 2.3 – Isothermal DeOxidation Reactor	Support	Lead	Support
WBS 3.0 – Pilot Testing	Lead		
WBS 3.1 – Test Planning	Lead	Support	Support
WBS 3.2 – Commissioning	Support	Support	Lead
WBS 3.3 – Testing	Support	Support	Lead
WBS 3.4 - Canadian Feedstock Testing	Support	Support	Lead

Legend: Lead | Support

Project is organized with clear roles and responsibilities to facilitate task performance

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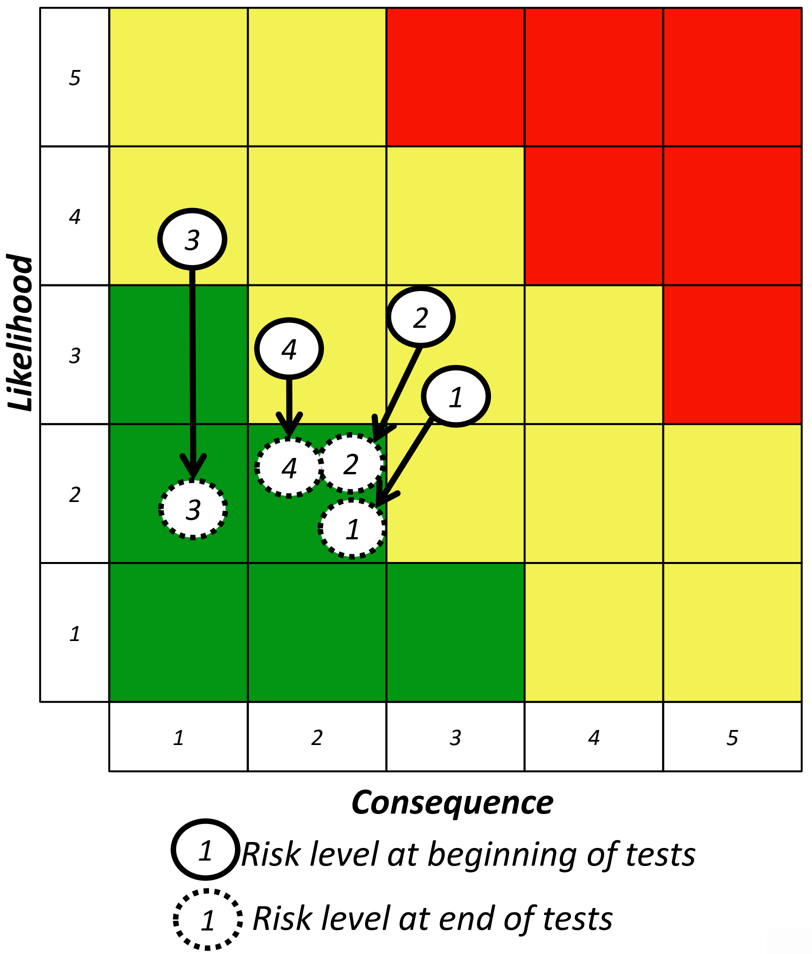
Risks and Mitigation – Technical Risks

1) ***Risk:*** *Uneven oxygen mixing creates local reducing zones*
   Mitigations*: Heritage designs available. Inject through multiple ports.*

2) ***Risk:*** *Second stage temperature is too high (caused by short reactor)*
   Mitigations*: Characterize thermal profiles in pilot. Reduce firing rate kW/m2 in two-stage test.*

3) ***Risk:*** *Lack of familiarity with SCO2 working fluid results in unpredicted behavior*
   Mitigation*: Standard safety precautions, HAZOPS. Design system to tolerate failures of single components.*

4) ***Risk:*** *Packaging of De-Oxidizer heat exchanger prevents accurate cooling where needed in catalyst bed.*
   Mitigation*: Phase II pilot reactor data will guide design. Can incorporate extra cooling to mitigate a moving reaction front.*



Risks and Mitigation – Nontechnical Risks

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management Mitigation and Response Strategies
Resource Risks:			
Inadequate personnel available	Low	Moderate	Bring people in from AR that are outside of the Energy group. If sufficient AR people are not available, bring in outside contract personnel on a temporary basis.
Management Risks:			
Lack of coordination between team members	Low	Moderate	Continue to conduct weekly team meetings to coordinate activities and assess impacts of project results across multiple organizations. Daily tagup meetings for relevant team members will be established as necessary for tasks requiring intense interactions, such as during test preparation and test campaigns.
Schedule Risks:			
Inadequate schedule for completing pilot testing	Low	Moderate	Maintain two months of schedule slack between the end of Oxy-PFBC Phase II pilot testing and installation of equipment for testing on this program.
Budgetary Risks:			
Inadequate budget	Low	Moderate	Monitor technical progress against expenditures and develop action plans when necessary to maintain project on schedule and budget. Use experienced test crews to minimize risk of cost overruns on testing.
Environmental, Safety, and Health Risks:			
Injury during testing	Low	Moderate	Conduct Haz Ops and Level of Protection Analysis (LOPA), design hardware to applicable safety standards, conduct safety training of all personnel, conduct regular safety meetings and reviews, follow established safety procedures.
External Influences Risks:			
None identified			

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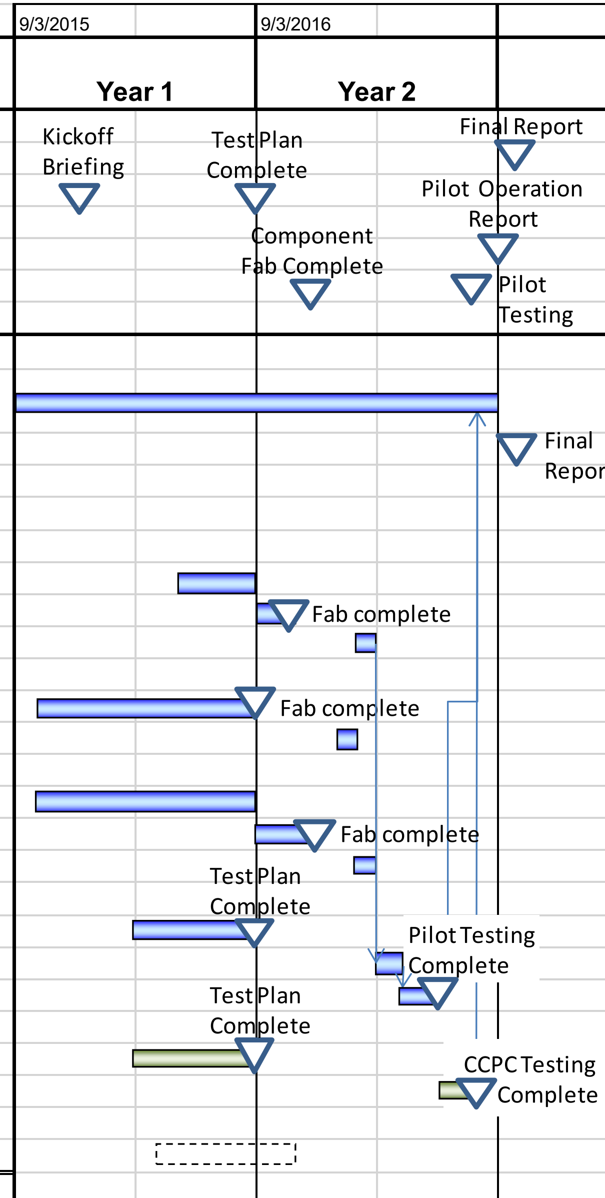
Schedule

Tasks	WBS	Start date	End date	Cost ($M)
Key program milestones				
WBS 1.0 Program Management				**0.34**
Management	1.1, 1.2	9/3/15	9/2/17	
Reporting	1.4	10/1/15	10/2/17	
WBS 2.0 Component Development				**1.32**
In-bed SCO2 HEX	2.1			
Design and component acquisition		5/1/16	8/31/16	
Assemble		9/1/16	11/30/16	
Install		2/1/17	2/28/17	
Staged coal combustion	2.2			
Design and assemble		10/1/15	8/31/16	
Install		1/1/17	1/31/17	
Isothermal DeOxidation Reactor	2.3			
Design and component fab		10/1/15	8/31/16	
Assemble		9/1/16	11/30/16	
Install		2/1/17	2/28/17	
WBS 3.0 Pilot Test				**0.95**
Test Planning	3.1	3/1/16	8/31/16	
Commissioning	3.2	3/1/17	3/31/17	
Testing	3.3	4/1/17	5/31/17	
Canadian Feedstock Testing	3.4			
Test Planning		3/1/16	8/31/16	
Testing		6/1/17	7/31/17	
Oxy-PFBC Ph. II Testing (for reference)	N/A	4/1/16	10/31/16	
			Total	**2.61**



Deliverables

Budget Period	Task No.	Milestone Description	Planned Start	Planned Comp	Actual Comp	Verification Method
1	1.4	Conduct Kickoff Briefing	10/1/15	10/31/15	10/23/15	Presentation file
1	2.3	Complete Design of Isothermal DeOxidation Reactor	10/1/15	5/31/16		Design Review briefing file
1	2.2	Complete Design of Staged Coal Combustion Assembly	10/1/15	4/30/16		Design Review briefing file
1	2.1	Complete Design of SCO2 Heat Exchanger	5/1/16	5/30/16		Design Review briefing file
1	3.1	Complete Pilot Plant Test Plan	3/1/16	8/31/16		Pilot Plant Test Plan file
1	2.2	Complete Coal Injector Fab	10/1/15	8/31/16		Photos of completed hardware
2	2.1	Complete In-Bed HEX Fab	5/1/16	11/30/16		Photos of completed hardware
2	3.3	Complete Pilot Testing	3/1/17	5/31/17		Pilot Plant Operation Report file
2	3.4	Complete CCPC Testing	6/1/17	8/15/17		Pilot Plant Operation Report file
2	1.4	Pilot Plant Operation Report	7/31/17	8/31/17		Pilot Plant Operation Report file
1, 2	1.4	Periodic, Topical, and Final Scientific/Technical Reports	Varies	Varies		Reports

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Budget and Spend Plan

➢ Program Funding Profile

	Budget Period 1 9/3/2015 - 9/2/2016 Government Share	Cost Share	Budget Period 2 9/3/2016 - 9/2/2017 Government Share	Cost Share	Total
Aerojet Rocketdyne*	$ 443,599	$ -	$ 507,642	$ -	$ 951,241
Canmet	$ 483,056	$ 87,824	$ 361,980	$ 237,535	$ 1,170,395
Linde	$ 151,806	$ 37,951	$ 48,670	$ 12,167	$ 250,594
CCPC Testing	$ -	$ 158,760	$ -	$ 79,360	$ 238,120
Total	$ 1,078,461	$ 284,535	$ 918,292	$ 329,062	$ 2,610,350
Cost Share %	79%	21%	74%	26%	

*Aerojet Rocketdyne portion will become GTI once contract is novated from Aerojet Rocketdyne to GTI

Budget and Spend Plan

➢ Program Costing Profile

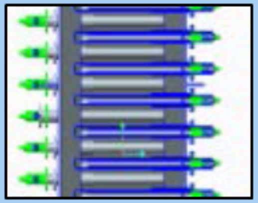
	Budget Period 1 9/3/2015 - 9/2/2016				Budget Period 2 9/3/2016 - 9/2/2017			
Baseline Plan	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Federal	$ 112,349	$ 252,673	$ 163,363	$ 550,074	$ 213,343	$ 302,673	$ 305,378	$ 96,878
Non-Federal	$ 13,891	$ 15,641	$ 50,201	$ 204,804	$ 12,167	$ 118,768	$ 138,764	$ 59,384
Total Planned	$ 126,240	$ 268,314	$ 213,564	$ 754,878	$ 225,510	$ 421,441	$ 444,142	$ 156,262
Cumulative Plan								
Federal	$ 112,349	$ 365,022	$ 528,385	$ 1,078,459	$ 1,291,802	$ 1,594,475	$ 1,899,853	$ 1,996,731
Non-Federal	$ 13,891	$ 29,532	$ 79,733	$ 284,537	$ 296,704	$ 415,472	$ 554,235	$ 613,619
Total Planned	$ 126,240	$ 394,554	$ 608,118	$ 1,362,996	$ 1,588,506	$ 2,009,947	$ 2,454,088	$ 2,610,350

Summary

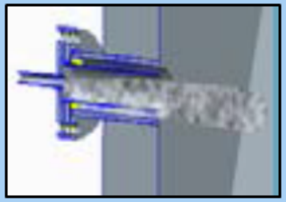
- Oxy-PFBC with SCO2 Brayton cycle exceeds DOE targets for COE and CO_2 capture, approaching DOE Transformative Goal

- The Enabling Technologies program will test three key technologies at the pilot scale to demonstrate improved performance and reduce scale up risk

Enabling Technologies for Oxy-PFBC



Supercritical CO2 Heat Exchanger
SCO2 enables over 8% reduction in Cost of Electricity



Staged Coal Combustion
Improved efficiency and operability with reduced slagging risk

Isothermal Deoxidation Reactor
Provides additional heat recovery for improved efficiency

- GTI / Linde / Canmet team has the skills and depth to successfully develop and demonstrate the proposed technologies