the Energy to Lead

Enabling Technologies for Oxy-fired Pressurized Fluidized Bed Combustor Development

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Agenda

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

Enabling Technologies for Oxy-PFBC Development

Overview

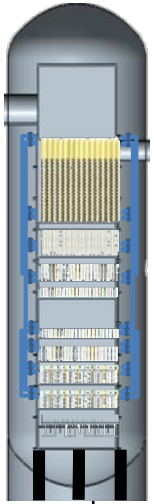
Description and Impacts

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



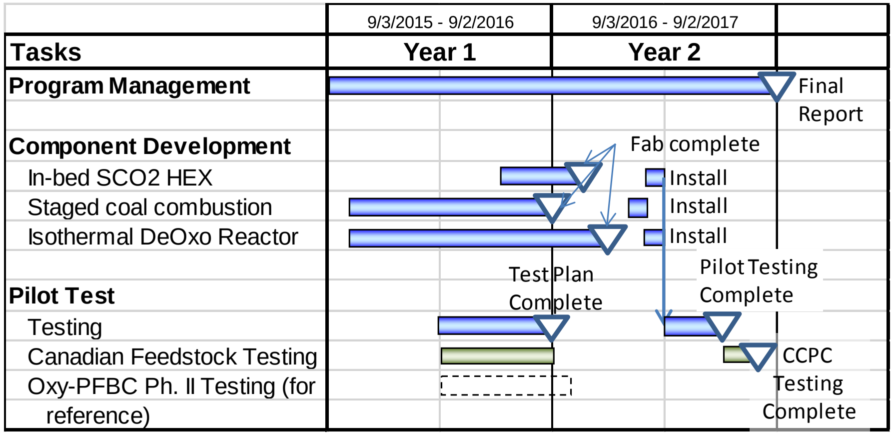
Team Members and Roles

- **GTI (Gas Technology Institute)** – Lead, PFBC technology
- **Linde, LLC** – Isothermal DeOxo Reactor technology and integration with SCO2 cycle
- **CanmetENERGY–** 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



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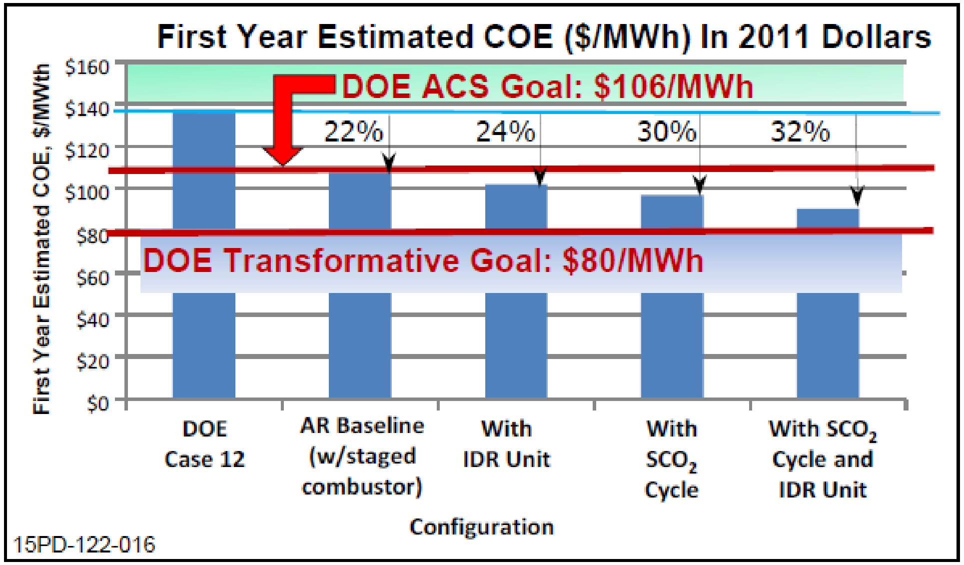
Project Background and Benefits

- 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

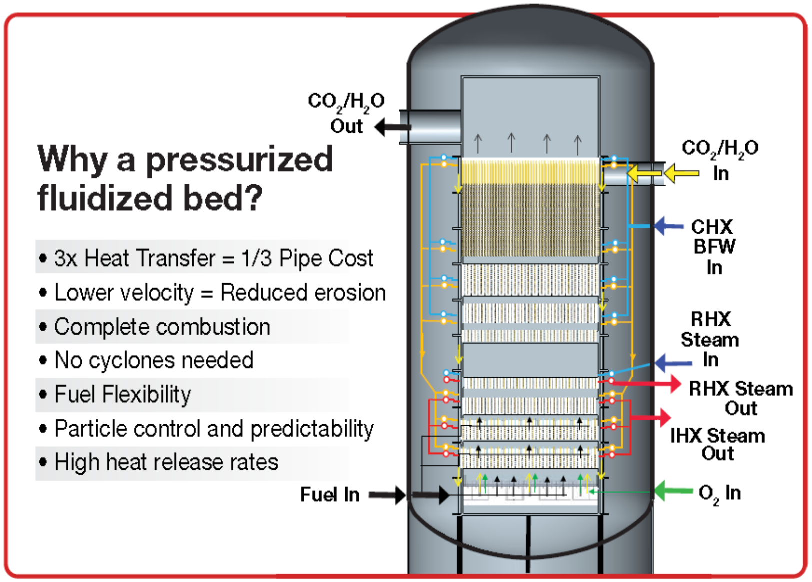


Projected performance exceeds the DOE Advanced Combustion Goal and approaches the DOE Transformative Goal

Oxy-PFBC Technology Overview

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



Commercial Scale PFBC Concept

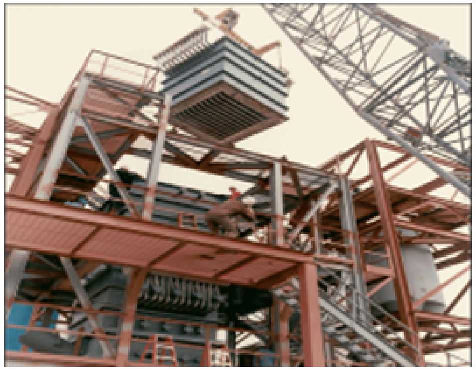
BENEFITS

- 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 and CHP
- Heavy oil production (once-through steam)
- Light oil production (CO_2 floods)

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



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

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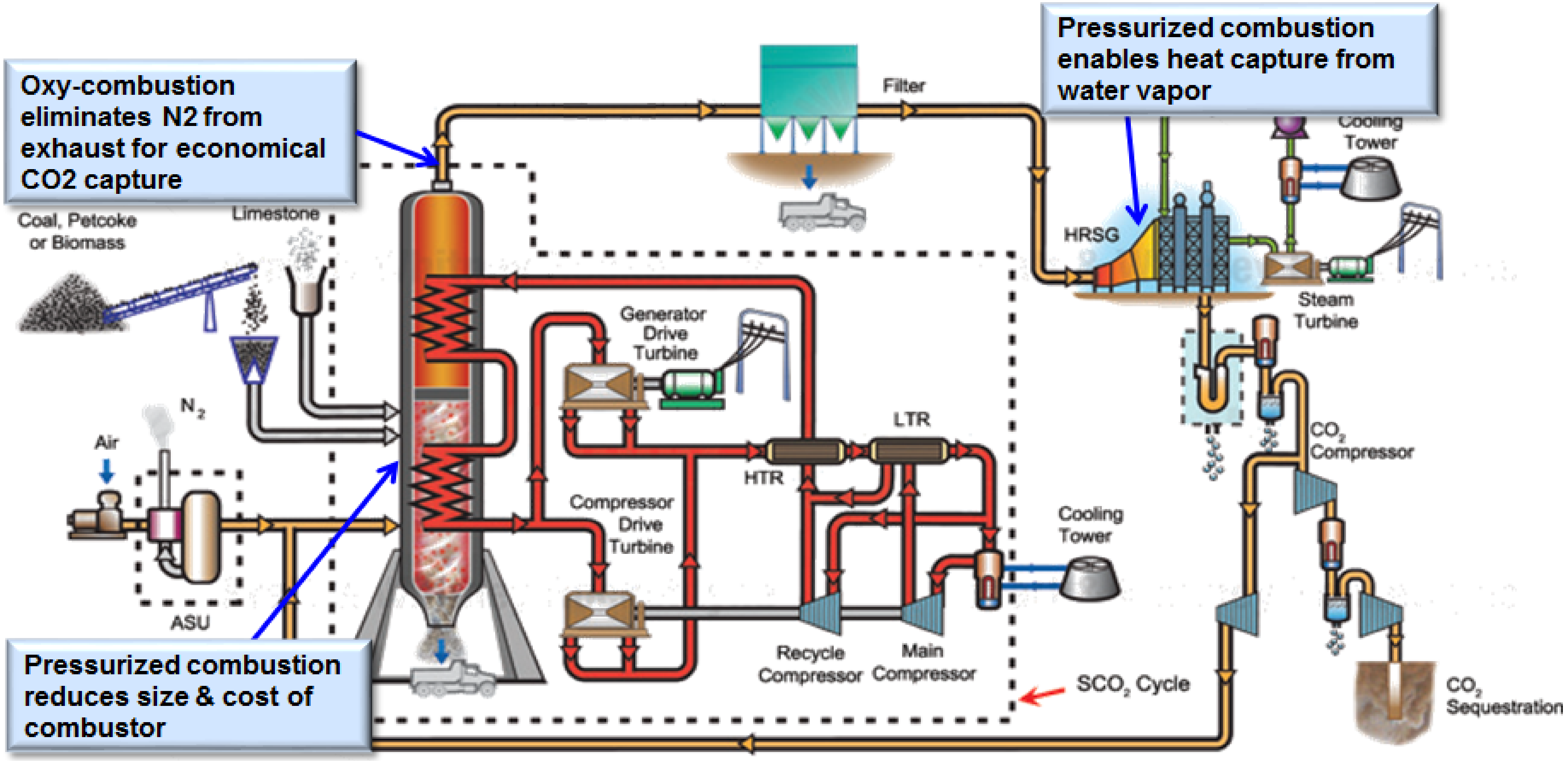
ZEPS™ Powerplant Concept Vision



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

ZEPS = Zero Emissions Power and Steam

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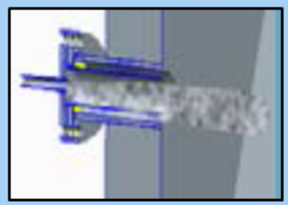
Approach

- Develop three technology upgrades for the Oxy-PFBC system and test at pilot scale
  - **Supercritical CO_2 (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 O_2 concentration for an isothermal catalyst bed and demonstrate heat recovery

Enabling Technologies for Oxy-PFBC

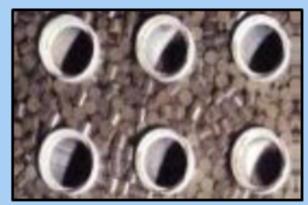
Supercritical CO_2 Heat Exchanger

SCO2 enables over 8% reduction in Cost of Electricity



Staged Coal Combustion

Improved efficiency and operability with reduced slagging risk



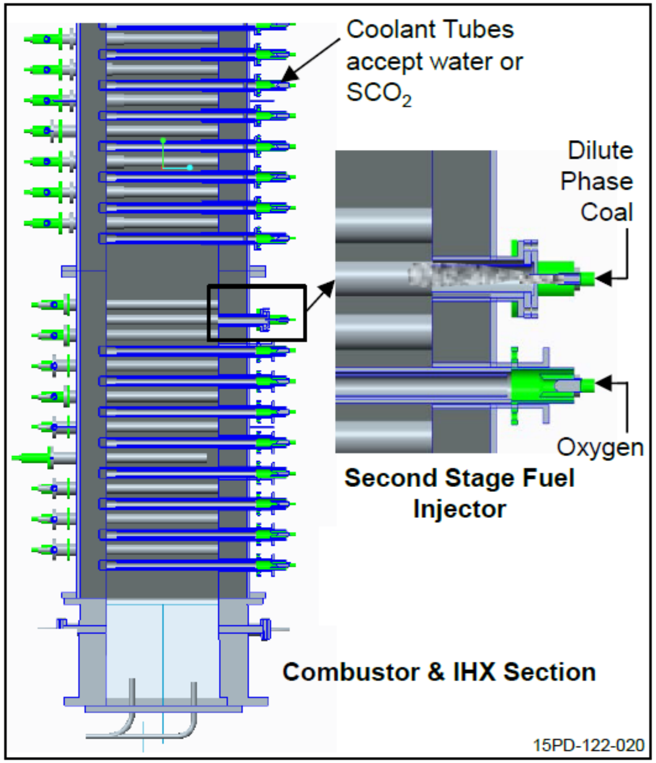
Isothermal Deoxidation Reactor

Provides additional heat recovery for improved efficiency

In-bed SCO_2 Heat Exchanger

Technology Overview and Approach

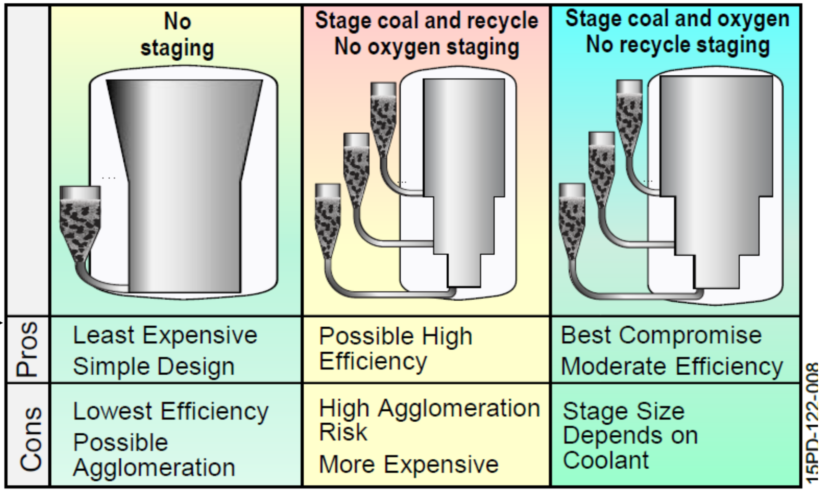
- Background
  - One technology gap for SCO2 is integration with the heat source, including use of SCO2 as the working fluid in the in-bed heat exchangers
- Approach
  - Operating conditions
    - SCO2 at 2500 psia and between 400F and 700F
    - Conditions avoid potential condensation on the bed-side surface of the tubes
  - To enable scaling, determine hot and cold-side heat transfer coefficients, and coolant pressure drop
  - Establish design performance for heat exchangers
  - Minimize scaling risk
    - Heat exchanger tube Re and Pr numbers enable scaling to the predicted commercial operating conditions
    - Use 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 planned for the commercial scale Oxy-PFBC design to maximize power density 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
  - Demonstrate and characterize operation of second stage injectors
    - Fuel: Illinois #6, Alberta subbit, Saskatchewan lignite
    - Characterize impacts of flue gas recycle rate, fuel particle size and ash content, and coolant flow control
    - Vary oxygen / fuel flow rates and bed cooling
  - 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



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Isothermal Deoxidation Reactor (IDR)

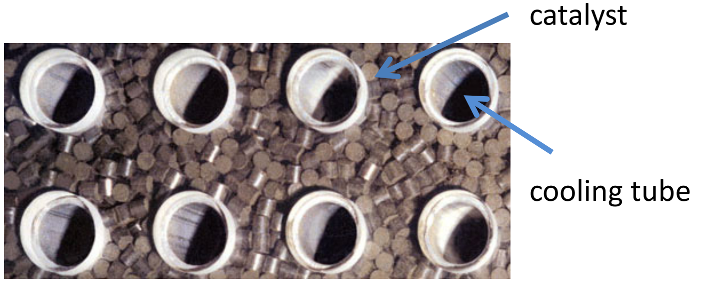
Technology Overview and Approach

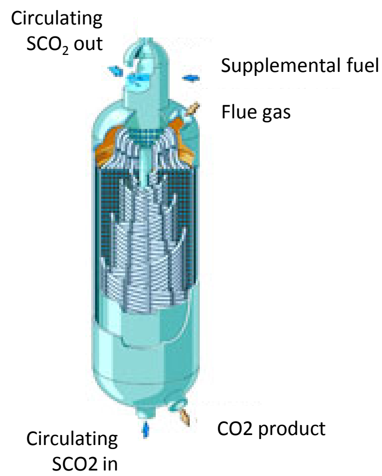
Background

- 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 O_2 content in the flue gas below 100 ppm to meet EOR specs
- Test the benefits of integrating the heat of oxidation reactions into the SCO2 Brayton Cycle

Approach

- The IDR will use an internal heat exchanger with SCO_2 coolant to maintain a near constant catalyst bed temperature
- Characterize and define operational limits, in terms of flue gas O_2 content and heat recovery
  - 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
  - The amount of O_2 removed is controlled by the fuel flow rate into the catalytic reactor.
  - Temperature of the catalyst bed is controlled by matching IDR fuel flow rate with catalyst heat exchanger coolant flow





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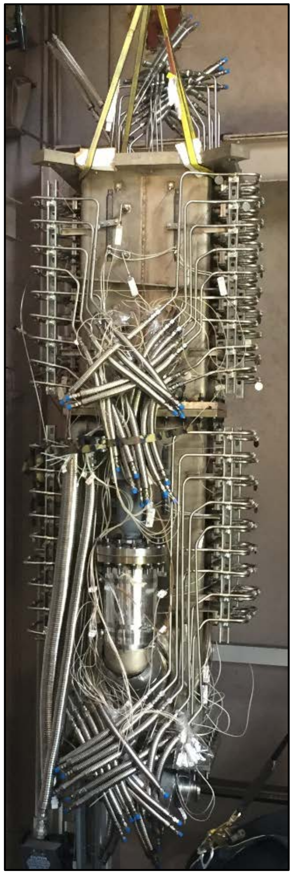
Significant Accomplishments

- In-bed SCO2 heat exchanger
  - In-bed SCO2 heat exchanger fabricated and installed in 1 MWth pilot scale combustor
  - SCO2 cooling loop design, process and instrumentation drawings and equipment sizing complete; procurement in progress
- Staged coal combustion
  - Completed design of staged coal combustion assembly
  - Injector fabrication in work
- Isothermal De-oxidation Reactor (IDR)
  - Process design complete

In-bed SCO2 heat exchanger

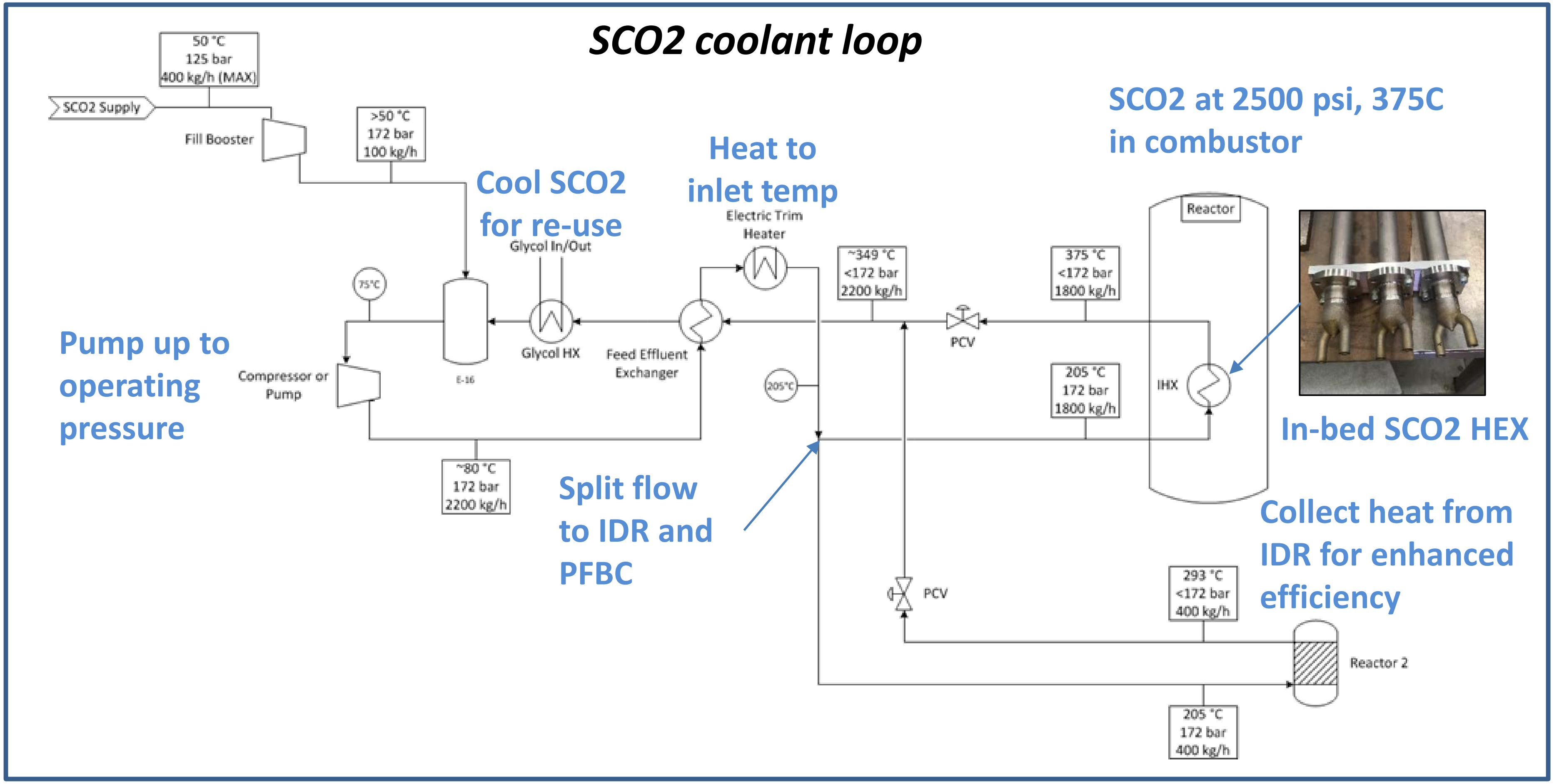
- SCO2 manifolds designed to support high pressure (2500 psi) coolant
- Manifolds fabricated using additive manufacturing and passed CAT scan inspection
- Manifolds installed in 1 MWth pilot combustor at CanmetENERGY facility

SCO2 manifolds and in-bed heat exchanger assembly



Assembly installed on the combustor

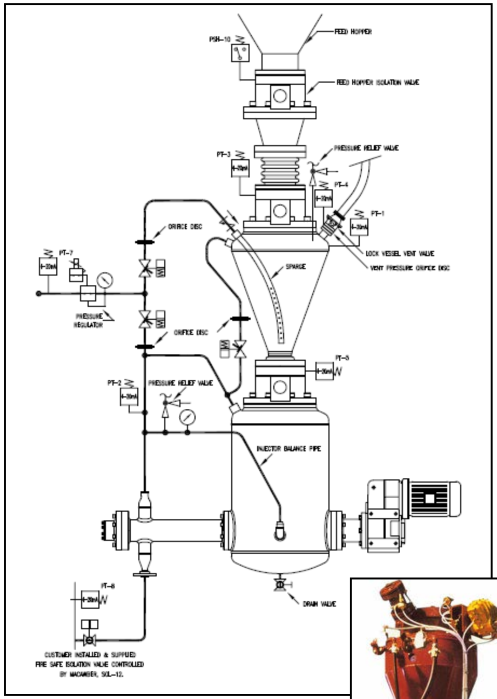
In-bed SCO2 heat exchanger



SCO_2 cooling loop design complete; procurement in progress

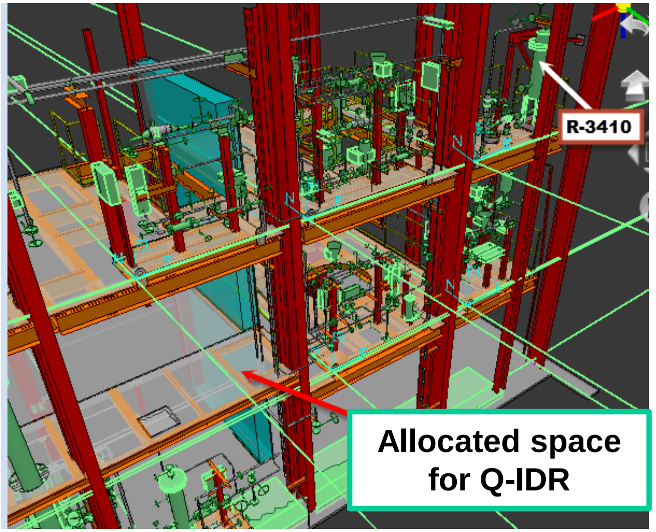
Staged Coal Combustion

- ➢ Second stage fuel injector fabrication in work
- ➢ Procurement in work for pneumatic fuel pump and related equipment
  - Pressure balance capability to handle variable process back pressure and maintain flow accuracy
  - Continuous injection accuracy to ±3% by volume, even against changing back pressure

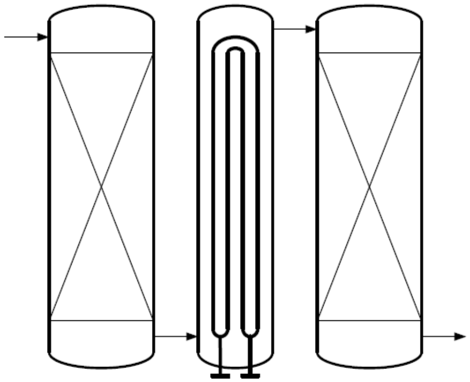


Quasi-isothermal deoxidation reactor concept: Plans for pilot implementation

- Implementation of a fully isothermal catalytic deoxidation reactor, with immersed spiral wound heat exchanger determined to be very challenging and expensive to design, manufacture and control, for a small scale pilot demonstration.
- Comparable process benefits will be demonstrated with a Quasi-Isothermal Deoxidation Reactor, consisting of two adiabatic catalytic reactors with an interstage cooler.



Partial 3D view of existing CPU skid



Simplified schematic of Quasi-Isothermal Deoxidation Reactor (Q-IDR)

- Detailed process design completed, including: Detailed M&E Balances, Equipment Sizing, Fuel Injection and Control logic.
- Mechanical design and RFQs are in progress
- Final piping layout and connections are pending completion of current skids

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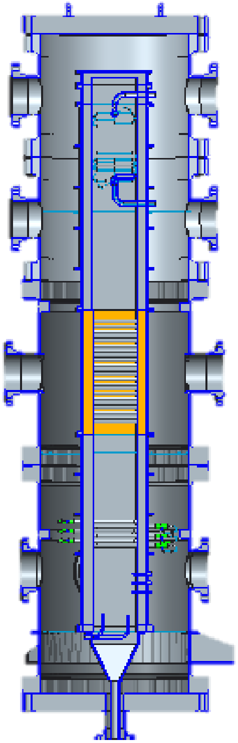
Future Plans

- Complete fabrication of hardware upgrades
- Install hardware into 1 MWth pilot at Canmet
- Conduct testing with Illinois #6, Alberta subbituminous and Saskatchewan lignite

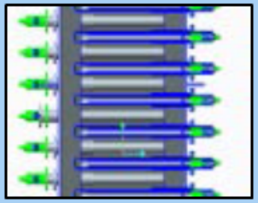


1 MWth pilot scale Oxy-PFBC

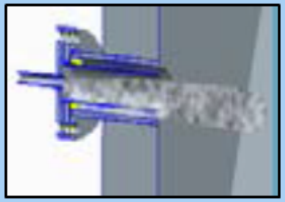
Summary

- Program will test three key technologies at the pilot scale to demonstrate improved performance and reduce scale up risk
- First combined test of Oxy-PFBC and SCO2
- In-bed SCO2 heat exchanger installed
- Staged coal combustion hardware in fabrication
- IDR process design complete using quasi-isothermal approach
- Testing to start in spring 2017

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

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