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

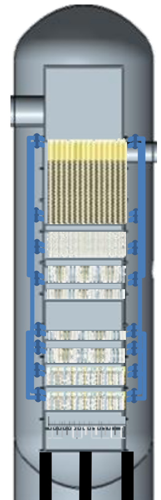
Description and Impacts

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



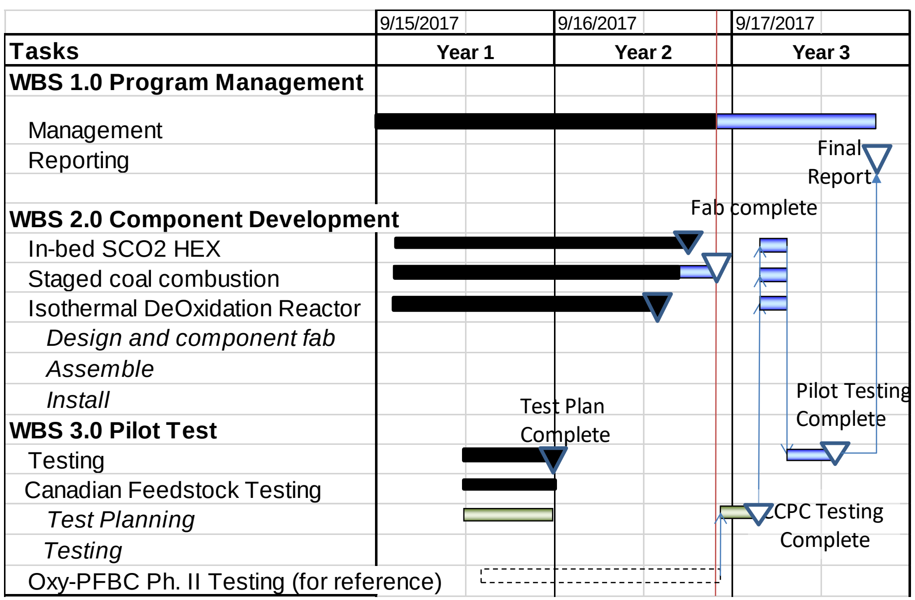
Team Members and Roles

- **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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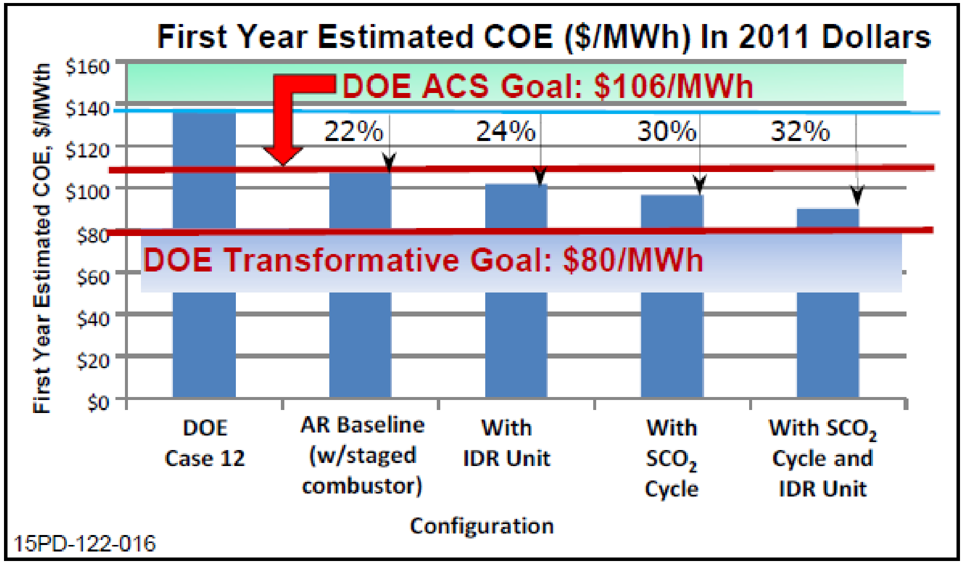
Project Background and Benefits

- 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

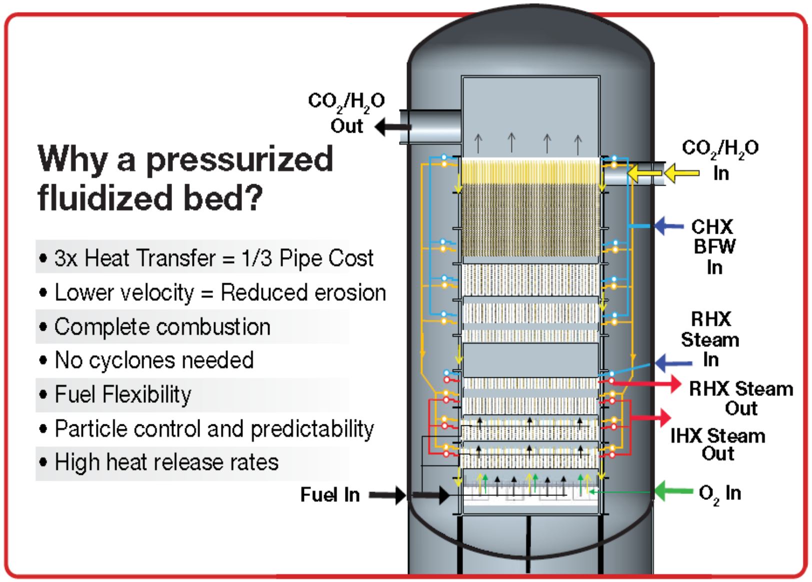


Projected performance exceeds the DOE Advanced Combustion Goal and approaches the DOE Transformative Goal

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

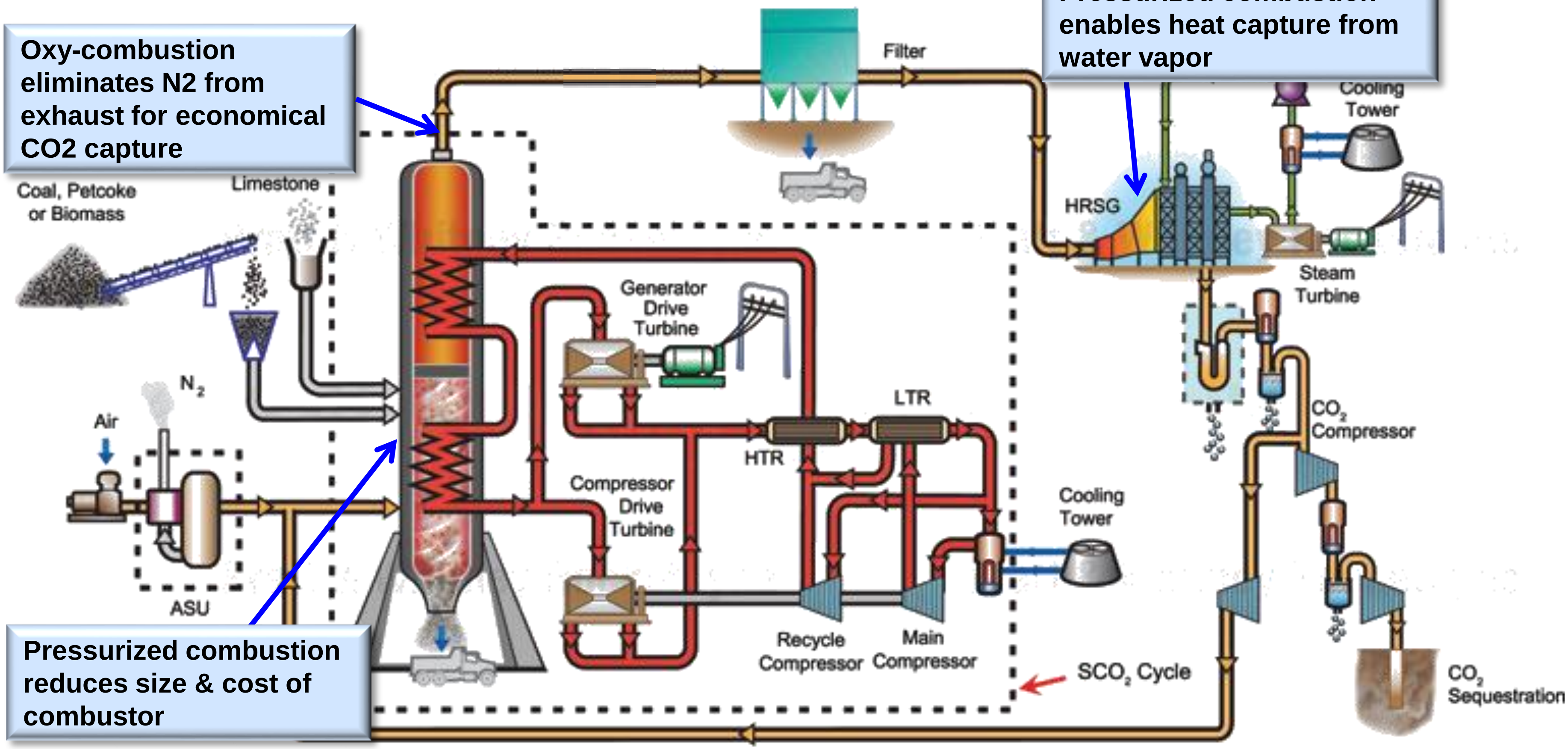
STATUS

- 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

ZEPS™ Powerplant Concept Vision

Oxy-combustion eliminates N2 from exhaust for economical CO2 capture

Pressurized combustion enables heat capture from water vapor



Pressurized combustion reduces size & cost of combustor

- **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

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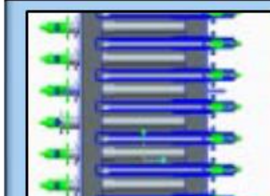
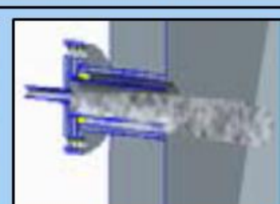
Enabling Technologies for Oxy-PFBC



Supercritical CO2 Heat Exchanger

SCO2 enables over 8% reduction in Cost of Electricity



Staged Coal Combustion

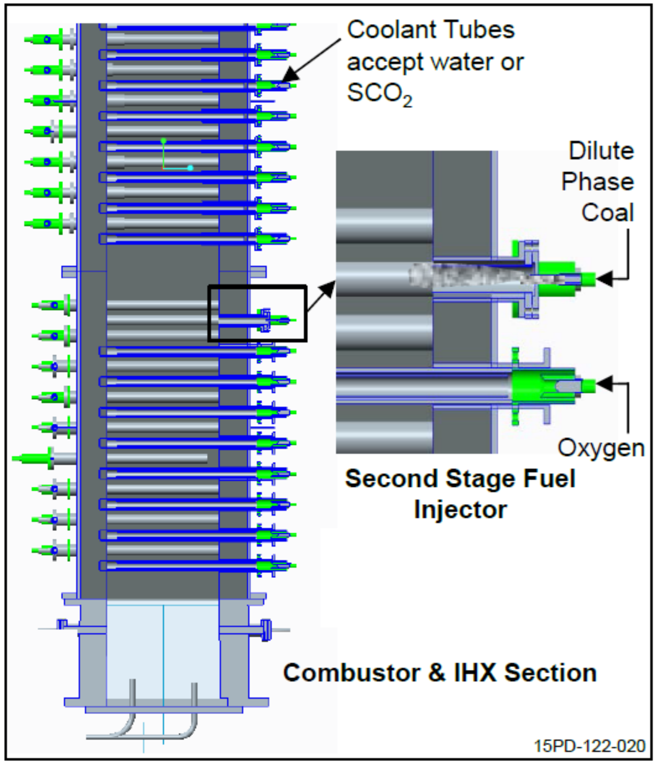
Improved efficiency and operability with reduced slagging risk

Isothermal Deoxidation Reactor

Provides additional heat recovery for improved efficiency

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

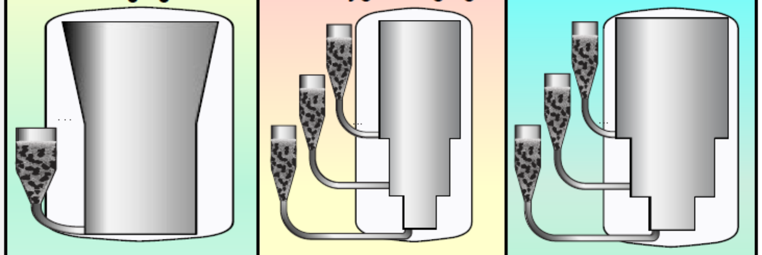


Modular pilot design enables retrofit of SCO2 coolant and fuel / oxygen injectors

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



	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

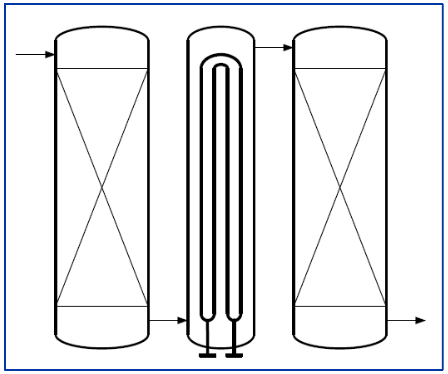
Quasi - Isothermal Deoxidation Reactor (Q-IDR)

Technology Overview and Approach

- **Background**
  - A Quasi-Isothermal Deoxidation Reactor (Q-IDR) concept
    - Enables wider range of O_2 removal than a single adiabatic reactor
    - Maintains thermal operating window within the range tolerated by the catalyst.
  - This project will also test the benefits of integrating the heat of oxidation reactions of supplemental fuel and/or CO_2 impurities into the SCO_2 Brayton Cycle

- **Approach**
  - The Q-IDR consists of two adiabatic catalytic reactors with a single inter-stage cooler with supercritical CO_2 working fluid.
    - Interstage cooler reduces temperature of the gas exiting first reactor before entering second reactor
  - Tests will 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

Single IDR installed at Canmet



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

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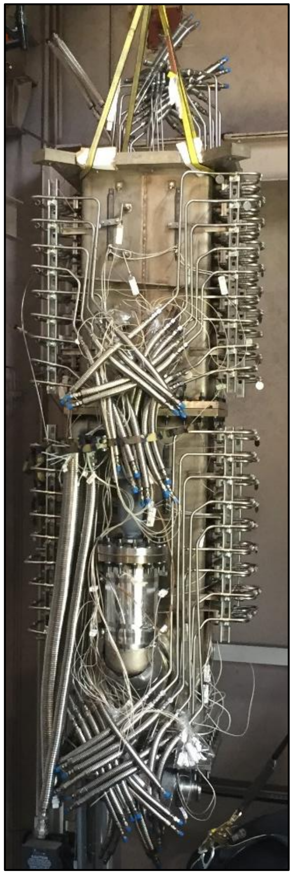
Significant Accomplishments

- In-bed SCO2 heat exchanger
  - Fabrication of SCO2 compressor is complete
  - SCO2 heat exchanger is installed in combustor
  - Basic Engineering Package for the SCO2 loop is complete
- Staged coal combustion
  - Injector fabrication complete
  - Fuel pump fabrication in work – incorporating lessons learned from Oxy-PFBC Phase II program
- Quasi-Isothermal De-oxidation Reactor (Q-IDR)
  - Major hardware fabrication (heat exchangers and reactor) complete

In-bed SCO2 heat exchanger

- SCO2 heat exchanger installed in 1 MWth pilot combustor at CanmetENERGY facility
- SCO2 compressor fabrication complete

SCO2 manifolds and in-bed heat exchanger assembly



Assembly installed on the combustor

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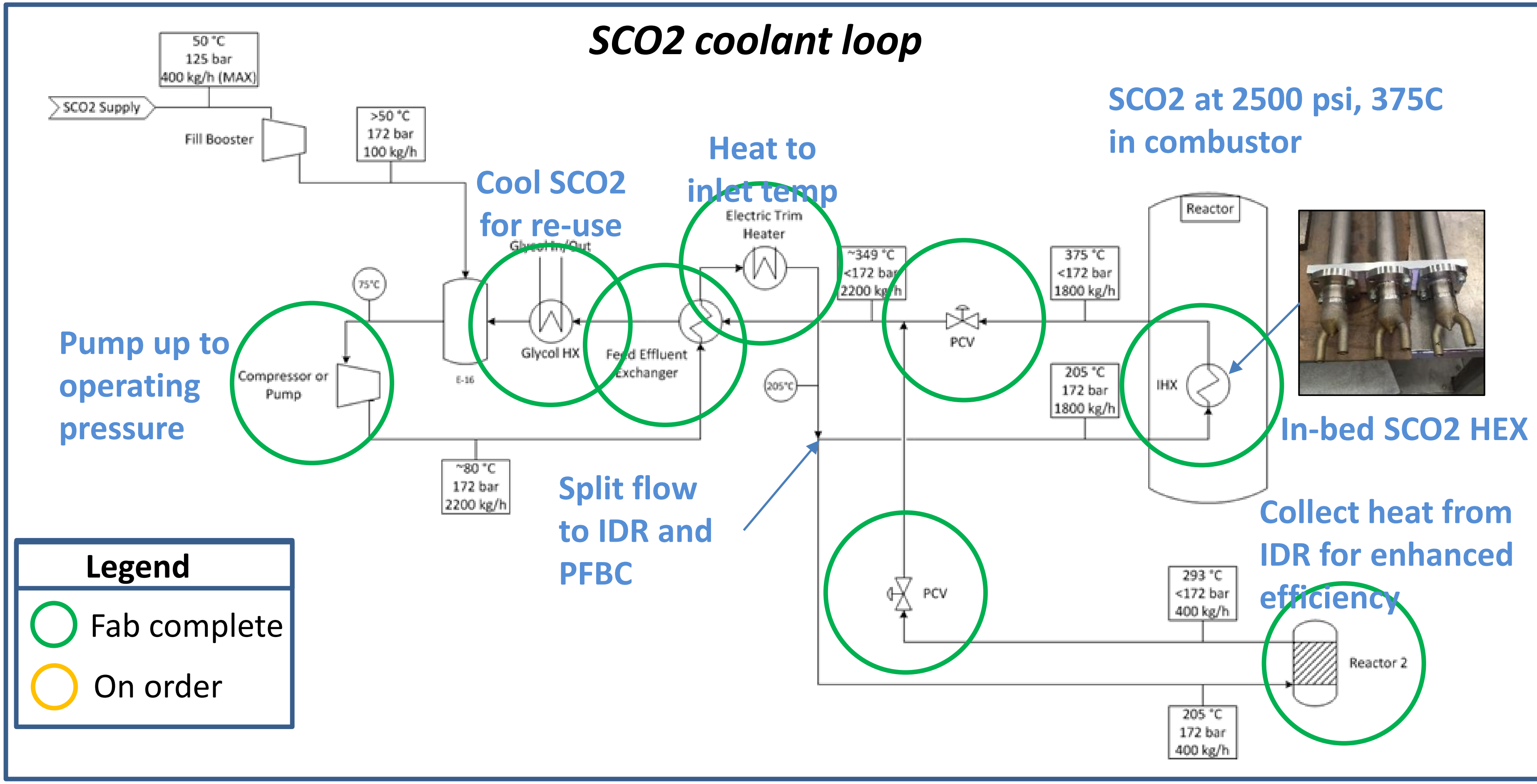
In-bed SCO2 heat exchanger



SCO_2 cooling loop design complete; procurement in progress

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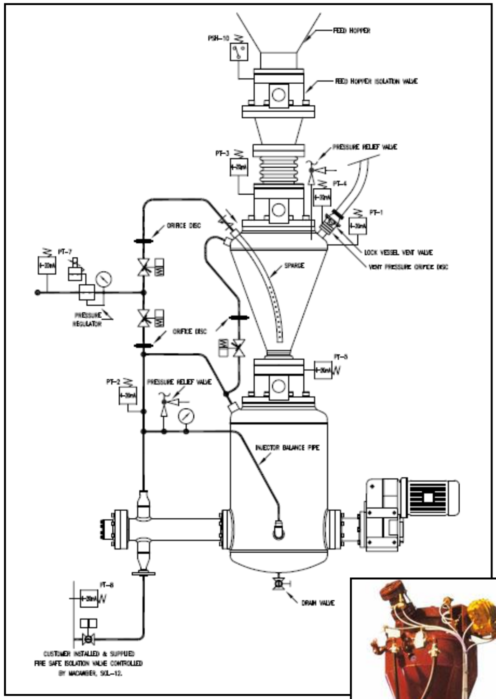
Staged Coal Combustion

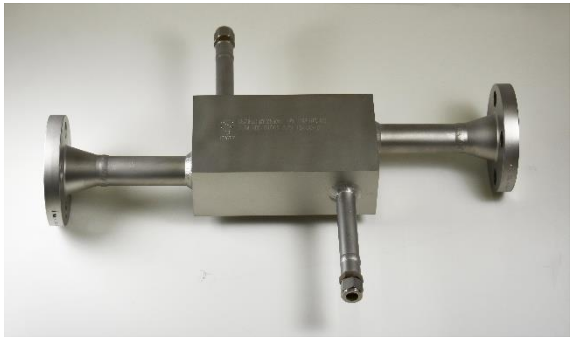
- Fabrication complete for second stage fuel injectors (two types fabricated)
- Fabrication in progress for pneumatic fuel pump and related equipment
  - Lessons learned from Oxy-PFBC Phase II program incorporated into fuel pump design



Quasi-isothermal deoxidation reactor

- 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 two-stage Quasi-Isothermal Deoxidation Reactor, consisting of two adiabatic catalytic reactors with an interstage cooler.

Interstage cooler: Diffusion bonded Micro Channel Heat Exchanger (MCHE)



5.2 kW MCHE delivered to Canmet Dimensions: 8”x5”x3”

- MCHE selected over conventional shell and tube heat exchanger due to lower cost and size, while still capable of operating under extreme pressure and temperature gradients.
    - MCHE is an order of magnitude lighter and smaller and multiple times less expensive than shell & tube HEX

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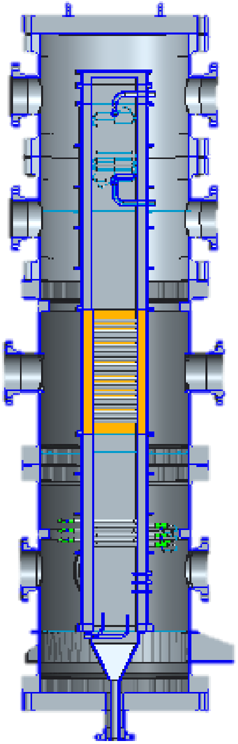
Future Plans

- Conduct testing with Canadian feedstock starting in October
- Complete installation of hardware upgrades into 1 MWth pilot at Canmet in winter
- Conduct testing with US feedstock in spring 2018

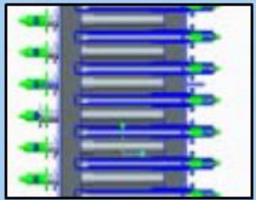


1 MWth pilot scale Oxy-PFBC

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 SCO_2
- Major SCO_2 loop components fabricated
- Staged coal combustion injector fabrication complete
- IDR reactor and MCHE fabrication complete
- Testing to start in October

Enabling Technologies for Oxy-PFBC



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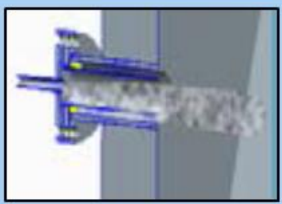
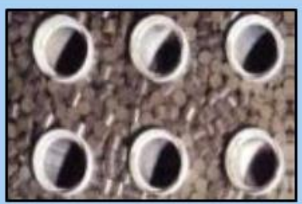


Staged Coal Combustion

Improved efficiency and operability with reduced slagging risk



Isothermal Deoxidation Reactor

Provides additional heat recovery for improved efficiency

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