CO₂ Capture Project (CCP) Phase 3 – Advancing to Deliver Results

Mark Crombie – CCP3 Program Manager

BP Group Technology, UK

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An Oil Refinery Scenario

A Joint Workshop organized by IEA Greenhouse Gas R&D Programme (IEAGHG) and IEA Industrial Energy-related Technologies and Systems (IETS)
CO$_2$ Capture Project (CCP) – History
CCP4 “Advancing CCS technology deployment and knowledge for the oil and gas industry”

CCP1 2000-2004 Screening/proof of concept

CCP2 2004-2009 Intensive development

CCP3 2009-2014 Demonstration phase

CCP4 2014-2018 Further Advancement
CO₂ Capture Project (CCP) – Teams
The project consists of four work teams, supported by Economic Modeling:

- **Capture**: aiming to reduce the cost of CO$_2$ capture from a range of refinery, in-situ extraction of bitumen and natural gas power generation sources, supported by Economic Modeling: building a fuller picture of the integrated costs for CCS

- **Storage Monitoring & Verification (SMV)**: increasing understanding and developing methods for safely storing and monitoring CO$_2$ in the subsurface

- **Policy & Incentives**: providing technical and economic insights needed by stakeholders, to inform the development of legal and policy frameworks

- **Communications**: taking rich content from the ongoing work of the other teams and delivering it to diverse audiences including government, industry, NGOs and the general public
Capture Program – Refinery Scenario
## The Refinery Scenario

### Refinery Scenario

#### Technology demonstration
- Oxy-fired Fluid Catalytic Cracking (FCC) Pilot Plant demonstration
  - Vacuum Gas Oil & Atmospheric Residue Feeds

#### Development projects
- Capture of CO2 from refinery heaters using oxy-fired technology
- Membrane Water Gas Shift (MWGS)

#### Economic evaluation
- Hydrogen production for chemical use (Steam reforming)

### Heavy Oil and NGCC Scenario

#### Technology demonstration
- Oxy-fired Once Through Steam Generators (OTSG)
  - 50 MMBTU/hr OTSG retrofit

#### Economic evaluation
- Natural Gas Combined Cycle (NGCC) power station (400 MW)
Field demonstration of Fluid Catalytic Cracking (FCC) oxy-firing capture (Petrobras)
Refinery Scenario

- Field demonstration of Fluid Catalytic Cracking (FCC) oxy-firing capture technology at Petrobras, Brazil
- FCC is one of the main sources of oil refinery CO₂ emissions (20-30%)
- Aim: to evaluate operability, test start-up and shut down procedures and obtain data for scale-up

*Image courtesy of Petrobras*
**FCC Large Scale Pilot Unit**

- **Catalyst inventory**: x 150
- **Feed flow rate**: x 200
- **Full scale unit**: x 280 to 2000

**Capacity**: Cat. Inventory = 300 kg; feed flow rate = 200 kg/h (30 bpd) VGO; 1t/d CO₂ emission

*Image courtesy of Petrobras*
FCC Summary and Conclusions

- The technical viability of oxy-firing an FCC unit was demonstrated on a large scale pilot test unit.

- The results have shown the CO$_2$ content in flue gas to be over 94% (dry basis). For industrial application the purity is expected to be even higher.

- Two oxy-combustion conditions have been tested: same heat balance and same inert flow rate. The first showed very little impact in product slate while the second showed a gain in feed conversion. Alternatively, the feed rate may be increased by about 10% while keeping constant conversion.

- Corrosion inside the recycle compressor was observed, indicating the need for adequate handling of the gas and use of resistant material for long-term operation.
Refinery Heaters and Boilers – Oxy-firing of process heaters (John Zink Company)
Background

• In CCP Phase 1, oxy-firing showed potential
  • Lower energy requirements: flue gas contains mostly CO\textsubscript{2} and water (minimal nitrogen and O\textsubscript{2} separation)
  • ASU cost is significant - investigated ion transport membrane to generate O\textsubscript{2}

Objectives

• Assess the feasibility of utilizing conventional process heater burners for oxy-firing
• Confirm the feasibility of oxy-firing in process heaters by conducting single burner testing with flue gas recycle
• Construct computational fluid dynamics (CFD) models to simulate oxy-firing in typical multi-burner heater geometries
Objective: Identify feasible operating conditions in typical process heating in oxy-fuel mode

- Overall heater efficiency
- Maximum film temperature and tube metal temperature limitations
- Radiant / convection heat absorption ratio
- Flue gas recycle requirements

Results:

- Without flue gas recycle, high levels of excess oxidant would be required
- Conditions with 0.5 - 2 wet vol% O\textsubscript{2} concentration in flue gas, recirculation rate 72%
- Oxy-firing provides a ~14% improvement in heater efficiency compared to ambient air base case
- Met maximum film and tube metal temperature constraints; small changes to radiant/convection section duty split; minimized O\textsubscript{2} use
Single Burner Test Furnace

- Two John Zink burners tested
  - PSFG: low NO$_x$ diffusion flame burning with staged fuel injection
  - COOLStar: ultra low NO$_x$ diffusion flame burner with internal flue gas recirculation and staged fuel injection

- Test furnace cooled by single-pass water tubes in radiant section; no convection section

- Measurements: flame appearance, flame stability, flame length, incident heat profile, stack emissions, CO/O$_2$ measurements upstream of burner, temperature

Furnace for burner tests (courtesy of John Zink Co.)
Single Burner Tests

- External boiler to cool flue gas prior to recirculating fan (carbon steel)

- Oxidant:
  - Ambient Air (baseline)
  - O₂ (5.2% O₂ in flue gas and 1.3% O₂ in flue gas)

- Fuel:
  - Tulsa natural gas
  - Simulated refinery fuel gas
Result of Single Burner Tests

- No burner modification required for either burner; minimum to maximum heat release
- Transition from air to oxy-fire operation demonstrated
- Satisfactory turn down with both burners and both fuels at 72% flue gas recycle
- FGR rate and O₂ concentration are important operating parameters:
  - Large FGR can push combustion process to flammability limit, especially under low O₂ conditions
  - A less “reactive” fuel, e.g. natural gas, may need a higher percentage of oxygen in the oxidant during oxy-firing
- Significant reduction in NOₓ emissions
- To make oxy-firing effective in process heaters, proper sealing would be essential to minimize air ingress
  - Even under certain low draft test conditions, N₂ concentrations as high as 11% was measured in the recirculated flue gas
Development of Pd-Alloy Membrane for CO$_2$ Capture and H$_2$ Recovery (Pall Corporation)
Background

Capturing CO₂ from refinery heaters and boilers (H&Bs)

- H&Bs are a significant source of CO₂ in a refinery
  - They are usually scattered throughout a refinery
  - Post-combustion and oxy-combustion technologies are not generally practical in a space-constrained refinery
  - Pre-combustion capture technology with the production of low-carbon H₂ fuel in a centralized location provides an economical alternative for capturing CO₂ from H&Bs

Producing low-carbon H₂ in a refinery

- Steam methane reformers (SMRs) are widely employed for producing <200 MMSCFD H₂
- For larger H₂ quantities, such as for H&Bs, autothermal reformers (ATRs) provide certain advantages, e.g. a single source of CO₂ available at high pressure.
- CO₂ removal in aMDEA® solvent is the conventional technology
- CO₂ separation using H₂ membranes has several advantages:
  - High purity H₂ stream can be obtained at a suitable pressure (1–2 barg)
  - CO₂ stream is available at high pressure, thus reducing the compression energy
  - Removal of H₂ at high temperature improves the equilibrium in the WGS reaction
• ATR produces the syngas containing $\text{H}_2$, CO, $\text{CO}_2$, $\text{H}_2\text{O}$
• Two membrane stages are preceded by a high temperature shift reactor to convert CO into $\text{H}_2$ and thus increase the overall $\text{H}_2$ recovery in the membranes
• The retentate from the membrane unit is processed in a cryogenic purification unit (CPU) to recover a high purity $\text{CO}_2$ product stream
• Overall targeted $\text{H}_2$ recovery is 90% with purity >95 mol%
Project Objectives and Methodology

Project Objectives

• Evaluate the performance of Pd alloy-based membranes in separating H₂ from simulated syngas
• Use the performance data along with a model to design and cost a commercial scale membrane system for producing 5,000 MMBtu/h (LHV) of low-carbon H₂ fuel stream in an ATR process while producing a purified CO₂ stream at high pressure suitable for sequestration

Methodology

• Perform experiments on Pd alloy-based membranes/modules to develop and calibrate a simulation model
• Use the performance data for design and costing of a commercial scale membrane module system
Steam Methane Reforming - Hydrogen Plants Techno-Economic Evaluations (Foster Wheeler Energy)
Background

- Hydrogen production is energy intensive
- CO₂ emission from Hydrogen plants can contribute up to 20% of refinery emissions
- Steam Methane Reforming (SMR) is the industrial workhorse to produce hydrogen
- CO₂ from SMR unit is produced from two sources:
  - High pressure in main process stream - Reforming and shift steps (50-60% of total)
  - Low Pressure in flue gas stream - Fuel combustion in the reformer furnace (40-50% of total)
Objectives

1. To identify the process scheme with 90% overall CO₂ capture from the SMR unit
2. Conduct techno-economic feasibility analysis with Foster Wheeler for the identified scheme/technology for a 50,000 Nm³/hr hydrogen plant

Process Scheme

Post combustion with 90% capture from the reformer flue gas with 18-22 vol% CO₂
Design

- 50,000 Nm\(^3\)/hr hydrogen plant with Pressure Swing Adsorption (PSA)
- 5% flue gas bypass to stack
- Remainder 95% flue gas is sent to absorber with 90% capture from this feed
- MHI-KS1 – current state-of-the-art technology is used for post combustion capture
- Stand-alone steam boiler package supplies the steam required for Capture plant
- Power needed is imported over the fence
- Captured CO\(_2\) is dehydrated and compressed to 150 barg for pipeline transport
Capture Program – Heavy Oil Scenario
Oxy-fired Once Through Steam Generators (Cenovus)
Heavy Oil Scenario

• Capture from multiple Once Through Steam Generators (OTSGs) in the Canadian oil sands was studied in CCP3
• Cases were designed to provide the same amount of useful injection steam as the reference case

Image courtesy of Cenovus
Once Through Steam Generator (OTSG)

Two Phase Project:
- Phase I (completed 2010): Develop design basis and cost estimates for test and commercial scale OTSGs
- Phase II (2011-present): Pilot oxy-fuel combustion on 50 MMBTU/hr test OTSG

Overall Objective:
- To demonstrate that oxy-fuel combustion is a safe, reliable and potentially cost-effective technology for CO₂ capture from once-through steam generators

Demonstration System Process Schematic
Results

- The best technology to capture CO₂ today appears to be post-combustion
- Although the CO₂ sources are large, the remote location complicates technology application and costs
- Capture from OTSGs is therefore one of the least economically viable CCS applications studied by CCP (levelized CCP3 capture cost 200 $USD/tonne)
Economic Modeling (Foster Wheeler Energy)
Calculated capture and avoidance costs include transportation and storage

<table>
<thead>
<tr>
<th>Base Assumptions</th>
<th>Units</th>
<th>Value</th>
<th>Source</th>
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<tbody>
<tr>
<td>Fuel Gas Price – US</td>
<td>USD/GJ</td>
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<td>Gulf Coast Public Data</td>
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<td>Electricity Price - US</td>
<td>USD/MWh</td>
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<td>Fuel Gas Price – AB</td>
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<td>Electricity Price - AB</td>
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<td>Time Horizon</td>
<td>Years</td>
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<td>CCP Assumption</td>
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<tr>
<td>Power Intensity</td>
<td>tCO₂ /MWh</td>
<td>0.60</td>
<td>Gulf Coast Public Data</td>
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<tr>
<td>Steam Intensity for WHB FCC</td>
<td>tCO₂ /t</td>
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<td>Heat to Produce Steam for FCC</td>
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<td>CO₂ Transportation and Storage *</td>
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<td>9.1</td>
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- Post-combustion steam consumption for solvent regeneration in the range of 2.7-3.0 GJ/ton of CO₂
- Transport costs based on capital costs factored from NETL data
CCP3 Economic Results

- Post-combustion solvent-based technology is still the most economic (or close second)
- CO$_2$ avoidance costs are very high, especially for the Heavy Oil (oil sands) scenario due to the Alberta location
- The economic assumptions, such as fuel cost, location factor, imported power cost/CO$_2$ footprint, process scale/configuration, all have an impact on the costs

<table>
<thead>
<tr>
<th>Application Scenario and Case Description</th>
<th>Fuel</th>
<th>CO$_2$ captured</th>
<th>CO$_2$ capture</th>
<th>CO$_2$ avoided</th>
<th>CO$_2$ capture cost</th>
<th>CO$_2$ avoided cost</th>
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<tbody>
<tr>
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<td>FCC - Post Combustion</td>
<td>Carbon</td>
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<td>OTSGs - Post-Combustion</td>
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<td>NGCC - Post-Combustion</td>
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<td>85.5</td>
<td>73.7</td>
<td>97.9</td>
<td>113.6</td>
</tr>
</tbody>
</table>
Capture Summary and Conclusions

• Three scenarios pertinent to the oil and gas industry were targeted in CCP3
  • Post-, pre- and oxy-combustion technologies were investigated at lab, bench, pilot and demo scale
  • Supplemented by independent technical and economic assessments
  • Significant amount of knowledge was obtained in CCP3
  • CO₂ avoidance costs are very high, especially for the Heavy Oil scenario due to the location
  • The economic assumptions, such as fuel cost, location factor, imported power cost/CO₂ footprint, process scale/configuration, all have an impact on the costs
CCP Conclusions
CCP Conclusions

- CCS is the only technology that could enable continued large-scale use of fossil fuels in a tightly constrained world.

- Post combustion capture technologies have seen some recent improvements, but what does the future look like versus alternatives, and will this achieve the end goal?

- Commercial complexity exists along the value chain, within an uncertain business and policy environment.

- Significant government funding is required for demonstration, and transitional support is needed for wider deployment to achieve learning curve cost reduction.

- There are some promising technology solutions to dramatically reduce capture costs & effectively verify safe/secure storage at scale, so R&D needs to continue.

- CCP looks to build on its experience & expertise, welcome new partners and collaborate with others to ensure success.
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Questions?
End