CO_2 Capture Project (CCP) Phase 3:
Field Trials Move Capture Technology Closer to Deployment

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Project Overview

The CO_2 Capture Project (CCP) is an award-winning partnership of several major energy companies working to advance the technologies that will underpin the deployment of industrial-scale CO_2 capture and storage (CCS). The CCP is currently in its third phase of activity:

- Phase 1 (CCP1, 2001-2004) technology screening/proof of concept – **completed**
- Phase 2 (CCP2, 2004-2009) intensive development – **completed**
- Phase 3 (CCP3, 2009-2013) demonstration – **on going**

The CCP is funded primarily by:

- Member and associate member contributions
- Government grants
- In-kind contributions

CCP3 project members are:

BP (Program Operator), Chevron, Eni, Petrobras, Shell and Suncor.

Program Objectives

To move CCS towards commercial deployment, as one way to reduce emissions from power plants and heavy industrial processes such as oil refining and gas processing, the CCP objectives are to:

- **Increase technical and cost knowledge** associated with CO_2 capture technologies and confirm that geological storage of CO_2 is a secure and viable means of reducing greenhouse gas emissions
- **Reduce CO2 capture costs by 20-30%** by supporting the development of improved technologies
- **Quantify remaining assurance issues** surrounding geological storage of CO2 through site assessments, field surveys and numerical approaches; and rapid dissemination of results to stakeholder groups
- **Validate cost-effectiveness of monitoring developments** with design and testing of emerging and integrated systems
- **Cooperate with interested parties to share information** about both capture and storage demonstrations

CCP3 Team Overview

The detail work of CCP3 is managed by 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
- **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
- **Economic Modeling**: building a fuller picture of the integrated costs for CCS

CO_2 Capture Team – Key CCP3 Projects

Economic evaluation (Scenario-based)

- A detailed study by Foster Wheeler on capture of CO_2 using state-of-the-art technologies.
  - Refinery process heaters (4x150 MMBTu/hr) – US location
  - Regenerator of Fluid Catalytic Cracking (FCC) unit (60,000 bpd) – US location
  - Hydrogen production for chemical (Steam reforming) or fuel (Autothermal reforming) use – US location
  - Natural Gas Combined Cycle (NGCC) power station (400 MW) – European location
  - Once-Through Steam Generator (OTSG) for Steam Assisted Gravity Drainage (SAGD) oil extraction – Alberta location

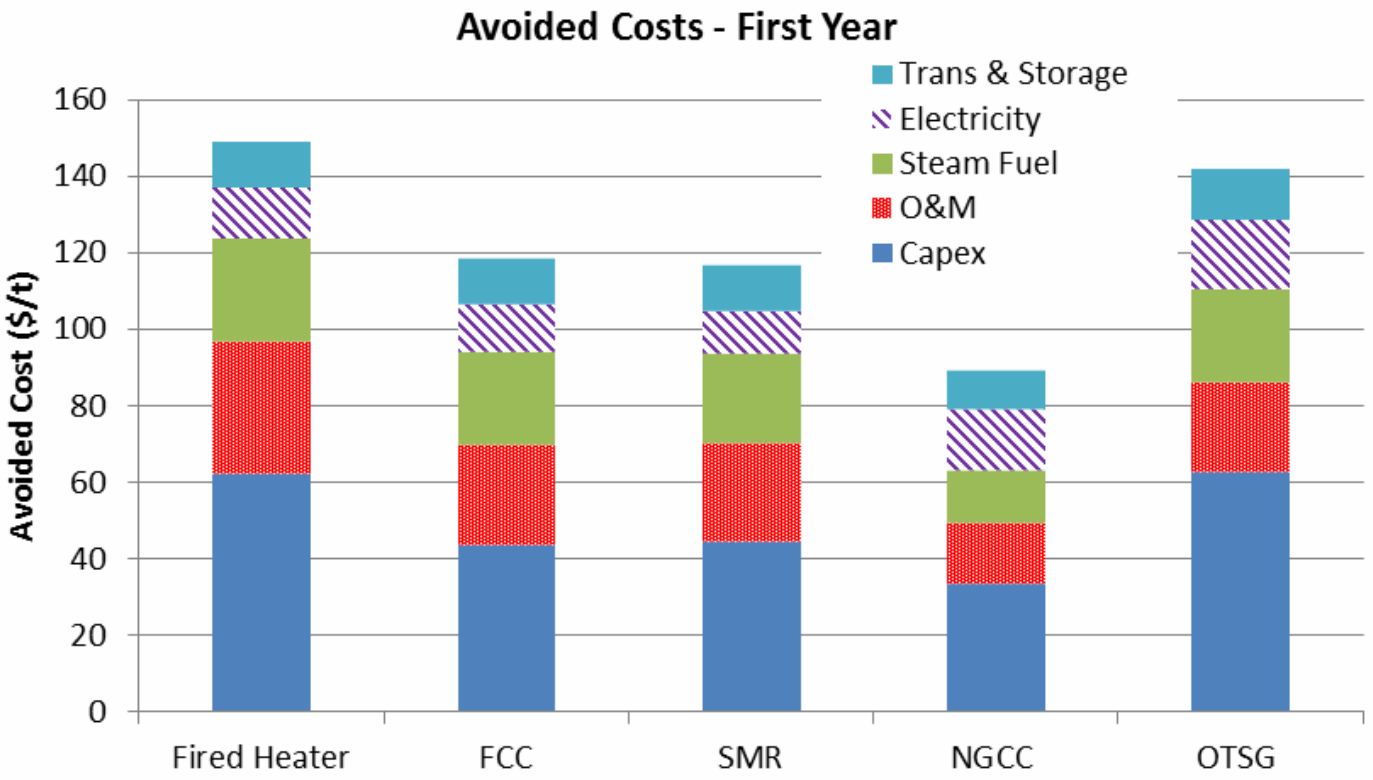
Technology demonstration

- **Oxy-fired Fluid Catalytic Cracking (FCC) Pilot Plant catalyst regen demonstration**
  - Vacuum Gas Oil & Atmospheric Residue Feeds
- **Oxy-fired Once Through Steam Generators (OTSG)**
  - 50 MMBTU/hr OTSG retrofit
- **Capture of CO_2 from refinery heaters using oxy-fired technology**
  - Burner testing at John Zinc

Development projects

- Chemical Looping Combustion
- Membrane Water Gas Shift

Avoided Cost – First Year



FCC Oxy-fired Catalyst Regen Demo Overview

Image courtesy of Petrobras

The Fluid Catalytic Cracking (FCC) unit is often the largest single source of CO_2 emissions in a refinery.

CO_2 Capture Project Capture Cost Study*:

- Oxyfiring delivers lower avoided cost than Post-C capture.
- Oxyfiring has higher capex, but lower opex.
- Site specific factors are very important (i.e. fuel value, steam value, plot space).
- Bench & small pilot testing showed no fatal flaw.

Based on this study, CCP has funded a demo, hosted by Petrobras.

- The test unit has a capacity of up to 33 bbl/d of hydrocarbon feed (1 ton/d of CO2). Testing started in April 2011.

The project's main goals are to:

- Test start-up and shut-down procedures
- Maintain stable operation of the FCC unit in oxy-combustion mode
- Test different operational conditions and process configurations
- Obtain reliable data for scale-up

* A technical and economical evaluation of CO2 capture from FCC units," de Mello *et al* (Petrobras), *Energy Procedia* 1 (2009) 117–124 (GHGT9)

FCC Oxy-fired Catalyst Regen Demo Status and Results

- ✓ **The technical viability of oxy-firing an FCC unit has been demonstrated on a large scale pilot test unit**
- ✓ **The transition from air to O_2 and back was shown to be fast and simple, however care must be taken with the excess oxygen in flue gas**
- ✓ **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 extreme conditions have been tested: *same heat balance* and *same flow rate*. The first showed very little impact in product slate while the second showed a gain in feed conversion.**
- ✓ **Corrosion inside the recycle compressor was observed, indicating the need of adequate handling of the gas and use of resistant material for long term operation.**

Oxy-combustion in Once-Through Steam Generator - OSTG

Three Phase Project:

- Phase I (completed): Develop design basis and cost estimates for test and commercial scale OTSG
- Phase II (2011-13): Demo oxy-fuel combustion on 50 MMBTU/hr test boiler
- Phase III (proposed): Demo oxy-fuel combustion, compression and purification on test boiler

Overall Objective:

To demonstrate that oxy-fuel combustion is a safe, reliable and cost-effective technology for CO_2 capture from once-through steam generators

Image courtesy of Cenovus

Funding Partners: Cenovus Energy (host site), CO_2 Capture Project, Devon, Praxair, Statoil, Meg Energy

Technology Providers:

Praxair – industrial gas & combustion technology
TIW Western – boiler technology

Oxy-Firing of Process Heater Burners

Overview:

- Assess the **feasibility of retrofitting burners for oxy-firing** in process heaters. A secondary objective is to confirm this feasibility assessment by conducting single burner oxy-fired testing with flue gas recycle.
- The CO_2 Capture Project commissioned the John Zink Company to conduct oxy-fired testing on two of their **conventional process heater burners**, an SFG staged gas low NOx burner and a COOLstar® Ultra-Low NOx burner

Results:

- The **process burners operated satisfactorily** under oxy-fire conditions.
- **Multiple air to oxy and oxy to air transitions** were executed with no issues.
- **Flue gas re-circulation rate and oxygen concentration** in the system were varied without adverse effects on burner performance.
- **Air leakage into the system is a significant concern** as it is desirable to obtain a CO_2-rich stream for ease of sequestration. Unlike boilers, process heaters operate under negative pressure relative to atmosphere.

CO_2 Storage Team – Key CCP3 Projects

Theme 1: Assurance R&D

1. **Well Integrity** – Alteration rate / extent and longer-term barrier performance prediction
2. **Subsurface Processes** – Experimental protocols, impurities impacts, geomechanical case studies
3. **Monitoring & Verification** – Retrospectives, modular borehole design, emerging sensors
4. **Optimization** – Certification Framework, economics

Theme 2: Field Trialing of monitoring technology

Theme 3: "Contingencies"

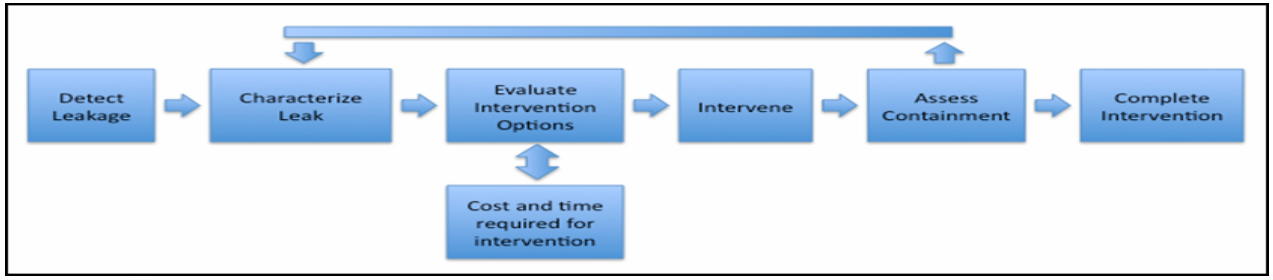
Field Trialing of monitoring technology

Technology	Site	Date
Well Logging		
- Borehole Gravity	Cranfield	2010
- Resistivity (through casing)	Otway	2010
- Modular Borehole Monitoring (MBM)	Citronelle	2012
Well-Based Seismic		
- VSP (Walkaway, 3D)	Otway	2010
- Microseismic	---	---
Surface Seismic		
- 3D surface seismic	Otway	2010
Remote		
- InSAR	Decatur	2012
Other		
- EM	*Aquistore (feasibility)*	*2012*
- Soil Gas	*MRCSP site (planning)*	*2013*

Contingencies

Management of unexpected CO2 or displaced fluid migration. Detection, localization, characterization, intervention and remediation. Phases

1. CCP3 Workshop (Houston, May 2011) ~ 35 experts in geology, geophysics, reservoir engineering & well engineering. Focus on wells, conformance and top seal fractures / fault seal reactivation
2. Modeling & simulation (Stanford) – Four sets of geologic models with injection project / basic monitoring scheme; Simulations of leakage with detection / characterization and intervention (ends Q3 2013; two expert workshops)
3. Design of field-ready intervention plan
   - Mont Terri UGL considered only practical site
   - Fracture sealing experiment concepts with timing / costs consultancy report
4. Field experiment
   - Proposed; Possibly within CCP3 cost / time frame



Courtesy S. Benson & A. Agarwal (Stanford University)

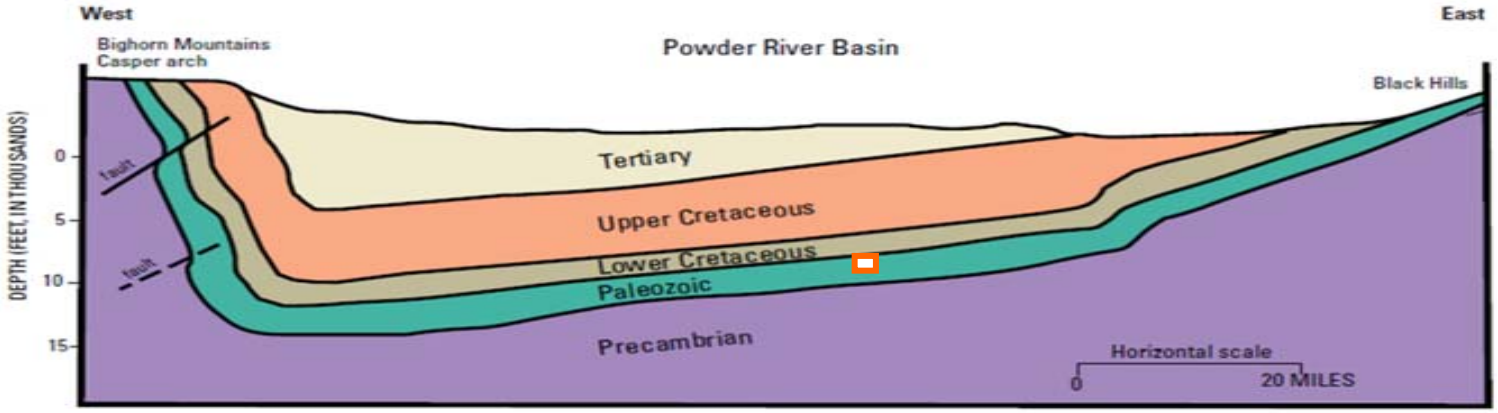
3. Contingencies: Phase 1 (Scenarios)

Scenario	Detection	Response Current	Novel	Remediation Need (HES)	Relative Cost (or Project Threat)
Well Barrier Loss					
• Accessible Well	Well P; Seismic?	Perforation Isolation	BGCO* Agents	Possible	V. Low
• P&A Well	Aquifer / Air	Mill & Re-P&A	Intercept & Seal	Likely	Low-Medium
• Unknown Well	Aquifer / Air	Locate, Mill & Re-P&A	Intercept & Seal	Likely	Medium
Conformance					
• Thief Zone	Well P; Seismic?	Perforation Isolation	BGCO* Agents	None	Low-High
• Compartments	Well P	New Wells	Stimulation	None	Low-Medium
• Spill Zone	Well P; Seismic?	New Wells	Intercept & Seal Hydraulic Barrier	Possible	Medium-High
Natural Barrier Breach					
• Top Seal Fracture	Well P; Seismic?	New Wells/ Shutdown?	Intercept & Seal Hydraulic Barrier	Possible	High-V. High
• Top Seal Thinning	Well P; Seismic?	New wells or shutdown	Hydraulic Control Intercept & Seal	Possible	Medium-High
• Fault Reactivation	Seismicity	Shutdown?	Intercept & Seal	Likely	V.High-Extreme

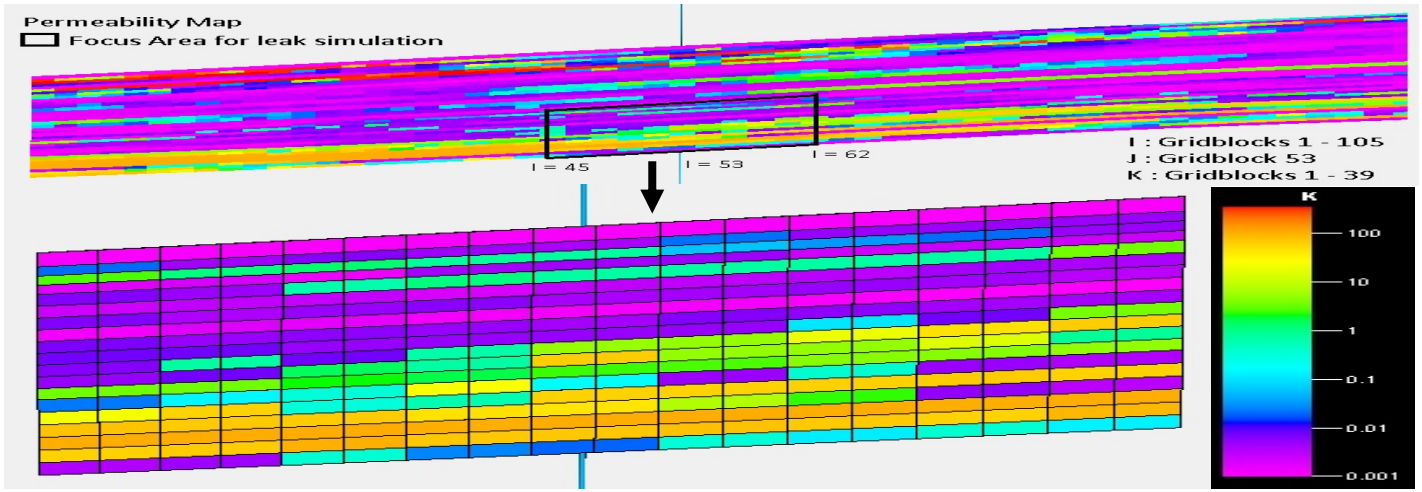
* BGCO – Biological (e.g., biofilms), geochemical (mineralization), conventional (oil field sealants), Other (foams, nano-particles)

Imbus et al. (2012) – GHGT11

Contingencies: Phase 2 (Modeling)



Case study 1 – Injection of 3MTPA into Paleozoic of the Powder River Basin

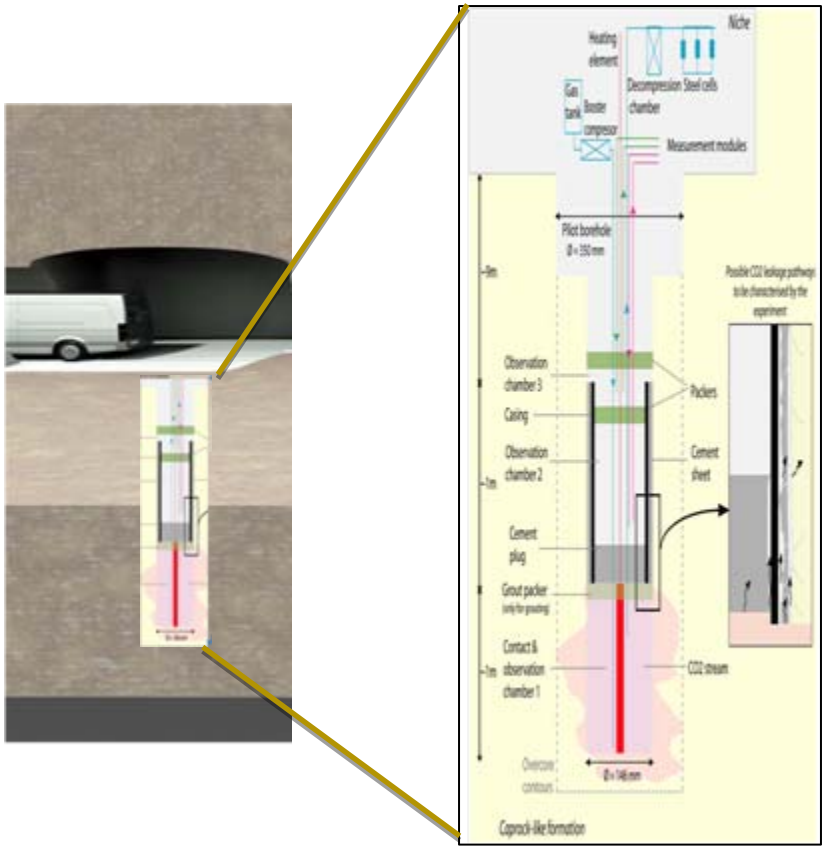


Permeability map of cross section of study focus area

Courtesy S. Benson & A. Agarwal (Stanford University)

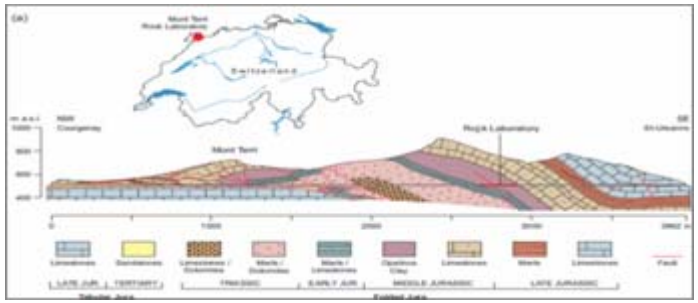
Contingencies: Phase 3 (Field trial - pending)

Defective CO2 well exposure and sealing experiment (CS-A)

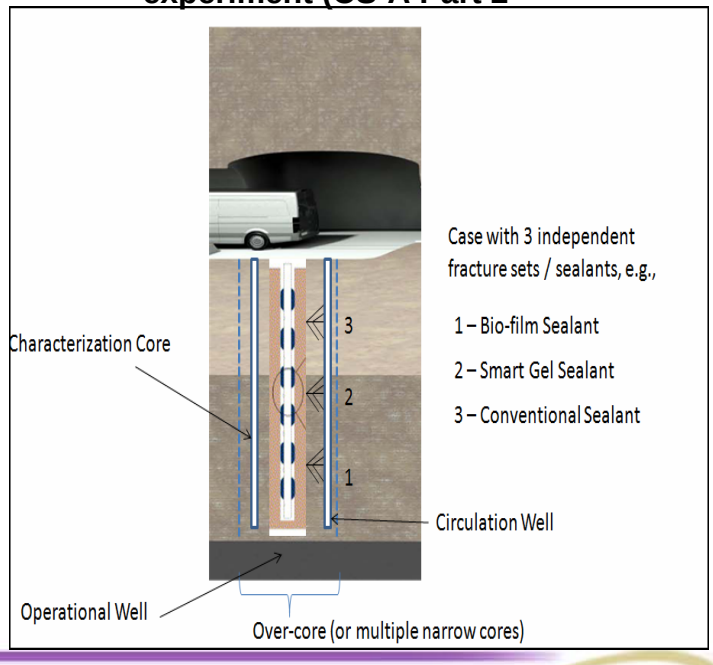


Schematic illustrations courtesy of Harvey Goodman (Chevron)

Mont Terri Underground Lab



Possible fracture sealing experiment (CS-A Part 2



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