CO_2 Capture Project (CCP) Phase 3 – Advancing to Deliver Results

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CCS in Process Industries - State-of- the-Art and Future Opportunities - Tuesday 11th March 2015

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

CCP3

CO_2 Capture Project (CCP) – Teams

CCP3 Team Overview

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

•*Image courtesy of Petrobras*

- Field demonstration of Fluid Catalytic Cracking (FCC) oxy-firing capture technology at Petrobras, Brazil
- FCC is one of the main sources of oil refinery CO_2 emissions (20-30%)
- Aim: to evaluate operability, test start-up and shut down procedures and obtain data for scale-up

FCC Testing Unit

FCC Large Scale Pilot Unit

Typical pilot plant		Test unit		Full scale unit
Catalyst inventory	x 150 →		x 280 to 2000 →	
Feed flow rate	x 200 →		x 580 to 2000 →	

Capacity: Cat. Inventory = 300 kg; feed flow rate = 200 kg/h (30 bpd) VGO; 1t/d CO_2 emission

•*Image courtesy of Petrobras*

Refinery Scenario – FCC Summary & Conclusions

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 and Objectives

Background

- In CCP Phase 1, oxy-firing showed potential
  - Lower energy requirements: flue gas contains mostly CO_2 and water (minimal nitrogen and O_2 separation)
- ASU cost is significant - investigated ion transport membrane to generate O_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

Heater Performance Modeling (OnQuest, FRNC-5)

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_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_2 use

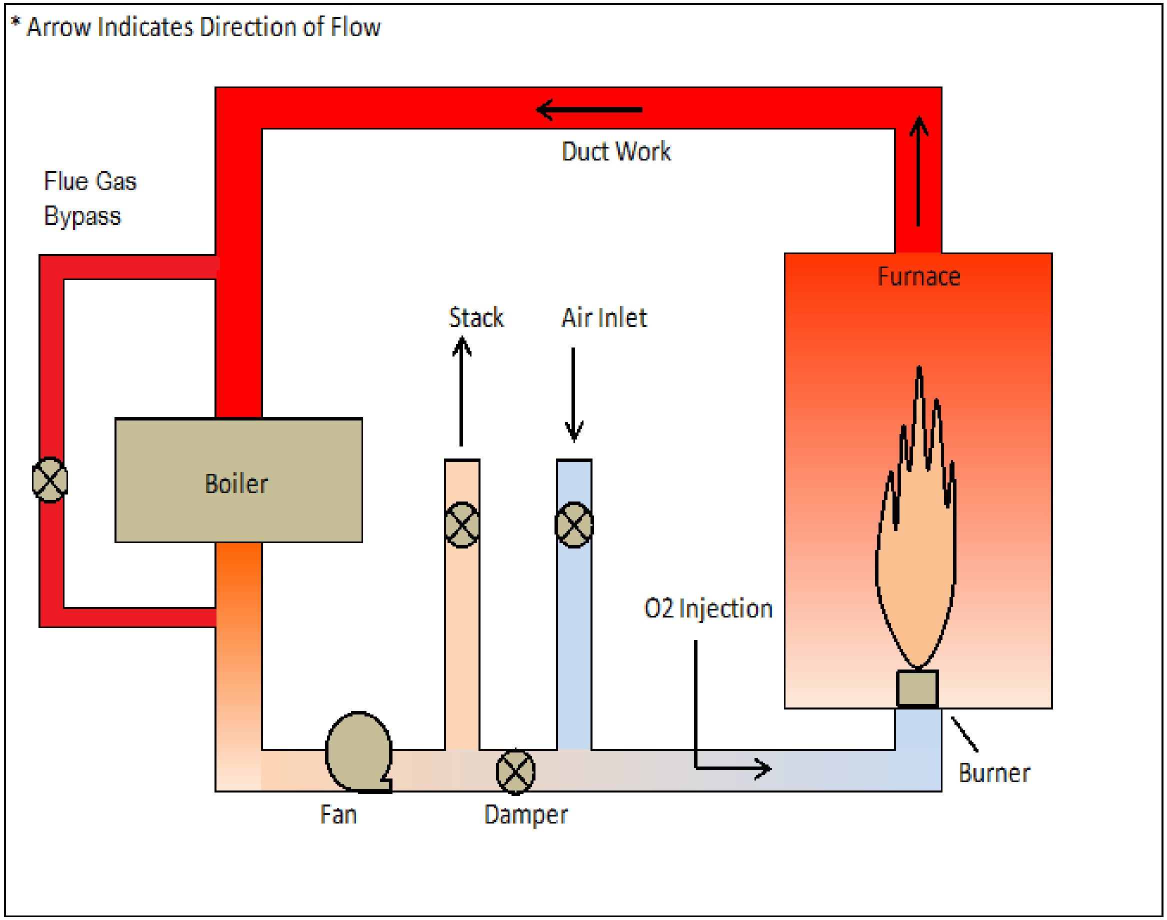
Single Burner Test Furnace

- 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)
  - O_2 (5.2% O_2 in flue gas and 1.3% O_2 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 O_2 concentration are important operating parameters:
  - Large FGR can push combustion process to flammability limit, especially under low O_2 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 NO_x 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, N_2 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 CO_2 from refinery heaters and boilers (H&Bs)

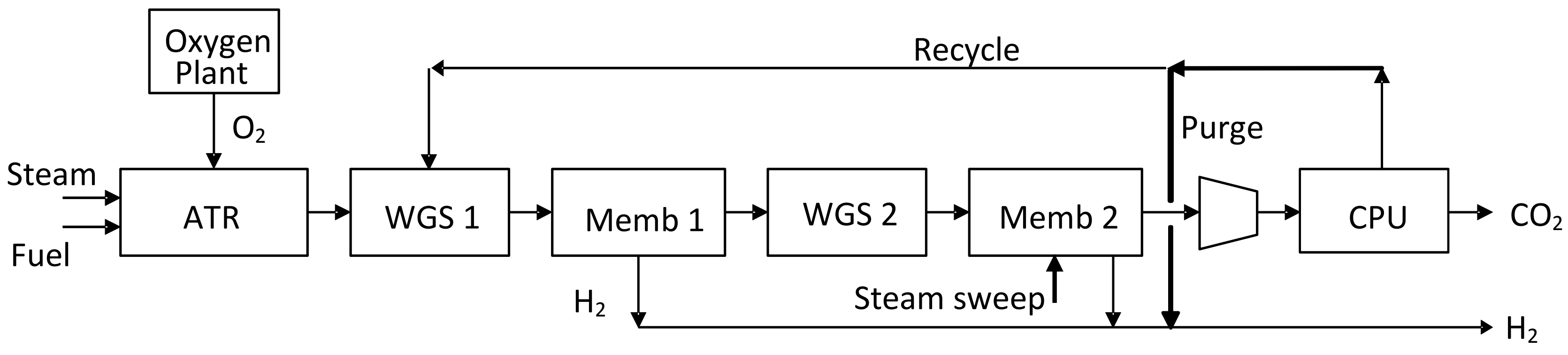
- H&Bs are a significant source of CO_2 in a refinery
  - They are usually scattered throughout a refinery
  - Post-combustion and oxy-combustion technologies are not generally practical in a space-constrained refinery
  - Pre-combustion capture technology with the production of low-carbon H_2 fuel in a centralized location provides an economical alternative for capturing CO_2 from H&Bs

Producing low-carbon H2 in a refinery

- Steam methane reformers (SMRs) are widely employed for producing <200 MMSCFD H2
- For larger H_2 quantities, such as for H&Bs, autothermal reformers (ATRs) provide certain advantages, e.g. a single source of CO_2 available at high pressure.
- CO_2 removal in aMDEA® solvent is the conventional technology
- CO_2 separation using H_2 membranes has several advantages:
  - High purity H_2 stream can be obtained at a suitable pressure (1–2 barg)
  - CO_2 stream is available at high pressure, thus reducing the compression energy
  - Removal of H_2 at high temperature improves the equilibrium in the WGS reaction

Background (cont'd)

Process Configuration



- ATR produces the syngas containing H_2, CO, CO_2, H_2O
- Two membrane stages are preceded by a high temperature shift reactor to convert CO into H_2 and thus increase the overall 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 CO_2 product stream
- Overall targeted 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 H_2 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 H_2 fuel stream in an ATR process while producing a purified CO_2 stream at high pressure suitable for sequestration

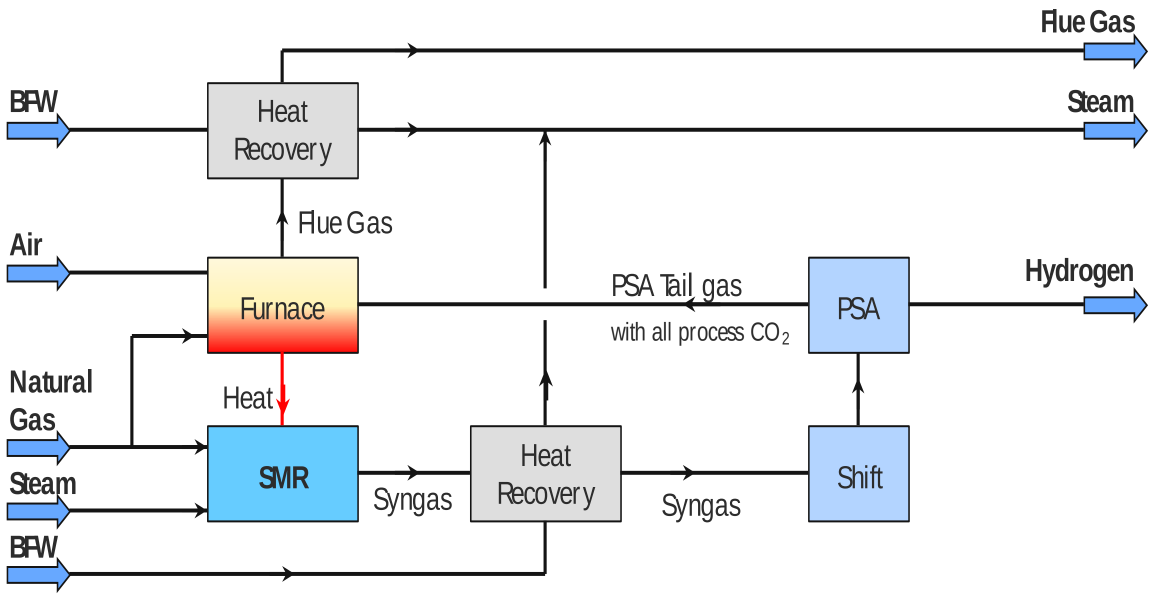
Methodology

- 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
- CO_2 emission from Hydrogen plants can contribute up to 20% of refinery emissions
- Steam Methane Reforming (SMR) is the industrial workhorse to produce hydrogen
- CO_2 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)



CCP3 bp Chevron eni BR PETROBRAS SUNCOR ENERGY

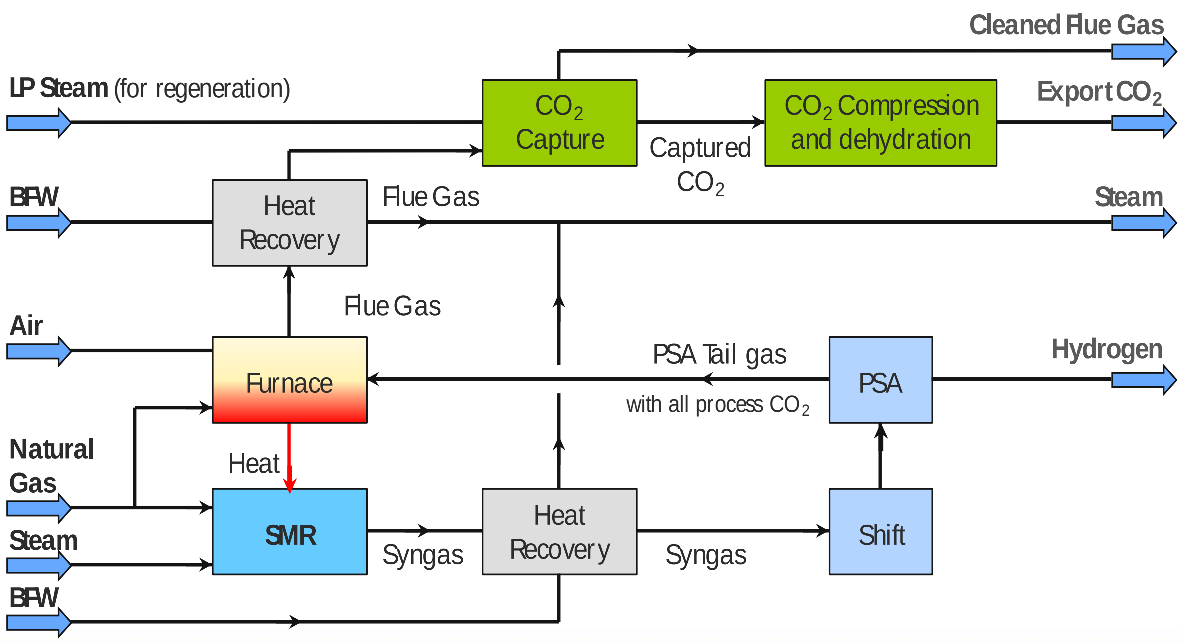
Background (cont'd)

Objectives

1. To identify the process scheme with 90% overall CO_2 capture from the SMR unit
2. Conduct techno-economic feasibility analysis with Foster Wheeler for the identified scheme/technology for a 50,000 Nm^3/hr hydrogen plant

Process Scheme

Post combustion with 90% capture from the reformer flue gas with 18-22 vol% CO_2



Premises – Design and Economics

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

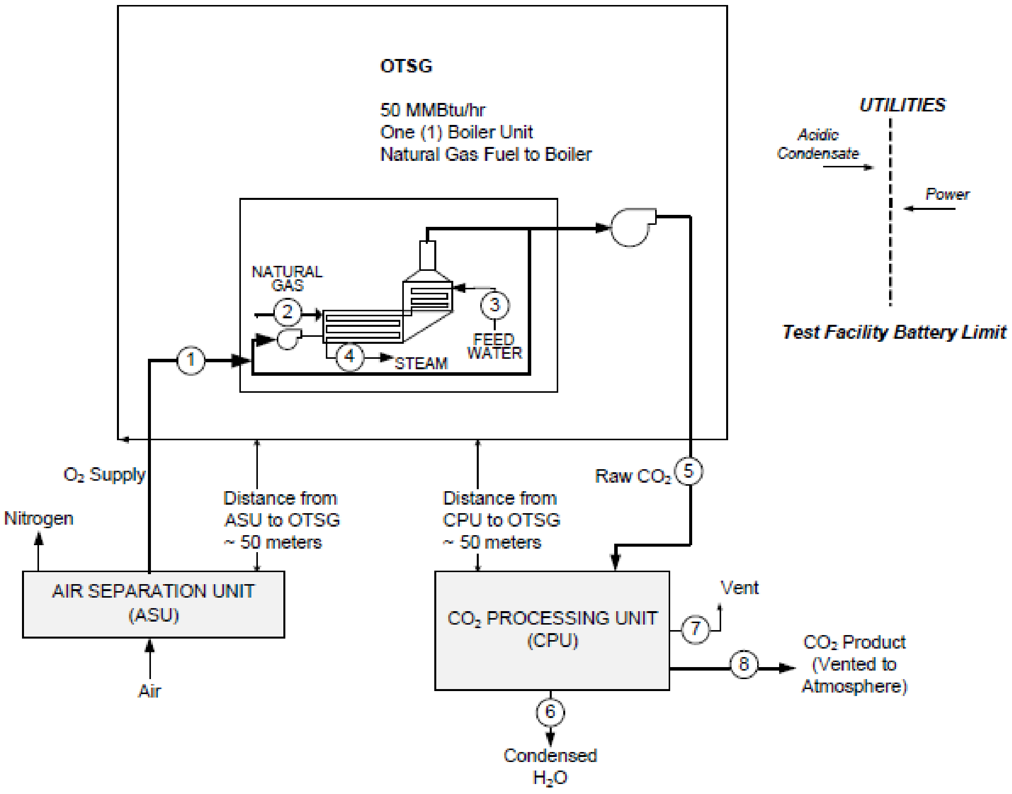
Once Through Steam Generator (OTSG)

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 CO_2 capture from once-through steam generators



Demonstration System Process Schematic

Heavy Oil Scenario – Summary and Conclusions

Results

- The best technology to capture CO_2 today appears to be post-combustion
- Although the CO_2 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)

Economic Evaluation – Key Assumptions

Calculated capture and avoidance costs include transportation and storage

Base Assumptions	Units	Value	Source
Fuel Gas Price – US	USD/GJ	4.50	Gulf Coast Public Data
Electricity Price - US	USD/MWh	70.00	Gulf Coast Public Data
Fuel Gas Price – AB	USD/GJ	4.50	
Electricity Price - AB	USD/MWh	60.50	
Time Horizon	Years	25	CCP Assumption
Power Intensity	tCO_2 /MWh	0.60	Gulf Coast Public Data
Steam Intensity for WHB FCC	tCO_2 /t	0.19	CCP Generated Figure
Heat to Produce Steam for FCC	GJ/t	3.13	CCP Generated Figure
CO_2 Transportation and Storage *	$/t	9.1	CCP Generated From Published Data

- Post-combustion steam consumption for solvent regeneration in the range of 2.7- 3.0 GJ/ton of CO_2
- *Storage costs – based on the WASP Study – Porous brine-filled aquifer http://www.ucalgary.ca/wasp/reports.html
- Transport costs based on capital costs factored from NETL data

CCP3 Economic Results

Application Scenario and Case Description	Fuel	CO_2 captured	CO_2 capture	CO_2 avoided	CO_2 capture cost	CO_2 avoided cost
Units		t/h	%	%	$/t	$/t
Refinery - US Gulf Coast						
FCC - Post Combustion	Carbon	55.5	85.5	65.5	94.2	112.9
FCC Oxyfuel Retrofit	Carbon	64.8	100.0	83.5	108.3	129.7
Fired Heater - Post Combustion	Fuel gas	26.6	85.0	65.0	118.6	156.5
Fired Heaters Pre-Combustion	Fuel gas	284.0	90.0	76.0	111.1	160.1
Refinery SMR with Post-Combustion	Nat gas	58.4	85.5	65.5	95.9	123.3
Oil Sands Steam Generation - Fort McMurray						
OTSGs - Post-Combustion	Nat gas	67.4	90.0	76.0	170.7	237.9
OTSGs CLC	Nat gas	63.3	100.0	86.0	195.7	236.4
Gas-Fired Power Generation - US Gulf Coast						
NGCC - Post-Combustion	Nat gas	126.1	85.5	73.7	97.9	113.6

- 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

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
- CO_2 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/CO_2 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

Acknowledgements

Acknowledging...

Our teams:

SMV:

Mark Bohm (Suncor), Marco Brignoli (eni), Stephen Bourne (Shell), Andreas Busch (Shell), Mark Chan (Suncor), Walter Crow (BP), Rodolfo Dino (Petrobras), Kevin Dodds (BP), Grant Duncan (Suncor), Scott Imbus (Chevron), Dan Kieke (Chevron), Claus Otto (Shell)

Capture:

Jonathan Forsyth (BP), Ivano Miracca (eni), Raja Jadhav (Chevron), Betty Pun (Chevron), Leonardo de Mello (Petrobras), Gustavo Moure (Petrobras), Jamal Jamaluddin (Shell), Mahesh Iyer (Shell), Frank Wubbolts (Shell), Dan Burt (Suncor), Iftikhar Huq (Suncor), David Butler (David Butler & Associates), Michael A. Huffmaster (P.E. LLC)

Acknowledging...

P&I:

Arthur Lee (Chevron), Sarah Edman (ConocoPhillips), Mark Bohm (Suncor), Eric Beynon (Suncor), Stephen Kaufman (Suncor), Mark Crombie (BP), C. T. Little (BP), Renato de Filippo (eni), Richard Rhudy (Electric Power Research Institute), Wolfgang Heidug (Shell)

P&I partners:

Environmental Resources Management (ERM)

Communications:

Rachel Barbour (BP), Renato DeFilippo (eni), C V Greco (Petrobras), Tanis Shortt (Suncor), Peter Snowdon (Shell), Morgan Crinklaw (Chevron)

Comms partners:

Pulse Brands

Acknowledging...

Capture Research partners, collaborators and funders:

Alberta Climate Change and Emissions Management Corporation (CCEMC), Cenovus FCCL LTD., Chalmers Tekniska Hoegskola AB (Chalmers), Consejo Superior De Investigaciones Cientificas (CSIC), CO2Solutions Inc., Devon Canada, Flemish Institute For Technological Research (VITO), Foster Wheeler Energy Ltd., Ion Engineering LLC., Johnson Matthey Public Limited Company (JM), John Zink Company LLC., Josef Bertsch Gesellschaft MBH & CO KG (Bertsch), MEG Energy, NTNU Faculty of Engineering Science and Technology Department of Energy and Process Engineering, Pall Corp., Petróleo Brasileiro S.A., Process Design Center B.V., Praxair Inc., Shell Global Solutions International B.V, Suncor Energy Services Inc., Statoil Canada Ltd., University of North Dakota Energy & Environmental Research Center (EERC), Vienna University of Technology (TUV)

SMV Research partners, collaborators and funders:

Lawrence Berkeley National Lab (LBNL), Los Alamos National Lab (LANL), Southeast Regional Carbon Sequestration Partnership (SECARB), Univ. Texas Bureau of Economic Geology (UT-BEG), Univ. Texas Center for Petroleum & Geological Engineering (UT-CPGE), Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), Midwest Geological Sequestration Consortium (MGSC), Colorado School of Mines (CSM), Stanford University, Schlumberger, TRE Canada, Univ. of Florida, EPRI, ARI, Groundmetrics, Merchant Consulting, Taurus Reservoir Solutions, Univ. of Aachen RWTH, Silixa, Geoscience Ltd Denbury.

Questions?

End