ANNUAL REPORT 2017

CO_2 Capture Project

Innovating to deliver lower cost CCS

PARTICIPANT ORGANIZATIONS

bp Chevron BR PETROBRAS

ABOUT THE CCP

The CO_2 Capture Project (CCP) was formed in 2000 to advance technologies for CO_2 capture and geological storage to help make CCS a viable option for CO_2 mitigation.

CCP is now in its fourth phase of activity, which began in late 2014. The program is planned to last for five years and is driven by three of the world's leading energy companies – BP, Chevron and Petrobras – supported by numerous experts.

Today, this group is focused on delivering further progress in CO_2 capture and geological storage technology through research, development and demonstration.

This 2017 Annual Report provides an update from the Teams that make up the CCP – Capture, Storage, Policy & Incentives, and Communications.

CCP AIMS:

- To drive down the cost of existing CO_2 capture technologies for future use by the oil, gas and power generation industries, through further technology R&D as well as demonstrations of next-generation technology
- Advancing knowledge of well integrity, natural site characteristics amenable to containment and subsurface processes governing CO_2 trapping
- Adapting subsurface monitoring technologies to track CO_2 underground and developing approaches to respond to out-of-zone migration of CO_2
- Providing technical and economic insights needed by a range of stakeholders, most notably governments and regulators, to inform the development of legal and policy frameworks.

CHAIRMAN'S INTRODUCTION

Jonathan Forsyth
BP, CCP Chairman

Welcome to this 2017 Annual Report from the CO_2 Capture Project (CCP). I am delighted to introduce this report as it showcases an important year where our teams have continued to establish a really strong portfolio of work.

CCP is committed to actively reducing the cost of CO_2 capture and developing improved tools and techniques for CO_2 storage. As well as our progress towards these important goals, it is equally encouraging to see external signs of regulatory support for CCS. This has been informed by the results of a number of credible whole energy system integrated assessment models, which have shown that CCS may form part of the lowest cost pathway to climate change mitigation. In the United States, the push to increasing the value of the 45Q tax credit for stored CO_2 is just one positive example of the real stimulus now surrounding CCS projects.

In this report, you will find a rich portfolio of technology that our teams have been working on including advanced materials and new chemistry in combination with additive manufacturing, process intensification and digital monitoring technologies. A highlight project for me has been our work on CO_2 injection wells at a purpose-built underground test facility operated by the Swiss Topographic Survey (swisstopo) at Mont Terri in Switzerland, which involves nano-structured functional materials for modifying flow and potential CO_2 leak-paths.

Looking ahead, we hope to continue to add further key projects to our portfolio in 2018 and our current programme of work will continue to mature into 2020. The CCP partnership is always open to new innovators and participating members. We continue to gratefully receive valuable support from leading government R&D funding bodies and we would encourage any interested parties to engage with us and collaborate in our work.

CCP4 CAPTURE PROGRAM

The CCP4 Capture program, led by Raja Jadhav, made good progress in 2017 with the initiation of several technology development projects focused on pilot-scale testing of novel capture technologies. These included two pilot projects related to novel solvent development, one of which was completed in 2017. Another project, involving development of an adsorbent using a novel 3D printing technique, was also initiated.

The evaluation of novel CO_2 capture technologies continued as a key part of the CCP4 Capture program in 2017. A detailed assessment of two promising options identified in earlier phases of work was carried out, while further work was initiated on a new set of novel capture technologies.

CCP4 Scenarios

The Capture program consists of four key scenarios. Much of the work has focused on applications in refining operations, heavy oil extraction and natural gas combined cycle (NGCC) power generation. Capture from natural gas extraction is the latest scenario for CCP4.

Refinery
Identify and develop technologies for pre-combustion capture from steam methane reformer (SMR) H_2 plants

NGCC
Seek and develop breakthrough capture technologies with less than $50/tonne CO_2 avoided cost

Natural gas extraction
Understand landscape and potential for CO_2 capture from offshore gas production and support pilot testing of a promising technology

Heavy oil
Seek and develop breakthrough capture technologies with less than $50/tonne CO_2 avoided cost

PROJECT: NOVEL CAPTURE TECHNOLOGY ASSESSMENTS

STATUS:
WORK PACKAGE (WP) 1 & 2 COMPLETED; WP3 COMPLETION EXPECTED IN MARCH 2018

Work continued in 2017 on the evaluation of novel capture technologies as part of WP2 and WP3 scopes, following completion of WP1 in 2016, in which LEAP (Laboratorio Energia e Ambiente Piacenza, Milan) undertook a techno-economic assessment of five such technologies.

WP2 work

WP2 was completed in 2017, which included detailed analysis of two technologies from WP1 – a high-pressure solvent absorption option (Pi-CO_2); and a molten carbonate fuel cell option (MCFC) for post-combustion capture from natural gas-fired processes.

The Pi-CO_2 technology assessment in WP2 involved evaluation of a hybrid process scheme that included a high-pressure aqueous solvent and a membrane. This was evaluated and the avoided cost estimated to be lower than the non-hybrid configuration in WP1 but still higher than the MEA base case.

For MCFC, detailed evaluations of integrated and non-integrated (retrofit) process configurations were carried out. The integrated process scheme was found to have the lowest CO_2 avoided costs at ~$50/tonne, which is 30% lower than the MEA case. For the non-integrated case, the CO_2 avoided cost was estimated to be ~$76/tonne, which is slightly higher than the MEA base case.

WP3 work

A scope for WP3 was agreed during 2017 and the work is underway. The scope includes assessment of piperazine (PZ) and C-Capture solvent processes for comparison with WP1 cases; estimation of cost of CO_2 capture from small gas engines using the MCFC technology; and evaluation of the PZ solvent process for CO_2 capture from high-efficiency gas turbines. Work on these projects, briefly described below, is underway with results expected in March 2018.

C-Capture solvent process assessment

LEAP carried out techno-economic assessment of a novel solvent developed by C-Capture Ltd., based on the preliminary performance information available from laboratory tests. The analysis indicated that the regeneration energy of the novel solvent was about 1.5 GJ/tonne CO_2, although additional electrical energy will be required in the regeneration process. The preliminary analysis indicated that the CO_2 avoided cost of the C-Capture process was lower than the MEA base case.

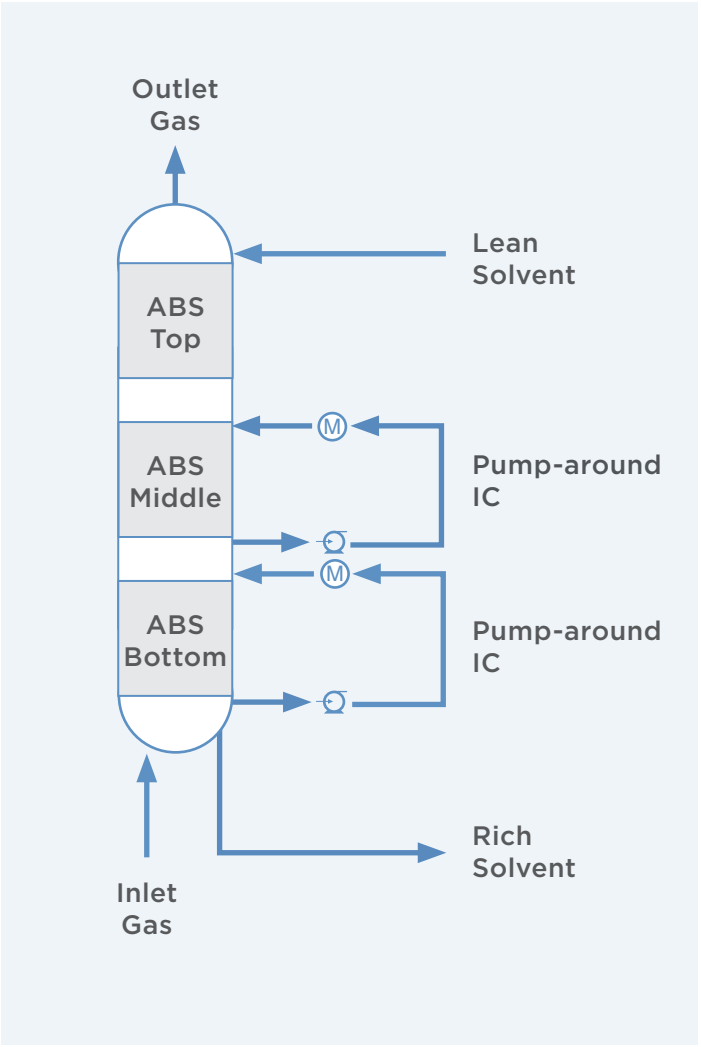
PROJECT: NOVEL CAPTURE TECHNOLOGY ASSESSMENTS CONTINUED

CO_2 capture from small-scale gas engines

LEAP is performing a preliminary techno-economic assessment of CO_2 capture from small-scale gas engines using the MCFC technology. The combined CO_2 emission rate of the gas engines is about 57 tonnes/day. The aim is to understand the cost advantages of the MCFC technology, if any, over MEA-based systems for CO_2 capture from smaller combustion sources.

PZ Solvent process assessment

Based on a recommendation from the University of Texas (UT) group, CCP and LEAP employed an unconventional absorber configuration without a direct contact cooler (DCC) — see diagram. Two Pump-Around (PA) intercooler (IC) systems were employed – the one at the bottom of the absorber was used to cool the incoming hot flue gas, whereas the second PA IC was used to remove the exothermic heat of absorption in the solvent. This configuration is expected to save capex due to the elimination of the DCC.



Simplified look at PZ solvent process configuration. *Image courtesy of UT*

PROJECT: PILOT-SCALE TESTING OF PZ SOLVENT

STATUS:
COMPLETE

The CCP participated in pilot-scale testing of the PZ solvent at University of Texas (UT), Austin. The testing was conducted under simulated NGCC flue gas conditions (3.5 mol % CO_2) with 5m PZ solvent and the performance was evaluated under eight operating conditions. An Advanced Flash Stripper configuration was employed to achieve a lower energy requirement for the solvent regeneration.

The pilot scale tests were successful – more than 90% CO_2 capture was achieved and the solvent regeneration energy was estimated to be <3 GJ/tonne, which included some heat loss from the smaller-scale pilot plant. The pilot scale results matched well with those predicted by a comprehensive simulation model prepared by UT Austin. The CCP has decided to participate in a larger-scale pilot of the PZ solvent process in 2018.

Pilot-scale testing site of the PZ solvent at the University of Texas, Austin.
Image courtesy of UT

PROJECT:
DEVELOPMENT OF NOVEL C-CAPTURE SOLVENT AND PILOT TESTING

STATUS:
ONGOING

Pilot testing apparatus of novel c-capture solvent.
Image courtesy of C-Capture Ltd.

CCP is participating with C-Capture Ltd. and SINTEF in a Department for Business, Energy and Industrial Strategy funded project under the Energy Entrepreneurs 5 program to develop and evaluate novel low-energy solvents for post-combustion CO_2 capture. Several solvent compositions will be prepared by varying the amounts of the capture agent, reactivity moderator and solubilizing agent. The goal is to evaluate the solvents at 1kg/h scale and perform pilot tests of promising solvents at 0.2 tonne/day scale and ultimately, optimize and validate the process at 1 tonne/day scale.

CAPTURE PROGRAM

PROJECT: SORBENT-BASED CAPTURE USING NOVEL 3D PRINTING TECHNIQUE

STATUS:
ONGOING

In 2017, CCP finalised details of participation as a co-funding partner in the 3D-CAPS Project Consortium (ERA-NET ACT Program[1]) on using novel 3D printing technologies to manufacture structured adsorbents for capture of CO_2. The aim of the project is to achieve a ten-fold increase in productivity compared to conventional packed beds. Other partners in the project include ECN, SINTEF, Aker Solutions, 3D-Cat and UBB.

The scope of work includes manufacture of adsorbents and pre-pilot testing of CO_2 capture from post-combustion flue gas and pre-combustion syngas conditions. This will be carried out at medium temperature (300-500°C) for pre-combustion conditions using the Pressure Swing Adsorption (PSA) technology employing alkali-promoted hydrotalcite adsorbents, and at low temperature (40-130°C) for post-combustion conditions using Vacuum PSA technology employing amine-functionalized silicas and immobilized amine adsorbents. This will be followed by optimization of structure configuration and processes through modelling.

Results are expected in late 2019 or early 2020.

[1] The ACT 3D-CAPS project #271503 has received funding from RVO (NL), RCN (NO), UEFISCDI (RO), and is co-funded by the CO_2 Capture Project (CCP) and the European Commission under the Horizon 2020 programme ACT, Grant Agreement No. 691712

CCP4 STORAGE, MONITORING & VERIFICATION PROGRAM

The year saw good progress in a range of projects from the CCP Storage, Monitoring & Verification (SMV) Team, led by Scott Imbus, despite some difficulties which had previously hindered progress in some areas.

The Mont Terri well sealing experiment team has successfully tested the first sealant, while a number of other SMV projects were completed, including the FOAK/NOAK cost assessment and a study into the quantification of CCS in Enhanced Oil Recovery (EOR) as de facto storage.

CCP4 Themes

The SMV Team's CCP4 work has the overarching objective of ensuring the long-term security of geologic CO_2 storage approached through the following themes:

Storage assurance
Subsurface processes: clarification and understanding of complex processes impacting storage security

Well integrity: solutions to identify and mitigate CO_2 leakage

Monitoring & Verification: modelling the cost-effectiveness of emerging and integrated sensors

Contingencies
Models for detection, characterization and mitigation of out-of-zone fluid migration (CO_2, brine) through wells and natural or induced geologic conduits

Field trialing
Deployment and assessment of emerging monitoring technologies at third-party sites with research and operator partners

PROJECT:
WELL SEALING EXPERIMENT

STATUS:
COMPLETION EXPECTED MID-2019

The overall objective of the project, which is being carried out at the Mont Terri rock laboratory in Switzerland, is to test novel sealants for their ability to treat small but persistent behind-casing migration of CO_2 from wells.

The 15m well installed is equipped with multiple intervals with input/output ports for fluid circulation and pressure surveillance. The well was thermally stimulated to induce a micro-annular (<120µm) defect between the casing and cement sheath. Sound progress has been made in the project following some delays caused by complications from well design/construction and unexpected fluid-rock-cement chemical reactions discovered in 2016.

The SMV Team worked closely with its partners to assess the nature of the well complications, eventually identifying incomplete cement coverage, complex induced defects and high fluid pH as the main issues that required remedy. The key actions agreed were to employ a cathodic protection system to protect the exposed metal casing and change water composition to be compatible with the cement. Following successful implementation, the system was then tested for stabilized permeability.

Image courtesy of E. Gygax, swisstopo

PROJECT: WELL SEALING EXPERIMENT CONTINUED

Three novel sealants had been selected for testing, each capable of reaching small voids otherwise not accessible in wells. Once the Team was satisfied as to the stability of the well, the first of these underwent testing.

Two batches of the first sealant, a low pH-triggered hydrogel (with different particle sizes), were initially injected into the lower permeability interval and pressure data indicated occlusion expected from sealant triggering. This was then followed by a second injection to test aiming to seal a higher permeability interval. Pressure data indicated limited and temporary sealing, which reflects the permeability limits of this sealant formulation in well leakage applications.

The results of this first sealant test have been deemed a success. Pressure testing in the lower permeability module has shown a high-pressure (40 bar) loading was achieved before failure, showing potential for providing a successful seal in a reservoir environment. Planning for the second and third sealant tests is underway.

Image courtesy of E. Gygax, swisstopo

PROJECT: EOR AS DE FACTO STORAGE

STATUS:
COMPLETED

The CCP4 SMV team sought to quantify the extent to which CO_2 EOR constitutes de facto CO_2 storage through a simulation study, which was completed in 2017. The study provides valuable insights into the optimization of hydrocarbon recovery vs CO_2 storage, with implications for revenue and credits.

The project was conducted with the University of Texas Bureau of Economic Geology (BEG) and partially funded by the US Department of Energy (DoE). It used production and fluid analytical data from a recently operated CO_2 EOR flood at Cranfield, Mississippi, USA, and reservoir simulation to predict the trapping mechanisms and storage volumes of CO_2 75 years into the future (after 25 years of EOR and 50 years of post-injection).

Four injection simulation scenarios were examined:

- CGI – continuous gas (CO_2) injection
- WAG – water alternating gas injection
- WCI – water curtain injection (water injection wells at the water-oil contact) with CGI
- Hybrid WAG and WCI.

The most important overall finding was that the field development strategy selected by the EOR operator has a very significant impact on the relative importance of the different CO_2 trapping mechanisms for a reservoir.

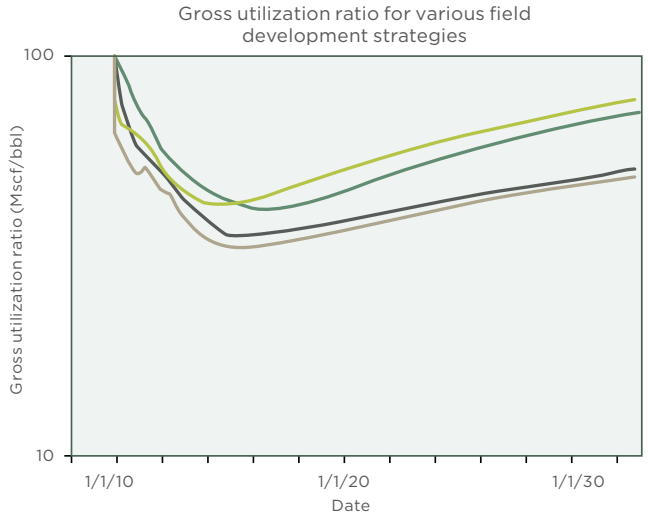
In simulations, while CGI maximizes oil recovery and CO_2 storage in absolute volume terms (mainly because more CO_2 is injected in this scenario), WAG, the most commonly employed approach currently, appears to offer a more balanced approach. WAG can produce large amounts of oil and store large volumes of CO_2 with the lowest gross utilization ratio (the amount of CO_2 injected to produce one unit of oil). WAG also improves storage security by reducing the amount of mobile CO_2 relative to CGI, as it is the mobile CO_2 phase that has the greatest potential to move towards the surface.

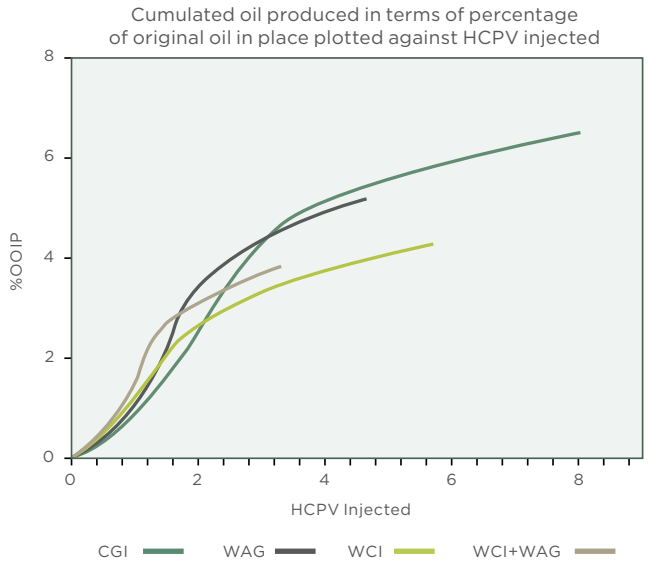
PROJECT: EOR AS DE FACTO STORAGE CONTINUED

- The CGI and WAG scenarios yield the greatest percentages of CO_2 dissolved in the water leg, with approximately 35% of CO_2 stored permanently through dissolution in brine
- The largest percentage of CO_2 in the mobile gas phase corresponds to the CGI (45%) scenario, followed by WCI (35%), WAG (33%) and hybrid WAG+WCI (23%) scenarios
- Only 5-7% of CO_2 is stored in the immobile gas phase for all modelled scenarios, a consequence of the low residual gas saturation status of the reservoir.

This study did not consider the economics of these flooding methods. In reality, considerations of oil price, the cost of CO_2, the value of tax credits for storing CO_2 and the economics of development will all play into considerations of which development strategy is most appropriate for a given field.

Image courtesy of The University of Texas Bureau of Economic Geology





SELECTED PROJECTS AND NEW INITIATIVES

FIRST OF A KIND/NTH OF A KIND (FOAK/NOAK) COST ANALYSIS

STATUS: COMPLETED

The CCP study that began in 2016 with the aim of understanding what cost reductions might be expected as commercial CO_2 storage projects evolve from First of a Kind (FOAK) to later Nth of a Kind (NOAK), has been completed. Advanced Resources International (ARI) performed the study.

Following work in 2016, which delivered FOAK financial analyses for two representative case studies and a documented set of costs and associated assumptions for 60 SMV-specific activities (characterization, modelling & monitoring), a second phase was undertaken in 2017. This comprised two tasks:

- Extending the FOAK/NOAK assessment to CO_2 storage associated with ongoing CO_2 EOR operations at four representative sites (Permian, Gulf CoastC, Mid-Con & Rockies)
- Examining the impact on evolution of costs by employing an Assessment of Low Probability Material Impacts (ALPMI)

The results of the work are significant for project selection and development. Pathways were identified to significantly reduce costs from a FOAK to a NOAK position, where the experience and understanding developed over time and from an increasing number of projects should drive down project costs.

Phase 1 work showed a relatively low cost per tonne stored for CO_2 storage in saline formations and for CO_2 EOR converted to storage. Phase 2 also showed low add-on cost as well as an impact on monitoring costs from FOAK to NOAK after the Low Probability Material Impacts (LPMI) assessment.

SELECTED PROJECTS AND NEW INITIATIVES CONTINUED

PLUGGED AND ABANDONED (P&A) WELL CONTINGENCIES

STATUS: ONGOING

The CCP SMV Team has begun a new project with the aim of addressing leakage issues that can occur with older plugged and abandoned (P&A) wells. The study is jointly conducted by Lawrence Berkeley National Lab (LBNL) and Stanford University.

Vintage wells of poor or unknown construction, location or P&A method may introduce an unexpected vulnerability to CO_2 storage projects. Such fluid leaks are particularly problematic given their inaccessibility to determine the location and nature of the defect/conduit and the potential for long-term, persistent leakage that could impact groundwater.

A four-phase program has been set up with Stanford-LBNL to address this, with data compilation and modelling eventually leading to the design of a slim well Modular Borehole Monitoring tool and shallow and deep site tests of intervention technologies.

To date, the joint team has developed an earth model and flow simulation and assessed how an existing monitoring system (or landowner observations) may reveal an anomaly. Also, what technology can be brought to bear to qualify that anomaly as originating from a storage reservoir and, if so, how to localize and characterize it so that it can be accessed and mitigated.

The first phase of the project will be completed in mid-2018, at which time a decision will be made on whether to launch the second phase.

MECHANICAL ANNULUS SEALING

STATUS: ONGOING

The SMART tool, developed by Suncor for preventing annular space from developing during cooling of thermal wells, comprises a new approach to well abandonment. The tool exerts mechanical force on the inside of the casing which expands the casing to maintain contact with the cement. Due to operation upsets in Alberta resulting from wildfires and the relative rarity of shutting down a thermal flood reservoir sector, it has been difficult to secure a suitable well and agreeable owner to conduct a test. Whereas this effort continues, Suncor is looking into re-sizing the SMART tool to where it can be tested in a larger population of wells in Canada or the US.

SELECTED PROJECTS AND NEW INITIATIVES CONTINUED

AQUISTORE CO_2 STORAGE PROJECT COLLABORATION

STATUS: DEVELOPING

CCP4 is planning a repeat Electromagnetic Monitoring (EM) survey (over the 2013 CCP3 baseline) to better assess the viability of electromagnetics as a cost-effective monitoring technology, following injection of ~80MT of CO_2 by the operators at the Aquistore site in Saskatchewan, Canada. Currently, modelling of expected resolution for placing a downhole source in the observation well is being updated using the most recent reservoir simulation data. The repeat survey is scheduled for mid-2018.

The Aquistore CO_2 storage project presents an opportunity for other surveys, including testing a borehole microgravity logging tool. This is an emerging technology that would bring substantial cost savings to CO_2 monitoring programs if found to be effective.

Discussions with Aquistore staff continue, with the aim of developing a common reservoir flow model as the basis to integrate results of multiple monitoring surveys (e.g. surface seismic, EM borehole microgravity and possibly others) at the site over the past several years.

PERMEABILITY MODIFIERS FOR SEAL ENHANCEMENT, WELL MITIGATION & FLOOD CONFORMANCE

STATUS: ONGOING

The University of Texas has been engaged to simulate the viability of using injected permeability modifiers to occlude top seal defects (e.g. fractured or high permeability streaks) distal to the delivery well. Comparison simulations of two injected agents (polymer gel with a Cr(III) crosslinker and silica gel) illustrated the lateral distance of delivery relative to setting time and the effectiveness of expected permeability reduction as a barrier to CO_2 migration.

A third agent, with application only to the near well bore area, was also tested. Sensitivities to in situ conditions such as pH, temperature and salinity were also considered. These simulations were intended to assess barrier enhancement prior to CO_2 injection. The likely forward path is to use literature data on the effect of CO_2 on these agents for the post- (or during) injection scenario where CO_2 is discovered to be migrating through a seal defect. If results are promising, the next step would entail experimentally refining the sealing agent properties under different conditions and using these data to update the simulations.

CCP4 POLICY & INCENTIVES PROGRAM

The CCP Policy & Incentives (P&I) Team, led by Arthur Lee, followed up its 2016 study on the regulatory implications of transitioning CO_2 EOR sites to CO_2 storage with a deep dive report on the same subject in two areas of important CCS/EOR activity – Alberta and Texas.

The starting point for these studies is that oil production/EOR regulations were not originally written to cover long-term underground storage of CO_2 as a CCS project. The 2016 report has identified that although there are no technological barriers to be overcome, there are legal, regulatory and economic challenges across jurisdictions which must be addressed to allow EOR projects to serve as CCS projects.

The 2017 report – *CCP4: Review of CO_2 EOR Transitioning to CCS in Texas and Alberta* – took this further and looked at the jurisdictions of Texas and Alberta through two lenses – firstly, the existing regulatory pathway for CCS permitting without EOR; and then, what is needed for a CO_2-EOR scheme to gain credit as CCS and where regulation may be a barrier to that transition. Each key project stage is covered, from planning and permitting, through to operation, decommissioning and closure, with case studies from each jurisdiction providing real-life insight.

The report found that, even in two relatively advanced EOR/CCS areas like Texas and Alberta, there are still gaps and uncertainties in the regulatory frameworks that need to be addressed for CO_2 EOR projects to transition successfully to CCS.

The full *Review of CO_2 EOR Transitioning to CCS in Texas and Alberta* report is available at www.co2captureproject.org.

P&I activity

The Team provides technical and economic insights needed by a range of stakeholders, most notably governments and regulators, to inform the development of legal and policy frameworks which are so vital for the deployment of CCS.

CCP4 COMMUNICATIONS PROGRAM

The main focus of activity for the CCP Communications Team in 2017 was in ensuring CCP's messages were heard at leading industry events throughout the year.

The first of these took place in Chicago in April, when CCP made a number of presentations and took stand space at the annual CCUS conference. Co-located for the first time with the Electric Power conference, the CCUS event attracted several hundred participants who attended a range of CCS presentations on technology, R&D and policy. Presentations were given by CCP team members and the CCP exhibition stand attracted a good flow of visitors who spoke with stand representatives and picked up factsheets, leaflets and Volume 4 of the CCP Results book.

In June, CCP was a Gold-level sponsor at the bi-annual conference in Trondheim, Norway, organized by NCCS – International CCS Research Centre under the auspices of NTNU and SINTEF. The event attracted over 350 people from 24 countries, the second highest in the event's history and was an intensive two-day event with a packed programme of plenary, poster and thematic sessions. CCP also took part as an exhibitor and the stand again attracted a good number of visitors who picked up a range of CCP information material.

Both events provided opportunities to engage with interested parties from a range of CCS and related organizations to reinforce the work being done by CCP.

The year also saw the Communications Team continue to maintain the profile of CCP online and in key media. Press releases were issued, updates made to the CCP website and news alerts issued to the 4,000-strong CCP database. An Annual Report for 2016 and internal CCP member communications materials were also published.

Communications activity

The Team is responsible for supporting the work of the SMV, Capture and P&I teams and ensuring it is seen by relevant interested audiences. This typically involves a mixture of online, print and face-to-face communications routes.

STRUCTURE
CCP TEAMS 2017

The CCP is made up of four Teams – Capture; Storage, Monitoring & Verification; Policy & Incentives; and Communications.

The Teams consist of experts drawn from each of the member organizations.

Each participating member is represented on a CCP Executive Board that comes together quarterly.

The CCP is also supported by a Technical Advisory Board (TAB) responsible for conducting independent peer reviews on the activities of the CCP Teams and their respective programs. The TAB comprises independent assessors from industry and academia.

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WWW.CO2CAPTUREPROJECT.ORG

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