CO2CRC ANNUAL REPORT

2018 – 2019

BUILDING A LOW EMISSIONS FUTURE

HIGHLIGHTS

July 2018

Work starts on the engineering and design of the hydrogen purification plant for the HESC pilot plant project.

Testing of new and novel adsorbent and membrane CO_2 separation materials commences at the Otway capture skid.

CO2CRC co-hosts GHGT-14 conference in Melbourne with over 1,000 delegates.

140 CCS experts from around the globe visit Otway National Research Facility.

CO2CRC awarded funding to investigate reducing emissions in steel production.

Cutting-edge scientific instrumentation deployed in Gippsland to measure greenhouse gas emissions as part of the GipNet Atmospheric Monitoring Network.

Phase 2 of the Otway Fault Project begins to better understand how CO_2 behaves around a geological fault.

Completion of seismic and pressure data analysis and documenting of seismic acquisition, processing and interpretation methods as part of Otway Stage 2C Project.

CO2CRC's flagship research program, Otway Stage 3, gets the green light.

Successful completion of membrane-solvent contactor demonstrations at Vales Point Power Station.

Appointment of CO2CRC Distinguished Scientists, Professors Peter Cook, Kelly Thambimuthu and John Kaldi.

June 2019

CONTENTS

A GLOBAL LEADER IN CCS RESEARCH

Operating since 2003, CO2CRC is a world leader in carbon capture, utilisation and storage (CCS) research. It is an incorporated not-for-profit research organisation (company limited by guarantee) funded through government grants, membership fees and direct investments from industry and research bodies.

CO2CRC owns and operates the Otway National Research Facility located in Nirranda South, south-west Victoria, Australia. It has been at the forefront of Australian advances in CCS for over 15 years. To date over $100 million has been invested in the Otway facility to demonstrate real-world capture, injection, storage and monitoring techniques.

CO2CRC is Australia's key designer, initiator, and manager of CCS research. It is the only company in Australia to have demonstrated CCS end-to-end. It brings together the world's best scientists, engineers and industry leaders to advance the implementation of CCS worldwide.

* The terms CCS (carbon capture and storage) and CCUS (carbon capture, utilisation and storage) are both used in this document and are interchangeable.

OUR MISSION

The world's leading CO_2 storage technology centre, globally recognised for innovative carbon capture and utilisation solutions.

OUR VISION

Add value to customers by testing, developing and demonstrating CCUS research, products and services as viable options for a lower emissions future.

OUR VALUES

Excellence | Integrity | Delivery

CHAIRMAN AND CEO'S REPORT

For CO2CRC, 2018-2019 was a year of considerable progress with achievements in key areas critical to the organisation's future.

Firstly, the organisation recorded a major achievement in securing all financial, operational and regulatory approvals for commencement of our flagship project, Otway Stage 3, in May 2019.

The project aims to significantly reduce the ongoing costs of monitoring subsurface storage of CO_2. Over its three-year duration, it will apply new and innovative techniques that provide permanent subsurface monitoring making data available on demand. The techniques will be demonstrated at the Otway site and subjected to rigorous performance testing. We are grateful for project funding from the Commonwealth Government's Education Investment Fund (EIF), COAL21 through ANLEC R&D, BHP and the Victorian State Government.

Otway Stage 3 is the largest capital project undertaken by CO2CRC and required the installation of new infrastructure at the Otway site, including four new 'monitoring' wells, each drilled to a depth of between 1600 and 1700 metres. Each well was equipped with advanced instrumentation and fibre optic cabling and successfully completed as scheduled by October 2019. Over the next year, scientific and operational preparatory works will continue in advance of the next major milestone for the project - the injection of 15,000 tonnes of CO_2 in October 2020 to enable the acquisition of essential experimental data.

We are well on track towards realising our ambition of providing industry with the technologies and techniques that will reduce the cost and environmental impact of long-term CO_2 storage monitoring.

Secondly, noteworthy progress was achieved on major projects within CO2CRC's broader research and project agenda:

- Under Phase 2 of the Otway Fault Project, two appraisal wells intersecting a shallow fault at the Otway Facility have been installed. The outcomes from this experiment will greatly improve our understanding of the influence of faults on the safe long-term storage of injected carbon dioxide.
- The Otway Stage 2C project has successfully demonstrated and verified the performance of seismic technologies for monitoring plume behaviour. Time-lapse 3D seismic using an array of near surface geophone receivers in conjunction with conventional vibroseis sources have successfully detected and tracked the plume of Buttress-sourced CO_2 injected at the Otway site. The data received will be used to verify plume stabilisation.
- A new rock property model based on digital core analysis of 40m of whole core from the Otway CRC-3 has been developed under the Multiscale Flooding Dynamics of Otway Core research program. This new approach has the potential to reduce resource-intensive acquisition of core samples. It utilises the high-resolution whole core scanner installed at the Australian National University and funded by the Commonwealth's Education Investment Fund.
- Initial work to develop a rapid plume forecasting tool is complete. This tool, which uses machine learning to make short-term predictions of future time-lapse seismic images of the injected carbon dioxide plume based on the observed past images, will both reduce the cost of long-term monitoring and the lead-time required for making operational decisions based on monitoring results.

- New CO_2 capture technologies have been demonstrated at Vales Point Power Station (membrane gas-solvent contactor process in continuous mode operation, with solvent absorption and regeneration occurring simultaneously) and the Otway Facility (field testing of novel adsorbents and membranes for the separation of CO_2 under natural gas processing conditions).

Thirdly, over the last year, the organisation expanded efforts to work closely with industry, resulting in a growing list of new projects and collaborations in exciting new areas and industries:

- A study (funded by Coal Innovation NSW) exploring pathways for reducing greenhouse gas emissions in BlueScope's steelworks in Port Kembla by converting steel mill exhaust gases into fuels and investigating the viability of deploying CCS.
- Selection of CO2CRC to provide engineering and project management services for the hydrogen purification aspect of the hydrogen production pilot plant being built as part of the Hydrogen Energy Supply Chain (HESC) Project.
- A study (funded by COAL21) in partnership with Geoscience Australia to screen and rank all prospective onshore and offshore basins in Australia for their potential for CO_2 EOR and associated CO_2 storage.

Fourthly, the CO2CRC Board approved a comprehensive five-year business strategy which redefined the organisation's vision and aligns its efforts in four strategic focus areas: optimising storage, reducing capture costs, enhancing CO_2 utilisation and leadership and collaboration. We aim to position CO2CRC favourably to compete for opportunities to provide services for CCS projects globally.

Major initiatives under the strategy include:

- Transforming the Otway National Research Facility into a globally acknowledged Otway International Test Centre (of Excellence);
- Optimising storage technology development for commercial scale application;
- Expanding and scaling-up CO_2 separation facilities to substantially reduce the cost of CO_2 capture in new settings (offshore natural gas separation, clean hydrogen); and
- Investigating CO_2 utilisation pathways including enhanced oil recovery, enhanced gas recovery and industrial applications such as biofuels.

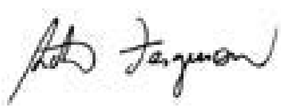
Fifthly, as part of our drive to consolidate CO2CRC's role as the technical leader in CCS in Australia, we have renewed efforts to build collaboration across the Australian CCS 'community':

- We co-hosted the premier international CCS conference, GHGT-14, in Melbourne in October 2018. The conference set an attendance record for the conference series with over 1000 delegates from thirty countries, 140 of whom visited our Otway National Research Facility;
- In November, we held our annual open day at the Otway facility – an opportunity for members of the general public to learn from guided tours of the site conducted by CO2CRC staff;
- We took a key role in coordinating the activities of the newly formed Australian CCS Network - a network of researchers, advisors and industry with an interest in advancing CCS technologies. The network's activities culminated in three round tables in Canberra with senior Australian Government officials on the state of global and Australian CCS research and policy developments.

Finally, we were very pleased to appoint three Distinguished Scientists to CO2CRC – Professor Peter Cook, Professor Kelly Thambimuthu and Professor John Kaldi. Each will add further depth to our research and development agenda and their extensive global networks will be particularly valuable in building collaborations with research institutions worldwide, keeping CO2CRC positioned at the forefront of CCS scientific developments.

The last year has been a milestone year not just for CO2CRC but also for the broader CCS industry. In that regard, we congratulate Chevron and its Gorgon LNG Project participants, Shell and ExxonMobil on the successful commissioning of the Gorgon carbon dioxide injection project in August 2019. With plans to store more than 100 million tonnes of carbon dioxide over the project's life, it is one of the world's largest greenhouse gas mitigation projects ever undertaken by industry and a major milestone in efforts to develop commercial scale carbon capture projects.

We are clearly at a significant juncture in our company's journey to deliver the next wave of CCS research and innovation. We thank our funders, partners, members and Otway landowners for their support and inspiration over the past 16 years. And we thank our management and staff, including our researchers, for the immense amount of work they have done to build a solid base for CO2CRC to take on the new wave of challenges.



Martin Ferguson AM
Chairman

David Byers
CEO

CO2CRC'S BUSINESS STRATEGY

CO2CRC's Business Strategy is built from the achievements of the past 16 years – applying the best scientific research to develop next generation technologies and operational methods that support the commercial deployment of CCS.

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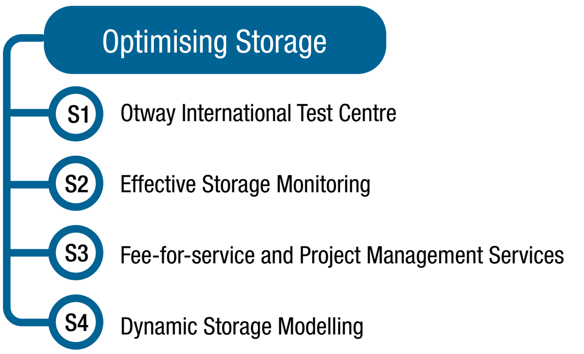
Over the period 2020 to 2025, CO2CRC's business plans are aligned under four strategic focus areas:

- Optimising Storage
- Reducing Capture Costs
- Enhancing CO_2 Utilisation
- Collaboration and Leadership

The four areas identified for growth were carefully selected and designed with input from our member companies and research institutions. The business strategy was endorsed by the CO2CRC Board in April 2019. Development plans for individual projects under each area are long-term in nature but sufficiently dynamic to allow the incorporation of new ideas and emerging technologies. The strategy contemplates an expanded range of fee-for-service offerings by CO2CRC across all four strategic focus areas in Australia and internationally. We aim to position CO2CRC favourably to compete for opportunities to provide services for CCS projects globally.

A brief description of each area follows:

1. Optimising Storage



The Optimising Storage Program of CO2CRC will develop new and innovative technologies and enable the deployment of CO2CRC's demonstrated technologies for commercial scale application.

The Otway National Research Facility is the centre piece of CO2CRC's business plan and key to developing national R&D capabilities, informing policy and regulatory settings and conducting community education. The facility, with the addition of the Otway Stage 3 Project, will enable CO2CRC's demonstration of optimal storage technology solutions and pave the way for the commercial deployment of emerging storage research.

CO2CRC intends to build on these strengths to convert the Otway facility into an internationally prominent test centre for applied carbon capture and storage R&D – the Otway International Test Centre (OITC). The research facility will also be made accessible for global customers and researchers, across the various industry sectors pursuing CCS technology applications to collaborate, trial and validate technology and processes at field scale. An example of a targeted use of the OITC is the GeoCquest Field Validation research project which aims to validate quantifiable guidelines for CO_2 storage site planning, closure and risk analysis by acquiring infield geological measurements of CO_2 secondary trapping. The operation requires a purpose drilled well and the OITC is ideally suited as a site for a field validation including the capability of combining remote observation facilities with in-situ downhole measurement tools and facilities to inject CO_2 into a saline formation.

CO2CRC's storage R&D program will focus on collaborative research in the following areas:

- Storage Monitoring: This program aims to mature CO_2 storage monitoring capabilities towards commercial application, enabling at scale effective and compliant life-of-project surveillance both onshore and offshore. A key storage monitoring example is the development of subsurface-based monitoring through the Otway Stage 3 project. Other key activities proposed in this focus area include developing an overarching storage monitoring workflow (methodology); assessing saturation and residual gas trapping; and conducting baseline and commercial assurance monitoring for the onshore and offshore environment.
- Storage Modelling: This program aims to mature the modelling capability of appraising potential CO_2 storage sites, optimising storage operations, and predicting long term fluid trapping processes. This will safely enhance storage of CO_2 and improve the confidence in long term storage for both CCS operators and regulators to enable ultimate closure of a storage site. Key activities proposed include effectively modelling a migrating plume's distribution; maximising efficiency in use of storage reservoirs; and developing well integrity solutions.

2. Reducing Capture Costs

Reducing Capture Costs

- **C1** Gas separation & CO_2 capture– membranes, adsorbents & hybrid systems
- **C2** Developing hybrid CO_2 separation technologies to optimise separation under different conditions
- **C3** Fee-for-service and Project Management Services

CO2CRC's capture research builds on the long-standing history of the organisation in developing innovative carbon capture systems. Since 2003, research and development of membrane, adsorbent, potassium carbonate-based solvent (precipitating and non-precipitating) and cryogenic capture technology has been undertaken at a range of scales from laboratory to demonstration scale.

Key areas of focus include:

- Investigating compact CO_2 separation technologies for offshore environments. CO2CRC's experimental capture skid was installed at the Otway facility in late 2016 and is designed to test new membrane and adsorbent capture materials for cost-effective, compact natural gas processing technologies for the gas industry. Improvements to the Otway capture skid and the development of a larger demonstration scale facility are planned to enable testing of CO_2 separation technologies in hybrid configurations (such as bulk separation of CO_2 using membranes followed by separation with adsorbents or cryogenics).
- The further development of membrane gas-solvents contactors as a novel, hybrid carbon capture technology for post combustion capture – progressing our current field demonstration of this promising technology.
- Investigating ways to translate novel CO_2 separation processes for use in the production of hydrogen from fossil fuels.

3. Enhancing CO_2 Utilisation

Enhancing CO_2 Utilisation

- **U1** EOR – test and demonstrate application of EOR (Cooper /Eromanga; Surat)
- **U2** Participate in an Australia-wide regional study to understand the potential for EOR.
- **U3** Industrial Application of CO_2 Utilisation

There is a growing demand for the conversion of CO_2 into value-added products to offset the cost of implementing CO_2 capture and storage technologies:

- CO2CRC is currently working with Geoscience Australia to develop the scope of work for a study to examine the feasibility and potential of using CO_2 in Enhanced Oil Recovery (EOR) in Australia. It is also seeking to advance the understanding of the technical and economic potential for the application of Enhanced Gas Recovery (EGR) and Enhanced Coal Bed Methane Recovery (ECBMR) in Australia. In addition to desk-top studies, efforts will be made to test and demonstrate the application of these technologies at lab scale and field scale in Australia.
- Other areas of focus include a feasibility study exploring the development of a biorefinery industry based on the valorisation of non-food biomass and CO_2 to produce biofuels and biodegradable plastics. The technology involves the fermentation of lignocellulose into platform chemicals which are then upgraded into biofuels and biodegradable plastics. The project will commence with a feasibility study for a 10 tonne/day demonstration scale plant and assess the development of a large commercial scale biorefinery and the impact on regional economies.
- Providing technical and leadership support to research and develop products and services along various aspects of the utilisation chain. Areas of current interest include carbonate mineralisation and the conversion of steel mill and industry exhaust gases into fuels with further opportunities currently under consideration as part of ongoing discussions with stakeholders.

4. Collaboration and Leadership

Collaboration & Leadership

1. Lead technical nexus & forum for the CCS community in Australia
2. Provide expert CCS advice for government industry, and key decision makers
3. Collaborate with Australian CCS community to overall CCS advocacy leveraging technical proficiency and research track record (Australian CCS network)
4. Pursue training & education opportunities

CO2CRC accesses the expertise of many of the world's best researchers across the fields of carbon capture, utilisation, storage and monitoring. The strength of this partnership has resulted in more than a decade of successful research outcomes from desktop and laboratory scale trials to field scale demonstrations.

This track record, together with its established relationships with industry, government and regulators has allowed CO2CRC to become a trusted technical focal point and knowledge hub for the CCS community in Australia and internationally.

The biennial R&D Symposiums offer the CCS community the opportunity to communicate new research and technologies to stakeholders. The next Symposium will be held in November 2019.

CO2CRC has bolstered its efforts at the national and state level to provide advice on contemporary developments in CCS science and policy globally as well as practical on-the-ground research and development. As well as providing submissions to government inquiries, key areas of focus include:

- Coordinating the formation of the Australian CCS Network to bring together researchers, advisers and industry participants (Peter Cook Centre for CCS Research, ANLEC R&D, the Global Carbon Capture and Storage Institute, MCA, APPEA and the Cement Industry Federation) in a collaborative effort to advance the uptake of CCS technologies.
- Convening round-table discussions in Canberra between the Australian CCS Network participants and senior government officials to highlight global and Australian advances within the field of CCS and provide advice on the policy settings that industry believes would foster further investment in Australian CCS projects.
- Publication of a regular newsletter to inform stakeholders nationally and locally about key developments in CCS globally and within CO2CRC.

"The Otway National Research Facility is the centre piece of CO2CRC's business plan and key to developing national R&D capabilities, informing policy and regulatory settings and conducting community education"

CO2CRC'S RESEARCH

CO2CRC's research projects have made some noteworthy progress over the past year. A detailed update on each project is provided on the following pages, including its objectives, outcomes from the year and plans for the year ahead.

OPTIMISING STORAGE

Otway Assurance Monitoring

Project owner: Dr Ulrike Schacht, University of Adelaide

Objectives

To provide a comprehensive soil gas, ground water and reservoir fluid dataset for assessing storage compliance for regulatory compliance for Stage 2C.

Outcomes

Environmental monitoring has indicated no indication of CO_2 migration to shallow levels as a result of CO2CRC Otway operations.

Introduction

Otway Assurance Monitoring continues routine groundwater and soil gas monitoring of the Otway site to meet EPA Victoria requirements.

At the CO2CRC Otway National Research Facility, an environmental monitoring program has been in place since 2006. It was designed to assure compliance with regulatory requirements and to verify that the injected CO_2 is behaving as predicted.

In addition to providing evidence that the projects are meeting key performance indicators established with the regulators, Environment Protection Authority (EPA) Victoria, the Otway monitoring program has been designed to meet the following objectives:

- Ensure safe operations
- Demonstrate compliance with regulatory requirements
- Evaluate a range of monitoring methods
- Provide data with which to calibrate models
- Ensure monitoring is both technically sound and cost effective.

Methods and outputs

Environmental monitoring methods that have been applied at the CO2CRC Otway National Research Facility since Otway Project inception include the following measures to confirm that the plume remains within the subsurface:

- Annual measurement of soil gas composition at approximately 2m depth on a 2km grid, to determine any changes to the naturally occurring CO_2 in the soil. These analyses are designed to determine if any changes in soil gas composition are attributable to CO2CRC storage activities (this project).
- Annual measurement of groundwater chemistry in wells penetrating the 800m-deep Dilwyn aquifer and from wells penetrating the shallower Port Campbell aquifer. These data analyses monitor any changes to the groundwater composition to determine if any are attributable to CO2CRC's storage activities (this project).

Key publications

Boreham, C, Underschultz, J, Stalker, L, Kirste, D, Freifeld, B, Jenkins, C and Ennis-King, J, 2011. *Monitoring of CO_2 storage in a depleted natural gas reservoir: gas geochemistry from the CO2CRC Otway Project, Australia.* International Journal of Greenhouse Gas Control, vol. 5 (4), pp. 1039-1054

de Caritat, P, Hortle, A, Raistrick,M, Stalvies, C and Jenkins, C, 2013. *Monitoring groundwater flow and composition at a demonstration site for carbon dioxide storage in a depleted natural gas reservoir: the CO2CRC Otway project*. Applied Geochemistry, vol. 30 (3), pp. 16-32.

Schacht, U and Jenkins, C, 2014. *Soil Gas Monitoring the Otway Project Demonstration Site in SE Victoria, Australia*. International Journal of Greenhouse Gas Control, vol. 24, pp. 14-29.

Next steps

Complete reporting for 2018-9 surveys conducted in March and May 2019.

Otway Project Stage 2C

Project owner: Dr Roman Pevzner, Curtin University

Objectives

- Detect injected CO_2 in the subsurface: ascertain minimum seismic detection limit
- Observe the gas plume development using time-lapse seismic
- Verify stabilization of the plume in the saline formation using time-lapse seismic

Outcomes

- A workflow for predicting, monitoring, verifying and assuring CO_2 storage in saline formations.
- Technical limits of various seismic technologies to detect and monitor CO_2. Results from this project shall inform stakeholders of minimum detection limits for various subsurface seismic monitoring technologies.
- Trialling novel seismic monitoring tools, such as distributed acoustic sensing and permanent seismic sources (surface orbital vibrators).
- Evaluation of the performance of permanently deployed fibre optic sensors and permanently deployed seismic sources, with results used to design the seismic monitoring program for the CO2CRC Otway Stage 3 project, in which it is planned to demonstrate feasibility of this approach through a field experiment.

> "In order to optimise the use of seismic monitoring, it is important to understand its limitations in terms of resolution and sensitivity when detecting small quantities of CO_2 in different geological formations"

Introduction

In Australia, the storage of CO_2 in saline formations is an important carbon abatement option, with adequate capacity for the country's CO_2 storage needs. To assess CO_2 storage in deep saline formations, the interplay of various trapping mechanisms during CO_2 plume migration needs to be better understood. Seismic (both surface and well-based), when used in conjunction with pressure measurements and reservoir modelling, has been demonstrated previously to be a key storage surveillance technology. In order to optimise the use of seismic monitoring, it is important to understand its limitations in terms of resolution and sensitivity when detecting small quantities of CO_2 in different geological formations. In particular, an important consideration is the potential leakage of supercritical CO_2 into overlaying aquifers.

Overall, while time-lapse seismic has been effective in tracking large CO_2 plumes (such as Sleipner and Snøhvit offshore Norway), detection and quantification of CO_2 leakage from the target formations is an important topic of current research (Chadwick et al., 2014)[1] . This is particularly topical for onshore Time Lapse (TL) seismic monitoring, which faces additional challenges due to temporal variations of near-surface conditions, coupling of sources and receivers to the ground, and ambient noise caused by wind, rain and human activity (Lumley, 2001; Pevzner et al., 2011; Johnston, 2013)[2]

Stage 2C of the CO2CRC Otway Project addressed these challenges by injection of ~15,000 tonnes of Buttress-sourced gas (80% CO_2 and 20% CH4) into a saline aquifer at the Otway site 240 km south-west of Melbourne, Australia, accompanied by TL seismic monitoring. The focus of this stage of the project was to demonstrate the temporal stabilization of a small plume injected into the Paaratte formation at 1.5 km depth

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[1] Chadwick, R.A., Marchant, B.P., Williams, G.A., 2014. CO_2 storage monitoring: leakage detection and measurement in subsurface volumes from 3D seismic data at Sleipner. Energy Procedia 63, 4224-4239.

[2] Lumley, D.E., 2001. Time-lapse seismic reservoir monitoring. Geophysics 66, 50-53. Pevzner, R., Shulakova, V., Kepic, A., Urosevic, M., 2011. Repeatability analysis of land time-lapse seismic data: CO2CRC Otway pilot project case study. Geophys Prospect 59, 66-77.Johnston, D.H., 2013. Practical Applications of Time-lapse Seismic Data. SEG Books.

through a series of TL seismic surveys in conjunction with matching modelling results. Another important goal of Stage 2C was to assess the seismic detectability threshold for small amounts of CO_2 injections. TL seismic activities during Stage 2C was able to detect 5,000 tonnes (Which is equivalent to a small amount of leakage in large scale projects) of the injected gas.

Methods and outputs

Time-lapse 3D seismic using an array of near surface deployed geophone receivers in conjunction with conventional vibroseis sources have successfully detected and tracked the plume of Buttress-sourced gas injected as part of the CO2CRC Otway Stage 2C Project. The Stage 2C program included the following activities:

- Detailed feasibility study and experiment design
- Design and installation of the buried receiver arrays
- Acquisition of the baseline seismic data in 2015
- Injection of 15,000 tonnes of Buttress gas into the saline aquifer (Lower Paaratte Formation) located at 1.5 km depth
- Demonstrating the capability to monitor the plume evolution through acquisition of two monitor seismic surveys during the injection and one survey at the completion of the injection
- Acquisition of two additional post-injection surveys (one year and two years after completion of the injection, in 2017 and 2018 respectively) to provide inputs into plume stabilization workflow
- Acquisition of a baseline and three 4D Vertical Seismic Profiling (VSP) surveys
- Downhole pressure measurements before, during and after injection in the injection zone and above zone to history match models with to be used in the plume stabilization workflow.

The migration of the plume, as tracked by 3D surface seismic, is shown below.

Key publications

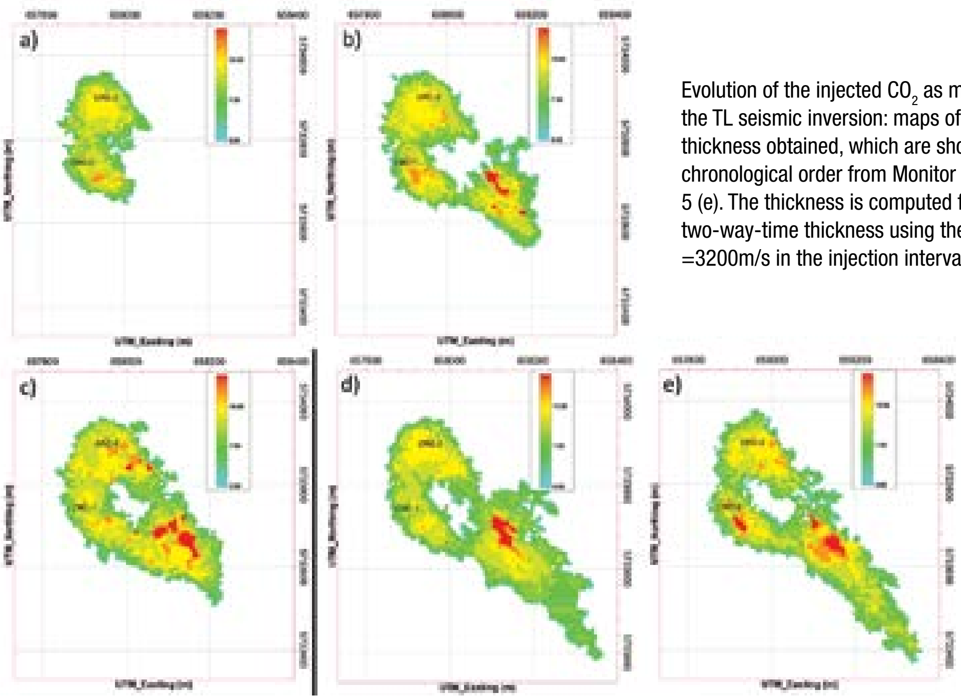
Pevzner, R, Caspari, E, Gurevich, B, Dance, T and Cinar,Y., 2015. *Feasibility of CO_2 plume detection using 4D seismic: CO2CRC Otway Project case study. Part 2 detectability analysis*. Geophysics, vol. 80 (4), pp. B105-B114.

Pevzner, R, Urosevic, M, Tertyshnikov, K, Gurevich, B, Shulakova, V, Glubokovskikh, S, Popik, D, Correa,J, Kepic,A, Freifeld, B, Robertson,M, Wood,T, Daley, T and Singh, R, 2016. *Stage 2C of the CO2CRC Otway Project: Seismic Monitoring Operations and Preliminary Results*. Energy Procedia

Pevzner, R et al, 2018. *Seismic monitoring of a small supercritical CO_2 injection into the subsurface: Stage 2C of the CO2CRC Otway Project*. Melbourne: CO2CRC.

Gurevich, B, Pevzner, R et al, 2017. *4D surface seismic tracks small supercritical CO_2 injection into the subsurface: CO2CRC Otway Project*. International Journal of Greenhouse Gas Control

Yavuz, S, Freifeld, B, Pevzner, R, Robertson,M, Tertyshnikov, K, Dzunic,A. and Daley, T, 2017. *Subsurface imaging using buried DAS and geophone array: initial results from CO2CRC Otway Project*. Geophysical Prospecting.



Evolution of the injected CO_2 as mapped in the TL seismic inversion: maps of the plume thickness obtained, which are shown in the chronological order from Monitor 1 (a) to Monitor 5 (e). The thickness is computed from the two-way-time thickness using the average VP =3200m/s in the injection interval.

Egorov,A, Pevzner, R, Bona, A, Glubokovskikh, S, Puzyrev,V, Tertyshnikov, K and Gurevich, B, 2017. *Time-lapse Full Waveform Inversion of Vertical Seismic Profile Data: Workflow and application to the CO2CRC Otway Project*. Geophysical Research Letters.

Correa, J, Pevzner, R, Bona, A, Tertyshnikov, K, Freifeld, B, Robertson,M and Daley,T, 2018. *3D VSP acquired with DAS on tubing installation: a case study from the CO2CRC Otway Project*. Interpretation Journal.

Pirogova, A, Pevzner, R, Gurevich, B, Glubokovskikh, S and Tertyshnikov, K, 2018. *Multi-well study of seismic attenuation at CO2CRC Otway Project geosequestration site: comparison of amplitude decay, centroid-frequency shift and 1D waveform inversion methods*. Geophysical Prospecting

Dance, T, La Force, T, Glubokovskikh, S, Ennis-King, J and Pevzner, R, 2019. *Illuminating the geology: post-injection reservoir characterisation of the CO2CRC Otway Site*. International Journal of Greenhouse Gas Control

Pevzner, R et al, 2018. *Active surface and borehole seismic monitoring of a small supercritical CO_2 injection into the subsurface: experience from the CO2CRC Otway Project*. In: Active Geophysical Monitoring, 2nd Edition, Elsevier, pp. 497-522.

Glubokovskikh, S, Pevzner, R, Gunning,J, Dance, T, Shulakova, V, Popik, D, Popik, S, Bagheri, M and Gurevich, B, 2019. *How well can time-lapse seismic characterize a small CO_2 leakage into a saline aquifer: CO2CRC Otway 2C experiment (Victoria, Australia).* International Journal of Greenhouse Gas Control

Popik, S, Pevzner, R, Tertyshnikov, K, Popik, D, Urosevic, M, Shulakova, V, Glubokovskikh, S and Gurevich, B, 2019. *4D surface seismic monitoring the evolution of a small CO_2 plume during and after injection: CO2CRC Otway Project study*. Exploration Geophysics

Next steps

A workflow for evaluating the plume for stabilisation has been established and will be used to make conclusions regarding stabilisation by June 2020 when the project concludes.

Highlights

Achievements in the reporting period:

- A plume stabilization verification workflow is proposed and will be tested by the end of the project (June 2020)
- Analysis of source/receiver technology combinations complete and documented
- Further analysis of Stage 2C seismic data using Quantitative Interpretation (QI)
- Further work on DAS/VSP data for anisotropic velocity modelling
- Summarizing of acquisition, processing and interpretation of the results across all seismic methods used in Otway Stage 2C
- Several abstracts were submitted to CO2CRC Symposium.

Multiscale Flooding Dynamics of Otway

Project owner: Dr Mark Knackstedt, Australian National University

Objectives

The aim of this project is to demonstrate the application of digital core analysis in estimating static and dynamic properties of core plugs. This will ultimately reduce the cost of reservoir characterization whilst improving the reliability of the models to predict the behaviour of the injected CO_2 plume. The main deliverables of the project are:

- An integrated geological description and calibrated static and flow property database pore to plug on 40 meters of Otway core
- Upscaled the results from pore scale to the whole core scale using dynamic reservoir solvers
- Generated anchored SCAL data for important reservoir rock types including generation of trapping curves and tensor-based flow properties (Including sensitivity and uncertainty analysis)
- Calibrated core data to well log data
- Whole core imaging and semi-continuous (each 3mm) permeability measurements from 45m whole core acquired from the Otway Stage 3 appraisal well CRC-3.

Outcomes

The program has illustrated the importance of incorporating realistic geological structures at multiple scales to offer greater confidence in static and multiphase flow predictions at the reservoir cell scales (inputs to static and dynamic model). Deliverables from this 2nd year of the project address the stated objectives.

The permeability data is summarised in continuous permeability logs along with identified geological facies, where we observe permeability variations over 7 orders of magnitude. Permeability from the continuous data is consistent with Routine Core Analysis (RCA) routine core analysis and log data.

High resolution inspection of the data illustrates the heterogeneity that exists even in the 'best' or 'high quality' intervals.

Flooding experiments through high quality rocks show the flow properties are strongly impacted by the lower permeability layers and that the saturation profiles are vertically heterogeneous.

A Digital Rock Analysis (DRA) workflow was applied to four samples from the Paaratte sandstone formation in the Otway Basin. The samples represent four main reservoir facies: massive sand; laminated massive sand; cross-bedded massive sand; and conglomerate sand. 3D X-ray computed tomography (micro-CT) images of the samples were acquired at the ANU National CT Lab. Inspection of the images revealed that cross bedded massive sand sample contained some horizontal mineral features but no significant laminations. It has therefore been reclassified as a second massive sandstone. This showed the benefit of the micro scale facies identification to characterise the reservoir.

Introduction

The CO2CRC Otway Stage 3 project requires accurate predictions of the extent of plume movement within the storage reservoir, however, small-scale geological features and heterogeneities have a significant impact in the subsurface that cannot be directly incorporated into field scale simulation models because of limitations in computer speed.

These small-scale heterogeneities can now be accounted for via an integrated multiscale workflow proposed here. The project utilises a multiscale workflow being developed in a parallel ANLEC R&D project to consistently address the impact of small-scale geological heterogeneity on static and dynamic rock properties.

Methods and outputs

Parallel components carried out for the two- year program have included:

- Building an integrated geological description and calibrated static and flow property database from pore to plug on 40 meters of core from Para sequence 1 in Paaratte formation in CRC-3.

- Generating anchored SCAL data for important reservoir rock types including generation of trapping curves and tensor-based flow properties—permeability and relative permeability data. Perform in situ imaging of CO2:brine contact angle on samples at reservoir pressure and temperature. Undertake sensitivity / uncertainty analysis of the resultant SCAL data.
- Utilising dynamic reservoir solvers that honour the physics of dynamic flow and geological heterogeneity at scales up to whole core and towards the individual reservoir static/dynamic model scales.
- Upscaling static and dynamic data to whole core and well log data.

Key publications

Knackstedt, M., 2019. *Multiscale flooding Dynamics of Otway Core, Phase 2*, Melbourne: CO2CRC.

Knackstedt, M et al., 2019. *In-situ pore-scale imaging and image-based modelling of capillary trapping for geological storage of CO_2*, International Journal of Greenhouse Gas Control (accepted).

Next steps

Next steps involve applying the acquired data and analysis in a workflow to update the static and dynamic models and compare the resulted models with conventional models. The key important data for this purpose are:

- Continuous permeability and porosity measurement
- Identified facies at pore scale and the upscaled versions to the whole core and log data
- Multiphase flow data identified at pore scale for different facies and upscaled data to the whole core.

Highlights

- The outcomes of this project can be used to update static and dynamic models to verify the improvement in the reliability of the model predictions (this can be shown on Otway Stage 3 models as a benchmark for the industry).

Rapid Plume Forecasting: Opportunity Definition

Project owner: Dr Stanislav Glubokovskikh, Curtin University

Objectives

To assess the feasibility of a workflow to provide:

1. Frequent (daily – weekly) predictions of 3D seismic images for a CO_2 plume based on a set of actual data acquired up to the time of prediction.
2. Accurately predict future seismic images from the set of available images using statistical learning algorithms.
3. Automated early-warning leakage detection based on anomalous plume dynamics.

Outcomes

The Opportunity Definition confirmed that the use of artificial neural networks is feasible for providing short-term predictions of the plume image.

Introduction

Machine learning (ML) and deep learning (DL) methods are successfully applied to similar tasks in many domains such as computer vision, robotics, speech recognition, augmented reality and others. The rich archive of geophysical data available for the CO2CRC Otway Research Facility (Victoria, Australia) enables development, training and testing of ML/DL algorithms for reliable detection and characterization of the injected CO_2 behaviour. In this project, we seek to unlock the potential of ML methods for real-time forecasting of CO_2 plume evolution based on time-lapse data. This work has potential application in the CO2CRC Otway Stage 3 project through the large seismic data set to be produced and the opportunity to use this as a training data set with which to test this technique.

Methods and outputs

Plume migration monitoring is important to both operators and regulators to ensure the injected CO_2 is not approaching the high-risk boundaries. To predict the areal plume evolution, a more sophisticated tool than time series models is required: artificial neural networks. A critical review of the artificial neural network predictors developed in machine vision indicates two most promising approaches: generative convolutional networks and recurrent convolutional networks.

The key to an accurate neural network prediction is a good training data set and training workflow. In order to capture the physics of the subsurface fluid flow in the data-driven plume forecasting, the neural network was trained on Eclipse-like fluid flow simulations. A set of 'simple' reservoir models and history-matched 'realistic' plumes generated for Stage 2C of the CO2CRC Otway Project were used. The neural network was focused on learning only the physical relationships relevant to the Stage 2C injection, but scenarios suffice for the training process to converge.

Another important feature of the training data set is binarisation of the images. This operation accounts for the limited accuracy and sensitivity of the Time Lapse (TL) seismic data.

The Otway Stage 2C data was used as the training data set to validate the proposed workflow, for which successful forecasting model was measured through two accuracy metrics:

- Relative area change error (relates error to plume growth)
- Absolute area change (last observed plume state).

The main features of the developed artificial neural network predictors are:

- The architecture implements either generative approach to neural network architecture or is based on the two-dimensional convolutional long short-term memory layer;
- The loss functions used for training are L_2, IoU or L_{2+IoU};
- Backpropagation uses the AdaGrad algorithm;
- Successful training requires first pass of the ANNPs through the simple scenarios.

Key publications

Glubokovskikh, S. et al., 2019. Rapid Plume Forecasting: Opportunity Definition, Melbourne: CO2CRC

Next steps

In this project, it has been shown that deep learning algorithms are capable of forecasting the future plume evolution based on relatively recent past geophysical observations. This key result guarantees that the deep learning may effectively process information to facilitate timely decision making of a site operator.

The continuation of the project will have to do with further development of the practical data analysis workflow that will be applied to the Stage 3 experiment. Key reasons to proceed with the work into Stage 3 include:

- Stage 3 provides a unique opportunity to develop/test/benchmark algorithms for real-time assimilation of data obtained by various geophysical monitoring techniques:
- The area of automated data assimilation for optimization of reservoir management is a very active field of research. Stage 3 will be the first of a kind project with real-time data assimilation algorithm. As the key objectives have to do with cost-effective monitoring techniques, such a data analysis system may be one of the main outcomes.
- The feasibility phase resulted in a very successful prototype of the deep learning predictor.

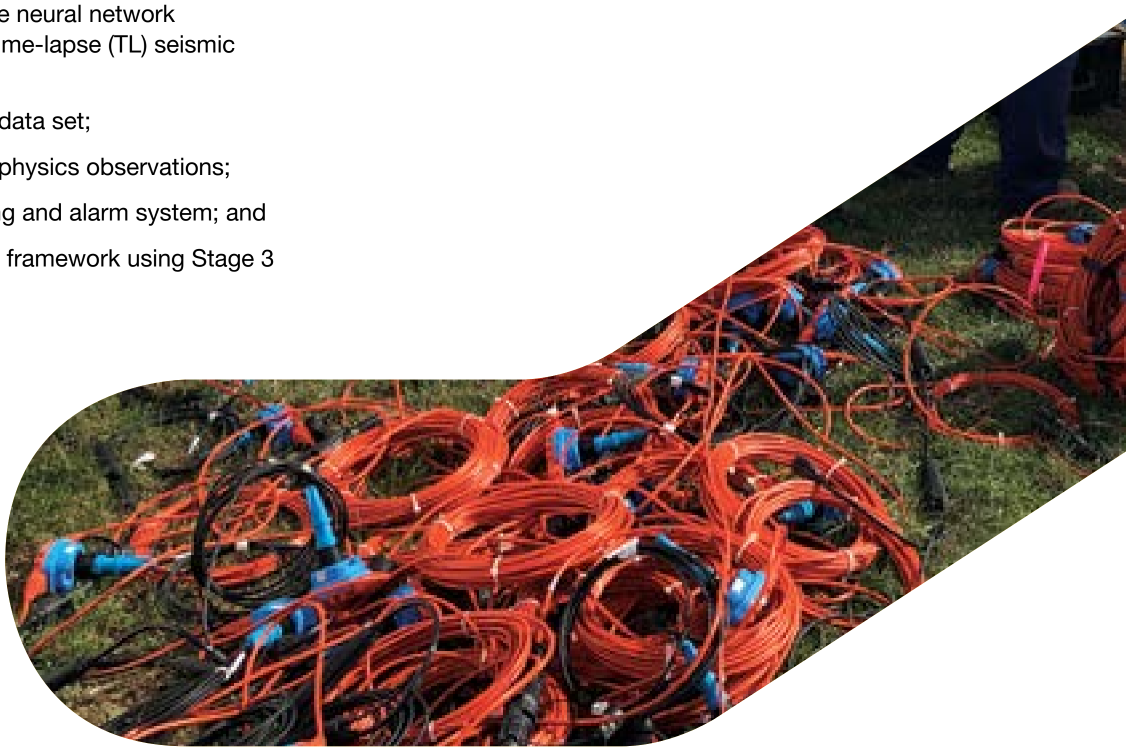
The next work steps would include:

- Further development of the neural network framework model for the time-lapse (TL) seismic data;
- Generation of the training data set;
- Incorporation of the multi-physics observations;
- Subsurface model updating and alarm system; and
- Validation of the proposed framework using Stage 3 of the Otway Project.

Highlights

Machine learning represents a major opportunity for significantly reducing the cost associated with CO_2 storage monitoring as well as early detection of plume behaviour.

By utilising the many sources of monitoring data available, the Otway Stage 3 project is a key candidate for testing this technique on account of the infrastructure in place and the large existing and planned data sets for use in refining and varying the application of machine learning for rapid plume prediction.



Passive Seismic and Seismic Interferometry: Opportunity Definition

Project owner: Dr Stanislav Glubokovskikh, Curtin University

Objectives

The objectives of this feasibility study were to:

- Demonstrate that there is enough detectable ambient body and surface wave energy that can be recorded by DAS equipment;
- Perform initial analysis of the wave field composition and identify prospective approaches for data utilisation;
- Test performance of interferometry-based imaging using both active seismic data and ambient noise;
- Evaluate the likelihood of fluid-induced seismicity caused by the injection.

Outcomes

The work carried out in this study has shown that:

- There is an abundance of elastic energy recorded by distributed acoustic seismic (DAS) in the subsurface for the entire depth on the wells. Surface ambient noise sources (machinery, impulse sources, and even cattle activity) are detected at distances of up to 0.8 km from the well.
- Persistent subsurface ambient noise sources can be detected and located by the downhole DAS installations at the Otway site
- Through analysis of the seismogenic index using both historical and new data, the microseismic response to CO_2 injection is likely to be detectable and provide information about the pressure front propagation and stability of nearby faults.
- The changes of amplitudes of the body waves can be used to estimate changes of the reservoir impedance, and therefore plume movement, in the direct vicinity of the well.
- Interferometric imaging algorithms tested on synthetic and field data demonstrate the viability of the passive interferometry for enhancing the results of active seismic monitoring. This is an important outcome for the application of DAS for the CO2CRC Otway Stage 3 seismic monitoring program due to remaining uncertainties in the direction and speed of CO_2 migration.

Introduction

Despite the fact that Time-Lapse (TL) surface seismic is proven to be a reliable geophysical method for monitoring of the injected CO_2, it has some disadvantages:

- The high cost of data acquisition;
- Relatively high level of invasiveness;
- Land access issues to conduct multiple surveys.

these factors motivate the development of more environmentally friendly seismic techniques that can provide sufficient quality of subsurface images at a fraction of the cost of surface seismic.

Recent improvements in DAS technology have had a significant impact on the application of seismic monitoring. Relatively cheap and highly durable fibre optic cables are easy to deploy and can acquire good quality seismic data (Correa et al., 2017). Hence, the use of permanently deployed optical fibre cables as receiver arrays in borehole reservoir surveillance can significantly reduce the cost and invasiveness of monitoring.

Further reduction of cost and the level of invasiveness of seismic monitoring operations could be achieved through the reduction of the active seismic source effort. To this end, one can use seismic energy associated with ambient noise and non-primary body waves excited by the controlled seismic source, including multiples and converted waves. The CO2CRC Otway facility has a unique setup consisting of multiple closely spaced wells, which will be instrumented with dense receiver arrays and fibre optic cables. This setup will provide a perfect opportunity to investigate interferometric and other relevant data analysis techniques in seismic monitoring applications. This project evaluated the feasibility of these approaches using both simulations and analysis of field seismic data and made recommendations on the requirements for the acquisition geometry and instrumentation for use in CO2CRC Otway Project Stage 3.

Methods and outputs

Continuous field data were acquired at the Otway site during two experiments for up to 78 days. The data were a combination of:

- DAS and downhole geophone tools conducted in 2018-2019
- Results of seismic modelling
- Analysis of the available well logs and active seismic data.

As a result of passive data analysis, it was established that there is an abundance of the elastic energy recorded by DAS in the subsurface for the entire depth of the wells. Surface ambient noise sources (machinery, impulse sources, and even cattle activity) were detected at distances of up to 0.8 km from the well.

Downhole DAS installations were also found to be useful to monitor low-magnitude events sourcing from several kilometres away from the site.

Analysis of the geomechanical and seismotectonic information for the Otway site was performed to estimate the seismogenic capacity of the proposed injected CO_2 during the CO2CRC Otway Stage 3 project. Both historical data and this analysis of the seismogenic index, demonstrated that the microseismic response to the CO_2 injection is likely to be detectable and provide information about the pressure front propagation and stability of nearby faults

Key publications

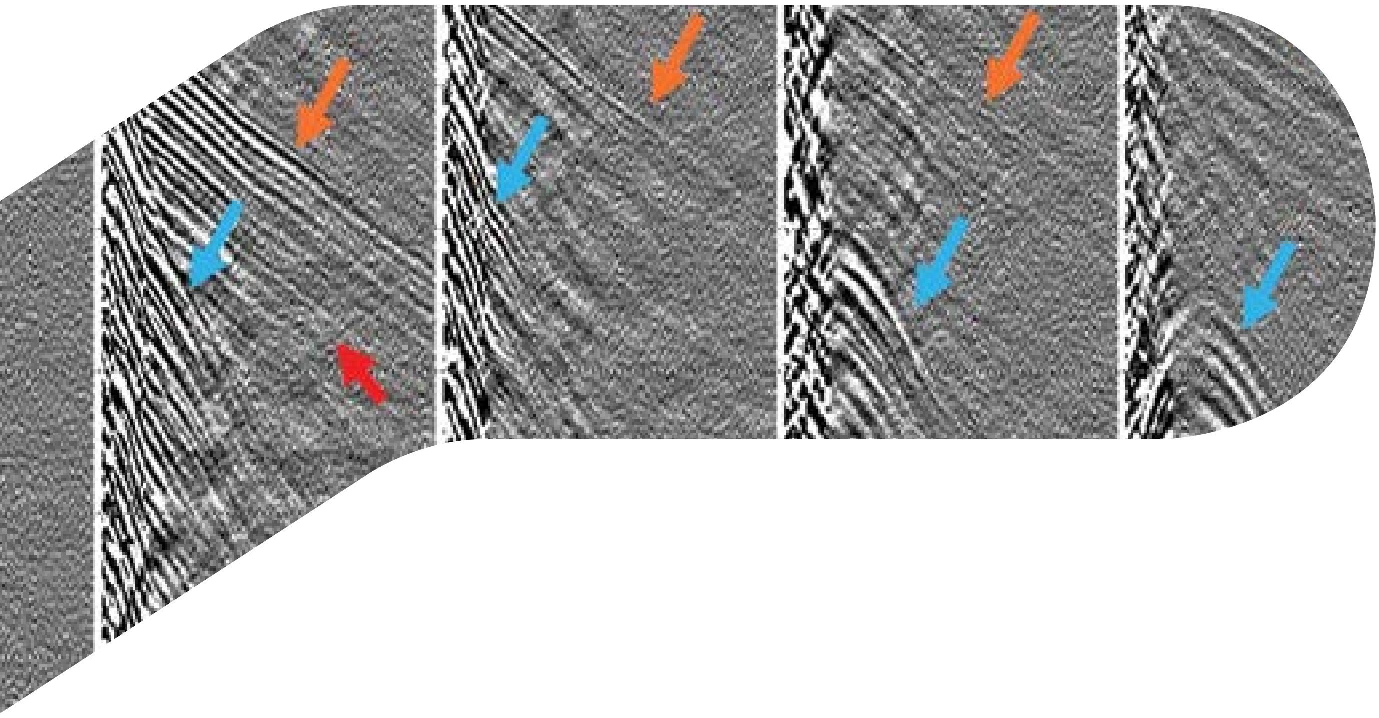
Pevzner, R. et al., 2019. *Feasibility study of passive downhole seismic monitoring, micro seismic monitoring and seismic interferometry using DAS data from CO2CRC Otway Project Stage 3 wells*. Melbourne: CO2CRC

Next steps

Given the favourable outcomes of the feasibility phase, a potential next step is to verify that the ambient noises can illuminate the injected plume in the subsurface.

Highlights

The project shows high potential for plume monitoring using seismic data acquired passively (without active sources, which represent a cost and land-access challenge). This will further reduce cost and footprint for plume monitoring.



Otway Fault Project (Prediction and Verification of Shallow CO_2 Migration) – Phase 2

Project owner: Dr Andrew Feitz, Geoscience Australia

Objectives

The objectives of Phase 2 of this project are to:

- Reduce the risks of the planned injection experiment (Phase 3) by drilling and coring two appraisal wells through Brumbys Fault and collecting critical information on the nature of the fault and the sub-surface geology, which are:
  - Rock strength, which will be used to determine the maximum and safe injection pressure for the experiment
  - Permeability, identify the best injection interval and enable modellers (+ max injection pressure) to estimate the total volume of CO_2 that can be safely injected
  - Mineralogy, which will enable modellers to estimate the extent of impact on groundwater chemistry
  - Fault extent, physically confirm that the fault extends to the base of the clay layer
  - Fault thickness, collect core to confirm the width of the damage zone.
- Develop a science case for the planned controlled release experiment, including well injection design and monitoring plan.
- Obtain the regulatory approvals required for Phase 3.

Outcomes

Analyses of the data including core, cuttings, logs and seismic acquired from Brumbys-1 and Brumbys-2 is well advanced. The static model is being updated as interpreted data becomes available.

Introduction

The ability to predict the influence of faults on the migration of the injected CO_2 is important in understanding the parameters of long-term safe CO_2 storage. Development and testing of new strategies to predict fluid migration pathways in the near surface will enable enhanced modelling and increased confidence in injected gas behaviour.

This project seeks to harness the improvements in monitoring techniques demonstrated over the last decade that have been applied for tracking CO_2 migration in both the reservoir (e.g. Otway 4D seismic, DTS) and near surface (e.g. Ginninderra soil gas) and use these techniques to image CO_2 migration up fault in the shallow sub-surface. This will provide unparalleled insight into CO_2 migration up a fault and an opportunity to assess the effectiveness of contingency monitoring, i.e. in the event that leakage from a storage complex has been detected, how to ramp up the monitoring response and target more likely leakage pathways.

In addition, the experiment provides a unique opportunity to evaluate the effectiveness of near surface monitoring strategies and validate the theories of 'hot spot' surface expression and of CO_2 gas migration into the vadose zone.

CO2CRC has embarked on a phased project to characterise the near surface, design, execute and operate a controlled release and monitoring project, as follows:

- **Phase 1:** Characterisation of the CO2CRC Otway site near surface, including the identification of a suitable structural control (fault) for CO_2 migration (Opportunity Definition) — completed 2017;
- **Phase 2:** Experiment site appraisal and subsurface sampling (Evaluate & Define) — This project;
- **Phase 3:** Controlled release experiment execution and operation (Execute & Operate) — proposed.

CO2CRC in partnership with Geoscience Australia is currently appraising the region in the vicinity of Brumbys Fault at the Otway Research Facility, identified during Phase 1 of this project, to determine its suitability for hosting the injection of a small volume of CO_2.

Methods and outputs

Phase 1 of this project used the following methods to characterise the Otway near-surface and to locate a fault suitable for injection:

- Ultra-high-resolution 3D shallow focussed seismic survey
- Two electrical resistivity imaging surveys, mapping the thickness of the top clay layer
- Ground penetrating radar and EM31 surveys, looking for 'holes' in the clay layer
- Groundwater slug tests to determine the permeability of the Port Campbell Limestone aquifer
- NMR logging of groundwater wells to determine porosity and estimate the vertical distribution of permeability in the Port Campbell Limestone aquifer
- LIDAR and aerial imagery survey to map elevation.

In Phase 2 in 2019, the methods employed to achieve the stated objectives include:

- Drilling two appraisal wells, Brumbys-1 and Brumbys-2 (shown in the figures next page), through a shallow fault and collection of first core from the Port Campbell Limestone (PCL) – completed Feb-Mar 2019
- Mechanical testing and petrophysical analysis of PCL core and fault material – complete
- Fluid-rock testing of PCL core and evaluation of contamination potential from CO_2 impacts
- Baseline soil gas and soil flux surveys across the fault and assessment – in progress
- Updating of the Otway shallow geology static model with appraisal well data – in progress
- Assessment of fault and site suitability for fault injection experiment – in progress
- Installation of piezometers and collection of accurate groundwater table information – complete
- Vertical seismic profile survey and collection of formation velocity data to determine feasibility of VSP for monitoring the injected CO_2 – in progress
- A methodology for appraising faults as potential leakage pathways – in progress
- A Science Case for the planned controlled release experiment, including well injection design and monitoring plan for Phase 3 – in progress.

Key publications

Feitz, A, Pevzner, R, Harris, B, Schaa,R, Tertyshnikov,K, Ziramov,S, Gunning,M, Ransley,T, Lai,E, Bailey,A, Schacht, U, Fomin,T and Urosevic, M, 2017. *The CO2CRC Otway shallow CO_2 controlled release experiment: Site suitability assessment*. Energy Procedia, vol. 114, pp. 3671-3678.

Bailey,A, Pevzner, R, Urosevic, M, Popik, D and Feitz, A, 2017. *Shallow geology of the CO2CRC Otway Site: Evidence for previously undetected neo-tectonic features?*. Energy Procedia, vol 114, pp.4424-4435.

Ziramov,S, Tertyshnikov,K, Pevzner, R, Urosevic, M, Harris, B, Costall,A, Pethick,A, Schaa,R, Buckerfield,S, Fowlkes,C, Goodwin,J, Fomin,T and Feitz, A, 2016. *High resolution geophysical baseline surveys of the Otway site: Interim report for project SRD3.3*. Melbourne: CO2CRC.

Radke,B, Hossain,M, Harris, B, Schaa,R, Tan,K, Pethick,A, Ziramov,S, Urosevic, M, Kalinowski,A, Tenthorey, E, Pan,Z, Ennis-King, J, Gunning,M, Lai,E, Ransley,T, Schacht, U and Feitz, A, 2017. *Otway Static and preliminary Dynamic Model: 3D Geological modelling of the fault and shallow sequence at the Otway site*. Melbourne : CO2CRC.

Feitz, A, Wang,L, Pan,Z and Ennis-King, J, 2017. *SRD3.3 Prediction and verification of Shallow CO_2 Migration (Phase 1): 3D CO_2 migration simulations and recommendations.* Melbourne: CO2CRC.

Radke,B, Hossain,M, Harris, B, Schaa,R, Tan,K, Pethick,A, Ziramov,S, Urosevic, M, Kalinowski,A, Tenthorey, E, Pan,Z, Ennis-King, J, Gunning,M, Lai,E, Ransley,T, Schacht, U and Feitz, A, 2017. *Otway Static and preliminary Dynamic Model: 3D Geological modelling of the fault and shallow sequence at the Otway site. Melbourne*: CO2CRC.

Feitz, A, Radke,B, Hossain,M, Harris, B, Schaa, R, Pethick,A, Ziramov,S, Urosevic, M, Tenthorey, E, Pan,Z, Ennis-King, J, Wang,L, Gunning,M, Lai,E, Ransley,T, Tan,K, Schacht, U, Kalinowski,A, Black, J and Pevzner, R, 2018. *The CO2CRC Otway shallow CO_2 controlled release experiment: Geological model and CO_2 migration simulations.* In: GHGT-14, Melbourne, 22-26 October.

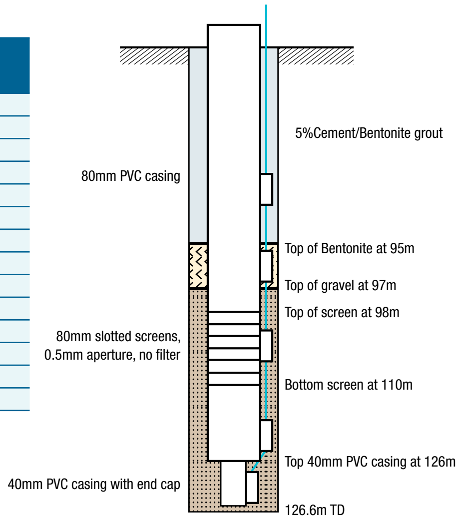
Next steps

Subject to a favourable recommendation on site suitability and securing funds, injection of CO_2 into Brumbys Fault will take place in the next phase of this project, during which a range of geophysical and environmental monitoring techniques will be used to image CO_2 migration.

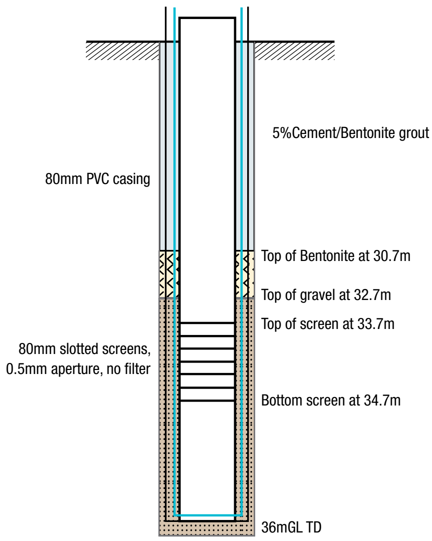
Highlights

Evaluation of the core from Brumbys-1 has shown that the interval within the Port Campbell Limestone (PCL) initially proposed as the target for injection in Phase 3, to be quite friable, looking like a muddy fine carbonate sand. Finalisation of the porosity and permeability and inorganic chemistry analyses will inform the recommendation on suitable interval for injection but will likely include seeking out a relatively marl-dominated interval within the PCL (rather than a more consolidated/indurated but potentially fractured one) which would support the injected CO_2 being directed toward and into the Brumbys Fault rather than being dispersed ahead of reaching its target.

GEOPHONE #	DEPTH (MGL)
1	33.9
2	40.9
3	47.9
4	55
5	62
6	69
7	76
8	83
9	90
10	96.9
11	103.9
12	111
13	118
14	125



Brumbys-1 well schematic (azimuth 200°, deviation 10°)



Brumbys-2 well schematic (azimuth 250°, deviation 45°)

"The ability to predict the influence of faults on the migration of the injected CO_2 is important in understanding the parameters of long-term safe CO_2 storage"

Marine Monitoring and Verification Method Development

Project owner: Dr Andrew Ross, CSIRO

Objectives

This project aimed to demonstrate detection limits and operational constraints of acoustic systems that could be integrated with Unmanned Surface Vehicles (USVs) in the acoustic detection of CO_2 released from the seabed.

Outcomes

In summary, this work has demonstrated that the SIMRAD Wide Band Transceiver (WBT) Mini acoustic sensor that is fitted to the Saildrone can detect low flow rate bubble leaks if the transect spacing is small and survey duration long. These flow rates are well below the upper limit proposed by IPCC (2005) for a release of 1% escape in 1000 years. It may be possible in the future to achieve detection updates in real time through the development of on-board processing of the acoustic data integrated with ML and AI methods. These developments would improve detection and reduce the false alarms that have not been considered in this work

Specifically, the outcomes of the testing and validation activities carried out in this phase of the project were:

- Development of a bubble release system to release small volumes of CO_2 (~100-600 litres) from, or close to, the seabed into the water column. These volumes will be varied;
- Assessment of detection capability of the SIMRAD Wide Band Transceiver (WBT) mini-acoustic sensor for detecting CO_2 releases,
- Evaluation of acoustics to detect gas seeps in a shallow water CCS site; and
- Building of a simulation model to test different survey designs for the SIMRAD Wide Band Transceiver (WBT) Mini acoustic sensor and calculate detection probability.

Introduction

Understanding measurement, monitoring and verification (MM&V) needs in the environmental context of potential subsea CO_2 storage projects is a challenging task globally, with off-the shelf solutions still several years away.

Recent developments in research and technology have opened the door to improved platforms, sensors and methodologies for undertaking this work, with potential to deliver lower false alarm rates and a better understanding of underlying processes. The applicability of these technologies for coastal shallow-focused MM&V still requires validation.

There is a requirement for in-situ technology validation regarding the capabilities of Unmanned Surface Vehicle -mounted sensor systems, which was the focus of this project.

This project centred on the in-situ validation of acoustic CO_2 detection systems to be mounted to USVs. Water column acoustic backscatter methods proven highly effective in the detection of low-volume methane seepage into the marine environment, during hydrocarbon exploration activities Whilst there have been prior experiments on controlled releases of CO_2 at the seabed. These tests have not demonstrated acoustic detection using systems that could be mounted to USVs.

A potential application for the technology tested in this project is the CarbonNet project. The CarbonNet Project (managed by the Victorian Department of Jobs, Precincts and Regions [DJPR]) is investigating the potential of the Gippsland offshore area for establishing a commercial scale CCS network which could see the injection of up to 5 million tonnes (MT) of CO_2 per year over a 25-year period into near-shore reservoirs in the Gippsland Basin. CarbonNet's preferred storage site is located under a shallow coastal shelf-sea with potentially significant ecological status, complex oceanography and multiple active stakeholders, making it a useful global case study for coastal CCS opportunities.

CarbonNet's existing MM&V plan foreshadows the development of environmental baselines and using mature technology from 2020 onwards.

Methods and outputs

The work centred on the use of testing the CO_2 plume detection capability and sensitivity under a range of seabed conditions, of the SIMRAD Wide Band Transceiver (WBT) Mini acoustic sensor that will be mounted to Saildrone acoustic equipment. Through bubble release experiments, the acoustic sensor's detection capability was demonstrated.

Field experiments took place at three locations in waters off Hobart in Tasmania, Australia, between November 2018 and April 2019 using RV South Cape, a 7 m vessel operated by CSIRO, for the purpose of measuring CO_2 flow rate and making acoustic recordings of the bubble plumes using the acoustic sensor.

A series of flow measurements were made between February and April 2019. Measurements were made at water depths between 9-22 m. Three flow rates tested ranged from 0.1 to 2.0 litres per minute which amounts to between 0.24 and 3.3 tonnes of CO_2 released per year. This is considerably less than the 1250 tonnes yr-1 that is considered acceptable for a 125 Mt store of CO_2 (Hardman-Mountford et al., 2015).

Based on the simulation studies the SIMRAD Wide Band Transceiver (WBT) Mini acoustic sensor system was very effective at detecting a leak which improved, depending on the number of sources and clusters within the survey area. At the two scenario extremes, a bubble plume can be detected with 100% probability if only 2 sources (>0.48 tonne yr-1) are within the area assuming a survey time of 600 hours (25 days). As the number of sources increases to 30 (> 7.2 tonne yr-1) within the survey area the survey duration is 110 hours (4.6 days) for 100% probability of detecting a bubble plume.

Key publications

Gerbing,C and Myers, J, 2018. SRD3.4: *Communications Strategy. Melbourne*: CO2CRC.

Marouchos,A, Tilbrook,B, Ryan,T, Passmore,A, Kloser,R, Cordell,J and Van Ooijen,E, 2017. *Saildrone USV Commissioning: Commissioning of two unmanned surface vehicles (USV) from Saildrone in support of CCS activities.* Canberra: CSIRO, and Melbourne: CO2CRC.

Marouchos,A, Passmore,A, Ryan,T, Van Ooijen,E, Tilbrook,B and Kloser,R, 2018. *Validation of Autonomous Surface Vehicle technology for shallow-focused marine MM, Phase 1*. Melbourne: CO2CRC.

Scoulding, B & Kloser, R., 2019. *Testing CO_2 detection sensitivities for marine MM&V method development, Phase 2 — Survey Plan*, Melbourne: CO2CRC.

Scoulding, B & Kloser, R., 2019. *Testing CO_2 detection sensitivities for marine MM&V method development, Phase 2 — Final Report*, Melbourne: CO2CRC.

Next steps

The results generated will initially be applicable to coastal environments with similar characteristics to the Gippsland offshore environment. The knowledge gained from understanding this project will inform the design of coastal MM&V programs around Australia and internationally, where development of marine MM&V is at an early stage of development.

Highlights

The experimental flow rates of 0.24 to 3.3 tonne/yr- were detected and through a simulation survey model evaluated flow rates from 0.48 tonne/yr to 660 tonne/yr. As an example, these flow rates are well below the 1250 tonnes/yr upper limit proposed by IPCC (2005) for a release of 1% escape in 1000 years of a 125 M tonne storage facility as proposed for the CarbonNet Pelican geological storage site.

Enhanced Containment through Barrier Formation

Project owner: Professor Ralf Haese, University of Melbourne

Objectives

- Develop and validate a reaction mechanism leading to barrier formation under reservoir conditions, including utilisation of CO2CRC Otway site parameters.
- Simulate reactive barrier formation scenarios using the derived reaction mechanism and realistic reservoir conditions.
- Provide an initial science case for barrier formation in the Otway, to support decisions for field scale validation.
- Characterise reservoir microbial communities and determine conditions and likelihood of microbial barrier formation under high CO_2 conditions.

Outcomes

The key outcomes of this project are:

- A low-cost reagent (alkaline Na-Si-solution) and the respective reaction mechanism has been identified to form a flow barrier in the form of a Silica gel. The barrier is formed when the reagent comes into contact with supercritical CO_2 or CO_2-enriched water. Laboratory experiments have shown a reduction in permeability by up to two orders of magnitude caused by the reactive barrier;
- Reactive-transport modelling is in principle able to predict reactive barrier formation. However, Si-gel formation requires modifications to existing thermodynamic and kinetic databases used for the modelling. Those changes are best informed by dedicated laboratory experiments;
- Most recent simulations have used reactive barrier formation at the top of the injection interval as a diverter of CO_2 allowing horizontal migration of CO_2 away from the well before buoyancy-driven upward migration commences. We expect this will lead to slower migration and higher residual trapping capacity;
- Barrier formation can be achieved by injecting the two reagents in sequence. A slag of water in between the two reagents inhibits clogging adjacent to the well;
- Barrier formation can be achieved by co-injecting the two reagents at a given ratio, so that the barrier formation proceeds over several days. The barrier will serve as a flow diverter which may also enhance residual trapping in reservoirs with only minor flow barriers (baffles).

Introduction

Long-term CO_2 containment is a key criterion for safe CO_2 storage, which is currently assessed through a range of seal integrity studies. While these site-specific studies will always be necessary, developing and testing the process of creating a flow barrier will help to understand how to manage and remediate undesired migration in future storage sites where containment is at an insufficient risk level.

The only robust CO_2 leakage mitigation technology so far is pressure management as demonstrated in modelling studies so far. However, this approach requires permanent termination of the CO_2 injection and continued pumping as a means to stir the CO_2 plume away from the leakage point. Here, we propose the development of procedures leading to 'engineered' permanent mineral barriers:

- as a remediation option in case of a CO_2 leakage; and
- as a (precautionary) CO_2 leakage mitigation technology for areas where seal integrity is possibly at risk.

In addition, this project will characterise reservoir microbial communities and will test whether high CO_2 conditions may lead to biofilm formation and / or biomineralisation reducing CO_2 mobility

The Enhanced Containment through Barrier Formation Project achieved modelling and laboratory testing of an engineered Silica gel mineral barrier which shows capability for reducing permeability in the near-wellbore region for increasing containment due to longer residence time.

While due diligence applied to CO_2 storage site selection removes/minimises the risk of leakage, methods for leak mitigation also need to be available. One method with potential to do this effectively is to reduce the permeability of the wellbore or caprock by forming a geochemical barrier using a reagent.

Methods and outputs

This project was designed around two activities centred on the development of an 'engineered' barrier to determine the information that would be needed to test the technology in the field at the CO2CRC Otway National Research Facility. The project has utilised desktop studies, laboratory experiments, testing of microbial metabolic behaviour, mineral dissolution and precipitation experiments, and reactive-transport modelling to predict the effectiveness of the engineered barrier and its effect on CO_2 migration.

In this project, a low-cost reagent and the related reaction mechanisms have been identified to form a flow barrier in the form of a silica gel. The barrier is formed when the reagent contacts supercritical CO_2 or CO_2-enriched water. Barrier formation can be achieved by co-injecting the two reagents at a given ratio, so that the barrier formation proceeds over several days.

The barrier will serve as a flow diverter which may also enhance sweep efficiency and residual trapping in hetregenous reservoirs containing high permeability streaks.

Key publications

Castaneda Herrera, C, Black, J, Stevens, G and Haese, R, 2016. *Preliminary experiments for a chemical reactive barrier as a leakage mitigation technology*. In: *Energy Procedia*, *GHGT-13*, Lausanne, Switzerland, 14-18 November 2015.

Black, J, Llanos, E, Castaneda Herrera, C and Haese, R, 2018. *Enhanced containment through barrier formation (SRD 4.1, final project report)*. Melbourne: CO2CRC

Castaneda Herrera, C, Black, J, Llanos, E, Stevens, G and Haese, R, 2018. *Formation of an Amorphous Silica Gel Barrier under CO_2 Storage Conditions*. *International Journal of Greenhouse Gas Control*, vol 78(11), pp. 27-36.

Black, J, Castaneda Herrera, C, Llanos, E, Stevens, G and Haese, R, 2018. *Performance of Silica-gel as a Geochemical Barrier under CO_2 Storage Conditions*. In: *GHGT-14*, Melbourne, Australia, 21-25 October.

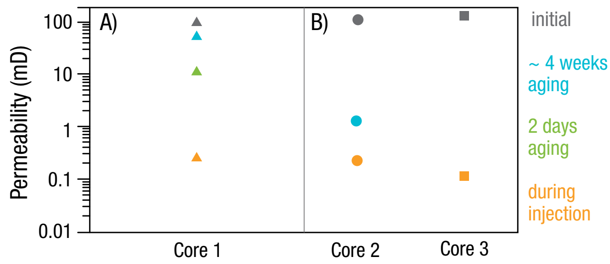
Next steps

A follow-on work program would involve demonstration of the silica-gel in improving well integrity. This can first be performed at a shallow field site such as CO2CRC Otway National Research Facility, followed by deeper deployment adjacent to a wellbore and directed at an injection interval to demonstrate containment enhancement.

Highlights

As a result of this work, recommendations for implementing alkaline sodium silicate solutions for forming silica gel barriers in a reservoir include:

- The application of the sodium silicate reagent as a means of mitigating risk of leakage by injecting the reagent above the overlying caprock of a CO_2 storage reservoir is a technically feasible and effective option. The density of the reagent can be optimised so that it sinks to the top of the caprock where CO_2 leakage could occur through high permeability zones.
- Where a leak has occurred, the use of the sodium silicate reagent may be a useful remediation tool if it can be injected to the site of the leak. This option depends on the localisation of the leak more than on the technical feasibility of forming a flow barrier using the sodium silicate reagent.
- Modification of reservoir permeability can also be achieved by adjusting the pH of sodium silicate solutions prior to its injection so that the gel forms within a specific time period. Implementing the reagent in this manner may help improve sweep efficiency in a reservoir.



Permeability of three Berea Sandstone cores (core 1: triangles, core 2: circles, core 3: squares) pre-saturated with barrier forming reagent following the injection of A) CO_2 saturated water, B) supercritical CO_2.

Otway Stage 3 project

Project Leader: Paul Barraclough, CO2CRC
Science Leader: Dr Charles Jenkins, CSIRO/CO2CRC

Objectives

The project will develop and provide field testing for innovative sub-surface monitoring technologies, which will significantly reduce the cost and environmental impact of monitoring programs for commercial CO_2 storage projects. The proposed techniques will also provide regulators and communities with ongoing confidence that CO_2 injected deep underground is permanently stored within the bounds of a storage formation. These innovative techniques provide a permanent, on-demand monitoring solution, which will enable faster acquisition and analysis of plume data.

Outcomes

CO2CRC's Otway Stage 3 Project is a $45.8m investment that aims to field test innovative technologies to enable CCS Storage Projects around the world. It does this by offering monitoring technologies and associated operational workflows that provide:

- Fit-for-purpose data;
- On-demand monitoring;
- Cost effective monitoring programs; and
- Minimised impact to the environment and communities.

While the infrastructure will be built in the second half of 2019 and the experimental program continuing until Dec 2022, a preliminary cost analysis shows the proposed subsurface monitoring techniques can reduce storage monitoring cost by up to 75%. The subsurface monitoring solution could remove the need for on-going conventional seismic acquisition, thus saving significant operational costs.

Finally, the Otway Stage 3 Project is a long-term investment in Otway International Test Centre that offers industry and the research community an accessible and fully instrumented test centre for benchmarking M&V tools, testing CO_2 storage processes and management techniques, and field testing technologies that have uses in a wide range of industrial applications.

Introduction

CO2CRC is developing fit-for-purpose monitoring technologies that aim to provide on-demand, key information on CO_2 storage sites with minimal surface impact. This will deliver substantial cost savings in future storage site monitoring design.

Initiated in 2015, the Stage 3 Project is the next major undertaking at the Otway National Research Facility, costing $45.8M and delivering five new wells with cutting-edge downhole seismic and pressure monitoring equipment. A trial injection of 15,000 tonnes of CO_2 will be used to validate innovative subsurface monitoring techniques on the resulting CO_2 plume. The primary monitoring methods are pressure tomography and downhole seismic, with other monitoring modalities and techniques being investigated as added components to the base design where possible.

The Otway Stage 3 Project injection well, CRC-3, was drilled in April 2017 to initially serve as the geological appraisal well and provide the data necessary to validate the proposed location of the additional monitoring wells. In July 2019, a drilling program was initiated to install the remaining four monitoring wells and their associated downhole sensors. By September 2019, the wells were drilled and completed, with injectivity testing and reservoir evaluation beginning in October 2019.

Methods and outputs

The project will inject 15,000 tonnes of high CO_2 natural gas into a saline aquifer at a depth of 1.6km, via a single injector well. The subsurface monitoring techniques will then be tested on the resulting plume using the array of monitoring wells and associated infrastructure. Primary monitoring methods will be:

1. Pressure tomography and inversion; and
2. Downhole seismic utilising permanently deployed sources.

The pressure tomography and inversion technique will seek to locate the gas plume in the subsurface by inducing a pressure wave into the storage aquifer and recording the response at the monitoring wells. This technique is especially useful in monitoring the boundary of the gas plume as it nears a high-risk area or sensitive boundary and could provide an early warning function should the plume migrate in an unexpected manner. This technique can be fully automated with data transmitted and analysed remotely to provide a history of plume position episodically or on-demand.

Downhole seismic measurements will use permanently deployed, low profile surface orbital vibrators (SOV), which generate sufficient source energy that can be detected by the sensitive fibre optic cables installed in the monitoring wells. Each SOV can provide a 2D image of the subsurface to each of the monitoring wells, creating a multitude of sub-surface transects that can be used to monitor the position of the plume as it migrates in the sub-surface. This innovative technique can be used as part of an ongoing, long term monitoring program, by replacing conventional seismic surveys, which require extensive source and receiver arrays, with a significantly reduced number of permanent sources and monitoring wells.

The new subsurface infrastructure installed on site will also be used to test the feasibility of further novel monitoring techniques. These techniques include passive and micro-seismic monitoring and the use of earth tides to detect plume movement in the subsurface.

The key outputs of this project are the delivery of:

- A fit-for-purpose, on-demand monitoring capability. The technologies will provide an early warning solution for industry and regulators that can be implemented in commercial projects immediately;
- Non-invasive monitoring techniques that will be acceptable for community and regulators; and
- A prospectus of technologies and workflows that can be used to define costs in commercial monitoring projects.

This validated toolbox of techniques will present a range of options for commercial CCS projects to ensure low cost, fit-for-purpose, real-time monitoring operations that addresses local needs, manages expectations of the wider public, and ensures minimal impact from an environmental, socio-political, economic and governance perspective.

Key publications

Watson, M and Jenkins, C, 2015. *Opportunity Definition Report: The CO2CRC Otway Stage 3 Project.* Cooperative Research Centre for Greenhouse Gas Technologies, Canberra, Australia, CO2CRC Publication Number RPT15-5353.

Jenkins, C, Dance, T, Ennis-King, J, Glubokovskikh, S, Gurevich, B, La Force, T, Marshall, S, Paterson, L, Pevzner, R, Tenthorey, E and Watson, M, 2016. *Validating subsurface monitoring as an alternative option to surface M*. In: GHGT-13, Lausanne, 114-18 November 2015.

Jenkins, C, Dance, T, Ennis-King, J, Glubokovskikh, S, La Force, T, Paterson, L, Pevzner, R and Tenthorey, E, 2017. *CO2CRC Otway Project Stage 3: Science Case at the conclusion of Evaluate.* CO2CRC Ltd, Melbourne, Australia, CO2CRC Publication Number RPT17-5755. 37pp.

Marshall, S, 2017. *Otway Stage 3: Otway Field Development Plan*. CO2CRC Ltd, Melbourne, Australia, CO2CRC Publication Number RPT17-5756. 39pp.

Ennis-King, J, Gunning,J and Jenkins, C, 2018. *Refinement and testing of inversion algorithms for pressure tomography*. CO2CRC Ltd, Melbourne, Australia, CO2CRC Publication Number RPT18-5894.

Pevzner, R, Correa, J, Popik, S, Glubokovskikh, S, Tertyshnikov, K, Yavuz, S and Gurevich, B, 2018. *Seismic monitoring program for CO2CRC Otway project Stage 3: Define Phase*. CO2CRC Ltd, Melbourne, Australia, CO2CRC Publication Number RPT18-5893.

Paraschivoiu, E, Dance, T and Glubokovskikh, S, 2018. *Stage3 Define: Static modelling and Uncertainty In support of monitoring well planning*. CO2CRC Ltd, Melbourne, Australia, CO2CRC Publication Number RPT18-5884.

Otway National Research Facility update

Project owner: Kwong Soon Chan: Operations Manager, CO2CRC

Objectives

The Otway National Research Facility (ONRF), accessing eight CO_2 production, injection and monitoring wells and a capture research skid, offers an unprecedented R&D platform to develop, demonstrate and advance CCS technologies and progress their technology readiness level (TRL).

Introduction

The Otway National Research Facility (ONRF) makes an important contribution for CCS technology advancements in Australia; contributing to the process of maturing CCS technologies, informing policy and regulatory settings and conducting community education.

CO2CRC operates strategic projects to develop and demonstrate transferable CCS technologies and solutions to support an emerging CCS industry in Australia and overseas.

The portfolio comprises research on novel materials and technologies towards high-performing compact capture technologies as required to separate CO_2 from natural gas in gas processing facilities, and comprehensive sub-surface research projects towards cost-effective, high resolution and low footprint monitoring of industrial scale carbon storage.

All projects conducted at the ONRF completed comprehensive feasibility studies and passed rigorous international peer-reviews prior to commencing operations. Projects are governed by CO2CRC's Program Advisory Committee (Science) and the Operations, Safety and Environment Committee (Operations).

Active Projects at the Otway National Research Facility in 2018–19

(The section below describes operational activities at the site. Scientific results are presented for each project under the Storage and Capture sections.)

Annual Assurance Monitoring

The annual assurance monitoring for 2018/19 at the Otway National Research Facility was successfully completed. The annual report was submitted to the Environment Protection Authority to demonstrate compliance with the licence conditions. As part of the assurance monitoring, soil gas and groundwater surveys were conducted in April and May 2019, confirming that over 80,000 tonnes of CO_2 rich gas remain safely stored in a depleted natural gas field and a deep aquifer.

Stage 2C Seismic

Repairs to the 1km2 buried seismic array were undertaken in March 2019 in preparation for the sixth and last seismic survey (M6) for the Stage 2C project, also serving as the baseline survey for the upcoming Stage 3 project. The repairs were undertaken by component suppliers Sercel in conjunction with Curtin University and a local earthmoving contractor.

Stage 3 Project

All regulatory approvals were obtained in time for the Stage 3 infrastructure work to commence in April 2019 with civil works for two well-pads, new fences and access road. CO2CRC contracted InGauge to design, contract and supervise the drilling campaign. The campaign to drill four new deviated wells for Stage 3 was successfully completed between 22 July 2019 and 30 September 2019. The wells are equipped with the latest technologies in fibre optics sensing and subsurface gauges. Pressure communication between wells has been confirmed and the seismic imaging system is functioning on all wells as designed. CO2CRC's Stage 3 project represents the largest single project undertaken by CO2CRC and will be used to validate technologies which can provide data on demand, as well as reducing the cost and impact of long-term CO_2 storage monitoring for CCS projects both within Australia and globally.

Otway Fault Project

The Otway Fault Project has the objective to understand the influences of geological faults on injected CO_2 migration and is led by Geoscience Australia. A suitable shallow fault was identified at the Facility. Two shallow 126m and 36m deviated wells were drilled through the fault from 8 February 2019 to 1 March 2019 and two pairs of piezo bores were also completed. Logging operations were undertaken, and good quality cores retrieved from Port Campbell limestones to support this research.

Otway Capture Research

The Capture Research Skid installed at the Buttress-1 location started using high pressure Buttress CO_2 rich gas after gaining approval from EPA Victoria in July 2018. Phase 1 and Phase 2 of the research was successfully completed during the reporting period. Phase 3 of the capture research considering the impact of impurities such as H_2S on the efficiency of various absorbents and membrane materials is currently in progress. The Capture Skid is a valuable addition to the Facility, enabling the testing of novel materials to separate CO_2 from methane in a high-pressure environment at various concentrations and pressures, as encountered in industrial gas processing facilities.

Operations and maintenance

Site operator, Upstream Production Solutions, continues to provide outstanding services for the CO2CRC Otway National Research Facility. In March 2019, CO2CRC undertook maintenance on the buried seismic array in preparation for the M6 survey for Stage 2C and the upcoming Stage 3 project This maintenance works involved excavation of sections of buried fibre optic cable and geophones around properties of surrounding landowners. Access to these properties are obtained through the goodwill of neighbouring farmers. A special thanks is owed to these landholders for their ongoing cooperation and assistance for this important maintenance on the burrier fibre optic cable and geophones. In March 2019, CO2CRC also upgraded its Distributed Control System (DCS) with the latest to easy-to-use automation system that simplifies operational complexity. The state-of-the-art suite of products and services increases CO2CRC facilities' performance with intelligent controls that are easy to operate and maintain in preparation of the Stage 3 project.

Local engagement and support

Close engagement with the local Nirranda and Nullawarre communities continues to be high priority for CO2CRC's Otway National Research Facility. In November 2018, 65 people attended an Open Day at the Facility. Participants included members of the local community, people from nearby regional cities and towns, individuals, families and university students from Melbourne. Various activities were organised including interesting science-based activities for children. A BBQ lunch was cooked and served by the Nullawarre Parents Club and tours held to explain CO2CRC's R&D achievements and ongoing activities. To further enhance local engagement, two Community Reference Group meetings were held in October 2018 and March 2019, chaired by Moyne Shire Councillor Colin Ryan. These community reference group meetings are important to update the local community and general public on recent and upcoming activities at CO2CRC's Otway National Research Facility. These meetings are also attended by regulators. Minutes are distributed to local landholders and interested parties. Routine newsletters were distributed to thousands of local households in October 2018 and March 2019 to provide research updates on the Facility and other interesting and useful information about CCS and CO2CRC.

Site visits and Visitor Centre upgrade

CO2CRC hosted 279 visitors in 2018/19 at the Otway National Research Facility. In October 2018, 145 international CCS experts visited the site in conjunction with the Carbon Storage Leadership Forum (CSLF) and the International GHGT-14 Conference. In January and February 2019, members of the local community and representative from industry and researchers from ENI, National Tsing Hua University, National Taiwan University visited Otway National Research Facility to better understand CO2CRC's R&D activities. In March 2019, the Executive Director and Director of Victoria's EPA visited the Facility to understand the contribution of CO2CRC's R&D activities to policy and regulatory settings in Australia. During March and May 2019, students from the University of NSW Student Engineers Group and Melbourne based universities also visited. In June 2018, two senior executives from the Austrian Company RAG, visited the Otway National Research Facility to better appreciate CCS advancement in Australia including some of the leading R&D activities on site.

In consultation with Moyne Shire, minor works were undertaken to our Visitor Centre focussing on enhancing accessibility. The works included modification of site toilets to provide a universal access facility, installation of a glassed-in area surrounding our deck, providing better weather protection and reduced risk of falling from heights, and slight changes to doorways, access stairs and the ramp for wheelchair access. The Otway National Research Facility has a modern appeal and meets all current building code requirements.

Highlights

- As of June 2019, Otway National Research Facility has, since its inception, achieved 4564 days (~12.5 years) without any lost time incident.
- 145 visitors from over 20 countries visited the Facility in conjunction with GHGT-14.
- Infrastructure works for Stage 3 were completed to a high standard, enabling drilling work to proceed on the wellpads over the winter months in a timely and safe manner.
- The Facility's capture skid commenced using high pressure gas from our Buttress-1 following Earth Resources Regulation approval.
- CO2CRC continues to sponsor the local Nirranda Football Netball Club.

OTWAY STAGE 3 HIGHLIGHTS

Drilling complete as part of research to develop low cost, low impact CO_2 monitoring

The project is proving up technologies which provide data on demand, as well as reducing the cost and impact of long-term CO_2 storage monitoring for carbon capture and storage (CCS) projects. The next six months will see teams from CSIRO and Curtin University calibrating the pressure tomography monitoring system and performing baseline seismic acquisitions using fibre optics cables and permanently deployed surface orbital vibrators.

“These new technologies provide data quicker, protect the environment, and cost significantly less than the seismic surveys currently used. Initial estimates show cost savings of up to 75 percent,” said David Byers, CEO of CO2CRC.

Technical and scientific work programs are being carried out in partnership with Curtin University and CSIRO and are expected to be complete by June 2022.

REDUCING CAPTURE COSTS

Membrane Gas-Solvent Contactor Pilot Plant Trials (at Vales Point Power Station) (C1)

Project owner: Dr Abdul Qader, CO2CRC

Project leader: Dr Jai Kant Pandit, CO2CRC

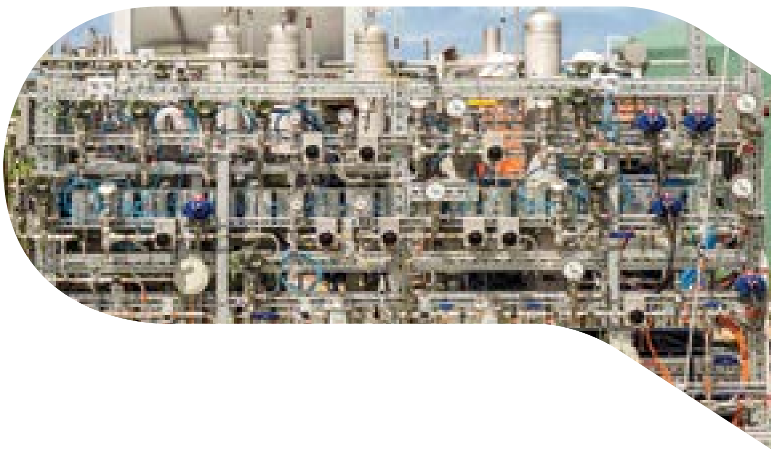
Science leaders: Dr Colin Scholes and Prof Sandra Kentish, The University of Melbourne

Objectives

- Develop a novel, compact and hybrid carbon capture technology for post-combustion capture through a detailed analysis of process performance to enable scale up and commercialisation use of the membrane contactor process.
- To demonstrate operation of the membrane contactor process in full continuous mode, with solvent absorption and regeneration occurring simultaneously for extended periods of time.
- Achieving the performance of the pilot plant with overall mass transfer coefficient for absorption >0.0004 cm/s and for regeneration >0.002 cm/s (chosen based on literature survey).

Outcomes

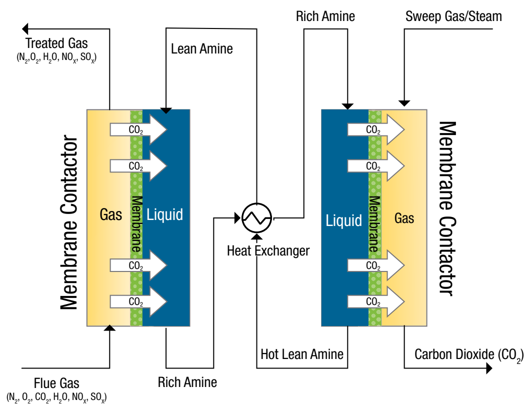
- The pilot plant undertook both CO_2 capture and solvent regeneration using membrane contactors successfully and efficiently. This represents the world's first demonstration of membrane contactor technology in a continuous process in an industrial environment. Other studies undertaken elsewhere are limited to smaller scale demonstrations and focus only on CO_2 absorption from the flue gas.
- The project has established that commercially available membrane modules can successfully be implemented within the novel contactor process developed by the University of Melbourne and CO2CRC.
- The success of the pilot plant trials also highlights the current development level of the technology, with the continual process proven over an extended period of time and all research objectives achieved.
- The contactor technology has been demonstrated to be competitive in terms of energy penalty with current commercial post-combustion capture technologies (MEA based solvents) and has a lower energy penalty than current gas separation membranes. Furthermore, the pilot plant performance is in agreement with literature and laboratory scale performances, when operated under high Reynolds Number conditions to obtain better mass transfer coefficients.
- The research outcomes have achieved a viable membrane contactor process for the efficient capture of CO_2 from post-combustion flue gas streams. The success of the project will enable subsequent development of the contactor technology into the next phase of commercialisation.
- During Campaign 2, mass transfer coefficients of 0.08 (absorption) and 0.045 (regeneration) were achieved with the Airrane membrane. That means we achieved over 200 times better absorption and 22 times regeneration than the laboratory results indicating significantly better CO_2 recovery.



Introduction

A $1.64 million project to develop membrane contactor technology for carbon capture from post-combustion capture has been funded by the Coal Innovation NSW (CINSW) — Department of Planning, Industry and Environment of the NSW State Government. The project is primarily focused on successful technology outcomes from the membrane contactor pilot plant, located at Vales Point power station. In association with the pilot plant trials was laboratory research undertaken at the University of Melbourne to support the development of the contactor technology, as well as economic and lifecycle analysis to place the technology in the broader carbon capture field.

Membrane gas-solvent contactors are a hybrid technology, which undertakes traditional solvent absorption within a membrane module as shown below. The technology involves the transfer of CO_2 from the flue gas through a hollow-fiber membrane, where it is chemically absorbed into a solvent. This takes advantage of the highly selective nature of solvent absorption technology, while the membrane acts to physically separate the solvent and gas phases. This enables much higher CO_2 mass transfer into the solvent phase to be achieved compared with traditional solvent absorption. In addition, the separation of the solvent and flue gas phases eliminates foaming and reduces liquid channeling; the two major operating issues in solvent absorption columns. Membrane contactor technology is also able to replace the solvent regeneration step. The membrane replaces the packed column of a solvent regenerator and enables a pure CO_2 product stream to be efficiently generated. This is partially achieved by using steam as a sweep gas within the membrane contactor to remove the CO_2 product, and hence enables some of the heating duty needed for regeneration to be undertaken within the membrane contactor. This reduces the size of the solvent reboiler and enables lower temperature solvent regeneration to be achieved. Therefore, membrane contactors reduce the energy demand of the solvent regeneration process and subsequently, the parasitic load of carbon capture on power generation. The equipment size for carbon capture can be reduced by up to two thirds, while the flexibility and modular nature of membrane technology enables the capture process to be easily accommodated into limited spaces.



Schematic diagram of absorption and desorption processes using membrane contactors

Methods and outputs

A membrane contactor pilot plant is located at the Vales Point coal-fired power station with the capacity to capture 0.1 tonnes per day of CO_2. This pilot plant consists of membrane contactors that can undertake both CO_2 solvent absorption and solvent regeneration. The design accommodates generic CO_2 selective solvents starting from monoethanolamine (MEA) to advanced solvents.

The process is based on the application of commercial membrane contactors for both the absorption of CO_2 into the solvent and subsequent solvent regeneration. The novel aspect is the process design, i.e., the application of membrane contactors and operating conditions. The use of readily available commercial membrane contactors is important, because it means the process can be readily scaled up and commercialised in the near term.

The pilot plant was operated in two campaigns, the second campaign completed in March 2019.

Key publications (included related references)

Scholes, C. A.; Qader, A.; Stevens, G. W.; Kentish, S. E., *Membrane gas-solvent contactor trials of CO_2 absorption from flue gas*. Sep. Sci. Technol. 2014, 49, 2449-2458

Zhao, Z.; Feron, P. H. M.; Deng, L.; Favre, E.; Chabanon, E.; Yan, S.; Hou, J.; Chen, V.; Qi, H., *Status and progress of membrane contactors in post-combustion carbon capture: a state-of-the-art review of new developments*. J. Membr. Sci. 2016, 511, 180-206

C. A. Scholes, S. E. Kentish, G. W. Stevens, D. deMontigny, *Asymmetric composite PDMS membrane contactors for desorption of CO_2 from monoethanolamine*, International Journal of Greenhouse Gas Control (2016) 55: 195-201

Scholes, C. A.; Kentish, S. E, Qader, A., *Membrane Gas-Solvent Contactor pilot plant trials for post-combustion CO_2 capture*, submitted for publication, Industrial and engineering Chemistry Research, 2019

Next steps

The current project started its activities towards end of 2016 and was completed in March 2019. Further works have been recommended for the next phase assuming funding is available:

- The next phase of technology development is to undertake larger scale pilot plant testing that integrates key components of the contactor technology directly with the power station (steam circuit integration, flue gas return, heat integration) as well as detailed computer simulation modelling of the contactor process, needed for thorough process and economic analysis.
- The future campaigns should test next generation solvents with improved CO_2 absorption efficiency and lower regeneration energy duty. This should also identify if there is a compatibility issue between the membrane material and the next generation solvents over extended periods of time.

Highlights

- World's first successful demonstration of membrane contactor technology in a continuous process in an industrial environment with simultaneous operation of absorption and solvent regeneration.
- This will also provide the opportunity to identify any compatibility issues between the membrane material and the tested solvents over extended period of time.

"The pilot plant undertook both CO_2 capture and solvent regeneration using membrane contactors successfully and efficiently. This represents the world first demonstration of membrane contactor technology in a continuous process in an industrial environment, while other studies are limited to smaller scale and only CO_2 absorption from the flue gas"

Reduction of greenhouse gas emission in steel production (C6)

Project owner: Dr Abdul Qader, CO2CRC
Project leader: Dr Jai Kant Pandit, CO2CRC

Objectives

- Analysis of CO_2 emissions with respect to emission sources and their location for an integrated steel plant.
- Evaluation of CO_2 capture options from all major emission sources at the BlueScope integrated steel making facility at Port Kembla.
- Evaluation of emerging global technologies for emissions reduction from BlueScope's integrated steel making facility at Port Kembla.
- Ascertain suitability of bio-chemical process to convert by-product gases to value added ethanol as an alternative fuel for the transport industry.
- Evaluate viability of various transport and storage options for captured CO_2 including a review of potential CO_2 storage locations and a high-level review of the economics and viability of CO_2 transport options to these sites. (trucking, piping, shipping).
- Assist BlueScope with technical and costing information to develop concept level financial evaluations that allow comparison between, and viability of, various emissions reduction options.

Expected outcome from this project

- Pathways for emission reduction in BlueScope Steel's Port Kembla facility including geological CO_2 storage potential in NSW and a proposal to convert a by-product gas to value added products.
- Summary of latest methods and technologies to reduce CO_2 emissions in an integrated steel plant and commentary on the suitability of latest technological developments on CO_2 reduction in steel manufacturing for the Australian steel industry.
- Information and data to enable BlueScope to develop a cost benefit analysis and a business case for the utilisation of steel plant waste gases containing CO_2 and CO.

Introduction

Steel making is an energy and carbon intensive process in which coal has traditionally been used as a source of energy and carbon. As a result, the steel industry is a major source of industrial greenhouse gas emissions and accounts for 7-9% of direct emissions from the global use of fossil fuel. The iron and steel industry provide both challenges and opportunities in reducing the greenhouse gas emissions and making the industry sustainable. In January 2019, Coal Innovation New South Wales (CINSW) — Department of Planning, Industry and Environment, NSW State Government engaged CO2CRC to conduct a research study into reducing greenhouse gas emissions in steel production. CO2CRC received strong support from BlueScope Steel who has provided the relevant information for this study from their steelworks in Port Kembla.

Methods and outputs

- Literature review.
- Analysis of CO_2 emissions data provided by BlueScope Steel, which form the basis of the full study.
- Evaluation of utilisation technologies for CO_2 and steel mill gases (bio chemical as well as chemical) aimed at reducing CO_2 emissions by producing value added products.
- Discussions with BlueScope on suitability of various emission reduction processes and technologies.

Key publications

- Four quarterly reports
- Final report

Next steps

Work on the study continues in close cooperation with BlueScope, Thyssenkrupp and Lanzatech.

BlueScope Steel may develop a cost benefit analysis and a business case for the utilisation of steel plant waste gases containing CO_2 and CO to reduce the emission from its Port Kembla Steelworks.

Highlights

The project will explore the suitability of biochemical processes (from Lanzatech Ltd.) and chemical processes (from ThyssenKrupp Germany) to reduce Scope 1 (Total direct) emissions from BlueScope Steel at Port Kembla.

"The steel industry is a major source of industrial greenhouse gas emissions and accounts for 7–9% of direct emissions from the global use of fossil fuel"

Gas refining package for Latrobe Valley hydrogen energy supply chain

Project owner: Dr Abdul Qader, CO2CRC
Project leader: Dr Jai Kant Pandit, CO2CRC

Objectives

- To design, engineer and supply the gas refining package on EPCM basis to produce 99.999% pure hydrogen from coal gasification syngas.

Outcomes

- Design and delivery of a gas refining and hydrogen purification process skid for the pilot plant of the Victorian Hydrogen Energy Supply Chain project that can produce 99.999% pure hydrogen.

Introduction

After completing two feasibility studies (Gas clean-up & hydrogen purification, CO_2 capture for HESC project) with industrial partners focusing on the conversion of brown coal to hydrogen, CO2CRC has been awarded a contract to implement a major component of the hydrogen production pilot plant for the HESC project at Latrobe Valley, Victoria.

The project commenced in August 2018 and involves the purification of syngas obtained by gasification of brown coal.

In the gas refining section, the syngas from the coal gasification plant will be cleaned to remove impurities such as chlorides, sulphides and cyanides. The cleaned gas will undergo a shift reaction to enhance hydrogen recovery and finally will be purified using pressure swing adsorption (PSA). The final product will be 99.999 % pure hydrogen.

Methods and outputs

The following methods/tools are used to deliver the project on time and to meet the quality and performance standards:

- Subcontracting major works
- Design Review
- Risk assessment
- Hazop workshop
- 3D model
- Hazid workshop
- Third party inspection
- Inspection and test plans
- Technical discussions and design deviation
- Document control and management.

Project outputs

- Basic engineering documents like PFDs, P&IDs, control philosophy, functional description, process set point list, cause and effect diagram.
- Detailed engineering documents including general arrangement drawings, equipment datasheets, 3 D model, electrical equipment, PLC design, electrical junction boxes, electrical and mechanical calculations, electrical single line diagrams.

Key publications

Not available, the details of the project are commercial in confidence.

Next steps

The equipment will be tested at the contractor's premises and delivered to site in late 2019.

Upon completing of commissioning and performance test runs, the plant will be operated for one year. Successful operation of the plant will prove the hydrogen production component of HESC project and may lead to a scale up design and operation in the Latrobe Valley.

Highlights

The equipment has been con3structed and assembled for Factory Acceptance Tests.

Otway Capture Project (06)

Project owner: Dr Abdul Qader, CO2CRC

Project leader: Saw Hong Lim, CO2CRC

Science Leaders: Prof Paul Webley, The University of Melbourne for adsorption, Prof Vicki Chen, The University of New South Wales (UNSW) for hollow fiber membranes, Prof Greg Qiao, The University of Melbourne for CAP membranes

Objectives

- To facilitate field testing of materials for evaluation of low footprint second generation capture technologies (state-of-the-art CO2CRC adsorbents and membranes) for separation of CO_2 during natural gas processing.
- To develop robust and compact CO_2 capture technology for high CO_2 content natural gas separation.
- To reduce the cost of capture in natural gas separation (onshore and offshore) to open up opportunities for high CO_2 content natural gas reserves to be developed.

Outcomes

Continuous operation of the fully automated high-pressure capture rig at the Otway National Research Facility has resulted in significant milestones for CO2CRC:

Adsorbents

- Assessed advanced adsorbent materials with enhanced kinetics by ion-exchange developed by the University of Melbourne under the banner of CO2CRC. The adsorbents were selected and designed for the separation of natural gas to achieve high purity CO_2 with high methane recovery. Successful completion of the test campaigns showed better performance of adsorbents indicating good potential candidates for commercialisation. Field test compositions matched well with laboratory isotherms.
- Trialed for the first time, adsorption technology at pressures of up to 50 bar for natural gas separation.
- Successfully executed adsorption cycles in the field paving the way for an efficient and safe deployment for compact, low cost separation technology for natural gas separation.

Membranes

- Stable membrane performance was observed during the continuous tests, demonstrating in stable CO_2/CH_4 selectivity with values similar to those observed in the lab pre-tests of the same modules.
- The stable separation performance of the thin film composite hollow fiber is particularly interesting. The superior CO_2 permeate rate and moderate selectivity of the Pebax imbedded with ZIF-8 nano-particles offers a great potential for industrial application, although the membranes withstood pressures of up to 13 bar only.
- CAP-10 Flat Sheet membranes had improved permeance (over 1000 GPU) with selectivity (2.1 - 4.0). Although it possesses very good permeance, selectivity needs to be higher (~20) for CO_2/CH_4 separation. Compared to commercial PolyActive tested in-house, the CAP membranes showed improved permeance and were able to sustain pressures as high as 20 bar without significant plasticisation.

Introduction

- Having successfully demonstrated CO_2 capture from flue gas and syngas streams sourced from coal fired power stations during the period 2007-2014, CO2CRC expanded the capture program in 2016 to include R&D in separating CO_2 from a high-pressure, high CO_2 content natural gas feed stream. Working with some of the world's leading researchers from The University of Melbourne (UoM) and the University of New South Wales (UNSW), CO2CRC commissioned a pilot scale capture facility at the Otway National Research Facility designed to test innovative adsorbent and membrane materials using natural gas from its own Buttress well.
- Beyond dehydration of natural gas, adsorption processes have not to date been used for separating CO_2 from CH_4 in high CO_2 fields. There is significant potential for adsorbents in this application as natural gas is frequently sourced at high pressure – this high pressure can provide the driving force for the separation in contrast to solvent based processes which require an external source of heat for solvent regeneration. The project provides an opportunity to test this concept and validate the design and operations to accomplish this separation.

The design of the Capture Facility allows for the feed gas composition to be changed, spanning the range of most naturally occurring gas fields.

- Membranes are compact and are considered to be suitable for natural gas under high pressure, provided they have high permeance and moderate to good selectivity and robust in nature. The use of an ultra-thin polymer film for the selective layer of the membrane ensures an increase in performance by significantly reducing the resistance to permeation. CAP (Continuous Assembly of Polymers) and thin film composite membranes developed by the University of Melbourne and hollow fiber membranes developed by UNSW with higher permeance and selectivity than the commercially available membranes were selected for this project. Hollow fibre membranes of high CO_2 permeance and excellent selectivity (CO_2 / N_2 and/or CO_2/CH_4) could lead to reduced production cost for membrane modules and reduced capture cost, however tests at elevated pressure need to be conducted to verify their ability to withstand high pressures.

Methods and outputs

The carbon capture skid at CO2CRC's Otway National Research Facility accommodates a single stage, two beds pressure swing adsorption (PSA) unit and three parallel membrane modules. Buttress gas at 90 bar pressure from the gas well head at Otway is used for testing. The buttress gas has a very high CO_2 content (~over 80 vol%) with methane as the other major component (~18 vol%). The gas is mixed with compressed methane (CNG) from cylinders to vary the CO_2 composition between 15 to 70 vol% in the feed gas to the test skid thus mimicking various gas fields composition. The skid also has the facility to inject impurities like H_2S in the feed gas so that effects of impurities on adsorbents and membrane performance can be tested.

A comprehensive stage-gated research plan has been implemented to test materials to confirm the performance, robustness, and tolerance of the adsorption and membrane technologies:

- Obtaining bench marking data using commercially available materials.
- Testing advanced adsorbent and membrane materials developed by the University of Melbourne and the University of New South Wales (NSW) under the banner of CO2CRC.
- Testing selected materials against impurities, such as H_2S.
- Improve simulation model based on test results and perform process scale up.
- Perform techno-economic analysis.

Key publications (including related references)

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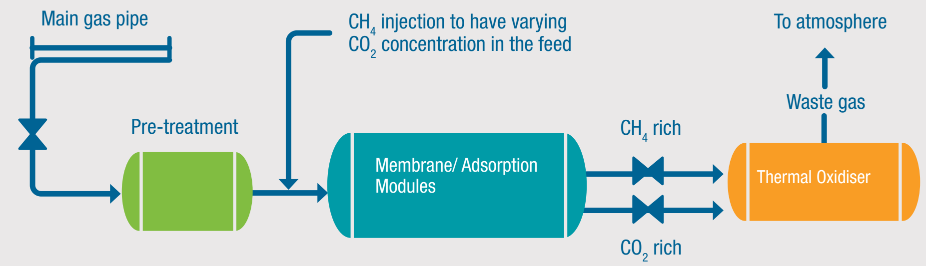
Qader, A, Webley, P, Xiao, P and Tao. *CO_2 capture from high CO_2 content natural gas by pressure swing adsorption at the CO2CRC's Otway site*, Australia., FOA 2019, Cairns

P.D. Sutrisna, J. Hou, H. Li, Y. Zhang, V. Chen. *Improved operational stability of Pebax-based gas separation membranes with ZIF-8: A comparative study of flat sheet and composite hollow fibre membranes*, Journal of Membrane Science, 524 (2017) 266-279.

Q. Fu, J. Kim, P.A. Gurr, J.M.P. Scofield, S.E. Kentish, G.G. Qiao. *A novel cross-linked nano-coating for carbon dioxide capture.* Energy Environ. Sci. 2016, 9: 434-440

Schematic Diagram of Otway Capture Rig



Next steps

Adsorbents

The current tests are rated at a Technology Readiness Level (TRL) of 4. The next step would be to conduct TRL 5-6 investigations with a higher number of adsorption beds to mimic industrial practice and obtain data for commercial scale up.

- Develop scale-up simulation.

Membranes

- TRL 5-6 tests would be necessary before commercial testing.
- Develop scale-up simulation.

The tests with H_2S are to be carried out in Campaign 3 during the July-Sept 2019 period after which the final reports will be submitted.

Highlights

- PSA using commercial and developed adsorbents were conducted at 30 and 50 bar, making it the first PSA facility operating at pressures of up to 50 bar to separate CO_2 from natural gas.
- Novel zeolite adsorbent HZ2 with enhanced kinetics by ion-exchange were developed by the University of Melbourne.
- Adsorption, a compact second-generation technology is very suitable for natural gas separation, contrary to general perception.
- The stable separation performance of the thin film composite hollow fiber is particularly interesting. The superior CO_2 permeate rate and moderate selectivity of the Pebax imbedded with ZIF-8 nano-particles offers great potential for industrial applications.

International cooperation in CO_2 capture

- CO2CRC is a member of the International Test Centre Network (ITCN), participating in international meetings to share knowledge on operational experience, establish generic performance indicators and promote technology standardisation for CCS. Current members include the US National Carbon Capture Centre (NCCC); the Norwegian Technology Centre Mongstad; CSIRO Australia; the UK CCS Research Centre; the Canadian CCS Knowledge Centre, SINTEF in Norway, CERI and NICE in China and KIER in Korea. Participation in the network confirms CO2CRC's place within a group of global capture research and development leaders.

Adsorbents

CCSNET AND GIPNET

Research organisations involved
CO2CRC, University of Melbourne, CSIRO
University of Wollongong, ANU, University of Adelaide
Federation University

Objectives

To establish a research infrastructure network to produce technologies that will drive down costs and make CCS a price-competitive emissions reduction technology.

Outcomes

CCSNET has delivered:

- Otway Subsurface Laboratory (OSL).
- Gippsland Monitoring Network (GipNet).
- LabNet Storage.
- LabNet Capture.

The expected outcomes and added values from the five-year research programs related to each asset above are summarised in Table 1.

Introduction

CCSNET comprises laboratory upgrades, new plant and equipment located at universities and national research centres in Victoria, ACT and South Australia. These build upon existing research and development infrastructure at the CO2CRC Otway National Research Facility and enhance its global profile as one of the premier CCS subsurface laboratories in the world.

CCSNET is funded via an Australian Government Education Investment Fund (EIF) grant and its primary objective is to support the Victorian Government's CarbonNet Project, which is also a proxy for other offshore CCS projects in Australia and worldwide. CarbonNet is investigating the potential for a commercial-scale CCS hub in Victoria. It is jointly funded by the Commonwealth and Victorian governments and aims to bring together multiple CO_2 capture projects in Victoria's Latrobe Valley, transport CO_2 via a shared pipeline and inject it deep underground, into offshore storage sites in Bass Strait.

CO2CRC utilised its strong governance processes to review assets for fitness for purpose and direct benefit to CCS research and development in Australia, including for the benefit of CarbonNet, and to oversee the procurement and development of the five-year research plans. The CCSNET Steering Committee considered advice from the Joint Project Committee and the Scientific Advisory Committees (Storage and Capture) and then took their own recommendations to the CO2CRC Board.

Methods and outputs

Table 2 overleaf outlines the infrastructure and equipment deployed under CCSNET. Three projects (GipNet, LabNet Storage and LabNet Capture) have completed deployment with the OSL scheduled for completion in the next financial year.

CO2CRC undertook a review in December 2018 to determine the amount of co-funding and in-kind contribution to support the five-year research programs associated with each asset. Up to that date, the assets have been able to leverage $50 million dollars of research funding and in-kind support. This support has come from the Universities and Research Organisations themselves but also from external funding sources such as ANLEC R&D, CO2CRC and the Australian Research Council.

Key publications

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Remaining milestones

The upgrade of the Otway Subsurface Laboratory forms a major component of CO2CRC's Stage 3 project and provides a comprehensive capital infrastructure for the CCS research. This project is well underway, more information regarding this can be found at Otway Stage 3 project, page 28. 2019–2020 will see deployment completion for the Seismology Monitoring Network and the completion of the 3D imaging project, resulting in the successful deployment of the entire CCSNET portfolio.

Highlights of the 2018-19 projects

The 2018-19 reporting period saw the following highlights:

Completion of the following CCS projects:

- Special Core Analysis (SCAL) equipment and building refurbishment.
- Deployment of the GipNet Atmospheric Monitoring Network.

Deployment of research equipment:

- Ocean Bottom Seismometer (OBS) in the Seismology Monitoring Network.
- Moorings and Landers in the Marine Monitoring Network.

SCAL equipment and building refurbishment

This project aims to better quantify the efficiency of residual trapping. The core scanning facility obtains micro-scale (pore) measurements of geometries and processes which can be compared to macro-scale measurements of bulk petrophysical properties derived from SCAL. This allows for upscaling to be calibrated between pore and sample scale, equivalent to progressing from sample scale to reservoir flow unit.

The project will explore the influence of various factors on residual trapping, including wettability, initial saturation and injection rate. A major focus is to use cross-scale imaging, modelling and experiment to construct better methods for upscaling these trapping efficiencies in heterogeneous formations such as laminated sands.

The research schedule for this asset includes:

- Perform in situ imaging of samples at reservoir pressure and temperature to determine CO_2:brine contact angle. Generation of anchored SCAL data for important reservoir rock types including generation of trapping curves and tensor-based flow properties—permeability and relative permeability data on chosen plugs from whole core samples.
- Undertake sensitivity analysis of the resultant SCAL data.

Atmospheric Monitoring Network

Researchers are testing and verifying that atmospheric monitoring equipment applicable for on- and offshore projects that is reliable and durable in the near-shore and coastal environments.

This reporting period saw the deployment of the Open-Path NIR. The instrument uses near infra-red light to detect CO_2 concentrations across distances of up to 1.5kms. Monitoring such large distances increases the chance of detecting the micro changes that are of interest to scientists. Traditional techniques rely on much smaller air samples passing through an instrument.

Researchers are testing the sensitivity of the sensors to answer questions such as:

- How precise are the open-path measurements?
- How does precision change with pathlength?
- What impact does the near-shore environment have?

Modelling is being used to determine:

- What is the optimum open-path pathlength?
- Where should deployment occur?
- Understanding how to adapt these configurations for Gippsland near-shore environment.

Seismology Monitoring Network – OBS deployment

The OBS test deployment will enable the performance of the instrument to be tested in shallow-water Australian conditions for the very first time. It will enable vital information of noise levels in the deployment environment to be gathered. This information will be used to constrain input parameters for theoretical models describing the minimum magnitude detection and location thresholds of the GipNet networks. With the collection of accurate OBS data, these models will be able to theoretically determine the minimum magnitude earthquakes which are able to be located by the network across areas of potential future CCS activities. In addition, this workflow will allow network design options to be tested for a variety of both onshore and OBS configurations, taking into account station performance, density, geometry and quantity.

Marine Monitoring Network – mooring and landers

The moorings and landers are equipped with a range of sensors to measure parameters such as CO_2, pH, oxygen, methane, temperature and salinity. Passive acoustic sensors and underwater sonar systems (echosounders) will provide information on CO_2 bubbles.

In addition to these static platforms, conventional repeat marine surveys will characterise the marine environment through acoustic methods using multibeam echo sounder and a sub bottom profiler and allow the collection of samples. These manned surveys will be augmented by surveys by an unmanned surface vehicle (saildrone) which will also be equipped with a number of sensors and trialled to determine its suitability as a monitoring tool for CCS. This will be the first time that these platforms have been deployed in Australian waters.

The data gathered will be used to calibrate 3D models which simulate water movement as well as chemical and biological processes in the near shore Gippsland environment. These simulations will allow better predictions of natural variability as develop guidance on the best configuration and suitability of sensors for CCS measurement, monitoring and verification (MMV) purposes.

The outcomes from this project will not only be relevant to Australia but also to the international community, informing best practice for monitoring CCS in shallow marine environments globally.

This project has received funding from the Australian Government's Education Investment Fund, CO2CRC and ANLEC R&D.

> "The outcomes from this project will not only be relevant to Australia but also to the international community, informing best practice for monitoring CCS in shallow marine environments globally"

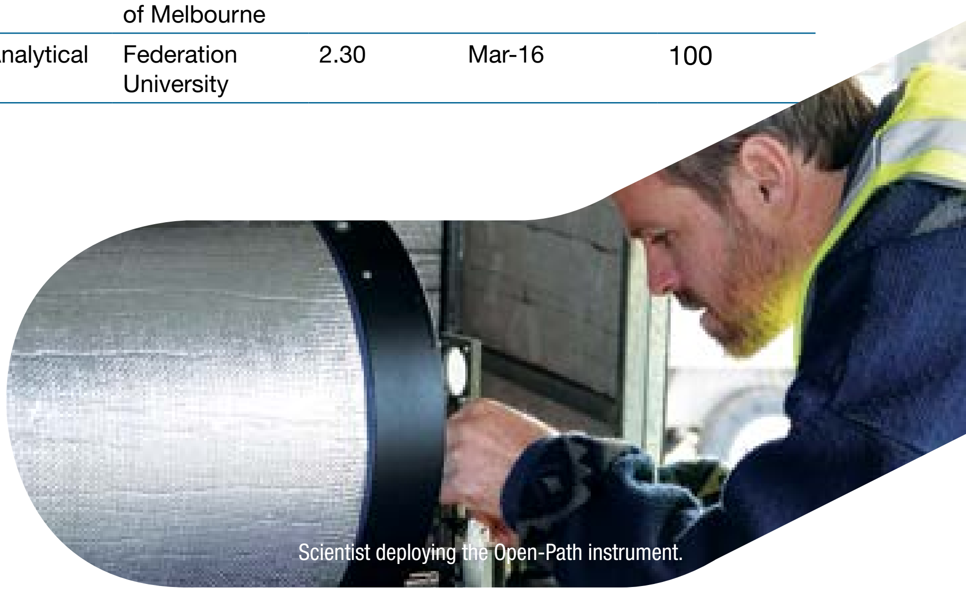
Image: CSIRO

Table 1: Expected outcomes and added values of the five-year research plans associated with the CCNET assets.

ASSET	EXPECTED OUTCOMES AND ADDED VALUES FROM THE FIVE-YEAR RESEARCH PLANS
Otway Subsurface Laboratory	› Reduce the cost of monitoring › Reduce the environmental footprint of monitoring techniques › Develop on-demand, sub-surface and permanent monitoring solution incorporating current market-available technologies › Perform faster acquisition and continuous transmission of plume monitoring data for immediate user access › A thoroughly equipped subsurface laboratory with 7 interconnected wells to be used by the CCS industry to test and verify technologies to de-risk the CCS projects
GipNet	› Development and validation of a combined model-measurement assurance system › Establishment of multiple scales of verification of the atmospheric state. › Numerical investigation of 3D plume structure using a coupled hydrodynamic-carbonate system model › Investigation of natural variability in monitoring targets from a network of fixed platforms › Investigation of natural variability in monitoring targets from integrating ASV with fixed network
LabNet Storage	› Construction of an integrated geological description and flow property database from pore to plug scale › Generation of routine and special core data using digital core analysis methodology as a more efficient technology than traditional RCA and SCAL experiments › Upscale measured properties through DCA at core scale to well and reservoir scale › Develop methods for stimulating and detecting subsurface biofilm formation, as a barrier technology to mitigate potential CO_2 leakage. › Impacts of changes in microbial activity, resulting from exposure to elevated CO_2 levels, on the formation or dissolution of minerals within the CO_2 storage aquifer. › Characterisation of reservoir microbial communities, their metabolic activity and the potential for biofilm formation / biomineralization in laboratory experiments.
LabNet Capture	› Novel solvents for CO_2 capture › Efficient delivery of CO_2 from flue gas to microalgae ponds › Novel promoters › Alternate dynamic capture models › Appropriate storage models for CCS chain models › Mechanisms of corrosion using samples from PCC plants › Characterise waste and product streams associated with different pre-and post-combustion capture technologies › Recommendations for treatment of degraded capture system components

Table 2: CCSNET Asset Summary.

NO.	ASSET	RESEARCH ORGANISATION	EIF GRANT [$M]	CONTRACTED FINISH DATE	DEPLOYMENT COMPLETION STATUS [%]
Otway Subsurface Laboratory					
#01	Otway Subsurface Laboratory	CO2CRC	27.04	Dec-19	75
Gippsland Monitoring Network					
#04	Seismology Monitoring Network	The University of Melbourne	1.28	Aug-19	90
#05	Atmospheric Monitoring Network	The University of Melbourne	0.40	Sep-18	100
#06	Marine Monitoring Network	CSIRO	4.07	Dec-17	100
LabNet Storage					
#07	3D Imaging	ANU	1.50	Oct-19	80
#08	Quantitative Mineralogy	ANU	0.85	Aug-14	100
#09	Special Core Analysis Equipment (SCAL)	ANU	1.01	Sep-18	100
#10	Building Refurbishment	ANU	1.68	Sep-18	100
#11	Bioreactor Laboratory	The University of Melbourne	0.25	Nov-14	100
#12	High Resolution Display-Wall Modelling Room	The University of Melbourne	0.42	Dec-17	100
#13	Fluid Flow and Geochemistry Laboratory Refurb and Equipment	The University of Melbourne	3.56	Dec-15	100
#15	MICP Replacement	University of Adelaide	0.16	Mar-17	100
LabNet Capture					
#16	Analytic Capture Equipment	The University of Melbourne	1.48	Jul-15	100
#17	Dynamic CCS Modelling Platform	The University of Melbourne	0.75	Dec-17	100
#18	Building Refurbishment	The University of Melbourne	2.27	Mar-16	100
#21	Building Refurbishment + Analytical Equipment	Federation University	2.30	Mar-16	100



Scientist deploying the Open-Path instrument.

BOARD MEMBERS

Martin Ferguson AM
BEc (Hons)

Martin Ferguson has a long history of public service and work in economic and social policy.

From 1984 until 1990 Martin served as the General Secretary of the Miscellaneous Workers Union and from 1990 until 1996 as President of the Australian Council of Trade Unions (ACTU). As a senior trade union official, from 1984 until 1996 he sat on the ACTU National Executive, participating directly in shaping and implementing many of the economic reforms of the Hawke and Keating Governments.

In March 1996, Martin was elected as a Member of the Federal Parliament in the seat of Batman, in Melbourne, which he held until retiring in 2013. He was appointed a Member of the Order of Australia in June 1996.

During the Howard Government, Martin served in a range of economic shadow portfolios, including Employment and Training; Immigration and Multicultural Affairs; Regional Development, Infrastructure, Transport, Regional Services and Population; Urban and Regional Development, Transport and Infrastructure; Primary Industries, Resources, Forestry and Tourism; and Transport, Roads and Tourism.

Upon the Rudd Government assuming office in December 2007, Martin was appointed the Minister for Resources and Energy and the Minister for Tourism, and acted as the Chair of the Standing Council on Resources and Energy and the Ministerial Council for Tourism. He held the Resources, Energy and Tourism portfolios until March 2013, when he resigned from the Ministry.

Martin is chair of an advisory board to the Australian oil and gas industry association, APPEA and is the Strategic Director of Natural Resources to SGH Energy. He also chairs the CO2CRC and Tourism Accommodation Australia organisations.

Martin was a member of the University of Western Australia's Industry Advisory Board on Resources and Energy from 2013 until it was abolished in late 2018. From 2014-16 he was an Independent Director of the BG Group in London prior to its takeover by Shell and he chaired the University College of London's, Adelaide Campus Advisory Board until it merged with the University of S.A. in late 2017.

Martin has an honours degree in economics from Sydney University.

Special responsibilities: Chairman of the Board, Chair of Appointments and Remuneration Committee.

David Byers
BEc, LLB, G Dip. Energy & Resources Law, GAICD

David joined CO2CRC as Chief Executive Officer in July 2018. He has more than 30 years' experience across the oil, gas and minerals industry in Australia and internationally with appointments in chief executive and senior leadership roles in public, membership and commercial organisations.

Some highlights include his appointment as interim Chief Executive of the MCA (Minerals Council of Australia) prior to joining CO2CRC, his earlier role as Vice President Government Relations and Public Policy for BHP, four years as Chief Executive of APPEA (Australian Petroleum Producers and Explorer's Association), three years as Chief Executive of CEDA (Committee for Economic Development of Australia) and 17 years working in senior leadership roles for ExxonMobil in Australia, Singapore and the United States.

In 2018, he was appointed a member of the Australian Statistics Advisory Council, the key advisory body to the Federal Assistant Treasurer and the Australian Bureau of Statistics (ABS) on national statistical services. He was recently appointed Honorary (Senior Fellow), Chemical Engineering, University of Melbourne and is a member of the Peter Cook Centre Advisory Council, Melbourne University.

Special responsibilities: Chief Executive Officer.

Mick Buffier
BE (Civil) (Hons) from The University of Sydney, MBA from The University of Newcastle

Mick is responsible for Sustainable Development and Industry Relations for Glencore's coal assets, a role he took on following Xstrata's merger with Glencore in May 2013.

He has more than 30 years' experience in the coal mining industry. Appointed Group Executive, Xstrata Coal in March 2009, he was responsible for Corporate Affairs, Government Relations and Sustainable Development across Xstrata's global coal operations.

From 2002-09, he was Chief Operating Officer of Xstrata's NSW coal mining operation.

Mick is the former Chairman and a current director and member of the NSW Minerals Council (NSWMC), a ministerial appointee to the NSW Coal Innovation Council, a director of the Australian Coal Association Low Emission Technologies Pty Ltd (ACALET) and ANLEC R&D.

On an international level, he is a former Chairman and current Vice Chairman of the World Coal Association (WCA) and an Associate of the International Energy Agency (IEA) Coal Industry Advisory Board (CIAB).

Special responsibilities: Member of Finance, Risk and Audit Committee

Dr James Johnson
BSc (Hons), PhD

James has been the Chief Executive Officer of Geoscience Australia since April 2017. James is a geologist with over 30 years' experience, including private sector mining and mineral exploration. He has led teams of geoscientists for over 20 years with a range of diverse achievements. These range from discovery of over two million ounces of gold reserves in industry, to national scale pre-competitive geoscience programs that have attracted exploration investment to Australia.

James first joined Geoscience Australia in 2006 and in that time has been head of various divisions with diverse duties including carriage of energy and mineral programs. He has been a board member of the National Computational Infrastructure (NCI) at the Australian National University since 2017, and on CO2CRC's board since 2014.

James has a Bachelor of Science majoring in Geology from the University of Sydney and a PhD from the Australian National University.

James's vision for Geoscience Australia is one of unity in deploying geoscience for the economic, social and environmental benefit of Australians. He is driving a strong agenda of inclusiveness, particularly new programs to engage with aboriginal Australia.

Fiona Hick
BEng (Hons), BappSci, FIEAust, MAICD, AFAIM

Fiona is currently acting Executive Vice President Operations at Woodside, accountable for safe, reliable and efficient operations across all of Woodside's assets plus logistics, maintenance, HSEQ, drilling and completions, subsea and pipelines and reservoir management.

Fiona was previously Vice President Strategy Planning and Analysis and has held various roles across exploration, development, operations and corporate roles in Woodside. Previous roles include Vice President Health, Safety, Environment and Quality where under her leadership Woodside achieved its best personal safety performance in company history and improved how the company prevents major incidents, including receiving a global award from the Institute of Chemical Engineers for innovative use of data analytics in incident prevention. Fiona has also been Head of Strategy and Governance for Australia Business Unit, Chair and Director of Pluto LNG's Burrup Train 1 LNG Pty Ltd and Burrup Facilities Company and Acting Senior Vice President Engineering. Prior to joining Woodside, Fiona worked for many years with Rio Tinto both in corporate and site-based roles.

Fiona has a Bachelor of Engineering from The University of Western Australia, a Bachelor of Applied Science in Energy Studies from Murdoch University and has 25 years' experience in resources across both the oil and gas and mining industries.

She is a member of the Australian Institute of Company Directors, Associate Fellow of the Australian Institute of Management and a Fellow of the Institute of Engineers. She was the winner of the 2019 Chamber of Minerals and Energy Western Australian Outstanding Woman in Resources award.

Special responsibilities: Member of Finance, Risk and Audit Committee

Brian Kitney
MA, MBA, GAICD

Brian has over 25 years' experience in the oil and gas industry in Australia and Asia. He is currently the Commercial Lead on AGL's proposed LNG import project to be located at Crib Point near Melbourne, Australia. Prior to this he held senior industry positions including Vice President Commercial at Osaka Gas Australia, spending nine years managing their upstream investments in Australia and Papua New Guinea. Brian has also held the position of Vice President Commodities at JPMorgan Securities Japan, based in Tokyo. He has also worked in senior marketing and development positions at Apache Energy Ltd and Mitsui & Co (Australia) Ltd.

Brian has an MBA from Curtin University, a Master of Applied Japanese Linguistics and a Graduate Diploma in Diplomacy and Trade from Monash University, a Graduate Diploma from Swinburne University and a Graduate Diploma of Applied Finance from Kaplan. Brian is also a Graduate of the Australian Institute of Company Directors and was previously Director and MD of a number of Osaka Gas subsidiaries.

Special responsibilities: Member of Finance, Risk and Audit Committee

Bill McKenzie
BE (Chem) Hons, FIChemE, CEng, RPEQ, MAICD

Bill is a chartered chemical engineer with significant experience across oil refining, coal bed methane developments and conventional oil and gas developments.

After 16 years with BP in refining, he joined Origin Energy in 2008 where he led their Oil & Gas Division's safety, engineering and operations functions before becoming General Manager Technical in 2010.

In 2011 he became accountable for APLNG's Upstream CSG operations as General Manager Qld CSG. In 2013 he joined QGC becoming Vice President Developments in 2015.

With the Shell acquisition of BG Group in 2016, Mr McKenzie joined Shell as General Manager QGC Development and was accountable for Shell's exploration, appraisal and development activities in eastern Australia. In 2019 he assumed his current role of GM Arrow accountable for Shell's shareholding in the Arrow Energy Joint Venture. Mr McKenzie has previously served as a member of the editorial panel of the Institute of Chemical Engineer's Loss Prevention Bulletin and has been appointed as a Fellow of the Institute of Chemical Engineers.

Special responsibilities: Deputy Chair of Operations, Safety and Environment Committee

Tim Walton
BA, MBA, GAICD

Tim joined the CO2CRC board in November 2014 as a research sector representative. He is the Director, Energy Research Initiatives, at Curtin University's Research Office in Perth, WA.

With a professional background in corporate communications, government policy and strategy, Tim has worked in science administration and resources development within the Western Australian Government's minerals and petroleum, and science and innovation portfolios.

Previously he has worked in a diverse range of areas including conservation education, natural resources management, policy and regulation, heavy industry and port logistics. He was the interim CEO and Bid Director for the Future Battery Industries CRC, which was awarded in round 20.

Tim is a board member of the Western Australian Marine Science Institute which oversees an alliance in coastal marine research; the Western Australian Defence Industry Council and the Fuels and Energy Technology Centre. He has been a board member of the Western Australian Energy Research Alliance, Centre of Renewable Energy in Sustainable Transport (CREST), the Parker Centre CRC for Hydrometallurgy and the Australian Centre for Natural Gas Management.

Special responsibilities: Chair of Operations, Safety and Environment Committee, Member of Appointments and Remuneration Committee

Dr Graham Winkelman
BE (Met), MEngSc, MAppFin, PhD

Graham is Practice Lead Climate Change at BHP based in Melbourne, Australia, where his global role covers BHP's response to climate change policy, including broad engagement across company executive leadership, federal and provincial governments, industry associations (including MCA, APPEA, BCA and CMI in Australia), peer companies, research institutes, think tanks and multilateral associations (e.g. IEA, UNFCCC). Graham's role also includes leadership of BHP's carbon capture and storage initiatives, with on-the-ground investment, research activity and policy engagement in various locations including Australia, the US, China, Canada, Japan and the UK.

Graham is Chair of the board of the International Carbon Capture and Storage Knowledge Centre (Regina, Canada) and a board member of the Australian Industry Greenhouse Network and the Energy Policy Institute of Australia. Graham has a PhD in Materials Engineering from Monash University, and has been contributing to the resource sector's response to climate change for 13 years in both direct and consulting roles.

CO2CRC DISTINGUISHED SCIENTISTS

Professor Peter Cook

Peter is one of Australia's foremost scientists and technology leaders in the areas of energy, greenhouse technology and sustainability. He is a Professorial Fellow at the University of Melbourne, a company director, author, consultant and senior advisor to organisations and governments worldwide. His work on CCS with the Intergovernmental Panel on Climate Change (IPCC), alongside Kelly Thambimuthu, made both contributors to the award of the 2007 Nobel Peace Prize to the IPCC, and prior to that in 2005, the adoption of CCS as a climate change mitigation technology under the United Nations Framework Convention on Climate Change (UNFCCC). Peter was CO2CRC's chief executive from its inception until 2011.

Professor John Kaldi

John is CO2CRC's former chief scientist as well as professor and SA State Chair of Carbon Capture and Storage at University of Adelaide. John's career includes being the inaugural head of the Australian School of Petroleum (ASP) and earlier, Director of the National Centre for Petroleum Geology and Geophysics (NCPGG) at University of Adelaide. Prior to academia, John spent 18 years working in the petroleum industry. He has received numerous awards, is an accomplished lecturer and trainer and has been the author and presenter of over 150 journal articles and technical conference papers.

Professor Kelly Thambimuthu

Kelly has over thirty years' experience in low-emissions technology. For over two decades he has chaired the IEAGHG, a technology collaboration program of the International Energy Agency to reduce greenhouse gas emissions. He pioneered advances in cleaner fossil fuel technologies while heading the Centre for Low Emissions Technology in Queensland from 2004 – 2009. Kelly has been a scientist and program director at CANMET Energy, Natural Resources Canada and professorial fellow at the University of Queensland and has received many awards for his work.

PUBLICATIONS

From 1 July 2018 – 30 June 2019 CO2CRC delivered the following journal articles, conference papers and reports:

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Pevzner, R. et al., 2019. *Feasibility study of passive downhole seismic monitoring, micro seismic monitoring and seismic interferometry using DAS data from CO2CRC Otway Project Stage 3 wells*, Melbourne: CO2CRC.

Glubokovskikh, S. et al., 2019. *Rapid Plume Forecasting: Opportunity Definition*, Melbourne: CO2CRC.

Marouchos, A. et al., 2018. V*alidation of Unmanned Surface Vehicle technology for shallow-focused marine MM&V, Phase 1*, Melbourne: CO2CRC.

Pevzner, R. et al., 2018. *Seismic monitoring of a small supercritical CO_2 injection into the subsurface: Stage 2C of the CO2CRC Otway Project,* Melbourne: CO2CRC.

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Qader, A., Webley, P., Xiao, P., Qiao, G., Fu, Q., Kentish, S., Scholes, C., Chen, V., Li, H. and Pandit, J., *An Overview of CO2CRC's Capture Program*. GHGT-14 Conference, Melbourne, 2018. CNF18-5927.

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Tao, L., Xiao, P., Danaci, D., Singh, R., Webley, P. and Qader, A., CO_2 *capture from high concentration* CO_2 *natural gases by pressure swing adsorption at CO2CRC Otway site,* Australia, GHGT-14 Conference, Melbourne, 2018. CNF18-5925.

Xiao, P., Fu, Q., Qader, A., Webley, P. and Qiao, G., CO_2 *capture from natural gas by a hybrid technology combining adsorption and membrane processes*, GHGT-14 Conference, Melbourne, 2018. CNF18-5813.

Li, H., Fam, W., Satrisna, P., Hou, J. and Chen, V., *New generation high performance composite hollow fiber membranes for low cost* CO_2 capture, GHGT-14 Conference, Melbourne, 2018. ABS17-5810.

Scholes, C., Mirza, N., Kentish, S. and Qader, A., *Membrane Contactors for efficient carbon capture,* GHGT-14 Conference, Melbourne, 2018. ABS17-5797.

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PARTNERS

CO2CRC appreciates the strong relationship it has with industry, community, research organisations, government and agencies, in Australia and around the world.

INDUSTRY

ANLEC R&D (on behalf of ACALET)

BHP

Chevron Australia

COAL21

Global CCS Institute

J-POWER

Shell Australia

Total

Woodside Energy

COMMUNITY

Landowners near Otway National Research Facility

Moyne Shire

Nirranda South

GOVERNMENT

Australian government – Department of Education

Australian government – Department of Industry, Innovation and Science

CarbonNet project

Geoscience Australia

NSW government – Department of Planning, Industry and Environment

Victorian government – Department of Jobs, Precincts and Regions

RESEARCH

Australian National University

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BUILDING A LOW EMISSIONS FUTURE

CO2CRC Limited, 11-15 Argyle Place South,
Carlton VIC 3053, Australia
PO Box 1182, Carlton VIC 3053

p: +61 3 8595 9600
e: info@co2crc.com.au
www.co2crc.com.au