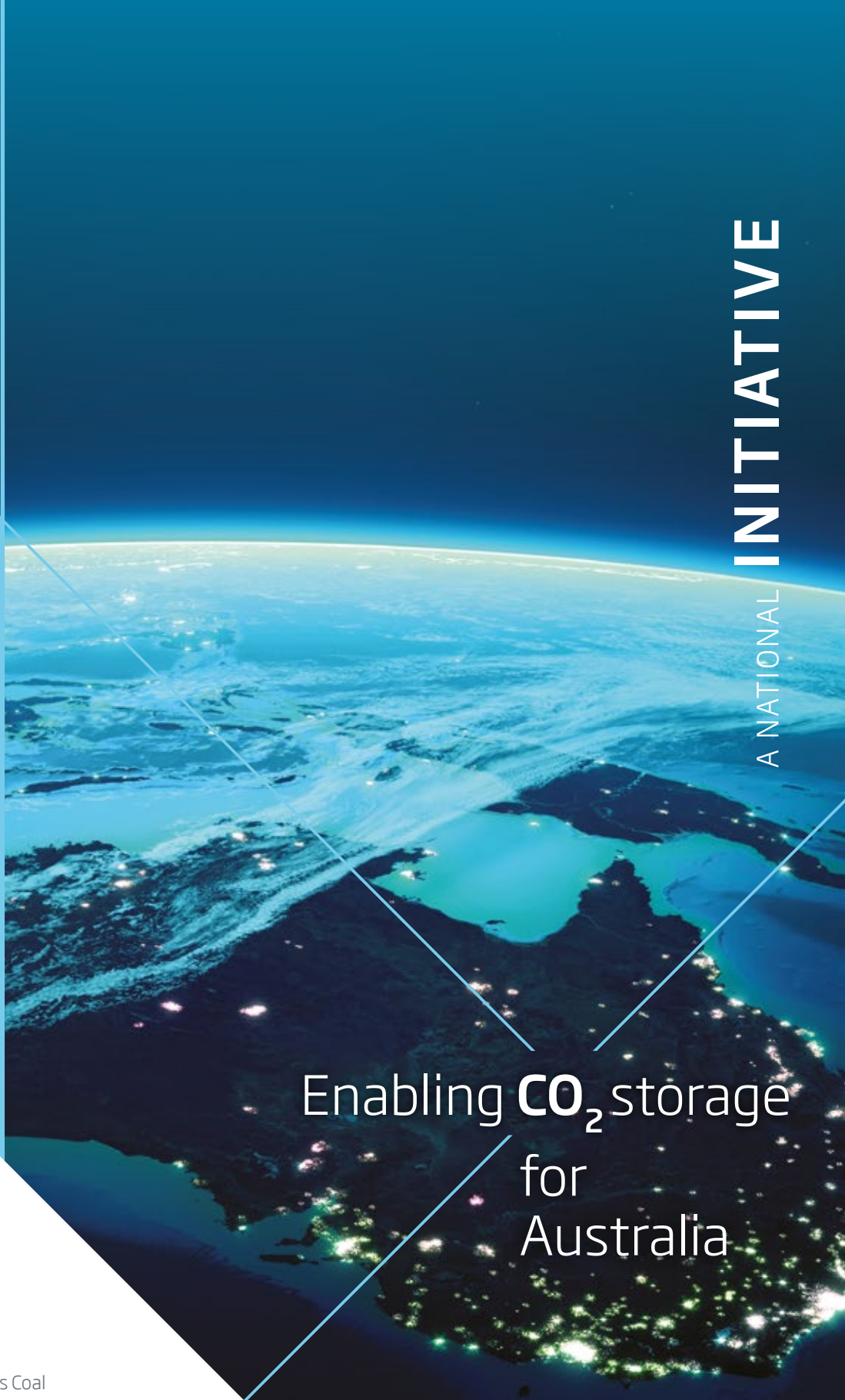
ANLEC R&D

A NATIONAL INITIATIVE



Enabling CO_2 storage for Australia

anlecr&d

Australian National Low Emissions Coal Research & Development

Australian Government

Department of Climate Change, Energy, the Environment and Water

LETA

Low Emission Technology Australia

A partnership between the Australian Government and Low Emission Technology Australia (LETA)

FINAL REPORT 2023

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Annual Milestones

2011

- Reported on flue gas quality and its control for Callide Oxyfuel Demonstration Project
- SW Hub CCS Flagship announced for Southern Perth Basin
- Commissioned study on environmental performance of amine based Post Combustion Capture
- Major initiative to reduce reservoir characterisation times by enhanced up-scaling workflows commences

2010

- Commonwealth and Coal Industry sign ANLEC R&D Funding Agreements
- Delivered with Department of Industry - EPRI Technology Cost Study for National Coal Council
- Otway 2 Huff-n-Puff experiment co-funded at CO2CRC
- Relationship Agreement signed for brown coal research in Victoria

2012

- Reported trace element speciation, partition and flow sheet impacts for Callide Oxyfuel Demonstration Project
- Delivered environmental regulatory review for Post Combustion Capture
- Reported on slag disposal and use from gasifiers
- Delivered Novel Capture Taskforce Report
- Published assessment of Oxy-CFB technology
- Estimated emissions to the atmosphere from amine based PCC processes for a black coal fired power station
- ANLEC R&D Strategic focus shifts to CO_2 storage
- CarbonNet CCS Flagship announced for Gippsland Basin
- ACALET Funding for CTSCo demonstration in the Queensland Surat Basin extended
- Co-funded report on CO2CRC Otway stage 2B - residual saturation and dissolution test
- Developed a state-of-art review of integrity of wellbore cement in CO_2 storage wells
- Delivered initial geo-mechanical modelling as part of the site investigation for CO_2 injection in the onshore part of the Gippsland Basin

2013

- Research validates lower cost options for oxyfuel technology at the Callide Oxyfuel Project Demonstration
- Updated 'EPRI Technology Cost Study' for ACALET and the National CCS Council
- Studies published showing emissions from amine based post combustion capture are lower than that from conventional power plants
- Pilot studies validate process control and operating parameters for stable performance of concentrated piperazine as a carbon dioxide capture agent
- Techno-economic study on the Direct injection coal fired engine completed*
- Drilling of Harvey-1 well confirms unconventional stratigraphy
- Advanced geophysical data analysis at Harvey-1 and fault seal first order analysis delivered for the SW Hub
- Initial simulations of CO_2 storage and ground water flow in the Surat Basin, Queensland
- Interim assessment delivered on regional stress and predicted hydro-geochemical impact of CO_2 storage in the Surat Basin
- First results delivered on enhanced upscaling workflows using digital core assessments for the Surat Basin
- Delivery of advanced core analyses for predicting CO_2 injectivity across prospective Australian basins

KEY

Capture Storage General

2014

- ANLEC R&D Funding Agreements extended to 2020.
- On-site measurements of trace element deportment on oxy-combustion for the Callide Oxy-fuel Project
- Guidelines delivered for estimating CCS Total Project Costs
- DICE fuel development research commissioned for pilot testing in 2017
- Novel contactor design proven to reduce costs for CO_2 capture
- Study demonstrates improved estimates of reservoir capacity enabled by more accurate use of tracers
- Recommended protocol for assessing resource interaction and management for CO_2 storage in existing reservoirs
- Desk-top study completed to inform SW Hub injection strategy
- Field validation of advanced seismic methods and analysis informs fault structures in the near-surface for the SW Hub
- First validated comparison of stratigraphic forward modelling with predictions from conventional approaches
- Dynamic seal capacity assessment delivered for the Gippsland Basin
- Published lessons learned from community level engagement for the SW Hub
- Preliminary near-shore aquifer modelling of CO_2 geological storage in the Gippsland Basin completed
- Feasibility and design assessed for robust passive seismic monitoring arrays for CO_2 sequestration

2015

- Callide Oxyfuel Project Demonstration data validates mechanisms for mercury removal in oxyfuel technology
- Delivered 'Strategic Country Review & Low Emissions Outlook' to inform export coal industry
- Co-funded updated 'Australian Power Generation Technology Cost Study for Australian Energy Stakeholders'
- Assessment shows chemical looping can deliver lower cost oxygen separation, though for power generation processes it remains uneconomic in the present carbon pricing environment*
- Researcher patents alloy for a catalytic membrane reactor for hydrogen separation
- Assessments of geo-mechanical and geo-chemical testing shows prospects for enhanced injectivity in the Surat Basin
- Published updated monitoring well design for maximising long term acquisition of data
- Preliminary assessment of advanced processing and analysis of 3D seismic data delivered for the SW Hub
- Report shows using nitrogen as a surrogate for CO_2 in injection tests may overestimate reservoir capacity
- An assessment delivered on geochemical impacts and monitoring of CO_2 storage in low salinity aquifers
- Delivered scoping study for marine monitoring research supporting the Gippsland Basin
- Workflows and processing to deliver multi-scale reservoir characterisation in commercial software initiated
- Published pore-to-core upscaling methods for dynamic properties and integration from core to logs
- A desktop study of authigenic carbonates as natural analogues of mineralisation trapping in CO_2 sequestration completed

2016-2017

- Managing Flexibility whilst de-carbonising the Australian Electricity Grid
- A techno-economic study on the lowest cost options for de-SOx and de-NOx options in small flue gas streams
- The first application of hyperspectral mapping of the Surat Basin (Precipice Sandstone) outcrop to quantify spatial variability in mineralogy
- Data analysis and processing for the classification and upscaling of reservoir saturation-dependent properties
- CO_2 assurance monitoring strategies for the Perth Basin
- An advanced and integrated analysis of seismic and well logs to deliver new data as input to the static and dynamic models of the Wonnerup storage complex
- Chemical and physical evaluation of fluid rock interactions and their impact on rock properties from CO_2 injection in the Perth Basin
- Geophysical and geomechanical assessment of preferential fluid flow through faults and fractures
- Predictions of the subsurface behaviour of injected CO_2 through modelling of CO_2 dissolution in storage formations
- Precipice sandstone outcrop study as an input for geological simulation modelling in the Surat Basin
- A geochemical analysis to study the evolution of reservoir water composition during CO_2 storage in the Gippsland Basin
- Modelling of structural and aquifer traps for CO_2 storage in the Gippsland Basin

*Several concepts for CO_2 capture were assessed as not viable to proceed with further research

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Annual Milestones

2017

- Delivered a feasibility and design study of robust passive seismic monitoring arrays for CO_2 geosequestration
- Modeled optimisation of highly integrated post-combustion carbon capture processes
- Reported on development of the advanced aqueous ammonia-based post combustion capture technology*
- Concept tested of adsorption-based oxygen generation technology*
- Concept tested post combustion capture of carbon dioxide using solid sorbents*
- Delivered a desktop design study for SW Hub monitoring wells
- Completed Advanced 3D processing in South Perth Basin
- Scoped comprehensive work program for near-shore marine monitoring in Gippsland Basin
- Delivered comparative power generation option analysis with policy & techno-economic variables
- Completed hyperspectral scanning of Precipice outcrop in Surat Basin
- Funded a CCS Roadmap for Australia
- Reported on balancing flexibility whilst decarbonising electricity on the NEM
- Reported on the Lesueur vertical connectivity, injectivity and residual trapping

2018

- Reviewed priorities for CCS research
- Reported on study of deposition, rocks, facies and properties of the Lesueur sandstone
- Tested the feasibility of monitoring an injected CO_2 plume in the South Perth Basin
- Reported on the feasibility of using managed aquifer recharge for carbon storage in the Surat Basin
- Reported on technological options for SO_X treatment for the CTSCo project
- Completed a techno-economic assessment of a novel aqueous CO_2 removal: process*
- Reported on analysis to improve seismic response and attributes in the South Perth Basin
- Reported on understanding of the evolution of the solute plume composition in the Precipice Sandstone of the Surat Basin
- Delivered an advanced assessment of heterogeneity and diagenesis on injectivity and containment in the South Perth Wonnerup Member
- Delivered several case studies on modelling electricity generation and grid services for the NEM
- Completed and reported on passive seismic investigations at the SW Hub
- Reported on the distribution and geometry of Latrobe Group intraformational seals, Gippsland Basin
- Advanced assessment of multi-barrier systems for CO_2 containment in the Yalgorup Member

2019

- Completed a feasibility study for assessing storage potential in the Southern Surat Basin
- Reported on characterisation of CO_2 interactions with basal coal seam intraformational seals in the Gippsland Basin
- Undertook assessment of a process-based approach for monitoring near-surface leakage in the South Surat Basin
- Delivered an isotopic characterisation of source CO_2 and naturally occurring CO_2 at Glenhaven
- Reported on seabed processes in the nearshore Gippsland Basin
- Reported on Alternative Dynamic Modelling for Structural and Aquifer Traps and CO_2 Solubility
- Assessed anomaly detection threshold setting for environmental baseline
- Tested concept for headspace gas monitoring to infer dissolved gas concentrations downhole
- Delivered a regional geological study of the Hutton Sandstone
- Processed passive seismic dataset for stress induced events and tomographic imaging

KEY

Capture Storage General

2020

- Assessed groundwater geochemistry of the Moolayember formation in the South Surat Basin
- Demonstrated digital rock applications for spatial resolution of mineralogy through the Precipice Sandstone
- Evaluated the configuration of an atmospheric assurance system for the Gippsland near-shore environment including leakage quantification techniques
- Concept tested borehole to surface electromagnetic surveying

2021

- Demonstrated the role of electricity systems modelling in optimising planning decisions for a low emissions grid
- Assessed the use of downhole Raman Scattering as a monitoring technique
- Concept tested the joint inversion of geophysical monitoring data to infer higher confidence in modelling results
- Software developed for rapid conversion of outcrop measurements into geological model assessment

2022-23

- Delivered assessment of shallow-focused MMV methodologies for subsea CCS
- Delivered a feasibility and design study of a cabled marine monitoring and verification system
- Demonstrated an uncertainty analysis of diverse petrophysical data for Injectivity Prediction Using Machine Learning Methods
- Completed multiscale static and dynamic modelling of Precipice Facies in the South Surat Basin
- Reported on the regional hydrogeology of the Southern Surat Basin
- Tested the concept to estimate Precipice Sandstone water salinity from spontaneous potential logs
- Test completed for the Surat Basin to validate a two deposition centre hypothesis:
- Demonstrated in field validation for optimising earthquake monitoring and characterisation for CCS applications in Gippsland Basin
- Delivered a lowest cost power sector asset development pathway to net-zero emissions
- Reported on geochemistry interactions for the South Surat Basin

*Several concepts for CO_2 capture were assessed as not viable to proceed with further research

REPORT COMPILED BY

Dr Noel Simento

Mr Kevin Dodds

ACKNOWLEDGEMENTS

The ANLEC R&D initiative is grateful to:

The Australian Proponents of CCS – The Executives and Technology Directors of CTSCo, Southwest Hub and CarbonNet who seek to deploy CCS in the Surat, Perth and Gippsland Basins respectively. They assist shape the relevance of the ANLEC R&D Research Program.

The CCS Scientific Community – The quality of ANLEC R&D outcomes are premised on excellent science and are a testament to the effort of all its contributing scientists.

DISCLAIMER

Contents

Message from the Chairman

The National Carbon Capture and Storage Council took the opportunity to establish ANLEC R&D - a visionary partnership between the Commonwealth of Australia and the Coal Industry. Its objective was to lay the scientific platform that demonstrated the options to lower emissions from coal use technologies. A product of the National Low Emissions Coal Council, ANLEC R&D had the unique objective to work with large scale coal fired energy projects in Australia to enable and support their low emissions deployment.

The body of science, research and technology development catalogued in this final report is the result of 14 years of delivering these objectives.

The CTSCo/Glencore project is awaiting the outcome of its carbon dioxide storage permit application in Queensland's South Surat Basin. ANLEC R&D has shown the value of targeted research to inform both the project proponents as well as the regulators with comprehensive science to underpin their decisions. While not progressed as far, this is also the case for both CarbonNet in the Gippsland Basin and the South-West Hub in the South Perth Basin of Western Australia.

ANLECR&D studies reinforce conclusions by international agencies such as the IEA and the UN-IPCC that CCS is an essential technology if Australia is to have any possibility of meeting its net-zero targets post 2050. Australia's own Climate Change Authority has concluded that CCS is a necessary part of any rapid,urgent decarbonisation and represents a huge opportunity forAustralia.

Therefore, the paradoxical decision by the Commonwealth Government to terminate its contracted Funding Agreement - for convenience - while ANLEC R&D is solidly supported by Industry comes as a surprise and with a measure of dismay.

ANLEC R&D has been an exemplary model for targeted research to support large scale deployment of low emissions technologies for fossil fuels. Demonstrating these commercial pathways give our industry exports its licence to operate.

Mr Richard Wells
Chairman

"Carbon capture and storage (CCS) is extremely critical technology if we want to meet the 2°C target..."

- Dr Fatih Birol
Executive Director, International Energy Agency

Message from the Managing Director

ANLEC R&D is proud to submit this Final Report to its Funders - the Commonwealth Government and the Coal Industry represented by Low Emissions Technology Australia (LETA). It embodies over 14 years of targeted research and technical development to enable and accelerate commercial scale low emissions coal technologies in Australia.

Highlights of this research program include:

- Unique systems assessments demonstrating the lowest cost pathways to decarbonize the Australian electricity sector
- Field validation of a commercial scale CO_2 storage reservoir in the South Surat Basin, Queensland
- Comprehensive criteria for configuration and monitoring of the near shore marine environment of the Gippsland Basin, Victoria
- The detailed pre-competitive characterization of the South Perth Basin for CO_2 storage in Western Australia
- An Australian DigitalCore Technology fully adapted to application for CCS

At its last review in 2022, the ANLEC R&D governance model was described as "leading edge". It has demonstrated how technology deployment in the public good can be supported through marshalling and coordinating the use of research infrastructure available across the country.

These significant deliverables are the result of over 150 research and development projects completed over 14 years. Summaries of these studies and the effectiveness of the initiative are catalogued in this report. Access to detailed reports are available in the storage device attached to the inside back cover.

ANLEC R&D is grateful to its Funders and its Board of Directors for their support over the term of the partnership. We also acknowledge the scientists, technology managers and staff for their dedicated service to the pursuit of a low emissions future for coal.

Dr Noel Simento
Managing Director

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Chairman

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2016-2018

Key Lessons

ANLEC R&D was conceived as a strategic and key input to government and industry on low emissions technology pathways for the energy sector.

Recognising that there would be no quick returns on investment, both Industry and Government sought to resource an initiative to support, enable and accelerate low emissions coal technology deployment in Australia.

In addition to the technical outcomes catalogued earlier in this report, key lessons learned included:

- Technology pathways need dependable resourcing with realistic deployment timetables to undertake staged strategic research and demonstration.
- Cooperative relationships between government, industry and research offered significant benefit to facilitating new technology deployment towards strategic national objectives.
- The active management of projects with rigorous processes for Industry oversight gave confidence to the funders of the initiative.

"Stakeholder consultations also indicate that ANLEC R&D is highly regarded as a research organisation and that its project inception and management procedures are considered to be highly effective, even leading edge..."

- David Pearce
Centre for International Economics
ANLEC R&D Review, October 2022

Highlights

Managing Electricity Grid Systems (MEGS)

MEGS study highlights need for Carbon Capture & Storage

ANLEC R&D delivered an independent study that – for the first time – values low emissions power generation technologies by the services they deliver to the Australian electricity grid. This is an innovative modelling approach. It shows that as decarbonisation transforms Australian electricity generation, the services provided by low emissions fossil fuel – Coal and Gas with CCS – will be increasingly relied upon to deliver reliability and strength for the grid system. Importantly, CCS is expected to become the lowest cost option at a threshold penetration of intermittent renewable technologies.

Photo courtesy of CTSCo

South Surat Appraisal Wells

Field testing Australian CO_2 storage reservoirs

ANLEC R&D delivered two wells in the South Surat Basin and will shortly complete a fit-for-purpose seismic survey. These will deliver the scientific validation analysis of reservoir, seal and containment uncertainties for the region. Dedicated research themes were aimed at maximising the R&D contribution towards fluid property, injectivity and pore space efficiency.

The project is located proximal to major coal-fired emission sources with the storage potential to take the combined Kogan and Millmerran Power Stations' emissions for more than 20 years. On completion, the project would be a key enabler for other commercial operators in Australia seeking to use deep aquifer storage.

Geological Storage of CO_2

ANLEC R&D enables marine monitoring configuration for near-shore

The Gippsland Basin is one of the most prospective reservoirs for CO_2 storage, however, much of the resource is off-shore in marine environments. ANLEC R&D funded research has assessed the likely performance of the latest monitoring methods and instruments in near shore conditions, in Australian site-specific circumstances.

Prospects for favorable injectivity reported in the Surat Basin

Initial research studies showed that geochemical reactions between CO_2 and the precipice sandstone in the Surat Basin are unlikely to pose constraints to injection. There was also evidence for CO_2 improving the permeability of the system with time.

3D digitising technology reduces reservoir characterisation times

ANLEC R&D funded research has delivered methods and procedures for faster characterisation of CO_2 migration and storage in reservoirs. Small scale measurements on rock types are translated to meaningful information at well and basin scale.

Informing Regulation

Minimising exploration costs & strengthening local relationships

Innovative mathematical processing has ensured that the ANLEC R&D work program has delivered better structural imaging, improved processes for lower cost data acquisition, informed state governments decision making and aided in the building of trust with local land owners in the Southern Perth Basin.

Recommendations delivered for managing resource interaction

CO_2 storage in reservoirs of the Surat and Gippsland Basins will need to consider interaction with many other industry resources such as gas production, coal seam gas, and water. To assist regulators to manage competing priorities for access to reservoir pore space, researchers have delivered a first analysis and recommended options for resource management decisions for these basins.

Business Principles

Making a difference

ANLEC R&D funded research at a relatively mature technology readiness level. In order to accelerate deployment, focus was on research that enabled application rather than early stage fundamental science. It aimed to take innovative ideas out of the lab and into the field.

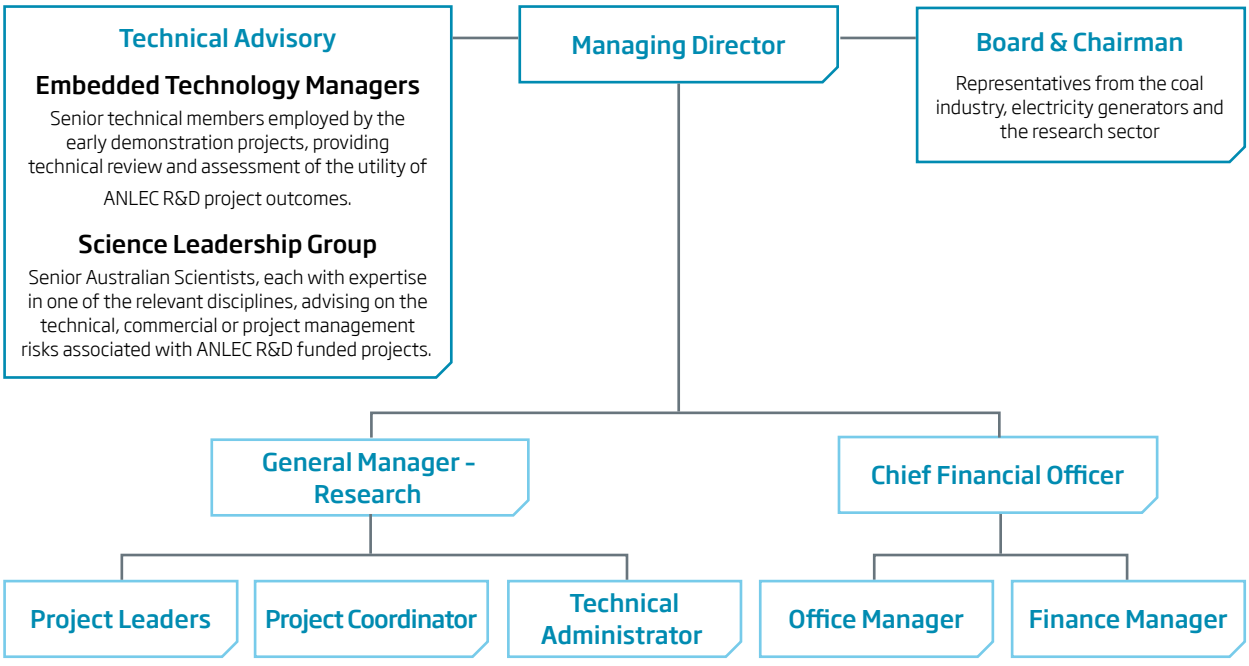
Service Model

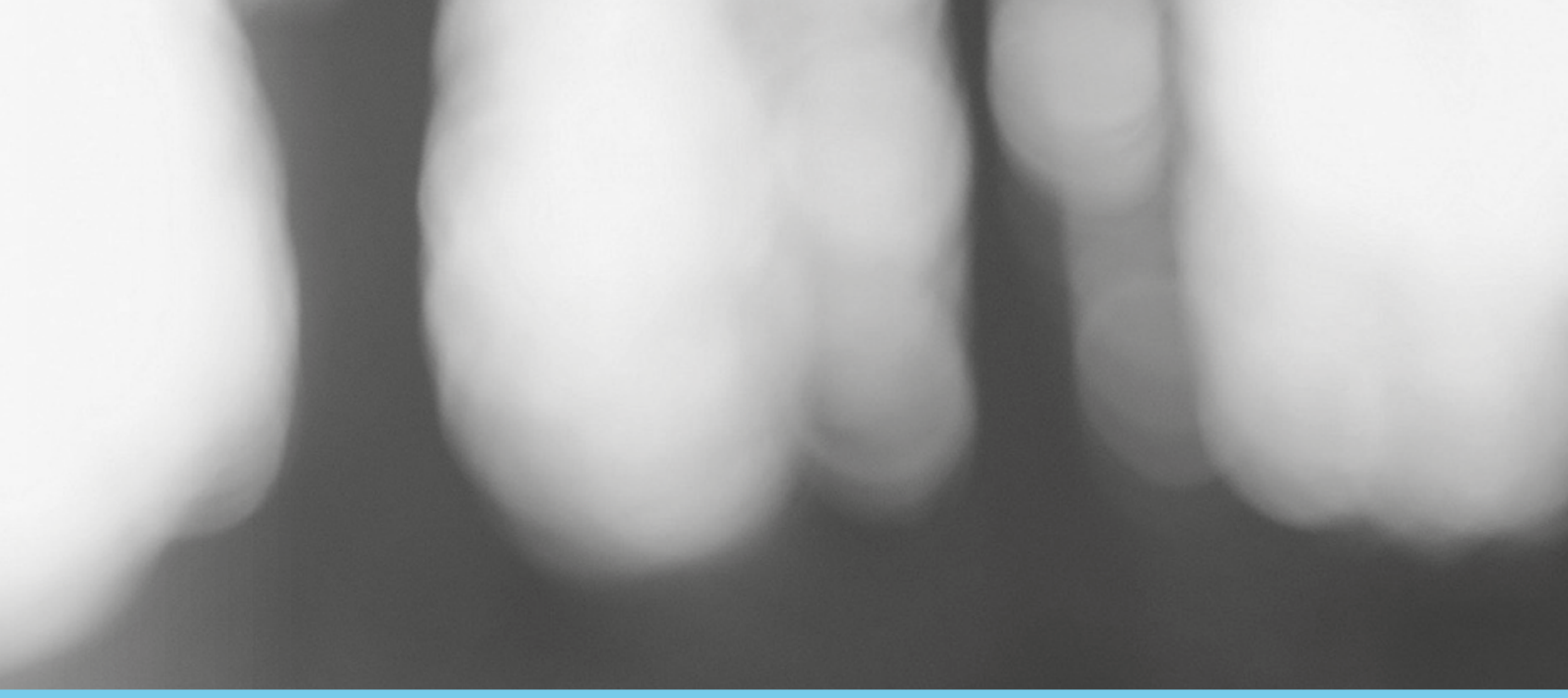
The ANLEC R&D business model was premised on the provision of research services to commercial scale carbon capture and storage (CCS) proponents. It sourced research services principally from Australian infrastructure; targeting the best expertise, capacity and capability wherever they present.

Priority setting

Focusing on the needs of CCS demonstration proponents was a powerful filter to balance the encouragement of scientific creativity with the relevance of application at commercial scale in the field. Undertaken in a competitive research environment, it allowed for innovative science methods to reduce real investment risks to targeted CCS project proponents.

Organisational Structure





Transparency and Governance

The Board of Directors was comprised of an independent Chairperson and representatives from ANLEC R&D's funding providers, the power sector and the research sector, ensuring robust and diligent governance.

Customer Focus

ANLEC R&D Embedded Technology Managers were senior technical persons from the demonstration proponents who recognised and advised on those project investment risks that would benefit from targeted research.

Informed Decision Making

Systematic reviews of research performance and progress were regularly undertaken by Management with the engagement of expertise from the commercial demonstration proponents, Australian science leadership and the funding providers. It delivered the demonstration proponent with the most up-to-date science and data relating to their project throughout the duration of the research.

"ANLEC R&D has demonstrated well that it is a fit-for-purpose organisation to manage investment in R&D from public and private sector funders..."

- Dr Bruce Godfrey
Wyld Group
ANLEC R&D Review, May 2018

Partnerships and Investment Leverage

ANLEC R&D delivered a unifying objective for research to support CCS deployment. It was achieved through coordinated advice, funding and memberships across several partnerships and collaborations.

CO2CRC

Since 2015, the Coal Industry has retained ANLEC R&D to manage an additional $10M investment into experiments at the Otway Pilot CO_2 storage site in Victoria. The facility is owned by CO2CRC, a leader in Australia's early CCS initiatives, and has operated as a subsurface laboratory for over 10 years. The industry, through many industry participants, has been an important sponsor of this work.

GLOBAL CCS INSTITUTE

The Global CCS Institute has established a knowledge sharing platform to enable widespread dissemination of CCS related information. As a research member of the Global CCS Institute, ANLEC R&D has, since inception, made its own scientific studies available to the Global CCS Institute's audience.

Government of Western Australia
Department of Mines and Petroleum

Through partnering with ANLEC R&D, the WA Department of Mines and Petroleum embeds technology management within the scope of its demonstration activities and has chosen to allocate funding for research purposes. ANLEC R&D was the agency of choice for administering such funds.

AUSTRALIAN CARBON INNOVATION

Brown Coal Innovation Australia was set up by the Victorian Government to manage research for its vast resources of brown coal. The Commonwealth's commitment to enabling such innovation for Victorian brown coal was managed through ANLEC R&D. As a member and part of BCIA governance, ANLEC R&D was able to acquit its brown coal research requirements using local brown coal expertise.

Photo courtesy of CO2CRC

"The knowledge or 'learning' from demonstrating CCS technology in new applications at different sites and different settings is critical for reducing costs and strengthening investor and stakeholder confidence."

- Global CCS Institute

INTERNATIONAL CENTRE FOR SUSTAINABLE CARBON

ieaghg

ANLEC R&D coordinated the Australian membership of the IEA-Clean Coal Centre. The Centre is constituted in an implementing agreement of the International Energy Agency, Paris, and is funded by member countries and industrial sponsors. It is a foremost provider of information on the clean and efficient use of coal worldwide, particularly clean coal technologies. ANLEC R&D also funded a share of a second implementing agreement relating to the IEA Green House Gas R&D Program.

NSW GOVERNMENT Department of Industry Resources & Energy

ANLEC R&D was a trusted advisor to Coal Innovation New South Wales (CINSW). CINSW is a $100M initiative of the New South Wales Government to fund research, development, demonstration and community awareness of low emissions coal technologies. Membership of the governing Council and the Technical Working Group brings both expertise and a national perspective to inform decision-making.

ptrc Petroleum Technology Research Centre

The Petroleum Technology Resources Centre (PTRC)'s Aquistore manages and monitors large-scale CO_2 storage project associated with the Boundary Dam in Saskatchewan Canada. ANLEC R&D has supported the Aquistore research consortium since 2016 to provide insights of measurement, monitoring and verification (MMV) experience in anticipation of the commencement of large-scale CO_2 injections within an Australian context. This association has offered an opportunity to commission monitoring activity jointly with the CO_2 Capture Project (CCP), as well as for Australian research providers to participate in the Aquistore storage research.

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Class VI Solutions, Inc.

Storage Research Strategy

The importance of storage geology to early mover demonstrations cannot be overstated. Project timelines, and indeed the viability of the early demonstrations, is strongly dependent on storage availability, how this storage can be proven, and how well the storage geology can be monitored and controlled.

The storage geology is the most critical technical component of any LECT project and the least well understood. Hence the need for a strong applied R&D effort.

Key targeted outcomes from the ANLEC R&D subsurface program include:

- Reduced project development risk via increased acceptance of the project by stakeholders including financiers, regulators and the public;
- Reduced cost and time required to find and define storage capacity;
- Increased understanding of the opportunities available to enhance injectivity, thereby reducing the number of wells and reducing costs;
- Reduced cost to operate storage capacity, through understanding opportunities to move away from an oil and gas industry cost basis to a cost basis that reflects the lower returns available in the power sector;
- Reduced cost and time to close the injection site.

CO_2 Storage in Australian Geological Basins

For decades, carbon dioxide capture and re-injection into subsurface geological formations has been a well-established practice for enhanced oil recovery. It is a technology well suited to carbon dioxide emissions from coal fired power generation. However, deployment will be required at engineering scales much higher than presently available.

The availability of pore space in a reservoir is, in general, related to the depth of its origin through geological time. Deeper rocks are more compacted and consequently less permeable. There are many other variables that also contribute to the viability of reservoir rock for storage purposes. Importantly, the storage of CO_2 must also consider interaction with other sub-surface resources present (coal, oil, gas, geo-thermal, etc.).

Science underpinning the storage of CO_2 in Australian geological basins

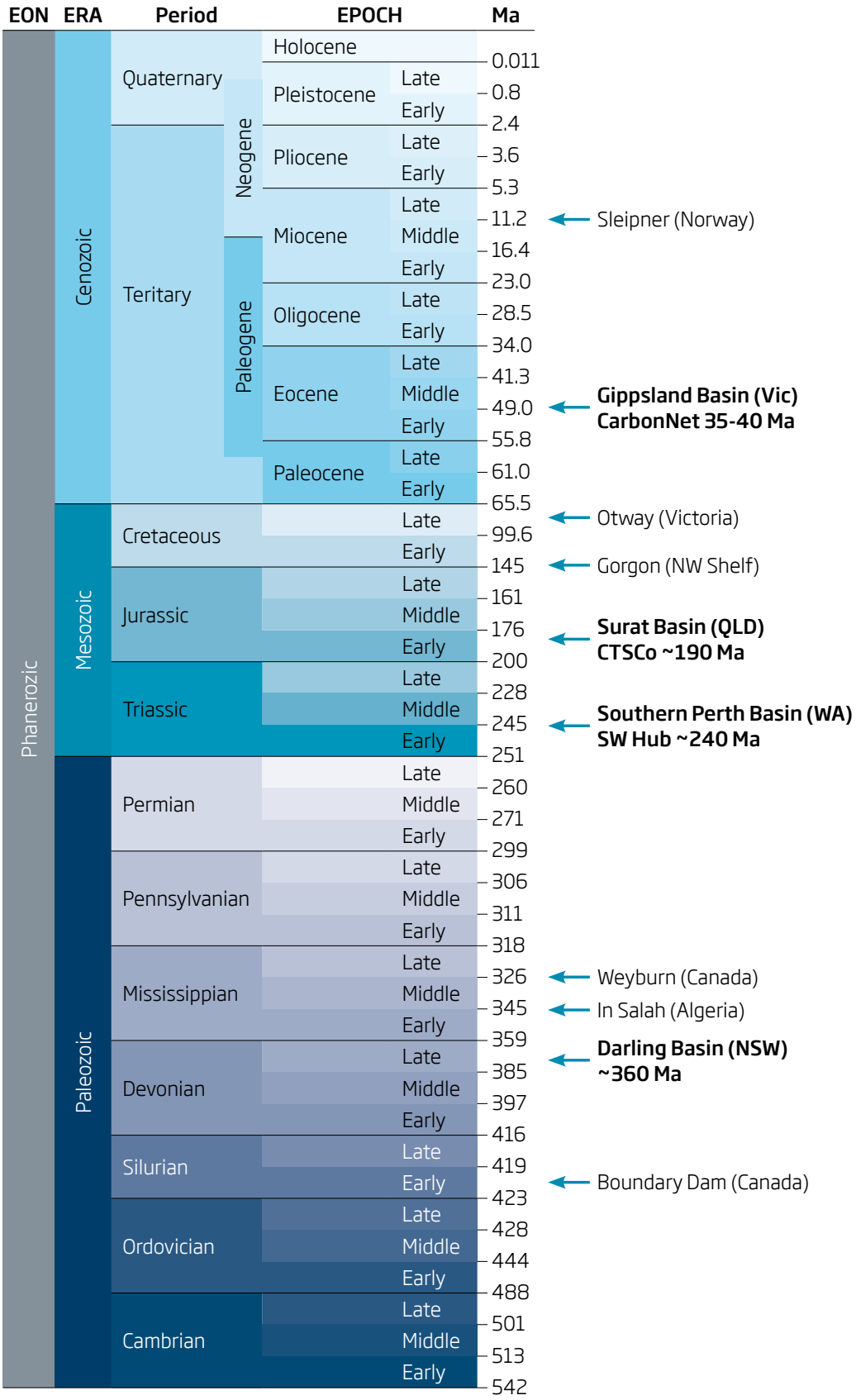
Each basin has unique features that either advantage or disadvantage CO_2 storage. In considering first-of-a-kind deployment for Australia, decisions for exploiting the resource must be underpinned by sound scientific bases. The ANLEC R&D research program was designed to enable, and help accelerate, deployment of CO_2 storage in Australia by expediting that research necessary to deliver the required science to the public record.

Managing financial investment risk for carbon dioxide storage

The financial investment risk for a CCS project can be categorised as;

- Project Viability Risks: These are critical factors that can cripple the CCS project; typical examples are CO_2 containment and public acceptance, or
- Project Engineering Risk: These are engineering cost factors that can be mitigated but would have impact on the project finances; typical examples are reservoir injectivity and capacity.

Age of CO_2 Storage Reservoirs



Surat Basin

An integrated Surat Basin carbon capture and storage project was established to demonstrate the technical viability, integration and safe operation of carbon capture and storage in the region to benefit all emitters of CO_2. CTSCo has been funded by industry to deliver the feasibility study and front end engineering design (FEED) stage. The company was granted a single GHG exploration permit for tenement EPQ 7 in the Surat Basin as the preferred site for a pilot injection. Test injection of CO_2 was scheduled to begin in 2020.

Goal

To support carbon dioxide storage in the Surat Basin

Queensland

Scale Key

- In lab
- In Field

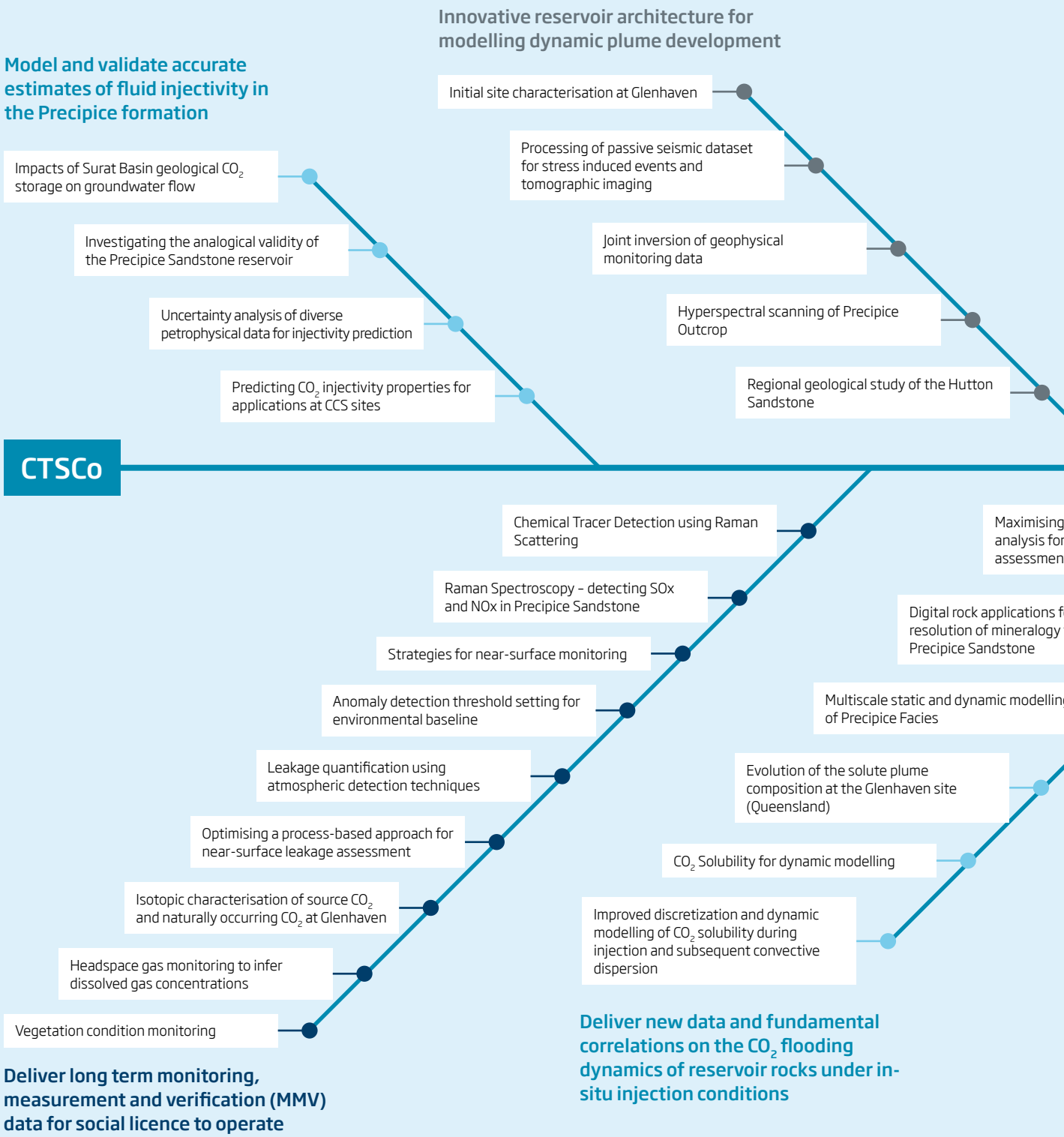
Delivery Key

- New Data
- New Application
- Field Validation
- New Service
- New Correlation
- New Software
- Permitting & Public Communication

Impact Area	Impact Statement	Delivery
Reservoir Containment	*Investigate and identify innovative methods for reservoir containment monitoring*	
	Test innovative remediation concepts for CO_2 containment	
Public Acceptance	*Deliver long term monitoring, measurement and verification (MMV) data for social licence to operate*	
	Deliver robust data and information that allows accurate assessment of environmental behaviour of a CO_2 plume in a storage reservoir	
Reservoir Capacity	*Validate rapid reservoir characterisation strategies and methods at scale*	
	Develop and validate performance of state-of-the-art instrumentation for application in the field	
	Deliver new data and fundamental correlations on the CO_2 flooding dynamics of reservoir rocks under in-situ injection conditions	
Reservoir Injectivity	*Model and validate accurate estimates of fluid injectivity in the Precipice formation*	

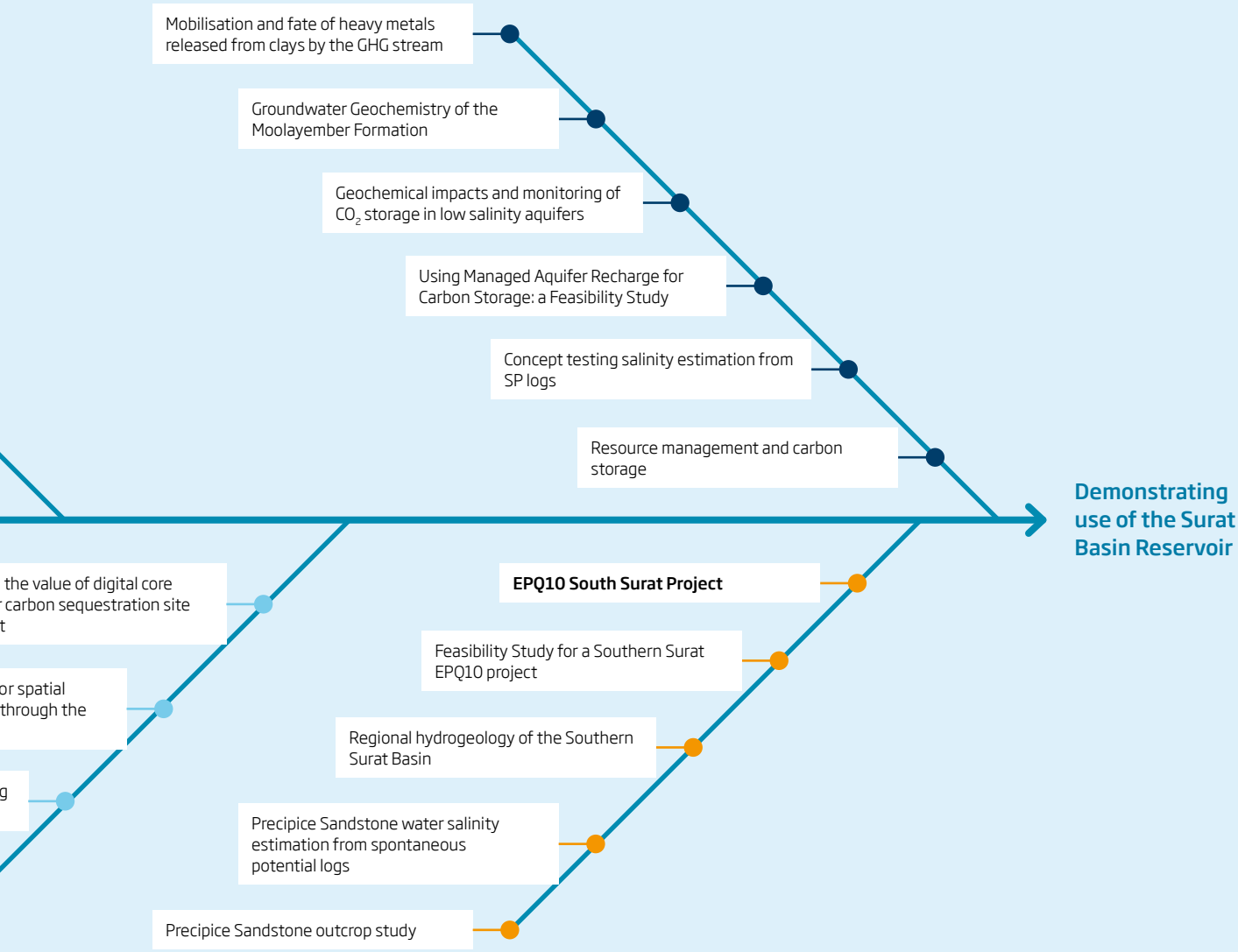
Adapted from CSIRO: M. Bazzaco, CSIRO Impact Evaluation Guide, 2015

Supporting Research: Surat Basin



CTSCo Project Director	
Alan Du Mee	2009–2016
Darren Greer	2016-2023

CTSCo Technology Manager
Rob Heath



Research Key

- Reservoir Containment
- Public Acceptance
- Reservoir Capacity
- Reservoir Injectivity

Research Projects

Basin resource management and CO_2 storage

We will understand how to better manage several overlapping resources - such as land, water, gas, coal and CO_2 storage reservoirs – at the same time.

Geological formations are connected to their adjacent structures in one way or other. At one extreme, this connection allows material to move easily from one structure into another; at the other extreme, only indirect interactions may occur. Some of these interactions may be synergistic and helpful while others may be detrimental.

This two-part CSIRO report sought to clarify the possible interactions in a range of potential geological settings. It aligned 'best in class' international studies to the Australian context, to propose relevant "resource interaction" decision flow-charts.

Coal, oil and gas are contained in various geological structures in addition to shallow and deep ground water resources.

This study recommended a risk based approach focusing on the potential for:

» Adverse interactions – which could include potential contamination by carbon dioxide, resource competition for water disposal reservoirs, brine displacement into adjacent reservoirs and seal compromises.

» Positive synergies – that may include increased formation pressure (re-pressurising), enhanced oil and gas recovery. Carbon dioxide may also provide a working fluid for geothermal applications.

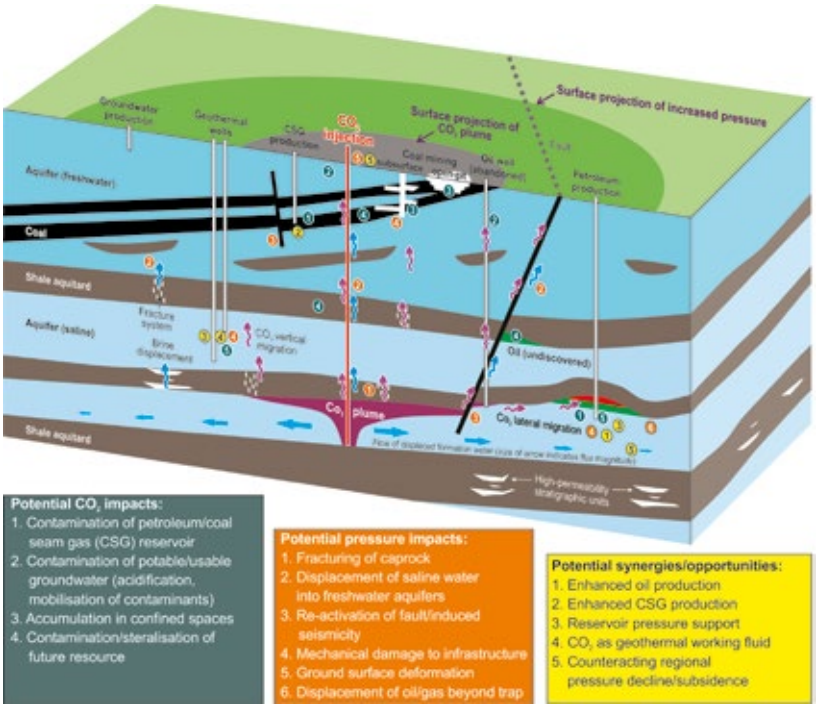
Decisions on the productive use of resources required consensus to be drawn between various stakeholder interests. These included private business, state and federal regulators, and local community groups.

High-quality information and transparent decision processes were key to enabling these conversations.

This assessment provided initial recommendations on the nature of information and processes that could be adopted or adapted by custodians of the resources. It was likely that State "Advisory Bodies" could be the best customers to benefit from this study.

Reference

K. Michael, et al 2013, Resource Management and Carbon Storage (3-0510-0057)



Cross-section illustration showing various subsurface features and hydrocarbon extraction methods.

Feasibility for CO_2 Storage in the Precipice Sandstone

The CTSCO Integrated Surat Basin CCS Project is an industry and Government funded project to demonstrate the safe storage of CO_2 in the Surat Basin reservoirs in Queensland.

A four-stage approach was developed to deliver a low risk/low cost pathway to Industrial Scale CCS deployment in the Surat Basin by 2035. The Surat Basin is a highly prospective area for greenhouse gas tenement (GHG) storage in Eastern Australia, with a thick, relatively undisturbed sedimentary sequence providing large potential storage volume adjacent to major emission sources from coal-fired power stations.

The geological setting for this project was the Mimosa Syncline to the west of the Moonie Oilfield. Researchers explored techniques to measure and improve storage efficiency in this non-anticlinal setting. The strategy involved drilling a well to provide core and fluid samples in order to test low-cost monitoring solutions for plume tracking and storage efficiency monitoring. They would validate water quality interfaces as predicted by prior studies in the most prospective CO_2 storage intervals. The study used the same facilities testing and trials as that for long term commercial storage, with minimal additional expenditure.

In contrast to the developed oil and gas fields to the west and north, the Mimosa Syncline is under-explored with seismic and drilling, and existing data is generally older vintage unsuitable for state-of-the-science analysis and imaging.

Key project uncertainty fell into five areas:

» *Fluid properties*–trends in water quality (potable/non-potable aquifer boundaries) with depth from the shallower northern to deeper Southern Surat Basin and limits on heavy metal release under CO_2 injection.

» *Injectivity*–optimised injection stream (CO_2/water) to maximise injectivity and pore space utilisation.

» *Containment*–CO_2 plume behaviour and deep imaging under migration assisted storage mechanisms (density-driven buoyancy and settling).

» *Storage capacity*–reservoir/seal characterisation and storage volumetrics.

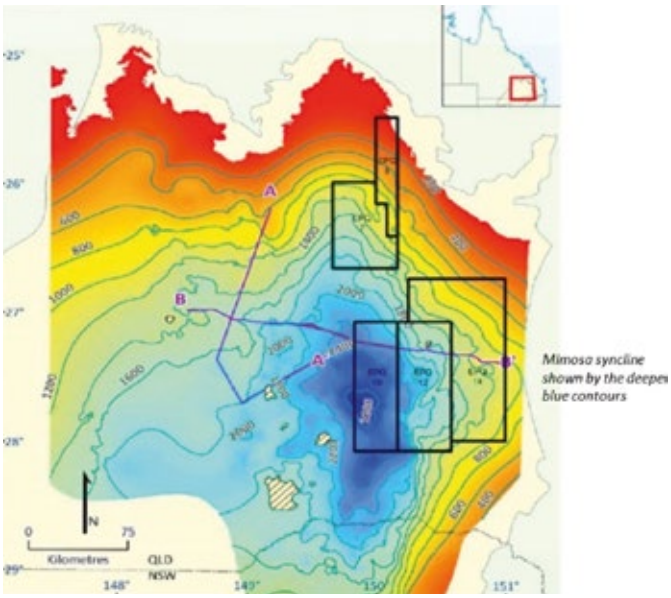
» *Permitting and injection support infrastructure*–considerations for power supply, access and transportation into preferred injection sites.

The R&D program to address these uncertainties within the target period comprised four project elements:

1. Hydrochemical profiling of major aquifers in the Mimosa Syncline – applied R&D to underpin updated understanding of groundwater chemistry profiles axially and across the flanks of the Mimosa Syncline.
2. Mimosa MAS R&D well in EPQ10 – drill a CO_2 storage exploration well in the Mimosa Syncline and acquire a comprehensive suite of rock and fluid samples for R&D application.
3. Injectivity efficiency and pore space utilisation under Migration Assisted Storage – representative permeability and saturation functions in the Mimosa Syncline to better constrain modelling of injected CO_2 under dynamic simulation; applied R&D to enhance storage efficiency including injection stream makeup.
4. Data integration and advanced modelling – integrate all new data and update storage models to underpin technical plan for forward CO_2 storage appraisal program.

Reference

R Heath, A Du Mee, et al 2017, Feasibility Study for a Southern Surat EPQ10 project (7-0218-0311)



Structure contours to top of Evergreen Formation regional seal (using datum 450mASL) showing the position of the EPQs relative to the deepest parts of the Surat Basin

Validating CO_2 storage potential in the South Surat Basin

Over 33 scientific research projects were conceived with the CTSCo CCS Project hosted by Glencore Australia. Extensive studies were undertaken to estimate fluid injectivitiy, configure monitoring and under resource interaction and deliver robust data for accurate assessment of CO_2 behaviour in the subsurface.

Historical data suggested that there is potential for commercial scale CO_2 volumes in the Precipice Sandstone located in the Southern Surat Basin. The geological setting is the Mimosa Syncline to the west of the Moonie Oilfield.

While much of the science undertaken confirmed the suitability of the reservoir, there remain a need to validate these findings with new data obtained from the precise location of proposed storage. This would answer the focus question: "Do we have a viable CO_2 storage complex?"

Several foundation studies were completed to inform storage viability that included:

- A framework for storage capacity assessment
- An updated geological database
- An updated petrophysical database and evaluation
- An updated rock typing assessment
- Regional depth structure mapping
- Water chemistry database

The activities proposed were to drill wells for sampling and appraisal, complete seismic testing and obtain water flow-test data to assess the suitability of the reservoir for its injection and storage potential.

The West Moonie 1 well was completed in November 2021 in the South Surat. It showed good cement across the Precipice Sandstone and Evergreen Fm. The high permeability (multi-darcy) Precipice was perforated at 2318 m and water was air-lifted using coil tubing. It was shown to have high alkalinity and very high fluoride level completely unsuitable as potable water. West Moonie 2 spud date was 1st July 2021 and the rig released 23 days later.

The well was drilled under budget and without safety or environmental incidents. The Project maintained good communication and relationship with landowners and the community. The well met all pre-drill objectives, including reaching target, core cutting and wireline logging. Well evaluation confirmed hydraulic isolation.

The Precipice Sandstone from the Upper Evergreen seal showed greater than 7000 psi pressure difference, confirming seal integrity in the well. A successful horizontal versus vertical permeability test.

Drilling in the South Surat

References

The following reports from Project 7-C318 remain confidential at closure.

N Hall, R Heath, 2020, Geological Database

I Djamaludin,R Heath, 2020, Geo-Physical Database

A Buffin, N Hall, R Heath 2020, Petro-physical Database

D Bowyer, N Hall, R Heath 2020, Water Chemistry Database

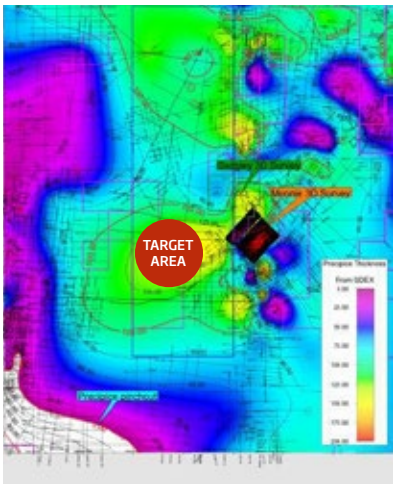
S Tiainen, N Hall, R Heath, 2020, Rock Typing Study

R Heath, N Hall, 2020, Metal Content of Cuttings Study

I Djamaludin,R Heath, 2020, Regional Depth Structure Mapping

N Hall, R Heath, 2020, Southern Surat Static Modelling Study

D Price, R Heath, 2020, Framework for Capacity Assessment (7-C318)



Target location is the Mimosa Syncline in the South Surat Basin

Hydrogeology of the Southern Surat Basin

The primary aim of this study was to provide an overview of the current understanding on groundwater in the southern Surat Basin and to improve the conceptual ideas of groundwater flow and groundwater quality in the basin.

The Precipice Sandstone in the southern Surat Basin is a primary target location for geological carbon sequestration as it is believed to fulfil these primary criteria. There is always a need to improve knowledge on regional groundwater flow processes and groundwater quality of the Precipice Sandstone of the southern Surat Basin. In the northern Surat Basin hydrogeological understanding has increased over the last 10-20 years due to coal seam gas development, Managed Aquifer Recharge, water well drilling and regulatory work by organisations such as the Office of Groundwater Impact Assessment. However, most studies have not extended to or focused on the deeper southern part of the basin, and this project addresses this hydrogeological knowledge gap.

This research has significantly enhanced the conceptual understanding of groundwater flow in the southern Surat Basin.

Through a combination of groundwater modelling and geochemical analysis the work indicates that the majority of the groundwater in the Surat Basin appears to discharge to lower topographic areas in the east (Clarence-Moreton Basin). Furthermore, it has been demonstrated that groundwater flow velocities are likely to be minimal in the central part of the Surat Basin.

This work demonstrates that hydraulic heads are distinctly different between the Hutton Sandstone and the Precipice Sandstone with up to 75-100 m (equivalent to 735-980 kPa). Groundwater modelling shows this can only be explained by the bulk vertical hydraulic conductivity in the Evergreen Formation being lower than previously thought. Groundwater flow from the northern basin is predominately toward the south and the east towards the Clarence-Moreton Basin.

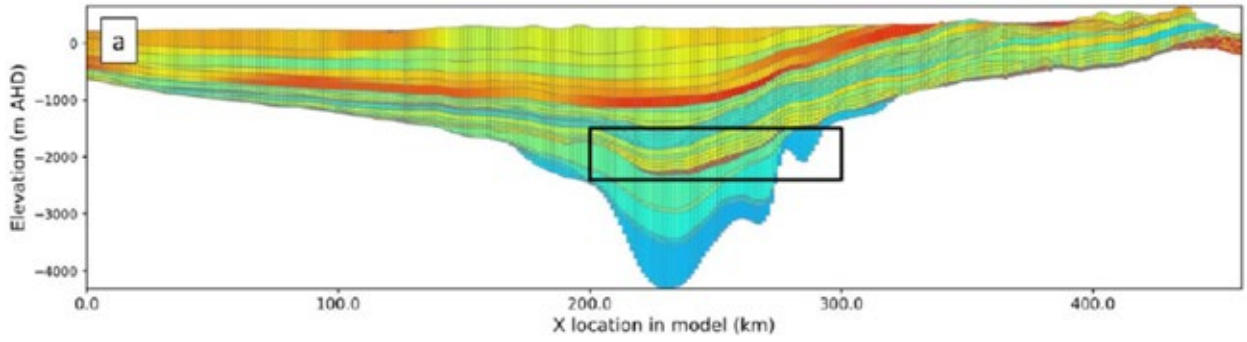
While the salinity in the Precipice Sandstone in the central part of the Surat Basin is moderate, it is too high for the water to be used as a drinking water supply.

Water quality is also compromised by elevated Fluorine concentrations in the Precipice Sandstone and the Hutton Sandstone. The results from the groundwater modelling work and the geochemistry are in agreement with respect to the groundwater flow paths in the Surat Basin. Estimated residence times from isotopic studies and particle tracking in the groundwater model reflect the flow conditions.

Much of the central part of the Surat Basin has minimal flow to stagnant conditions.

Reference

H Hofmann, J Pearce, I Rodger, S Golding, P Hayes; Hydrogeology of the Southern Surat Basin, 2022 (7-0316)



East-West cross sections showing the Precipice Sandstone with relatively higher hydraulic conductivity (orange).

Investigating Analogical Validity in the Precipice Sandstone Reservoir

An important study of the Precipice Sandstone to Evergreen Formation stratigraphic interval was completed by the UQ-SDAAP Project in 2019.

It posed the hypothesis that the Precipice Sandstone may represent a composite sedimentary system fed by multiple source terranes depositing sediment into two depo-centres –one in the north and one in the south. These studies were undertaken in ANLEC R&D to test the hypothesis.

If proven to be true, the implications of this hypothesis would be that the work done in the EPQ7 tenement (northern sub-basin) may be of limited application to understanding the EPQ10 tenement (southern sub-basin) as they may consist of strata with differing petro-physical, sedimentological, and geochemical properties.

Using diagenetic mechanisms

Undertaken by CSIRO, A suite of micro-structural and in-situ geochemical data was collected on quartz-rich samples from the clean sandstone lithologies of the Precipice Sandstones from two wells, West Wandoan 1, and West Moonie 1 EPQ10 representative of the northern and southern Surat Basin respectively.

The results of this project indicate that samples from the two well locations have similar mineralogical composition and can be classified as quartzarenites with monocrystalline quartz as the dominant mineralogical component, with only minor amounts of additional detrital minerals (muscovite, zircon, and rutile). Diagenetic phases identified in samples from the two well locations are of similar nature and include minor kaolinite and siderite and more widespread quartz overgrowth cements.

These results support the interpretation that the quartz rich units of Precipice Sandstone at both well locations share the same provenance and are possibly derived from a common source in granitoids of permetaluminous/peralkaline composition.

Using Zircon geochronology

Undertaken by the University of Queensland, this study examined the mineral composition and sediment provenance of the Precipice Sandstone. The research successfully integrated the mineralogical analysis, CA-TIMS zircon dating, detrital zircon geochronology and palaeo-flow analysis, with the sedimentology and stratigraphy data acquired across the basin.

It concluded that the palaeo-flow during deposition of the Precipice Sandstone to Evergreen Formation succession did not differ significantly between the northern and southern parts of the basin, and flow directions corroborating previous work. No significant difference in sandstone composition was noted between the northern and southern regions of the Surat Basin. The main blocky sandstone facies exhibited the general southerly flow, but this transitioned upwards to dispersed but northerly flow directions as the transition boundary was approached.

There is no significant difference in sandstone composition between the northern and southern regions of the Surat Basin, except for an interval in the upper part of the Precipice Sandstone (J10-TS1 interval) where wells in the south - including West Moonie 1 - differ from wells in the north. At the most fundamental level, the study found little evidence to support the hypothesis of two distinct depo-centres for the Precipice-Evergreen interval in the Surat Basin.

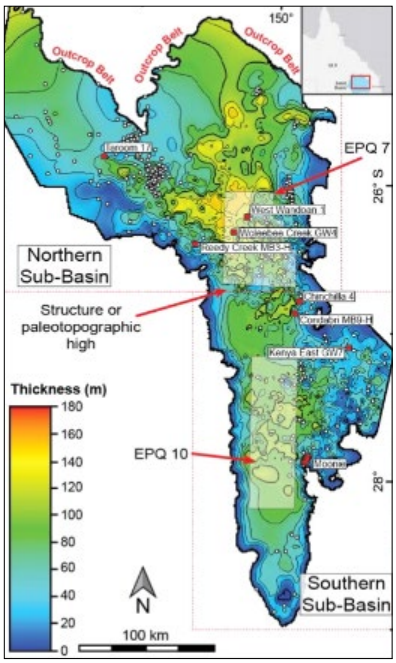
Taken together, these two studies have provided strong evidence for a consistent depositional and burial history across the Surat Basin.

Reference

Testing the Surat Basin two deposition centre hypothesis: 2022 (7-0326)

Part A - Zircon geochronology, K Sobczak, A La Croix, J Esterle, P Hayes, H Holl

Part B – Diagenitic Mechanism, C Delle Piane and J Bourdet



Surat Basin showing the two depocentres and tenements EPQ7 and EPQ10.

Querying the influence of CO_2 storage on water flows and salinity

Modelling helps understand how formation water is displaced by CO_2 injection for long term storage.

This project sought to quantify pressure fluctuations and fluid fluxes that could be expected in the far field for large scale CO_2 storage in the Surat Basin; in an effort to reduce the risk for implementing large-scale CCS.

It focussed on regional to basin-scale modelling scenarios of the Precipice Sandstone, the overlying Evergreen seal and potential for impacts to the overlying Hutton aquifer.

A commercial reservoir simulator (Eclipse300TM) was used to run simulations of CO_2 injection into a water-filled formation. First, a series of simulations were run on a simplistic idealised generic numerical model to establish the key factors affecting groundwater resources. This was done in order to understand how different processes interact and it bears no relation to any real CO_2 injection site. Later, the methodology established from these simplistic generic simulations was applied to evaluate the effects of a large-scale CO_2 injection in a more realistic regional Surat Basin model. A static geological model which was built for the ZeroGen Project was made available by the Queensland Geological Survey for this study. This static model was modified before use in the dynamic simulations. Pressure and salinity changes, at different locations in the groundwater and storage formations, were extracted from the numerical model forecast during and after the simulated CO_2 injection.

All of the simulations in this study were at the basin-scale and plume-scale effects which require finer scale grids were not investigated.

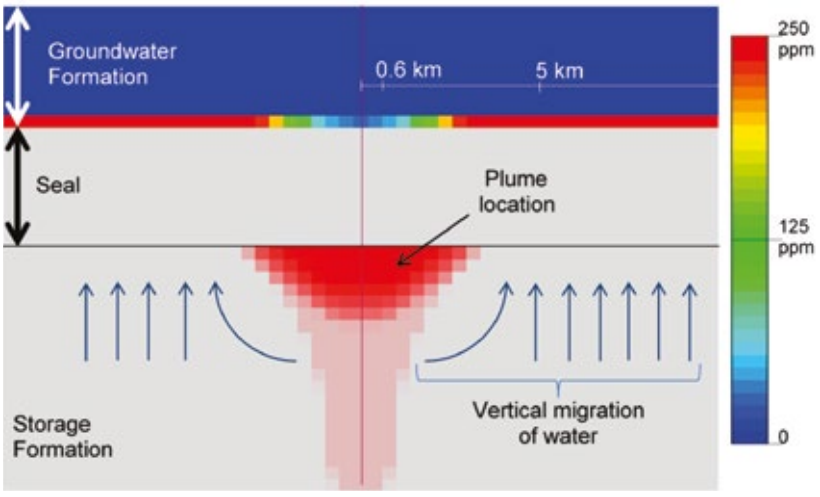
Previous studies have shown that pressure propagation in CO_2 storage formations due to commercial-scale injection has a larger radius of influence than the plume of free-phase CO_2. As a result, it is expected that some portion of the brine residing in storage formations migrates away either vertically through top seal or laterally in the storage formation potentially towards updip shallow sections of the reservoir or even to the surface.

Therefore, when considering the impacts of geosequestration on groundwater resources, the potential for lateral displacement of saline formation water in the far-field of the injection site and its migration through the seal needs to be characterised.

A new method was developed to assess the possible impact of CO_2 injection on groundwater resources by tracking salinity changes in a numerical model forecast. In all of the simulation scenarios the pressure build-up remains less than the fracture or threshold pressure of the seal.

Reference

F. Hussain, et al 2013, Impacts of Surat Basin geological CO_2 storage on groundwater flow (3-1110-0092)



Simulations investigated the impacts of CO_2 injection on pressure and salinity in overlying groundwater aquifers.

Concept Testing Salinity Estimation from SP Logs

The target Precipice Sandstone is deeper in the south where prospects for storing commercial volumes of CO_2 are highest. At this depth, it is important to understand the provenance, quality and character of the formation water.

Working with demonstration proponents, ANLEC R&D seeks to deliver new field data and validation testing for large-scale CO_2 storage in the South Surat basin.

This project aimed to use available wireline logs to map the distribution of the Precipice Sandstone groundwater salinity in the southern Surat Basin. Researchers had access to 115 wells with Spontaneous Potential (SP) curves as a primary dataset for the analysis. The SP curve is one of the basic wireline curves that responds to formation water resistivity and thus the water salinity. Results could be calibrated with good quality laboratory water analysis data.

This work completed a detailed search through existing well logs within the Surat Basin identifying wells that penetrate the Blocky Sandstone Reservoir (BSR) with spontaneous potential and resistivity logs of sufficient quality for further analysis. These logs have been analysed using theory and workflows to estimate equivalent salinities of formation waters. The work has also included the development of a probabilistic workflow for SP log analysis using Monte-Carlo methods to explore uncertainties in measured and derived input parameters.

The geophysical log salinity estimates have been compared against equivalent salinities from several water wells with chemistry samples, and at wells where both SP logs and chemistry is available.

From the work the following conclusions are drawn:

- The SP analysis results are mainly in the range of salinities seen in the BSR, based on water sample analysis. However, comparison of the limited dataset of seven wells with both SP and water chemistry results shows the method to be relatively inaccurate, and that it cannot be relied on to estimate equivalent salinity of BSR formation water across the Surat Basin.
- The probabilistic SP method reduces the tendency to estimate outlier values compared to the deterministic method, but it does not improve the outcome sufficiently to provide confidence in results.
- The resistivity ratio method is simpler to apply and provides lower values of estimated salinity.

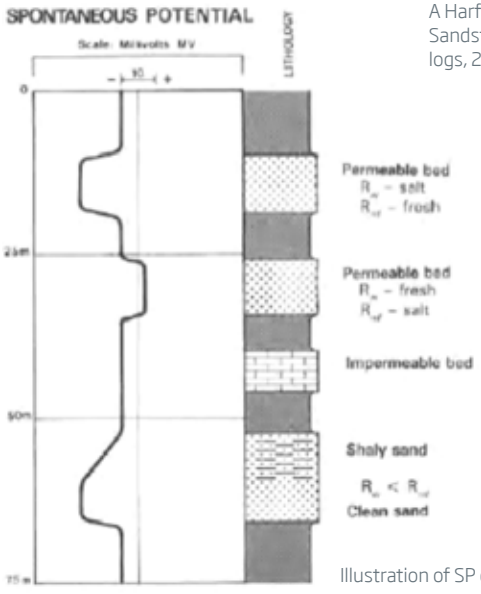


Illustration of SP deviations from the shale baseline.

While such low salinity values are observed in parts of the northern Surat Basin, this extends across all but one of the results strongly suggesting a systematic bias to lower values. There is only a single well with both resistivity logs and water samples, the recently drilled West Moonie 1, that is the only well where a higher, more realistic salinity is estimated.

It is concluded that the resistivity ratio method cannot be relied on to estimate equivalent salinity of BSR formation water across the Surat Basin. The range of assumptions made between the two methods, the number parameters, conversion factors and equations and measurement error likely all contribute to the inability to produce reliable results. Whilst further work could be completed looking for correlations or revising the estimated probability distributions applied in the Monte-Carlo SP analysis, it is considered unlikely that reliable results would be achieved.

Reference

A Harfoush, P Hayes, J Pearce, H Holl; Precipice Sandstone water salinity estimation from SP logs, 2022 (7-0322)

Adapting advanced hyper-spectral scanning technology to make in-situ rock measurements

The Precipice Sandstone, Evergreen Formation and Hutton sandstones make up important strata for the storage of CO_2 in the Surat Basin.

Dynamic simulations that predict the subsurface distribution of the injected greenhouse gas at Glenhaven were influenced by the assumption of the distribution of the vertical component (Kv). Defining the distribution of clay layers and lenses, the clay and other minerals within and between lithological facies, their presence, continuity and extent impacted on modelling permeability and reactivity of the Precipice reservoir. These key sedimentological and diagenetic attributes impacted the Kv of storage reservoir permeability.

Hyperspectral scanning of drill cores became a popular method for understanding the mineralogy of rocks in addition to other complementary mineralogical methods such as X-ray diffraction (XRD). It has a variety of geological applications in mineral exploration, sedimentary geology, and hydrocarbon resources studies.

In this study, we used the TSG-Core™ software to analyse hyperspectral data from HyLogger™ to study the Short Wavelength Infrared (SWIR) and Thermal Infrared (TIR) hyperspectral characteristics of the open file Woleebee Creek GW4 core in the Surat Basin in order to identify dominant and secondary minerals in the Precipice Sandstone, Evergreen Formation, and Hutton Sandstone.

The main aim of the project was to test the use of hyperspectral sensors for investigating the mineralogical composition, in particular the occurrence of potentially low permeability or baffling layers containing clay and other reactive minerals, of the Precipice Sandstone at the outcrop scale.

The above data can be integrated with sedimentary interpretations of outcrop, wireline and other available core data and can be used to condition the interpretation and interpolation of reservoir properties within both static and dynamic 3D models of the Precipice and overlying formations. This technique was relatively new and although remote airborne and core-based sensors are widely available, field-based systems are rare and still require development.

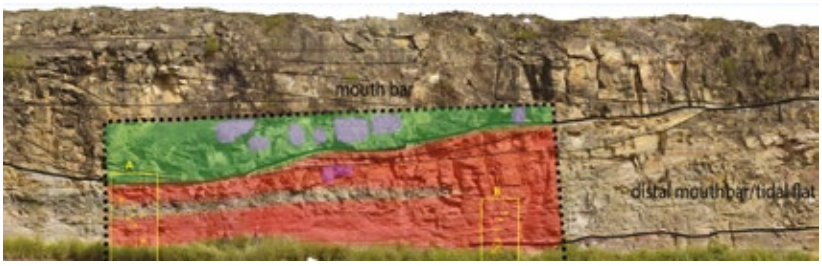
Achievements included:

- This field trial is a "first of kind" in Queensland and in Australia to collect mineralogical data from outcrop using hyperspectral scanning combined with photogrammetry.
- Formation mineral details can be recognised based on the HyLogger™ data interpretation to a level needed to inform variations in permeability.
- Demonstrated value and applicability of the technique to investigate an outcrop of the Precipice formation and derive more quantitative estimates of mineralogical variation.

References

D. Pistellato, et al 2016, Report on the trial hyperspectral images of the Precipice Sandstone

A. Sansoleimani, et al 2016, Hyperspectral analysis of minerals in the Precipice Sandstone and overlying formations, Woleebee Creek gw4 and West Wandoan 1 boreholes using tsg core (7-0115-0237)



Processed Hyperspectral images acquired in the field trial on a Precipice Sandstone outcrop. Shown here is the interpreted kaolinite (red overlay), weathered iron oxides (green) and water (purple) features interpreted from the Short Wave Infrared (SWIR) spectra imaged on the outcrop. Sampling locations for validation shown in yellow rectangles at A and B.

Precipice Sandstone outcrops provide accurate measurements for reservoir modelling

The objective of this work was to allow the construction of the best possible static geo-cellular model of the Precipice Sandstone storage reservoir by maximising the geological data relevant to fluid flow that can be derived from detailed examination of relevant Precipice outcrops.

The results of this project improved both the general understanding of the basin and the models that can be built to predict the behaviour of injected CO_2 in the basin. The project took advantage of the fact that the reservoir unit for the Surat Basin project can be seen at an outcrop not far from the proposed demonstration site, and can therefore be studied in more detail than is possible from just subsurface sampling.

To populate static geocellular models, the project developed a series of outcrop models, using detailed interpretation of sedimentary geobodies, their bounding dimensions and internal fabric, and their grain-size distributions that define facies. A densely drilled area with open file data near to the Glenhaven area was selected to develop a workflow for modelling the distribution and connectivity of potential baffling units, using depositional concepts developed from the outcrop studies.

This is the first time that data gathered from the outcrop was directly relevant to the construction of a static geological model which can be up-scaled to a regional model.

The study has:

- challenged our understanding of the depositional setting of the Precipice Sandstone that leads to its reservoir properties,
- developed a catalogue of sedimentary geobodies, their dimensions and their sedimentary features, to assist in subsurfacing modelling of the Precipice Sandstone reservoir flow units,
- developed a workflow for further, more sophisticated, subsurface facies modelling for the Precipice Sandstone, and to test the influence of the variograms on the lateral connectivity of the baffling units within the Lower Precipice allo-stratigraphic unit, and
- tested hypotheses for structures that may act to control flow pathways in the reservoir.

Implementing Results

Recognising that there is a preponderance of rapid and inexpensive avenues to acquire high-resolution models of terrestrial environments including outcrops, the study was extended to deliver practical outcomes. An objective to identify and implement a state-of-the-art software for digitising and exporting bounding surfaces of architectural elements identified on outcrop photogrammetry into commercial 3D reservoir modelling software was completed. It is a bespoke Windows based application, OpenOutcrop, and can accessed at: http://teraterra.com.au/OpenOutcrop/DownloadingAndInstalling.htm

Reference

V. Bianchi, et al 2016, Outcrop mapping and photogrammetry of the Precipice Sandstone (7-0314-0228)

W Sulda, Outcrop to model – the missing link, 2021 (7-0327)

Texture mapped with coarsely sampled vertices

Triangulated mesh used in vertex coloring

Vertex colored triangulation

Geochemical testing informs water resource interactions

Research informed the development of fit-for-purpose regulation to ensure safe storage of CO_2.

A post-combustion captured greenhouse gas (GHG) stream, derived from the combustion of Walloon Coal, may contain up to 5-30 ppm SO_x, 100 ppm NO_x and 30 ppm O_2 along with other gases including N_2 and Ar.

When this fluid is injected into the quartz-rich Precipice Sandstone and interacts with the clay-rich Evergreen Formation seal at the Surat CCS Project, preliminary geochemical studies suggest that some heavy metals and metalloids may be released.

Site specific information about the processes that control trace element behaviour is essential. It is necessary to accurately predict the likely concentrations of heavy metals and metalloids present in formation water, as a result of reactions with rock and water at the site.

The results from this project assisted in understanding the type, amount and fate of heavy metals and metalloids, both before and after GHG stream injection, and provided a baseline and calibration data for the site's environmental and groundwater impact assessment.

The project used geochemical modelling, together with detailed geochemical and mineralogical analysis of Precipice Sandstone and Evergreen Formation core from the West Wandoan 1 well, and from laboratory batch experiments. This approach allowed comparisons between simulations of water chemistry and measurements from experiments, providing confidence in the validity of model predictions of long term water chemistry impacts.

Recent results suggested four potential processes may occur (highlighted by natural analogues, injection trials and experimental studies). They were:

- Dissolution/precipitation reactions are affected by pH and redox but are also important in controlling these parameters and may drive metal sorption and/or desorption on iron oxides, hydroxides and clay surfaces.
- Ion exchange reactions of reactive clays in response to fluid migration and mixing or elevated concentrations of Ca from calcite or plagioclase dissolution liberate major ions including Na.
- Sorption of anions on Fe-oxides and hydroxides including bicarbonate, sulphate (and potentially nitrate) from the GHG stream may cause desorption of trace metals and metalloids.
- Oxidation/reduction of the system as a result of injected CO_2, O_2, NO_x and SO_x (oxidizing) or H_2S and CH_4 (reducing) makes some metals more or less soluble and will alter major and trace element behaviour. The precipitation of Fe-oxides under oxidising conditions can act as a sink for metals through co-precipitation and adsorption.

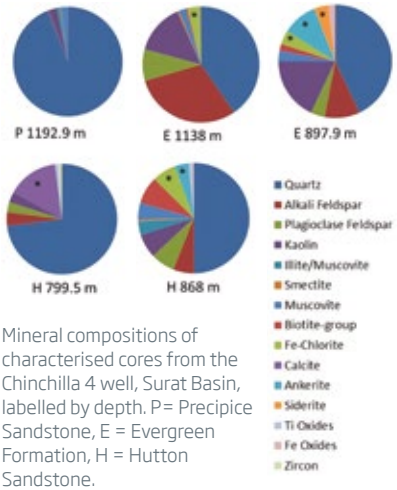
Continuing studies showed supercritical CO_2 migration was dominated by buoyancy, moving upward until encountering lower permeability HSU at which point lateral migration dominated. The trace gases SO_2, NO and O_2 were sequentially stripped out of the migrating supercritical CO_2 based on the trace gas solubility in the formation water. The migration of O_2 was considerably more extensive and contributed to the oxidation of Fe and precipitation of Fe(OH)3. It quantified the extent of potential mobilisation and showed that the important factors that contributed to decreasing concentrations of the trace elements were depletion in the source volumes, adsorption and advective mixing.

The potential for groundwater monitoring locations in the lower Precipice Sandstone was investigated and it was determined monitoring of EC, pH, Fe, K, Mg, and total alkalinity in addition to minor and trace elements would make useful tools for identifying migration and processes occurring along the migration pathway.

Reference

S.D. Golding, J.K. Pearce, G.K.W. Dawson and D.M. Kirste, 2019: Mobilisation and fate of heavy metals released by the GHG stream, (7-0115-0236)

Dawson G , Kirste D, Pearce J, Golding S, 2023: South Surat metal mobilisation and fate of heavy metals released, (7-0320-C323)



Mineral compositions of characterised cores from the Chinchilla 4 well, Surat Basin, labelled by depth. P= Precipice Sandstone, E = Evergreen Formation, H = Hutton Sandstone.

* indicates minerals which dissolved on CO_2-water reaction as described in Farquhar et al. (2015) 10.1016/j.chemgeo.2014.10.006

Characterising the Surat CO_2 storage complex; the Moolayember Formation

The purpose of this project was to acquire more knowledge of the mineralogy and chemical composition of the Moolayember Formation at the Glenhaven site. It assessed the mineralogical and chemical changes that could occur resulting from interaction of the injected greenhouse gas (GHG) stream with Precipice groundwater was to interact with this material.

The modelling and experimental output provides CTSCo with crucial information about the chemical stability /reactivity of the Moolayember Formation.

Virtually all the geochemical work to date on the potential impacts of CO_2-water-rock reactions in the Surat Basin were focused on the mineralogical changes that could occur in the Precipice Sandstone and the Evergreen Formation when the fluid comes in to contact with the different rock materials. However, none has been undertaken on the changes that could occur if the plume was to come in to contact with the Moolayember Formation.

The upper boundary of the Moolayember Formation is a regional unconformity, overlain with variable angular discordance by the Early Jurassic Precipice Sandstone. The Moolayember Formation consists of argillaceous sandstone, siltstone and mudstone, all of which could react with CO_2 saturated water.

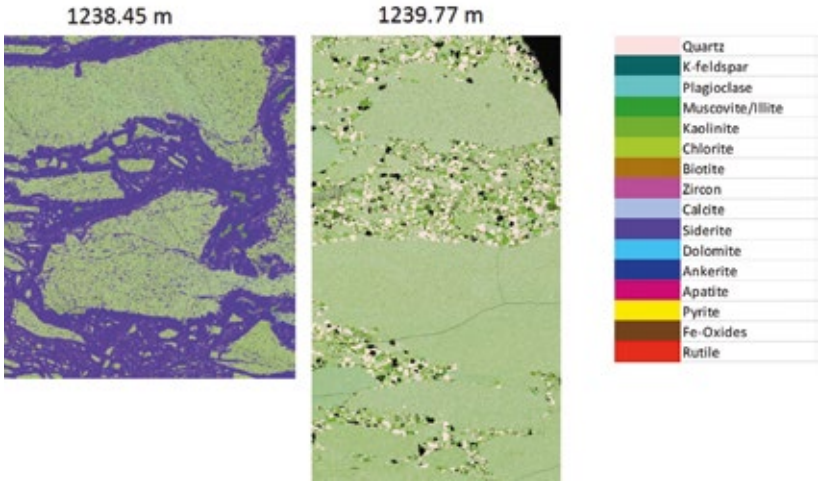
The Precipice Sandstone (thickness ranging between 70-80 m) is stratigraphically located between the Evergreen Formation and the Moolayember Formation. If the GHG stream is injected, it will first migrate up towards the Evergreen Formation due to buoyancy, but as GHG dissolves in the Precipice aquifer a dense plume of CO_2 rich water will form. With time, the denser water will migrate down towards the Moolayember Formation while reacting with the rock material of the Precipice Sandstone.

The project produced:

- Better understanding of the Moolayember Formation petrology and mineralogy at the Glenhaven site.
- Geochemical modelling of potential dissolution and precipitation processes, over time, as a result of interaction of representative Moolayember Formation lithologies with the GHG Stream.
- Batch reactor experimental data from high PT reactions of selected core samples with a GHG stream, and geochemical reaction path modelling of the experimental results to determine the chemical reactivity of selected samples of the Moolayember Formation.

Reference

S. Golding, et al 2017, Groundwater geochemistry of the Moolayember Formation (7-1116-0295)



West Wandoan-1 QEMSCAN images of two core depth sections of the Moolayember Formation

Groundwater Geochemistry of the Moolayember Formation

As an extension to prior work, this study evaluated the chemical stability of the Moolayember Formation.

It sought to improve understanding of potential impacts of CO_2 injection on groundwater geochemistry as a result of fluid-rock reactions at the proposed Glenhaven carbon storage site in the Surat Basin. It assesses the impact of CO_2 storage on the base layer of the Surat Basin storage complex

To best reflect flue gas composition from power stations, the research combined geochemical modelling with mineralogical, geochemical and petrophysical analysis with laboratory batch reactor experiments to investigate the groundwater chemistry impacts resulting from CO_2 impurities such as O_2, NO and SO_2 gas.

The modelling concluded that CO_2 migration was dominated by buoyancy, moving upward into and through the different hydro stratigraphic units until reaching the lower permeability (Upper Precipice Sandstone) at the top, beneath which lateral migration dominated. The generation of impurity acids within meters of the edge of the dry-out zone produced very low pH over the range of those few meters. Outside of that zone, the pH was controlled by the amount of CO_2 dissolved.

In all cases, an important factor that contributed to decreasing concentrations of the trace elements was depletion in the source volumes. Two main processes contribute to the depletion, the first is equilibration between the carbonate mineral and the formation water meaning less potential for reaction and the second is transport of the trace elements out of the source volumes. As the source areas show decreasing concentrations, the density driven formation water leaving the source volumes will have lower concentrations. This process of dispersion brings formation water with lower trace element concentrations downward to mix with the earlier migrated higher concentration water.

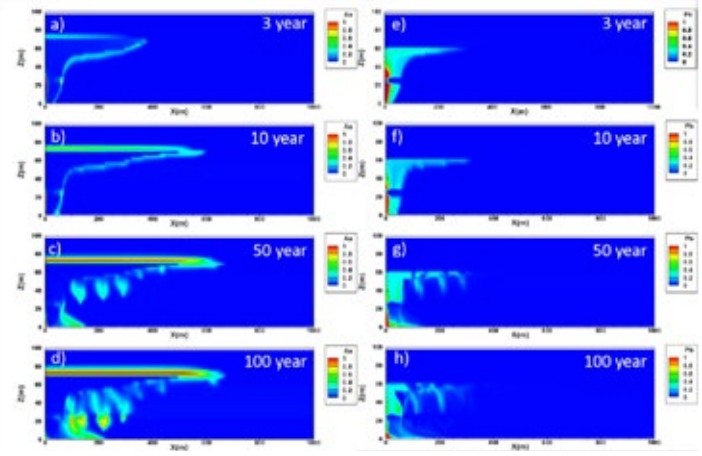
Although the modelling of the role of the Moolayember Formation did not include adsorption, several important observations were made. Permeability is a critical factor in governing the dynamics of density contrasting fluids. Low permeability and heterogeneity will limit the extent to which density driven migration can occur downwards into the Moolayember Formation. The likelihood of significant water infiltration into the Moolayember Formation at the Glenhaven site is low at the average permeabilities of 0.2-1 mD.

As fluid transport simulations indicate fluids will only infiltrate at a permeability of some 10 mD or higher. On the other hand, the maximum permeabilities measured for unreacted samples may be sufficient for density driven migration of CO_2 impacted water into the Moolayember Formation where such lithologies dominate beneath the unconformity in the immediate vicinity of the injector.

A further factor limiting trace element mobilisation in the Moolayember Formation is that the fluids migrating downward have often already undergone significant water-rock interaction, and so may have much lower thermodynamic drive for ongoing or extensive reaction. Mixing along the migration path will substantially reduce the trace element concentrations. The results of this study and the methodologies developed in this, and prior studies are applicable across the Surat Basin.

Reference

G. Dawson, D. Kirste, J. Pearce S. Golding; Groundwater Geochemistry of the Moolayember Formation, 2022 (7-0320)



East-West cross sections showing the Precipice Sandstone with relatively higher hydraulic conductivity (orange).

Assessing the longer term fate of dissolved CO_2

Numerical simulations were an essential tool for assessing the long-term storage of CO_2 in saline aquifers, such as the proposed pilot project at the Wandoan site in Queensland's Surat Basin.

However, the robustness of the numerical predictions depends on accurately modelling the important physical processes involved. Numerical predictions of the amount of dissolved CO_2 during the early stages of a CO_2 storage project, particularly during the injection period where the CO_2 plume grows rapidly, overestimate the actual amount of dissolved CO_2 due to the use of finite-sized grid blocks. A simple theoretical scaling was used to demonstrate that this discretisation error can be accurately accounted for and effectively removed in numerical simulations.

In the long-term, however, the necessary use of coarse grid blocks in a computational model prohibits the accurate simulation of enhanced dissolution due to density-driven convective mixing. This type of mixing typically occurs at a spatial length scale that is smaller than the size of the grid blocks necessary in a field-scale simulation. In order to improve the long-term numerical predictions of CO_2 dissolution in models that feature large grid blocks, a better understanding of the convective mixing process in heterogeneous reservoirs and the role of geochemical reactions is required.

A simple heterogeneity model consisting of a random distribution of impermeable horizontal barriers in an otherwise homogeneous porous media was used to demonstrate that an equivalent anisotropic model provided an adequate approximation of the long-term flux. The long-term flux for an anisotropic reservoir was shown to scale as $(kv/k_h)^{1/2}$ times the isotropic estimate, a result that was confirmed by numerical simulations.

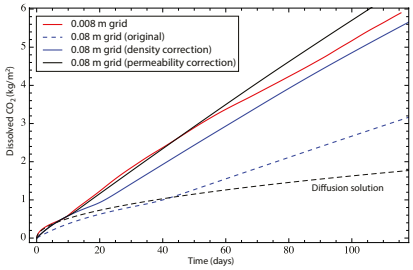
A sub-grid-scale scheme, for reducing the error in the numerical predictions of long-term CO_2 dissolution due to convective mixing, was developed. Several possibilities for implementing the scheme using grid-corrected properties were proposed and assessed using numerical simulations. This correction significantly reduced the difference between the fine-scale results and the results using much coarser models.

Key outcome:

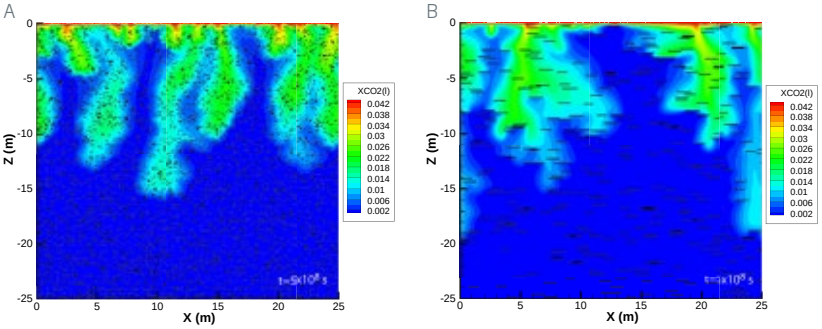
The results obtained in this project can be implemented in commercial simulation software to improve the modelling of the short-term and long-term behaviour of injected carbon dioxide.

Reference

C. Green and J. Ennis-King 2014, Improved discretisation and dynamic modelling of CO_2 solubility during injection and subsequent convective dispersion (7-1011-0190)



Dissolved CO_2 per unit cross-sectional area. Fine-scale 0.008m × 0.008m grid (solid red line); Coarse-scale 0.08m × 0.08m grid (dashed blue line); Coarse-scale 0.08m × 0.08m grid with grid-dependent density correction (solid blue line). This correction significantly reduces the difference between the long-term dissolution rate of fine-scale models (accurate but at great computational expense) and coarse-scale models (with much lower computational expense).



Dissolved CO_2 mass fraction for heterogeneous models with k_v/k_h = 0.6 after 5 × 108 s (15.8 years). A) Short barriers (L = 0.1 m); B) Long barriers (L = 1.0 m). Barriers are shown in black. CO_2 dissolution rate is similar in both cases.

Understanding CO_2 injectivity properties for the Surat, Gippsland and Southern Perth Basin

Improved CO_2 injectivity into reservoir rock will reduce the cost of storing CO_2 from coal fired power generation.

Seven cores from potential Australian storage reservoirs (plus one Berea sample for calibration purposes) were tested, using four different laboratory techniques; providing four sets of data – core flooding, CT scanning, geomechanics and geophysics.

The cores analysed were as follows:

- The Berea sandstone
- The Otway (CRC-1 well, Waarre-C formation) sandstone plug
- The Pinjarra-1 well (Lesueur-Wonnerup member) sandstone
- The Harvey-1 well (Lesueur plug 55H) sandstone
- The Wandoan Precipice sandstone
- The Golden Beach sandstone
- The Hutton-1 sandstone
- The Yalgorup sandstone

The initial four cores were analysed by a CSIRO CT scanner and, from then on, the second four cores were analysed by a Curtin University micro-CT scanner. The result was a new approach to CO_2 flood CT interpretation, with rather more complexities due to the higher resolution of the microCT machine.

Key conclusions:

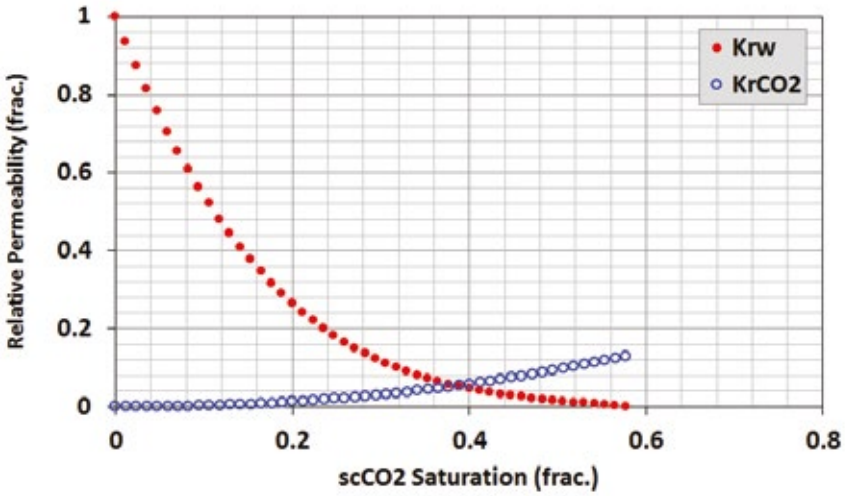
- Demonstrated understanding of how permeability may change as a function of CO_2 injection.
- The results also highlighted the need to analyse the water produced from the core flooding experiments, as well as core mineralogy. This is needed when there are unexpected results.

The recommendations:

- A number of example reservoir cores must be taken from the same reservoir member, but from different wells.
- They must initially be core flooded with $scCO_2$ and their permeability data then established.
- If there are permeability changes both the core mineralogy and produced water must be analysed.
- In addition, it is clear that geomechanical core tests should be done before and after flooding to observe if there is any CO_2-induced weakness in the cores.

Reference

B. Evans, et al 2014, Predicting CO_2 injectivity properties for application at CCS sites (3-1110-0122)



Changes measured during CO_2 injection.

Prospects for improved CO_2 injectivity shown for the Precipice Sandstone

The near wellbore area is critical in CO_2 injection for geosequestration since most of the resistance to flow occurs in this region.

The fluid flux is high because the swept volume is low and any changes to the permeability in this region can have significant economic impact in terms of well utilisation efficiency and compression costs. In the far field regions, away from the well, the affected reservoir is much bigger and changes to permeability, through blocking or enhancement, have relatively low impact, though they can still affect the direction of CO_2 plumes over longer time scales.

This project supported Australian CO_2 geosequestration field demonstration and commercial projects by:

- geochemical reaction investigations of the CO_2-H_2O-rock system of target host formations, identifying changes to mineralogy, porosity and permeability, with leading-edge tools and methodology;
- measurement of the anisotropic mechanical properties and permeability of samples, investigating dynamic changes as a result of geochemical reactions; and
- advancing the development of physicochemical and numerical models, to replicate the lab findings of fluid and mass transport, for application at different spatial and time scales.

Lab experiments were conducted on archived and fresh cores from the target formations of the Wandoan CCS project in the Surat Basin, Queensland and Berea Sandstone supplied by ANLEC R&D for the purpose of benchmarking of permeability results across related ANLEC R&D projects.

Geomechanical tests provided the basis for stress/permeability relationships.

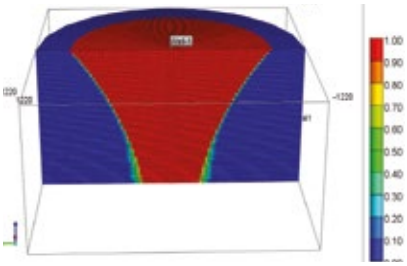
The experimental and kinetic geochemical modelling studies indicated that the injection of CO_2 into water-bearing reservoirs would reduce the formation water pH and cause dissolution of some minerals. Regarding pore-scale modelling that seeks to track more closely the actual physical transport through the porous media, the in-house extended LBM (XLBM) modelling provided a useful tool for understanding the fluid flow and local changes to the flow architecture at the mesoscale including the porosity change with calcite dissolution and feedback impacts on fluid flow. This, in turn, implied that small components within the samples, be these pore throats or fine particles, may be what is most affected by the applied stress prior to any geochemical reactions taking place.

Key conclusions were:

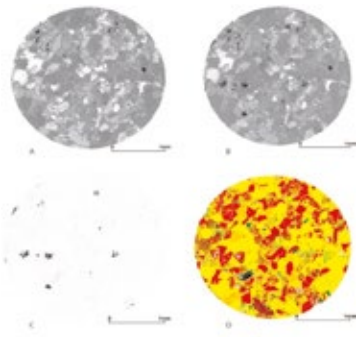
- Mineral dissolution far outweighs precipitation in the immediate wellbore area. This is usually not taken into account but is commercially important as it influences the decisions about the number and size of the injection wells.
- Near wellbore modelling, even using very conservative simplifying assumptions, showed/displayed substantial improvement in injectivity. More comprehensive dynamic modelling would push these predicted results to even bigger (more realistic) increases.
- This was shown to have significant (beneficial) design and commercial consequences.

Reference

G.K.W. Dawson, et al 2014, Geochemical and Geomechanical Testing of Near Wellbore CO_2 Injectivity Improvement (7-1110-0101)



Plume dispersion for case 1 after 2 years of injection.



Registered tomogram images of WW1-1043-Evergreen sub-plug slice, a) Pre-reaction, b) post-reaction, c) difference image (dark areas = loss of material, d) QEMSCAN after reaction with mineral key shown. Source: Golab et al. (2014), used with permission.

Upscaling: multi-scale reservoir characterisation – from pore to core to geocellular models

Multi-scale reservoir characterisation – seven scales from pore to core to geocellular models.

Provide within commercial software packages a quantitative and auditable translation between plug scale measurements, wireline log responses, and geocellular model properties.

Commercial scale sequestration into subsurface reservoirs depends critically on predicting the dynamic behaviour of the CO_2 plume. The plume dynamic behaviour is dictated at the large scale by the micro-scale facies and structures of the reservoir. Traditionally the general practice is to make measurements at core scale, find qualitative correlation with wireline logs and seismic, and then upscale into large geocell simulation models. Much of the fine-scale behaviour and physics are lost in this process, leading to uncertainties and idealised predictions.

The process of changing the scale of rock properties is known as upscaling. The only effective way to analyse the properties which control the transport of CO_2 in rock at the pore-scale is to undertake digital rock analysis (micro-CT) at scales much finer than core plug scale. Such analyses have been undertaken (see page 31). These results are rigorously and quantitatively correlated from the pore-scale to the core plug scale and then the whole core-scale before being cross-correlated with the wellbore wireline logs response over the full reservoir interval with a quantitative upscaling workflow.

To validly achieve this, it is necessary to classify (cluster) the rock at each scale into rock types that can then be treated as distinct units in the upscaling process. This classification needs to be both mathematically exact and geologically meaningful. The employed approaches to upscaling bypass this requirement to classify before upscaling and thus frequently resulted in unrepresentative properties at the upscaled level.

This project delivered two auditable workflows to correctly and conveniently carry out the classification and upscaling processes:

» Component A: Methods to classify and upscale from pore to whole core

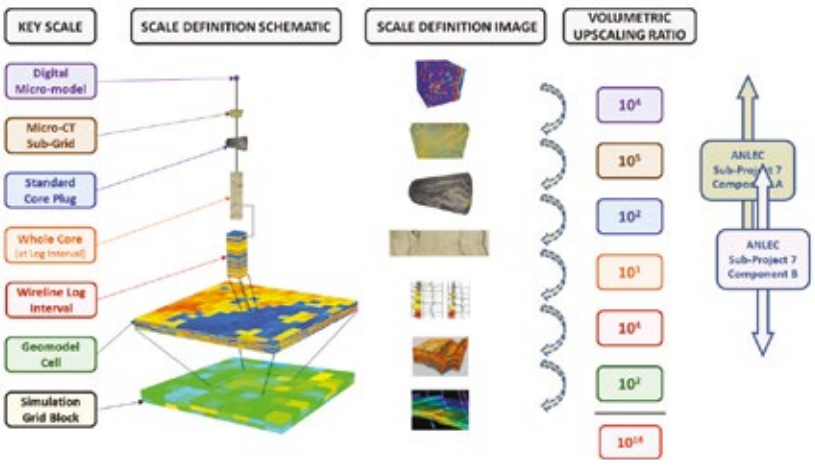
» Component B: Methods to classify and move from core plug and whole core to the geocellular dimensions.

The workflows were designed to upscale simple single-value rock properties, as well as saturation-dependent properties (complex properties that depend on the relative saturations of the fluids in the reservoir including CO_2).

The final products of this project are a module in FEI's software to implement the pore to whole core workflow and a second module in the eGAMLS software, called the *"Classification and Upscaling of Saturation-dependent Properties"* (CUSP) module, to move data from core plugs through whole core to geocellular models. The CUSP module will be made available to the industry by standard commercial software licencing and will be of major importance to successful CO_2 sequestration modelling.

Reference

Curtis, et al 2016, Multi-scale Reservoir Characterisation - From Pore to Core to Geocellular Model, FEI, eGAMLs (7-0314-0128 Sub Project 7)



The 7 levels of scaling from micro level to geocell over 18 orders of magnitude. This project conducts a rigorous classification and correlation pore to wireline log scale.

Digital Rock Technology allows faster and cheaper assessment for CO_2 storage

This program's objective was to combine new Australian developed step-change technologies of 3D Digital Rock Technology (DRT) with conventional oil industry Routine Core Analysis (RCA) and Special Core Analysis (SCAL).

The DRT workflow presented a paradigm shift in the geoscience industry's approach to core analysis. The program leveraged a comprehensive set of Surat Basin core material and multi-scale property data, along with an unprecedented understanding of the physics of CO_2-brine systems at the pore-scale. Implications to quantitative understanding of properties at larger scales, whole core to log to geo-cellular scales were also established. This workflow can be used to assess other potential CO_2 storage sites.

Research groups at ANU and FEI have pioneered a novel 3D image and analysis technology over the last 10 years. The collaborating groups at UQ, UNSW and CSIRO are leaders in the fields of conventional CO_2 flow analysis studies, geochemical trapping of CO_2 and upscaling data from pore to reservoir scales. The achievements of this program included:

» Site-specific full suite of properties and multiscale images of core material from the Evergreen Formation (seal) and Precipice Sandstone (reservoir). Imaging was performed in 3D by X-ray computed tomography (CT; whole core, core plug, sub-plug) and in 2D by Scanning Electron Microscopy (SEM; pore-scale). Digitally calculated comprehensive dataset at the pore and core plug scale.

» Accessible database of multiscale, high resolution images and petrophysical and SCAL data. Developed an interactive catalogue for fast data retrieval/interrogation and 3D visualisation of data via direct online access.

» Demonstrated site specific 3D imaging of in-situ supercritical CO_2 saturation at the pore scale. Conducted direct, 3D pore-scale imaging of supercritical CO_2 and brine within Surat Basin core material during CO_2 injection at aquifer pressure and temperature conditions, by microCT. Illustrated that capillary trapping is a significant mechanism for CO_2 storage in the Precipice Sandstone and likely to be stable over timescales of decades to centuries and that CO_2-brine displacement properties are typical of a strongly water-wet system.

» Developed robust flow simulators for CO_2-brine flooding
A new, geometrically accurate pore-scale model for CO_2-brine flooding was developed. CO_2-brine relative permeability, saturation, and capillary pressure curves for different rock types were derived. Showed that DRT results are consistent with laboratory data from numerous labs (e.g., Stanford, Imperial College). Data sets allowed identification of potential uncertainties associated with laboratory data (e.g. impact of wettability, initial water saturation).

» Performed time-step 3D imaging before and after geochemical reaction with CO_2:brine. Performed pore-scale 3D imaging before and after reaction of the reservoir, seal and over-lying formation. Pure CO_2 and mixed gas containing SO_2 and O_2 were tested. The images showed some localised changes including the dissolution of some carbonate minerals, degradation of some minerals and precipitation of others.

» Validated application of DRT to CO_2 reservoir and seal characterisation with comparison to laboratory and provided correlations to wireline log data. Showed that DRT results are acquired in faster and at potentially reduced cost compared to traditional laboratory methods. Illustrated importance of rock heterogeneity at all scales to provide a quantitative bridge between plug measurements and log scale data.

Reference

A. Golab, M. Knackstedt, A. Sheppard et al. 2016, Maximising the value of digital core analysis for carbon sequestration site assessment (7-0311-0128)

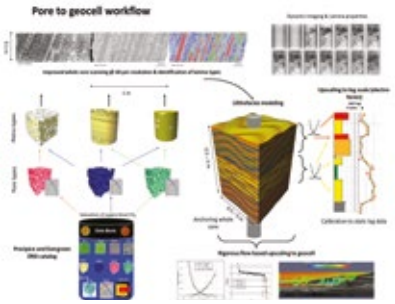


Illustration of pore to geo-cell workflow to support the Surat CCS project.

Improving simulation using micro-scale reservoir data

CCS storage demonstration projects require accurate predictions of the extent of plume movement within the storage complex. This project developed a multi-scale workflow which consistently addresses the impact of small-scale geological heterogeneity on the static and dynamic rock properties.

Small-scale geological features and heterogeneities have a significant impact on the plume movement in the subsurface but cannot be directly incorporated into field scale simulation models because of limitations in computer speed. The average effects of small scale heterogeneities must be accounted for via an integrated multiscale workflow. To offer greater confidence in the static and dynamic models, it is necessary to incorporate the impact of flow dynamics at these finer scales; incorporating information from the pore and laboratory to whole core scales to the wireline log scale, and ultimately through to the geo-cellular model scale. Resolving all pertinent scales and their interaction is imperative to give reliable qualitative and quantitative reservoir simulation results.

To overcome the problem of multiple length scales, it is customary to use an upscaling, or homogenization, procedure in which rock-type-specific reservoir properties are captured, as well as their flow behaviour.

The CO_2 flow is solved at the storage-site scale on a coarse reservoir grid populated with the representative rock types and their associated upscaled properties. Unfortunately, most upscaling techniques do not capture all relevant scales of heterogeneity and only give reliable results for a limited set of parameters and flow scenarios. The primary outcome of the program was to illustrate the importance of incorporating realistic geological structures at multiple scales and to offer greater confidence in static and multiphase flow predictions at the individual geocell scale.

The research built on the results of a comprehensive core analysis catalogue, developed by ANLEC R&D, with static and dynamic data for an extensive suite of Precipice Sandstone samples. It extended the workflow to accurately describe flow and storage in this reservoir at larger scales. The results of the project are specific to the Surat Basin demonstration project. However, the workflow developed could be applicable to other CCS Demonstration projects in Australia and globally.

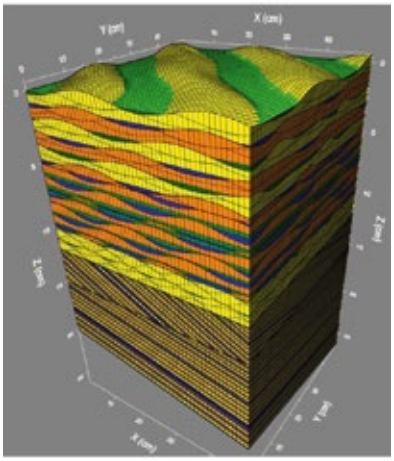
The project developed a multiscale workflow which consistently addresses the impact of small-scale geological heterogeneity on the static and dynamic rock properties.

Three parallel components were undertaken:

- Building an integrated geological description and calibrated static and flow property database from pore to whole core scales on a continuous 100 meters of core from West Wandoan Well 1.
- Create a library of discrete facies-based, single geocell scale models and their associated static reservoir properties.
- Develop dynamic reservoir solvers that honour the physics of dynamic flow and geological heterogeneity at scales up to the reservoir grid block scale.

Reference

M. Knackstedt, et al 2017, Multiscale static and dynamic modelling of Precipice facies (7-1115-0258)



Near wellbore geological model example, created with SBED software (~400,000 cells)

Digital rock delivers spatial resolution of mineralogy in the Precipice Sandstone

The project explored the distribution of minor component metals along a Precipice core by using a calibrated imaging method applied to a digitally scanned core. Researchers extracted carbonate cement volumes along the whole 100m core image data. The project was able to quantify the distribution of pyrite/calcite/siderite – the possible source of these minor component metals.

This project complemented the geochemical investigations undertaken in the precipice sandstone in a prior project, by identifying the location and distribution of minor components in minerals. Prior ANLEC R&D research used a combination of whole rock leaching methods to determine the extractable major, minor and trace element content of a small suite of Precipice Sandstone and Evergreen Formation core samples from the West Wandoan 1 well. The results suggested that the maximum potential release of trace metals is determined by the abundance of source minerals – principally pyrite and Fe-carbonate. Spot trace metal analyses identified at least two populations of pyrite, and the most abundant of these carried very little trace metals.

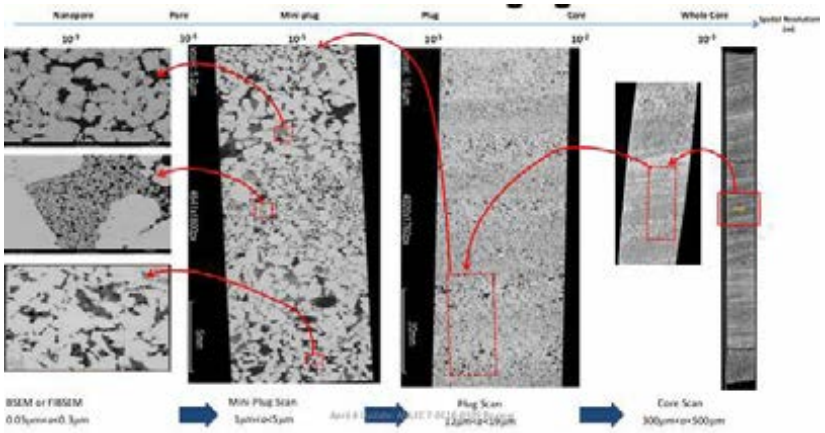
The results of this project demonstrated the capability of X-ray microCT to define the distribution of potential source minerals for trace metals in a continuous core. Measurements at the small scale were extended from the mm to metre scale via an upscaling process to accurately assess the potential heavy metal and arsenic release from the full length of the Precipice Sandstone interval. ANU have designed a large-scale high-resolution CT scanner, optimised for whole core, that is able to scan metre lengths of core at a voxel size of 40 microns or better. Plug and sub-plug samples were also acquired from the whole core sample and imaged in 3D using a HeliScan MicroCT system with an optimized space-filling trajectory that yields sharp images. Image resolutions vary depending on the sample size, ranging from below 2µm for small sub-plugs to 8 µm for a 19mm diameter sample. An integrated multi-scale methodology was used to obtain whole core mineralogical information from plugs via a high-resolution micro-CT and registered QEMSCAN data calibrated by independent Microprobe data. Image analysis tools were used to superimpose or register images along various scales to calibrate data segmentation to provide mineral distributions through the sample and their relative volumes.

The project successfully demonstrated the the application of digital core technology for the whole core from the Precipice Sandstone.

The West Wandoan core had very low carbonate mineral content so that similar image analysis for carbonate mineral tracking was confined to a single sample but nevertheless was able to define the distribution of the approximate volume percent of carbonate. The micro-analyses demonstrated that there were at least two populations of pyrite and that the most abundant of these (framboidal pyrite) carried very little As and Pb in the samples. The maximum potential release of heavy metals and arsenic during interaction between reservoir rocks and injectate is determined by the abundance of source minerals - principally pyrite and Fe-carbonate. The application showed this potential may be quantified by a multimodal approach using X-ray CT of core material. In combination with microprobe analyses of reactive mineral populations, a relative scale of the hazard may be provided in order to assess technical risks and select injection sites and well casing programs.

Reference

M Knackstedt, L Knuefing, R Henley, 2021: Digital rock applications for spatial resolution of mineralogy through the Precipice Sandstone (7-0118-0309)



Example of multiscale imaging, from whole core to Mini-plug. Information gained at the nano scale level is then propagated back to the whole core.

New instruments allow for more accurate measurements

This research delivered the spectral calibration parameters necessary for real time CO_2, SO_x and NO_x measurements down hole using Raman spectroscopy.

Accurately quantifying the concentration of CO_2 and ancillary gases SO_x (SO_2, SO_3) and NO_x (NO, NO_2) in formation water was a good indicator of the extent and impact of a subsurface plume.

Raman spectroscopy is a powerful molecular vibrational application that has been employed widely for more than 70 years to analyse, non-destructively, various materials and mixtures in the laboratory.

Raman spectroscopy is based on the process of scattering light off molecules, with each type of molecule having a specific fingerprint spectrum reflecting the molecular bonding and structure of the molecule. Higher concentrations of a particular molecule result in observation of more photons at the fingerprint (spectral) energies specific to that molecule. Hence, with the correct calibration, the concentration of specific dissolved species can be determined. Raman spectroscopy has been used to analyse dissolved methane *in-situ* and, to a lesser extent, nitrogen and carbon dioxide in coal seam reservoirs.

This work initially combined a desktop study of Precipice Sandstone groundwater composition with batch reactor experiments at Surat Basin sequestration conditions (120 bar and 60 °C) for up to 35 days. Highly quartzose Precipice Sandstone core samples from the *West Wandoan 1* well were reacted in low salinity brine with both inert N_2 (for baseline equilibration) and CO_2/NOx gas mixture to determine CO_2 and NO dissolution species, concentrations and behaviour. Based on a determined post-combustion capture CO_2 stream composition, and current and previous work, a total of thirteen SO_x, NO_x and CO_2 dissociation products were identified which may be already present in Precipice Sandstone groundwater, or formed during injection of an impure greenhouse gas stream. These included seven sulphur derived, three nitrogen derived and three carbon derived species.

Results showed:

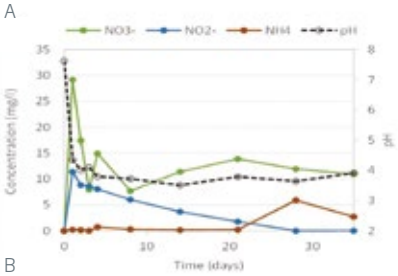
- delivered a guide to the expected Precipice Sandstone groundwater near the site;
- determined concentrations, identities and time resolved behaviour of dissociation species during N_2 and CO_2/NO Precipice Sandstone core reactions, for example nitrate (NO_3-) is the main NO_x dissolution species (Fig. A);
- determined calibration factors for adaptation of the proprietary Welldog DRRS technology and further understanding of its accuracy for application in a Surat Basin geo-sequestration environment;
- identified thirteen dissolution and dissociation products of green-house gas streams injected into an aqueous environment and their theoretical characteristic Raman spectral features showed that twelve of the thirteen species were found to exhibit unique Raman signatures (Fig. B) that will allow for qualitative and quantitative analysis of mixtures of these chemicals. An alternative to the monoatomic sulphide ion, which exhibits no Raman emission, was identified;
- identified that these thirteen chemical species will be differentiable by Raman spectrum analysis, though advanced chemometrics will likely be necessary for quantitative analysis, especially in the case of mixtures of very similar components.

References

L. G. Turner, et al 2016, Desktop study and batch reactor experiments to determine baseline levels of CO_2, SO_x and NO_x in Precipice Sandstone

G. A. Myers, et al 2016, Theoretical basis for detection of products by Raman spectroscopy (7-0314-0229)

A



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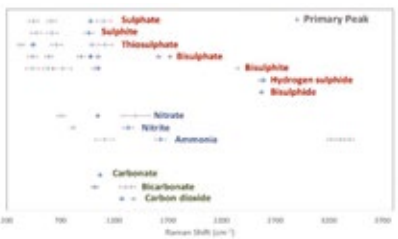


A) Dissolved N species and pH during Precipice Sandstone reaction with CO_2/NO.
B) Raman bands of 13 dissolved species of $CO_2$$SO_x$ and NO_x.

In-situ Downhole Measurements using Raman Scattering

In-situ down hole sampling and measurement is difficult. This research extended application and use of a proprietary downhole Raman spectroscopy borehole instrument to detect track a carbon dioxide plume. Several approaches were investigated. The ability of a tool to perform at the surface and downhole would provide a low cost and unique solution to detect and analyse these chemical tracers in near real-time.

Fluorescent tracers

It was proposed that the Reservoir Raman System (RRS) could be used to detect fluorescent compounds. Two tracers were chosen for testing in laboratory simulated reservoir conditions – rhodamine-WT for the liquid phase of the plume and Nile Red as a supercritical CO_2 tracer. Rhodamine -WT performed well under flowing conditions in a sandstone core at 70° C and emerged as an excellent choice for tracking water flow and leakage. Nile Red for use in supercritical CO_2 was not successful.

Three solvent-class dyes, Neeliglow-Solvent Red 175, Novaflour-Solvent Red 149 and Bodipy- M596 were identified as potential alternatives to Nile red for tracing of injected greenhouse-gases in a saline aquifer. The dyes were selected for optical characteristics consistent with the proprietary RRS excitation and detection system and for chemical characteristics that would be expected to be compatible with dense-phase CO_2.

On testing dye behaviour in a system including $scCO_2$ and water at reservoir temperature and pressure, none of the dyes passed this test.

Isotopic Signatures

CCS Projects require to confirm compliance with environmental licences and to validate their business case for carbon storage. The aim was to progress development of a downhole measurement technology that will monitor and verify (M&V) the integrity of a CO_2 storage reservoir by a method of signal attribution.

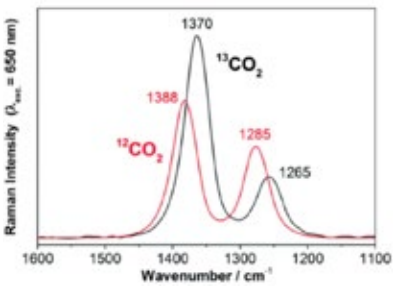
Monitoring & verification (M&V) is also necessary to confirm the absence of greenhouse gas leakage as part of verification of containment. If CO_2 is detected outside the storage reservoir, then it must be attributed either to leakage from the storage formation or some other source not related to CO_2 storage. The most widely used method for source attribution is isotope ratio analysis using isotope ratio mass spectrometry (IRMS). The most prevalent method for signal attribution is isotopes ratio analysis. This method can be costly and difficult to sustain in a hostile environment.

Proprietary technologies under development had developed a downhole tool and surface Raman spectrometer to monitor reservoir gases such as CO_2 and CH_4. A proof-of-concept testing was undertaken with the current RRS to achieve resolution for minute variations in CO_2 isotopologues. The Raman results reported demonstrate that although the isotopic signatures of naturally occurring gas mixtures can be resolved with the modified optical system, the precision of the Raman measurement is not sufficient to distinguish among the samples in the calibration set.

Development of this technology continues with recent advances indicating that a commercial product is close to being available.

Reference

G Myers, J Pope, S Fernando, T Brown; In-situ Isotopic Attribution Using Raman Scattering, 2020 (7-0301)



Raman Shift of Carbon Dioxide at two different isotopic compositions.

Surat basin reservoir analysis delivers new options for monitoring CO_2 containment

Unique local geology delivers innovative methods for monitoring and CO_2 storage assurance.

Jurassic formations in the Queensland portion of the Surat Basin were used as a case study, representing prospective low-salinity, siliciclastic geological CO_2 storage reservoir systems. Geochemical investigations showed that the principle reaction pathways in low-salinity aquifers are the same as in high-salinity aquifers.

However, since more acid is formed in low-salinity water and the acid buffer capacity is low in formation water of the Surat Basin, Queensland, the formation water becomes relatively acidic, leading to a typical pH of 4. The prospective reservoir in the Surat Basin is the Precipice Sandstone, a very homogenous rock unit, largely dominated by quartz. As this mineral is hardly reactive under CO_2 storage conditions, the geochemical reactivity of this unit overall is very low. Consequently, the long-term CO_2 trapping capacity in the form of carbonate mineral precipitation is very low as well.

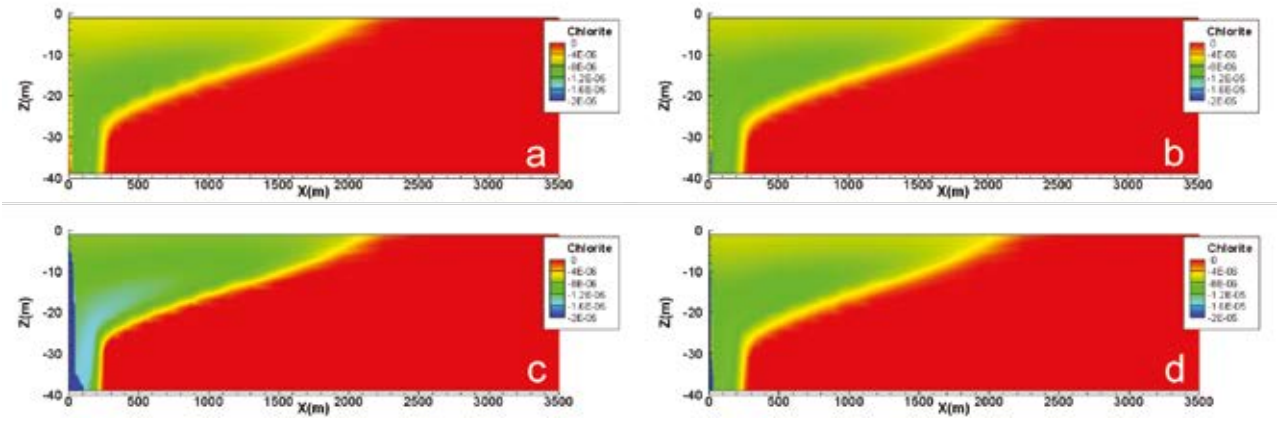
Detailed mineral analysis of units above the Precipice Sandstone revealed the Boxvale Sandstone Member may be suitable for above-reservoir monitoring purposes.

Relatively high porosity, permeability and a thickness of several meters are characteristic for the Boxvale Sandstone Member, making it a good secondary containment formation with the Evergreen Formation sealing strata above. This rock unit is also distinct in its mineral composition as it contains a large proportion of feldspar, a mineral known to dissolve relatively quickly in CO_2-enriched water. This would lead to rapid changes in the water composition and could serve as an indication of CO_2 leakage from the primary storage reservoir (Precipice Sandstone).

In addition, the compilation of stress field data led to a much higher data density in the Surat Basin than anything previously published and thereby reduced the uncertainty in predicting the rock mechanical response to CO_2 injection and storage. Preliminary rock mechanical considerations suggest faults with strikes that are approximately at 30 degrees to the maximum horizontal stress direction will be at greatest risk of reactivating due to the fact they have the highest shear to normal stress on the fault plane.

Reference

R. Haese, et al 2016, Geochemical impacts and monitoring of CO_2 storage in low salinity aquifers (7-1110-0088)



Distribution of chlorite dissolution in volume fraction at 20 years for the pure CO_2 (a), CO_2 with 100 ppm SO_2 with calcite (b) and without calcite (c) and CO_2 with 500 ppm SO_2 (d) (3500 m radial).

Exploring a natural analogue to CO_2 mineralisation trapping

Knowing the mechanism of carbonate formation in the local geology can help control and immobilise carbon dioxide.

Differentiating between carbonate formed via different mechanisms, and determining controls on the extent of authigenic carbonate formation, could lead to options for engineered accelerated mineralisation in reservoirs.

This work recognised authigenic carbonates as a natural analogue of mineralisation trapping. It sought to understand control mechanisms for their formation in low salinity, siliciclastic aquifers of the Great Artesian Basin (GAB).

More than 250 well completion reports were selected, from among tens of thousands of publically available petroleum, coal seam gas and stratigraphic drilling records, on the basis of spatial and geological coverage, the detail of included information, and type and availability of associated samples. The well completion reports were assessed in detail for the presence of significant carbonate mineralisation, and samples of carbonate cemented sandstone, as well as carbonate fracture mineralisation, were taken from some 50 localities. All Mesozoic units within the chosen wells were subject to sampling, whether the strong carbonate cement was sporadic or extensive. The samples included both chipped and cored intervals.

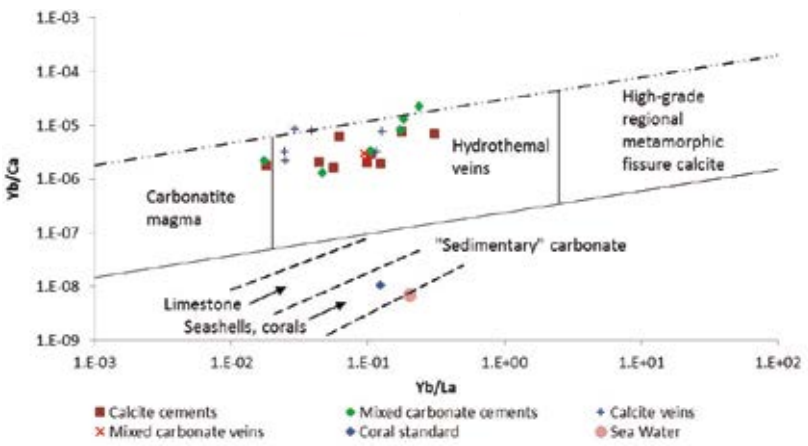
Key parameters derived from petrological and geochemical analyses of the carbonates were fed into a model for carbonate authigenesis within the GAB Laboratory experiments were undertaken to explore processes of enhanced carbonate mineral trapping of CO_2 in Precipice and Hutton sandstone core.

The study concluded:

- The oxygen isotope values and fluid inclusion data for GAB cement and vein carbonates indicate that deeper, hotter fluids mixed with shallower and fresher fluids during, or just prior to, carbonate precipitation in a number of cases.
- Most of the modelled fluid carbon isotope compositions are indicative of remobilised marine carbonate or mantle/magmatic CO_2, whereas a subset of carbonate samples had very negative modelled carbon isotopes consistent with an organic carbon source.
- Fault-assisted fluid migration apparently played a major role in the carbonate authigenesis, and a subset of samples was associated with hydrocarbon migration.
- Elevated fluid inclusion temperatures ≥120°C, in samples from wells located within the Moonie-Goondiwindi and Leichardt-Burunga fault corridor in the eastern Surat, are anomalously high relative to what is known about the regional thermal history.
- Gaseous hydrocarbons found in fluid inclusions in the Eromanga Basin samples are sourced from the underlying Cooper Basin.
- The availability of cations for precipitation of dissolved CO_2 as carbonate minerals can be a rate limiting step in the process of CO_2 mineral trapping. Engineering injection, to take advantage of CO_2 migration paths (e.g. injecting below baffle units and down-dip from a structural closure), is one way to maximise carbonic acid dissolution of minerals encountered by the CO_2-water mixing front.
- Co-injecting CO_2 dissolved in brine or other waste water would increase the available cations for carbonate precipitation as would co-injecting a small quantity of SO_2 to form dilute sulphurous or sulphuric acid at specific depths, e.g. below baffle units.

Reference

S. D Golding, et al 2016, Great Artesian Basin Authigenic Carbonates as Natural Analogues for Mineralisation Trapping (7-1011-0189)



The different kinds of carbonate collected from the Surat Basin. Variation diagram modified after Möller (1983).

Configuring fit-for-purpose environmental monitoring at Glenhaven

This project completed a first geochemical characterisation for the Glenhaven site. The study underpins any Surat Basin CCS projects' compliance with environmental requirements for Monitoring and Verification (M&V) of CO_2 containment.

This initial characterisation informed early project stakeholder engagement, shape environmental monitoring at the CTSCo Surat Basin project site and ultimately assisted project sites within other Australian sedimentary basins.

Scientist's acknowledged that the overall approach to environmental M&V was thorough and well-planned; incorporating a variety of innovative and proven technologies for all of the major components of environmental M&V (leakage location, attribution and quantification). A high priority was placed on the well-being of the local community and the protection of the resources of local importance.

The geochemistry of the near-surface system was found to be simple with respiration as the main process and no detectable methane. The system was therefore highly sensitive to indicating a leakage signal using a process-based monitoring approach. Sensor installations were well-constructed and robust, providing high quality real-time soil vapour data; however, there is an indication that sensors may lose accuracy over differing concentration ranges.

Carbon dioxide sensors appeared to lose accuracy at higher concentrations, oxygen sensors potentially lost accuracy at lower concentrations, and there was an indication that methane sensors overestimate concentrations.

However, a sensitivity analysis of the system to leakage shows that sensor inaccuracies are not large enough to significantly compromise the ability to detect leakage signal using process-based geochemical relationships. The system is extremely sensitive to leakage signals and even with sensor error, leakage would be detected early and would be clearly identifiable.

It was important to test the in-situ soil gas sensors deployed over varying gas concentration ranges, to accurately define sensor performance under fluctuating field conditions. This information is important for understanding sensor performance over the long term when the environmental conditions may change. Initial assessment of CO_2 isotopic signature in the soil vapours and dissolved gases in underlying groundwater suggests significant overlap among the various deep and shallow inputs. The study shows that further assessment of isotopic signatures, including characterisation of C^{14}, is required.

Reference

K. Romanak, et al 2017, Initial site characterisation at Glenhaven (7-1116-0297)

One of CTSCo's monitoring stations comprising two soil vapor wells and two groundwater wells (top). Instruments are deployed downhole within a packer system and provide real-time data acquisition (bottom)

Informing robust regulation by atmospheric volume sampling of CO_2

Emissions may arise from a number of sources below the ground surface. Therfore, having a near surface assurance strategy to identify, locate and quantify the presence of greenhouse gases is important. It will especially require an accurate and balanced method that can measure near-surface and atmospheric CO_2 flux.

The project compared multiple CO_2 flux monitoring systems and develops automated data visualisation tools. This project demonstrated CO_2 flux monitoring as a routine, non-specialist activity that addressed regulatory assurance required from near-surface M&V. This system is not new and has been developed at the Otway pilot facility in Victoria. It does, however, need to be adapted and proven as effective in the Surat Basin environment.

Design

The Project designed an array of 8 stations with low cost sensors. One for CO_2 concentration and others that can sense air temperature (T), relative humidity (RH), and barometric pressure (P). One of the stations incorporated a 3D sonic anemometer, which provided detailed information on wind speed and direction and provides critical parameters for the dispersion modelling software. The project was undertaken through several tasks.

Sensor calibration and performance test

» Regular on-site calibration of the CO_2 sensors were necessary to ensure the accuracy of CO_2 concentration measurements and therefore requires a robust calibration methodology.

Simple Measurement-Model Verification

» Once the sensors were confirmed to operate within specification, a rudimentary investigation of their response to a plume from a controlled release of CO_2 from a point source during appropriate atmospheric conditions was compared to that predicted by the dispersion model.

Full System Verification

» To fully test the system the ring array of sensors was arranged around a CO_2 source. A controlled release of CO_2, either continuously or co-ordinated by wind speed and direction.

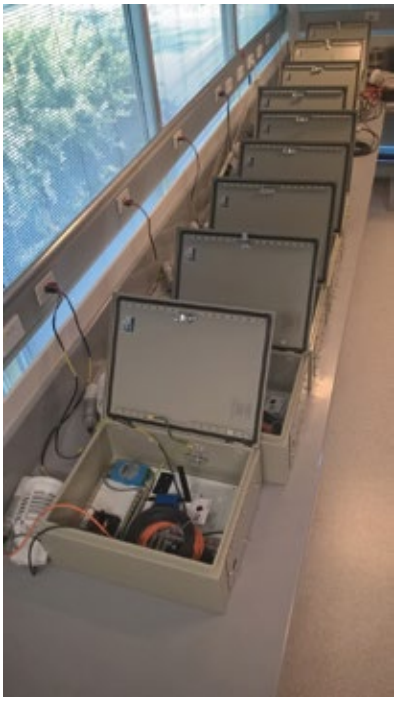
Field deployment testing - Area of null detection

» The data collected allowed for the analysis of false positive anomalies and the statistics of detection to be determined. Direct comparisons to the data output of the standard eddy covariance system was undertaken and a comparison of the results produced.

Success was to be determined when the model output of source location is accurate, quantification of the leak is small and the system is producing reliable results over an extended period.

Reference

P. Jensen, et al 2016, Leakage Quantification Using Atmospheric Flux Techniques (7-1116-0302)



Tomographic array to be deployed on site

Borehole headspace gas monitoring to infer dissolved gas concentration

Several operators and US state regulators note that sampling of well headspace is simpler to implement, and is less error-prone than direct water sampling.

For example, regulations in the province of Alberta target headspace concentrations and observations from the research-oriented Groundwater Observation Well Network program show a good but not perfect correspondence between headspace and dissolved gas concentrations. Several other groups (Colorado, Louisiana, Texas) have also tried to use headspace concentrations as an indicator of dissolved concentrations. The specifics of the relationship are different for each site and have no general predictive power.

This research project was set to investigate the feasibility of using headspace gas concentrations as a much simpler and more reliable proxy for dissolved gas concentrations in the wellbore fluid. The project studied the elements of the semi-open system of gas-water-wellbore and determine which parameters control the headspace gas concentrations by developing a piece of software that will model the various physical processes at play. Overall, we wished to generate a methodology that would enable deployment of gas-based sensors to measure headspace gas concentrations to infer water quality in the actual aquifer.

There is no mechanistic study documenting the general relationship between dissolved and headspace concentrations. Direct measurement of dissolved gas concentrations can be cumbersome and yield inaccurate results unless specific tools requiring highly technical expertise are used.

Much simpler and more reliable measurements of headspace gas concentrations could be routinely used under some conditions, namely in a well that is not perfectly closed. Headspace gas readings can be good estimators of dissolved gas concentrations. Overall, this project proposed to measure the headspace quality at the near surface water level as an inference to water gas components.

New knowledge was developed by:

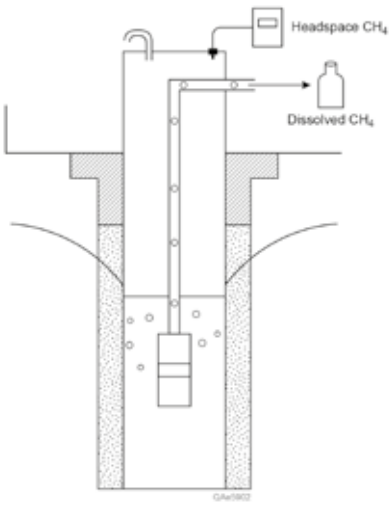
» Literature review of previous work, from unconventional oil and gas literature, assessment of available data of the Surat dataset, and decision to use either a custom code (most likely) or off-the-shelf software.

» Desktop modelling of headspace gas measurements in an imperfectly sealed chamber and sensitivity analysis. The main task of the research project consists in developing a mechanistic model including major physical processes relating to gas exsolution in a water well wellbore followed by a sensitivity analysis that will determine the factors controlling headspace gas concentrations.

» Application to the Surat Basin: design of a reliable headspace monitoring technique, taking operational and cost constraints into account, as well as regulator M&V requirements.

Reference

J.P. Nicot et al 2017, Headspace Gas Monitoring to Infer Dissolved Gas Concentration (7-1116-0292)



Water well schematics showing gas and water sampling ports

Anomaly detection threshold setting for environmental baselines

A monitoring and verification program at the Surat CCS demonstration project must be able to distinguish natural variations in measured data with those that can be attributed to the CO_2 storage reservoir.

Monitoring data must be able to refute a hypothesis to draw rigorous conclusions about null signals.

This project was developing a robust modelling and predictive framework that could be applied to all components of a near-surface monitoring and verification program planned for the Surat CCS demonstration project. This statistical framework allowed measured anomalies to be attributed to leakage events if the data exceeds a specified threshold value. In response, an action plan detailing a mitigation strategy was implemented, in order to satisfy stakeholders and regulatory bodies.

To ensure compliance with its environmental licence, a monitoring and verification program in the Surat must be able to distinguish natural variations in measured data with those that can be attributed to the CO_2 storage reservoir as a source. Stakeholders and regulators looked for evidence of the "absence of anomalous gas signals" in environmental measurements. They required assurance that measurements below specified threshold values can be reliably interpreted as confirmation of the integrity of the CO_2 storage reservoir.

This project demonstrated evidence for the "absence of detectable signals" based on a credible scientific method. Simple yet rigorous statistical models are required to interpret environmental data and distinguish anomalies that can be attributed to plausible leakage scenarios.

> *"In so far as a scientific statement speaks about reality, it must be falsifiable and, in so far as it is not falsifiable, it does not speak about reality."*
>
> – Popper, The Logic of Scientific Discovery

A suitable "Warning and Escalation Plan" was also required to define suitable actions and mitigation strategies when measured anomalies exceed pre-determined threshold values which are indicative of probable fugitive events.

New knowledge to be created:

- Set of models to determine the range of natural fluctuations in GHG stream components calibrated and tested using available environmental datasets.
- Suite of credible predictive fugitive models (for example, through the wellbore) to determine anomaly thresholds in data and a statistical framework to allow robust attribution of anomalies to possible fugitive scenarios.
- An adaptive/escalation-based notification and warning plan for Stakeholders and Regulators.

Reference

C. Green, et al 2017, Setting an anomaly detection threshold based on the real-time dataset for Glenhaven Environmental Baseline (7-1115-0303)

How can isotopic distribution identify naturally occurring CO_2

Correct attribution of near-surface leakage signals was critical for the success of CCS projects and the protection of stakeholders. The ability to predict how a leakage signal would manifest itself is important for "proving a negative".

Isotopes can act as tracers for attribution and can be used to define the expected signature of leakage. However, a complete site-specific characterization of all potential "fugitives" is required to minimize uncertainties from signature overlap. Creative approaches armed with a prior knowledge of each component are necessary to develop potential in-situ isotope monitoring strategies. The potential for combining isotope methods with other approaches (such as process-based soil gas monitoring) should also be considered to optimise best practice.

The purpose of this project was to characterise all potential isotopic inputs and an assessment of the sensitivity of the system to each input was used to identify the most feasible approach in the Surat Basin.

The results of this research has contributed to our ability to quickly and accurately attribute the source of any anomalous gases in the near-surface which may signal fugitives from depth and avoid confusion that could lead to false positives.

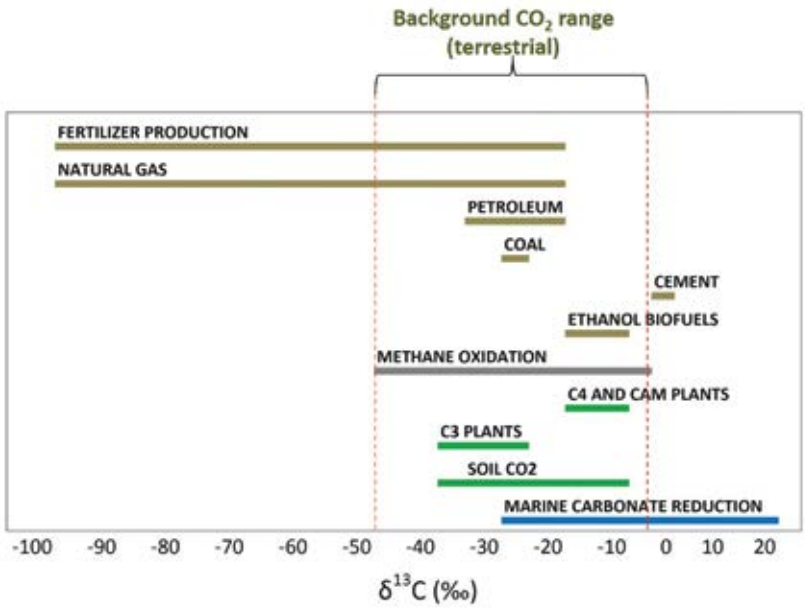
Near surface gases attributed to emissions can trigger project shutdown, intensive quantification activities, surrender of credits and loss of stakeholder trust. It is critically important that a thorough assessment of the potential for isotopes to be used as tracers of leakage be undertaken. This project was of importance because of the complexity that coalbed methane and other hydrocarbons impart to attribution.

New knowledge;

- A characterization of the δ13C, 14C and δ18O for the various inputs in the Surat Basin and an assessment of other potential isotopic methods.
- Prediction of the geochemical signature of leakage and the sensitivity of the system for indicating leakage using the isotopes measured.
- Recommendation of the most feasible approaches to isotopic monitoring in the Surat Basin.
- Assessment of how applicable the method might be at other sites.

Reference

K. Romanak, et al 2017, Isotopic characterisation of source CO_2 and naturally occurring CO_2, Glenhaven (7-1116-0293)



Stable carbon isotope signatures of source and naturally occurring signals at CCS sites (Dixon and Romanak, 2015)

Optimising a process-based approach for near-surface fugitive assessment

Current "baseline" methods in environmental monitoring fall short of what is necessary for successful industrial deployment of geologic CO_2 storage. This project proposed further application of a process-based approach to environmental assessment.

Soil gas baselines show increasing presence of CO_2 due to climate change. Thus with baseline CO_2 concentrations trending upward, current methods will result in false positive fugitive claims that could severely impede CCS projects and public acceptance of CCS. For this reason, a process-based approach was developed for environmental assessment.

Fast, simple, and accurate methods that attribute the source of anomalies, do not currently exist and are sorely needed. A process-based approach shows significant promise for meeting these needs and has been employed successfully in a number of environments. However, the process-based ratios that result in areas where methane is a major environmental component, such as where coal seam gas (CSG) is prevalent, have not been rigorously defined or assessed. An additional gap is that continuous real-time monitoring technology for all gases required for a process-based assessment does not exist and should be developed to support industrial deployment of CCS. Knowing how process-based ratios will manifest in CSG areas will inform the technology needs for continuous monitoring in these and other hydrocarbon-rich areas.

The project updated process-based attribution methodology for methane-rich sites.

The current process-based matrix was refined and updated with data measured at the methane-rich Surat Basin site; strengthening its application in complex environments. Quantification methodology for surface emissions was tested using a process-based approach. Factors that limit the precision of the quantitative method were identified and used to define realistic constraints to the proposed approach. The potential for further development was assessed.

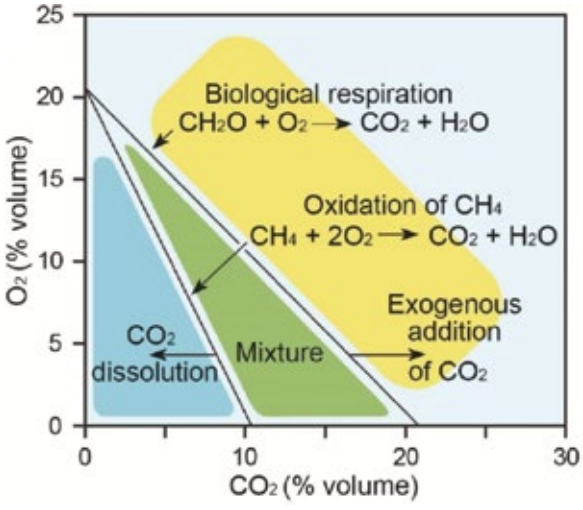
The overall objective was to rigorously assess (and mature) a process-based methodology into a reliable and practical monitoring technology to support industrial implementation of CCS in hydrocarbon-rich environments.

Objectives were:

- update and refine the current process-based geochemical matrix to include various methane inputs;
- demonstrate the capability of Raman technology to provide continuous real-time measurements;
- demonstrate the use of process-based ratios for quantification, and
- choose the measurement technology most appropriate for advancing as best practice in environmental monitoring.

Reference

K. Romanak, et al 2017, Optimizing a process-based approach for near-surface leakage assessment (7-1116-0291)



A "process based" method uses simple geochemical soil gas ratios to illuminate how gases are formed and modified in the near surface.

Using vegetation as a CO_2 sensor

Correct attribution of near-surface leakage signals was critical for the success of CCS projects and the protection of stakeholders. The ability to predict how a leakage signal would manifest itself was important.

Isotopes can act as tracers to detect sources of gas emissions and can be used to define the expected signature of gas leakage. However, a complete site-specific characterisation of all potential "fugitive" gas inputs is required to minimize uncertainties from signatures that overlap. Creative approaches armed with a prior knowledge of each gas component are necessary to develop potential in-situ isotope monitoring technologies. The potential for combining isotope methods with other approaches (such as process-based soil gas monitoring) should also be considered to optimize best practice approaches.

The purpose of this project was to characterise all potential isotopic inputs and an assessment of the sensitivity of the system to each input was used to identify the most feasible approach to monitoring using isotopes in the Surat Basin.

The results of this research contributed to our ability to quickly and accurately attribute the source of any anomalous gases in the near-surface which may signal fugitives from depth and avoid confusion that could lead to wrong conclusions.

Near surface gases attributed to emissions can trigger project shutdown, intensive quantification activities, surrender of credits and loss of stakeholder trust. It was critically important that a thorough assessment of the potential for isotopes to be used as tracers of leakage be undertaken. This project was important due to the complexity that coalbed methane and other hydrocarbons impart to attribution.

New knowledge:

- A characterisation of the δ13C, 14C and δ18O for the various inputs in the Surat Basin and an assessment of other potential isotopic methods.
- Prediction of the geochemical signature of leakage and the sensitivity of the system for indicating leakage using the isotopes measured.
- Recommendation of the most feasible approaches to isotopic monitoring in the Surat Basin.
- Assessment of how applicable the method might be at other sites.

Reference

J. Guerschman, et al 2017, Vegetation condition monitoring (7-1116-0299)

remote sensing

	Spatial (how small)	Spatial (what extent)	Temporal (how often)	spectral how many colors	How expensive
Satellite (Landsat, Sentinel)	coarse	very large	very often	some	free
Satellite (planet)	medium	large	often	a few	cheap
Airborne	medium	medium	a few times	a lot	very expensive
UAV (drones)	fine	small	a few times	a lot	expensive
in situ (phenocams)	very fine	very small	very often	a lot	expensive

Schematic representation of the advantages and disadvantages of several possible sources of remote sensing data for monitoring vegetation health.

Evolution of the solute plume composition at the Glenhaven site

CTSCo has developed a solid geological and reservoir model; and has now defined a representative baseline water, mineral and GHG stream composition. While the number of experimental studies on the impact of CO_2 with impurities on water composition and fluid-mineral reactions is relatively large, relatively few studies have addressed the question at reservoir scale through modelling.

The Lawrence Berkeley National Laboratory (U.S.A.) has developed specialized simulation code which allows for inclusion of impurities in the CO_2 and provides a framework for quantifying coupled hydrological and geochemical processes resulting from injection of CO_2 and impurities into the subsurface.

This project supplements a previous study (Haese et al., 2016), which showed a fractionation of gases in the reservoir due to differences in gas solubilities. For example, SO_2 accumulates near the well bore. The objective of this supplemental study was to develop a dual-phase geochemical model across the Evergreen Formation and Precipice Sandstone, which explored the dynamic changes in the solute plume in greater detail and assisted in assessing chemical impacts of the GHG stream injected in the Precipice Sandstone.

The Surat Basin geological model has significantly refined the rock types and formation water composition of the Precipice Sandstone and the Evergreen Formation since the earlier study, to provide more realistic predictions.

The type and degree of changes in the water composition under CO_2 injection and storage conditions was assessed for the Glenhaven site, through two complimentary geochemical modelling approaches:

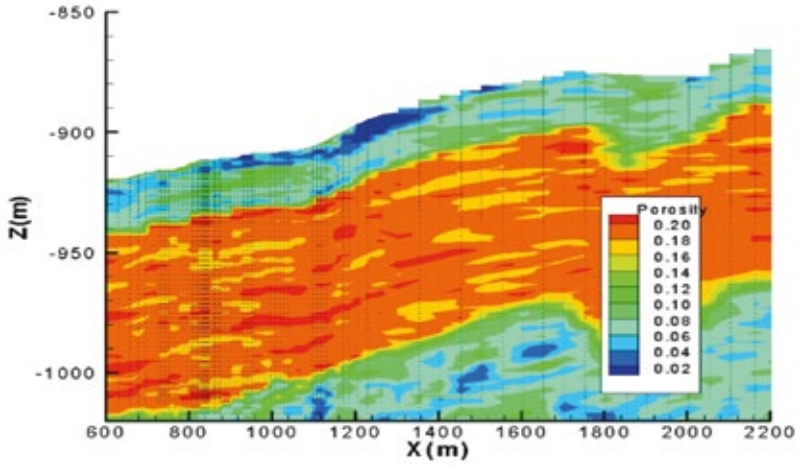
- The overall trend in water compositional changes over time was assessed using reaction path modelling, as implemented in The Geochemical Workbench software. The principle water speciation and fluid-mineral reactions were determined, which feeds into the second approach.
- 2D reactive transport modelling at reservoir scale was carried out using the Laurence Berkeley code for selected transects, in order to predict and visualise dynamic changes in the solute water composition.

Together, the two approaches provided a good understanding of the expected ambient hydrogeochemical conditions in the reservoir. As impure CO_2 is injected into the Precipice Formation, subsequent changes in these conditions were assessed using up-to-date regional data and the most advanced simulation software.

Particularly, the 2D graphs, derived from the reactive transport modelling, was a meaningful and intuitive way to illustrate the results to non-experts including the regulator.

Reference

R. Haese, et al 2017, Evolution of the solute plume composition at the Glenhaven site (7-1116-0290)



Close-up of the geologic grid and numerical mesh (near well and larger grid blocks at distance), showing porosity along cross-section J-69, adopted for reactive transport modelling of CO_2 injection at the well location shown.

Joint Inversion of Geophysical Monitoring Data

Improving mathematical and statistical analysis for injected CO_2 plume movement

Mathematical and statistical analysis (an inversion) of geophysical data helps researchers create a model of injected CO_2 movement. This research tests the concept of a joint inversion to see if a more confident and complete model of plume movement can be extracted.

Monitoring changes in geophysical rock properties – their density, electrical conductivity, and seismic properties – are a key method for understanding movement of injected CO_2 plumes. However, such a model is limited when it is only from one data set. This work implements a joint inversion using several differing geophysical data sets – such as time lapse seismic and electromagnetic (EM) data and density from borehole gravity.

Borehole to Surface EM (BSEM) data, using a downhole current injection electrode with a surface array of receiving electrodes was acquired at Aquistore, a CO_2 injection project in Saskatchewan, Canada.

Fluid flow modelling provided starting models for the inversions. It is important to note that the forward modelling study did not address all potential sources of error in the BSEM data. This question of detectability versus resolvability is a crucial one. The BSEM data was inverted using a two-stage procedure. The first stage resolved near-surface conductivity features. Then in the second stage the model was held fixed outside the reservoir zone and the downhole electrode data were fitted.

The scientists were able to fit the BSEM data but a wide range of reservoir resistivities were found to be consistent with the data and they could not be confident that their results accurately imaged the plume.

The BSEM data is sensitive to the resistivity of the entire subsurface in the survey area and not just the injected CO_2. With a single survey it was not possible to separate the plume signal from other effects in the data.

A third starting resistivity model was derived from the results using in-house two-phase fluid flow modelling. The final stage of the project was to derive a synthetic study to assess how well the plume could have been recovered, had a follow-up survey using the same configuration as the original survey be performed. However, a second survey was planned, but was not completed by Aquistore in the ANLEC R&D timeframe.

An analysis of the potential impact of sensor positioning errors between the baseline and follow-up surveys showed that positioning discrepancies were critical to the inversion.

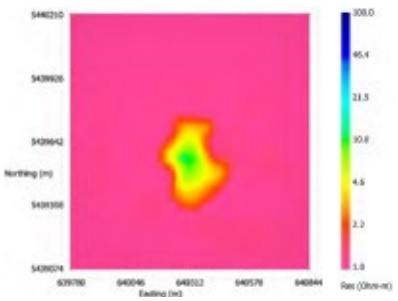
Multiple factors including seasonal variations in surface moisture will affect the near surface conductivity. Ideally, baseline and follow-up surveys would be conducted at similar times of year under similar conditions to minimize these discrepancies.

Overall, monitoring CO_2 injection at Aquistore with single survey BSEM data is not feasible. It is possible to generate a reservoir EM signal well above instrument noise levels, but the plume signal is far too small to be separated from other electromagnetic effects and resolved by inversion. With time-lapse surveying, many of these other effects in the data are eliminated.

In this case electromagnetically imaging a target comparable to the Aquistore plume at such a large depth should be possible but will still be quite difficult. For a shallower reservoir, the signal from a comparable plume will be much larger and likely that borehole to surface electromagnetics can be an effective monitoring technique, especially when combined with other geophysical modalities.

Reference

P Belliveau, M McMillan, E Haber; Joint Inversion of Geophysical Monitoring Data, 2018 (7-0314)



Depth slice at -2730 m. Plan view slice through the final reservoir resistivity inversion model.

Predicting CO_2 solubility at large scale dynamic modelling

Dissolution of injected CO_2 into formation water is a key storage mechanism, in addition to residual trapping of gas, and is important for limiting the eventual migration of the plume. CO_2 dissolution is well understood at laboratory scale. Using this information at the reservoir scale requires deeper understanding.

Field-scale simulations of CO_2 injection have unavoidable computational limits on spatial grid resolution and this can lead to overestimation of dissolution in the short-term (due to the assumption of instantaneous equilibrium within a grid cell) and underestimation in the long-term (due to suppression of density-driven convection). In previous works, the authors demonstrated ways in which the coarse-grid solutions can be corrected. However, there are some unresolved issues; about both the underlying physics and the best way to represent these sub-grid scale effects in commercial simulation software.

The fundamental time-dependent dissolution process on the sub-grid scale is not well understood. This project uses a pore-scale model of CO_2 distribution, to match laboratory observations on dissolution of CO_2 in cores and investigates how this time-scale affects the coarser scale simulations.

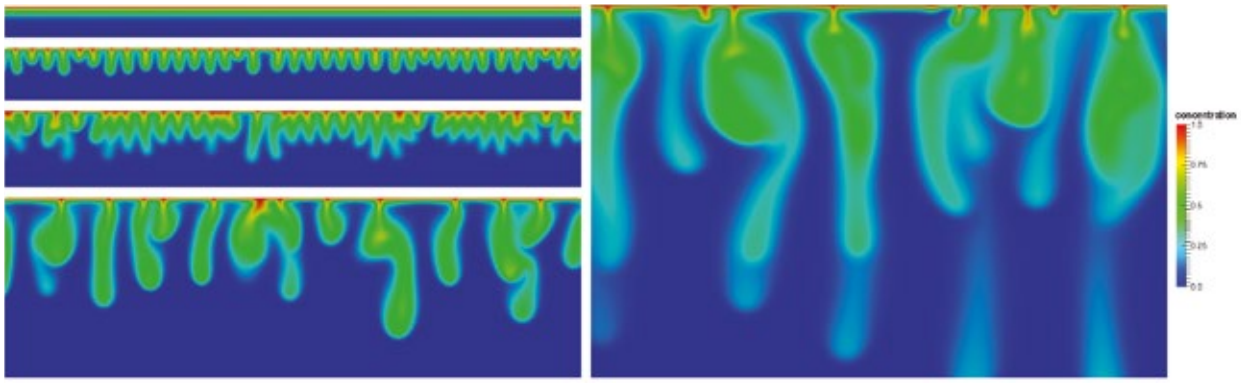
For the reservoir scale, the previous work on upscaling of dissolution is extended to improve the quality of the match and is implemented in commercial software, relevant to the CTSCo project. For long-term dissolution, density-driven convection is a key mechanism, especially when coupled with geochemical effects.

The representation of sub-grid scale density-driven convection in heterogeneous porous media is improved by calculations of the steady 3D dissolution flux using the massively parallel MOOSE code (Multiphysics Object Oriented Simulation Environment) which extends the earlier work in the 2D case. The coupling to geochemical effects, especially density effects of dissolved species, is tested. The upscaling of the convective dissolution flux to field-scale models is investigated and tested on appropriate grids.

These results can be incorporated into an algorithm, to correct coarser grids for sub-grid scale dissolution, and implemented in commercial simulation software. This algorithm is based on an estimate of the fundamental time scale for CO_2 dissolution at the core level, as well as an understanding of how this impacts on field-scale simulations. Analysis of the steady convective dissolution flux and coupled geochemistry is extended to 3D heterogeneous systems, and the algorithms for upscaling this to field-scale models for long-term dissolution modelling could be demonstrated with commercial software.

Reference

J. Ennis-King, et al 2017, CO_2 solubility for dynamic modelling (7-1115-0256)



Vertical cross-sections of high-resolution simulations of the onset of density-driven convection in the subsurface, whereby the dissolution of carbon dioxide into the formation water is accelerated by the density instability

Testing the capability of AI and machine learning to predict permeability

Often there is a limited and outdated set of well data that provides information for prospective CO_2 storage basin geology. To test the capability of Artificial Intelligence (AI) and machine learning algorithms, the opportunity was taken to use this little information to predict the petrophysical properties at the EPQ10 well locations in the South Surat Basin.

The project used artificial intelligence techniques and uncertainty analysis to provide sensitivity ranges for permeability estimation based on multiple wireline logs. These algorithms were trained on existing wells to predict fluid and petrophysical properties of future exploration wells. The first EPQ10 exploration well data was also part of the training material. The outcome was expected to address information gaps, including reservoir fluid properties, rock properties variation between the two wells, and injectivity.

Unlike other petrophysical properties, permeability is a difficult parameter to acquire from conventional well logs due to its dynamic nature. This approach improves the prediction of CO_2 injectivity in the target formations. Well logs and core data were collected from five boreholes in the Surat Basin where extensive core data and complete sets of conventional well logs exist for the Precipice Sandstone. All well logs were quality controlled and overburden core porosity and Klinkenberg corrected permeability were calculated for all cored sections. A small number of data points were identified as outliers and were removed from the data set.

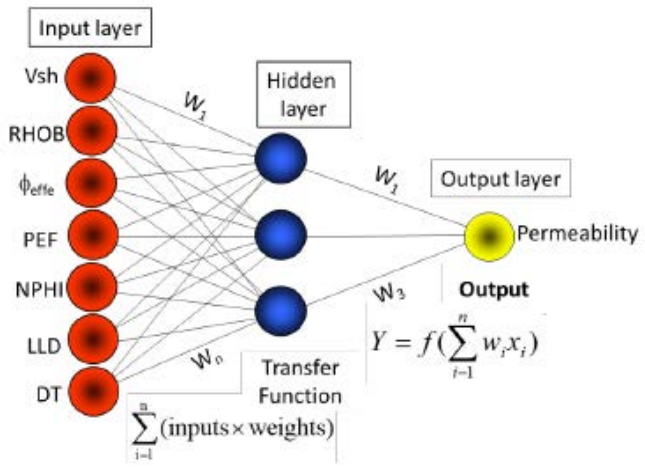
Based on Spearman's rank correlation coefficients, the volume of shale (Vsh), effective porosity, and bulk density (RHOB) were found to have the highest correlation with permeability. Four different machine learning (ML) techniques including Random Forest (RF), Artificial neural network (ANN), Gradient Boosting Regressor (GBR), and Support Vector Regressor (SVR) were independently trained with a wide range of hyper-parameters to ensure that not only the best model is selected, but also the right combination of model parameters is selected.

Cross-validation for 20 different combinations of the seven available input logs was used for this study. Based on the performances in the validation and blind testing phases, the ANN with all seven logs used as input was found to give the best performance in predicting permeability for the Precipice Sandstone with the coefficient of determination (R^2) of about 0.93 and 0.87 for the training and blind data sets respectively.

The uncertainty analysis showed that the developed model is relatively insensitive to noisy inputs. However, the use of different combinations of input logs could increase the uncertainty in the calculated permeability values. Multi regression analysis also appears to be a successful approach to calculate reservoir permeability for the Precipice Sandstone. Models with a complete set of typical well logs can generate reservoir permeability with R^2 of more than 90%.

Reference

R Rezaee, J Ekundayo, Uncertainty Analysis of Diverse Petrophysical Data for Injectivity Prediction, 2021 (7-0329)



A typical neural network is composed of three layers.

Applying big data technology to CO_2 storage monitoring

The Earth's crust is mobile. There are a large number of micro-seismic signals available from natural geo-tectonic processes. Can these be used in real-time to monitor CO_2 storage activity?

To be of greatest value, passive seismic monitoring should be conducted prior to CO_2 injection, to enable baseline and comparative studies during and after injection. With current Nodal-geophone technology, passive seismic surveys are now available to be recorded as a very low-cost add-on to conventional 3D seismic surveys.

The projects objective was to:

» process the passive seismic data using latest technology, to identify pre-existing faults, micro fractures/cracks, high density seismicity, anisotropy and stress within the Glenhaven 3D seismic survey, and

» integrate the result of the passive seismic survey into the conventional Glenhaven 3D seismic survey.

The main risk with existing datasets was the lack of discernible natural seismicity and potential "elevated ambient seismic activity" from nearby coal seam gas operations.

A deployed array acquired the 10,055-station passive seismic survey as a baseline survey prior to CO_2 injection in July 2015. The objective of the survey was to detect pre-existing faults, micro fractures/cracks, high density seismicity, anisotropy and stress for the interval between ground level and the base of the Precipice Sandstone prior to CO_2 injection.

The results of the processed passive seismic survey data provided information on:

» the geomechanical strength of the Precipice Sandstone;

» the capability and the integrity of the Evergreen Formation seal; and

» the preferential plume movement due to anisotropy, stress direction and micro fractures/cracks between the surface and the base of the Precipice Sandstone storage reservoir.

A monitoring passive seismic survey was conducted after CO_2 injection. The comparison between the baseline and monitoring surveys provided information on potential geomechanical deformation due to pore pressure changes and CO_2 plume movement. Passive seismic processing is a novel technology. A limited number of companies in the industry have the ability to process these datasets. The processing of the passive seismic data uses the newly developed Tomographic Fracture Imaging technology also known as Brightness Method, Ambient Noise Surface Wave Tomography, diffraction stacking methodology or double difference tomography method.

The project deliverables;

» Cumulative seismic activity volume.

» Tomographic Fracture Imaging or Brightness Method volume.

» Fracture density volume/maps.

» Anisotropy volume/maps.

» Shear and compressional wave velocity model volumes.

The project was designed to maximise the identification and understanding of information present in the passive dataset. Such data is highly relevant to the issues of lower cost options for M&V of the plume extent and of providing the basis for demonstrating, and quantifying, the magnitude of the presence/absence of induced seismicity and geomechanical deformation arising from CO_2 injection.

Reference

G. Olivier, et al 2017, Processing of passive seismic dataset for stress induced events and tomographic imaging (7-1115-0254)

Array of 10,055 1-C stations of passive seismic survey in Glenhaven

Assuring reservoir containment in the Surat Basin

For CO_2 storage in the Surat Basin, the Hutton Sandstone is the first aquifer unit of regional significance above the sealing Evergreen Formation. It acted as a second reservoir above the primary Precipice reservoir

In the public domain, there are few studies of the sedimentology of the Hutton Sandstone based on analysis of outcrop and high-resolution well data. Outcrop studies provide dimensions of geo-bodies, the nature of their bounding surfaces and their internal fabric (bedding) and texture. These assist in interpreting the same in cores. When coupled with diagenesis, the depositional environment influences the porosity and permeability of the reservoir. It therefore provides more complete information of stratigraphy that influence the regional conceptual models used in modelling.

The research integrated a detailed model of the architecture and heterogeneity of the Hutton Sandstone, with models developed for the underlying Evergreen Formation and Precipice Sandstone. The identification and mapping of fine grained units within the Hutton were a particular focus. The methods included:

- Facies analysis of outcrop and available core, with a focus on the Glenhaven area to define and detect lateral continuity.
- Photogrammetry and hyperspectral scanning of selected outcrop for comparison to Precipice scans and core data to illustrate mineralogical variation in sedimentary facies.
- Seismic interpretation of Hutton subsurface architectures, with detail in Glenhaven area, to support correlation and interpretation of units.
- Image log analysis on available wells for current palaeo studies to assist in understanding the mechanism of basin fill.
- Stratigraphic forward modelling of Hutton (and underlying Precipice-Evergreen) to test first principle understanding of the basin infill system and provide certainty to the static model.

New knowledge included:

- Field-based sedimentary model of facies and depositional environments;
- Catalogue of geo-bodies and facies observed in outcrop;
- Recognition of facies within core and development of a conceptual sedimentary model, both regionally and specifically for the Glenhaven area;
- Integration of seismic data to calibrate correlation between cores and look for internal bedding variation;
- Mineralogical distribution model through selected cores using Hylogger to verify reactive mineral zones within the Hutton Sandstone, relative to the Precipice Sandstone and Evergreen Formation;
- Integration of Hylogger and hyperspectral outcrop analysis to characterise the spatial extent with size and dimensions for potential baffle zones;
- Sediment dispersal from image logs and outcrops to provide information on bedding dip and direction for dynamic flow modelling and
- Stratigraphic forward modelling aimed to continuously predict the distribution of grain size from a neutral process-based approach.

Reference

V. Bianchi, et al 2017, Regional geological study of the Hutton Sandstone (7-1116-0294)

A panoramic view of outcrop in proximity of Injune in the West of the Surat Basin

Managed Aquifer Recharge for Carbon Storage

This study is a high-level techno-economic assessment of the potential to sequester CO_2 as a dissolved phase within the water that the coal seam gas (CSG) industry is currently injecting into the Surat Basin as Managed Aquifer Recharge (MAR).

The evaluation looks at critical elements: Volume, timing and location of CSG-MAR; surface plant, material requirements and operability of surface or wellbore dissolution; and through modelling of CSG- MAR scenarios, explore the fluid flow and mineral pH buffering (reactive geochemistry) to determine if there are any "showstoppers" to this niche CCS opportunity.

The Precipice Sandstone is a particularly desirable MAR target due to its high injectivity and the presence of an effective top seal, the Evergreen Formation. Total CSG industry water production is anticipated to peak at ~80 ML/day and this will occur roughly between 2015 and 2035 with a rapid drop in produced water available after that. The produced water is treated at some 20 water processing facilities distributed across the CSG assets. Were any of these water processing plants used to drive MAR in the future, they would provide a range of CCS options with different storage volumes. A surface mixing tank option was determined to be the most cost effective and operationally practical method of dissolving CO_2 in MAR water; however, the resulting drop in pH would require MAR injection infrastructure to be constructed with acid tolerant materials. This represents an added cost to otherwise normal MAR operations. In the study we use a reservoir injection pressure of 90% of the fracture pressure, which results in a surface mixing tank operating at ~17.5MPa. Under this condition the dissolved CO_2 would make up 6.6% of the injected CCS-MAR volume. Based on the Reedy Creek MAR example, each injection well would inject ~1500 ML/day which over a year would equate to ~36,200 tonnes CO_2 stored per year per well.

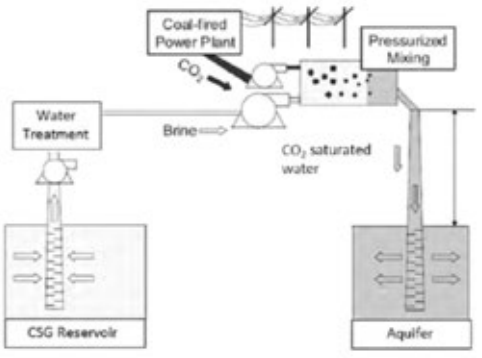
Numerical simulation of CCS-MAR for various scenarios including end member cases of closed boundary, semi-closed and open boundary conditions, were run to test the sensitivity of plume behaviour. The added density effects for CCS-MAR results in the plume eventually sinking towards the base of the aquifer, but this mainly occurs in the post injection period.

Some scenarios such as closed boundary conditions limit the total CCS-MAR injection volume to avoid reaching 90% of the estimated reservoir fracture pressure. None of these conditions was considered to be a showstopper for carefully planned CCS-MAR. The aquifer model numerical simulations predicted pH ~ 3.4 based on mixing of the injectant (i.e., CO_2-H_2O) with indigenous Precipice Sandstone groundwater to investigate the likely pH range from buffering, geochemical modelling was performed. Generalised mineralogies were determined using limited available information from several well cores. Dissolution of mainly carbonate minerals, especially calcite, under different scenarios buffered pH between 4-5. This is below the recommended pH guidelines for drinking water of 6.5 -8.5. Several potential strategies could be used to avoid the low pH, the most realistic solution may be using a different site with higher alkalinity and carbonate mineral content.

No clear showstoppers were identified if the injectant is deoxygenated and pH is between 3 and 9. Assessing the suitability of different sites from an existing groundwater quality/chemistry perspective (including sites with different local alkalinities) is also recommended in future. The report concludes that CCS-MAR has the potential to be a relatively low cost niche carbon storage "add on" option if the timing could be aligned with the availability of CSG-MAR operations. It has the benefit of resulting in highly secure CO_2 storage as a dissolved phase.

Reference

C Khan, J Pearce et al; Managed Aquifer Recharge for Carbon Storage: A Feasibility Study, 2017 (7-0268)



General process for CCR MAR with surface dissolution of CO_2.

Southern Perth Basin

The SW Hub commenced as Australia's first flagship CCS project in December 2011. It considered the storage potential of the Lesueur sandstone formation in an on-shore location of the Southern Perth Basin. This is a fluvial sandstone, therefore reservoir quality was expected to vary in the lateral direction. Historical data is sparse as the region is not well explored. The benefit of demonstrating and confirming the storage potential of this site was proving the significant increase in global storage potential of similar basins.

Goal

To support CO_2 storage in the on-shore Southern Perth Basin

Western Australia

Scale Key

- In lab
- In Field

Delivery Key

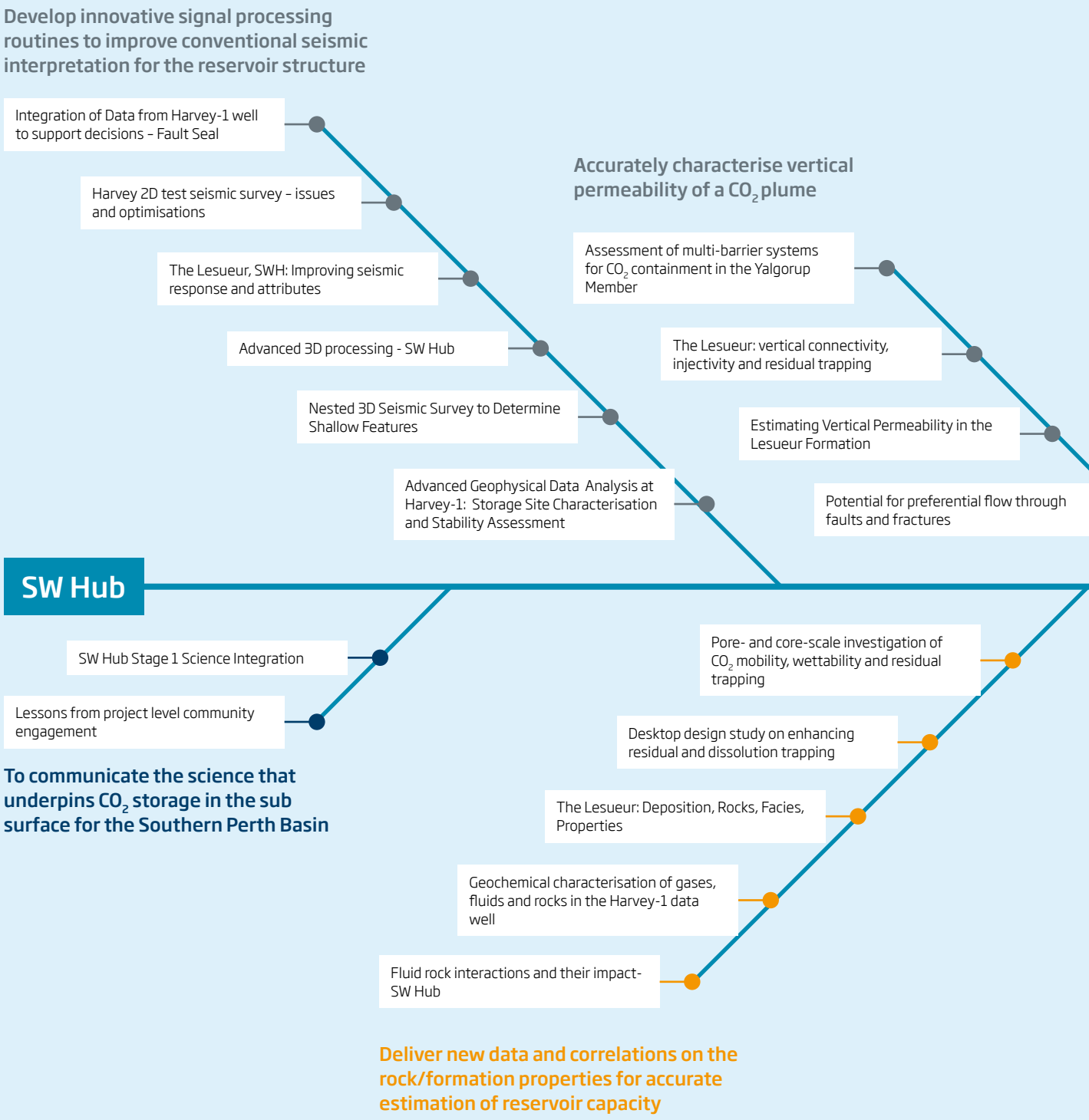
- New Data
- New Application
- Field Validation
- New Service
- New Correlation
- New Software
- Permitting & Public Communication

Photo courtesy of the Department of Mines and Petroleum, WA

Impact Area	Impact Statement	Delivery
Reservoir Containment	*Develop innovative signal processing routines to improve conventional seismic interpretation for the reservoir structure.*	
	Accurately characterise vertical permeability of a CO_2 plume.	
Public Acceptance	*Deliver long term monitoring, measurement and verification (MMV) data for social licence to operate*	
	To communicate the science that underpins CO_2 storage in the sub surface for the Southern Perth Basin	
Reservoir Capacity	*To predict and validate residual trapping in the Wonnerup Member*	
	Validate at field scale the lowest cost routes to reservoir characterisation	
	Deliver new data and correlations on the rock/formation properties for accurate estimation of reservoir capacity	
Reservoir Injectivity	*To determine new data and fundamental correlations on the CO_2 core flooding dynamics of reservoir rocks under in-situ injection conditions*	
	Investigate innovative strategies to maximise injectivity in the Wonnerup member	

Adapted from CSIRO: M. Bazzaco, CSIRO Impact Evaluation Guide, 2015

Supporting Research: South Perth Basin



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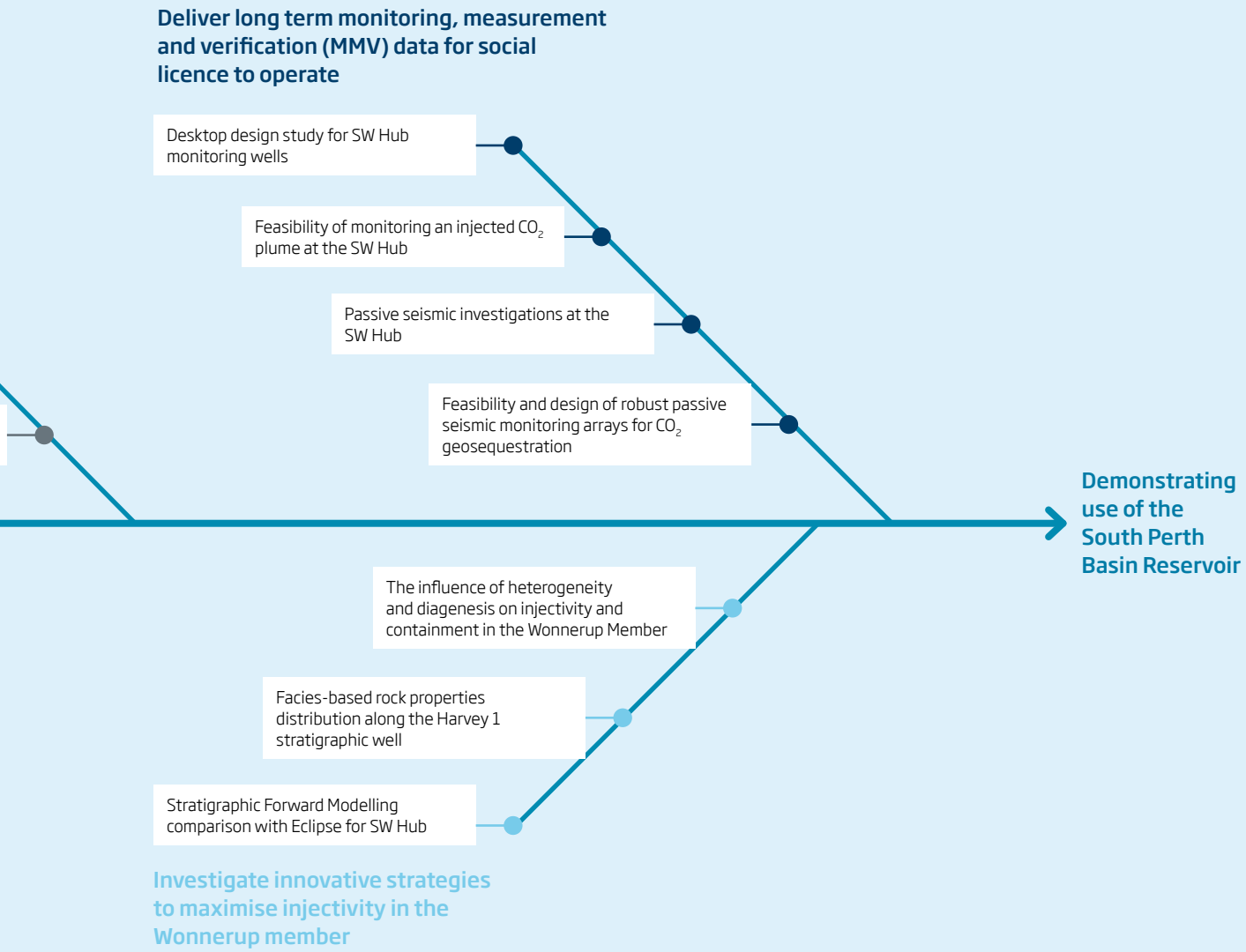


Research Key

- Reservoir Containment
- Public Acceptance
- Reservoir Capacity
- Reservoir Injectivity

Research Projects

Obtaining high quality data with a lower environmental footprint

A large 3D seismic survey at the South West CO_2 Hub Project near Harvey was acquired.

The survey was of great importance for the characterisation of the reservoir, seals and structures in the area. Often, the positioning of the seismic source point is not easy or convenient. These issues arose because of the nature of the land and vegetation in the area (wetlands etc.), and also because the larger size of the commercially owned vibrating trucks was likely to cause significant disturbance to the landowners. Gate removal and fence demolition were both impactful, and the trucks may leave very large footprints over soft ground. It was therefore of high importance to investigate the use of alternative sources to replace conventional seismic sources in parts of the commercial 3D survey.

This project was planned to evaluate and demonstrate the effectiveness of the UNIVIB sources acquired under the EIF granting scheme to the National Geosequestration Laboratory (NGL). The broad band signal generated by the UNIVIB trucks, in combination with tight geophone spacing, provided a technical solution for resolving shallow structures and lithological variations.

The latter are features of prime importance for the long term CO_2 storage program at this site. In addition, the system was be used to demonstrate to the community their low environmental impact.

This project described the results and findings from the experimental 2D seismic survey acquired along Riverdale Rd with newly acquired NGL UNIVIB seismic vibrating sources (in 2013). Results were compared to previous work from 2011 involving conventional large size vibrating trucks.

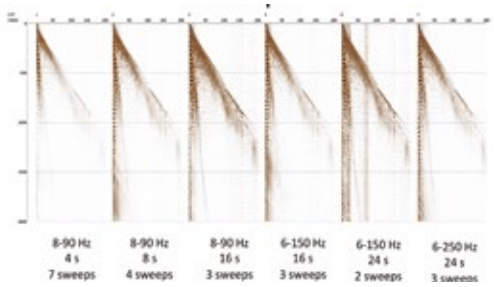
A high quality, broad band, low impact seismic source produced very high resolution data in the first kilometre of depth along Riverdale Road, Cookernup. Despite the high ambient noise (traffic and farming machinery) this source, combined with unconventionally light-weight seismic equipment, produced high quality data. Shallow sediments were imaged with superior resolution. The main unconformity can now be mapped with much improved accuracy in comparison to the 2011 data, which was acquired with much stronger sources.

Key outcomes:

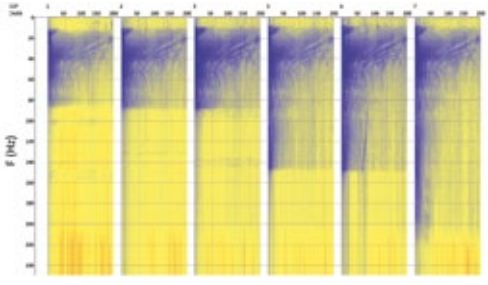
- With a relatively low environmental impact, the lighter weight UNIVIB proved very successful in demonstration to the general community. A vibrator truck was exhibited at the Harvey Agricultural Show in late 2013 and attracted a lot of interest and positive comments from the local community.
- The results of the new survey demonstrated that high resolution surveys were achievable for imaging the top 1000m of sediments and improving our understanding of the fault patterns.
- The new broad band source also proved to be quite a powerful source; capable of producing enough energy to record reflections from depths of over 3000m.
- It showed it was possible to utilise UNIVIB trucks in the existing large-size 3D survey, to close the gaps in survey coverage where access is otherwise not possible, due to local land conditions.

Reference

M. Urosevic, et al 2014 Harvey 2D test seismic survey – issues and optimisations (7-1213-0223)



Sweep tests going left to right using conventional narrow to unconventional broad band sweeps. Standard commercial sweep is compared to a long broad band sweep. Long sweeps performed the best.



Log-Amplitude spectra for sweeps. Useful frequency range extends even to 250Hz. The optimum sweep is considered to be: 6-150Hz, 24 seconds long.

Reducing costs by assessing the validity of alternative models

It is standard industry practice to use three-dimensional geological models to predict rock properties of a reservoir.

These 'static' geological models contain information at high resolution about the distribution of rock types (facies) usually interpolated from core analyses, and wireline information, measured at discrete well locations often kilometres apart. Additional parameters such as porosity and permeability are distributed throughout the model according to the spatial variability typically associated with the interpolated facies or from inversion of seismic information.

An alternative method, stratigraphic forward modelling (Sedsim), numerically simulates depositional processes such as erosion, transport, deposition, and compaction to predict lateral and vertical variations in reservoir and seal properties associated with predicted lithofacies distribution. An advantage is that forward numerical models may be constructed using a limited amount of data, useful for greenfield sites, and the resulting models may also reduce depositional uncertainty for the same amount of input data required by more conventional static methods.

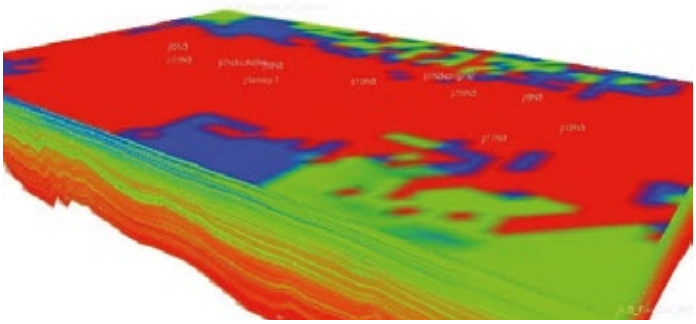
Because of the initially limited well and seismic data in the South West Hub area, ANLEC R&D identified the need to study the utility of forward stratigraphic modelling and sponsored a two phase project to:

» construct a static, cellular geological model for the area using Sedsim stratigraphic forward modelling software; and

» use this model as the basis for dynamic flow simulation and contrast the results with those obtained using a conventionally derived static model.

Phase 1 used Sedsim to create a stratigraphic forward model from 250 Ma to 182 Ma (Triassic to Lower Jurassic), from the base Wonnerup equivalent to top Eneabba equivalent, that predicted the distribution of grainsize and primary porosity (and permeability via a transfer function) of sediments below seismic resolution around the Harvey-1 well.

Phase 2 used this model as a basis to perform a flow simulation of CO_2 into the Wonnerup Sandstones using a nested 500m grid and dynamic model area of 25 x 15km.



Sedsim depositional model of South West Hub region at Top Eneabba (182 Ma) at scale for dynamic reservoir modelling. Low total porosity is red and higher total porosity grades to blue. The model covers an area of 375 km² (Griffiths et al., 2012).

The simulation of CO_2 injection used Eclipse 300 software and the results were compared to a previous simulation performed by Schlumberger based on a static model constructed using well data and geostatistical distribution of reservoir properties.

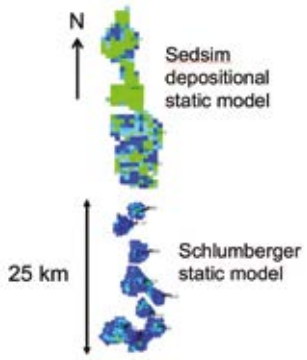
Both methods predict CO_2 plumes to develop and remain around the injection wells for the long term; the main difference being that the plume predicted by the 'Sedsim' input spreads more than the conventional model.

This was the first time such a comparison of dynamic simulation of geological models generated by these different methods has been performed and has provided insights into dynamic models for CO_2 sequestration.

Having an alternative approach to depict the geological framework allows building confidence and reducing risk and cost of obtaining accurate representation of the reservoirs and the forward models.

Reference

C. Griffiths and Y. Cinar 2014, Stratigraphic forward modelling comparison with eclipse for SW Hub (7-0212-0202)



Comparison of dynamic simulation results of CO_2 plumes after 40 years using the Sedsim un-faulted depositional static model and Schlumberger static model inputs. (Griffiths et al., 2014)

Advanced seismic processing discovers new reservoir features

The large-scale 3D seismic survey acquired in the first quarter of 2014 proved to be of great importance for characterisation of the SW Hub Project; mapping the main structures and key geological interfaces.

However, small to medium shallow structures were less clearly imaged in this survey, as the recording geometry was adjusted for the regional investigations and greater depths, rather than high resolution and shallower character of the formations.

A high-resolution 3D survey was undertaken to investigate whether the imaging of the shallow structures could be improved. The survey was centred at the Harvey-4 well. The principle objective was to image the complexity of the shallow structures in 3D. Close to 1600 seismic source positions were acquired over 5 days. Seismic receivers utilised single and 3-component geophones arranged into an odd-even receiver line pattern.

Preserved amplitude processing and pre-stack imaging proved to be a very effective processing approach for structural analysis. The same data can be used in the near future for more qualitative studies involving acoustic inversion and AVO studies after calibration to the Harvey-4 well logs.

The Nested 3D data cube was inserted into the large, regional scale Harvey 3D survey (see images).

A comparative analysis showed the following:

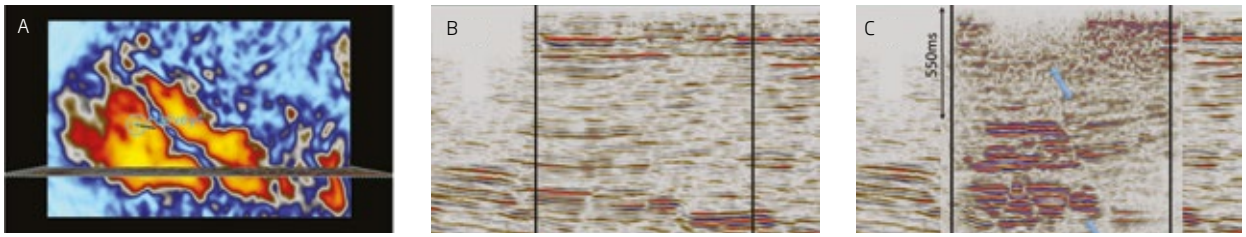
- Several faults were seen in the Nested 3D data, which were not previously identifiable in the regional 3D cube. This includes faults at different scales.
- All discontinuities (large and small) were of a much higher fidelity in the Nested 3D survey.
- Some faults appear to propagate near to the surface but were of a small-scale throw.
- Faulting in the area is highly complex.
- The Harvey-4 well appeared to have drilled through a fault of a large throw (several tens of metres).

Key conclusions:

- These results demonstrate that high-resolution surveys are important for imaging the top 1,000m of sediments. The Nested 3D survey produced higher fidelity imaging of faults down to at least 1,500m in comparison to the regional 3D data.
- New seismic images allowed for the interpretation of faults, previously unidentified in the regional 3D survey.
- Even some deep, large-scale faults were better imaged with the new high-resolution survey than the regional survey.
- The fault complexity revealed by the new data suggests that a much higher data density and resolution is required in order to accurately analyse and characterise the SW Hub reservoir.
- This data can enhance the static models to more accurately characterise the layering of the formations.

Reference

M. Urosevic, et al 2015, Acquisition of the nested 3D seismic survey at Harvey (7-1213-0224)



3D survey comparison: A) Time slice through similarity section, B) Regional Harvey 3D and C) Nested 3D inserted into the rectangular area. The location of the inline section shown is marked in A). The Harvey-4 borehole is shown as a green circle. The whie in-fill small circle is added to enhance the borehole position only in this display. The blue transparent double arrow is used to denote "new" fault images, not seen in the regional data.

Improved seismic response and attributes with innovative processing and quantitative interpretation

The Lesueur formation has several distinctive features that complicate conventional seismic characterisation of the subsurface: the Yalgorup member consists of finely layered shaley lenses and not continuous impermeable layers; the Wonnerup member, has no seismic reflections inside; intense faulting in the area causes lateral variations of the subsurface properties and further complicates seismic imaging conditions.

Advanced methods of seismic quantitative interpretation and joint analysis of a broad range of available geophysical/geological data may provide a refined model of the Lesueur formation and its properties. The project used the large commercial seismic and high resolution nested seismic survey around Harvey-4 to resolve a shallow part of the susbsurface. To constrain static geomodelling, all available 3D surface seismic data, VSP data from Harvey 1, 2, 3, and 4, well log data and the results of the core analysis performed in a preceding study was dedicated to geological data integration.

To date, a conventional quantitative interpretation (QI) approach was set up and applied to both seismic datasets. The principle goal of the study was the mapping of the concentration of potential fluid baffles – palaeosols. The workflow developed consisted of the following steps:

- true-amplitude seismic processing to allow for adequate interpretation of the intensity of seismic events on the seismograms,
- application of some conventional seismic attribute analysis,
- sparse-spike acoustic impedance inversion of the commercial seismic
- well-logs quality control and conditioning for seismic inversion,
- feasibility study/correlation analysis between acoustic and petrophysical properties within the Yalgorup and Wonnerup formations,
- matching commercial seismic to all four Harvey wells, wavelet extraction using reliable wells,
- model-based acoustic inversion of the commercial seismic,
- palaeosol bodies mapping in the acoustic impedance cubes,
- modelling test of AVO-effect in the nested survey, selection of the most reliable range of offsets; model-based elastic impedance inversion of the nested survey data, and
- mapping of the palaeosol facies and determination of its characteristic lateral sizes.

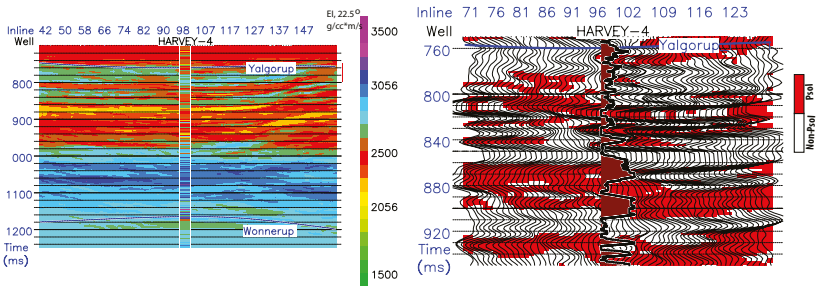
Results:

Fast-track QI of the available seismic data delivered the first approximations of palaeosol facies distribution within the Yalgorup and upper part of the Wonnerup formations. The study also provided the following recommendations for improved data acquisition for the SW Hub:

- Conduct a high-resolution nested seismic survey around Harvey-3 with sufficiently large offsets to allow for AVO-inversion without near-offset data.
- Well logs in Harvey-3 were of good quality, so we expected rather good well-to-seismic match.
- Drill Harvey-5 through the whole Wonnerup formation to provide data on seismic properties of the assumed injection formation.
- Drill Harvey-5 between Harvey-4 and Harvey-3, preferably within the nested survey.

Reference

S. Glubokovskikh, et al 2016, The Lesueur, SWH: Improving seismic response and attributes. Fast-track quantitative interpretation for South West Hub (7-0115-0241)



Inverted *EI* along inline 23 (top); crossplot of *dEI*/<*EI*> vs *EI*, used to interpret palaeosol geobodies (red on the bottom).

Research delivers more information on structure of the Lesueur storage complex

The South West Hub project entered an evaluation stage, aimed at reducing uncertainties related to the distribution of properties of the targeted subsurface formations.

Data is sparse and more confidence was needed in the storage potential for the basin. Ambiguities were particularly evident in the following aspects of the subsurface basin characterisation:

- Diagenetic history of the sediments and how diagenesis affected the pore space and therefore the injectivity and storage potential of the targeted units;
- Current and past nature of the formation fluids and reservoir compartmentalisation between the different fault blocks identified in the subsurface of the SW-Hub;
- Seismic constraints on the petrophysical character of the Lesueur Sandstone;
- Geomechanical properties of the storage reservoir and overlying units.

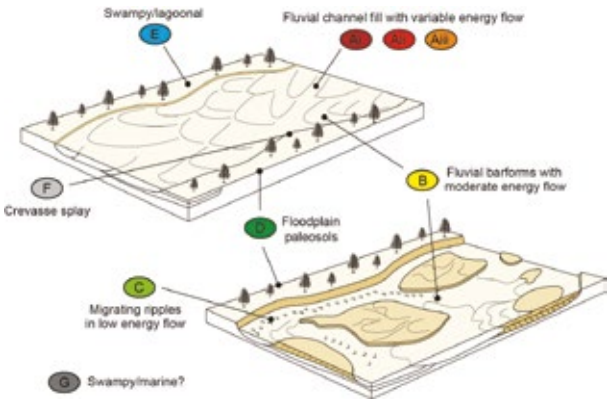
Results show:

- There was an overall consistency in terms of mineral content and interpreted diagenetic sequence from 4 wells relevant to SW Hub in the Southern Perth Basin. Similarities were also observed with material from the same formation currently buried at greater depth in the Pinjarra-1 well.
- Notably, the values of porosity, permeability and elastic wave velocities were seen to be markedly different at Pinjarra-1, although a kink in the lowermost part of the Wonnerup Member induces a major decline in the velocity vs depth trend.
- So far, fluid inclusion studies have been conducted on samples from Harvey-1 and Pinjarra-1 in an attempt to relate possible burial/ diagenetic effects to the observed petrophysical characteristics of the rock.
- It can be shown that palaeo formation water salinity at the two locations differed significantly, as did the homogenisation temperatures recorded in the diagenetic quartz cements. This may suggest a measure of compartmentalisation; not surprising given the 10's of kms distance between the wells.

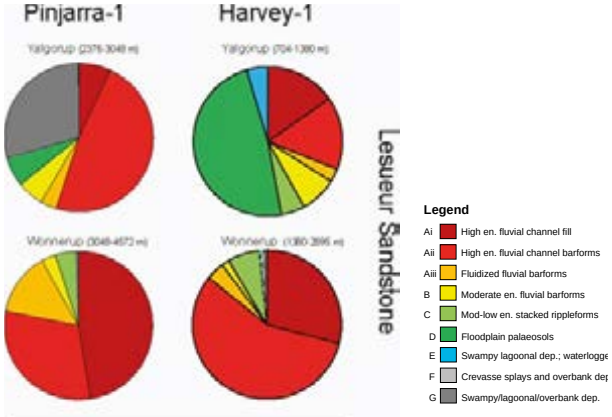
The drilling, coring and logging program comprising three wells: Harvey-2, Harvey-3 and Harvey-4 have been completed.

Reference

C. Delle Piane et al 2016, The Lesueur: Deposition, Rocks, Facies, Properties 7-0115-0240



Block diagrams to illustrate the sedimentary depositional environment and architecture of lithofacies.



Comparison of facies distribution within the cored sections of the Lesueur Sandstone encountered in wells Pinjarra-1 and Harvey-1.

A fresh look at faulting to inform deployment decisions

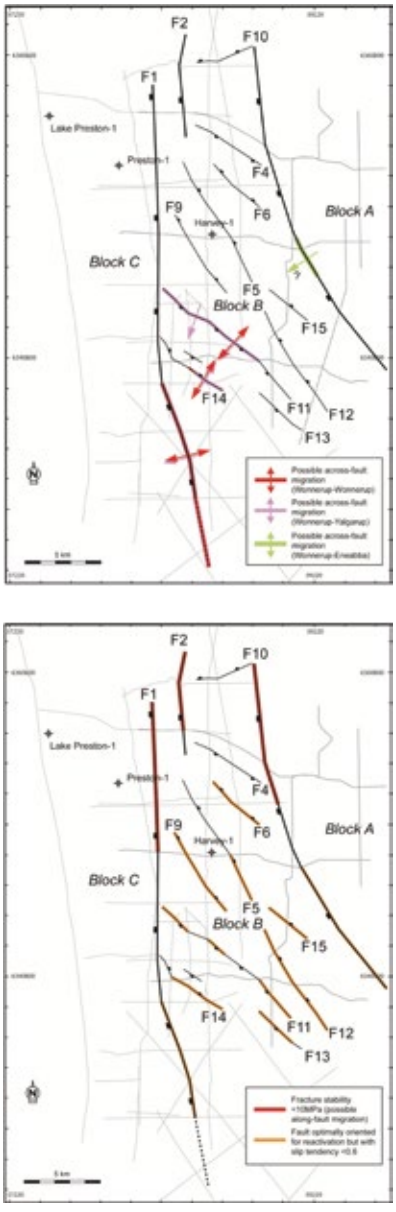
The available seismic data for the South West Hub indicated that multiscale faults affected the target CO_2 storage reservoir of the Lesueur Formations and the potential top seal Eneabba Formation.

Based on the integration of existing and new (2010 vintage) 2D seismic dataset and Harvey-1 well data, this project primarily targeted the evaluation of the faults hydraulic behaviour, i.e. the faults sealing potential for across-fault and up-fault flows. A secondary objective was to investigate the distribution of sub-seismic fractures and their impact on the trap integrity and reservoir compartmentalisation.

A new geological model, consistent with the integration of the latest 2D seismic reflection survey and available geophysical data, was built. It integrates five stratigraphic horizons tied to formation tops in the new Harvey-1 data well (Neocomian UC, top basal Eneabba Shale, top Yalgorup, top Wonnerup and top Sabina Sandstone) and 13 main faults that can be correlated between at least two 2D-seismic lines that show constancy in dip, strike orientation and offset. This represented a first-order geological model, and the acquisition of additional seismic and well data was critical to reduce remaining geological uncertainty and further constrain the structural framework.

Key findings from the study:

- The likelihood of lateral migration of CO_2 across faults between the Wonnerup Member and any interbedded sandstone (i.e. thief zones) in the Yalgorup Member can be locally high to the south of the SW Hub.
- The likelihood of lateral migration of CO_2 across faults within the Wonnerup Member can also be locally high to the south of the SW Hub, with potential of westward migration beyond F1 if the CO_2 column exceeds the local offset.
- Shale Gouge Ratio (SGR) values on the fault plane suggest an average to low likelihood of across-fault migration.
- The slip tendency magnitude for the SSE-NNW-oriented faults in the SW Hub were low (typically between 0.15 and 0.3) suggesting a low risk of fault failure under the present-day stress.
- The smallest critical pore pressure perturbations required to reach failure stress were located to the north of the SW Hub.
- The study provided a useful input into dynamic models to test compartmentalisation and containment.



Summary of across-fault (top) and along fault (bottom) CO_2 migration potential for the SW Hub.

Reference

L. Langhi, et al 2013, Fault seal first-order analysis – SW Hub (7-1111-0201)

Mapping lithofacies: validating storage potential in unconventional storage structures

The goal of the multidisciplinary work presented by this study was to understand the geological and geophysical parameters that would affect the safe and efficient storage of CO_2 at the proposed SW-Hub site in the Southern Perth Basin.

In particular, the areas of interest covered by this work were related to the characterisation of the geological units intersected by Harvey-1 in terms of storage capacity; injectivity and containment potential; elastic and mechanical properties and heterogeneity of the formations encountered.

The present work fed into and supported a wider program aimed at the integrated evaluation of the SW-Hub encompassing a detailed analysis of the seismic data available in the region; an assessment of the potential for fault reactivation around the proposed injection area; a study of the possible fluid-rock interactions at reservoir conditions and the forward stratigraphic modelling of the area.

The outcomes of the work indicated significant differences between the Upper and Lower Members of the Lesueur Sandstone in terms of sedimentology, petrophysical, geomechanical and elastic properties. The deep saline aquifer equivalent to the Wonnerup Member of the Triassic Lesueur Sandstone represents the targeted reservoir, whereas the Yalgorup Member and the Basal Eneabba Shale may acted as possible stratigraphic seals.

Good reservoir properties were recorded in the lower Member (Wonnerup 1380-2895m depth) of the Triassic Lesueur Sandstone with encouraging values of porosity (7 to 19%) and permeability (0.01 to 580 mD) and lithofacies homogeneity with depth.

Permeability anisotropy measured in the laboratory can be very significant at the tentatively predicted injection levels: across bedding permeability ranges between 0.01 and 3mD while along bedding permeability ranges between 38-580mD, resulting in anisotropy of up to 3 orders of magnitude.

Core flooding tests also gave positive indications for residual trapping (25 to 45%) as a principal containment mechanism. However, a marked decrease of permeability (up to 50%) was observed after sample flooding was also inferred from the tests. This phenomenon was identified for future studies.

By contrast, the overlying Yalgorup (704-1380m) was far more heterogeneous and, due to poor core conditions of the shaly layers, the characterisation work only focused on the sandy intervals, and the results cannot be regarded as representative of the whole stratigraphic unit.

Uncertainties remained regarding the geomechanical properties and containment potential of the different lithofacies within the Yalgorup. Nevertheless, the presence of interbedded sands and shale layers could be beneficial in terms of storage.

Reference

C. Piane, et al 2013, Facies-based rock properties distribution along the Harvey-1 stratigraphic well (7-1111-0199)

A summary of the lithofacies scheme developed for the Mesozoic stratigraphy of the central Southern Perth Basin. (A) Graphical sedimentary logs and descriptions. (B) Example core photographs from Harvey-1.

Monitoring the injected CO_2: geophysical remote sensing of CO_2 sequestration

No single geophysical method in isolation has the capability to monitor CO_2 because most extant geophysical methods cannot detect CO_2 directly.

This means that an effective geophysical monitoring and verification strategy should incorporate one or more methods. For particular scenarios, the exact remote sensing combination will vary, but such methods will generally include reflection seismics, electromagnetics or gravity.

The objectives of this project were to:

- Develop conceptual reservoir models which spanned the likely geometries and performance of the potential demonstration flagships;
- Forward model possible physical measurements;
- Understand the sensitivity of the measurements to CO_2;
- Recommend the combination of geometries and physics to be used for the pilot project measurements, including notional costs; and
- Recommend analysis and measurement technology that needs further development.

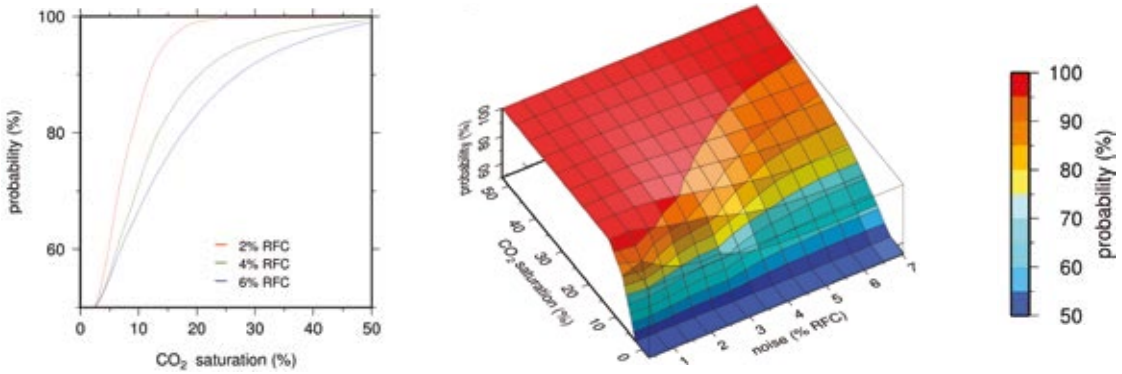
These objectives were addressed by modelling seismic, electromagnetic and gravity responses of idealised, conceptual models of two recently-approved flagship CCS projects; the SW Hub in Western Australia and the CarbonNet project in Victoria. Baseline and several data vintages (each representing the addition of increasing amounts of CO_2), were modelled in order to assess the suitability of each geophysical method to each flagship project. Geophysical data from different vintages were analysed in order to establish the sensitivity of each method to CO_2 injection.

This project found that:

- Time-lapse surveys are required of all geophysical methods studied in this report. It was not possible to infer CO_2 saturation from a single geophysical data vintage. The requirement for geophysical time-lapse surveys is concomitant with establishing high-quality baseline models;
- Extant high-quality well logging data are required to build high-quality geological models;
- Accounting for uncertainties in seismic modelling improves the ability to evaluate CO_2 saturation and is required for robust risk assessment;
- Permanent seismic arrays significantly improve S/N ratios, allowing for cost-effective acquisition of high-quality data with minimal impact to the community;
- In shallow (typically < 100m) water columns, marine electromagnetic surveys would be unlikely to detect CO_2 variation; and
- Due to the fall-off in response over distance, gravity and electromagnetic surveys should be conducted downhole. These need not be in vertical wells.

Reference

D. Annetts, et al 2012, A deployment strategy for effective geophysical remote sensing of CO_2 sequestration: Final report (3-0510-0030)



Time-lapse probability of detecting CO_2 in the Wonnerup reservoir at the SW Hub. The probability of detecting CO_2 decreases significantly at noise levels higher than 2% of RFC.

Using earth tides to sense reservoir connectivity

The vertical permeability of CO_2 storage formations, and specifically those of confining layers, are key parameters influencing the effectiveness of structural CO_2 trapping or the risk of leakage.

As a potentially attractive method to examine the integrity of a large CO_2 storage site, accurate and long-term passive monitoring of pressure variations in response to barometric pressure fluctuations and earth tide effects may provide a means to assess the continuity of the confining units and their hydraulic properties. This scoping study examined such responses, and their suitability for determining vertical permeability was then ascertained by numerical modelling combined with notional inversions and data-worth analyses.

The analyses suggested that the pressure fluctuations observed in deep boreholes may be used to infer hydrogeological and geomechanical properties. However, pore pressures induced by barometric and earth tide loading are controlled by the local hydro-geomechanical properties rather than the large-scale hydrostratigraphic features of the CO_2 storage system. This includes medium scale heterogeneity due to the deposition of high and low energy facies as well as small-scale heterogeneities within facies. It was concluded unlikely that reliable estimates of vertical permeability and/or continuity of the confining layer can be obtained by analysing pressure fluctuation data.

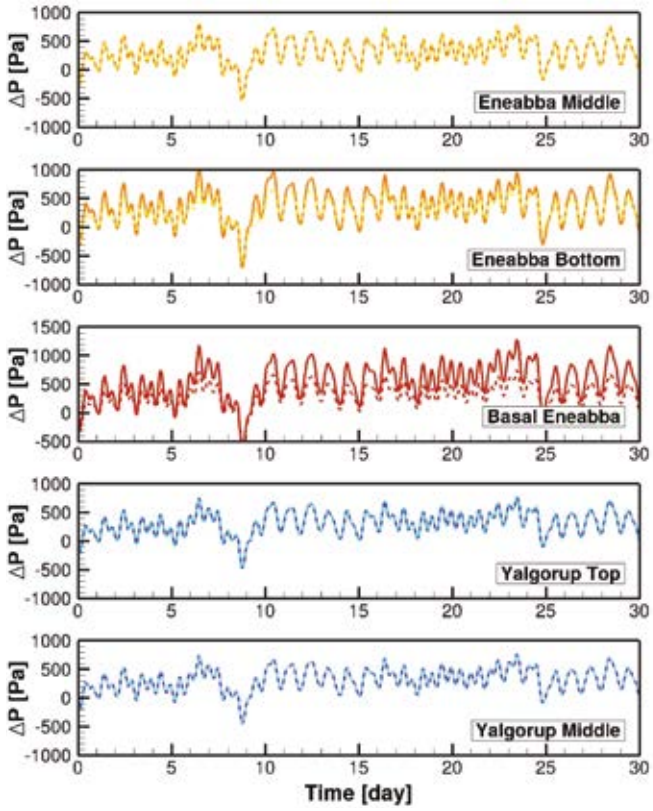
Key conclusions were:

- Loading effects from earth tides and barometric pressure fluctuations are instantaneous everywhere in the sub-surface and not due to fluid flow and pressure diffusion from the surface.
- Although these fluctuations are large-scale forcings, the induced pressure perturbations are controlled by local geomechanical properties and pressure dissipation, which is related to permeability and is determined by local hydro-geological properties.
- Hence, even with sensitive sensors and regionally induced gradients, the permeability estimates are related to the local conditions.
- Accurate long-term pressure measurements may be useful to estimate local permeabilities if analysed by a hydro-geomechanical forward simulator embedded in a robust inversion framework.

The study was/would also be useful in considering a future extended production/induction test design for the SW Hub project.

Reference

Y. Zhang, et al 2016, Estimating vertical permeability based on responses to barometric pressure fluctuations in the Lesueur Formation (7-0515-0246)



Simulated pressure response to barometric and earth-tide above and below Basal Eneabba Shales, without (solid lines) and with (dashed lines) discontinuity in Basal Eneabba Shales.

The fundamentals of pore-scale processes

The two primary CO_2 trapping mechanisms active during the first several hundred years of a storage project are structural and residual trapping. In the case of residual trapping the CO_2 plume is split into many micro-scale "bubbles" which are surrounded by brine and held in place by capillary forces.

In order to estimate leakage risk and storage capacities for a particular formation, buoyancy forces – which push the CO_2 upwards – need to be compared with the capillary forces that hold the CO_2 in place for such residually trapped CO_2.

Until now, such estimates and related reservoir models, which predict reservoir multi-phase flow, assume that all storage rock is strongly water-wet, which means that water spreads completely on the rock surface. This means that water can surround CO_2 and trap it by pore-scale snap-off processes leading to residual trapping.

However, recent evidence suggests that under certain conditions the storage rock may not be strongly water-wet but can be intermediate wet or even CO_2-wet. Moreover, pore-network modelling studies have predicted that CO_2-wettability also strongly influences the efficiency of residual trapping i.e. with increasing CO_2-wettability the amount of CO_2 that can be stored by residual trapping rapidly decreases.

This project utilised several different techniques in order to reduce the uncertainty in measurements of the CO_2 wettability of storage and seal rock and how this wettability is influenced by various parameters.

The nuclear magnetic resonance (NMR) response for a sandstone at reservoir conditions, at different CO_2 saturation stages, was measured for the first time. In addition, the project also measured supercritical CO_2/ sandstone/brine capillary pressures.

Key conclusions:

» Understanding the wetting characteristics of in-situ reservoir rock is important if structural and residual storage capacities are to be known accurately.

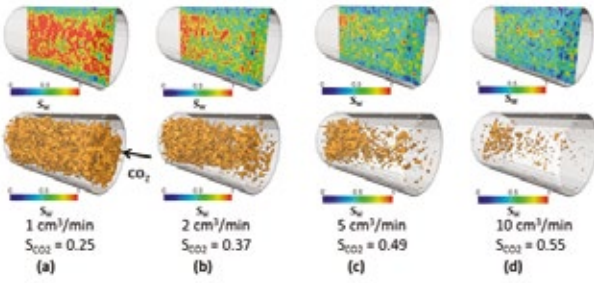
» Structural and residual trapping are likely to be viable storage mechanisms in clean quartz, and siliciclastic rock reservoirs that exhibit weakly water-wet characteristics.

» Certain parameters have a greater effect on wettability than others. Rock surface chemistry is judged to have a very important effect, with pressure and brine salinity having important effects and temperature and surface roughness effects being significant.

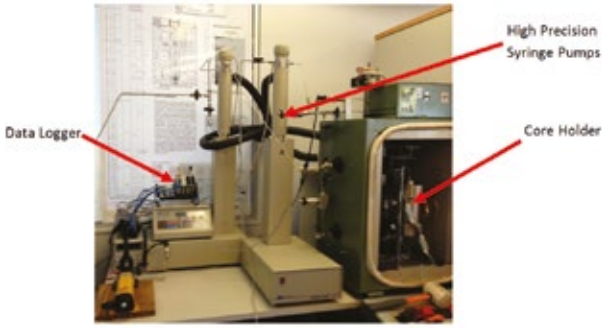
» It was proven by micro-computed tomography experiments that residual trapping is a viable storage mechanism at the pore-scale in clean sandstone.

Reference

S. Iglauer, et al 2014, Pore- and core-scale investigation of CO_2 mobility, wettability and residual trapping (3-0911-0155)



Visualisation of 3D water saturation maps in the core during primary drainage (injections CO_2 in the right side).



Apparatus for capillary pressure measurements at reservoir conditions.

Alternating water and gas injection for CCS - help or hindrance?

In a typical carbon capture and storage project it is important to maximise residual and dissolution trapping to minimise the risk of leakage. In this project, a techno-economic analysis of residual and dissolution trapping for the SW Hub Project was carried out.

The methodology used technically feasible engineering designs to optimise both of the above trapping mechanisms in the Southern Perth Basin storage formation by determining the most feasible injection schemes. The aim was to estimate the relative economics of different injection schemes with different trapping results. The project did not assess the overall profitability of injection in absolute terms.

Continuous CO_2 injection is usually preferred for carbon capture and storage (CCS) projects. However, the literature shows that this option does not necessarily maximise residual and dissolution trapping. The project chose to analyse the engineering and economic effects of several injection schemes. Some injection schemes and processes, such as foam injection, carbonated water injection and fines migration, were ruled out early on because they are believed to be extremely costly. As a result, the options that were analysed included:

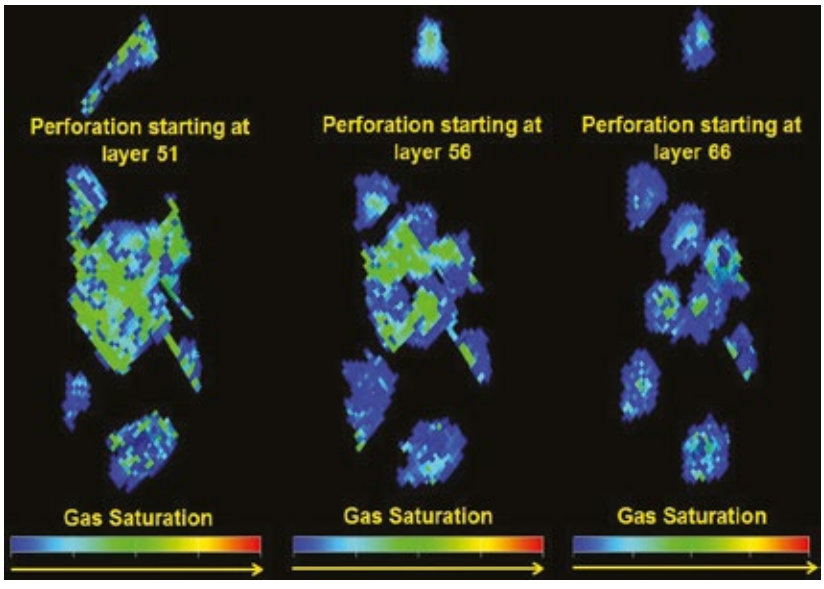
- Vertical injection wells;
- Horizontal injection wells;
- Vertical injection wells and production wells for pressure relief;
- Water Alternate Gas (WAG) wells and production wells for pressure relief;
- Simultaneous Water Alternate Gas (SWAG).

Key conclusions:

- Most of the injection designs tested in this study show that injecting through perforations starting at the upper-middle of the Wonnerup Member provides the greatest potential for residual trapping, dissolution trapping and injectivity.
- In order to minimise CO_2 production for the vertical CO_2 injection and water production well scenario, it is advantageous to locate the perforations in the middle of the formation.
- Horizontal and SWAG well scenarios show the least injectivity because layers in the formation have very low permeability.
- Vertical wells are the most economically attractive and show intermediate overall trapping benefit.
- Although WAG wells are the least economically attractive, they do show the highest overall trapping benefit, especially early in the injection period.

Reference

H. Baz, et al 2014, Desktop design study on enhancing residual and dissolution trapping (7-1012-0210)



Plan view of saturations for different depth layers of the CO_2 plume after 100 years of observation.

Long term data acquisition is important for CO_2 storage

Deploying CCS will require monitoring strategies over decades. Recognising this, ANLEC R&D commissioned a study to develop specifications for a set of well designs that included a range of complementary instrumentation with optimum configurations.

Specific features of the South West Hub (SW Hub) were used as the basis for design of such a system.

In Western Australia, 100km south of the city of Perth, the SW Hub targeted the saline aquifer of the Lesueur Sandstone at a depth of 2-3km for commercial-scale CO_2 sequestration. In support of the drilling of these wells, there was a need to consider the relative location of the wells and the monitoring instrumentation required to maximise their contributions to the overall SW Hub objectives. This research project provided the technical specifications and costs for various measurement, with monitoring and verification options that can be incorporated into the SW Hub well-based monitoring process.

This research added value to the core activity being conducted by SW Hub by:

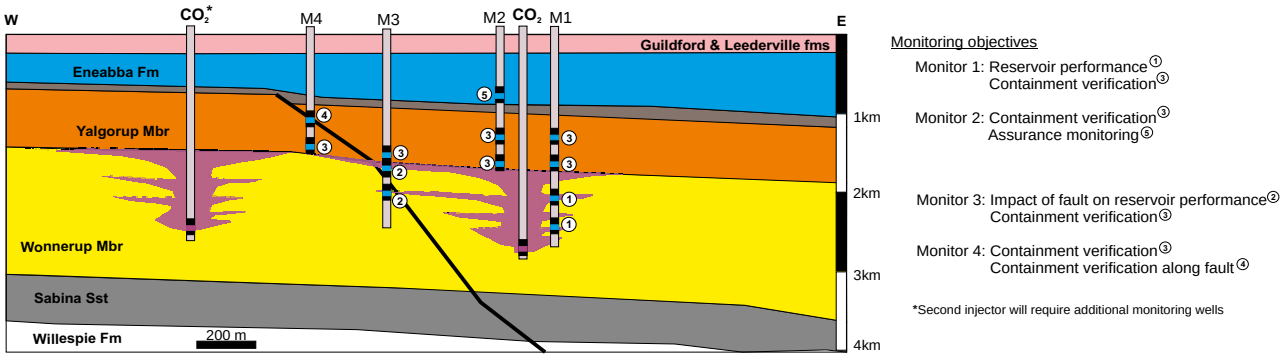
- delivering a series of options for the well-based monitoring program including downhole and surface requirements;
- considering optimal monitoring technologies and testing methodologies requisite for a potential early testing phase; and
- providing a monitoring system that allows for long-term monitoring and research opportunities to be taken at the SW Hub.

Key results:

- A critiqued list of data acquisition, monitoring technologies and applications for geologic carbon storage.
- Monitoring options, with more than one monitoring scheme to address the current uncertainties around storage suitability.
- An application-specific case study for the SWHub.
- Considerations (economic and technical) for pre-existing wells to be converted into monitoring wells.
- Monitoring emphasis on containment verification, with all four monitoring wells having completions in the Yalgorup Member above the storage interval.

Reference

L. Ricard, et al 2015 Desktop design study on South West Hub wells (7-1012-0214)



Schematic monitoring scheme for the SouthWest Hub project that shows different types of monitoring wells that may be required to address monitoring requirements specific to the SWHub case.

Understanding geochemical baselines for the Lesueur Formation

This project reported on the geochemical evaluation of the Harvey-1 stratigraphic well, as part of the South West Hub demonstration project.

Two gas samples from a potential source of CO_2 (CSBP and BOC in Kwinana) that may be used for a pilot scale test were analysed and found to contain almost pure CO_2, in excess of 98.3 mol.%. The carbon isotopic composition of this gas is $\delta^{13}C$ -37.6 ± 0.28 ‰, which is quite distinct from other background natural sources of CO_2 and might act as a tracer in the future.

Rock samples were extracted and the uppermost sample in the Yalgorup Member contained the highest concentration of liquid hydrocarbons (304.9 mg/kg rock). Other samples contained an order of magnitude less. Relative to commercial scale oilfields this amount is negligible, indicating that there is no active source rock of quantitative significance surrounding this well.

This indicated that there is unlikely to be any form of basin resource conflict in relation to oil or gas finds in the immediate area. It is also possible that the hydrocarbons may have come, in part, from drilling mud contamination.

Only one unconfined formation water sample was recovered from the well at 856 m and it was also extensively contaminated by drilling fluids (Figure B).

The sample from Harvey-1 is therefore on a mixing line between the drilling mud and the shallow bore water used.

Preliminary modelling of potential reactions in the Lesueur Formation samples suggests that the rocks have some capacity to maintain circum-neutral conditions, until all albite is converted to dawsonite (Figure A), with the removal of dissolved Na.

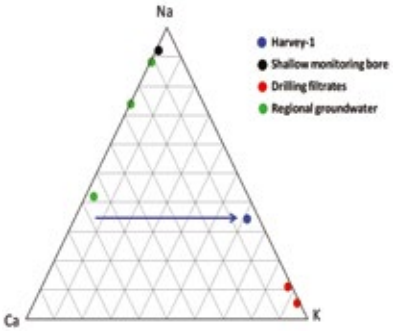
Only after this point, do changes in pH occur. These reactions illustrate the importance of clays and feldspars contributing to changes in the mineralogy. These preliminary models contain a large number of assumptions (e.g. formation fluid chemistry is unknown).

Core-flood analyses have been conducted to evaluate chemical and physical changes to some of the Lesueur Formation samples. One experiment conducted provided detailed analyses of core flood effluents far in excess of previous literature . Improved core flood experimental setup has allowed increased sampling and detailed geochemical analysis of > 60 cations and anions to monitor changes in chemistry when subjected to CO_2 injection. This workflow has provided "time-lapse" chemical data which enabled us to see discrete changes in the mineralogy caused by the passage of CO_2.

Reference

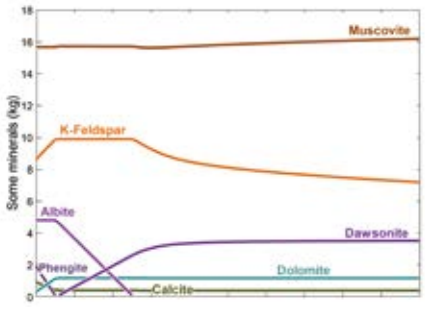
L. Stalker, et al 2013, w (7-1111-0200)

A)



Ternary diagram of major cation water chemistry in Harvey-1 at 856 m (blue), adjacent shallow bore 36 m (black), regional representative samples from the Binningup and Harvey Line water bores (green)* and the drilling mud filtrates (red). The arrows represent the influence of contamination of Harvey-1 from the more representative regional sample groundwater chemistry. *Data from Deeney (1989a & b).

B)



Major cations and anions released into solution from the simulated injection of CO_2 into the Yalgorup rocks.

Establishing the natural variation of seismic signals for the Southern Perth Basin

Passive seismic monitoring is the science of recording and analysing natural or induced seismicity with networks of seismic sensors, without the need for active (man-made) seismic energy sources (like Vibroseis Trucks).

The University of Western Australia (UWA) Geophysics deployed a sparse network of sensors over a period of 12 or more months in order to measure and interpret background seismicity and noise conditions for the SW Hub CCS project in the Southern Perth Basin; this is the first stage needed in a comprehensive seismic monitoring program.

The proposed network comprised 8 or more near surface and autonomous stations located round the SW Hub project area.

Magnitude-frequency curves using historical seismicity catalogues and data collected during the monitoring phase was developed to establish the rate of background natural seismicity in the project area.

As part of this research, seismicity data, within a 3D geological framework, was interpreted in order to assess the association of natural and induced seismicity with geological structure. This information will be integrated with other ANLEC R&D studies of tectonic stresses, local faults and geomechanical lab measurements.

Comparisons of state of the art sensor technologies were made to advance the techniques of passive monitoring and to assess monitoring limitations. Community engagement would also continue with information sessions and reports on the science of microseismicity.

Passive seismic recordings were used to build images of the subsurface. This informationcan could potentially be used for CO_2 injection monitoring directly (if the appropriate natural sources of seismic energy are present at the site) or used to design the active 4D seismic monitoring strategy. Towards this goal, an assessment of ambient noise sources at the site were made with the available data and, where possible, 1D images were made below the monitoring stations.

Reference

N. Issa, et al 2016, Passive Seismic Investigations at the SW Hub: Project report at 6 months (7-0215-0244)

Map of proposed network showing proposed UWA station locations (red S markers) and location of nearby Australian Seismometers in Schools station (white triangle). The Harvey-1 to Harvey-4 stratigraphic wells are labelled as H1, H2, H3, and H4.

The seismic stations are relatively small and self-powered. Recorded data will be transmitted to UWA remotely using the mobile 3G/4G network.

Feasibility and design of robust passive seismic monitoring arrays for CO_2 geosequestration

This project developed innovative approaches to optimise site-specific passive seismic array design, data analysis and imaging methods to apply for monitoring CO_2 storage.

Passive seismic monitoring can be useful in CO_2 geosequestration (storage) projects.

The objectives of the study were:

1. Measure and predict the expected microseismic energy at the SW Hub site by making geomechanical lab measurements on cores taken from wells at the site.
2. Measure and characterise the natural seismicity and signal/noise conditions at the SW Hub site with a small field test array of passive seismic sensors in shallow boreholes.
3. Simulate realistic 3D seismic wavefields using supercomputing algorithms, develop and test innovative 3D seismic wave-equation and VSP imaging methods to improve images of the subsurface with passive seismic array data.
4. Develop methods to optimise the sensor array design, in order to maximise the ability to detect/image microseismic events at the SW Hub and other CO_2 geosequestration sites.

Computational studies included:

» High-performance computational (HPC) modelling of 3D elastic passive seismic wavefield data, using a highly optimised, parallel algorithm on the Magnus cluster at the Pawsey Supercomputing Centre.

» Microseismic events were successfully simulated within a reasonable computation time using 1,536 CPU cores in parallel. Hypothetical microseismic source events were simulated in 3D as if located along faults in the Wonnerup or Yalgorup members, with two types of common microseismic source mechanisms (extensional and double-couple shear).

» Wave-equation based imaging of hypothetical microseismic events, using surface and borehole sensor arrays, including uncertainty analysis and velocity model analysis.

Field operations included:

» Successful deployment of a high-sensitivity broadband passive seismic array in a 50m shallow borehole array at the SW Hub site near the Harvey-4 well location.

» Calibration of the passive array with surface check shots which shows that the array deployment is among the quietest in the world, and is sensitive enough to detect microseismic events of at least Magnitude -1 (M-1) at a distance of 2km (CO_2 injection depths).

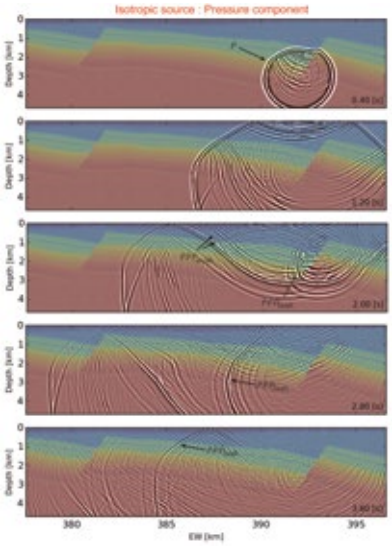
» Analysis of 75 days of passive recordings for analysis of site-dependent signal/noise conditions and ambient seismic noise versus time and sensor depth.

» Ongoing deployment of near-surface broadband (0.01-500Hz) earthquake seismic stations to detect local microseismic events M+1 or larger over the 200 sq.km. project area and surrounding areas, which fills a gap in the national Geoscience Australia network coverage to detect events smaller than M+2.

Background data collection was undertaken and assisted in defining the natural low level seismicity of the area. The project improved the potential of lowering monitoring costs for future projects through such non-invasive techniques.

Reference

Lumley et al., 2016, Feasibility and Design for Passive Seismic Monitoring at the SW Hub CO_2 Geosequestration Site (7-0212-0203)



Snapshots of the complex 3D seismic wavefield generated by a hypothetical micro-seismic source on the F10 fault (superimposed on the P-wave velocity model). First arrival direct P-waves, reflected P-waves off the F10 fault, and multiply-reflection P-waves from the surface and sand/shale layers, are identified.

Understanding the influence of particle entrainment on CO_2 injectivity

In mid-2014, a review of some of the core analysis performed on rock material from the South West Hub (SW Hub) carbon capture and storage site was conducted.

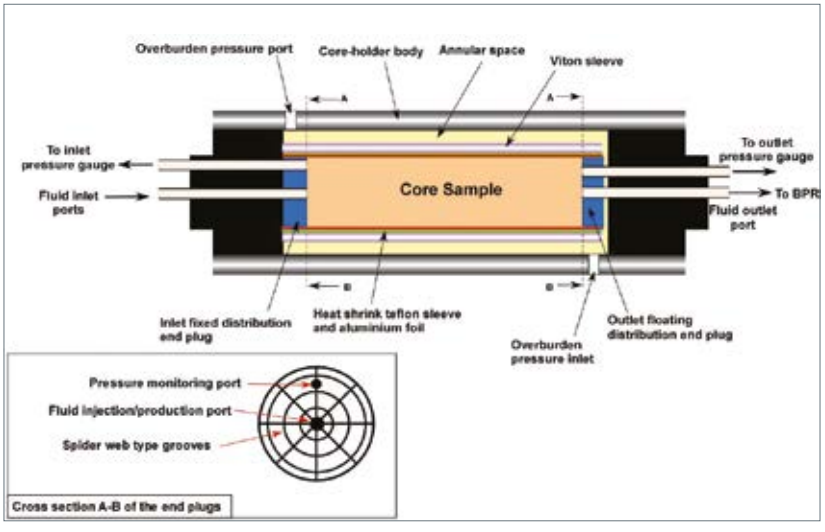
There were still some key uncertainties remaining about the nature of the mechanisms, the causes of the identified fluid-rock interactions, and the extent to which they could impact on the future planning of the SW Hub injection testing. It was observed that the permeability of the Harvey-1 samples would decrease substantially (up to 60%) after undergoing a laboratory core-flooding procedure. Such results could have significant implications for the CO_2 injectivity in the future injection wells at the SW Hub.

The overall objectives of this new work included:

- the identification and characterisation of the mechanisms behind the previously observed petrophysical variations in the post-flood samples;
- characterisation of the in-situ geochemical reactions which may occur at the SW Hub;
- identify the extent of fines migration that occurs, and thus;
- estimation of the relative contribution of geochemical reaction changes versus fines migration as contributors to changes in porosity and permeability induced by flooding.

Interim conclusions suggested:

- The Wonnerup exhibited a great degree of spatial diagenetic alteration. Such alterations have the potential to change the way the formation rock reacts to a CO_2-rich injection fluid during injection.
- The geochemical analysis of the fluid samples, collected during the core-flood experiments, have also revealed that the petrophysical alterations caused to the rock samples is due to the dislodgment and transport of the fine clay particles within the pore space of the rock.
- The computer modelling showed that the experimental conditions used were unlikely to result in major mineralogical and fluid changes, which is confirmed in the results of the core-flood eluent chemistry.



Schematic cross-sectional illustration of the core-holder assembly.

Reference

A. Saeedi, et al 2016, Understanding Fluid Rock Interactions and Their Impact on Rock Properties as a Result Of CO_2 Injection in the SW Hub (7-0314-0233)

Communicating with Communities

A systematic analysis of all existing landowner communications was undertaken to consider and help shape the overall strategy.

This project reviewed the communications strategy of the South West (SW) Hub following their 2014 seismic survey. The SW Hub projects' communications strategy included:

- Face-to-face contacts
- Community meetings
- Local schools
- Attendance at local shows
- Tours of the well site
- Ensuring the Project manager was locally accessible
- Responsive management

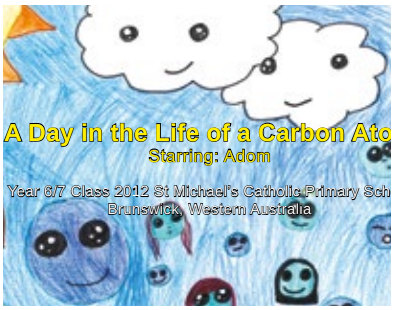
In total there were 125 landholders of whom 75 granted access for the 3D seismic test. Of the 125 customer file notes, every alternate file note was scrutinised in detail. This resulted in 63 records being analysed for this research. Of those, 37 allowed access for the 3D seismic testing while 26 did not. The analysis was then triangulated with secondary data from media articles and websites and 18 telephone interviews. These were conducted with a cross-section of impacted landholders, project proponents, contractors and representatives from the local consultative committee.

It is interesting to note that several key themes are common to both groups (those who granted access and those who denied access), which suggests such themes are not just project related. Examples of how DMP and contractors helped to overcome these are expanded on in the report.

Despite the positive outcome of the land access negotiations for the 3D seismic survey, many landholders were keen to ensure that everyone was aware that their granting access for the survey would not necessarily translate into support for the CCS project. Therefore, continuing to build and maintain a trusting and positive relationship would have been essential if the project progressed through its planned stages. A number of recommendations arose from this work for consideration by the project proponents, and these recommendations also have relevance for other CCS projects.

Reference

P. Ashworth, et al 2014, Lessons from project level community engagement (7-0414-0227)



Front cover of children's book produced as a result of Carbon Kids' education activities.

Community meetings.

The influence of heterogeneity and diagenesis on injectivity and containment in the Wonnerup Member

The CO_2 storage concept in the South Perth Basin relied significantly on trapping CO_2 in the pores of the reservoir rock as it moves. Heterogeneity at the sedimentary bed scale of tens of metres can be used to advantage by reducing the vertical movement of the CO_2 plume thus increasing the lateral spread and the amount of space in the reservoir filled by the CO_2.

In a storage complex that depends on non-structural trapping, heterogeneity at the sedimentary bed scale of tens of metres can be used to advantage by reducing the vertical movement of the CO_2 plume thus increasing the lateral spread and the amount of space in the reservoir filled by the CO_2. Conversely, reduced reservoir quality due to diagenesis on the regional scale presents a major risk for injectivity and total capacity. Therefore, properly assessing the sources and scales of heterogeneity, understanding the impacts on storage, and predicting reservoir quality away from the well control was a key focus for these types of storage sites.

This work characterised the sources of reservoir heterogeneity in the Wonnerup Member and assess its impact on injectivity, vertical migration, and containment, via a series of reservoir simulations.

The goal built on the existing database, reservoir formation evaluation, and models, integrating new core analysis, seismic attribute analysis, and reinterpreted down-hole well data. The various sources of data were reconciled into the static model to create a "three-dimensional risk map" showing parts of the site that have high, medium, or low prospectivity for storage. This model was tested in a series of dynamic simulation scenarios to better understand storage potential. However, the study aimed to go beyond standard characterisation and modelling, to deliver a comprehensive site risking workflow and tool. Rather than just a series of simulation results, this tool was a 3D model that could be used to easily identify the areas that either required more data or have the highest chance of success for injectivity and containment, which was essential for planning any future appraisal drilling operations.

A comparison of all the facies schema analysed in this study is presented in Figure 1. These are ordered in groups of facies with similar reservoir quality from high energy sandstones through to baffles. Core facies are considered the most reliable as they are based on hard data. Image logs provide the next best proxy for the core data for picking lithofacies, having the advantage of describing the cross-bedding, which is important for anisotropy. The expert assisted log derived facies and electro-facies, calibrated to the cores, are considered an appropriate substitute for cores particularly in defining baffles. The expert assisted facies classification picks up most of the baffles but may overestimate quality in sandstones at depth. The electro-facies approximate the core facies on a broad scale and also appear to pick up the lower quality reservoir sandstones that could be attributed to diagenetic processes at depth, which can further improve modelling assessments.

Reference

T. Dance, et al 2016, The influence of heterogeneity and diagenesis on injectivity and containment in the Wonnerup Member (7-1215-0263)

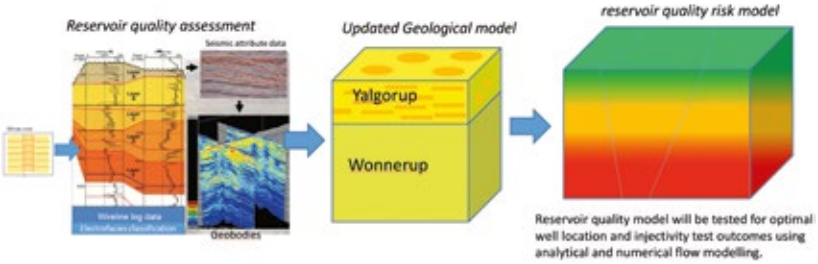


Figure 1: A workflow and system for reservoir quality 3D mapping analysis

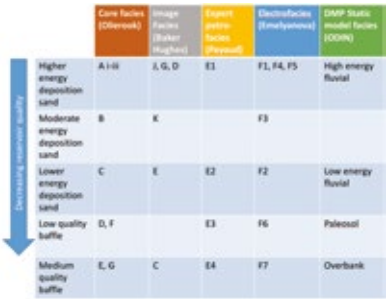


Figure 2: Matrix of all the facies schema against a scale of decreasing reservoir facies from high energy reservoir sandstone to baffles.

Presenting possible pathways for migration through faults and fractures

The area of the Harvey 3 well is a potential geo-sequestration test site. Using innovative approaches, this project aimed to provide structural and stratigraphic information necessary for the construction of a precise static model and subsequent dynamic studies.

With the absence of well-data in the South Perth Basin, uncertainty exists around its since structural features; these have been extrapolated from information several kilometres away. Fault tips and termination points are undefined, while distribution or even presence of palaeosols are uncertain.

Research is delivered, high-resolution seismic data which included a combination of nested surface 3D seismic data in combination with 3D Borehole seismic data that enabled detailed structural and stratigraphic analysis from very shallow depths (50 m), all the way to the reservoir depth. As the land access to the site is variable and problematic, an effective alternative access solution has been to acquire a set of high resolution offset borehole seismic surveys accompanied by the walk away vertical seismic profiles (VSP) along the accessible tracks/roads. These surveys complement the patch surface 3D survey.

As the land access to the site was extremely difficult and changed significantly during the planning stages, the solution chosen was to have a unique survey design with the best possible coverage on the surface and to smoothly merge the subsurface illumination.

This unique acquisition design was acquired with the following datasets;

- High density 3D surface seismic data (the total imaging area, utilising all ground equipment, is around 2.1 km^2).
- 3D VSP data.
- Multi -source offset borehole seismic (MOVSP) data consisting of 451 positions for each borehole receiver array of 10 levels.
- 5 x 2D seismic lines.

From the result, in Figure 2, it is clear that the data quality is high allowing very detailed interpretation. Several small discontinuities are indicated from 3D high-resolution seismic cube. These ae very discrete and small discontinuities and further confirmation is desirable. We expect that VSP images will be utilised to verify current interpretation together with the diffraction analysis. Six faults are interpreted in the Wonnerup Member, four being located to the east of the nested survey affected by pull-up effect. Eight faults are interpreted in the Yalgorup Member. Eight faults are interpreted in the Eneabba Formation.

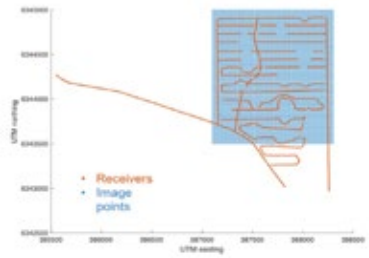


Figure 1: Survey layout: source lines are shown in red, image area in blue

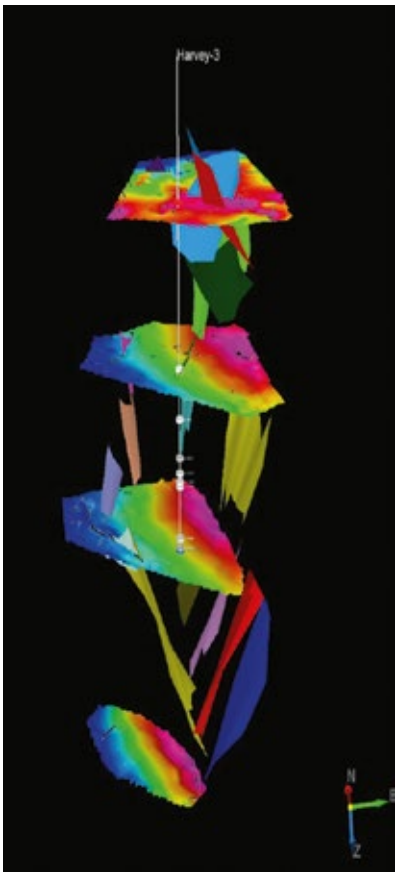


Figure 2: Geological interpretation of the H-3 nested 3D with top formations and faults

Reference

M. Urosevic, et al 2016, Potential for preferential flow through faults and fractures (7-1215-0261)

Using multiple barriers to contain CO_2

This project's goal was to improve knowledge of the nature of the Yalgorup Member. It tested the rock reactivity and transmissivity to CO_2-rich fluids, via a comprehensive multi-scale and multi-physics analysis.

Data exists across multiple scales for the Yalgorup member of the South Perth Basin requiring integration to provide reasonable constraints for the static and dynamic simulation models.

This work evaluated the petrographic, petrophysical and mechanical properties of the palaeosols and interbedded sand sequence, before and after sample ageing. The results constrain a conceptual model to study the hydrodynamic and geochemical feedback between the mud-rich facies and sand bodies. Assessing the intrinsic sealing capacity of the Yalgorup Member, uses current and palaeo-formation water salinities in the sand beds.

Facies-derived seismic attributes inversion and stochastic modelling calibrated using the multiscale petrophysical characterisation are designed to provide a facies and properties 3D geo-model of the Yalgorup Mbr. This assisted in carrying out initial connectivity assessment and investigate baffle distribution.

The project was articulated around four modules:

» Characterisation: establishing the nature and properties of the mudstones and associated facies,

» Compartmentalisation: investigating the existence of compartments,

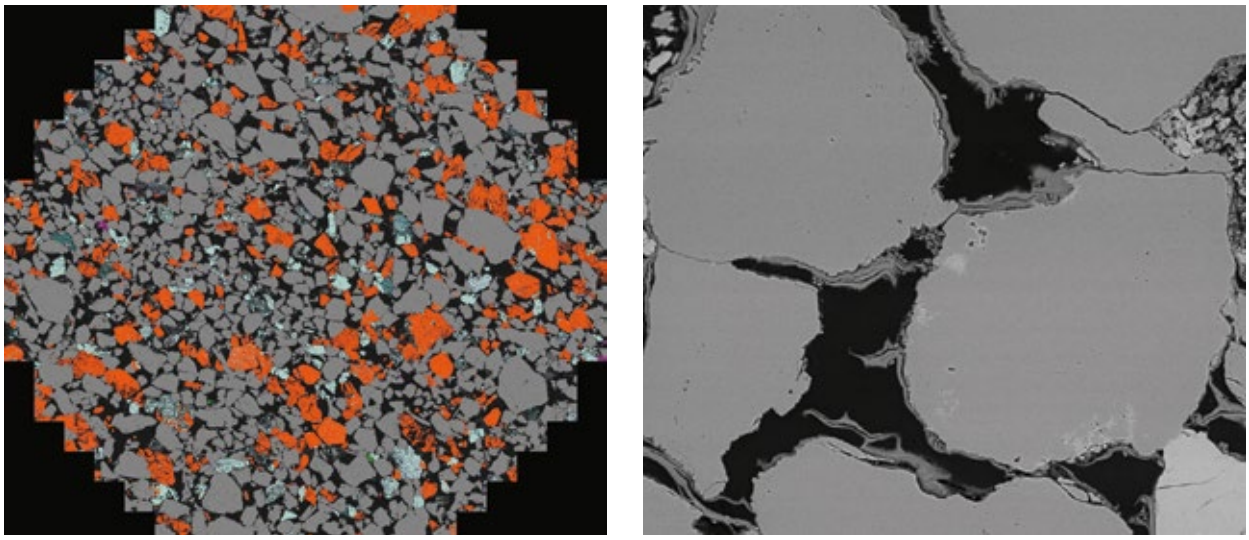
» Experimental geochemistry: testing reactivity to CO_2-rich fluids,

» Visualisation: assessing overall baffle distribution.

Overall, formation water salinities were used as a proxy for evaluating the existence of fluid compartments. Comparing fluid inclusion data and experimental electrical resistivity measurements data, the results showed similarity and the contrast in salinity between the Yalgorup and the Wonnerup Member appeared to be real but small. A salinity of 45,000 ppm or 45g/L for the Yalgorup Member was seen as the best estimation. Recent salinity data from fluid inclusions deeper in the Wonnerup Member indicate lower salinity values and support the existence of possible horizontal compartmentalisation between the sands in the Wonnerup and the Yalgorup members.

Reference

J. Bourdet, et al 2016, Assessment of multi-barrier systems for CO_2 containment in the Yalgorup Member (7-1215-0262)



SEM-EDS map (top) and SEM-BSE image (bottom) of a sandstone. Clay coating around grains, typically present in coarse alluvial material in upper phreatic zone, are frequently observed in the Yalgorup Member.

Predicting and testing CO_2 plume development in the South Perth storage complex

Significantly different plume migration is predicted, depending on the choice of model used for the South Perth reservoir. This work has delivered an assessment of the regions in the Lesueur Formation, where conventional Darcy flow models are most appropriate, and regions where invasion percolation models may be appropriate.

Several modelling approaches were available:

» Darcy flow – slow moving, continuous plume, limited distance.

» Invasion percolation – complex migration pathways, large distance.

» The difference in results is largely due to difference in resolution of capillary entry pressure heterogeneity.

Appropriate well testing was required to inform/validate modelling approach.

As currently understood, containment within the Lesueur Formation relies largely on a multi-barrier trapping system in the ~1500 m thick Wonnerup Member reservoir interval and the ~ 600 m thick overlying Yalgorup Member, which included:

» low-permeability intraformational seals or baffles,

» residual (capillary) trapping, and

» dissolution of CO_2 in the formation water.

The effectiveness of these trapping mechanisms in the Lesueur Formation can be assessed through modelling the vertical and horizontal migration behaviour of CO_2 injected into the lower portion of the Wonnerup Member.

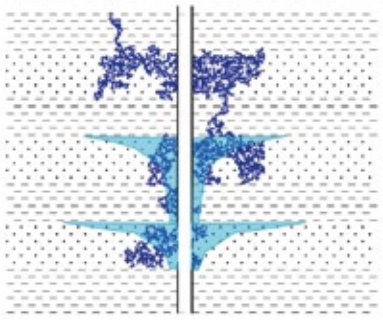
At the injection well, CO_2 will move laterally outward, predominantly through Darcy-type viscous flow that can be modelled using conventional reservoir simulators. Away from the injector however, CO_2 migration may be increasingly vertical and dominated by gravity and capillary forces. This migration behaviour can be modelled using an invasion percolation code when the Capillary Number is less than 0.0001.

This project:

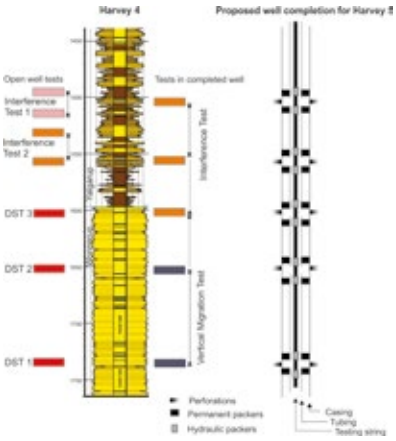
» delivered an assessment of the regions in the Lesueur Formation where conventional Darcy flow models are most appropriate and regions where invasion percolation models may be appropriate.

» developed generic models that tested sensitivities of capillary entry pressure values with respect to CO_2 migration and residual trapping in the SW Hub context.

This report also proposed concepts for a set of well test configurations for measuring parameters that affect the vertical sweep efficiency and, ultimately, the overall containment potential in the Lesueur Formation at the SW Hub site at a commercial field scale.



Conceptual depiction of a CO_2 plume predicted in a Darcy-flow simulation (light blue) versus a modelled flow path using an Invasion Percolation approach (dark Blue)



Close-up of the Harvey 4 well logs across the boundary between the Wonnerup Member and the Yalgorup Members showing options for open well test locations and well completion intervals for interference and vertical migration testing.

Reference

K. Michael, et al 2015, The Lesueur: Vertical connectivity, injectivity and residual trapping (7-1115-0242)

Feasibility of monitoring an injected CO_2 plume

The ability to detect and determine the extent of the injected CO_2 plume in the South Perth Basin was essential for the verification of storage containment and efficiency.

Monitoring technology needs to provide sufficient certainty for the regulator and the public that the injected CO_2 will remain in the defined storage complex and to verify reservoir model predictions regarding the behaviour of the CO_2 plume. This project assessed the appropriate technology and their resolution capable of mapping the movement of injected CO_2 over time.

Using current models and simulations, desktop studies were undertaken to evaluate the limits of detectability of the plume within the storage container. The outcomes of these studies were then used to consider the practical application of each technique in terms of field equipment, manpower, resolution, timing and cost. The techniques have been assessed and their application is compared in terms of their resolution, relative cost and timescale.

The workflow for each component included:

- Prediction of the time-lapse response associated with CO_2 injection for each technique using the latest geological and simulation model.
- Assessment of the detectability of the changes.
- Estimation of the uncertainties in monitoring plume development.
- Consideration of the practicalities of field deployment and data analysis.

The project assessed the ability of various surface geophysical and well-based monitoring techniques such as seismic, gravimetry, magneto-telluric (MT), electromagnetic (EM), InSAR in detecting and visualising the CO_2 plume.

Pressure monitoring requires investment and planning up front however, once the initial is made it is a sensitive and relatively inexpensive system to maintain. Seismic surveys bring difficulties in access and costs however it provides 3D visualisation of the plume. Inclusion of permanent buried arrays and borehole seismic significantly reduce the cost of obtaining the data.

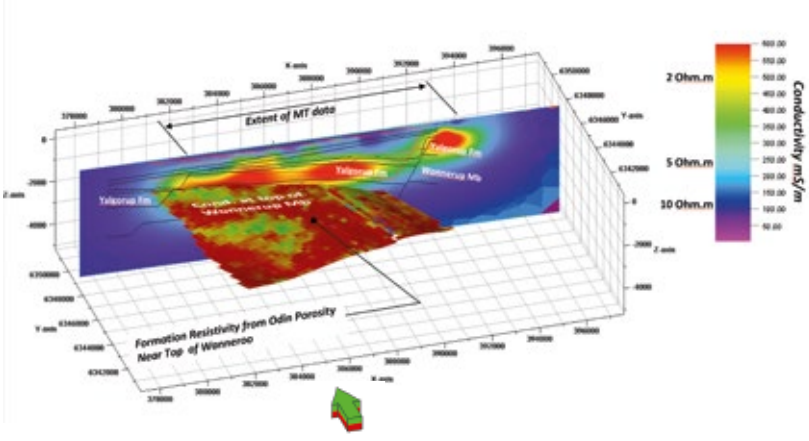
Gravity, MT and EM methods were well suited to complementing the pressure and seismic data. The technology is rapidly developing, producing increased resolution and reducing costs.

The technologies were also relatively cost effective to deploy and permanent stations can be set up to remotely produce and return data.

The deliverable provided recommendations for a selection of suitable monitoring technologies and a proposed monitoring strategy for CO_2 plume tracking and visualisation at the South West Hub project site.

Reference

A. Hortle, et al 2016, Feasibility of monitoring an injected CO_2 plume at the SW Hub (7-0314-0232)Integration (7-0314-0225)



First pass MT derived resistivity (17 stations) versus calculated resistivity at top of Wonnerup

Using passive seismic acquisition for imaging in South Perth Basin

Monitoring, Measurement and Verification (MMV) is an important aspect of any CO_2 geosequestration project. How to use passive seismic approaches remains unclear and each application will be site specific.

Regulators, stakeholders and local communities will likely required that each storage site be: 1) monitored before CO_2 injection to determine background or baseline conditions; 2) monitored during CO_2 injection to ensure that the CO_2 is filling and contained in the storage reservoir as expected; and 3) monitored after CO_2 injection ceases to ensure that the CO_2 plume is stable, the storage reservoir is performing as expected, and no migration outside the storage complex has occurred. Passive seismic monitoring is the science of recording and analysing natural or induced seismicity with surface and/or borehole sensor arrays, without the need for active (man-made) seismic energy sources.

This research was based on data acquired with a sparse network of sensors over a period of 12 months measuring and interpreting background seismicity and noise conditions in the South Perth Basin; the first stage needed in a comprehensive seismic monitoring program. The seismic network consisted of 7 near surface and autonomous stations located in the South Perth Basin area. The sensor choices and network design was developed under a previous ANLEC R&D project. Additionally, a shallow borehole test array was deployed and connected into the seismic network.

Magnitude-frequency curves using historical seismicity catalogues and data collected during the monitoring phase was developed to establish the rate of background natural seismicity in the project area.

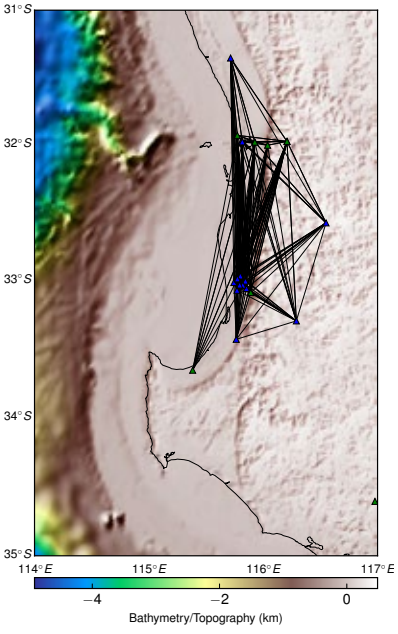
Seismicity data were interpreted, within a 3D geological framework assessing the association of natural and induced seismicity with geological structure and integrated with other ANLEC R&D studies of tectonic stresses, local faults and geomechanical lab measurements.

Both of the ambient seismic noise correlations and the Rayleigh wave ellipticity angle analysis (H/V) methods provided repeatable imaging without any acquisition cost except the running expenses of a seismic station. This information was used for CO_2 injection monitoring or used to design the active 4D seismic monitoring strategy.

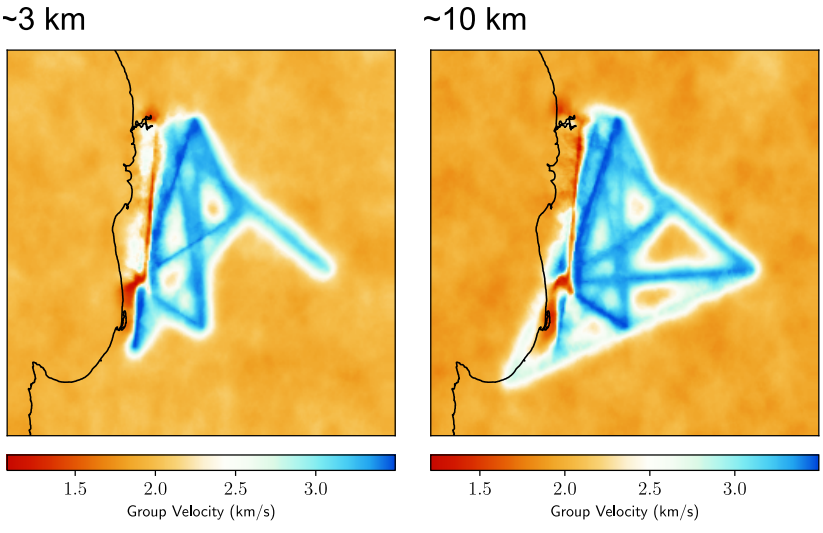
Comparisons of state of the art sensor technologies were discussed to advance the techniques of passive monitoring and assess monitoring limitations. Community engagement continued with information sessions and reports on the science of micro-seismicity.

Reference

E. Saygin, et al 2016, Passive seismic investigation at the SW Hub (7-0215-0244)



Seismic ambient noise correlation raypaths between station pairs



Ambient seismic noise tomograms

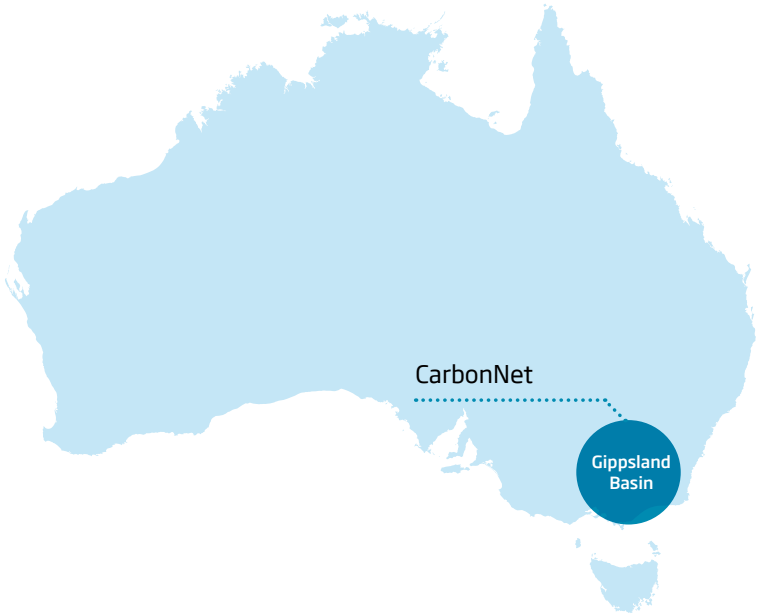
Gippsland Basin

In February 2012, CarbonNet was announced as the second national CCS flagship. In Victoria, a substantial history of geological characterisation has occurred in the Gippsland Basin owing to conventional oil and gas development offshore, brown coal development and significant groundwater resource utilisation on-shore. Prior regional characterisation of storage capacity has described the off-shore commercial storage potential in the Gippsland Basin as arguably the best in Australia.

Goal

To support CO_2 storage in the off-shore Gippsland Basin

Victoria



Scale Key

- In lab
- In Field

Delivery Key

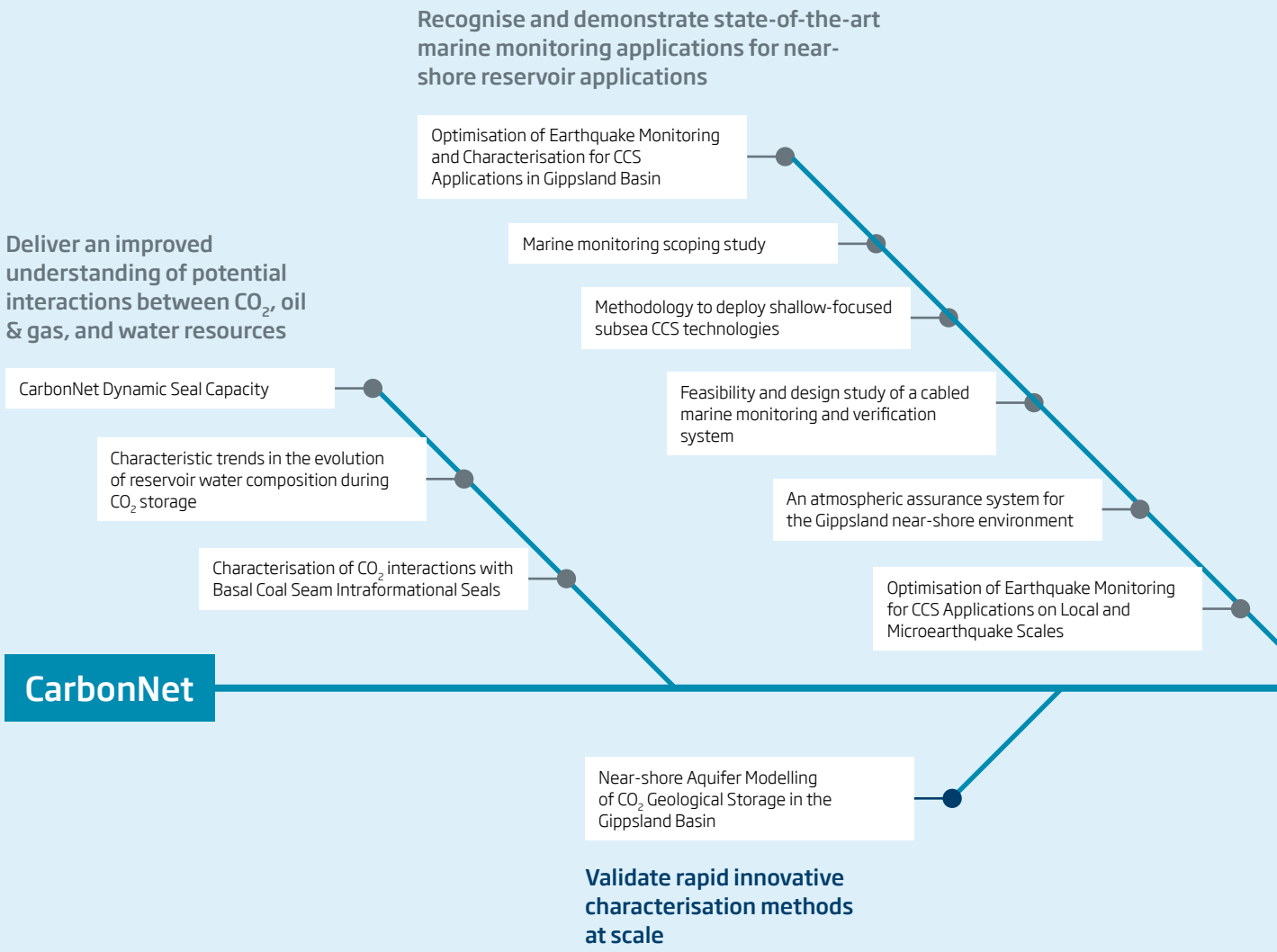
- New Data
- New Application
- Field Validation
- New Correlation
- Permitting & Public Communication

Photo courtesy of CO2CRC

Impact Area	Impact Statement	Delivery
Reservoir Containment	*To deliver an improved understanding of potential interactions between CO_2, oil & gas, and water resources*	
Public Acceptance	*To recognise and demonstrate state-of-the-art marine monitoring applications for the offshore reservoir applications*	
	To communicate the science that underpins CO_2 storage in the sub surface for the off shore Gippsland Basin	
Reservoir Capacity	*Validate rapid innovative characterisation methods at scale*	
Reservoir Injectivity	*Deliver new data and fundamental correlations on the CO_2 flooding dynamics of reservoir rocks under in-situ injection conditions*	

Adapted from CSIRO: M. Bazzaco, CSIRO Impact Evaluation Guide, 2015

Supporting Research: Gippsland Basin



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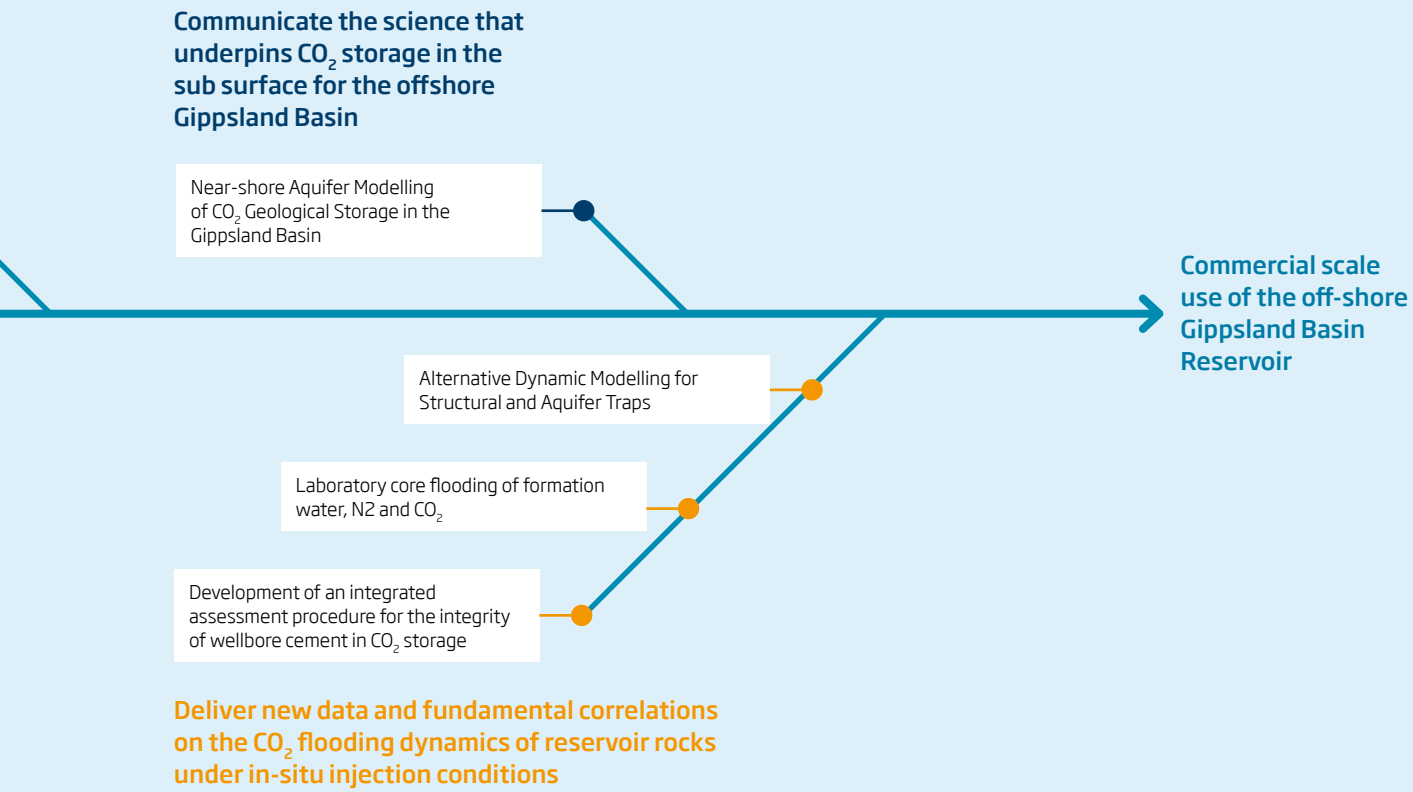


Research Key

- Reservoir Containment
- Public Acceptance
- Reservoir Capacity
- Reservoir Injectivity

Research Projects

Explaining seabed processes in the Nearshore Gippsland Basin

In the near-shore Gippsland basin, it is important to understand any unusual or unique features that may be perceived as 'at risk of potential impact' from a CCS development. One such feature is a limited area of prominent channels, or possibly sub-aqueous dunes, extending from the near-shore to depths of around 40m.

This research project investigated the nature, origin and biological significance of these 'channels'/ seabed features, initially from existing literature and datasets, with follow-up field survey. This investigation provided novel insights into dynamic processes in the nearshore Australian seabed. Understanding links between these features and biotic communities aided in ecological understanding and assisted conservation of these marine ecosystems. Understanding acoustic, visual and geochemical signatures associated with these features informed baseline monitoring needs for potential future marine monitoring and verification (MM&V), and permitted identification of false positives in monitoring data.

Project scope:

- Desktop study to formulate initial hypotheses regarding seabed features.
- Scoping for field surveys to test hypotheses of origin and habitat provided by coastal seabed features.
- Field surveys in the Gippsland Basin.
- Interpretation of field data.
- Hydrodynamic Modelling.
- Integration.

Conclusions from desktop study:

Structural geology

- There were no direct links identified between the deeper geology, structural elements and the dune-like features identified on LiDAR. However, there are indications of potential hydrocarbon leakage.
- Possible natural gas chimneys, not associated with faults, were identified; their location did not correlate with specific features on the seabed.

Hydrogeology

- There was no direct evidence in the literature for seepage of hypersaline brine originating from the Gippsland Lakes at the seafloor.
- If brine seepage is occurring, it is unlikely flow rates would be such that they could form channels at the sea floor.

Marine benthic habitats and fauna

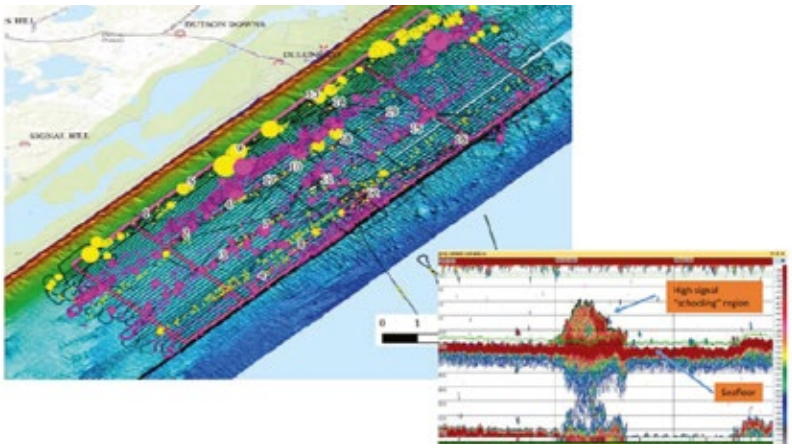
- Fauna in this area was characterised by high diversity, few common species and high spatial and temporal variability.
- The patchy, highly abundant and diversity in faunal assemblages also meant there is a need to find individual taxa or groups of taxa which can be shown to respond to elevated carbon dioxide (CO_2).

Outcomes:

- Determined the origin and composition of seabed features and produced an assessment of the nature of the seabed features identified and their associated biotic communities. This informed the risk profile of CarbonNet operations and could help inform possible future MM&V priorities and approaches.

Reference

A. Ross, et al 2017, Seabed processes in the Nearshore Gippsland Basin (7-1115-0250)



Left: spatial distribution of 120kHz acoustic backscatter, yellow circles chow day time while magenta circles indicate night time backscatter. Circle size is proportional to the total water column backscatter from seafloor to surface for ervery 100m interval. Right 120kHz echograms from day time (top panel) and night time (bottom panel).

Near-shore marine monitoring for CCS will have to account for large natural variations

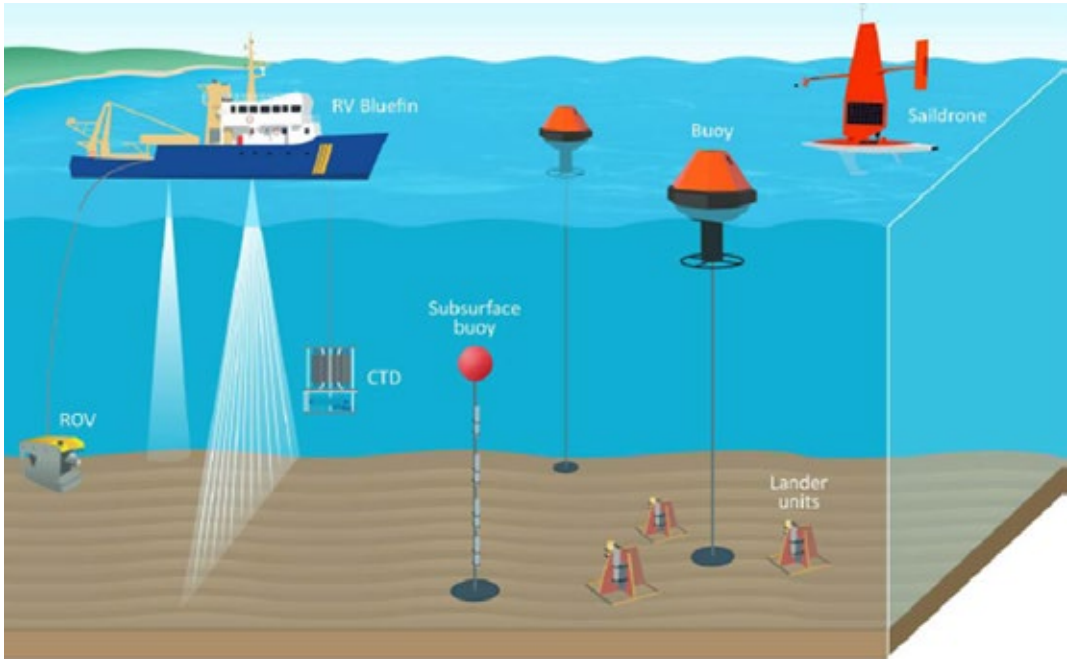
Offshore Gippsland was widely recognised as one of the most promising CCS sites in Australia, with its proximity to large point sources and promising storage offshore.

Measurement, Monitoring and Verification (MM&V) involves the systematic collection and interpretation of data to enable regulators to assess the CCS project operational and environmental performance. This project describes a major study to inform the development of marine assurance monitoring approaches for CCS operations in near-shore coastal regions. Over the course of the project, the CSIRO team completed 22 voyages in the Gippsland CCS study area, gathering data to characterise the area and test the suitability of equipment (moorings and sensors) for CCS monitoring.

This report synthesises the learnings of several research tasks to address three key technical assurance monitoring challenges. The "signal-to-noise" problem which distinguishes carbon dioxide release signatures from similar natural variability to reduce false alarm rates in future baseline monitoring designs. It characterises impact by determining the level of carbon dioxide release that would be associated with environmental impact at a range of scales. Attributing impact by distinguishing changes resulting from other drivers and pressures in multiple-use zones. The project outcomes have been delivered through several reports and includes information on network designs for CCS site marine measurement, monitoring and verification.

Part 1: Optimising sensor configurations on fixed and mobile platforms for improved signal retrieval. This report documents the key outcomes from the experimental investigation of optimal sensor configurations including the validation, in-field, of sensors integrated on several platforms. The initial testing of the sensor configurations on the Unmanned Surface Vehicle (USV), moorings and landers. The development of operational configurations and procedures for the USV. Limited demonstration of near-real time (NRT) data stream processing for data from the sensors. The development of initial recommendations for optimisation of the MM&V network design.

Part 2: Near Real Time and Delayed Mode data QC protocols. The report documents the near-real-time (NRT) and delayed mode (DM) data quality control protocols, metadata structures and archive file



formats for data generated by the fixed and mobile platforms deployed into the near shore area during 2018.

Part 3: Modelling. This report addresses the CO_2 plume signal analysis and optimised sensor network configuration within a 3D hydrodynamic model of Bass Strait. Two numerical ocean models were deployed for offshore Gippsland. The models provide unique insight into the morphology of a hypothetical CO_2 release and how it differs from the naturally varying background and allow the detection and impact length scales of any artificial release to be estimated providing critical information for monitoring design.

Part 4: Biological Investigation. This report focuses on the investigation of natural variability in biological indicators of environmental impact. The approach taken has been to first gather biological data on the Gippsland area via a number of targeted field surveys. This data has enabled an understanding of the patterns of diversity and abundance of subtidal benthic sediment infauna, meiofauna and flora present in the area. This data was then considered in the context of international literature on biological impacts of CO_2 to assess whether any biota present in the Gippsland region may prove to be useful parameters for CCS monitoring purposes.

Part 5: Fixed Platforms. This report highlights the application of fixed sensor network designs for CCS site MMV. The work demonstrates the instrumental and operational constraints of fixed MM&V platform deployment into the coastal Gippsland marine environment. The surface moorings and seabed landers tested during this project have been proven to be capable of sustained observations of the order of 6 to 9 months without intervention. The on-board sensor systems provided high quality datasets which have enabled characterisation of the oceanographically complex, high energy coastal Gippsland environment. The in-water measurements taken during the deployments have also begun to characterise the tidal, diurnal and seasonal variation at the Gippsland study site. These data have been critical calibration data for the 3D bio-geochemical models developed for the project.

Part 6: Mobile Platforms. The work reports on considerations for integration of mobile platforms with a fixed sensor design network. It investigates how the spatio-temporal variance structure of a marine CCS site may be characterised and monitored using mobile monitoring platforms. Within the marine technology domain, it is widely acknowledged that autonomy will underpin the future of ocean operations. Unmanned surface and autonomous underwater vehicles (USVs and AUVs) are rapidly evolving in their performance, sophistication, and accessibility. The work demonstrates that mobile platforms are an essential part of a MM&V program where both crewed vessels and unmanned surface vessels play a valuable and differentiated MM&V role.

Part 7: Feasibility and design study of a cabled marine monitoring and verification system. This work delivers a design study for integrating the sensor technologies into a cabled observatory concept. It was designed to provide a CCS proponent with several options that will permit robust and cost-effective Marine M&V plans to be developed. It reports on engineering constraints, data processing requirements and a suite of sensors and platforms that might be employed during the planning process. Several cabled observatory configuration scenarios, from sparsely to highly instrumented, were developed and discussed to compare and contrast different deployment configurations and replications of the core 3 – platform system. In addition, three potential construction and maintenance vessel options were examined and a cost model developed.

References

Volume 1

Ross A., Myers J, Van Ooijen. E, Greenwood J, Ryan T, Hughes D, Marouchos A, Keesing J, Scoulding B, Jenkins C, 2022: Synthesis Report on network designs for CCS site marine Measurement, Monitoring and Verification – (7-0816-0305)

Volume 2

Ryan T et al, 2019: Optimising sensor configurations on fixed and mobile platforms for improved signal retrieval within a shallow-sea monitoring network design

Slawinski D et al, 2019: NRT and DM data QC protocols, metadata structures and archive file formats

Greenwood J, Mongin M, 2020: CO2 plume signal analysis and optimised sensor network configuration within a 3D hydrodynamic model of Bass Strait

Keesing J et al, 2021: Investigation of natural variability in biological indicators of environmental impact

Hughes D et al, 2021: Application of fixed sensor network designs for CCS site marine measurement, monitoring and verification

Marouchos A et al, 2021: Considerations for integration of mobile platforms with a fixed sensor design network

Evaluating seismic events in the Gippsland Basin

Seismicity provides several issues for CO_2 storage proponents, both in regard to natural background seismicity and induced seismicity.

Natural seismicity emanating from existing compliant fault structures may indicate compromised integrity of seals on the timescale of millennia, while induced seismicity indicates an element of risk whenever subsurface operations have potential to increase formation pore pressures.

The project utilised the deployment of new seismic recording equipment, to understand and integrate into the existing Western Gippsland seismic network operated by the University of Melbourne. The instrumentation was used to test different design configurations that allow routine detection of micro seismicity of magnitude 1.0 across the western part of the Gippsland Basin, and magnitude 0.5 in target reservoirs. Seismic data from the entire network will be processed to recover precise locations; and inverted for stress regimes and velocity structure.

The geometry of the seismic network is based on monitoring at two complementary scales:

» A local earthquake scale to cover the earthquake activity of the Gippsland Basin

» A microearthquake scale using a dense network to detect small events in areas of particular interest around potential CCS sites.

Both scales were assisted by a number of Ocean Bottom Seismographs (OBS), which were located at sites appropriate for the main task at the time.

The Local Network

The local earthquake network incorporates an 'L' shape, with one arm northeast along the coast from Wilson Promontory to Lakes Entrance, and a perpendicular line southeast from Wilson Promontory to Flinders Island. This region has had no local seismograph coverage in the past, with all seismographs at moderate distances. The new network allowed improved accuracy in assessing earthquake epicentres and much better depth estimates, plus more details on the earthquake source, including moments and moment tensors, and focal mechanisms.

The Microearthquake Network

The microearthquake network is at a scale smaller than the local network, but larger than the typical seismograph network used to record earthquakes and rockfalls within mines.

It is at a scale comparable with induced seismicity networks installed around large water reservoirs. At larger scales the use of both P and S wave data provides good control on depth for earthquakes inside the network, with reducing control on depths of earthquakes outside the network. This large seismograph network utilises an efficient and reliable data management system.

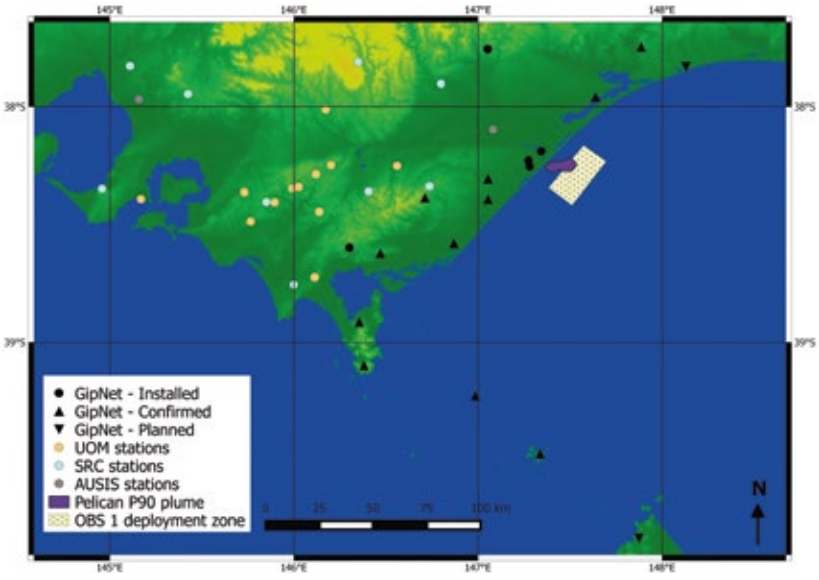
Key project outcomes were:

» The development of protocols for optimising seismic monitoring in coastal regions where seismic noise, mainly caused by ocean waves, was a particular issue.

» Establishment of much improved baseline seismicity levels, the natural state of tectonic stress, site response and seismic velocity structure in and around prospective storage sites.

Reference

M. Sandiford, et al 2016, Optimisation of earthquake monitoring for CCS applications on local and microearthquake scales (7-1115-0284)



Proposed GipNet local seismic network, shown with existing seismometers in the Gippsland Basin

Earthquake Monitoring and Characterisation for CCS Applications

This study was designed to optimise earthquake monitoring around reservoirs in the offshore Gippsland Basin being developed for commercial-scale carbon sequestration.

Using a mix of surface, posthole, borehole, and ocean bottom seismometers (OBS) it aimed to acquire field datasets and develop practical workflows computational tools and field protocols.

To satisfy regulatory requirements and provide confidence and assurance to key stakeholders and the public, such results would provide a means of assessing the security of CO_2 storage at a site prior, during, and post- injection.

Since 2017, over 2,500 natural earthquakes have been located, with the majority being too small to be felt by humans. Just 24 events were recorded with magnitudes (ML) > 3.0, and nine of these occurred as part of the aftershock sequence following Victoria's largest onshore event. Significantly, since 2017 no natural seismicity has been recorded within 15 km of the proposed storage site, and nearby events all have depths exceeding 10 km, placing them deep within the crystalline basement.

Over the course of three cycles of OBS deployments, it became evident that the shallow (~30 m water depth) marine environment around the Gippsland site is highly dynamic due to anthropogenic activity and weather conditions, making it challenging to operate submarine monitoring instruments. This necessitated the development of innovative computational workflows to process and improve OBS data which enabled improved accuracy of earthquake characterisation using this dataset.

The experience with operating OBSs in shallow Bass Strait has led to the development of new operational protocols and recommendations for future monitoring efforts in this environment, including the need for trawl-resistant sensors, site selection and operation based on the automatic identification system (AIS) used to monitor marine traffic.

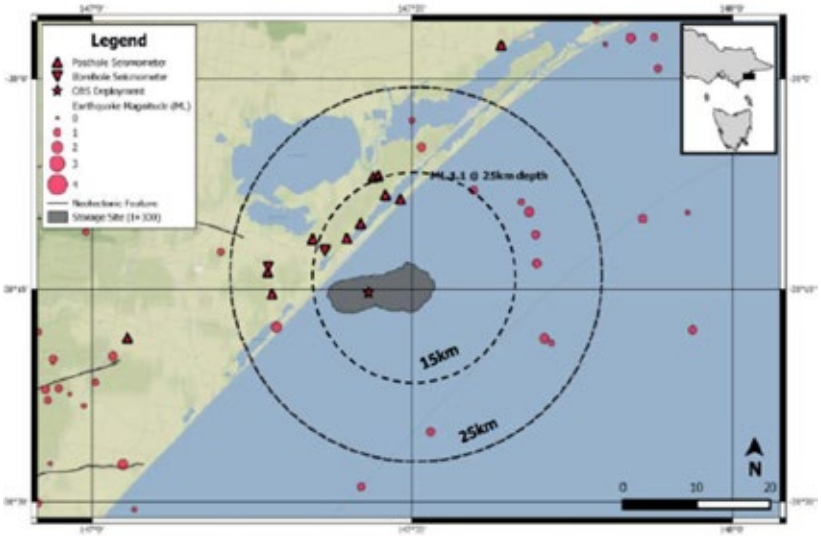
In the absence of natural seismic events recorded within 15 km of the storage site, two discrete software packages were developed to model detection and location sensitivities and other earthquake networks. Sensitivity analysis was conducted through two developed methods; a cloud-based, ray theoretical approach, and a more computationally intensive, full-waveform simulation performed with synthetic seismograms.

Based on the results of the analysis, the University of Melbourne Seismic Network (UMSN) is shown to be capable of detecting and locating earthquakes with ML ≤0 proximal to the CO_2 storage site

The research delivered two discrete software packages to model detection and location sensitivities of earthquake networks. SENSI uses a cloud-based, ray theoretical approach to assess network thresholds, and has been implemented as a user-friendly open-access web app and launched on the AVRE portal at http://avre.auscope.org/store. A more advanced, but computationally intensive, method of assessing network threshold was also developed.

Reference

J Attanayake, A Jones, T Mo, M Sandiford; Optimisation of Earthquake Monitoring Characterisation for CCS, 2023 (7-0324)



Earthquakes located close to Gippsland site. OBS location shown for test deployment.

Understanding the evolution of reservoir water chemistry composition during CO_2 storage

Site-specific characterisation, the prediction of CO_2 plume migration and changes in physical and chemical conditions over time are important elements during the exploration and appraisal of prospective CO_2 storage reservoirs.

The formation water composition and lithologies can vary significantly between and within reservoirs. Consequently, the evolution of the formation water composition as a reflection of reactions between minerals and CO_2-enriched water will vary as well. For example, the presence of minor carbonate content will buffer the acidity of water and the dissolution of potassium feldspar leads to a characteristic enrichment in dissolved potassium.

This project studied the geochemical changes in mineral and water composition in the Latrobe Group reservoir upon the injection of CO_2 with impurities (SO_2, NO_2, O_2) using reaction path modelling. Five mineral-composition scenarios (S1-S5) were selected to investigate the geochemical evolution:

- An immature sandstone (S1),
- A mature sandstone (S2)
- A sandstone with dolomite as carbonate cement (S3),
- A sandstone with siderite and dolomite as carbonate cement (S4),
- The Traralgon Formation T2 coal as the local seal (S5).

This study was one of the first attempts to predict the interactions between coal and CO_2-saturation fluid. In the Traralgon Formation T2 coal (S5), siderite dissolution and hematite formation was the main mineral reactions, leading to an increase in Fe^{2+} concentration (up to > 500 mg/L over 1000 years).

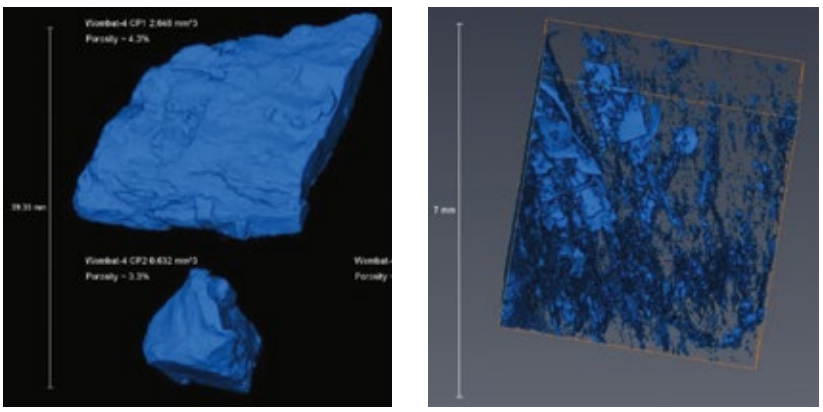
The release of Fe^{2+} is consistent with previous experimental work, which showed that Fe^{2+} was one of the most mobile ions and it was released from carbonates (such as siderite). Further, it was noted that water composition in S5 would stabilise within 5 years. Dissolution and precipitation of other minerals in the coal and the respective changes in concentrations of ions are expected to be negligible. This is due to the high rate of siderite dissolution which is higher than the dissolution rates for other minerals.

The results showed that the injection of CO_2 would initially lower the pH to ca. 3 to 4, as a consequence of CO_2 dissolution and the oxidation of the dissolved impurities H_2S, SO_2 and NO_2, in the presence of $O_{2(aq)}$. However, alkalinity of the formation water (mainly the bicarbonate) and additional dissolved carbonate from siderite and dolomite dissolution would provide a buffer capacity leading to a rapid stabilisation of the pH between 4.0 and 5.0.

Significant increases in dissolved K^+, SO_4^{2-}, Ca^{2+} and Mg^{2+} concentrations are observed as a result of the mineral dissolution. It is noted that SO_4^{2-}, Ca^{2+} and Mg^{2+} concentrations will stop changing in approximately 50 and 600 years, but K^+ will continue to increase even after 1000 years.

Reference

R. Haese, et al 2016, Characteristic trends in the evolution of reservoir water composition during CO_2 storage (7-1115-0249)



Characterisation of T2 coal (S5). Left: porosity scanning of samples and Right: pore voids are not connected

Confirming the integrity of reservoir seal rock to fluid CO_2

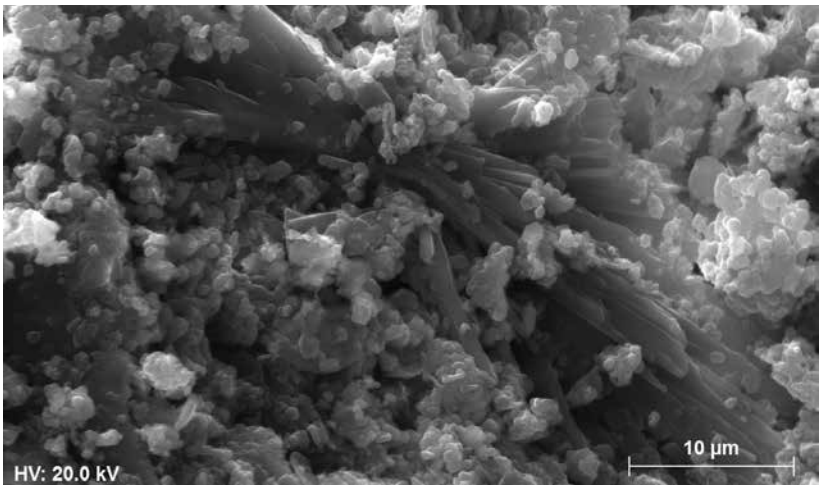
Since fluid transport is limited in shales or seals, due to very low permeability, then any chemical reaction will not proceed very far.

The Gippsland Basin has long been considered to have the potential as a major CO_2 storage site in Victoria, Australia. Some of the possible storage sites are characterised as storage complexes; having large anticlinal structures with four-way dip closure, a highly permeable reservoir and low permeability intra-formational seals and a regional top seal. One of the main leakage risks was likely to be the geochemical and petrophysical influence of the injectate on the seal strata. The cap rock seal efficiency evaluation is a vital part of the assessment of any CO_2 storage site. The main goal of this study was to examine dynamic seal capacity of several Latrobe Group intra-formational shales in the Gippsland Basin and to characterise their cap rock sealing efficiency before and after exposure to supercritical CO_2 ($scCO_2$).

In this study, brine-saturated shale samples were exposed to $scCO_2$ under reservoir conditions for a limited time of approximately 3 months. The study was a laboratory-based core analysis research program focusing on examining any changes to the cap rock mineralogical composition, capillary threshold pressure, pore size distribution and specific surface area before and after being exposed to $scCO_2$. Several analysis methods typically applied in the petrophysical assessment of seal rocks were used, including; x-ray diffraction (XRD), scanning electron microscopy (SEM) associated with energy dispersive spectrometry (EDS), mercury injection capillary pressure (MICP), nuclear magnetic resonance (NMR), low pressure surface area measurements, and micro-CT scanning.

Key conclusions:

- Scanning electron microscopy (SEM) examinations showed precipitation of kaolinite, gypsum and minerals from jarosite group after exposure to $scCO_2$.
- Mercury injection capillary pressure results show a distinct shift toward smaller capillary pressure values for samples exposed to $scCO_2$. This is in agreement with a general shift on the MICP curves toward larger pore and pore throat sizes for most of the samples analysed.
- Reduction of NMR signal after exposure to $scCO_2$ indicates that some of the waters inside the samples were reduced by CO_2.
- The low pressure nitrogen adsorption analysis shows the pore structure changed after shale samples were exposed to $scCO_2$. In general, for most of the samples studied there was an increase in the pore surface area and pore volume, whereas a reduction in the pore diameter can be noted.
- These results suggest that when some of the shale samples studied in this project come in contact with $scCO_2$/brine mixtures they may lose their original integrity as a cap rock and their seal efficiency may reduce. But it has to be noted that since fluid transport is limited in shales, due to very low permeability, then any chemical reaction will not proceed very far. Therefore, the reactions only penetrate a few centimeters and the seal capacity will be unaltered for a thick cap rock.



SEM images showing precipitation of fibrous gypsum and natrojarosite after CO_2 exposure, Sample 4.

Reference

R. Rezaee, et al 2013, CarbonNet Dynamic Seal Capacity (7-1011-0186

Developing an atmospheric assurance system for the Gippsland near-shore environment

This project goal was to establish appropriate monitoring methodologies and technologies for atmospheric environmental assurance in the Gippsland Basin.

New technologies and infrastructure for atmospheric trace gas detection is being developed by the Universities of Melbourne and Wollongong. The technologies combine point and long open-path measurements of atmospheric composition with high-resolution atmospheric inverse modelling. This combination features several new and unique capabilities; measurements of multiple trace gases, including isotopic CO_2, and fine scale regional modelling at spatial scales comparable to the open-path measurements. Together, the range of measurements and modelling will be combined to develop an assurance system for deployment in the Gippsland nearshore region. Such a system, if feasible, will provide data for public and to meet regulatory requirements.

Open-Path Fourier Transform InfraRed (hereafter "OP-FTIR") spectroscopy has been pioneered and applied at the University of Wollongong to the measurement of concentrations and fluxes of atmospheric trace gases. When mounted on an automated tracking head, the OP-FTIR is capable of observing multiple paths in sequence from one FTIR instrument and multiple reflector arrays. An OP-FTIR system using the shorter near-infrared wavelengths has been demonstrated for measurements of CO_2, CH4, and O_2 over a one-way pathlength of 1.5km.

Inverse modelling of greenhouse gases is the process of determining sources and sinks of GHGs from measurement of their concentration. More recently, with the arrival of high-precision continuous measurements, the technique has been increasingly used to determine sources and sinks at regional or point scale.

The atmospheric component of the CarbonNet monitoring and verification will enable the variability in the atmosphere to be characterised into natural and anomalous components.

Project development themes:

- Characterisation of open path-FTIR performance.
- Calibration of open-path FTIR measurements.
- Optimisation of the atmospheric measurement network design for Gippsland near-shore basin.
- Validation of the model-measurement assurance system.

The project goals were realised by:

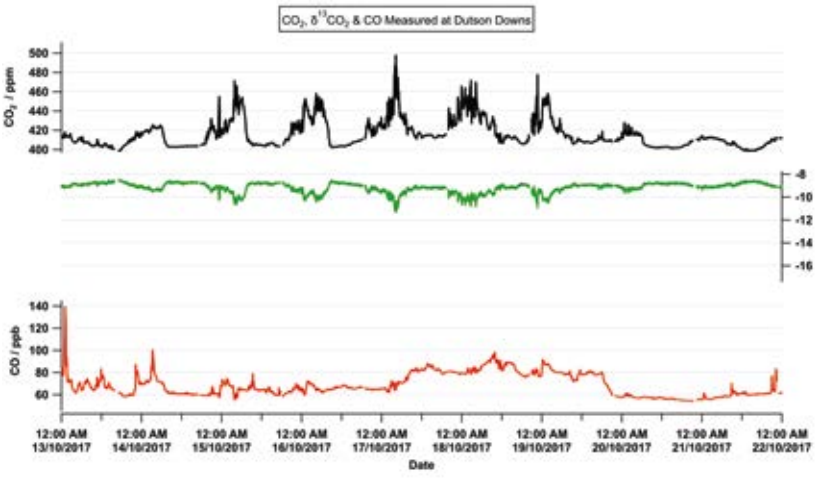
- assessing the spatial variability by deploying additional fixed and mobile *in situ* CO_2 measurements throughout the Gippsland Basin;
- combining these measurements with a high spatial and temporal resolution regional atmospheric model to incorporate the influences of topography and meteorology
- using this model to assess the optimum measurement combination and location for monitoring in the GipNet region.

The desired outcomes of the project were:

- A proven cost-effective atmospheric monitoring network in the GipNet region.
- A combined measurement-modelling atmospheric assurance system.
- Characterisation of the instrument and model performance.

Reference

N. Deutscher, et al 2017, An atmospheric assurance system for the Gippsland near-shore environment (7-0816-0304)



Time series of measurements of multiple trace gases, including the isotopic ratio of CO_2 made by instrument deployed near the proposed Gippsland Basin injection sire

Improved mapping of intraformational seals in the Gippsland Basin

This project provided a detailed understanding of the stratigraphy and structure of the Latrobe Group, with particular emphasis on the seal lithologies within the unit (largely coal and shale).

The work has delivered 2D stratigraphic sections which have produced an improved understanding of the geometry of the Latrobe Group coals and shales. Synthesis of seismic profiles, well logs and existing geological data (palynological and lithological open file reports) points to a depositional model where back-barrier coals prograde over estuarine shales. This produces a coal-shale (shale underlying coal) couplet that has great potential to act as a seal unit. The large lateral continuity of these lithologies (tens of km) is also encouraging in terms of these units acting as seals at an oil/gas-field scale.

Activities included petrological analysis of available core material and continuing analysis of 2D/3D seismic data in conjunction with wireline log analysis. All of this is aimed at refining the geological understanding of upper Latrobe Group lithologies.

The proposed depositional model for the Latrobe Group was at slight variance with many previous hypotheses for the setting of this unit. Unpublished open file industry sections generally show the marine-influenced facies of the Latrobe Group as being minor, with non-marine facies dominating.

Partridge (1976), also viewed marine incursions into the Latrobe Group as being the exception, rather than the rule. Bodard et al (1986) did suggest, however, that the upper Latrobe Group had a significant marine component, consistent with preliminary data derived from the present project.

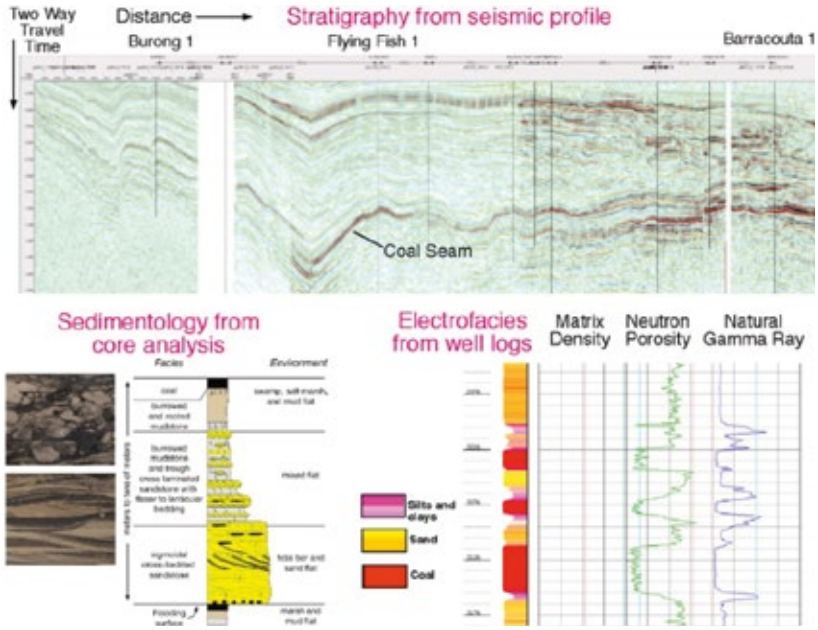
The simple presence of abundant coals within the upper Latrobe Group appears to have influenced many earlier researchers to suggest a purely non-marine origin for much of the Latrobe Group. The evidence presented above, indicates that the significant coal units within the succession are intimately connected with marginal marine coastal plain environments. This provides a predictive model for the distribution of rock types in the upper Latrobe Group.

Outcome:

» The single major outcome of this research project was a greater understanding of the geometry of seals within the Latrobe Group.

Reference

M. Wallace, et al 2016, Distribution and geometry of Latrobe Group intraformational seals, Gippsland Basin (7-1115-0289)



Methods of study: integrating seismic, well logs and core

Interactions of CO_2 with Basal Coal Seams in the Gippsland Basin

This study characterised the interactions that CO_2 could have with the intraformational low rank coals within the near shore Gippsland Basin targeted for CO_2 storage. Of particular importance is whether the intraformational coals behave as seals to the vertical migration of CO_2.

The project used a core flooding technique that is directly analogous to what would happen during geological storage. The core flooding consists of CO_2 injection to displace water from an initially saturated sample. The pressure difference between the CO_2 inflow and water outflow sides of the core was progressively increased until there was continuous flow, indicating that the capillary entry pressure for CO_2 had been exceeded. The pressure difference at the point of flow is equivalent to the CO_2-water capillary entry pressure (neglecting the influence of gravity because of the short length of the vertically aligned core samples).

The core flooding procedure used sandstone core plugs to spread the CO_2 and increase the area of contact that the CO_2 had with the coal. A core flood using just the sandstone core plugs was conducted to investigate the capillary entry pressure of CO_2 into the sandstone. It was found that CO_2 flow into the sandstone did not have a significant capillary entry pressure and that the sandstone was probably CO_2 wet. Therefore, measurement of an entry pressure during the core floods involving composite sandstone-coal core could be attributed to the coal not the sandstone.

The limited observations of CO_2-water entry pressures for coal (largely in the form of contact angles) in the scientific literature show that the entry pressure can be related to the coal rank, the pore pressure, and temperature.

Since coal oxidises after recovery from the reservoir upon exposure to air, fresh coal core is required for this work.

Since no preserved samples of the intraformational coals were available, a range of coals were investigated in the project to identify the potential for consistent behaviour. Experiments focused on available Victorian brown coals; however, these were lower in rank than the deeper intraformational coals. Coals of similar rank to that expected for the intraformation coals have been investigated.

These coals were not from Victoria but from the Walloons coal sequence of the Surat Basin which, at 0.4-0.5 vitrinite reflectance, are in the range expected for the intraformational coals.

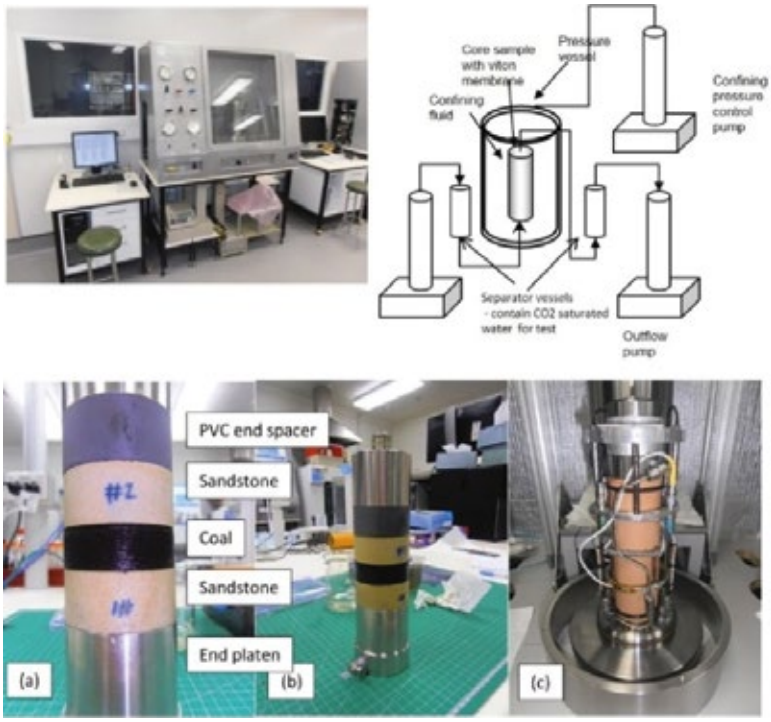
Initial conclusions:

- Low rank Latrobe formation coals had relatively low entry pressures equivalent to a maximum CO_2 column height of 26m
- Higher rank coals had small or negligible CO_2 entry pressures which could mean that these are CO_2 wet

The outcome from this project is an estimation of CO_2 seal behaviour of the intra-formational coals at reservoir pressure and temperature.

Reference

L. Connell, et al 2016, Characterisation of CO_2 interactions with Basal Coal Seam Intraformational Seals (7-1115-0285)



Core flooding equipment (top) and composite core assembly used in testing (bottom)

Evaluating Alternative CO_2 trapping in the Gippsland Basin

To date, standard petroleum industry software has been used to evaluate CO_2 storage processes, but this software neglects many physical phenomena which are known to occur with CO_2 injection, including enhanced dissolution, geochemical reactions (since dissolved CO_2 is a weak acid), and geomechanical effects.

Numerical modelling of fluid flow has been used to assess the behaviour and distribution of the carbon dioxide in the subsurface during and after injection.

To assess the limitations of the existing models, this project used advanced modelling software to evaluate the effect of including these additional physical phenomena. The Kookaburra site is located approximately 20km offshore in the Gippsland Basin. The target Latrobe Group reservoir (comprising the Latrobe and Cobia Subgroups) is a high permeability reservoir, with permeabilities up to several darcies. The Latrobe Group reservoir is up to 300m thick in this region. The overlying Lakes Entrance formation provides an excellent seal, reaching a maximum thickness of approximately 120-130m in the vicinity of the Perch wells.

The aim was to estimate the size of the effects, providing insights on limitations on injection pressures.

Modelling approach:

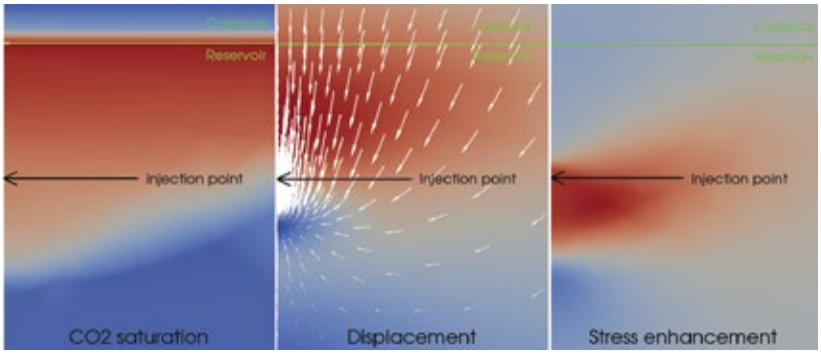
- Compare to simplified semi-analytical results.
- Extend to more realistic properties.
- Extend to more general geometry.
- Apply to specific conditions of Kookaburra site.
- Extended Model.
- Realistic fluid properties, with dependence on temperature and pressure.
- Radial thermal conductivity.
- Porosity depends on pore pressure, volumetric strain and temperature.
- Non-zero capillary pressure.
- CO_2 dissolution in aqueous phase.
- Diffusion/dispersion.

The simulations produced results that are broadly in agreement with the previous modelling efforts summarised in this report. In particular, the CO_2 injected into the Kookaburra field was contained within the structural enclosure. The amount of CO_2 immobilised due to dissolution into the groundwater predicted using this model was approximately 12% at the end of the injection period, which increased slowly to approximately 24% after 100 years. This result was smaller than previous modelling of the Kookaburra field, where dissolution was predicted to immobilise 20% of the plume at the end of a 20-year injection period, and over 33% after 100 years. This difference has been attributed to the finer resolution of the mesh used in this study.

The overall outcome was a thorough evaluation of the adequacy of the existing models being used within the Gippsland Basin for the candidate site. These results were generalised to comparable sites in the same basin, and further afield.

Reference

J. Ennis-King, et al 2016, Alternative Dynamic Modelling for Structural and Aquifer Traps (7-1115-0267)



Simulations coupling thermal and geomechanical effects with the injection of CO_2 made by instrument deployed near the proposed Gippsland Basin injection sire

Considering N_2 as a surrogate for CO_2 injection tests in geological formations

When it comes to underground CO_2 storage there are a number of factors related to the candidate storage medium which need to be thoroughly investigated before the commencement of the CO_2 injection, including: storage capacity, containment integrity, injectivity, the behaviour of the CO_2 plume and how it would evolve.

ANLEC R&D commissioned research to assess innovative ways to evaluate these uncertainties.

This project examined the concept of using N_2 as a surrogate for CO_2 in trial subsurface injections to characterise a storage resource. The technique would make regulatory compliance much simpler.

Methodology:

- Two sets of four conventional unsteady state core-flood experiments were conducted, one set using CO_2-water and the other using CO_2-N_2-water fluid systems.
- Three x-ray imaged core-flood experiments conducted using the CO_2-N_2-water system.
- Core-flood numerical simulations performed investigating the effect of a number of possible core-scale heterogeneities on the results of the core-flood experiments.

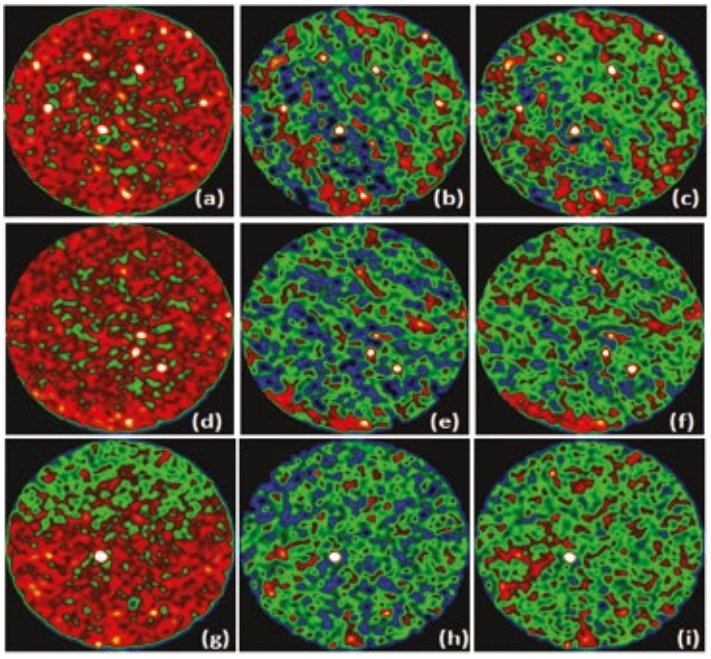
Dispersion coefficients were measured for the N_2-CO_2 system under reservoir conditions.

Key conclusions were:

- The levels of residually trapped N_2 during an N_2 trial injection may be an overestimation of that which may be achieved during a subsequent CO_2 storage process.
- Buoyancy forces during N_2 injection can reveal vertical pathways for subsequently injected CO_2 and therefore gain a better site characterisation.
- Sensitivity to capillary pressure and heterogeneity appears to be determined by core properties rather than by invading fluid.

Therefore, N_2 trial injection provides an inexpensive and low-risk way of understanding the heterogeneity structure of a reservoir, which is a critical unknown for CO_2 injection.

- The concept of site characterisation using the injection of an inert gas such as N_2 may deliver valuable information to any CO_2 geo-sequestration site.



Sodium Iodide saturated core: a) after N_2 injection; b) after CO_2 displacement of N_2; c) in three locations along the composite core. As can be seen, distribution of fluids after N_2 injection differs from that after subsequent $scCO_2$ injection.

Reference

A. Saeedi, et al 2014, Laboratory Core Flooding of Formation Water, N_2 and CO_2 (7-0912-0207)

Modelling CO_2 geological storage in the Gippsland Basin

The key focus for this study was to examine uncertainties related to numerical simulations of the effect of CO_2 injection on shallow groundwater resources and petroleum fields in the near-shore area of the Gippsland Basin.

The Latrobe Group forms a sloping aquifer containing freshwater in the onshore area and becoming increasingly saline towards the offshore where the majority of petroleum fields are located. Assessing how CO_2 injection affects the flow of formation water in the transition zone from fresh to saline water is critical for the selection of an appropriate storage site and for determining safe injection rates.

This project aimed to investigate the potential impacts of CO_2 geological storage in the near-shore area of the Gippsland Basin. In particular, the study focussed on: the displacement of formation water; any change in the pressure system; the possible effects on both offshore petroleum fields and onshore ground water levels, and the effects on the salinity in the Latrobe aquifer.

Research strategy:

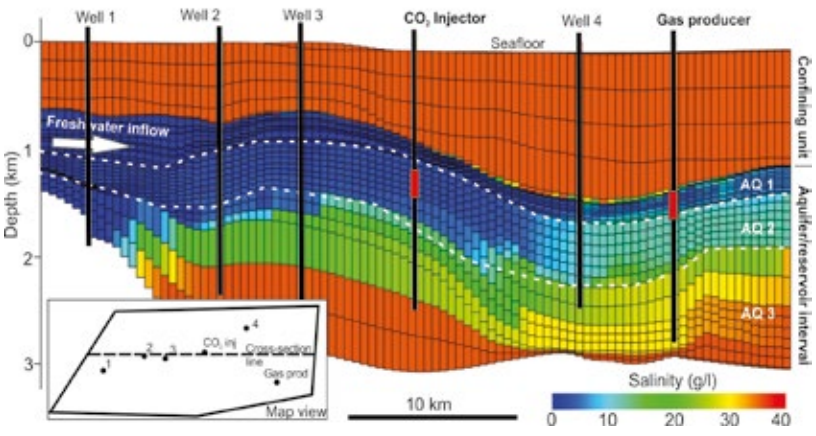
- Numerical simulations of storage scenarios based on the basin-scale hydrogeological model.
- Geochemistry of formation waters. A detailed analysis of the major and minor compositions, and their distribution and variation with salinity together with isotopic analyses, will help in understanding the evolution of formation water chemistry and underlying geochemical processes.

Following the simulation of injecting CO_2 for 20 years at 1-5Mt/year, the key conclusion were:

- The fluid inclusion data demonstrate that paleo-salinities of formation water in the Latrobe aquifer were generally higher than present-day salinities, suggesting that the low-salinity wedge is younger than the formation of the fluid inclusions and must have formed sometimes during the last 5 million years.
- No potential was shown for significant salinity increase in the onshore parts of the aquifer.
- Changes in formation water salinity occur mainly along the transition between freshwater and higher salinity water.
- CO_2 injection could introduce minor improvements to the production environment by creating a slight pressure increase in the onshore area to counteract the recent trend of under-pressuring due to petroleum production.
- This provided pressure support to petroleum industry and reduce water level decline rate to the onshore water users.

Reference

K. Michael, et al 2015, Near-shore aquifer modelling of CO_2 geological storage in the Gippsland Basin (7-1011-0187)



Simulations investigated the impacts of 42 years of petroleum production (water volumetric equivalent) and 20 years of CO_2 injection (1–5 Mt/year) on the distribution of CO_2, pressure and salinity.

Tracers to help quantify and monitor CO_2 storage volumes

Tracers are marker chemicals used for many processes. In CCS they are injected along with the CO_2, to help distinguish it from naturally occurring CO_2.

They are useful to locate the plume and recognise its migration character. If well understood, they can also be used to determine trapping processes. When a tracer is injected with the CO_2, some of the tracer dissolves (partitions) into the formation water whilst the rest of it remains in the CO_2 cloud.

Knowing the partition information for a range of tracer chemicals will result in:

» Improved estimates and correlations for calculating reservoir capacity, and

» Improved and accurate simulation of the tracers within a range of subsurface temperatures.

This project established general methods for determining the coefficients for other chemical tracers. The study has experimentally determined the partition coefficients for a number of chemical tracers relevant to CCS.

These included both reactive ester tracers, useful for determining residual CO_2 saturation using the single well chemical tracer test, and inert gas tracers, useful for inter-well tests and reservoir to surface tests. This data was then incorporated into computational simulations of CCS scenarios to understand the impact of partition coefficients on the interpretation of tracer field data.

Key conclusions:

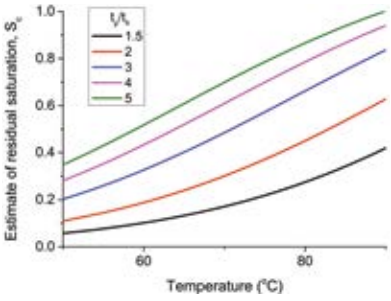
» The temperature dependent behaviour of the partition coefficients for a number of reactive ester tracers was determined. This information will lead to more accurate predictions of residual CO_2 saturation in instances where these chemical tracers are used for the single well chemical tracer test.

» In computational simulations of inert gas tracers, it was determined that, for bounded reservoirs, the behaviour of a chemical tracer is affected to a very minor extent by changes in the partition coefficient (air/water vs. supercritical CO_2/water); while for unbounded reservoirs, the differences are somewhat significant and could possibly be differentiated in a field trial.

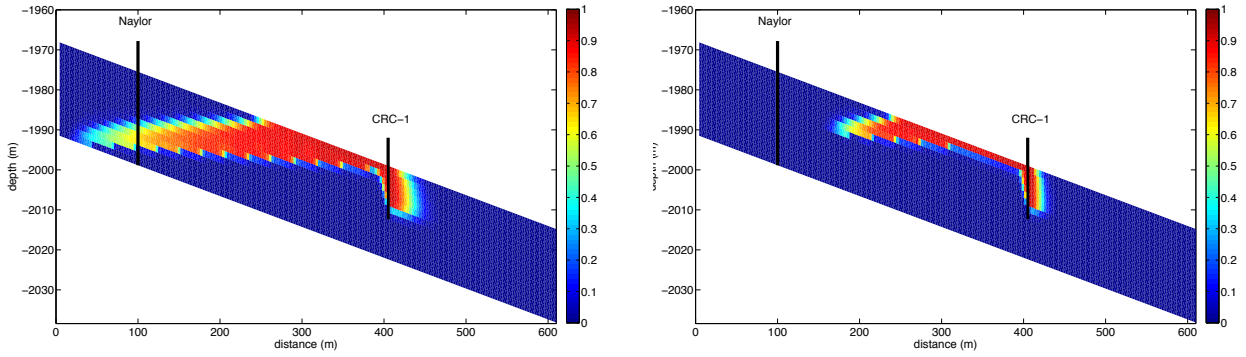
» Future work could include slim tube experiments packed with various sediments to experimentally determine the breakthrough curves for chemical tracers. This information could be used with future field studies to determine the possible influence that sorption onto sediment surfaces actually has on the behaviour of chemical tracers.

Reference

M. Myers, et al 2013, Chemical tracer partition coefficients for CCS (3-1110-0125)



Plot of the estimated CO_2 residual saturation vs. reservoir temperature.



Tracers in the reservoir for injection of mixed 80% CO_2 and 20% CH4 into a depleted reservoir with a gas cap shortly before injected gas is detected at U tubes 2 and 3: 156 (left), and 303 (right) days.

Integrity of wellbore cement in CO_2 storage wells analysed

Wells are the key technology for both storing CO_2 and monitoring its reservoir migration. Cement degradation is the result of a series of reactions that take place when acidic formation water, resulting from CO_2 dissolution, comes into contact with the well. In this project, a simple functional relationship was developed and a simulation scheme was developed based on this relationship to predict the erosion of cement around the well bore.

Cement degradation essentially occurs in two stages; first, cement carbonation occurs as the carbonic acid present in water with dissolved CO_2 reacts with the various constituents of the cement. These carbonation reactions form calcium carbonate, a solid. Loss of cement structure and strength can occur if this calcium carbonate is then dissolved. However, two conditions are required for calcium carbonate dissolution; a solubility deficit (i.e formation waters that are under-saturated in calcium and carbonate ions) and there has to be water flow to transport these solutes away and bring fresh water into contact with the cement. In practice, the potential for cement degradation could be largely determined by the mineralogy of the target formation and its ability to keep formation waters saturated in calcium carbonate as the solubility increases with CO_2 dissolution during CO_2 storage.

Previous published experiments of cement degradation relied on the measurement of the degradation process as the permeability of intact cement is very low, leading to time consuming experiments.

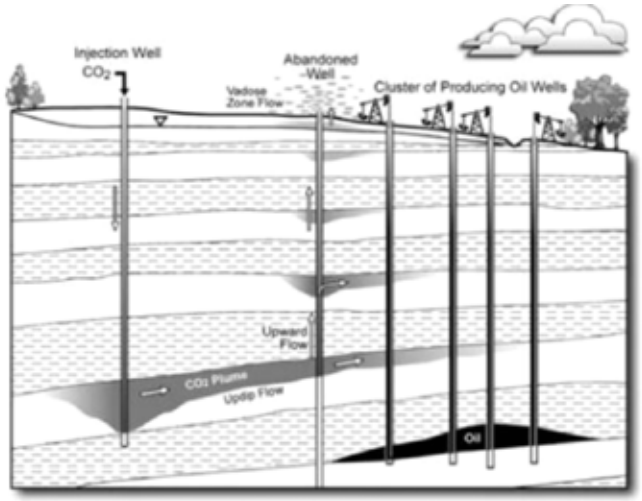
A different approach was used in this project; a composite cement-sandstone core plug was used in the core flooding experiments. While this reflects the cement-formation interface within a reservoir, it also allows sufficient flow for regular fluid sampling due to the relatively high permeability of the sandstone. The fluid flow through the sandstone means that fresh fluid is brought into contact with the cement and reaction rates are maximised. The contrast between inflow and outflow chemical compositions of the water samples were used to estimate the mass balance of key ions and thus the reaction rates with time. After each core flood, the mineralogy of the reacted cement was analysed using x-ray diffraction (XRD).

With this approach a more general set of results was obtained that could be applied to a broad range of sites. It was found that the dissolution rate (or cement erosion rate) was related to the flow velocity and the magnitude of the difference between inflow and outflow calcium concentrations. A simple functional relationship was developed and a simulation scheme was developed based on this relationship to predict the erosion of cement around the well bore.

To assess the risk of well cement degradation for a CO_2 storage site, the following decision process could be followed; Will formation waters be under-saturated in calcium after dissolution of CO_2? Will formation waters with dissolved CO_2 be contact with wells, over an extended period of time, where they pass through the structural seal? Is there potentially a continuous flow channel across the seal within the cemented annulus of the well? What is the likely magnitude of overpressure of the storage formation since this will drive water flow in the cement annulus flow channel? Where the first two points are met, the key strategy in avoiding cement degradation would be an assessment of the cement in wells at risk.

Reference

Connell L, Down D, Lu M, Hay D, Heryanto D, 2013: An assessment of the integrity of wellbore cement in CO2 storage wells (3-1110-0084)



Schematic illustration of the CO_2 injection, migration and leakage (from Celia et al., 2004).

Otway Basin Research Projects

Ground water monitoring is only effective close to the CO_2 injection site

The CO2CRC Otway project has been collecting water level data from three groundwater wells screened in the freshwater Dilwyn Aquifer since 2006.

The objective of this project was to investigate the usefulness of monitoring these wells for small leak detection, were it to occur, and to identify better locations for groundwater monitoring wells, were they to be purpose drilled. This was done through the application of spectral analysis techniques.

The water level dataset represents a continuous time-series prior to the injection of CO_2 and continuing post-injection. Spectral analysis of this dataset showed clear evidence of earth tides affecting the recorded water levels in the three wells. The spectra derived from this analysis were used to estimate aquifer properties, including specific storage and porosity. The values determined in this way compared reasonably well with published estimates from standard pumping tests and are significantly easier and less expensive to obtain.

A 2D TOUGH2 reservoir simulation model was built to investigate the spatial extent of the pressure pulse and chemical plume that would be generated were a slow, buoyancy driven, CO_2 leakage to occur from a slightly over-pressured storage reservoir. This model was originally intended to be based on the Dilwyn Formation. However, the initial simulations suggested that the current monitoring well locations in the Dilwyn Formation were too far away from the injection site to detect either pressure or chemical composition changes due to the presence of leaking CO_2.

In this model, CO_2 was allowed to move via buoyancy from the storage reservoir into an overlying monitoring aquifer. With consideration for the minimum leakage criteria of carbon storage for climate abatement, a minimum detection limit (MDL) that a shallow groundwater monitoring system would have to achieve was defined, and found to be virtually undetectable within the time frame of between 1-10 years.

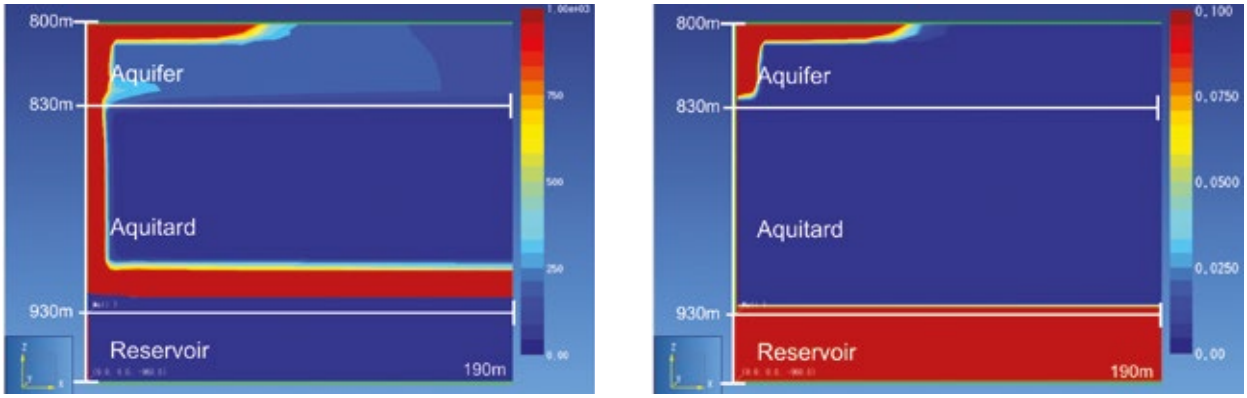
Further, it was found that, at the MDL, there was no detectible difference between the pressure pulse in advance of the CO_2 plume itself.

Key conclusion:

» The leakage rates in the scenarios developed here are primarily driven by buoyancy and are consequently so low as to be virtually undetectable in the short term. Therefore, for groundwater wells to provide effective short-term (less than 10 years) leakage indication or groundwater protection they would need to be located within a few metres of the site where CO_2 enters the aquifer.

Reference

A. Hortle, et al 2012, Signal processing of hydrographs for monitoring the integrity of freshwater aquifers near the Otway CO_2 storage site (3-1110-0073)



CO_2 pressure signal (left) and plume (right) after 10 years of flow.

Pilot injection Huff n' Puff

This study (co-funded by ANLEC R&D) provides an account of the Otway Stage 2B residual saturation and dissolution test.

This is the first field test of this nature in the world and the study reports on its execution and summary of the data obtained from the field test.

The goal of the CO2CRC Otway Stage 2B project was to measure large-scale residual trapping of CO_2 in an actual field project, using five different methods, then compare the methods and make recommendations. It was realised during design that substantial information would be collected on dissolution trapping also allowing for analysis of this mechanism.

Following a lengthy design period, the field test program for Stage 2B of the CO2CRC Otway Project commenced on 17 June 2011 and finished on 12 September 2011. All the planned components of the field test were completed, including the five methods for measuring residual trapping. Extensive high-quality data has been obtained throughout the program that allows detailed analysis within each method. The responses at each stage show that the injected CO_2 was driven to residual saturation and was detected by each of the five measurement methods.

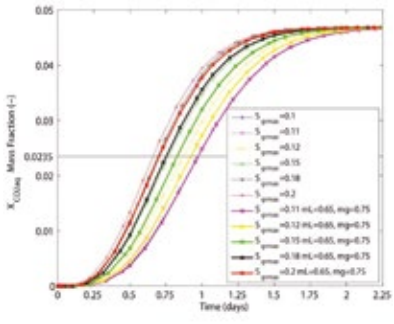
Key conclusions:

- Excellent quality downhole pressure data were acquired throughout the field program from the permanent gauges. The high permeability of the injection interval did not cause problems with getting a sufficient pressure response to give a good signal to noise ratio.
- Excellent downhole temperature data were also acquired. The instantaneous readout of downhole temperatures proved extremely useful in diagnosing operational issues at several stages.
- All three RST logs were run as intended. Current interpretation has residual CO_2 saturation around 0.18 in the lower half of the perforated interval and around 0.23 (average) in the upper half.
- Fluid sampling using the U-tubes was completed consistent with the test plan. The noble and organic tracers were added to the injection stream as planned and were measured during production stages at concentrations that were more than sufficient for analysis.
- The organic tracer test shows the partial breakdown of the three parent compounds, as hoped.
- Sampling for the dissolution test, including the added methanol, was performed as intended.
- Although not primary objectives of Stage 2B, the test sequence provided the opportunity to further test microseismic monitoring and provide controlled releases of CO_2 for atmospheric monitoring.

Reference

L. Paterson, et al 2011, The CO2CRC Otway stage 2B residual saturation and dissolution test: test concept, implementation and data collected (7-0810-0066)

The reservoir saturation tool (RST).



Mass fraction of dissolved CO_2 (XCO_2aq) versus production time, which is the data that will be used in the dissolution test. The sensitivity to various parameters is shown, and this indicates that Sgr is the parameter which has the greatest influence on XCO_2aq. The base case value of Sgr is 0.2. Note, a maximum mass fraction of 0.047 is equivalent to 1.07mol/L CO_2.

Validating CO_2 plume detection limits and stabilisation commences at Otway

Australian saline formations have the capacity to store all of the country's CO_2, provided uncertainties are addressed.

The CO2CRC Otway Stage 2C Project aimed to inject up to 15,000 tonnes of CO_2 into a saline formation to demonstrate important aspects relevant to large-scale geological storage of CO_2 in saline formations; as proposed by Australian CCS Flagships and other large-scale CCS projects around the world. The project involved the installation of the permanent seismic array in the summer of 2014/15, the completion of injection by mid 2016 and the conduction of post-injection annual seismic surveys to monitor the plume to 2018.

The Otway Stage 2C project had three scientific objectives:

1. Detect injected CO_2 (Buttress gas) in the subsurface and ascertain minimum seismic detection limits.
2. Observe the gas plume development using time-lapse seismic.
3. Verify stabilisation of the plume in the saline formation using time lapse seismic.

Progress to date has provided the required infrastructure for acquisition of the baseline data and for further monitoring and observation of the CO_2 injection. This included:

» Deployment of buried seismic geophones along 11 receiver lines. Length of the receiver lines tp 1460m, spacing 100m, and 15m between the receivers

» Deployment of two types of Distributed Acoustic Sensing (DAS) fibre optic cables along the same 11 receiver lines

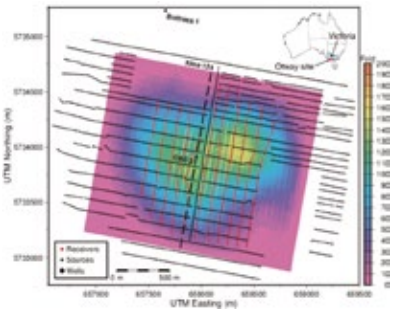
» Installing powered seismic recording facility in a dedicated container (Seismic Lab) in the vicinity of CRC-2 wellhead, to house the seismic and iDAS recording equipment.

More recently, the CO_2 injection phase and the first seismic survey were completed.

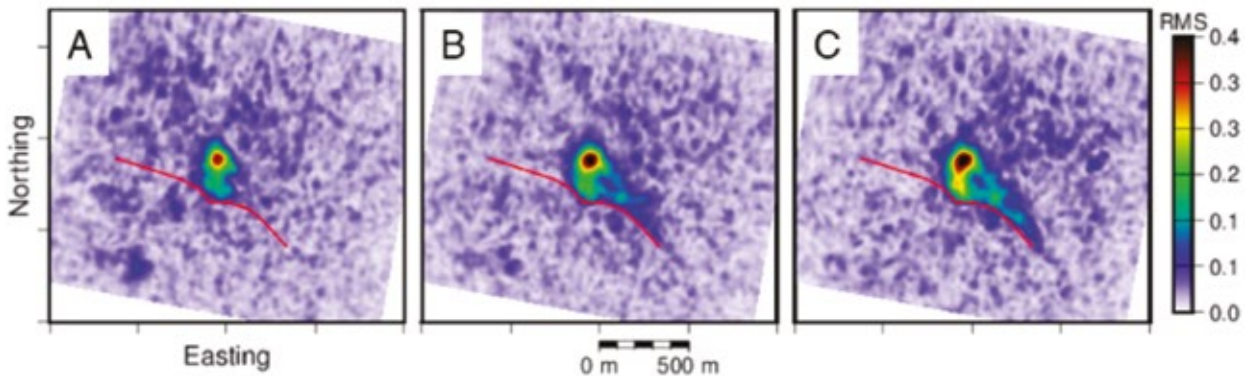
» The baseline survey was acquired in March 2015 followed by three monitor surveys in January, February , March and April 2016 after injection of 5, 10 and 15 kt of CO_2, respectively. Time lapse difference images show a clear anomaly localised around the injection well. The anomaly is initially approximately circular in shape, and as the injection progresses, the plume reaches a known sealing fault to the south of the injector and then spreads up-dip along the fault

Reference

R. Singh and M. Watson 2013, Project Initiation Document (7-0212-0204)



Map view of the 3003 production vibroseis source points (black dots). The red dots are the 11 receiver lines.



Plan maps of amplitudes (relative to the baseline amplitude after injection of 5 kt (A), 10 kt (B), and 15 kt (C) calculated from the difference cubes.

CO2CRC Otway Stage 3, Feasibility & Design

The CO2CRC Otway Stage 3's primary project objective was the appraisal, implementation, demonstration and validation of subsurface M&V for a CO_2 storage system and related operational issues. The Evaluate Phase provided a detailed field development concept for the installation of wells and surface facilities required.

Project Goals:

- Develop a high-resolution, real-time monitoring capability.
- Provide non-invasive monitoring techniques that will be acceptable for community and regulators.
- Provide a prospectus of technologies and workflows that can be used to define costs in commercial monitoring projects.
- The project will evolve technology from benchtop application to in-fiel validation.

The CO2CRC Otway Stage 3 project managed in distinct research, planning and operational phases: planning and operation phases (Figure 1).

The completed 'Evaluate' phase provided a detailed field development concept for the installation of wells and surface facilities required.

The "Define" phase constitutes the required conceptual development, modelling, data acquisition, interpretations and operational design for the many field-based research activities. The final deliverables for this phase were;

- Final Project Execution Plan, and Operation Basis of Design
- Final Stage 3 Technical Analysis and Post Operation R&D plan
- Techno-economic study, of proposed Stage 3 benefits to industry
- Regulatory and landowner approvals

Sub-Project 1. Site Appraisal (CRC-3 focus)
Generate a science case for the injection and subsurface monitoring of a CO_2 plume, sufficient to support drilling an appraisal well (CRC-3)

Sub-Project 2. CRC-3 (appraisal well)
Develop a Well Basis of Design (BOD). The CRC-3 well, which would ultimately act as the injector well for Stage 3.

Sub-Project 3. Site Appraisal (Otway 3 injection interval).
Analysed data from CRC-3 would be incorporated into the geological & plume models to predict the behaviour of the CO_2 plume.

Sub-Project 4. Geochemical barrier concept and trial development.
This sub-project was to generate a science case for trialling the in-field demonstration of partial to complete immobilisation of CO_2 through geochemical engineering processes within the Stage 3 facilities.

Sub-Project 5. Down Hole Fault Characterisation Design
In this task a petrophysical and rock mechanical workflow was to be developed in which various measured mechanical properties would be used to understand the behaviour of faults under pressurisation.

Sub-Project 6. Multi-scale flooding dynamics of Otway reservoir core under in-situ conditions
The task used digital core analysis and modelling techniques to develop a multi-scale workflow which consistently addressed the impact of small-scale geological heterogeneity on the static and dynamic rock properties.

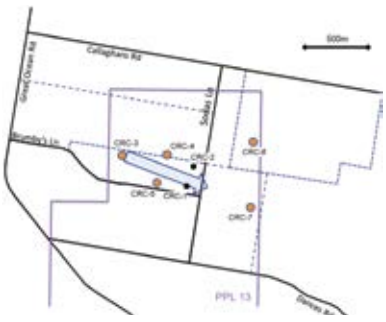
Sub-Project 7. Final Stage 3 Design, Long Lead Procurement and Approvals
This task completed the Define study for Stage 3, with the team finalising the basis of design (BOD) and Project Execution Plan from a technical and operational planning basis.

The outcome, after the successful completion of this Otway Stage 3 Evaluate and Define Project was the necessary scientific information and required operational details for the execution and operation of the stage 3 project.

Otway Stage 3 timeline

Reference

M. Watson, et al 2016, Otway Stage 3 (1-1117-A298)


in the Otway Stage 3 plan, a plume will be created at the injection well CRC-3 moving up-dip to be monitored from two pairs of monitoring wells.

Capture Research Strategy

Reducing the cost of CO_2 capture for coal fired power generation is very important if CCS is to remain a competitive low emissions technology. ANLEC R&D has completed over 65 concept testing projects.

To remain complementary with a global research effort, capture research in ANLEC R&D has pursued research enabling environmental performance and permitting in Australian conditions. High efficiency low emissions (HELE) coal technology concepts that offer disruptive opportunities for emissions reduction in established and emergent coal markets was also also tested.

It was especially important to consider technology developments that enable coal to integrate into a modern grid that requires fast ramp up and ramp down supporting high levels of renewables.

CO_2 Capture Processes

Managing Financial Investment Risk for Carbon Dioxide Capture

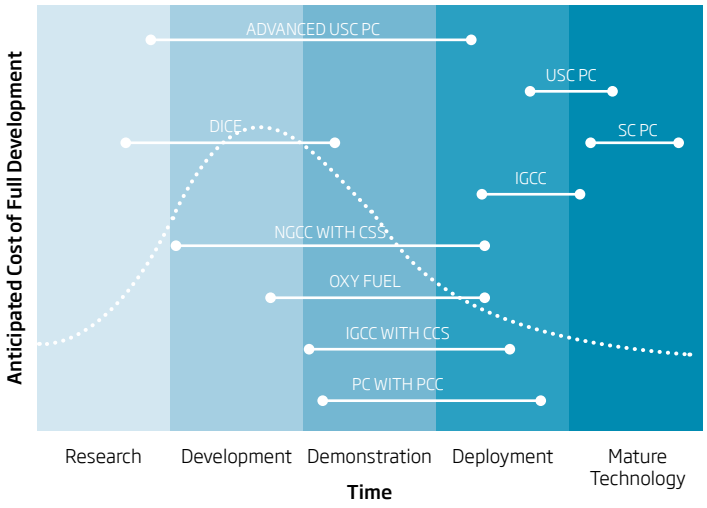
Power generation assets are long lived (40+yrs) and the financial investments is counted in billions of dollars.

Investment risk is therefore closely linked to financial performance, engineering performance and regulatory certainty. Processes to capture CO_2 are relatively well established, with most of them beyond the laboratory. ANLEC R&D research aimed to adapt these technologies to Australian conditions to enable permitting and deployment.

Goal

For CO_2 Capture processes to:

- ***test cost reduction concepts***
- ***enable environmental permitting***
- ***and adapt to Australian conditions***



Scale Key

In lab In Field

Delivery Key

New Data New Application

Field Validation New Correlation

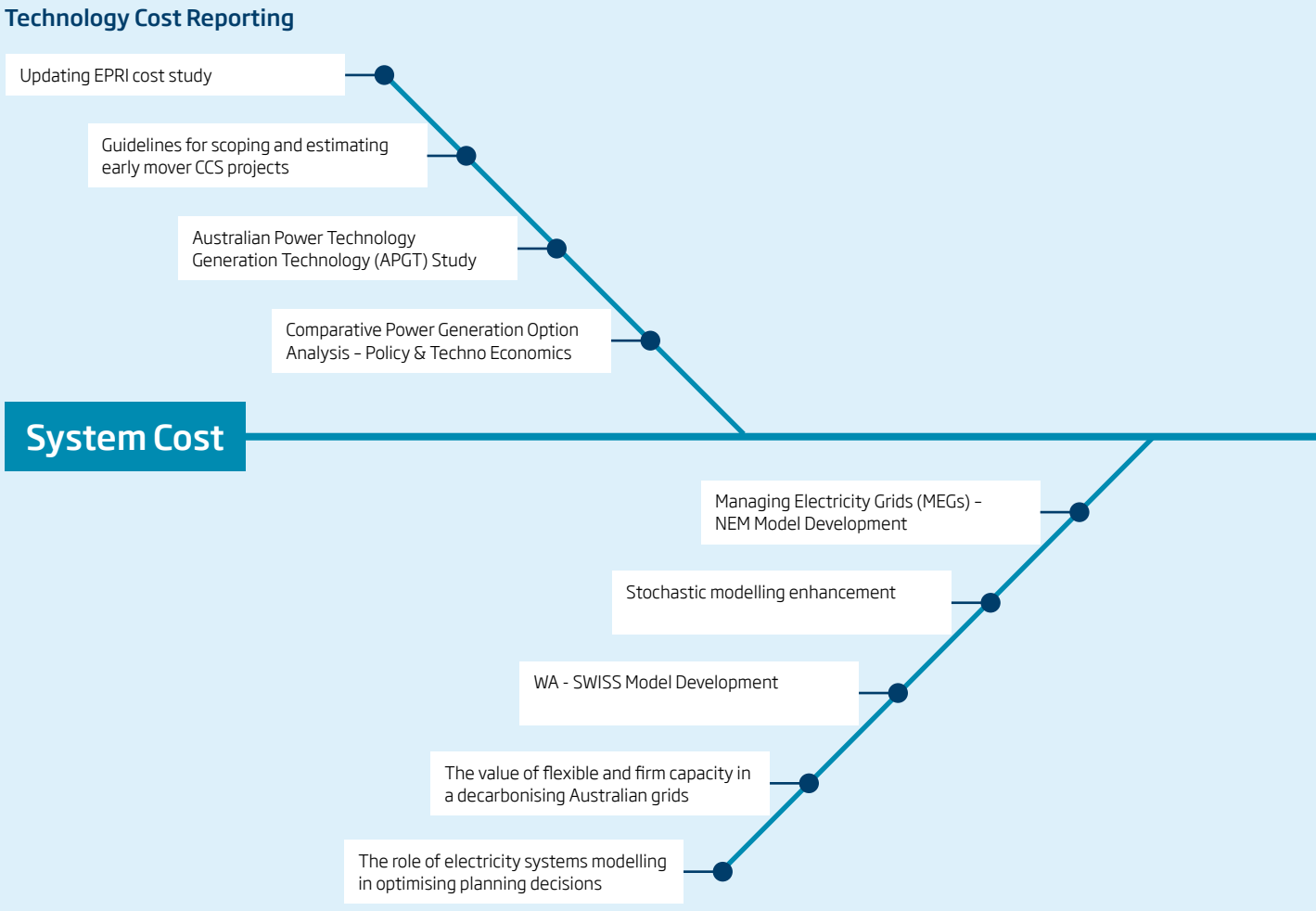
Permitting & Public Communication

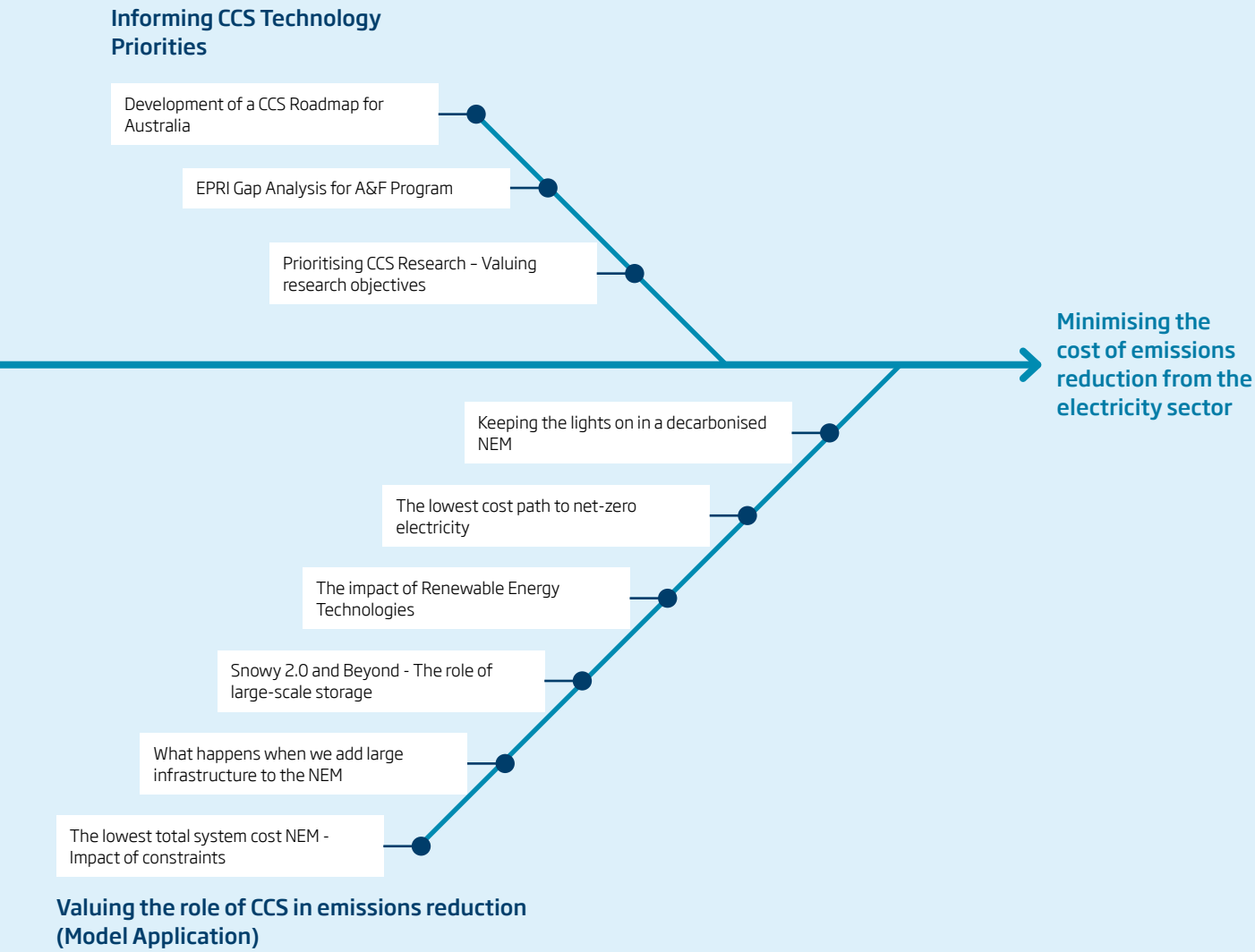
Photo courtesy of the Callide Oxyfuel Project

Impact Area	Impact Statement	Delivery
Oxy-fuel Combustion	*Support and enable the Callide Oxy-fuel Project, Queensland*	
	Assess process effects and controls on the quality of CO_2 gas delivered for storage	
	Examine the nature and implications for the deportment of trace element species during oxy-fuel combustion at scale	
Post Combustion Capture	*Validate the environment performance of emissions and waste disposal from an amine post combustion capture process at commercial scale*	
	Develop innovative flowsheet adaptation concepts for reducing the cost of post combustion capture processes in Australian applications	
	Test innovative concepts for low cost low emissions post combustion carbon capture technologies	
Integrated Gasification Combined Cycle	*Test innovative concepts to lower the cost of IGCC technology for application in Australian conditions*	
Techno-Economic Assessments	*Deliver technology assessment studies to inform strategic decisions regarding research, demonstration and deployment of lower cost low emissions coal technologies for power generation in Australia*	
Brown Coal Technologies	*To report on innovative concepts for lower cost carbon capture adapted to the use of Victorian brown coals*	

Adapted from CSIRO: M. Bazzaco, CSIRO Impact Evaluation Guide, 2015

Supporting Research: Techno-Economic Assessment




Informing CCS Technology Priorities
Development of a CCS Roadmap for Australia
EPRI Gap Analysis for A&F Program
Prioritising CCS Research – Valuing research objectives
Minimising the cost of emissions reduction from the electricity sector
Keeping the lights on in a decarbonised NEM
The lowest cost path to net-zero electricity
The impact of Renewable Energy Technologies
Snowy 2.0 and Beyond - The role of large-scale storage
What happens when we add large infrastructure to the NEM
The lowest total system cost NEM - Impact of constraints
Valuing the role of CCS in emissions reduction (Model Application)

Research Projects

Development of a CCS Roadmap for Australia

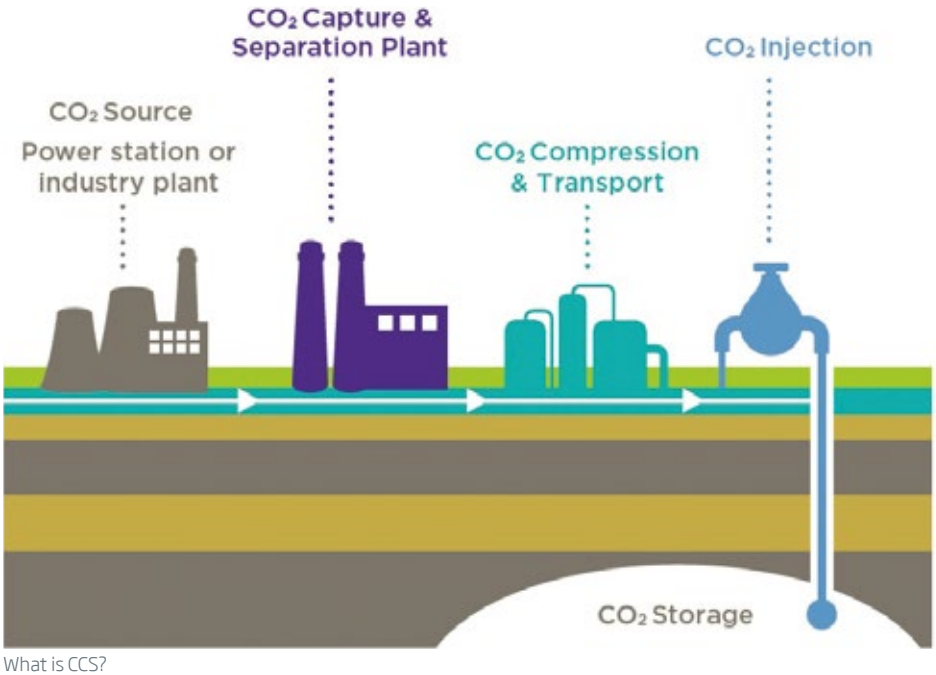
CCS is projected to feature prominently in the future suite of low-emissions technologies, as CCS is currently the only technology able to provide deep reductions in emissions from the use of fossil fuels.

The path to commercialising CCS will take considerable technological advancement, demonstration and early mover deployment to drive costs down, and therefore further investment globally from government and industry. It will also require consistency in policy engagement and consideration of a range of measures as Australia moves through the CCS development cycle.

Without attempting to predict *when* CCS might become a commercially viable carbon mitigation option, a CCS Roadmap is required to show *what* is required to get Australia to the CCS commercialisation starting line and once at the starting line, provide an insight into what the future landscape may look like.

The purpose of this work has been to:

- recap the rationale for Australia to invest in CCS to meet energy security, decarbonisation and retention of our trade exposed industries in a low carbon economy;
- define the role and schedule of critical activities that Australia can perform to maximise the contribution that low emissions fossil fuels technologies and specifically CCS can make in reducing GHG emissions globally; and
- develop a roadmap and an enabling work program for Australia to retain an option for significant CCS deployment in Australia (i.e. assuring Australia's CCS readiness).



What is CCS?

Reference

C. Greig, et al 2016, Development of a CCS roadmap for Australia (1-1115-0287)

Managing flexibility whilst decarbonising the National Electricity Market

This project demonstrates an innovative modelling approach. It considers the grid system cost by recognising the importance of firm generation, the cost of balancing the system, and the required flexibility, while on the "pathway" to a lower emissions grid.

The current Australian grid has delivered reliable and secure energy for decades. Most electricity is still currently provided by coal-fired power generation and, therefore, this technology has also delivered the services required for grid stability such as inertia, frequency control, etc.

Fossil-fuel technologies (coal and gas) have, to date, underpinned the energy competitiveness of the Australian economy. However, with increasing penetration of renewable generation, it is becoming important to plan for and manage generation asset investment to track the least cost and highest reliability path to a low emissions future.

Key facts:

» Including energy supply, each energy technology brings with it a different set of grid services such as low emissions, inertia, frequency control, flexibility etc. They each offer different value propositions to a grid.

» The NEM is unique, compared with other international grid systems, as it consists of 5 state-based grids that are only weakly interconnected.

» The characteristics of this host NEM plays a significant role in determining the value of an additional asset placed on the system. Each state grid will have unique asset requirements and a material impact on the overall NEM system.

Results show that:

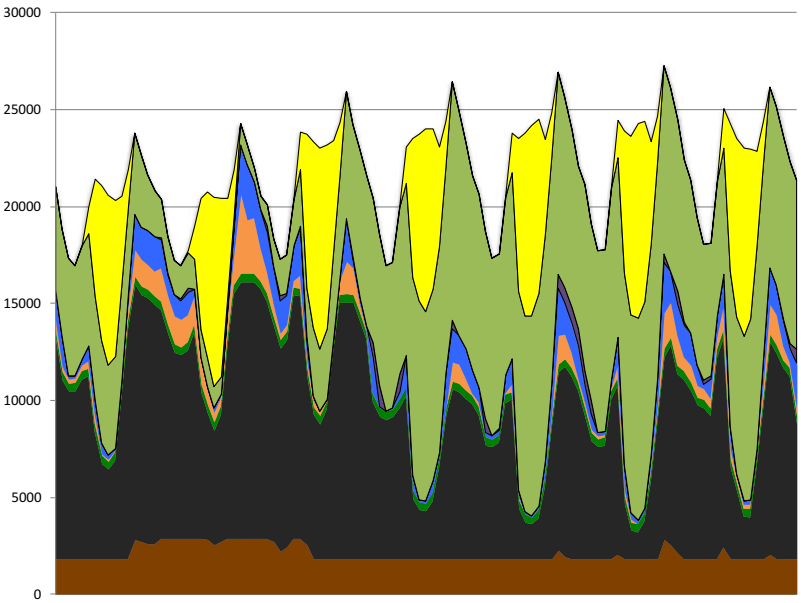
» Approaches to meet short-term emissions targets (e.g. Paris 2030) can lock in higher costs and compromise Australian energy competitiveness in the long term.

» The lowest cost energy supply technologies change as NEM decarbonisation proceeds. At high penetration renewables become increasingly expensive to the grid.

» Renewables costs increase due to intermittency and curtailment. Inflexions for other technologies occur when their emissions limits are reached. At high decarbonisation levels, dispatchable power like Coal+CCS will be required to deliver the required resilience for grid stability. Most importantly however, it can also deliver the deepest decarbonisation ambitions at lowest total system cost.

» High penetrations of wind and solar PV will require companion low carbon technologies if they are to provide firm capacity, available "on-demand" (Figure 1). Storage remains part of the solution but is no substitute for the value of low carbon firm capacity power plants.

» In high renewables scenarios, the existing fossil-fuelled power plant (especially black coal) will have to become increasingly more flexible on a daily basis during the transition.



Modelled 7-day generation – high renewables scenario

Reference

A Boston, G Bongers, S Byrom: Decarbonising Electricity – The lowest cost path to net zero emissions, 2021 (1-0719-0319)

Options for a lowest cost pathway for electricity decarbonisation

Total System Cost Matters, planning a system that does not take into account all the costs incurred and doesn't focus on minimising all these costs will lead to a less competitive and more expensive grid.

MEGS – Modelling Energy and Grid Services, departs from more traditional modelling as it captures the requirement and supply of grid services beyond the need to match generation with demand. This need has come about because in a grid, like the NEM, that is transitioning towards low emission renewables (especially wind and solar PV), there is increasing requirement on system operators to have access to frequency response, reserve and inertia services, and other grid services. The conventional sources of these services are being lost as unabated fossil-fuelled power generation is rapidly being displaced from the system.

The outcomes of the MEGS model seek to challenge current paradigms for understanding the total system cost (TSC) for electricity supply. Conventional modelling approaches make simple comparisons, which are made using traditional metrics like Levelised Cost of Energy (LCOE), do not consider the grid system requirements. This modelling defines the resilience of a grid by its level of inertia and seeks to ensure that the operator has sufficient frequency response and reserve services to maintain a stable grid.

Some important messages have emerged from our 2023 study into the NEM. These include some warnings on what may likely go wrong the in the short term and what might be a more sensible scenario than those proposed by others.

Key points:

» The lowest total system cost solutions always have a mix of nuclear, CCS, storage, biomass, renewables, and peaking plant. The solution gets more expensive and/or unreliable if a technology class is restricted or unavailable.

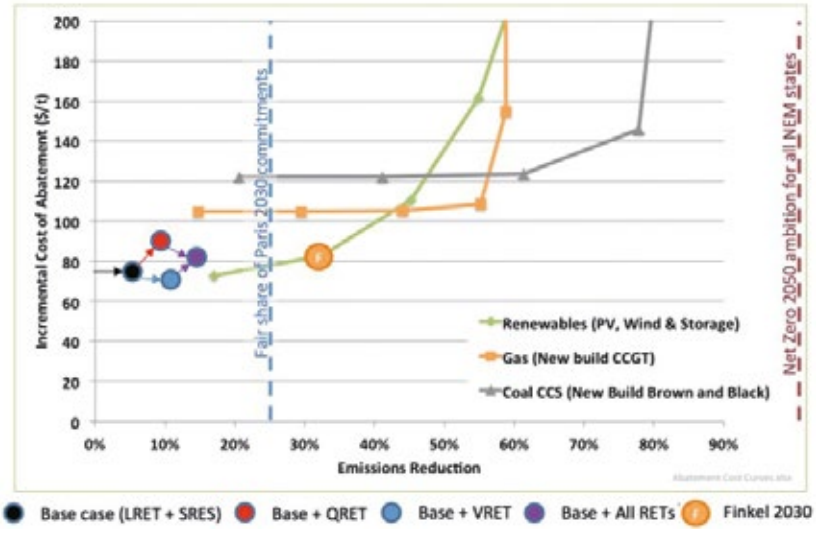
» When considering long term storage capacity, it's important to consider the whole year and a range of weather scenarios to ensure there's enough capacity and depth of storage.

» Changing the input Capex assumptions, and in particular the relativities between technologies, has a significant impact on the future generation capacity profile.

» The lights will go out if the system follows AEMO's 2022 Step Change ISP scenario, closing all coal and building only wind, solar, storage and interconnectors. There will be a detrimental impact on grid security as early as 2025.

Reference

A Boston, G Bongers, N Bongers, Keeping the Lights On:- Examining the options for a lowest cost pathway, 2023 (1-0719-0331)



Comparison of alternative decarbonisation pathways

Reporting more accurate cost estimates for early mover CCS projects

Many proposed carbon capture and storage (CCS) demonstration and commercial projects have failed to be constructed.

Reviews of these projects have shown that, in most cases, the cost estimates for these projects have increased markedly from the initial cost estimates to the final proposed cost. This has resulted in cost uncertainty, misinformation and a general lack of trust surrounding the costs and economics with regard to CCS project costs.

A robust cost estimate of carbon capture and storage projects is essential for public, regulator and investor confidence in the technology, which is critical to the deployment of the technology.

The study provided framework and guidelines for project scoping and cost estimation for early mover CCS projects.

The work reported on the results from scrutinising previous "new technology" introductions in the energy and process industries. From this work it was evident that:

» Uncertainty and increase in cost estimates are typical in first-of-a-kind and early mover projects.

» Behavioural issues amongst stakeholders, in relation to early underestimates and final costs, range from honest delusion to deliberate deception.

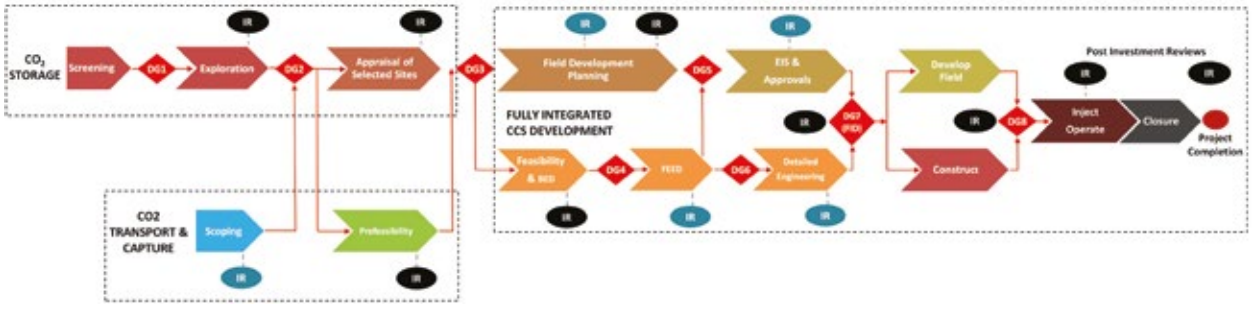
» Notwithstanding 'better' application of best practice in preparing cost estimates, known costing pitfalls continue to be a feature of modern day complex energy projects.

» The level of study detail in publically available reports, with regards to cost estimates, is frequently not entirely transparent. This can lead to information being taken and used out of context or misunderstood.

The report recorded that carbon dioxide capture technologies are commercially available today, despite the assertion that carbon capture and storage is an 'unproven' technology that will never be deployed. In addition, the storage of carbon dioxide in geological formations is also very well established.

Reference

C. Greig, et al 2014, Guidelines for scoping & estimating early mover CCS projects (1-0512-0205)



Decision roadmap indicating main focus of investment decisions towards an integrated project.

A techno-economic review of Direct Injection Carbon Engines (DICE)

Diesel engines have run on coal in the past. High thermal efficiencies and fast response times reportedly make this a potentially useful route to low emissions power generation, if the engine wear issues are resolved.

This study was commissioned to gain understanding of the techno-economic prospects for developing such a technology.

Micronised Refined Coal (MRC) fuel for DICE engines was successfully made from a range of black coals, and from brown coal.

The report analysed scenarios of the engine life required to compete with available thermal generation processes. Engine run hours, that must be achieved for breakeven economics with the alternatives, gave an indication of the degree of engine development effort required.

The results suggested that with relatively little development, DICE could be competitive for remote area power where the alternative is trucked diesel.

Markets relying on imported LNG for power appear to be the "sweet spot" for DICE; requiring modest engine development and opening new markets for engine manufactures and coal producers.

The study determined that should there be a demand for new-build plant, DICE could be competitive with combined cycle gas turbine (CCGT) at run lengths similar to the best available heavy fuel oil engines.

DICE emissions are lower than conventional pulverised coal technology. Carbon Capture and Storage (CCS) offers the possibility of deep emission reductions with the potential of reduced cost.

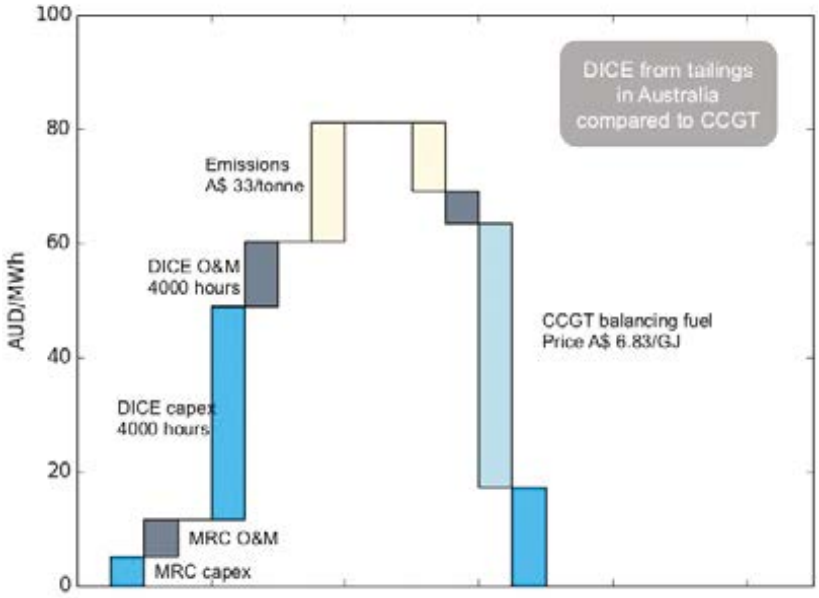
The small modular nature of DICE may open the potential for a matched CCS module that can be manufactured in the same low cost locations as the engine, and shipped as a complete package.

Required run lengths, as estimated in the report, may be used to set targets for an engine development program. DICE can be used as an enabling technology for a lower cost pathway to reduced emissions from coal.

This report analysed the commercial performance of a number of DICE scenarios and sensitivity to their market variables.

Reference

L. Jeffery 2016, A techno-economic review of Micronized Refined Coal fuelled Direct Injection Carbon Engines. (MRC DICE) (1-DICE-00SS)



MRC from tailings compared to CCGT in Australia – 4000 hours between overhaul.

A Techno-economic Assessment Tests the Concept for Hybrid CO_2 Capture

Post-combustion CO_2 capture (PCC) in power stations require a scale of engineering that is larger than prior applications. This study tests the concept for coupling solvent and adsorbent technologies to enhance capture performance.

PCC has been recognised as a necessary option for reducing the emissions from fossil fuel power plants, especially from coal-fired power plants. The current preferred technology for CO_2 capture from (PCC) is solvent scrubbing. These capture units are likely to be larger than any currently operating solvent scrubbers. This is partly because the flue gas flow rates are very large but is also due to the low concentration of CO_2 in the flue gas (10 – 15 %) and therefore the equipment size is governed predominantly by nitrogen flow rates. Solvent processes such as amines require high energy usage and are susceptible to degradation from the presence of oxygen in the flue gas, forming oxidised products. On the other hand, alternate technologies such as CO_2 capture by adsorption, are capable of producing variable enrichment of the CO_2 with low energy penalty and can be designed to simultaneously remove oxygen. This suggests that a hybrid of capture technologies (e.g., adsorption process integrated with a downstream solvent scrubbing unit) may offer large reductions in capture cost if the inherent advantage of each technology is exploited synergistically.

Specifically, the project has investigated the use of low energy capture processes for initial enrichment followed by smaller second stage capture processes for final enrichment to appropriate CO_2 concentration. Adsorption experiments based on activated carbon have been carried out for the initial enrichment stage and validated against Aspen Adsorption simulations. The Aspen Adsorption® model was then used for the design of the full-scale adsorption system from a 500 MW power plant. The simulations showed that these processes employing activated carbon can be operated at high CO_2 recovery (> 90 %) when enrichment to 50 % CO_2 is required with very modest energy requirements (electric power of ~ 0.6 GJ / tonne CO_2).

Removal of most of the oxygen in the flue gas was also achievable, an output that would alleviate downstream problems in the solvent scrubbing unit. The enriched CO_2 stream had a dramatically reduced volume (by a factor of approximately 3 when capturing 90 % of the CO_2 from the feed to the first stage at about 50 % CO_2 purity) leading to smaller solvent scrubbers (with diameters reduced from 20 meters to around 15 meters).

The economic assessment of the hybrid VSA-MEA processes showed that compared to the benchmark capture processes of MEA solvent and VSA 13X, the hybrid process has higher total capital costs and energy penalty due to the additional equipment compared to stand-alone processes and that the energy for solvent regeneration did not change for the hybrid processes compared to the standalone process. In addition, there is an energy requirement for the VSA process. However, one of the advantages identified for the hybrid process is that it uses practical equipment sizes with currently available technology, which can avoid extra large equipment sizes and associated technical risks associated with building these structures as well as the uncertainties of constructing them onsite.

Reference

G Xiao, P Webley, A Hoadley, M Ho and D Wiley, CO2CRC Report No:13-4321, 2013 (3-0046)

Pressurised water-based CO_2 dissolution as an alternative capture process

This study presents a comparison of the aqueous CO_2 capture process with a typical amine scrubbing process utilised at a large Australian coal-fired plant.

A novel post combustion capture of carbon dioxide (PCC) process has been proposed by Partnering in Innovation Inc., USA. It uses high pressure water to selectively dissolve CO_2 from thermal power plant flue gases..

The dissolved CO_2 is later released as the water pressure is reduced and then collected for subsequent compression and disposal. A proportion of the energy used to compress the flue gas is recovered via expansion turbines. The main advantage of the technology over existing amine-based processes is that water is both inexpensive as a solvent and is expected to meet environmental requirements for disposal. This ANLEC R&D project involved evaluation of the engineering practicalities of the large-scale application of the process and a subsequent high-level techno-economic assessment of the technology in Australian conditions.

Aspects compared include; parasitic load, impact on the thermal efficiency of the existing plant, ongoing operation costs, plant integration requirements and expected retrofit challenges. The comparison is conducted for an inland wet cooled, ultra-supercritical 695MW Unit.

The comparison demonstrates similar energy consumption values for the two processes, with a marginal benefit in favour of the aqueous process.

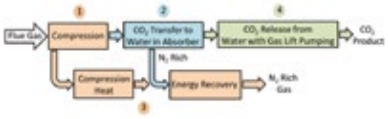
A critical aspect of the feasibility of retrofitting a carbon capture process to an existing power plant is the nature and number of plant interfaces and the extent of required integration between the power plant and the CO_2 scrubbing system. A qualitative comparison was carried out of the integration requirements of the aqueous system against that of an amine system. The main findings of this comparison include:

- The amine system requirement of significant mass flow of low pressure steam is not necessary with the aqueous system. The requirement for an associated steam condensate return is therefore not required either.
- Both systems require flue gas extraction from the main flue gas duct at the bottom of the stack and return of treated flue gas from the capture plant to main power plant stack.
- Apart from the flue gas interconnection, the main interface requirement of the aqueous system is the significant energy input required for flue gas compression.

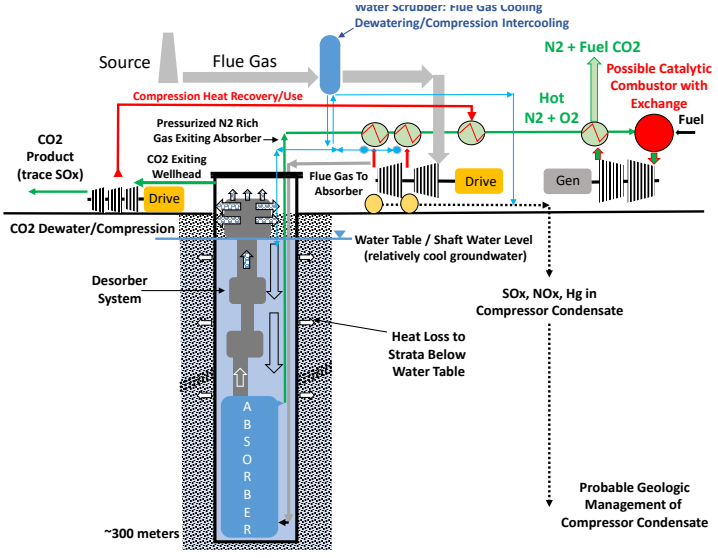
The ASPEN process simulations found that there were key design elements for successful application of the technology. One of these elements is the heat integration of the compression and expansion stages of the process. Optimised integration is necessary to minimise the parasitic power consumption of the process.

Reference

R. Boyd, et al 2016, PI-Innovation aqueous CO_2 removal: process modelling and costing (4-1115-0282)

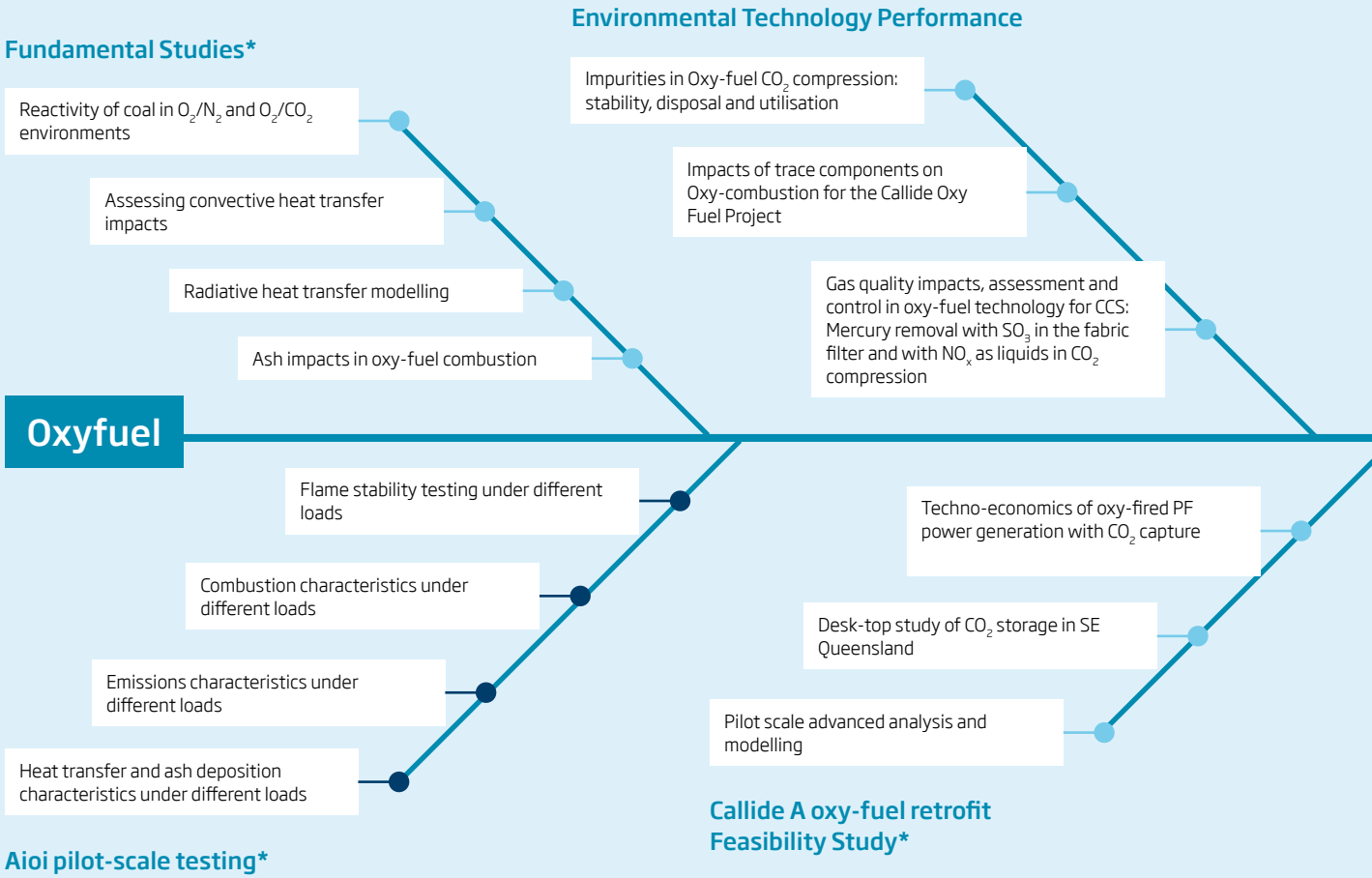


Schematic system of the CO_2-dissolved concept.



Simplified system sketch of water-based CO_2 capture technology

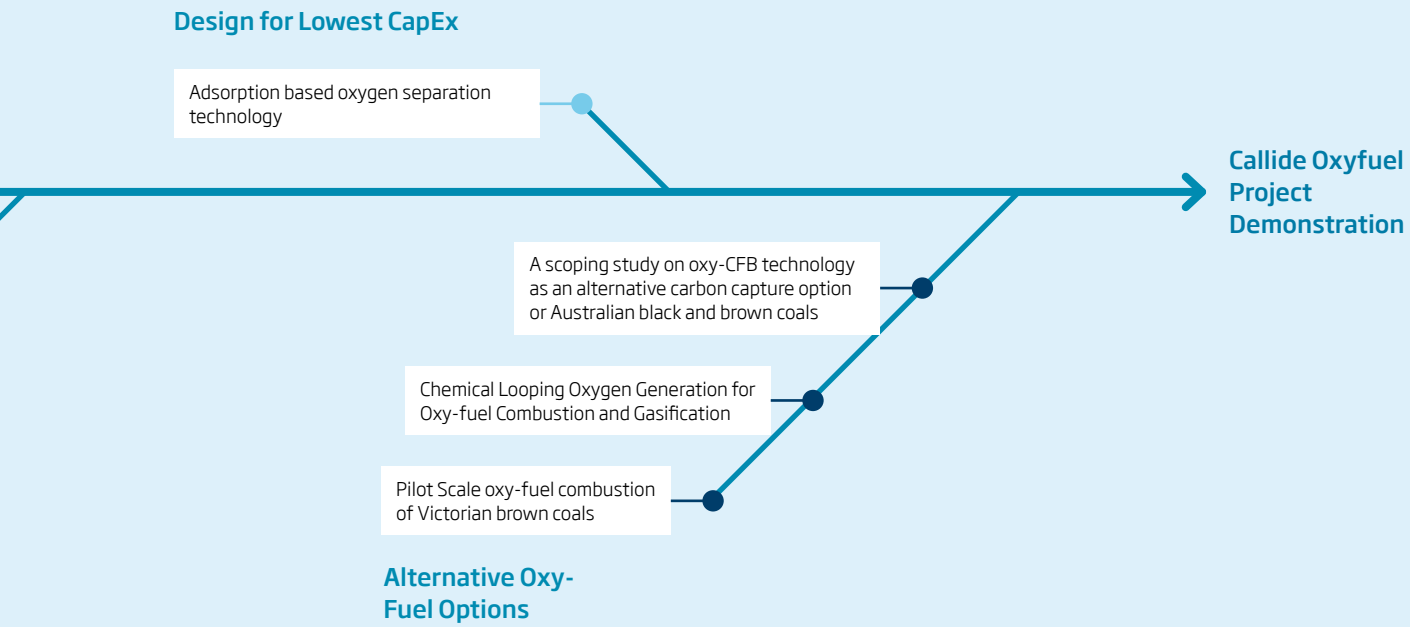
Supporting Research: Oxyfuel Combustion



* Studies undertaken prior to ANLEC R&D by the CRC for Coal in Sustainable Development (CCSD)

Project Director

Dr Chris Spero



Research Projects

A Scoping Study on Oxy-CFB Technology – An Alternative CCS option for Australian Coals

Different coals are favored by different combustion technologies. This study was undertaken in 2012, to assess alternative flowsheets to enable carbon capture from Australian black and brown coals required consideration.

Oxy-CFB operating at atmospheric pressure was emerging as a serious technology option for CO_2 capture. This was demonstrated by the rapid design and construction of world's first Oxy-CFB pilot scale facility at CIUDEN in Spain, which was commissioned in September 2011.

Compared to Oxy-PF, Oxy-CFB has potential advantages, including:

» Reduction of flue gas recycling, thereby reducing the size of the boiler island, and some of the auxiliaries consumption. This may potentially allow more compact and less expensive CFB boilers.

» Direct (in-bed) sulfur removal in Oxy-CFB may avoid the capital and operating costs associated with an FGD required for Oxy-PF.

» As CFBC's are operated at slightly over atmospheric pressure, possibility of air-in-leakage is greatly reduced.

» Oxy-CFB appears for the time being to be more suitable for low-rank or high-S or high-ash coals.

On reviewing results to date, the following observations were made:

» Combustion of coal particles under Oxy-CFB conditions is unlikely to be a problem.

» Agglomeration of minerals (from low-rank, high-alkali or high-S coals) under elevated levels of CO_2, SO_2 and water vapour may be a problem;

» Recarbonation in the back-pass of the boiler could be a problem, particularly for coals which have high Ca-content or coals that require added Ca for S-control.

» The extent of in-bed removal of sulfur gases in CFB and the need to sulfur removal by an additional operation exterior to the bed requires clarification.

» There is a lack of reliable information on emission of S-species, heavy metals and trace element emissions under Oxy-CFB conditions. It is not possible to speculate the extent of their emissions for Australian black and brown coals as no thermodynamic database can reliably make predictions under these conditions.

» Mercury speciation is not expected to be substantially different from Oxy-PF combustion, but data from only one study has been cited.

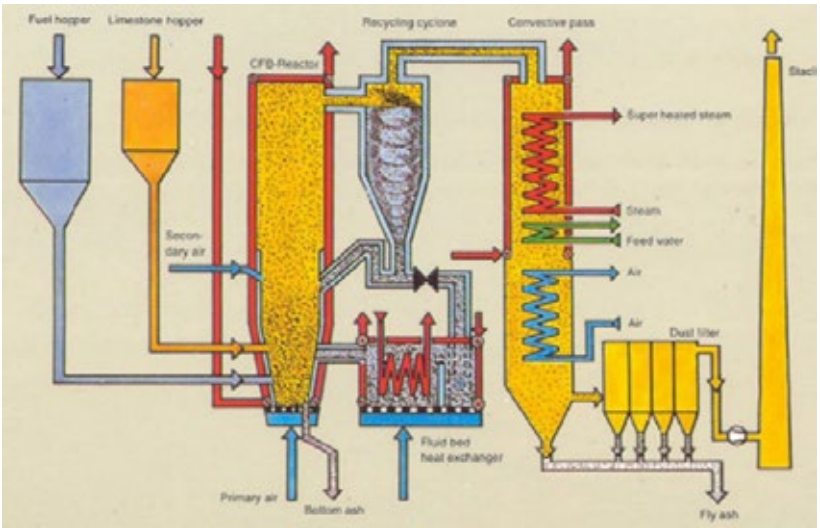
» The concentration of S-species, trace elements have significant implications for the gas cleaning requirement for CO_2 capture and transport.

» A detailed analysis should be undertaken to establish the economics of Oxy-CFB technology under supercritical and ultra-supercritical steam conditions and using Australian coals.

In 2012, due to the embryonic state of technical maturity of Oxy-CFB, a confident comparison of the cost and energy penalty figures between Oxy-PF and Oxy-CFB could not be made at this stage. Published literature was divided on comparative costs, with only scant details being available.

Reference

T. Wall, Y. Liu, S Bhattacharya, 2012, A Scoping Study on Oxy-CFB (3-0005)



Australian Research plays a key role in the Callide Oxy-fuel Demonstration Project

Oxy-Fuel involves firing a conventional pulverised fuel coal boiler with oxygen and recycled exhaust gases instead of regular air. This produces a concentrated stream of carbon dioxide that can be "captured" by compression in a CO_2 Processing Unit (CPU) and safely stored, indefinitely, deep underground.

Oxy Fuel combustion produces approximately 75% less flue-gas than air-fueled combustion, and produces exhaust that consists primarily of carbon dioxide and water.

Unlike the other developing coal-based low carbon dioxide emissions technologies, Australian application of Oxy-Fuel does not have any inherent gas cleaning technologies built into the process. While additional existing controls are available, they add considerable expense and some complexity to a retrofit.

Since 2004, this world-class low emissions fossil fuel project has progressed to a fully completed demonstration scale project.

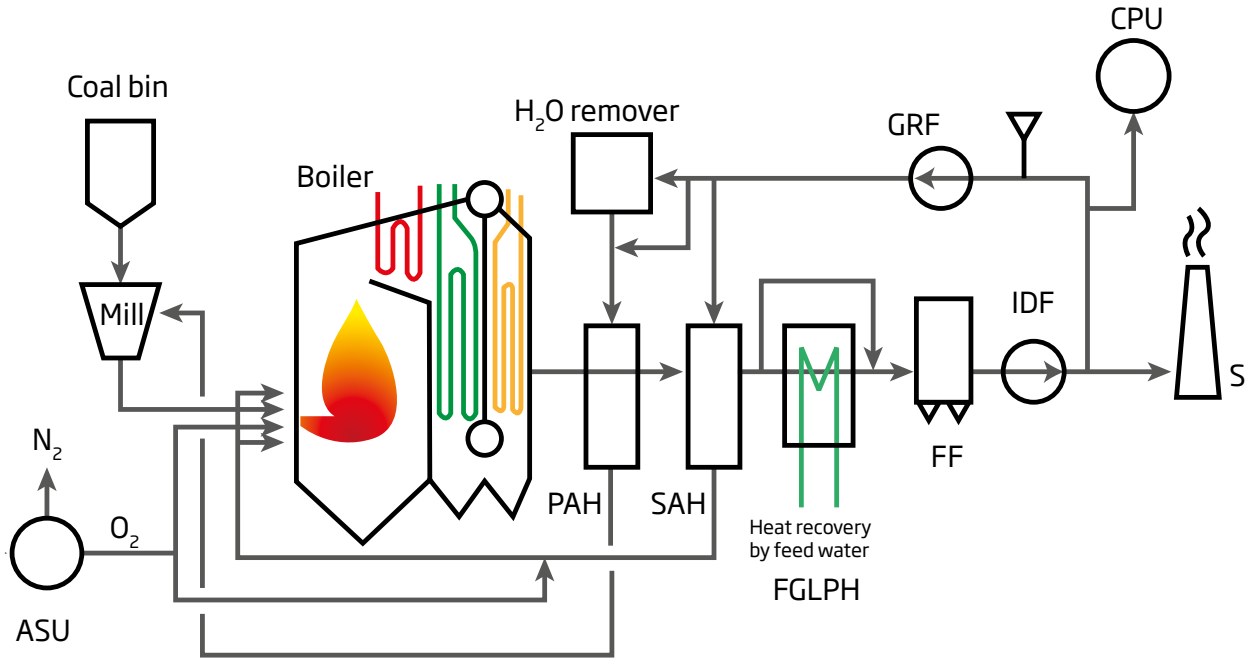
2004

» Research delivered a techno-economic systems assessment confirming Oxy-Fuel as one (among many) low emissions CO_2 capture alternative.

2005

» Research delivered technical performance of advanced power generation systems in Australian conditions, providing local mass and energy balances.

Callide Oxy Fuel Demonstration Project.
Photo courtesy of the Callide Oxyfuel Project



2006

» Research trialled Australian coal performance in Oxy-Fuel combustion conditions, in the IHI pilot plant in Aioi, Japan. For retrofits, results indicated a burner modification was necessary to maintain heat transfer conditions in the boiler.

» A memorandum of understanding, between CS Energy & JV partners, delivered an Australia/ Japan feasibility study for the retrofit of the 30MW Callide A Demonstration Project.

2007

» Research provided a status report on Chemical Looping for lower cost oxygen production compared to the standard Air Separation Unit.

» Low Emissions Technology Development Fund/ACALET funding for demonstration was established.

2008

» Callide Oxy-fuel Project Joint Venture agreements finalised.

» The variability of Oxy-fuel flue gas composition was examined, along with its effect on CO_2 compression and storage.

2009 - 2011

» ANLEC R&D supported fundamental laboratory studies on gas cleaning options determined pH control was important for effective SO_2 scrubbing – a pH range of 4 < pH > 5.5 was recommended.

» Laboratory and slipstream site-testing was designed.

2012

» Callide Oxy-fuel Demonstration Project (COP) commissioned.

» ANLEC R&D supported laboratory and COP slipstream site testing commenced.

» Research and onsite testing established the feasibility of carbon dioxide quality control in Oxy-fuel, by the removal of mercury and NO_x during compression. The presence of SO_2 had little impact on NO_x capture during compression.

2014-15

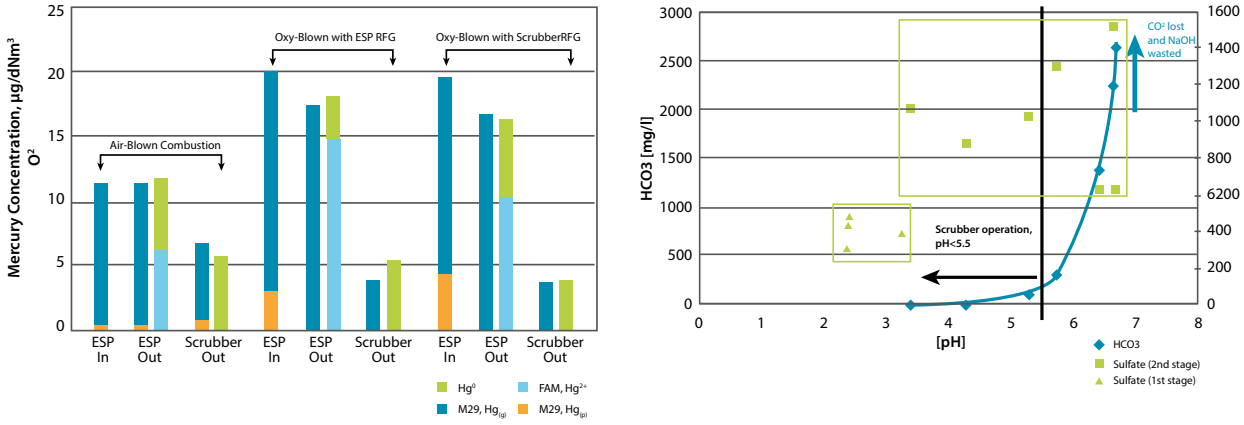
» It was found that gaseous mercury (Hg^0) in the flue-gas could be effectively removed using the carbon dioxide compression circuit during 'back end' carbon dioxide processing and may result in making a dedicated mercury removal unit redundant.

» The findings of the ANLEC R&D supported research at the Callide Oxy-fuel Project offer a paradigm shift in NO_x and mercury control in Oxy-fuel carbon dioxide purity management while reducing cost and risk.

Reference

R. Stanger, T. Wall et al, Gas quality impacts, assessment and control in oxy-fuel, 2015 (6-0710-0221)

R. Stanger, T. Wall et al, Impurities in Oxy Fuel CO2 compression; stability, disposal and utilisation 2016 (6-0215-0243)



Mercury species distribution during air-blown and oxygen-blown combustion.

Pilot Scale Oxy-fuel Combustion of Victorian Brown Coal

This work was undertaken because Victorian brown coal is the single largest source for the power generation in Victoria. It meets over 85% of the electricity needs of the State. Oxy-fuel combustion is one of the low emissions technologies suited to CO_2 capture.

This project successfully conducted the first pilot-scale research of brown-coal-fired oxy-fuel combustion. Apart from the retrofit case, a new purpose-designed oxy-firing scheme was proposed and examined intensively with independent external/internal coal drying coupled to address the potential of offsetting the energy penalty of air separation and thus achieving high-efficiency for this process.

The pilot-scale experiments have proven the viability for oxy-firing Victorian brown coal, either dry or as-mined wet. Under an estimate air ingress rate of about 2%, the purity of CO_2 in flue gas has been confirmed to reach approximately 80% in dry flue gas basis, with moisture reaching 40% in wet flue gas basis. SO_3 is negligible and NO_3 (mg/MJ) is reduced remarkably.

Pilot operations

Oxy-fuel combustion of Victorian brown coal occurs irrespective of dried or wet coal. The mode shift process is smooth, safety and reliable. The CO_2 purity reached 80% (dry) with a varying recycle ratio from 48% to 64% for flue gas.

For wet coal with 40 wt% moisture, the presence of 30% O_2 in flue gas is essential to match air for an identical flue gas temperature profile, due to the extra heat loss caused by coal drying.

For a timely and stable ignition of wet coal, the presence of 30% O_2 above in primary stream is essential.

The trial results provide the oxy-fuel performance and emission data in an industry relevant facility, which are a necessary basis for design and scale-up.

Effects on efficiency

The results show integration of pre-drying and supercritical steam condition compensates for the energy penalty for air separation and CO_2 compression, leading to a net efficiency of 25-29% LHV.

When employing wet type FGD for flue gas condensation, its outlet temperature is crucial in terms of water removal extent and process net efficiency.

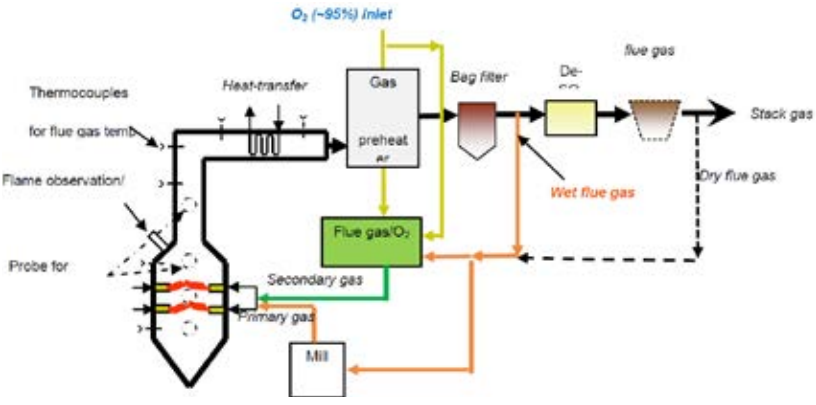
Ash deposition

A higher content of SO_3 and Fe_2O_3 and lower content of SiO_2 and $Al2O_3$ were found in the oxy-firing fly ash. The ash fusion temperature of oxy-firing fly ash is approximately 200°C lower than the air case. The enrichment of S and Fe in the oxy-firing sample is likely the main reason.

The fly ash base to acid ratio (B/A) value of 0.9 is around 2 times than that in the air case. Based on the equilibrium viscosity calculation, the serious deposition temperature zone of fly ash in the oxy-fuel case is around 880 ~1080°C, which is around 180°C earlier than that in the air case.

Reference

L. Zhang, 2014, Pilot-scale Oxy-fuel Combustion of Victorian Brown Coal (3-0113)



Achematic of the 3 MWth air-firing/oxy-firing facilities at SBWL

Techno-economic study of Oxy-fuel CO_2 compression products

The co-removal of SO_x and NO_x during CO_2 compression has recently emerged as an option in oxyfuel CO_2 compression based on an Air Products patent on sour gas cleaning. This would potentially reduce the capital and operating cost of oxyfuel CCS by avoiding the common inclusion of an SO_2 scrubbing unit operation prior to compression.

To clarify the three critical aspects of co-removal, controlled laboratory experiments on a small pressure vessel and bench scale compression unit were conducted to improve understanding regarding:

- The extent of the reactions of SO_x and NO_x associated with their absorption when in contact with water vapour.
- The conditions and liquids where N_2O is formed.
- The release of the absorbed gases on depressurisation.
- N_2O formation under real compression conditions.

Conclusions for the small pressure vessel:

- Experiments involving water vapour showed that acid condensates are readily formed associated with SO_x and NO removal but no N_2O is formed. Overall capture range between 59-91% for NO_x and 70-97% for SO_2.
- A mixture of SO_x and NO_x will readily react with liquid water, with release of N_2O at the pressures studied.

Conclusion using the laboratory compressor:

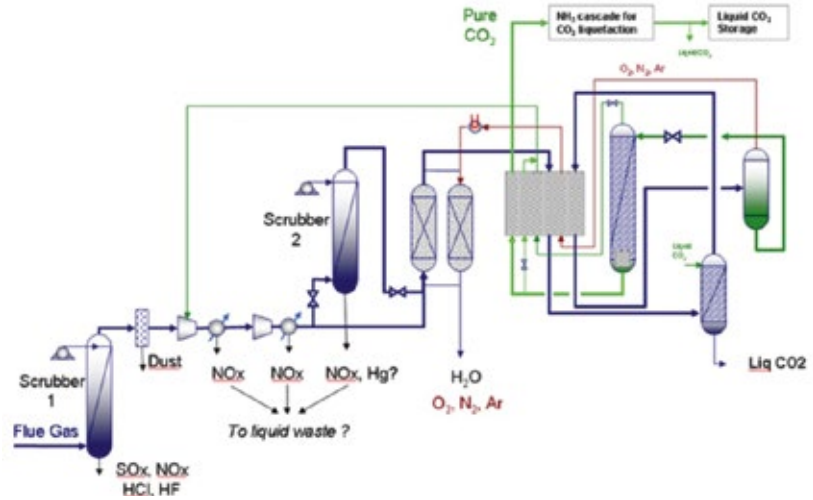
- The formation of N_2O has minor significance in GHG terms.
- The formation of N_2O was related to the capture of SO_2.
- The capture of SO_x and NO_x is significant; with SO_2, the compression process resulted in 100% capture, with 66-79% capture of NO_x.

This project quantified the removal of SO_x and NO_x in condensate wastes as dilute sulphuric and nitric acids during CO_2 compression in the CPU at the Callide Oxyfuel Project (COP). A literature review was undertaken to assess possible saleable products. The literature indicates that dilute mixed acids may potentially be used for various applications with economic value, including:

- pre-treatment of biomass such as bagasse to aid digestion in ethanol production,
- the recovery of rare earth elements from coal and ash wastes, and
- pre-treatment of ores used in mineral carbonation to improve their reactivity to form carbonates
- Higher acid concentrations are achieved for the acids at higher pressure. This may provide a higher concentration product option not considered to date.

Outcomes:

- Cost estimates for adjusting the pH of the liquids prior to disposal in an ash dam, along with the value of the products, indicate that a justification for transforming the mixed acid wastes into products may be to avoid these disposal costs rather than the value of the products themselves.



Simplified schematic of Callide Oxy-Fuel CO_2 purification unit.

Reference

T. Wall, et al 2015, Impurities in Oxy-fuel CO_2 compression: stability, disposal and utilisation (6-0215-0243)

Environmental performance of Oxy-fuel technology rigorously tested

Oxy Combustion is one of the coal-based candidates for carbon capture and storage. As part of developing the Oxy Combustion technology, the environmental, health, and operational risks associated with trace elements need to be understood.

The focus of this research was to investigate the behaviour of trace elements during Oxy Combustion (oxy-firing) and CO_2 capture and processing. The environmental and operational risks associated with trace materials was to be the primary focus of this work. It is understood that the behaviour of trace components may have important implications for process options, gas cleaning, environmental risk and the resultant costs of Oxy Combustion.

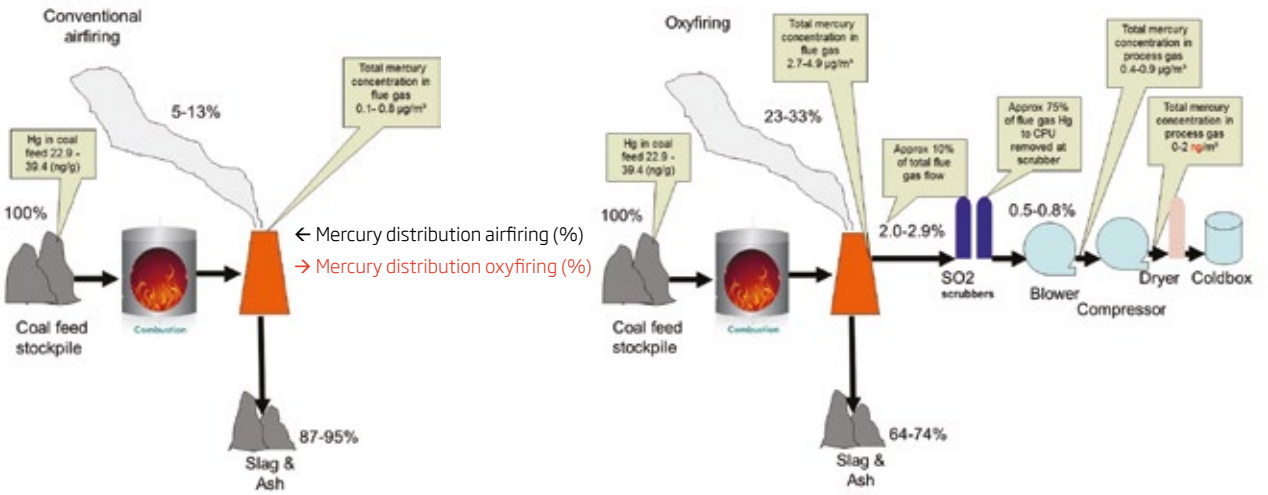
This study was based on a field experiment carried out at the retro-fitted Callide A power plant in December 2012. The power plant is capable of both oxy and air firing and the experiment involved both modes. Measurements were made of the trace metal and particulate matter emitted during the firing process, and the targeted metals included both mercury and chromium.

Key conclusions:

- The trace levels of metals in the purified CO_2 gas stream should not pose significantly higher operational risks within the CPU;
- Oxy-firing does not pose significantly higher environmental or operational risks than air firing;
- Levels of metals, SOx and mercury are below levels of concern in the CPU, beyond the first low pressure scrubber, and
- Mercury levels, measured in CPU produced gas, approach those measured in ambient air. However, in all cases the increased risks to the population of exposure were below the USEPA response level, such that no action would be required to reduce exposures.

Reference

A. Morrison, et al 2012, Impacts of trace components on Oxy-combustion for the Callide Oxy-fuel Project – Further results and analysis from Callide field-trials, December, 2012 (6-0411-0130)



Review of flue gas sulphur removal technologies at small scales

Sulphur removal from flue gas is well-established for commercial scale power generation. However, these are too expensive for low cost small scale deployment, where alternative technologies might appear.

Several flue-gas desulphurization technologies (FGD); namely alkali-based wet-FGD technology, calcium-based wet FGD technology and activated-carbon (AC)-based dry FGD technology were selected for techno-economic assessments in this phase-2 study. Aspen Plus modelling results showed that SO_2 concentration in flue gas can be readily reduced to 10 ppmv, or below, by all four FGD technologies, which satisfies the request of SO_2 level in flue gas prior to entering post-combustion capture unit.

In terms of maturity and from an economics view, this assessment has shown the sodium-based wet FGD unit is the lowest cost technology option at smaller scales. Australian experience with this FGD technology (at the Callide Oxyfuel Project) has shown it to have low maintenance costs and high availability.

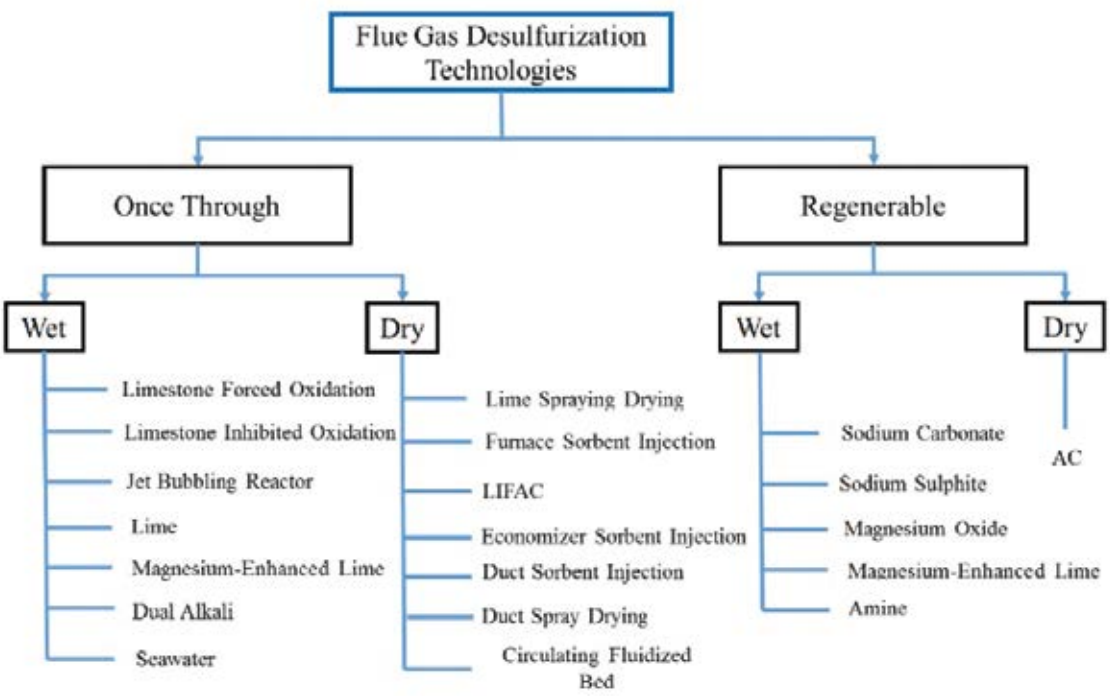
However, dual alkali wet FGD technology may also be considered, given the comparatively low reagent costs. This assessment has shown that the dual alkali FGD option is ~13% higher in the overall cost compared to the sodium-only unit. The shorter operational period (i.e. 3 years) of the project means that the cumulative costs of the more expensive Na_2CO_3 reagent may be offset by the lower capital costs of the sodium based FGD technology.

The project delivered a comprehensive literature/ technology review prior to technology screening. This includes a technical and economic analysis of best-suited FGD technologies for CCS integration. In particular, the evaluation is specific to Australian coal-fired power systems and also includes the waste disposal and co-removal of other contaminants.

The research team had access to the new activated-carbon impregnated $deSO_x$ process, developed at University of Newcastle, and access to the pilot-scale integrated $deSO_x$/ $deNO_x$ facility at the University of Science and Technology Liaoning (China). The project was to engage Huaneng CERI and CSIRO Energy Technology Australia.

Reference

J. Yu, et al 2016, Scoping Study of technological options for SOx treatment (4-1115-0255)



Classification of available Flue-Gas De-sulphurization Technologies (FGD) technologies.

Chemical looping air separation

Current commercial oxygen production systems have relatively high-energy demands and, as such, represent a significant parasitic load when integrated with either Integrated Gasification Combined Cycle (IGCC) or Oxy-fuel Combustion.

This study sought to test the chemical looping concept to deliver integrated high purity oxygen production at low energy and high throughput, based on their recent breakthrough work on air separation based chemical looping.

The study delivered results from laboratory and pilot scale experimental trials, in addition to a preliminary assessment of techno-economic feasibility for the technology.

The study showed:

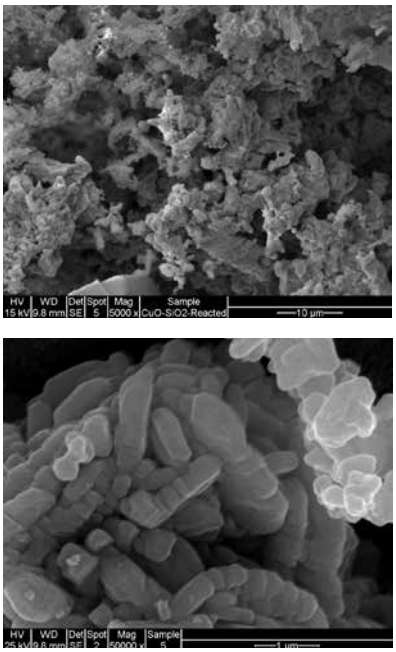
- That chemical looping air separation is a viable technique for the production of industrial scale oxygen.
- Suitable copper oxide species were demonstrated as oxygen carriers and enhanced material could be delivered from additional research.
- A spray drying technique for the production of high quality metal oxides proved very effective.
- Scale-up rules for chemical looping air separation were determined from data collected in a 10kWth facility.
- Detailed assessments of scaling parameters for the reduction reactor were carried out by a combined set of theoretical analyses and mathematical modelling.

While suggesting a positive potential for the technology in the report, several techno-economic variables require additional data to ensure that a more accurate and up-to-date assessment is possible.

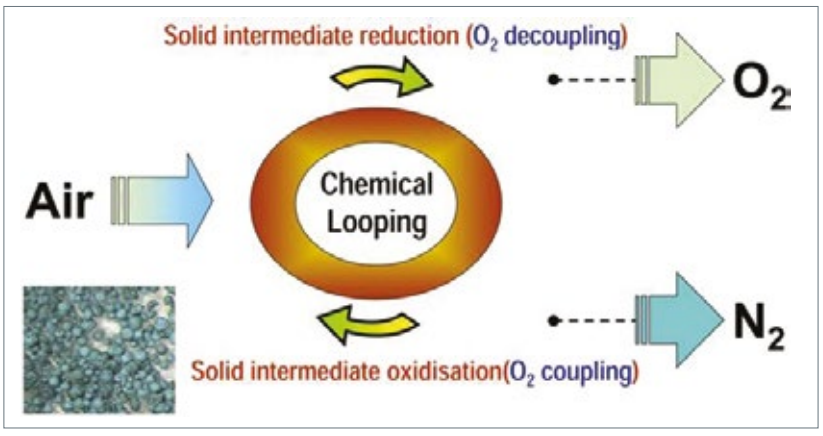
Consistent with most other low emissions technologies, the study suggests carbon pricing is necessary before such processes can become economically viable.

Reference

B. Moghtaderi, et al 2015, Chemical Looping Oxygen Generation for Oxy-fuel Combustion and Gasification (3-1110-0089)



Fresh and used CuO/SiO_2 oxygen carriers.



Chemical looping air separator concept

Adsorption Based Oxygen Separation Materials Tested

Low emission coal processes like oxy-fuel combustion require a low cost oxygen supply.

The aim of this project was to develop oxygen selective adsorbent materials and the associated process cycles for the separation of oxygen from air. Using materials that adsorb oxygen instead of nitrogen should significantly reduce equipment size and overall process costs.

Three broad categories of materials were investigated: inorganic materials, in particular metal oxides; porphyrin-based materials and polymers; and metallocene based materials and polymers.

In the category of inorganic materials, a variety of high temperature metal oxide materials were studied. While a suitable candidate was not found, these materials, may be useful as high temperature 'oxygen-getters' or as active components of thin films or membranes for integration with the boiler in the power plant to provide enriched air.

In the category of porphyrin materials, cobalt and iron based porphyrin polymers were synthesized with up to 8 wt% metal loading and oxygen and nitrogen sorption experiments were performed to determine the selectivity of these materials and their suitability for air separation applications. The separation properties of the porphyrins were not improved by increasing the iron content. On the other hand, an increase in the cobalt content led to an increase in both the oxygen selectivity and oxygen capacity. At 273 K, an O_2:N_2 selectivity of 1.33 was obtained. The uptake of both oxygen and nitrogen gas was shown to be fully reversible at room temperature, with cycling experiments (6 cycles) showing that the oxygen and nitrogen capacities of the materials were not reduced through repeated adsorption and desorption cycles. This was a significant achievement. The oxygen selectivity of the porphyrins may be further improved by incorporating more cobalt ions into the porphyrin rings in the polymer. Theoretically, by fully saturating the polymer with cobalt ions (i.e., the stoichiometric content as mentioned above), the polymer can achieve an oxygen selectivity of 14 and an oxygen capacity of 1.4 mmol/g.

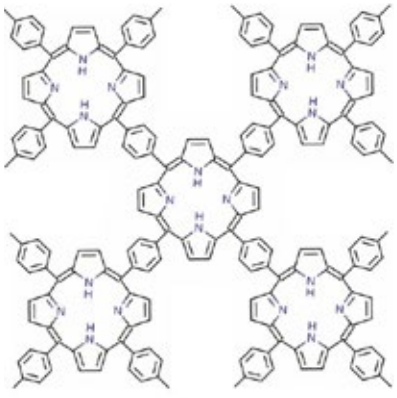
The third category of materials investigated were the metallocene materials. Early work on this strategy indicated that metallocene based polymers were more prospective than either the neat metallocenes or metallocenes impregnated into a highly porous substrate like SBA-15. The maximum amount of oxygen adsorption observed at 20 kPa (corresponding to the partial pressure of oxygen in air) was about 0.04 mmol/g, still too low to be useful. Similar nickelocene materials were prepared - there was minimal oxygen adsorption below 200 °C and the highest oxygen adsorption values were observed in the 250 - 300 °C range. The reduction in oxygen adsorption capacities at higher temperatures (350 - 400 °C) were linked to the thermal instability of the nickelocene copolymer in this temperature regime.

In addition to the materials development work, process simulations and economic evaluations for four case studies were conducted.

The results showed that the ideal porphyrin materials (Case D) may provide significantly lower operating costs than conventional adsorption-based air separation (Case A). In addition, when compared to cryogenic oxygen supply, (Case D) may provide a lower overall oxygen cost since the energy requirement is significantly lower. This depends on the relative contributions of power and capital costs to the total oxygen cost.

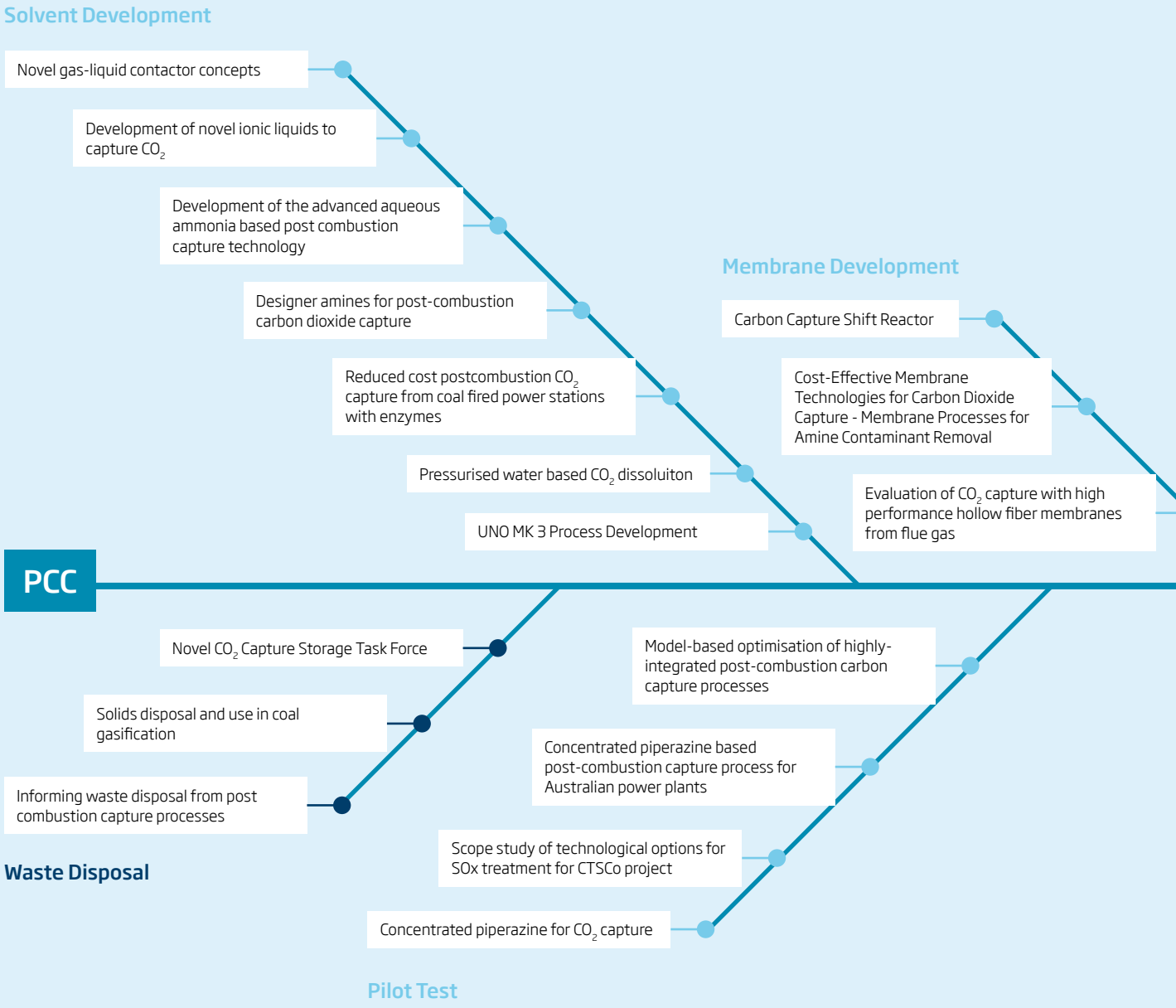
Reference

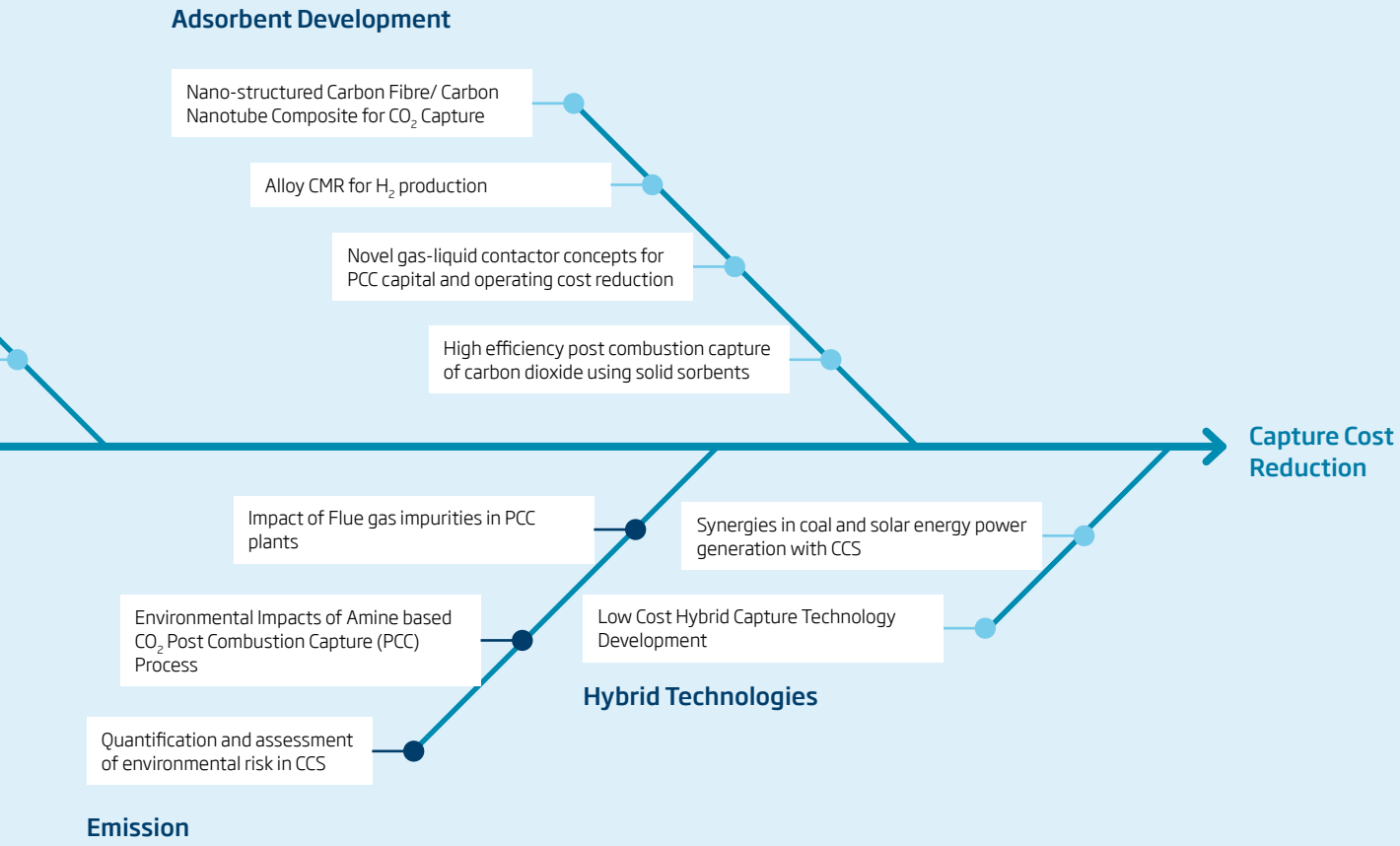
P Webley, M Chowdhury, W Tang, A D'Angelo, A Chaffee D Wiley, CO2CRC Report No:15-5306, 2015 (3-0044)



SEM structure of porphyrin porous organic polymers.

Supporting Research: Post Combustion Capture





Research Key

- Cost Reduction
- Environment

Research Projects

Concept testing for CO_2 capture cost reduction

CO_2 capture can amount to nearly 70% of the cost of a low emissions power generation project using fossil fuels. Demonstration and deployment will help reduce these costs.

ANLEC R&D implemented a concept testing program of research that canvassed the best ideas for cost reduction to capture, in an Australian context of fuel, environment and grid systems. This wide ranging program reported on several innovative ideas including:

Solvents

- Solvent precipitation system
- Designer amines for post-combustion carbon dioxide capture
- Novel ionic liquids for CO_2 capture
- Development of an advanced aqueous ammonia based post combustion capture technology
- Novel gas-liquid contactor concepts for PCC capital and operating cost reduction
- Enhanced CO_2 capture from coal-fired power stations with enzymes
- Pre-treatment of flue gas and capture of CO_2 from brown coal-fired power stations
- Development of froth generator gas/liquid absorption technology

Membranes

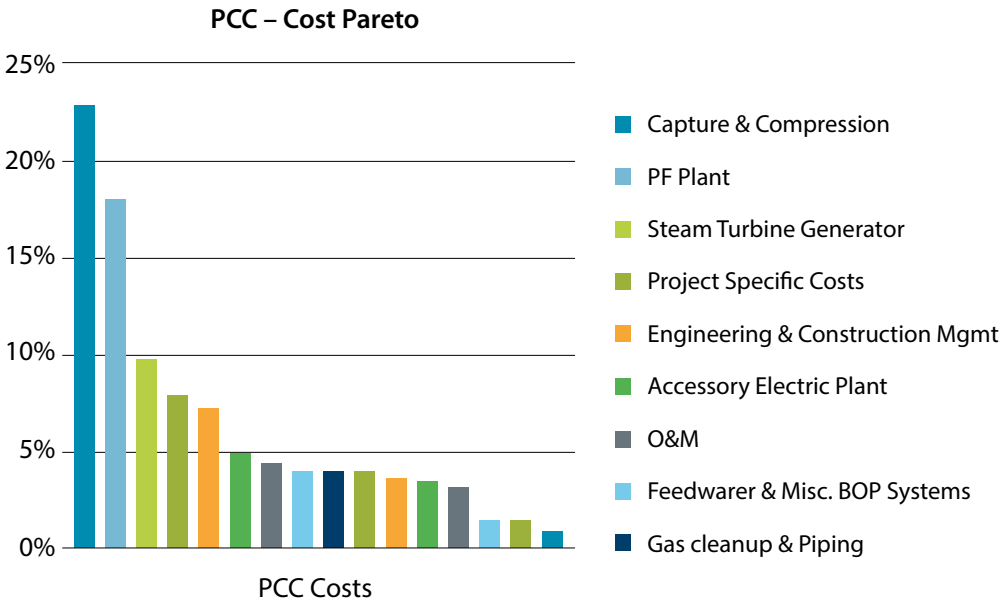
- Alloy catalytic membrane reactors for H_2 production
- Membranes for tonnage oxygen separation, suited to supply oxy-fuel and coal gasification applications
- Carbon Capture Shift reactor
- Membrane processes for amine contaminant removal
- CO_2 Capture with high performance hollow-fibre membranes from flue gas

Adsorbents

- High efficiency post combustion capture of carbon dioxide using solid sorbents
- Low cost hybrid CO_2 capture technology
- Adsorption based oxygen generation technology
- Nano-structured carbon nano-tube composites for CO_2 capture

Engineering

- Pilot-scale oxy-fuel combustion of Victorian brown coal
- Solids disposal and utilisation in IGCC
- Metal foam heat exchanger for dry cooling



Quantification and assessment of environmental risk in carbon capture and storage

Post combustion capture (PCC) of CO_2 using amine solvent scrubbing is the most mature technology that could be used for existing power stations.

Air emissions from power plants must be compatible with the environment to be a long-term viable solution. Since the reduction of carbon dioxide emissions from fossil fuel power plants will require the application of new technologies, emissions from these technologies must be understood.

This change in power generation technology will inevitably require changes in the way power plants are approved, regulated and monitored. The environmental performance of solvents will impact their commercial and environmental viability.

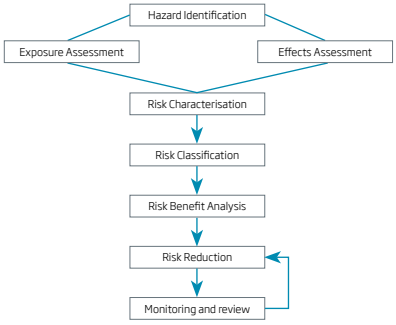
Post combustion capture (PCC) of CO_2 using amine solvent scrubbing is the most mature technology that could be used for existing power stations. However, amine-based PCC technology has the potential to emit toxic organic compounds whose environmental and health impacts must be assessed prior to regulatory approval.

In this study a modelling framework for undertaking a risk assessment for population exposure to formaldehyde is described. The modelled results showed that after installing PCC technology there may be an increase in overall atmospheric concentrations of formaldehyde – however in all cases the increased risks to the population of exposure were below the USEPA response level such that no action would be required to reduce exposures. The ambient concentrations of formaldehyde would need to increase by a factor of approximately fifty times to bring it to the levels at which the USEPA would require action. The dispersion calculations also show that maximum-modelled concentrations of MEA do not exceed health guidelines.

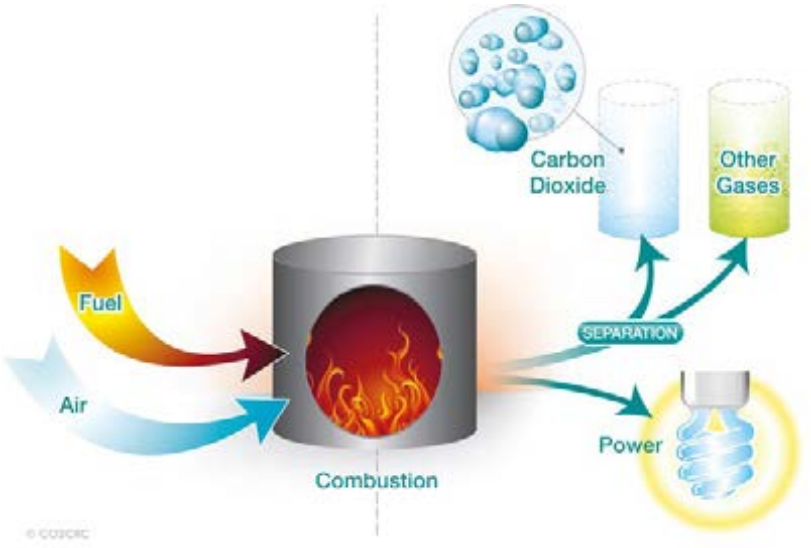
In summary, the implications of the increased regulatory focus on the environment for the traditional environmental issues associated with coal use in CCS will be profound. This study formed a solid foundation for environmental risk assessments, and more particularly information on formaldehyde and MEA emissions from a Post-Combustion Capture plant on a traditional coal fired power plant.

Reference

P. Nelson, el al 2014 Quantification and Assessment of Environmental Risk in Carbon Capture and Sequestration - Development of Risk assessment procedures for trace PCC components (7-0311-0127)



Above: Steps in the Risk Management Process.



Left: Air emissions from power plants must be compatible with the environment to be a long-term viable solution. Since the reduction of carbon dioxide emissions from fossil fuel power plants will require the application of new technologies, emissions from these technologies must be understood.

This change in power generation technology will inevitably require changes in the way power plants are approved, regulated and monitored. The environmental performance of solvents will impact their commercial and environmental viability.

Pilot Testing Aqueous Ammonia for CO_2 Capture

The cost of CO_2 capture can be reduced by more effective solvents. This study investigates the application and optimisation of using aqueous ammonia as a solvent.

Currently, commercially available PCC technology is mainly based on alkanol/alkyl amine solutions. However, aqueous NH3 has many advantages over amine-based capture technologies. They include no degradation in the presence of O_2, a higher CO_2 absorption capacity than monoethanolamine (MEA), and a low regeneration energy. It also has the potential to capture oxides of nitrogen (NOx) and sulfur dioxide (SO_2) from the flue gas of coalfired power plants, and to produce value-added chemicals, such as ammonium sulfate and ammonium nitrate, which are commonly used as fertilisers.

The project led to the development of an advanced, aqueous NH_3 based capture process which incorporated the following innovative features.

1. Integrated flue gas cooling, with SO_2 removal.

The integrated process cools flue gas removes SO_2 and recovers NH_3 simultaneously. SO_2 is removed in a pretreatment column and its presence in the wash water helps to recover NH_3 from the wash column, producing ammonium sulfite.

The rigorous rate-based process modelling and bench-scale experimental work showed that the integrated process can recycle >99% NH_3 and remove >99% SO_2 with very low energy consumption. This new process can eliminate conventional FGD and produce value-added products.

2. Two-staged absorption: This configuration can significantly reduce NH_3 slip in the absorption process by more than 50% compared to single-stage absorption.
3. Elevating CO_2 absorption temperature to ambient conditions (20–30°C) and using relatively high NH_3 concentrations (6–10 wt%).
   This can avoid both solid precipitation and the substantial energy input for solvent chilling, as well as improve the CO_2 absorption rate.
4. Two new stripper configurations:
   a. Stripper rich split configuration uses the cold, CO_2-rich solution to cool the uprising hot gas vapour and recover the NH_3 from the vapour. No external stream is involved in the modification. The process can help eliminate solid precipitation in the stripper overhead condenser and reduce reboiler duty and cooling water consumption.
   b. The inter-heating process configuration makes better use of the heat in the hot lean stream, and simultaneously reduces reboiler and condenser duty.

To improve on the reaction kinetics the study also investigated the feasibility of pressurised CO_2 absorption and the use of promoters.

Results suggested that pressurisation of flue gas may not be economically viable for CO_2 separation from low-pressure flue gas. Introduction of these 6 promoters significantly enhanced CO_2 mass transfer in the solvent, but at the expense of greater NH_3 vapour losses.

The work was validated in CSIRO PCC pilot-plant trials with an aqueous NH_3-based liquid absorbent under real flue gas conditions in an $A7 million pilot plant at Delta Electricity's Munmorah power station. The pilot-plant trials confirmed the technical feasibility of the process and confirmed some of the expected benefits. They also highlighted some of the issues when using aqueous NH_3 in a PCC process. These included a relatively low CO_2 absorption rate and high NH_3 loss. These issues currently limit the economic feasibility of the aqueous NH_3-based PCC process.

Reference

H Yu, L Wardhaugh, P Feron, et al, Development of an Aqueous Ammonia-Based PCC Technology, 2016 (3-0142)

Post Combustion Capture Pilot Plant.

Concentrated Piperazine for CO_2 Capture

New CO_2 capture solvents continue to emerge. This project was designed to evaluate the use of concentrated piperazine (PZ) for post-combustion capture of CO_2 (PCC) in black-coal fired power stations in Australia.

Concentrated PZ is an alternative to the standard MEA– an amine CO_2 capture solvent. Based on extensive laboratory research has shown PZ has attractive attributes such that they have the potential to reduce the costs of capture and compression of CO_2 by more than 50%, according to the University of Texas.

The results from this study at pilot scale showed that the solvent did deliver some aspects as indicated by laboratory studies such as lower volatility, more thermally stable and lower regeneration energy requirements but did not clearly show improvements in reaction rates as predicted. Operation of solvent regeneration at higher temperatures and pressures proved successful with some increased degradation, but this is still small compared to MEA.

Practical issues were very real when dealing with the PZ solvents tendency to precipitate when CO_2 loading and temperatures fall outside of the optimal range and this requires careful consideration if concentrated PZ is chosen as the operating fluid for PCC. Although with careful operation and appropriate plant modifications and additions the solvent can be successfully and reliably used for PCC and energetically performs better than the standard MEA process by around 15%.

From an environmental safety perspective, piperazine - being a secondary amine - is prone to forming stable nitrosamines in the presence of nitrite. The project has shown that using concentrated piperazine on a coal combustion flue gas containing NO_2 does form nitrosamines which build up and seem to reach equilibrium over time.

It was also shown that the nitrosamine concentration can be successfully managed by implementing an effective flue gas pre-treatment stage before CO_2 absorption as well as operating the solvent regeneration at a higher temperature which is thought to increase the rate of thermal degradation of the nitrosamine compound.

Assessing the piperazine process using a techno economic approach showed that the piperazine process is not significantly cheaper when compared to the MEA based process. However, both processes could be optimised further which would bring down their costs. It is envisaged that there is still significant savings to be had in optimising the concentrated piperazine process over the MEA process.

As more knowledge is gained about the concentrated PZ process further optimisations and process configurations to full take advantage of the solvent's properties should be explored. It will help deliver more reliable assessments and as this study shows, the PZ process has the potential to perform better than the reference MEA solvent.

Reference

A Cottrell, A Cousins, M Sinclair, P Feron, et al, Concentrated Piperazine based PCC, 2016 (4-0097)

Post Combustion Capture Pilot Plant.

Molecules Designed to Improve Performance in Post-Combustion CO_2 Capture

This project was commissioned to generate significant improvements in energy performance of amines in CO_2 absorption-desorption processes.

Undertaken as a fundamental study, it achieved its objective through amine synthesis, cyclic capacity tests, wetted-wall column (WWC) tests, vapour-liquid equilibrium (VLE) tests and kinetic studies.

Initially, thirty designer amines were synthesised at small scale and their cyclic capacity were measured via an established method using quantitative methods. Seven amines displayed more than 80% improvement in their cyclic capacity and approximately a 28% or more improvement in their estimated energy performance in comparison with MEA, and the largest improvement was 32%.

In addition to the improvement in energy performance, an estimation using ChemDraw software indicated significantly higher boiling points for the designer amines that should contribute to reduced environmental impacts of these amines when used in post combustion capture (PCC) of CO_2.

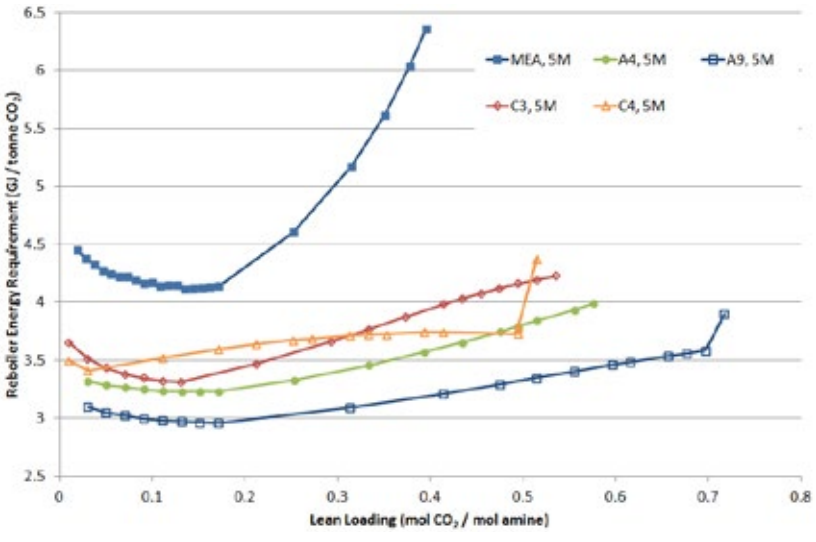
Four of the above seven top performing designer amines identified via estimation of energy performance were synthesised at larger scale in good yields and their scalable synthetic methods were developed. As part of the investigation, the kinetic (rate) constants and equilibrium constants describing the fundamental reactions of the amines with CO_2 have been determined at 25°C and 40°C together with the protonation constant(s) of the pure amine solutions over the temperature range 15 – 45°C.

All four designer amines synthesised at large scale showed reductions in estimated reboiler energy requirement of 21 – 34% relative to MEA, validating the methodology adopted to select the compounds for large scale synthesis, with 34% achieved by one formulation. Upon consideration of the rates of reaction with CO_2 this amine was measured to be about 2x faster than MEA. When viewed in combination with it achieving the lowest energy requirement estimate, it places firmly as the best candidate to achieve an overall cost reduction in terms of CO_2 avoided of 50% (relative to MEA). Such a performance level could correspond to a final cost of approximately A$30 / tonne CO_2. The next best candidate investigated had similarly fast kinetics and a 26% reduction in estimated reboiler energy requirement.

The kinetic study of these two proprietary amine formulations showed improvements in the kinetic rate constant for the reaction of CO_2 with amine relative to MEA at similar temperatures. The protonation enthalpy of at least one synthetic amine product was found to be the most promising for the post combustion carbon dioxide capture technology.

Reference

Q Yang, S James, M Bown, W Conway, G Puxty, P Feron, Designer Amines for Post-Combustion CO_2 Capture, 2013 (3-0091)



Synthesised amine capture performance compared with MEA.

Novel Ionic Liquids – Investigating Lower Cost Absorbents for CO_2 capture

To reduce the cost of CO_2 capture, the aim of this research was to develop novel ionic liquid absorbents that are suitable for post combustion capture (PCC).

Ionic liquids have been attractive as CO_2 absorbents in the past few years due to their relatively high CO_2 solubility and selectivity, high thermal and chemical stabilities, low vapour pressure, and importantly a potential to reduce energy consumption by up to 60%. A major problem however is their high viscosity originating from strong coulombic interactions between cations and anions, which results in slow absorption kinetics. A main focus of this project is to tackle the viscosity problem while balancing other advantageous properties.

This work demonstrated that ionic liquids having multi-amino groups in the anion can exhibit a CO_2 absorption capacity as high as 17 wt%, among one of the highest reported values. These ionic liquids show a balance in CO_2 absorption capacity, good thermal stability, and low viscosity with the presence of water. Among the ionic liquids, those having 2, 4-diaminobutyl carboxylate anion appear to have optimised properties for CO_2 capture. They exhibit some of the highest CO_2 absorption capacities (10-14 wt%), the lowest viscosities (17 and 31 mPa·s before and after absorption at 40 oC with 12 molar equivalents of H_2O) and thermal stability above 200 oC.

The study also extended to investigating the CO_2 absorption mechanism of tetrabutyl phosphonium 2, 4-diaminobutyl carboxylate under dry and wet conditions. Regeneration energy for the products developed is estimated to be 1.63 GJ·ton-1 CO_2 for neat ionic liquid, implying a potential of a significant reduction from that for 30% MEA system (3.8 GJ·ton-1 CO_2). The viscosity of the ionic liquid is 170 mPa•s at 40°C, was in the low to medium range.

Neat ionic liquids are likely to have a higher viscosity than current benchmark absorbents and potentially have higher mass transfer limitations. However, these may be addressed by new and novel improvements in contactor designs.

The study also demonstrated that adding a small amount of water or organic solvents is an effective way to reduce the viscosity while maintaining the energy consumption at significantly lower levels than that for aqueous amine solutions. Having four molar equivalents of water (about 16 wt%) would significantly reduce the viscosity down to 44 mPa·s at 40 oC while achieving a regeneration energy of 2.5 GJ·ton-1 CO_2. Having tetraglyme (TGM) or triethylene glycol (TEG) as additive also demonstrates to be an effective way to reduce the viscosity while achieving a low regeneration energy, i.e. about 2.3 and 2.5 GJ·ton-1 CO_2 for IL-TEG (1:1 w:w) and IL-TGM (1:1 w:w) respectively.

Power generation flue gas contains 3-9 vol% moisture. The absorption of water may reduce the viscosity while adding some energy penalty to the capture system. It is worthy of further study on the moisture absorption behaviour of the neat and mixture solvents to evaluate their performance under moisture effect.

The di-amino functionalised ionic liquid generates precipitates or emulsions upon CO_2 absorption. However, the precipitate can be dissolved in water. This unfolds two different capture processes, one based on a traditional solvent process, and one involving in a phase change process. The choice of processes requires more thermodynamic and kinetic parameters for evaluation.

In an effort to evaluate the influence of other flue gas components, SO_x and NO_x absorptions indicate that these gases are reactive to the ionic liquid, reducing the overall effectiveness of the ionic liquid toward CO_2. It is worth considering the use of a pre-scrubber for the removal of both SO_x and NO_x. Another option is to adopt the CSIRO patented SO_x and CO_2 co-capture process.

Reference

J Huang, A Rosamilia, H Liu, G Yu, Development of novel ionic liquids to capture CO2, 2013 (3-0050)

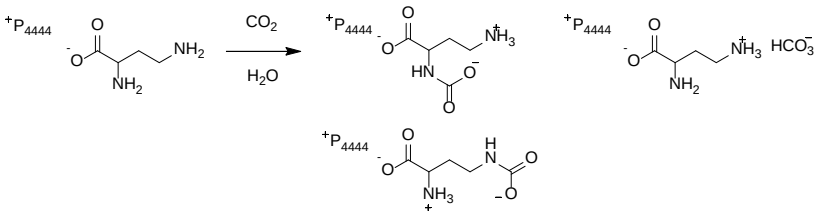


Figure. CO_2 absorption mechanism for the P_{4444} 2,4-diaminobutyl carboxylate water system.

Concepts Tested for Amine Enzyme Enhanced CO_2 Capture

This research aimed to demonstrate the utility of enzymes for reducing the capital and/or energy costs of post combustion capture.

The research has applied several methods to screen enzyme-base solutions for absorption of CO_2 from mixed gas streams and select for high CO_2 absorption rate among bases having lower vapour pressure, high absorption capacity, lower corrosivity, thermo- and metal ion stability and faster biodegradation, and lower energy of regeneration than monoethanolamine (MEA), our benchmark.

Enzymes are biological catalysts made of protein that can operate independently of a biological cell to facilitate reactions with high specificity and rapid turnover rates under mild conditions. Due to rapid rates and genuinely catalytic quantities used, there is potential for enzymes to increase the CO_2 mass transfer rate to capture solutions, facilitating the uptake of CO_2 and potentially reducing capital and energy costs of the process.

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In terms of enzyme performance for application in post combustion capture and sequestration processes we have concluded:

- Potassium carbonate, tertiary alkanolamines and amino acid salts such as sarcosine and alanine have the best prospects for combination with enzymes for CO_2 capture.
- The preferred operating temperature for use of standard enzyme (bovine carbonic anhydrase) in CO_2 capture is approximately 40°C and the pH of the capture solution should be ≤ 11 to obtain maximal lifetime from the biocatalyst.
- Alternative enzymes CSIRO 2&3 from diverse organisms show excellent long term stability in potassium carbonate and sarcosine pH 10 and are being assessed for long term stability at higher pH and temperature.
- Enzyme half life, that is, the time taken to reduce activity of the immobilised bovine carbonic anhydrase by 50% at 40°C was approximately 8 d in 1 M potassium carbonate and 21 d in 2 M alanine at pH 10. By contrast, no loss of activity has been recorded for extremophile enzyme CSIRO2 continuously exposed to 1 M K_2CO3 or 1 M sarcosine salt, both at pH 10 and 40°C after 63 d. For this enzyme both higher molarity solutions and higher pH conditions were also well tolerated.
- Successful immobilisation strategies have been developed for bovine, engineered and extremophile carbonic anhydrase enzymes.
- The rationally designed M4 enzyme developed in the project has greater stability and greatly increased activity in the presence of high ionic strength solutions which would normally inhibit other enzymes. It may have application to CO_2 capture in brine solutions or other saline waters.

The research has successfully identified new enzymes and basic solution combinations that provide longevity and effective uptake kinetics for CO_2. In particular, sarcosine amino acid salt was identified as a solvent with excellent potential for combination with enzymes as it exhibits CO_2 uptake kinetics equivalent to MEA but is relatively mild on enzymes.

Reference

V Haritos, CO_2 capture from coal-fired power station flue gas by using enzymes, 2015 (3-0099)

Schematic diagram of bCAII M 4 containing 18 substitutions increasing protein stability.

Innovative Rotating Liquid Sheet delivers significant capital and operating cost savings for CO_2 capture

Reducing the cost of CO_2 capture from flue gas is essential if carbon capture and storage is to be widely deployed as a low emissions coal technology for power generation.

The premise of developing a novel gas-liquid contactor is that without a "radical rethink" of the capture technology substantial cost reductions will not occur.

The gas velocity sets the contactor column diameter of a gas-liquid contactor and has a large influence on both the capital and operating costs.

The overarching objective of this study was to test a novel contactor concept. A new gas-liquid contactor was designed to widen the gas velocity operating window, which significantly restricts conventional contactor technologies, but not at the expense of higher pressure drop.

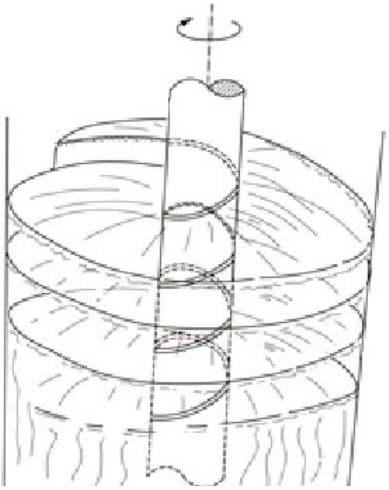
The novel Rotating Liquid Sheet (RLS) contactor developed not only achieved a significantly wider gas velocity operating window, it also eliminated the need for the solid packing elements used in conventional packed beds.

The potential cost reductions are as a result of eliminating conventional column packing, reducing or eliminating the need for external flue gas pumping and smaller contactors.

Overall capital cost savings are estimated to be approximately 30%, based on the elimination of the packing and the reduction in column diameter. Elimination of the flue gas blower provides a minor capital cost saving and, additionally, it provides the opportunity of a net reduction in electrical power consumption of 25%.

Other benefits include:

- The RLS contactor can be readily designed to deliver operating savings in other conventional chemical processes.
- Fluids with viscosity up to 50 mPas have been successfully run showing similar behaviour to low viscosity fluids and improved liquid sheet stability.
- The shorter residence time and the cyclonic nature of the gas flow may be particularly advantageous in dealing with flue gas streams with high ash, high SO_x and high NO_x levels as are typical of flue gas streams in Australian conditions.



Rotating Sheet Capture Concept.

Reference

L. Wardhaugh, et al 2015, Novel gas-liquid contactor concepts for PCC capital and operating cost reduction, (3-1110-0069)

Potassium Carbonate Solvent for CO_2 Capture

This study reviews the performance of a new build Australian black coal supercritical power plant with and without CO_2 capture.

Completed in 2013 CO_2CRC carried out extensive studies on CO_2 capture from coal fired thermal power plants and natural gas fired combined cycle plants with subcritical steam cycles.

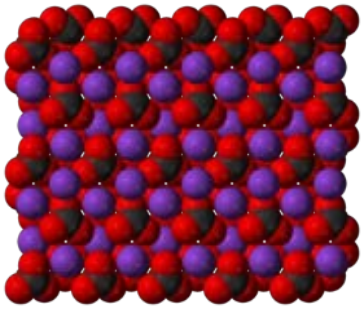
- The key objectives of this study were:
- To develop a model of an Australian black coal fired supercritical power plant in Aspen Plus®.
- To assess CO_2 emissions from coal fired, supercritical steam cycle based power stations and the impact of the UNO MK 3 CO_2 absorption process on the performance of the plant.
- To enhance the capability of an in-house heat integration program for supercritical and ultra-supercritical steam cycles.
- To develop heat integration strategies for reducing the CO_2 capture energy penalty on the same basis as previously completed for subcritical steam cycle based power plants.

A working model of a supercritical black coal power station with the UNO MK 3 process for CO_2 capture was developed.

The findings of the work completed on the UNO MK 3 process retrofitted to an existing Australian black coal subcritical power station have confirmed that lower costs of CO_2 capture can be achieved in comparison with amine-based processes. The study also showed the UNO MK 3 process for a new build American supercritical black coal power station was less expensive than all other leading capture technologies.

The study also completed a comparative life cycle assessment (LCA) between the use of MEA and the potassium carbonate based UNO MK 3 technology, for the capture of 1 tonne of CO_2 from a brown-coal fired power station. The results showed that the UNO MK 3 process is significantly better than MEA on ecotoxicity and other potentially toxic emissions and substantially better on all other indicators. The benefits of the UNO MK 3 process compared with MEA are due to avoidance of emissions from MEA degradation along with the savings in energy use for CO_2 removal. The significant environmental benefits of the UNO MK 3 process compared with MEA were not altered by an uncertainty analysis or sensitivity analysis of key inputs and assumptions.

Since 2013, this product has progressed in its commercial development to a demonstration phase at the National Carbon Capture Centre in Alabama.



Potassium Carbonate Solvent.

Reference

B Hooper et al, UNO Mk 3 Process Development, 2013 (4-0222)

A Precipitating Potassium Carbonate Solvent to reduce CO_2 Capture Costs

This work sought to advance potassium carbonate as a carbon capture solvent by removing the constraint of running a fully liquid system to improve the cost competitiveness of the process.

Potassium carbonate for carbon dioxide removal has been known for many years. Over time many variations to the basic process have been developed including operating the absorber column at higher temperatures and improving the packing systems within the absorber and regenerator columns. One aspect that had not been exploited was the development of a system that allows the concentration of bi-carbonate, which is formed by the reaction of carbon dioxide with carbonate, to exceed its solubility limit.

Developed at the CO_2CRC this concept (UNO Mk3) indicated that there would be many benefits thermodynamically if the system were allowed to form a precipitate.

The UNO MK 3 process uses higher concentrations of K_2CO_3 and precipitates potassium bicarbonate ($KHCO_3$) which allows lower solvent circulation rates and hence lower energy usage and smaller regeneration equipment sizes when compared to the non-precipitating system. Some of the key benefits of this process, compared to traditional amine-based capture processes, include lower regeneration energy, lower overall cost, low volatility and environmental impact, low toxicity and the ability to incorporate multi-impurity capture of CO_2, SO_x and NO_x and production of valuable by-products.

ANLEC R&D enabled a pilot plant to be built at the University of Melbourne for testing this precipitating K_2CO_3 process. The pilot plant has been designed to capture 4 - 10 kg/hr of CO_2 from an air/CO_2 feed gas rate of 30 – 55 kg/hr and equipment was chosen specifically for handling a bicarbonate slurry process.

Operational data was collected over a range of operating conditions including L/G ratios from 2 – 6, solvent concentrations from 20 to 45 wt% K_2CO_3 with and without a rate promoter and different absorber packing materials. Plant data has been used to validate thermodynamic models developed using Aspen Plus® simulations.

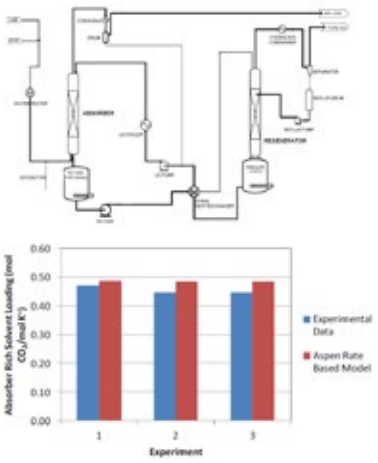
Although there was some precipitation observed around joints and fittings, no major operational issues were encountered with equipment such as pumps or heat exchangers while operating with a precipitating solvent system. Increasing the K_2CO_3 solvent concentration, operating with a higher CO_2 feed gas concentration and the addition of a rate promoter were all found to be important for increasing the CO_2 recovery results and optimising the regeneration energy of the process.

Aspen Plus® simulations have been developed to model the performance of the UNO MK 3 process. The simulations were validated with data from the pilot plant for K_2CO_3 concentrations up to 45 wt%. Both rate-based and equilibrium models were used with regressed physical property data in the e-NRTL model. The predicted values showed good agreement with the experimental results for CO_2 in the gas phase, rich solvent loading and temperature difference in the absorber.

This study was completed to confirm the thermodynamics and equilibrium conditions of the K_2CO_3 UNO MK 3 process and assess the equipment options for operating with a slurry process. Limitations to the equipment meant that efficient operation was not achieved in this work. However, subsequent IP development in a spin-off from the CO_2CRC has seen the UNO MK3 product continue to be offered as a solvent for carbon dioxide capture processes.

Reference

K Smith, K Mumford, B Hooper et al, CO2CRC Report No: RPT14-4855 P, 2014 (3-0043)



Validating absorber rich solvent loading.

Assessing the environmental emissions of post combustion CO_2 capture using amines

Air emissions from power plants must be compatible with the environment to be a long-term viable solution.

In time, commercial CO_2 capture systems for fossil fuel power plants will be deployed using solvents.

This change in power generation technology will inevitably require changes in the way power plants are approved, regulated and monitored. The environmental performance of solvents will influence their commercial and environmental viability.

Since many of these solvents have not been used at this scale on coal and natural gas flue gases it is important that we understand the emissions profiles of different solvent systems. This not only informed research and development teams, as they trial new solvents, but also environmental monitoring agencies who will need to regulate, approve and monitor emissions. These agencies are accountable to ensure safe and 'air shed' suitable emissions targets.

What could potentially enter the environment is highly dependent on the actual solvent. In a controlled laboratory environment, CSIRO tested three Post Combustion Capture solvents, which they exposed to a simulated flue gas. Using similar operating conditions to a potential real world application the solvent and gas stream were then rigorously tested using some of the latest analytical equipment.

The two key solvents studied were:

» Methyldiethanolamine (MDEA)

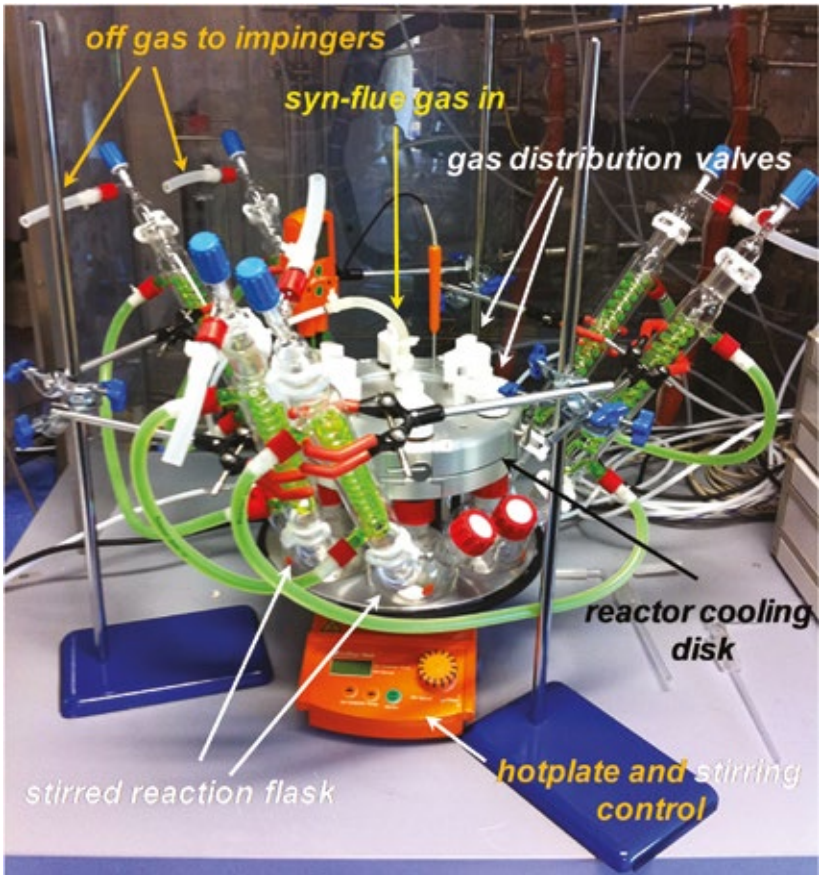
» Piperazine (PZ)

Importantly, in addition to the recommended chemical listing for emissions monitoring, the report concludes that, with the systems and analytical methods developed, amine-based solvent degradation products can be effectively screened and analysed.

What are the chemicals for which monitoring is recommended? For MDEA solvent applications, by far the most important degradation product is diethanolamine (DEA). For the PZ solvent, only two main products were found: ethylenediamine and 2-oxopiperazine. A list of other substances was also recommended to be monitored for both solvents.

Reference

P. Jackson, et al 2013, Environmental Impacts of Amine based CO_2 Post Combustion Capture (PCC) Process (4-0910-0067)



Carousel six-port reactor system used in the solvent degradation (ageing) experiments.

Informing waste disposal from Post Combustion Capture (PCC) of CO_2

There is currently very little quantitative data reported in the scientific literature relating to partitioning of trace elements in amine PCC systems.

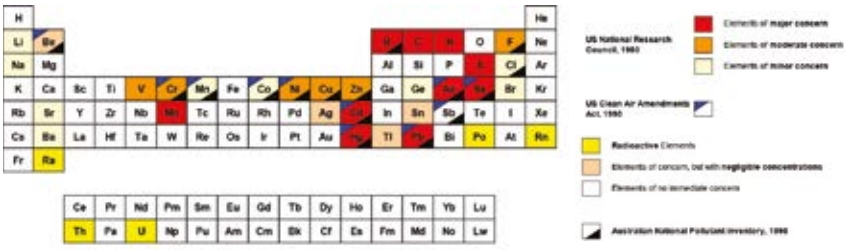
The most comprehensive dataset in existence (at least in the public domain) is from a study made by the US DoE nearly ten years ago. The results of that investigation indicated that trace elements from coal combustion were likely to concentrate in the reclaimer waste of the amine plant.

Despite the lack of data, it is apparent that most trace elements will be removed from the system by particulate emission control systems before they enter the CO_2 capture plant. However, volatile species, especially mercury, arsenic, selenium, along with fine particles not retained by the ESP (electrostatic precipitators) or fabric filter, have the potential to enter the CO_2 capture system.

Because of the effectiveness of flue gas desulphurisation (FGD) at removing trace elements, the solid product and process water will be major points for trace element discharge.

The conclusions from the laboratory study showed that:

- Apart from mercury, the selected elements are mostly retained within the Acid Gas Scrubber (AGS), with very little carry-over into the ASE (absorber/stripper).
- Some elements also show concentration changes in the AGS solution, possibly reflecting corresponding changes in pH of the absorbent solution.
- Mercury remains in a volatile phase passing through the system with very little or no retention.
- There is some variability in trace elements deportment related to the nature of the solvent, which is most likely due to the pH of the absorbent, precipitation and to carbonate formation, during the course of the experiment.
- The behaviour of the trace elements in the ASE, particularly in the stripper, most likely reflects the volatility of the selected trace elements and solubility in the solvent matrix.



Trace elements found in coals

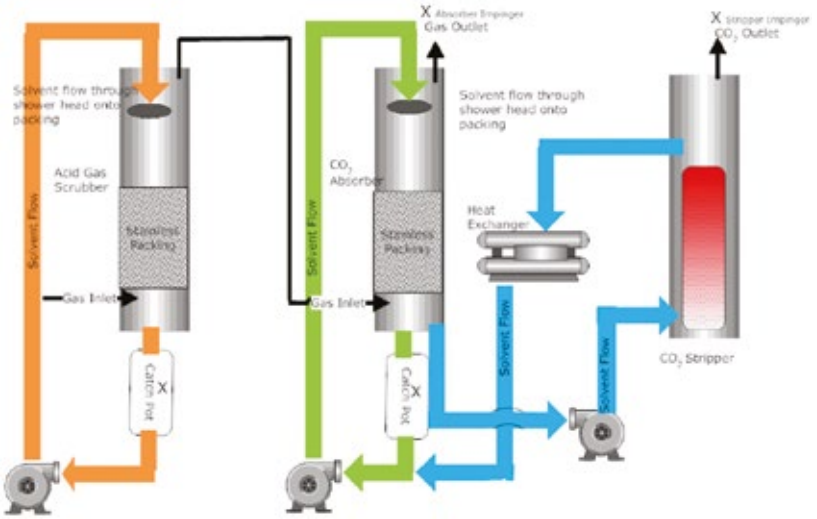


Diagram of the experimental PCC rig used for determination of trace element behaviour.

Reference

M. Azzi, et al 2013, Impact of Flue gas impurities in PCC plants (4-0411-0131)

Hollow Membrane Separation Tested for CO_2 Capture in Coal Flue Gas Conditions

This work aimed to fabricate high performance hollow fiber membranes for CO_2 capture from flue gases and to assess their performance with both a laboratory synthesised gas mixture and real flue gases from a power plant.

Based on the extensive review, screening and selecting benchmark polymer materials, two materials were selected for hollow fiber membrane development for laboratory and on-site tests with power station flue gases.

- The 1st generation membrane: hollow fiber membranes fabricated using Matrimid® blended with selected PEO and PEO-PDMS copolymer additives with improved separation performance and long-term performance sustainability.
- The 2nd generation membrane: composite hollow fiber membranes developed in this study with multi-layer coating using selected CO_2-philic PEO-PA block copolymers (PEBAX®) as selective layer.

Early results showed for the 1st generation membranes, improved CO_2 permeance between 24-34 GPU and CO_2/N_2 selectivity between 30-40 were achieved. This was better than commercially available products.

For the 2nd generation membranes, based on this fundamental knowledge, composite hollow fiber membrane development was conducted through selection of suitable microporous substrates. The composite hollow fiber membranes were made with polyvinylidene fluoride (PVDF) microporous fiber as substrate.

At the best combination of the conditions screened in this study, CO_2 permeance up to 560 GPU and CO_2/N_2 selectivity above 46 was achieved at room temperature, whereas 950 GPU and CO_2/N_2 selectivity of 30 achieved at the commonly reported temperature of 35°C. This performance was better than the best reported results in the literature for composite hollow fibers for CO_2 capture.

Flue gas tolerance

A major contaminant of concern in power station flue gas is nitrous oxide (NO). Both of the membrane materials developed were shown to be tolerant to NO when tested in laboratory condition.

Pilot Testing

With the purpose designed and constructed mobile membrane test units, the on-site tests were conducted at Delta Electricity in Vales Point with untreated flue gas.

Despite the good chemical and mechanical stability of the 1st generation membrane, it was not considered suitable for CO_2 capture from power station flue gas as they failed to reach the performance target set for this project.

The 2nd generation composite hollow fiber membranes were conducted with three membrane modules. Relatively stable permeance and selectivity were observed with all three modules with CO_2 permeance of 90-120 GPU and CO_2/N_2 selectivity of 3.5.

While the CO_2 permeance and the CO_2/N_2 selectivity was lower than what was achieved in lab with synthetic gas mixture, the mechanical integrity of the membrane was maintained through the flue gas challenge.

Importantly, When the membrane was subjected to the flue gas without any pre-treatment – a feature of Australian power stations -, severe loss of permeance and selectivity of all three modules were observed, and permanent damage to the membrane mechanical integrity was suspected as evidenced by the irreversible reduction of membrane selectivity after drying tested in the lab. The damage to the membrane was most likely due to flooding of the membrane module by condensed water.

While this concept for membrane separation did not achieve desired performance targets, there remains prospects for CO_2 membrane separation pursued in a large body of work underway globally.

Reference

H Li, V Chen, J Hou, G Dong CO2CRC Report number 14-5254, 2015 (3-0087)

Modifications of the on-site membrane pilot unit for the 2nd generation membrane testing.

Innovative Membranes Tested for Solvent Cleaning in CO_2 Capture

The disposal of degraded and spent CO_2 capture solvents can pose a significant cost to these low emissions technologies. In this project, the potential use of nanofiltration (NF) and electrodialysis (ED) as an in-situ treatment of degraded MEA solution is investigated.

Monoethanolamine (MEA) is commonly used in natural gas sweetening to selectively absorb CO_2 from a mixed gas stream. It has high CO_2 loading capacity and the reactions are fast compared to other amine based solvents. When applied to post-combustion capture, a major drawback from this operation is the formation of heat stable salts (sulfates, oxalates, acetates, nitrates and other species), which result from the parasitic reactions between MEA and other impurities (especially SO_2, and NO_2) in the feed gas stream. Since the formation of heat stable salts (HSS) can lead to corrosion and high viscosities, a fraction of the degraded solvent must be continuously purged from the system and replaced with fresh solvent.

In this project, the use of nanofiltration (NF) and electrodialysis (ED) as an in-situ treatment of degraded MEA solution is tested. The aim is to separate the heat stable salts from the system hence minimising the cost of CO_2 capture by reducing the amount of fresh solvent make-up required, the extent of corrosion and the cost of waste disposal.

The results with pure MEA solutions show that nanofiltration can be used to remove up to 90% of sulfates and oxalates from a 30 wt% MEA solution using a KOCH SelRO MPF-34 membrane.

Further testing using a smaller pore size membrane may achieve a better separation of these smaller heat stable salts.

A high salt removal can also be achieved by electrodialysis, when operated in a batch mode. In a continuous mode, the extent of the HSS removal can be related to the applied current density, the salt being removed, the flowrate through the unit, the membrane type and the effective membrane area.

In order to reduce the operating costs associated with power consumption and membrane area, it is important to use a membrane that exhibits a low electrical resistance and a solution that contains relatively high levels of heat stable salts. Neosepta membranes were found to be the most effective of the three supplier types trialled.

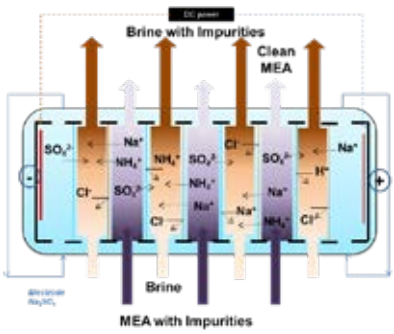
In the final stage of the project, MEA that has been used in pilot scale carbon capture operations has been obtained through a collaboration with CSIRO. Solutions that had been aged for 50+ and 1800+ hours were the focus of this work. The 50+ solution was at a high CO_2 loading and this was initially reduced through simple boiling. Earlier work had shown that neither NF nor ED is effective at high loadings. The solutions were first neutralised with sodium hydroxide to free amine-bound salts.

This resulted in the formation of precipitates, which were removed using a microfiltration membrane.

Nanofiltration of the aged solutions proved ineffective. The MEA rejection, which had been low in initial experiments increased; while the salt rejection, high in initial experiments declined. The flux through the membrane also declined significantly. These results reflect the non-zero CO_2 loading of the solution. Conversely, electrodialysis remained an effective approach to remove heat stable salts. Over 90% of these salts could be removed from the solution, with time constraints only preventing further removal. The heat stable salts were found to be predominantly sulfates and nitrates.

Reference

J Lim, A Aguiar, L Dumée, G Stevens, C Scholes, D Wiley, S Kentish, CO2CRC Report No:14-4873, 2014 (3-0045)



Electro-dialysis to remove solvent impurities.

Seeking synergies in coal and solar energy generation with carbon capture

A primary objective of this work was to test concepts that led to significant reductions in the cost and energy penalty to capture carbon dioxide from coal-fired power generation.

Using modelling, design and optimisation, this work specified control criteria for process integration and operation of low emissions coal power plants with solar-thermal technology.

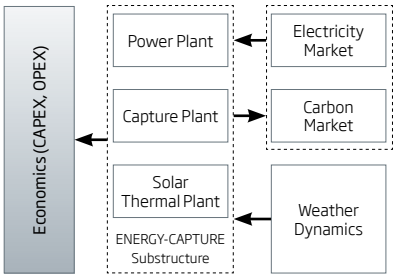
A key outcome was the development of real-time routines, to inform the techno-economic performance of Post Combustion Carbon Capture (PCC) integrated with solar-thermal systems.

Outcomes from the study included:

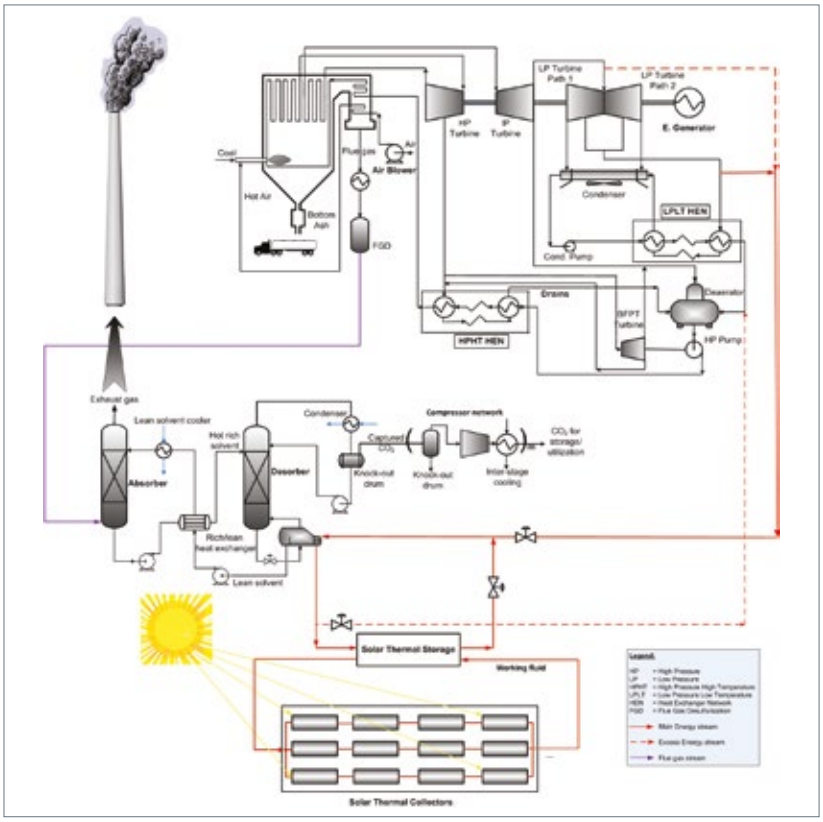
- Process integration and simulation analysis showed valuable efficiency improvements could achieve sound integration of a solar-thermal plant with coal-fired power generation, including capture.
- For the first time, a detailed dynamic model was developed, to simulate a solar-thermal plant, to repower the high pressure feed water heaters of a 660 MW power plant. It enabled the solar plant system to provide the thermal load dictated by the power plant.
- Five possible operating modes were recognised and discussed in detail, to provide a clear perspective of the solar-thermal plant operation in this integrated process situation.
- Using innovative control algorithms, the study showed scenarios where an integrated plant (power plant with PCC), subject to forecast 2020 electricity and carbon prices, can be profitable. Without a carbon price these solutions are not economically viable.
- Coal-fired power plants can operate sustainably in the future using carbon management systems built on model-based optimisation, such as the one proposed in this work, for flexible operation of PCC plants.

Reference

A. Abbas, et al 2016, Model-based optimisation of highly-integrated post-combustion carbon capture processes (3-0911-0168)



Interaction of the proposed hybrid super structure with the different systems including weather dynamics, economics, electricity, and carbon marked dynamics.



A hybrid plant superstructure integrating the power plant solar- thermal system and carbon capture process.

Targeting High Efficiency Post Combustion Capture of CO_2 using Solid Sorbents

This study examined whether post-combustion CO_2 capture (PCC) based upon CaO-looping was an economically viable option for the reduction of CO_2 emissions from coal. The study sought to develop and produce tailored CaO-based CO_2 sorbents on a large scale, and to determine whether such sorbents would be economically beneficial to CaO-based PCC.

In the laboratory, several tailored sorbents were produced, and the most promising was identified and tested under capture conditions relevant to CO_2 capture. The impacts of this tailored sorbent on process parameters and annual stream costs in a PCC plant were examined.

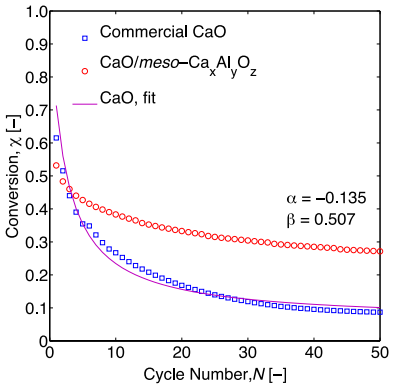
An updated techno-economic study was produced for the calcium-looping PCC case, using the guidelines laid out by Rubin et al. in a report published by the Global CCS Institute in March 2013. Among the variables considered in the sensitivity analysis were the cost and performance of the sorbent.

Key findings of this research are:

- Among currently accessible CO_2 capture technologies, CaO looping is the most viable from a techno-economic perspective. The decisive advantages of this technique are the availability of mature large-scale reactors and, more importantly, the integration of the heat from CaO carbonation into the steam cycles of the coal plant.
- CaO looping is the only currently accessible CO_2 capture technology that can *increase* the net efficiency of a supercritical-coal-fired power plant.
- The adoption of tailored CaO sorbents with stable CO_2-uptake capacities would enable sorbents with much lower make-up ratios to be used; i.e. the sorbent could be replaced much less frequently. This could lower the amount of material that had to be handled at a PCC plant, as well as the loss of heat via spent sorbent.
- Of the tailored sorbents developed in this work, the most stable was CaO/*meso*-$Ca_xAl_yO_z$. After 50 cycles of carbonation and calcination under industrially relevant conditions, this sorbent showed a significantly higher residual CO_2 uptake capacity than commercial CaO.
- Even if CaO/*meso*-$Ca_xAl_yO_z$ cost *ten times* as much as commercial CaO, it would still cause lower annual stream costs if used at a replacement rate at or below 0.001.
- A techno-economic model for the retrofitting of a PCC plant onto an existing coal plant was developed. Capital costs were by far the largest contributor to the plant, even over the course of 25 a.
- Improved CO_2 sorbents can definitely lower the variable operating costs of a PCC plant and may also lower its capital costs.
- The price of CO_2 is decisive for the viability and profitability of calcium-looping PCC.

Reference

A Harris, High efficiency post combustion capture of carbon dioxide using solid sorbents, 2013 (3-0082)



CO_2 uptake by commercial CaO and by CaO/meso-CaxAlyOz over 50 cycles of carbonation.

Nano-Structured Carbon Nanotube Composite for CO_2 Capture

As part of its early program on alternatives and fundamentals research, this study primarily aimed to improve the material performance properties of a novel carbon nanotube substrate for CO_2 capture.

Carbon dioxide capture using solid adsorption are considered prospective if the lower levels of energy necessary for the process can be realised in engineering application.

With the development of the nano-tube materials developed in prior research, its use in capture performance needs to be suitable for applications at the very high volumes encountered in coal fired power generation systems. The higher the adsorption capacity, the less energy will be required for adsorbent regeneration. An improved lower footprint for a PCC plant will result in reduced capital and operating cost for the process.

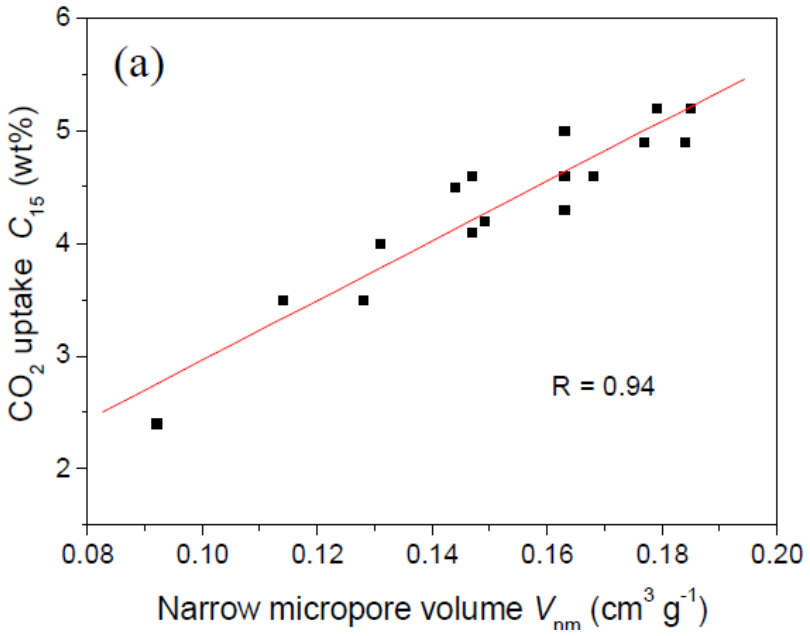
Experimental results from the study show that CNTs were successfully incorporated into the composite resulting in significant enhancement of the CO_2 adsorption capacity.

The newly developed CF/CNT composite adsorbents showed maximum CO_2 adsorption capacities of 5.2 and 15.9 wt%, at low and high partial pressures respectively. This was an equivalent of 48.6% and 35.9%, improved capacities in comparison with previous CF composites. The achieved CO_2 adsorption capacities in the CF/CNT composites met the agreed target capacity benchmark for the composite carbon materials as: >14.0 wt% for high partial pressures and >4.5 wt% for low partial pressures.

While material improvements were achieved in the project, preliminary techno-economic assessment shows that large challenges remain in achieving cost effective material characteristics for success of the technology. There also remains significant additional work to optimise the engineering process heat flow configurations.

Reference

S. Su, Y. Jin, C Huynh, S Hawkins 2014, Nano-Structured Carbon nanotube composites for CO_2 capture (3-0020)



Correlations of CO_2 adsoption capacity

Alternative Capture Concepts Research Projects

A Carbon Capture Shift Reactor

ANLEC R&D undertook the Carbon Capture Shift Reactor Project to develop and validate opportunities for significant cost reduction in pre-combustion power generation systems. The concept was to combine the shifting of syngas and capture of carbon dioxide in a single step to reduce capital infrastructure costs.

The key technical requirement in this project is to capture CO_2 from an air blown syngas stream, and to maintain the N_2 and H_2-rich stream at high pressure, for subsequent combustion in a turbine without the need for extra compression. The central idea for this project is that the H_2 diluted with N_2 can be directly combusted using current turbine technology. In addition, the sorbent materials need to be able to capture CO_2 up to 400 °C, after the water gas shift (WGS) reactors, thus improving process efficiencies, as there is no need to cool down large gas streams to low temperatures as required by conventional carbon capture technologies.

The project targeted to capture 90% CO_2 of the air blown syngas stream at 32 bar using sorbents with a CO_2 uptake capacity of 20 wt%.

Two sorbents were found useful for high temperature CO_2 sorption namely: layer double hydroxides (LDHs) and double salts (DSs). LDHs based on MgAl and CaAl proved to be stable, but their CO_2 sorption capacity was very low (2-4 wt%). DSs based on NaMg delivered high CO_2 sorption capacity of 26 wt%, well in excess of the project target of 20 wt%. A mixed DS-LDH sorbent reached CO_2 uptake of 13 wt%.

Testing the robustness of these adsorbents showed the hybrid version of DS-LDH proved to reach stability in a few cycles at ~12 wt% without any significant loss of CO_2 sorption capacity

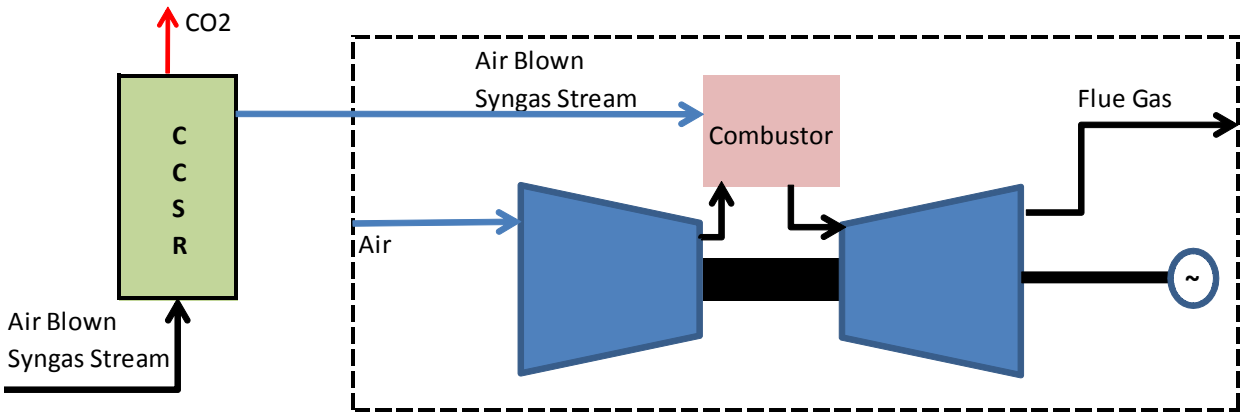
Unfortunately, the adsorbents failed performance tests in wet gas conditions – the original target for the project.

The project however innovated new material properties to improve adsorption capacities in dry gas conditions.

This report outlines the progress achieved by the laboratory studies to date. While targeted improvement was achieved for capture by the adsorbent materials under development, performance testing was not achieved under the wet syngas conditions typically expected in these process streams. Significant research and development are required before such adsorbent systems can be ready for deployment in a power generation context.

Reference

G Ji, J Motuzas, G Birkett, S Smart, J da Costa, Carbon Capture Shift Reactor (3-0033s)



Schematic of the carbon capture shift reactor concept in power production.

A new metal membrane reactor for H_2 production

Coal gasification is used widely for the production of chemicals.

The Integrated Gasification Combined Cycle (IGCC) technology also has potential to deliver much improved efficiencies for power generation. Further, it captures CO_2 ready for transport and storage.

Hydrogen production, separation and reaction is an integral part of the IGCC process.

This project targeted the development of membrane reactor technology that can contribute to both aspects of CO_2 emission reductions, efficiency and storage. The project also developed a prototype catalytic membrane reactor (CMR), a device which combines a hydrogen-selective alloy membrane with a water-gas-shift (WGS) catalyst.

The current benchmark alloy membrane material is palladium (and its alloys). Vanadium has higher hydrogen permeability and lower cost than palladium, but its susceptibility to hydrogen embrittlement has limited its application in hydrogen-selective membranes.

By alloying vanadium with aluminium, the susceptibility to embrittlement is drastically reduced. These findings are the subject of a provisional patent lodged in several jurisdictions. Although membrane durability has not been assessed during this project, this new alloy will prolong membrane lifetime considerably, and will increase the likelihood of meeting the durability target of 5 years.

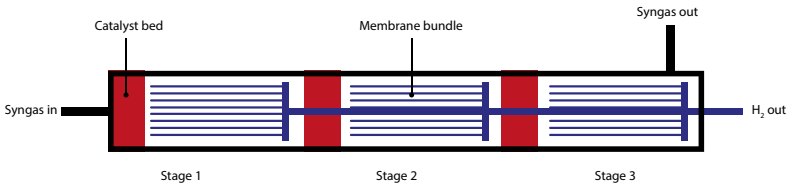
Key outcomes:

- CSIRO has developed a patent-pending vanadium alloy, which has equivalent hydrogen permeation properties, much improved resistance to embrittlement, and enhanced ductility to allow manufacture by tube extrusion.
- Several reactor geometries (planar or tubular) were evaluated, and determined that tubular geometries have the best prospects for low cost fabrication.
- Various surface finishing techniques for effective catalytic coating were tested.
- A 2-dimensional, axis-symmetric model of a membrane reactor has been developed using computational fluid dynamics (CFD). The model incorporates several sub-processes for heat transfer, mass transfer, hydrogen permeation and water-gas shift conversion, and has been validated against experimental data.
- A hydrogen flux of 0.4 mol m-2 s-1 at 400°C has consistently been achieved using Pd-coated vanadium tubing. This flux is independent of membrane thickness. Several hydrogen separation modules, up to 1000 cm2 in total membrane area, have been fabricated and tested.
- A 3-stage membrane reactor was demonstrated, in which catalyst and membranes were physically separated. Greater than equilibrium CO conversion was achieved in this multi-stage configuration, despite modest CO conversion and H_2 yield per stage. This configuration is scalable and will protect vanadium-based membranes from mechanical or temperature-related damage.

Reference

M. D. Dolan, et al 2015, Alloy membrane reactor for pre-combustion CO_2 capture (3-0510-0040)

Prototype 7-tube, 700 cm^2 membrane module



Schematic diagram of multi-stage CMR with separate conversion and separation zones.

Solids Disposal and use in Coal Gasification

This work presents a detailed analysis of legislation, regulations, data, and samples relevant to gasification by-product management in an Australian context. This will help Australian regulators and prospective IGCC-CCS project proponents to define and meet their obligations for managing solid wastes from gasification-based plants.

The review and subsequent laboratory work identified the key issues of current international practices, and potential Australian practices, associated with disposal and use options of coal gasification by-products. Together, they offer guidance for future work required to reduce the risks of deploying Australian gasification-based coal-fired power generation systems.

Legislative and regulatory status

While IGCC or gasification by-products are not specifically mentioned in current Australian legislation, they are likely to be assessed in the same manner as coal combustion products, such as fly ash and bottom ash. Relevant legislation is therefore based mostly on handling and disposal of fly ash and lacks a sound scientific basis regarding the characteristics and behaviour of slags from entrained flow gasification.

State and territory legislation varies considerably. A more uniform, national approach is required, based on sound scientific information regarding material characteristics, test conditions, and their relevance to the target disposal or use scheme.

By-product performance

This work has characterised gasification by-products from Australian coals using some of the limited number of samples obtained from recent research programs.

Results indicate that these gasification slags and fly ashes are generally low-leaching materials, as assessed by common regulative leaching tests (ASLP and TCLP). Their classification in Australian regulations is likely to be mainly affected by their total concentration of trace elements; only in some cases are leaching characteristics more important than the total element concentration. This has the potential to require more stringent environmental or use considerations than may be required based on the low leachabilities of these trace element species.

Slag use opportunities and challenges

An assessment of coal combustion by-product use was covered extensively in the report through a survey commissioned as part of this project.

Gasification slags produced from IGCC plants worldwide are used in applications such as cement manufacturing, road base and structural backfill.

The most immediately prospective application of IGCC slags from Australian coals would appear to be in the cement industry and some road base applications.

The lack of specific standards is compounded by the lack of local experience in the use of gasification residues. For example, Australian gasification slags do not always satisfy existing standards that are applied to the use of blast furnace. An example is AS 3582.2 applied to ground granulated blast furnace slag. This may impede some opportunities for using gasification by-products.

While gasification slags have similar chemical and phase compositions to fly ashes, the slags are generally more chemically stable. Their physical appearance is also different from fly ashes, and they therefore must be used differently in industrial fly ash applications.

Reference

A Y Ilyushechkin, D G Roberts, D French, D J Harris; IGCC Solida disposal and utilisation, 2012 (5-0065)

Bricks made from slag.

Brown Coal Research

In collaboration with Australian Carbon Innovation – Victoria

Brown Coal Research and Development: Concept testing new products and exploring new markets

Australia has access to very large resources of Brown Coal. Brown Coal has underpinned electricity generation and energy production for many decades in the state of Victoria.

Technical Development priorities and objectives for brown coal are very different to those for export orientated black coal. To recognise this difference ANLEC R&D engaged in a long-term partnership with Australian Coal Innovation (formerly Brown Coal Innovation Australia) to scope, leverage and undertake relevant research.

This partnership undertook several valuable studies that included:

Brown Coal Gasification

A scoping study to prioritise the research needs to develop Integrated Gasification Drying Technologies.

Chemical Looping Combustion

Laboratory Studies investigated the concept and economics for chemical looping combustion (CLC) on several brown coal and oxygen carriers. It concluded that the technology remains "in development" and will have a niche application for highly reactive low-ash coals such as the Victorian brown coals.

Oxy-fuel Combustion

With International collaboration pilot scale tests were completed to validate the stable and quicker combustion of wet Victorian brown coal with up to 40 wt% moisture in a 3 MWth furnace.

Pilot Plant CO_2 Capture Studies

Several pilot scale studies were completed that:

» Demonstrated frothing absorber technology can match the CO_2 removal rates with one-half the packing height and at least twice the superficial gas velocity compared to state-of-the-art structured packing.

» Patented technologies to capture SO_2 and CO_2 from brown coal flue gases potentially eliminating the need for separate FGD plant.

» Compare CO_2 capture and environmental solvent performance applicable to brown coal flue gases

Dispersion modelling from CO_2 pipelines

An assessment was provided to review and inform the applicability of CO_2 pipeline design standards and consequent risks for pipeline transport in the Australian context.

Carbon Fibres from Victorian Lignite

Carbon fibres have been successfully produced containing up to 40% Victorian lignite. Lignite is an inexpensive source of suitable carbon that can reduce the cost of fibre production.

Innovative drying

Pilot testing was conducted in international facilities that reports on the applicability and performance of the innovative COMBDry process to Victorian brown coal. The results recommend testing at a larger scale.

Humic Extraction

Brown coals (lignites) are inherently rich in humic compounds, which are niche agricultural bio-stimulants enhancing food production. This concept study targeted the development and refinement of lab-scale production technology to prepare target humic products from Lignites.

Low-Cost Hydrogen

The study provides an evaluation of technical and economic viability of the various options for producing CO_2-free hydrogen, including three brown coal pyrolysis-based processes, brown coal gasification, as well as electrolysis using renewable electricity from either wind or solar energy.

Reference

Reports on studies undertaken are available by contacting Australian Carbon Innovation at www.acinnovation.com.au

Carbon Fibre production using lignite

Lessons Learned

ANLEC R&D was conceived as a strategic and key input to government and industry on low emissions technology pathways for the energy sector. Recognising that there would be no quick returns on investment, both Industry and Government sought to resource an initiative to support, enable and accelerate low emissions coal technology deployment in Australia.

In addition to the technical outcomes cataloged earlier in this report, key lessons learned included:

- Technology pathways need dependable resourcing with realistic deployment timetables to undertake staged strategic research and demonstration
- Cooperative relationships between government, industry and research offered significant benefit to facilitating new technology deployment towards strategic national objectives
- The active management of projects with rigourous processes for Industry oversight gave confidence to the funders of the initiative

This section aims to draw some overarching conclusions from the motivations, management model and governance processes developed and implemented in the initiative.

Historical Context

There is wide recognition that the Australian economy benefits substantively from its coal and gas exports. As early as the 1990's these multi-national industries saw the emergence of greenhouse gas emissions as a risk to their businesses. These were both market and regulatory risks and it does not need 20/20 hindsight to realise that the regulatory risk predominantly arises from a community licence to operate.

The development, demonstration and deployment of commercial scale low emission coal technology became a priority if markets were to be maintained for the commodity. Industry partnered with Government and more than $3 billion in funding was announced as available to stimulate investment toward this objective.

ANLEC R&D was a key component of the Commonwealth Government Clean Energy Initiative of 2010 that included both low emissions coal as well as renewable technologies. Focussed on coal, ANLEC R&D was established with a decidedly different purpose – to recognise and mitigate the technical risk of large commercial scale investments in low emissions solutions like carbon capture and storage (CCS).

Established with funding of $150 million over 7 years, equally shared by the Commonwealth Government and the Black Coal Industry, ANLEC R&D was designed with a technology deployment focus. Why is this important?

Business Risk Reduction for Emerging Technologies

New technology configurations will always find it hard to get off the ground because the size of investment risk prejudices against large engineering expenditures. It has taken over 80 years to commercialise a "space industry" which until recently has been fully funded by governments. Doubling the cost of a conventional coal fired power generation facility – which is what low emissions entails -is no recipe for profit!

For established technologies, technical risk is – from prior experience – decidedly small. If small risk remains, it is largely mitigated by research undertaken internally by the developer and becomes part of the owners intellectually property. For example, if waste water from a process plant requires unique treatment prior to disposal, this is established and resolved by internal research by the developer and available for implementation at future process sites.

"...ANLEC R&D is a very well-run and effective research funding agency which, in many changing circumstances, has been able to progress understanding of low emission coal technologies as well as supporting specific flagship opportunities."

- David Pearce, Centre for International Economics

This development is paid for by the customer in the price of delivery for the technology product. Private business recognises this as a cost of doing "profitable" business. This research serves the higher purpose of a profitable business.

In the last 20 years, there has been no "profit" to be made from a technology like CCS. There has been an insufficient price on CO_2 emissions to warrant investment by private business. This is true for all low emissions technologies including renewable energy.

Energy Price in a Competitive Economy

Today, the Australian electricity price is expensive by world standards, yet this was not the case at the start of the century. Having added an additional full grid's worth (25GW) of the lowest cost clean renewable energy, prices have risen well ahead of inflation.

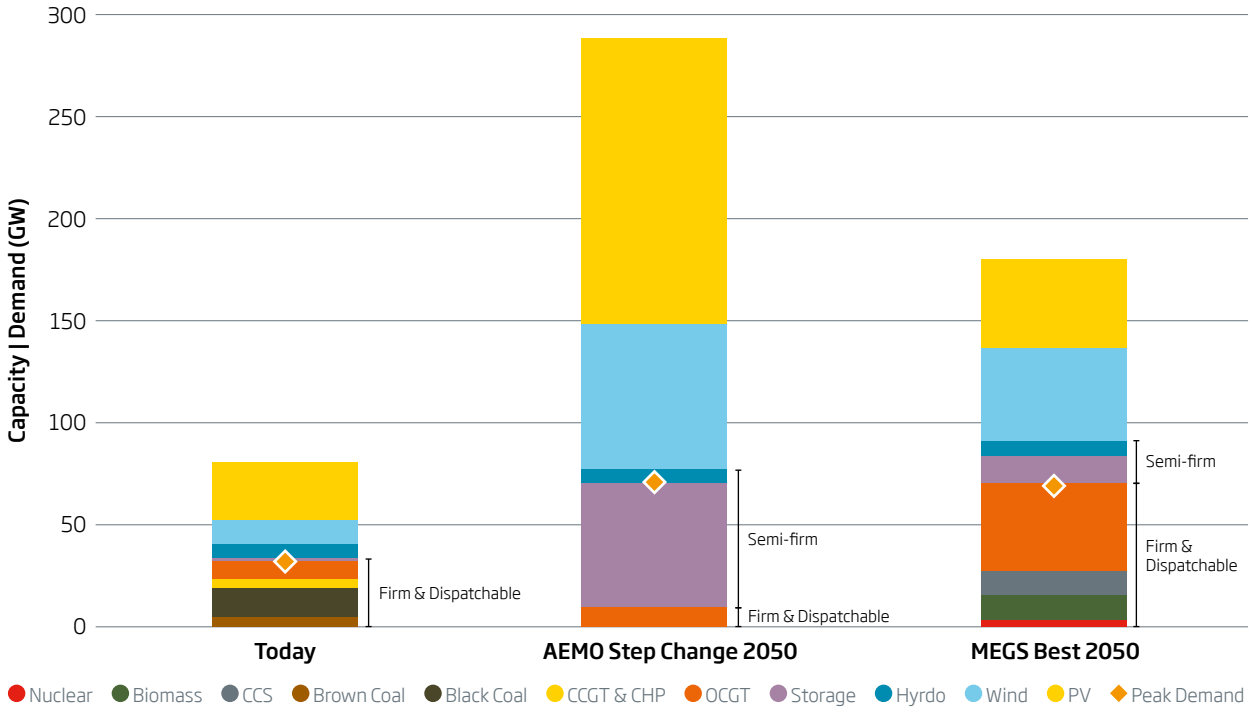
Electricity pricing is complex and has many drivers. In 2017, a seminal ANLEC R&D Study differentiated the influence of asset cost from system costs and their effect on pricing. Here, it highlighted that the lowest system cost is an optimised combination of cheaper assets like wind and solar and more expensive assets (e.g. CCS and nuclear). The reason is, they bring different grid services to the system.

There is no business driver or incentive to deploy large low emissions power generation assets like CCS and Nuclear technologies. When market over-supply for electricity keeps a lid on prices, there is a vested business interest to allow supply to leave the system and have prices rise which increases the profits of remaining players.

There is also a reluctance to bring on new supply with large assets. It is much easier and less risky to build small assets - hence the proliferation of perceived low cost solar and wind generation. But the benefits reflected in pricing are yet to be seen.

Meanwhile, who will build or invest in these large assets required? These are left unattended in a business and policy vacuum. When left unattended, the system cost to the economy will continue to rise and likely will become the apologue frog in the proverbial boiling pot. It will incrementally erode energy competitiveness and have industry and business progressively walk offshore to more competitive regimes.

MEGs 2050 Lowest Cost NEM Asset Portfolio



New Technology for Environmental Performance can only be driven by Regulation

ANLEC R&D research has shown, these largescale CO_2 mitigation technologies like CCS (and also nuclear) are essential to a national net-zero objective. Importantly, when deployed using current asset infrastructure, these technologies offer cheaper and faster pathways to net-zero emissions electricity.

A low emissions technology solution for coal fired power generation is very largescale engineering where costs are borne up-front. For a solution like CCS, the cost of establishing a geological storage resource is not only expensive, but its environmental permitting is time consuming – in the order of many years.

If low emissions are required – the government must either create the conditions for a market mechanism to address it or seek to fund the objective over long timeframes. Ideally, both will be required. The term of ANLEC R&D has seen too many announcements for "flagship asset" funding, only to see it taken off the table in short time. This has been both destructive to investment confidence and unfairly burdens the technology's credentials in the perceptions of a non-experts activist audience.

Deployment Focussed Research and Development

It was recognised at the time that Government Funding for large deployment projects would always be fraught with uncertainty. Therefore, it was in the Government and Coal Industry interest to ensure the lower cost pre-competitive research to enable such demonstration and deployment should not be subject to the same vagaries. The nature and scope of ANLEC R&D activity was thus set and differentiated from other research effort and agencies.

One of the largest benefits of a tight scope for the ANLEC R&D initiative was that it allowed the Executive to articulate clear criteria for funding research projects. While scientific merit and quality is an important metric for funding success, equal measure was given to whether the research proposed would contribute to a specific reduction of risk and/or cost to the customer demonstration asset. While there are always good research ideas, this filter allowed for targeted selection of research projects.

Research and Development is a servant of higher purpose. Two purposes are obvious:

» A primary higher purpose is reducing deployment risk for a low emissions specific asset.

» A secondary purpose is to lower emissions from electricity generation

Australian research and development infrastructure is impressive and largely held in institutions that pursue an academic agenda. These research assets and their associated diverse human intellectual capital however are a resource that can be marshalled to deliver the technology services required to support national priorities.

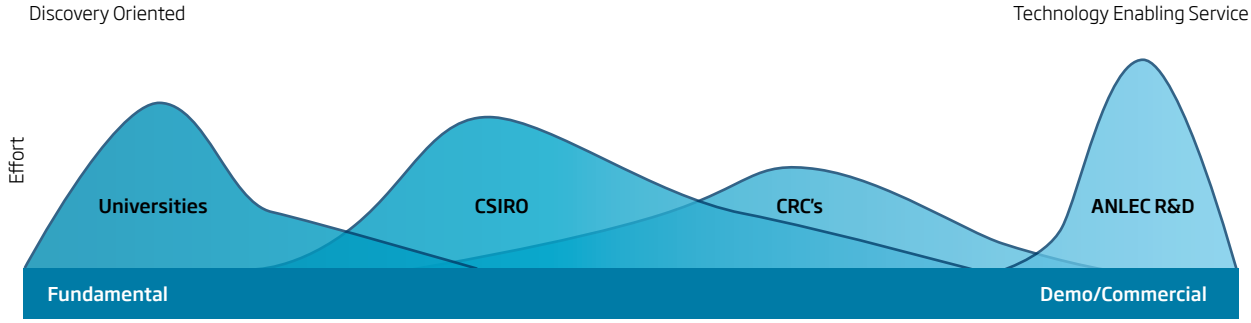
ANLEC R&D was designed as a governance model to tap this resource to support low emissions coal technologies. Differentiated from prior collaborative research efforts (eg: CRC's) this model viewed research institutions as research service providers. Some advantages are:

» It accesses the best expertise on offer. Researchers are differentiated by their strengths and expertise which is spread across many institutions. It avoids locking into specific institutions for research service.

» It makes researchers competitive. If there is more than one source of expertise, price will be a differentiator for services.

» The relevance and value of research output is more immediate than embryonic conceptions supported in other 'blue sky' funding programs.

Schematic of ANLECR&D Scope



From a service provider perspective, this model does not bring funding certainty to maintain specific institutional capabilities. This would be more dependent on the calibre of their innovation, the quality and relevance of their research and their ability to secure grant funding from other competitive programs for academia.

It was important to ensure that a) the research service was not a proxy for lower cost consultancy services and b) did not carry out technical investigations that would reasonably be expected of the demonstration proponent as part of their ongoing deployment costs.

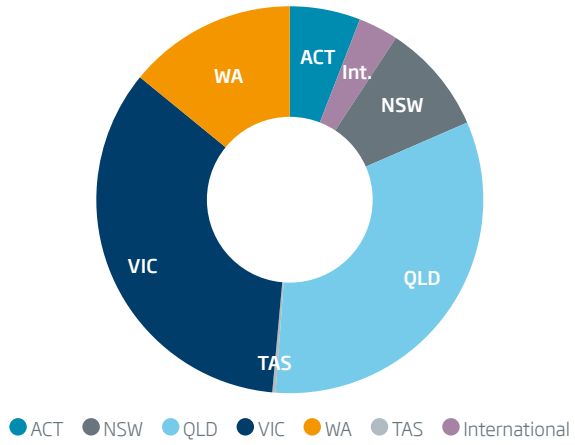
This was achieved by ensuring research concepts and projects had clear "innovation" objectives. Evidence was best demonstrated by the willingness of researchers to invest into the project their effort as "in-kind". It is worth noting that "in-kind" investment must be judiciously assessed and audited if it is not to unreasonably inflate research service pricing.

The following statistics attest to the demonstrated value sourced by the ANLEC R&D approach.

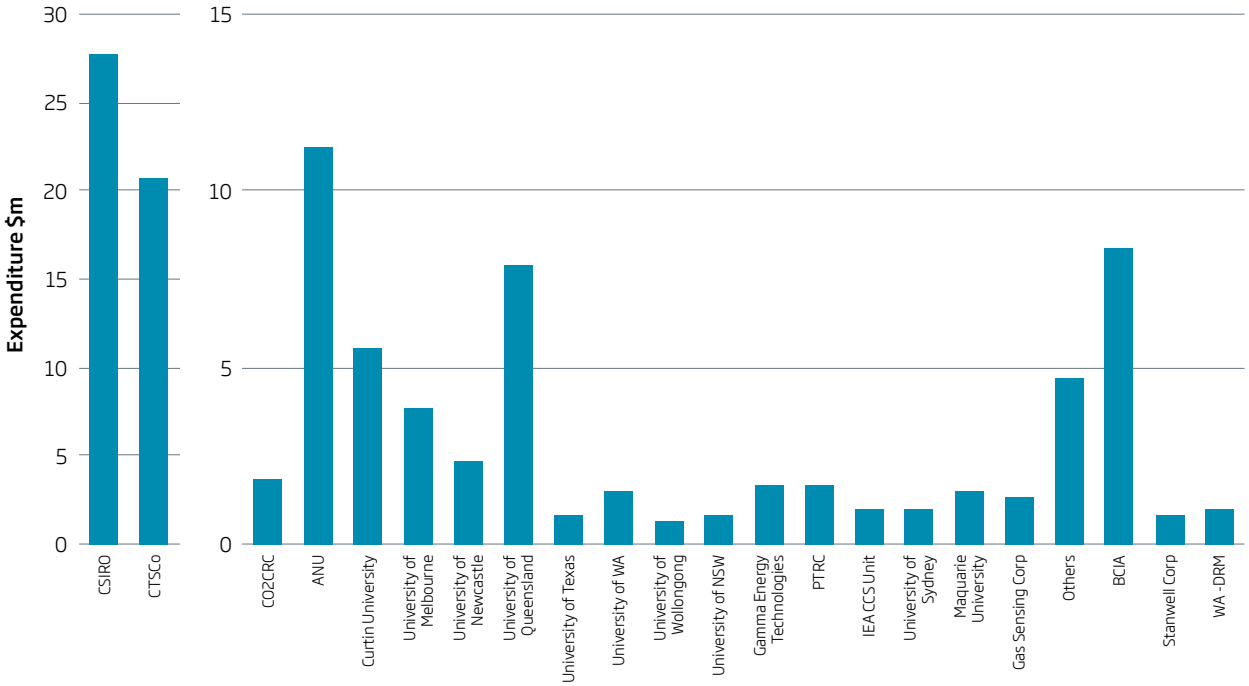
Co-investment attracted by ANLEC R&D funds

	ANLEC R&D Cash	Co-Investment (in-kind)	Total
Projects	120,648,179	142,701,655	263,349,834
Project Support	11,287,516	10,066,367	21,353,883
Total	**131,935,695**	**152,768,022**	**284,703,717**

Expenditure by state



Expenditure by institution



Intellectual Property

All ANLEC R&D Intellectual Property (IP) generated from its activities are contained in the research project reports delivered by the service providers. The reports are available in the public domain and in the learned academic literature.

The governance model adopted gives ownership of the intellectual property to the research service provider. The Australian Demonstration proponents are entitled to a royalty free licence for the use of the IP. If there are specific commercial services developed, the demonstration proponents are entitled to those services on favourable terms for a fixed period.

The objective for cost reduction research undertaken in the Alternatives and Fundamentals Program was to enable opportunities for widespread application. In certain cases, this required that the IP developed should remain unencumbered by the ANLEC R&D Funding requirements. With the Commonwealth and LETA Funders permissions, the standard contracting licence provisions were waived for such projects.

A Nimble Response to Changing Technology Priorities

Set up as an initiative to support and accelerate demonstration and deployment of low emissions coal technologies, one of the first difficulties ANLEC R&D faced was that there were no demonstration projects to support. The Callide Oxy-fuel project was already underway, but with the absence of funding support little else had made any progress.

Within the CCS Council deliberations on setting up the ANLEC R&D initiative, the research community had lobbied for a program to maintain institutional low emissions capabilities that had been established.

In formulating the ANLEC R&D Strategic Plan, the stakeholder leadership idetermined that maintaining institutional capability should not be a motivating objective. Rather, it chose to include an alternatives and fundamentals program to test concepts for low emissions technology cost reduction.

It was a prescient consideration at the time, especially in the absence of large-scale demonstration projects for ANLEC R&D to support. A vibrant Alternative and Fundamentals program on technology cost reduction was commenced almost immediately.

Tailoring CO_2 Capture Cost Reduction Research in an International Effort

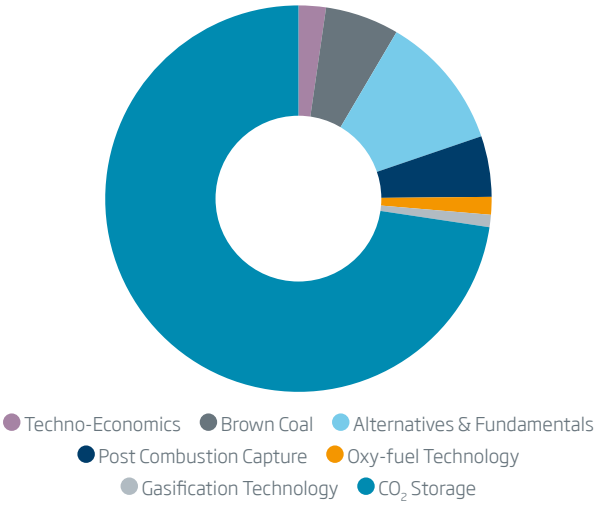
Capture of CO_2 is expensive and unprecedented at power generation scale at the time. Importantly, this was recognised world-wide and it attracted a very large research effort globally. The Australian program had to be tailored to fit within a global program to minimise duplication and take note that its investment would be comparatively modest. This was achieved by a focus on Australian flue gas conditions from coal fired boilers. As Australian demonstration proponents were mainly considering solvent based systems, ANLEC R&D also primarily chose to prioritise research into solvent performance. Secondly, Australian historical coal fired emissions licences uniquely do not require NOx and SOx removal. Hence ANLEC R&D capture research was directed towards solutions that were tolerant to these compounds. The Alternative and Fundamentals Program therefore favored CO_2 capture research during the early years.

The ANLEC R&D targeted research program awaited the development of large-scale demonstration proponents to inform ANLEC R&D research objectives. The Callide Oxyfuel Demonstration as well as the ZeroGen Demonstration project were willing collaborators in framing the early targeted research projects.

Local Geology Prioritises Storage Research

The Governments 2 billion dollar CCS Flagship Program began awarding demonstration funding in 2011. It quickly became evident that de-risking CO_2 Storage in localised geologies was where ANLEC R&D effort would be most effective.

Expenditure by node



Demonstration project feasibility studies identified that the critical path to deployment required an accelerated characterisation of prospective Australian CO_2 storage reservoirs. Three CO_2 Storage Flagship projects emerged – The South West Hub (2011) in the South Perth Basin of WA, CarbonNet (2012) in the Gippsland Basin of Victoria and CTSCo (2012) in the Surat Basin of Queensland. These large-scale storage proponents resulted in ANLEC R&D shifting to its core purpose - to support and accelerate Australian demonstration in local geologies.

The governance and management model adopted in ANLEC R&D allowed for a rapid pivot from generic capture research to storage research that targeted, enabled and supported deployment in these basins.

It was an inevitable consequence of this change in priority that the program of capture research in ANLEC R&D was substantively reduced after 2015.

Systematic Customer Focus

The customer for ANLEC R&D research was the CCS asset proponents. Supporting specific assets with research and development services brings an additional criterion to research management. While science quality and relevance are important criteria, the ANLEC R&D initiative would have been completely ineffective if it did not maintain the confidences of the demonstration proponents. Establishing and maintaining a trusted relationship with each CCS proponent was crucial to the effectiveness and success of ANLEC R&D.

To secure this trusted relationship research project selection and review were carried out by three essential overseeing roles:

- ANLEC R&D Science Leaders were appointed by expertise to oversight the quality, relevance and innovation of the research undertaken
- ANLEC R&D Embedded Technology Managers were assigned within each large-scale demonstration/ commercial asset proponent. The role of the ETM was to prioritise research of highest utility and be the gate-keeper for all research project external communications – including publications. It was important for ANLEC R&D research information to be released within the context of the demonstration asset communication strategy and plan.
- ANLEC R&D Executive conducted systematic project development and bi-annual review processes to monitor and communicate progress to all stakeholders without breaching customer confidences.

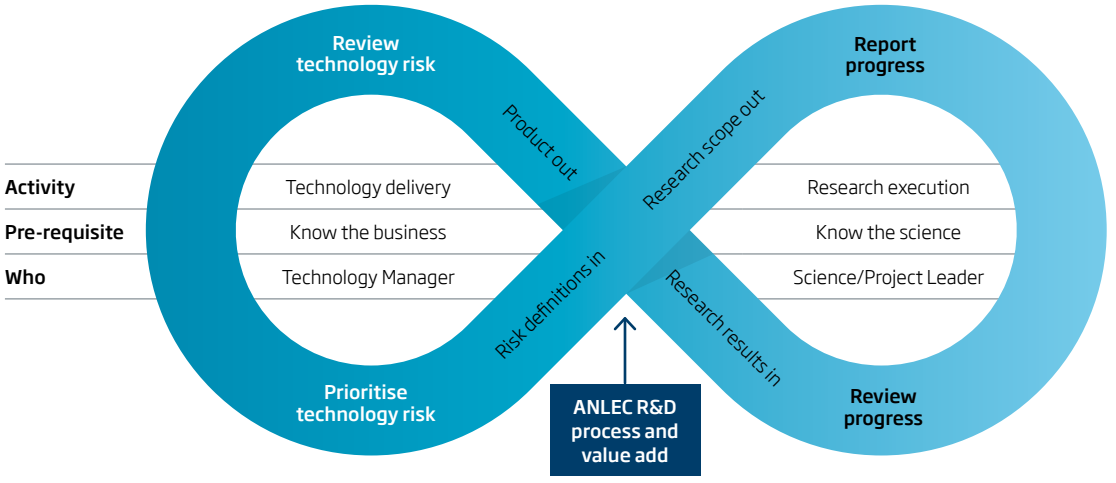
Managing these interfaces demonstrated the added benefit of creating peer review discussion forums where researchers and project proponents learned from each other's experiences.

The research effort maps shown later ahead of each basin study program highlight the differing risks and research priorities perceived by each CCS asset proponent.

ANLEC R&D expenditure by technical program node shows Australian CCS industry priorities over the term of the initiative. It highlights an agenda set by industry need rather than other drivers such as capability development and maintenance or academic interest.

A deployment enabling research effort for local CO_2 Storage will naturally have different priorities based on the local reservoir needs. A program driven by CCS industry will highlight such differences.

ANLEC R&D Activities development cycle



Desired outcome
Technology implemented (competitive)

Desired outcome
Scientists communiccate (co-operative)

Priorities for Surat Basin Research

The outer fringes of the Surat Basin are a relatively well explored resource. The CCS proponents therefore have confidence in the geological structures available for CO_2 storage in the reservoir. While capacity and injectivity estimates are being refined, this project provides opportunity for research to also explore other project investment risks. There is a particular need to understand storage in reservoirs containing formation water, resource management of carbon storage with coal seam gas development (and produced water re-injection) and groundwater resource utilisation from the Great Artesian Basin (GAB). Specific gaps requiring research are:

» Long term cumulative effects of carbon storage, coal seam gas development and GAB formation water utilisation;

» Water quality in fresh formation water systems co-located with active hydrocarbon systems i.e. dissolved organics etc;

» CO_2 trapping mechanisms including mineral trapping potential, geochemical trapping and dissolution and residual trapping for CO_2; and

» Top seal characterisation.

This, coupled with an on-shore injection in a region with high surface land use intensity, results in the need for highly reliable baseline characterisation together with innovative accurate, less intrusive MM&V techniques. ANLEC R&D also drilled two appraisal wells. These wells are designed as injection ready to test the reservoir and validate the body of research undertaken for this basin.

CO_2 storage research space showing basin priority topics in highlighted blue text. Bubble size reflects the research effort.

Priorities for Gippsland Basin Research

In Victoria, a substantial history of geological characterisation has occurred in the Gippsland Basin owing to conventional oil and gas development offshore, Brown Coal development and substantial groundwater resource utilisation onshore. Previous regional characterisation of storage capacity has described the far offshore commercial storage potential in the Gippsland Basin as arguably the best in Australia.

In the near-shore Gippsland Basin there is a particular need to understand carbon storage in reservoirs in a marine environment. The near-shore environment and shallow water depths present specific operational requirements for seismic acquisition and drilling operations.

Monitoring in the near-shore is unique and needed highly reliable characterisation together with innovative accurate MM&V techniques. Importantly, cost effective technologies, methods and monitoring configurations had to be established for accurate and less intrusive measurement, monitoring and verification in near-shore marine environments

There was also need to understand and exercise effective resource management between carbon storage, conventional oil and gas production and groundwater resources of the Latrobe aquifer system.

CO_2 storage research space showing basin priority topics in highlighted blue text. Bubble size reflects the research effort.

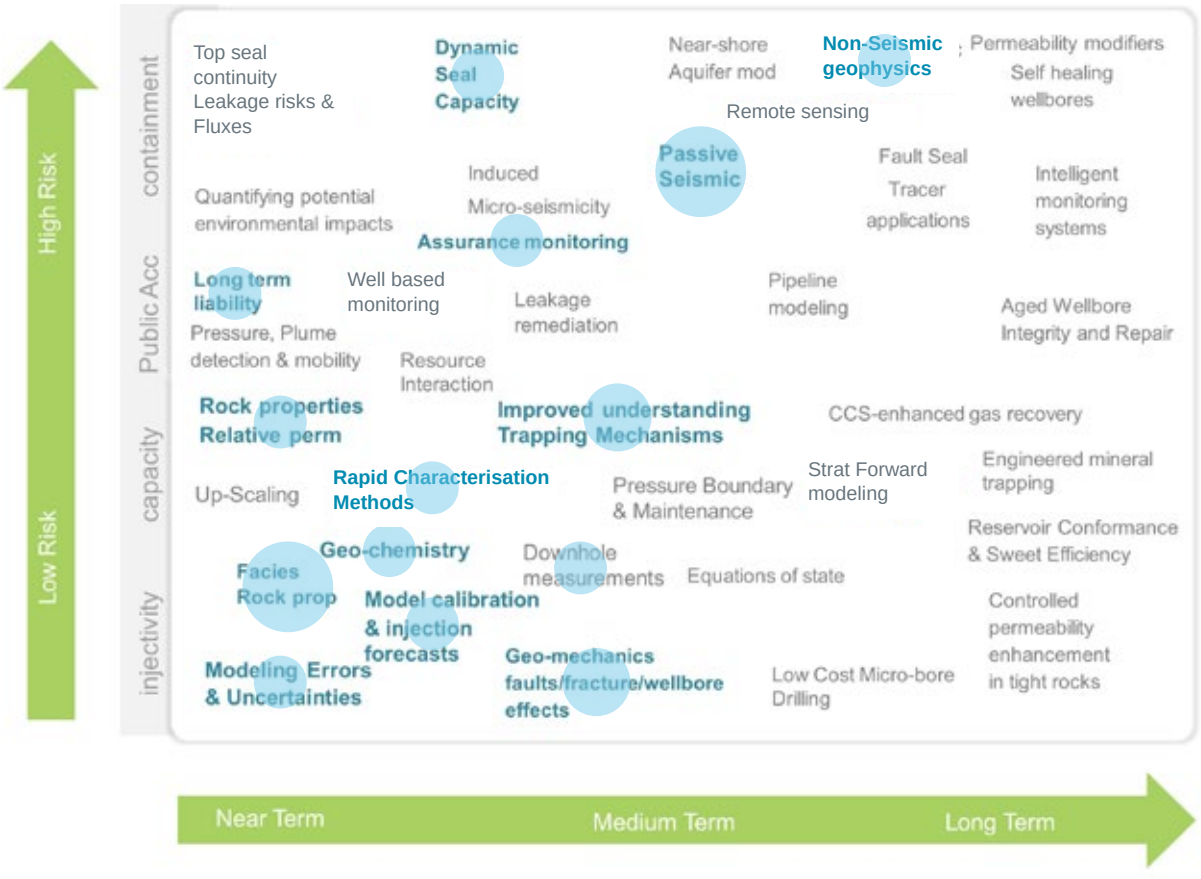
Priorities for South Perth Basin Research

The Lesueur sandstone formation on-shore was identified as a potential target reservoir for CO_2 Storage in the South Perth Basin. This is a fluvial sandstone therefore reservoir quality can be expected to vary in the lateral direction. The CCS proponent recognised an opportunity to demonstrate CO_2 storage in a geological storage reservoir with sealing units that are other than the conventional marine shale strata.

Historical data is sparse as the region is not well explored. In addition, the demonstration site is at a location with little pre-existing sub-surface data.

Early assessments suggest that there are prospects evident for CO_2 storage capacity in the saline reservoir. Investigation was necessary to interrogate the nature of the stratigraphy that will act to contain the CO_2 at the site and thus enhance the residual and dissolution trapping mechanisms. The benefit of demonstrating and confirming the storage potential of this site is the significant increase in global storage potential of similar basins.

The commercial site characterisation program also provided an ideal test bed for ground-truthing experimental measurement monitoring and verification (MM&V) research.



CO_2 storage research space showing basin priority topics in highlighted blue text. Bubble size reflects the research effort.

Expenditure by Geological Storage Basin

	$
Gippsland Basin	13,134,000
Surat Basin	42,860,000
South Perth Basin	12,303,000

The role of ANLEC R&D Communication

ANLEC R&D was designed as a fixed term initiative to serve an emerging CCS industry purpose. At the time of its inception, there were other CCS organisations represented at the National CCS Council that had already established a presence with many stakeholders – examples are the CO2CRC and the GCCSI. Each had their own outreach programs.

ANLEC R&D was not a lobbying organisation. Rather, it was set up as a focused partnership between industry and government to pursue mutually important research for carbon capture and storage.

ANLEC R&D did not focus on "building a brand" or marketing its achievements. ANLEC R&D recognised that CCS Demonstration and deployment proponents – by virtue of their large investment – would wish to control their own communication strategies. ANLEC R&D output was servant to the overall interest of its CCS customers.

While ANLEC R&D, at the invitation of CCS proponents, might be willing to support their communications effort, it was not seen as necessary or helpful to prosecute an independent communications strategy. It was therefore decided that advocacy for CCS technology was best left to the other organisations mentioned earlier. ANLEC R&D would only focus on delivery of a technical work program to the benefit of Australian technology proponents.

In hindsight, the absence of a strategy to market the ANLEC R&D brand almost certainly contributed to a withdrawal of Commonwealth Funding and their decision to terminate the initiative. The ANLEC R&D program – for all its valued delivery – was viewed as a legacy entity, established by a prior government that had reached the end of its useful life in the current political environment. Irrespective of three favorable reviews by the Commonwealth, (one as recent as October 2022) and despite having a highly supportive coal industry with additional Industry and Commonwealth funding already contracted, the government chose to exercise its right to terminate the initiative for its convenience. This is a paradoxical decision that does not appreciate the value of the governance model established over 14 years, the measure of delivery to its technical objectives and the importance of CCS to the national interest.

List of Contractors

A & SJ Lowe
Adelaide Petrographic
Aurecon Australia Pty Ltd
Australian National University
Brown Coal Innovation Australia
Boise State University
Carbon Projects Pty Ltd
CCUS Technologies
Clinton Foster
CO2CRC
Computational Geosciences Inc
CS Energy
CSIRO
CTSCO
Curtin University
Delta Electricity
Digitalcore Pty. Ltd.
Ecowise Australia
eGAMLS Inc.
EML Air Pty. Ltd
EPRI
Far Out Charters and Port Albert Fishin'
Gamma Energy Technologies
Gas Sensing Technology Corp (Welldog)
Geoscience Australia
Geotrack International
Greaney Petroleum Engineering Pty Ltd
Griffith University
GroundMetrics Inc.
HRL Technology
Hyvista
InGauge Energy
Institute of Mine Seismology Pty Ltd
KD.1 Pty Ltd
Kinerja Pty Ltd
King & Wood Mallesons
Lawrence Berkeley National Laboratory
Lincoln Paterson
Lithicon (FEI International)
Macquarie University
Makira Geotechnical PL
Mesa Photonics
Monash University
National Measurements Institute (NMI)
Parr Systems International Pty Ltd
Petroleum Hydrogeology International)
Petroleum Technology Research Centre
Phase Geo Pty Ltd
Queensland Department of Natural Resources, Mines and Energy
Queensland University of Technology
Red Vector, UK
RJC Consulting
Simon Fraser University
Spectrum Petrographics
Stanwell Corporation Limited
Stephen Schuck & Associates Pty Ltd
Steve Zeglin Pty
TerraTerra Pty Ltd
Ultra-Systems Technology Pty Ltd
University of New South Wales
University of Queensland
University of Adelaide
University of Melbourne
University of Newcastle
University of Sydney
University of Texas
University of Western Australia
University of Wollongong
University of Wyoming
Victoria – Department of Jos, Skills, Industry and Regions
WA Department of Mines and Petroleum
Worley Parsons

Financial Summary of ANLEC R&D from 2008–2024

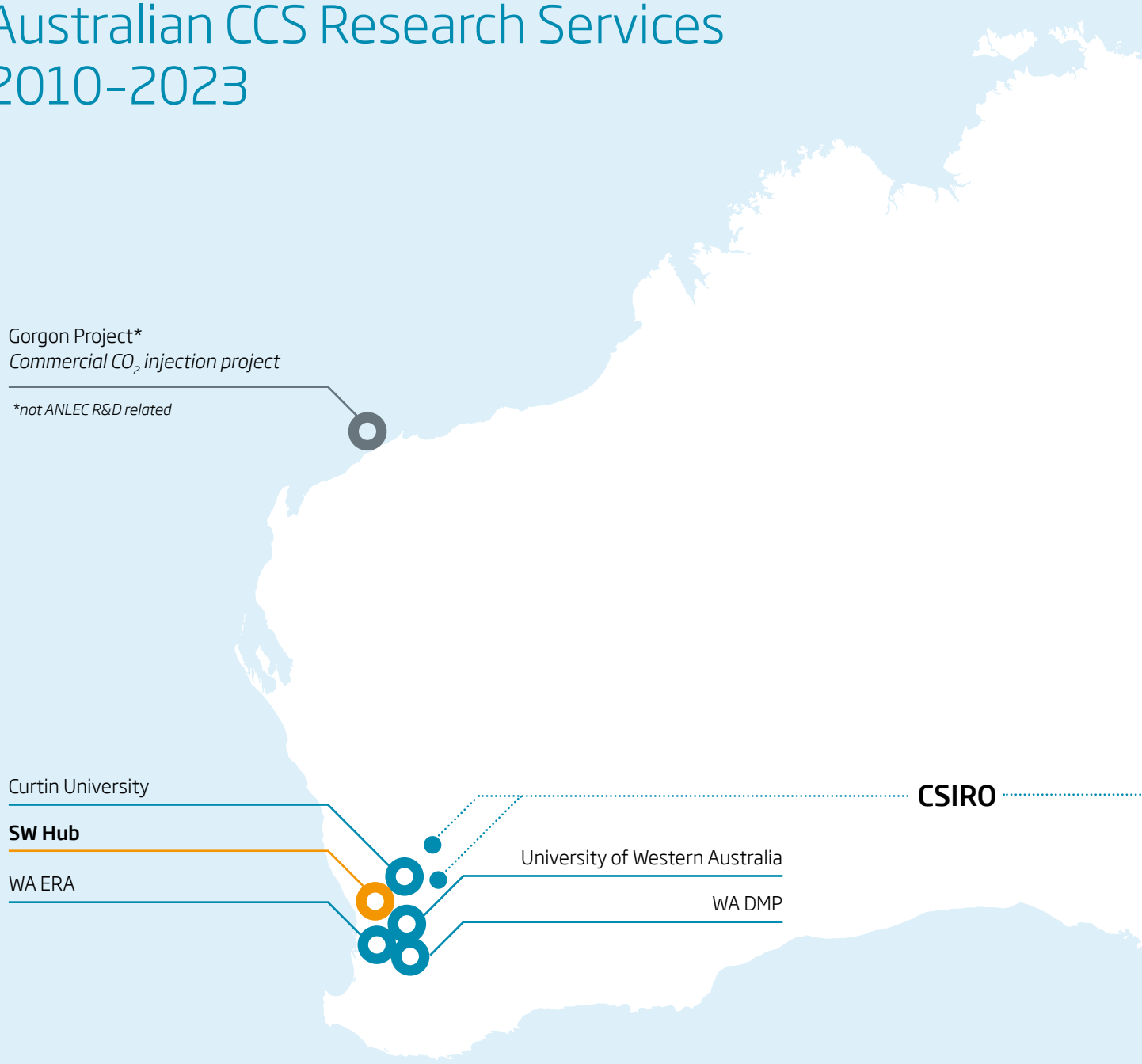
	Commonwealth Contributions	LETA Contributions	Other Contributions	ANLEC R&D Total
	$'Million	$'Million	$'Million	$'Million
Income	87.16	87.15	23.16	**197.47**
Expenditure				
Administration	13.28	13.27	0.11	**26.66**
Communications & Education	02.33	02.30	02.90	**07.53**
Research Node Funding:				
Node 1 - Economics and Modelling	0.52	02.53	0.00	**03.05**
Node 2 - Brown Coal	08.16	0.00	0.00	**08.16**
Node 3 - Alternatives and Fundamentals	07.17	08.33	0.00	**15.50**
Node 4 - Post Combustion Capture	04.12	02.09	0.00	**06.21**
Node 5 - Gasification (IGCC)	0.32	0.33	0.00	**0.65**
Node 6 - Oxy Firing	0.24	01.95	0.00	**02.19**
Node 7 - Geosequestration	34.47	39.79	20.15	**94.41**
TOTAL Expenditure	**70.61**	**70.59**	**23.16**	**164.36**

Acronyms

AC	Activated-carbon
AGS	Acid Gas Scrubber
AI	Artificial Intelligence
AIS	Automatic Identifications System
ANN	Artificial Neural Network
ANU	Australian National University
ASE	Absorber/Stripper
ASLP	Australian Standard Leaching Procedure
BSEM	Borehole to Surface Electro-Magnetic
BSR	Blocky Sandstone Reservoir
CCGT	Combined Cycle Gas Turbines
CCP	CO_2 Capture Project
CCS	Carbon Capture and Storage
CF/CNT	Carbon Fibre/Carbon Nano-tubes
CFD	Computational Fluid Dynamics
COP	Callide Oxy-fuel Project
CPU	CO2 Processing Unit
CSG	Coal Seam Gas
CUSP	Classification and Upscaling of Saturation-dependent Properties
DAS	Distributed Acoustic Sensing
DEA	Diethanolamine
DICE	Direct Injection Carbon Engines
DMP	WA Department of Mining and Petroleum
DRT	Digital Rock Technology
DSs	Double Salts
ED	Electrodialysis
EDS	Energy Dispersive Spectrometry
EIF	Educational Infrastructure Funds
EM	Electromagnetic
EM	Electro-Magnetic
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitators
FEI	FEI Co, USA
FGD	Flue-gas Desulphurization
GAB	Great Artesian Basin
GBR	Gradient Boosting Regressor
GHG	Greenhouse Gas
HELE	High Efficiency Low Emissions
HPC	High Performance Computational
HSS	Heat Stable Salts
IGCC	Integrated Gasification Combined Cycle
IRMS	Isotope Ratio Mass Spectrometry
KHCO3	Potassium Bicarbonate
LBM	Lattice Boltzmann Method
LCA	Life Cycle Assessment
LDHs	Layer Double Hydroxides
LECT	Low Emissions Coal Technologies
LETA	Low Emission Technology Australia
LiDAR	Light Detection and Ranging
M&V	Monitoring & Verification
MAR	Managed Aquifer Recharge
MDEA	Methyldiethanolamine
MDL	Minimum Detection Limit
MEA	Monoethanolamine
MEGS	Managing Electricity Grid Systems
MICP	Mercury Injection Capillary Pressure
ML	Machine Learning
MMV	Measurement, Monitoring and Verification

Mn	Manganese
MOOSE	Multiphysics Object Oriented Simulation Environment
MRC	Micronised Refined Coal
MT	Magneto-Telluric
NEM	National Energy Market
NF	Nanofiltration
NGL	National Geosequestration Laboratory
NMR	Nuclear Magnetic Resonance
NO	Nitrous Oxide
NOx	Nitrogen Oxides
O&A	Oceans & Atmosphere
OBS	Ocean Bottom Seismometers
OP-FTIR	Open-Path Fourier Transform InfraRed
P	Pressure
PCC	Post-Combustion Capture
PEO	Poly Ethylene Oxide
PDMS	Polydimethyl Siloxane
PTRC	Petroleum Technology Resource Centre
PVDF	Polyvinylidene Fluoride
PZ	Piperazine
QI	Quantitative Interpretation
RCA	Routine Core Analysis
RF	Random Forest
RH	Relative Humidity
RHOB	Bulk Density
RLS	Rotating Liquid Sheet
RRS	Reservoir Ramen System
SCAL	Special Core Analysis
scCO2	Super Critical Cardon Dioxide
SEM	Scanning Electron Microscopy
SGR	Shale Gough Ratio
SO2	Sulfur Dioxide
SP	Spontaneous Potential
SVR	Support Vector Regressor
SW Hub	South West Hub
SWAG	Simultaneous Water Alternating with Gas
SWIR	Short Wavelength Infrared
SWIS	South West Interconnected System
T	Temperature
TCLP	Toxicity Characteristic Leaching Procedure
TIR	Thermal Infrared
UMSN	University of Melbourne Seismic Network
UN-IPCC	United Nations International Panel on Climate Change
UNSW	University of NSW
UQ	University of Queensland
USEPA	United States Environmental Protection Agency
UWA	University of Western Australia
VLE	Vapour-Liquid Equilibrium
VSA	Vacuum Swing Adsorption
Vsh	Shale Volume
VSP	Vertical Seismic Profile
WAG	Water Alternating with Gas
WGS	Water Gas Shift
WWC	Wetted-Wall Column
XRD	X-ray Diffraction

Australian CCS Research Services 2010–2023



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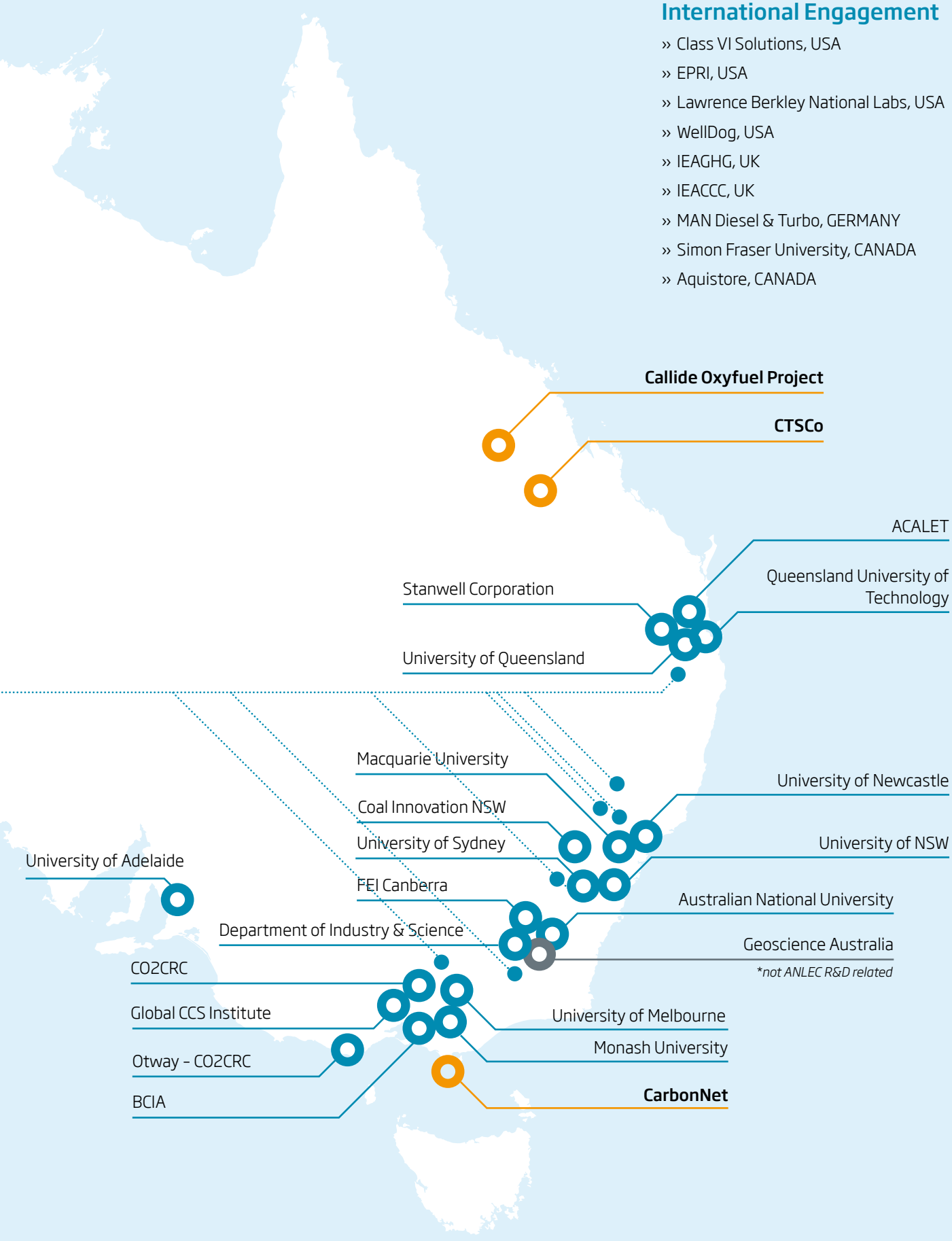
International Engagement

» Class VI Solutions, USA
» EPRI, USA
» Lawrence Berkley National Labs, USA
» WellDog, USA
» IEAGHG, UK
» IEACCC, UK
» MAN Diesel & Turbo, GERMANY
» Simon Fraser University, CANADA
» Aquistore, CANADA



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