ANLEC R&D

A NATIONAL INITIATIVE

Enabling CO_2 storage for Australia

Australian Government

Department of Industry, Science, Energy and Resources

LETA

Low Emission Technology Australia

A partnership between the Australian Government and the Coal Industry

2010-2018

Research Supporting CCS Deployment in Australia

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

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

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
- Low Emission Technology Australia (LETA). 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 Low Emission Technology Australia (LETA) 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

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

KEY

Capture · Storage · General

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

Message from the Minister 6

Message from Industry 7

Message from the Managing Director 8

Directors 9

Highlights 10

Business Principles 12

Partnerships and Investment Leverage 14

STORAGE RESEARCH

CO_2 Storage in Australian Geological Basins 18

Surat Basin 20
Case studies 22

Southern Perth Basin 50
Case studies 52

Gippsland Basin 76
Case studies 78

Otway Basin 91
Case studies 92

CAPTURE RESEARCH

CO_2 Capture Processes 100
Case studies 102

Alternative Capture Concepts 111
Case studies 112

Australian CCS Research Services 2010-2018 122

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.

Design & Layout: Beckon Designs, www.beckondesigns.com.au

"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 Minister

I am pleased to introduce this updated catalogue of work facilitated by ANLEC R&D and delivered by Australian low emission fossil fuel technology proponents and research partners. I am proud of the role the Australian Government, in partnership with the Australian coal industry, has played in supporting these achievements.

This catalogue demonstrates the range of research and development activities being undertaken by ANLEC and partners to reduce the technical and commercial barriers to deploying low emission fossil fuel technologies, including Carbon Capture and Storage (CCS).

Low emission fossil fuel technologies will continue to play an important role in unlocking the full economic potential of key resource commodities such as coal. That is why the Australian Government has invested around $620 million to accelerate deployment efforts including for CCS, coal-to-hydrogen and coal mine methane abatement technologies.

Coal is the world's second largest source of primary energy and the International Energy Agency assesses that 40 per cent of the world's electricity generation comes from coal, and projects that global demand will increase by 249 million tonnes by 2040. Australia is well placed to meet this demand, which is centred in Asia, given our high quality coal reserves, and our productive and safe mining practices.

Coal remains a significant contributor to the Australian economy and in 2017-18 Australia's coal exports were worth $60.1 billion, an all-time record and only marginally below our largest export commodity, iron ore (at $61.4 billion).

Over 68 per cent of electricity in Australia's National Energy Market (NEM) is generated from coal and will remain a low cost energy source well into the future.

ANLEC R&D is playing an important role in providing the science and collaboration that enables the sustainable use of coal in a low emissions future. I commend the Australian coal industry and research partners, for enabling this important ANLEC R&D initiative.

Senator the Hon Matt Canavan
Minister for Resources and Northern Australia

Message from Industry

Australia is endowed with some of the best coal reserves in the world, helping to provide affordable and reliable energy security. The coal industry is also a vital contributor to the Australian economy and the economic well-being of Australian families.

Despite the well-documented growth of renewables, fossil fuels – including coal – will remain dominant sources of energy in the global energy mix. Coal still accounts for a significant share of this mix and is an important resource to power growth in developing and emerging economies.

It's therefore essential that we recognise this and support the use of emission reduction technologies, allowing Australia and other countries to meet climate obligations while at the same time meeting economic imperatives.

Over the past 10 years the Australian black-coal industry has invested $300 million in the development of low-emissions technologies. In addition, the industry has recently announced an additional $200 million investment over the next 10 years to progress and deploy carbon capture and storage.

Australian National Low Emissions Coal Research and Development Initiative (ANLEC R&D) – developed as a national partnership initiative between industry and the Australian Government – is a key contributor to this endeavour. This portfolio of research and technology services demonstrates the rigour and diligence that the industry applies in its commitment to the environment and sustainable development.

Australian coal is ideally placed to meet the strong demand from Asia's fast growing and emerging economies because of its high quality – reducing emissions when compared to lower-quality coal from other exporters – and supplier reliability.

The key to using coal for energy and a low emissions future is the highest efficiency power generation assets coupled with investments in next-generation carbon capture and storage technologies to transition to the ultimate goal of near-zero emissions. ANLEC R&D is preparing for such investment nationally through the provision of relevant high-quality science and technology deployment services.

The COAL21 Fund is committed to lower emissions from coal and remains a strong investor in the work of ANLEC R&D.

Mr George J. Schuller Jr
Chair - Coal21

Message from the Managing Director

It is a pleasure to commend this catalogue of ANLEC R&D research to you. This volume reflects the vibrant body of research and development underway to secure the next phase of large scale emissions reduction for Australia.

Recent studies show the transformation underway in the Australian electricity grid. If Australian energy is to track the lowest cost path to remain competitive and meet its emissions reduction commitments, it is becoming increasingly evident that CCS will be a necessary technology.

ANLEC R&D and CCS in particular, has required the Australian science community to adapt and respond to a new paradigm for research and technology delivery. By validating research through in-field application, ANLEC R&D fills an important technical services role for each CCS project proponent. This relationship also delivers unique opportunities to foster innovation.

In this volume we have included the additional work brought into the portfolio in recent years. Delivering research and development to support, enable and accelerate CCS deployment requires an exclusive focus on those projects already underway by the Australian commercial CCS proponents. To date, these are located in the Surat Basin in Queensland, the Gippsland Basin in Victoria and the South Perth Basin in Western Australia.

I take this opportunity to acknowledge the commitment and support of the Australian Government and its Coal Industry in funding this unique partnership. It is also an equal credit to the embedded technology managers and scientists who have contributed to ensure effective delivery of the research services provided.

Dr Noel Simento
Managing Director

Directors

Mr Dick Wells
Chairman

Dr Noel Simento
Managing Director

Mr Mick Buffier
Glencore

Dr Peter Mayfield
CSIRO

Mr Brent Gunther
Intergen

Mr Mark McCallum
Low Emission Techology Australia

Dr Chris Greig
Princeton University (USA)

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 Injection Test

Field testing Australian CO_2 storage reservoirs

ANLEC R&D plans to deliver a R&D well in the Southern Surat Basin to provide the best-in-science analysis of reservoir, seal and containment uncertainties for the region. Dedicated research themes will be aimed at maximizing 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. If ultimately delivered, 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 show that geochemical reactions between CO_2 and the precipice sandstone in the Surat Basin are unlikely to pose constraints to injection. There is 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 funds research at a relatively mature technology readiness level. In order to accelerate deployment, focus is on research that enables application rather than early stage fundamental science. It aims to take innovative ideas out of the lab and into the field.

Service Model

The ANLEC R&D business model is premised on the provision of research services to commercial scale carbon capture and storage (CCS) proponents. It sources 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 is 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 allows for innovative science methods to reduce real investment risks to targeted CCS project proponents.

Transparency and Governance

The Board of Directors is 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.

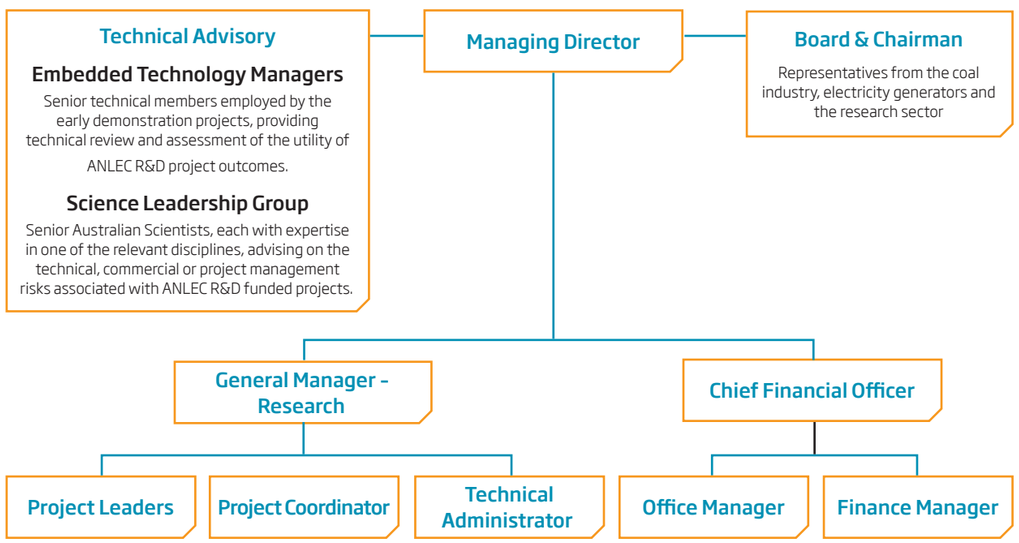
Customer Focus

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

Informed Decision Making

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

Organisational Structure



ANLEC R&D Management Team

Managing Director

Noel Simento

General Manager - Research

Kevin Dodds

Chief Financial Officer

Trevor Smith

Staff

Michela Secci

Clarissa Niap

Merinda Woodburn

Stephanie Rees

Louise Young-Wilson

Sarah Hughes

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

Partnerships and Investment Leverage

ANLEC R&D delivers a unifying objective for research to support CCS deployment. It is 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, Industry Regulation and Safety**

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

AUSTRALIAN CARBON INNOVATION
Creating a sustainable carbon future

Australia CarbonInnovation 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 ACI governance, ANLEC R&D was able to acquit its brown coal research requirements using local brown coal expertise.

IEA CLEAN COAL CENTRE

ieaghg

ANLEC R&D coordinates 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 funds 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 is 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.

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, will be 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 will have 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 is 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.

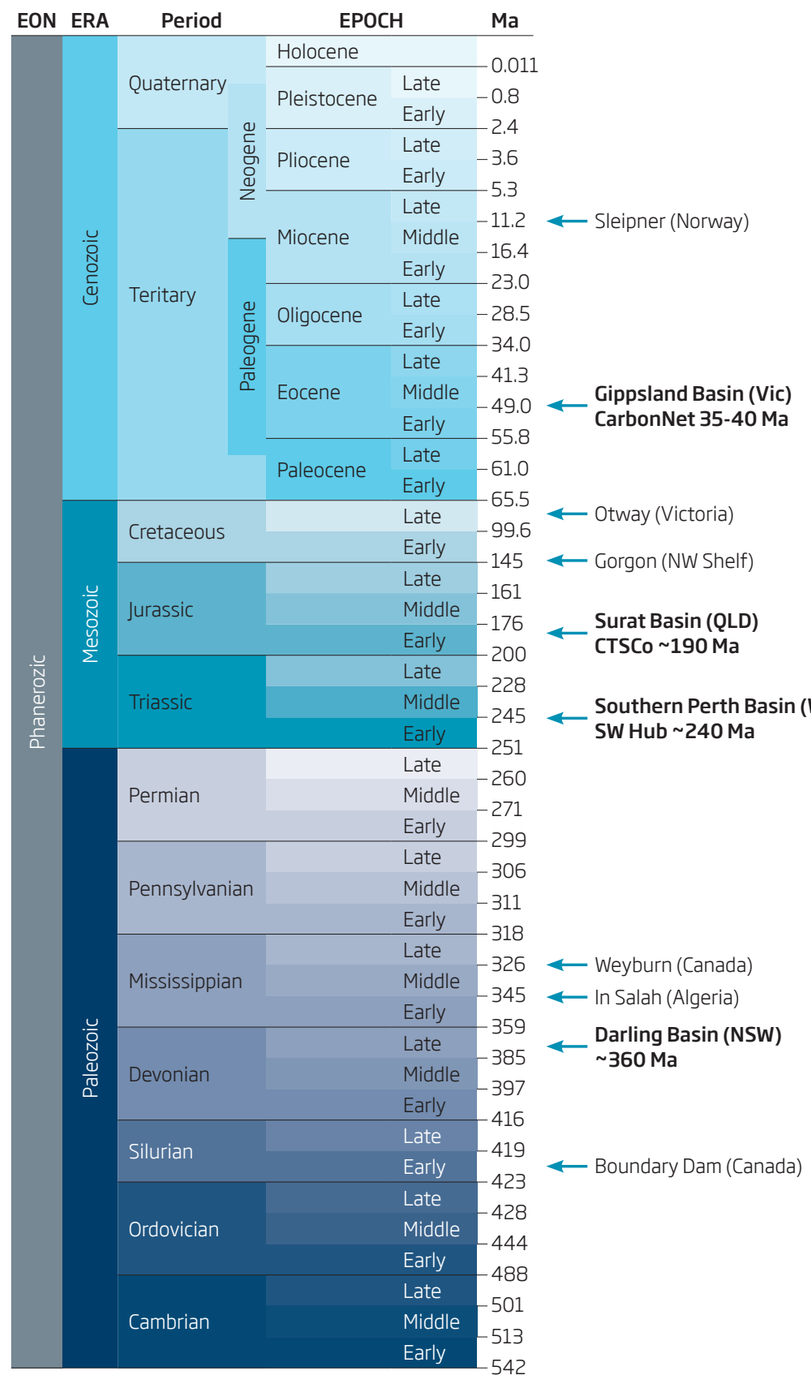
Managing financial investment risk for carbon dioxide storage

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


Photo courtesy of CTSCo

An integrated Surat Basin carbon capture and storage project has been 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 has been 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 is now 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*	New Data, New Application
	Test innovative remediation concepts for CO_2 containment	New Data, New Correlation, New Application
Publc Acceptance	*Deliver long term monitoring, measurement and verification (MMV) data for social licence to operate*	New Data, Field Validation, New Application
	Deliver robust data and information that allows accurate assessment of environmental behaviour of a CO_2 plume in a storage reservoir	New Data, New Application
Reservoir Capacity	*Validate rapid reservoir characterisation strategies and methods at scale*	New Data, New Correlation, New Application, Field Validation, New Service, New Software
	Develop and validate performance of state-of-the-art instrumentation for application in the field	New Data, New Correlation, New Application, Field Validation, New Service
	Deliver new data and fundamental correlations on the CO_2 flooding dynamics of reservoir rocks under in-situ injection conditions	New Data, New Correlation, Field Validation
Reservoir Injectivity	*Model and validate accurate estimates of fluid injectivity in the Precipice formation*	New Data, New Correlation, Field Validation

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

CASE STUDY

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 seeks to clarify the possible interactions in a range of potential geological settings. It aligns '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 recommends 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.

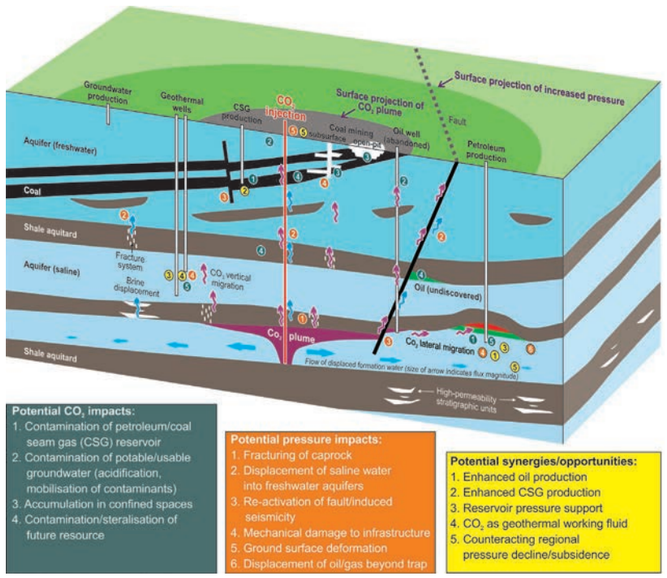
Decisions on the productive use of resources will require consensus to be drawn between various stakeholder interests. These would include private business, state and federal regulators, and local community groups.

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

This assessment provides initial recommendations on the nature of information and processes that could be adopted or adapted by custodians of the resources. It is 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.

CASE STUDY

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 are 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.

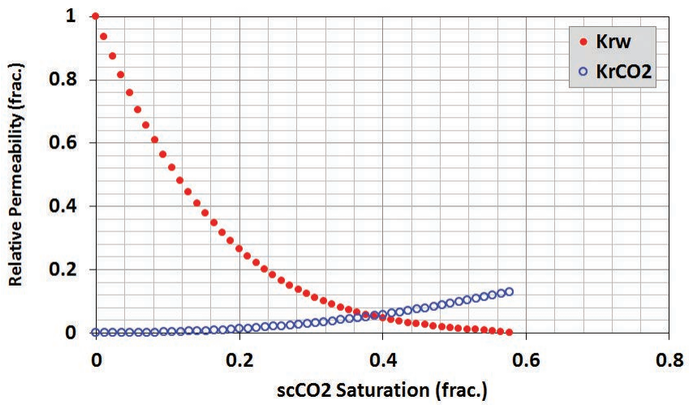
» They must initially be core flooded with $scCO_2$ and their permeability data then established.

» 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.

CASE STUDY

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.

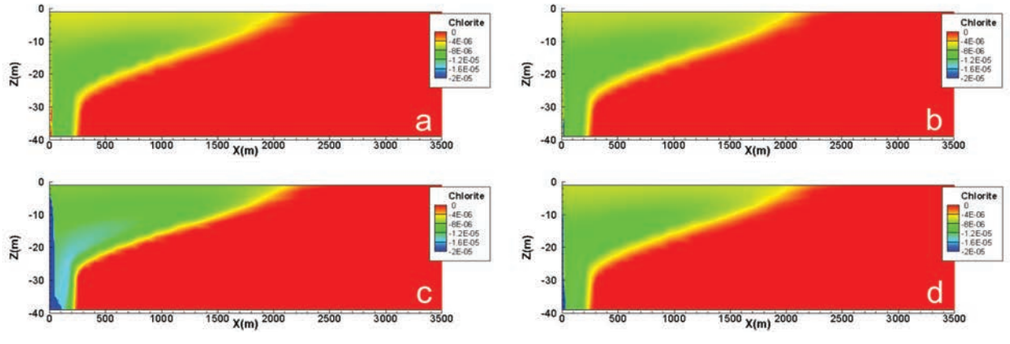
Detailed mineral analysis of units above the Precipice Sandstone revealed the Boxvale Sandstone Member may be suitable for above-reservoir monitoring purposes.

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).

CASE STUDY

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.

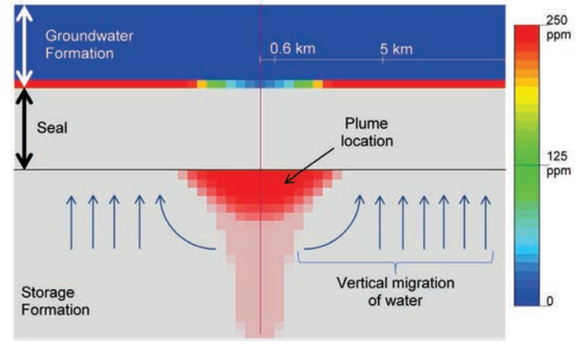
A commercial reservoir simulator (Eclipse300™) was used to run simulations of CO_2 injection into a water-filled formation. First, a series of simulations were run on a simplistic idealised generic numerical model to establish the key factors affecting groundwater resources. This was done in order to 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 has been 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.

CASE STUDY

Mobilisation and fate of heavy metals released by injected CO_2

Research informs 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 will help understand the type, amount and fate of heavy metals and metalloids, both before and after GHG stream injection, and provide a baseline and calibration data for the site's environmental and groundwater impact assessment.

The project uses 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 allows comparisons between simulations of water chemistry and measurements from experiments, providing confidence in the validity of model predictions of long term water chemistry impacts. The project also evaluates the application of partial and sequential extraction methods as a rapid, cost effective approach for investigating labile trace metal abundances in reservoir and seal rocks at carbon storage sites.

There is limited information on sources and sinks of trace metals and non-metals, or mechanisms of release, even with pure CO_2 reaction under low salinity carbon storage conditions. Natural analogue studies of CO_2 leakage sites have provided valuable data on the behaviour and fate of specific metals. Several initially elevated metals, including Ca, Fe and Mn, were repeatedly observed in previous field trials and experiments. Nevertheless, the sources of metals and non-metals are site specific and depend on mineralogy, water chemistry and the composition of the GHG stream.

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

» 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.

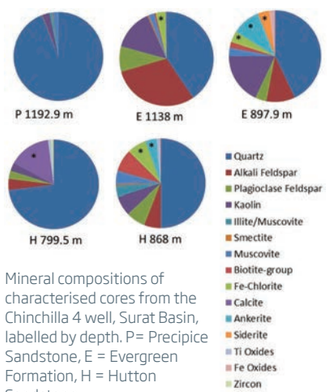
» Ion exchange reactions of reactive clays in response to fluid migration and mixing or elevated concentrations of Ca from calcite or plagioclase dissolution liberate major ions including Na.

» 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.

Reference

J. K. Pearce and S.D Golding 2016, : Mobilisation and fate of heavy metals released by the GHG stream – Literature review (7-0115-0236)



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

CASE STUDY

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 recognises authigenic carbonates as a natural analogue of mineralisation trapping. It seeks 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.

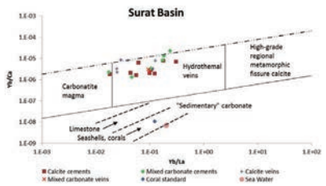
» Gaseous hydrocarbons found in fluid inclusions in the Eromanga Basin samples are sourced from the underlying Cooper Basin.

» 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).

CASE STUDY

Prospects for 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 supports 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.

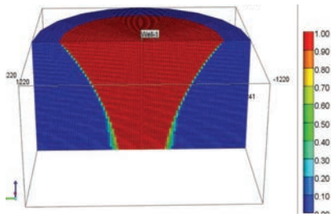
The experimental and kinetic geochemical modelling studies indicate that the injection of CO_2 into water-bearing reservoirs will reduce the formation water pH and cause dissolution of some minerals. Regarding pore-scale modelling that seeks to track more closely the actual physical transport through the porous media, the in-house extended LBM (XLBM) modelling provides 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, implies 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 are:

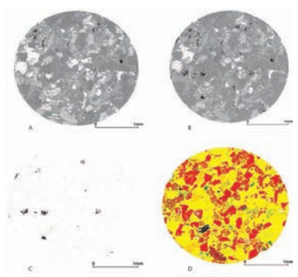
- Mineral dissolution far outweighs precipitation in the immediate wellbore area. This is usually not taken into account but is commercially important as it influences the decisions about the number and size of the injection wells.
- Near wellbore modelling, even using very conservative simplifying assumptions,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

CASE STUDY

New instruments allow for more accurate measurements

This research delivers 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 will be 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/NO_x 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 to date have:

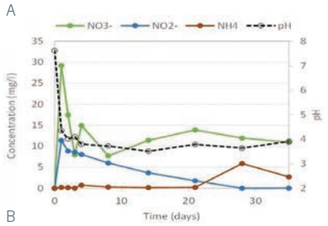
- delivered a guide to the expected Precipice Sandstone groundwater near the site;
- determined concentrations, identities and time resolved behaviour of dissociation species during N_2 and CO_2/NO Precipice Sandstone core reactions, for example nitrate (NO_3^-) is the main NO_x dissolution species (Fig. 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

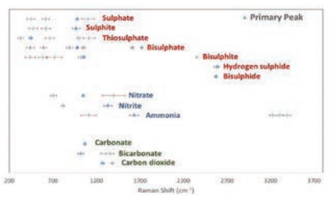
L. G. Turner, et al 2016, Desktop study and batch reactor experiments to determine baseline levels of CO_2, SO_x and NO_x in Precipice Sandstone

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

A



B



A) Dissolved N species and pH during Precipice Sandstone reaction with CO_2/NO.
B) Raman bands of 13 dissolved species of CO_2SO_x and NO_x.

CASE STUDY

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. Currently employed approaches to upscaling bypass this requirement to classify before upscaling and thus frequently result in unrepresentative properties at the upscaled level.

This project delivers 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

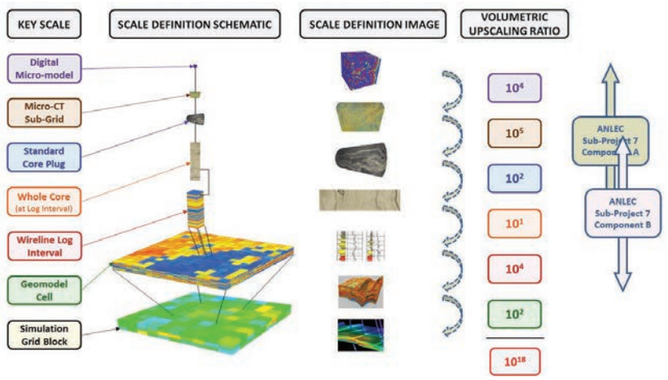
» Component B: Methods to classify and move from core plug and whole core to the geocellular dimensions.

The workflows are 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.

CASE STUDY

Digital Rock Technology allows faster and cheaper assessment for CO_2 storage

This program's objective is 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 presents a paradigm shift in the geoscience industry's approach to core analysis. The program has 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 have also been 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 include:

» 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 allow 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 show 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)

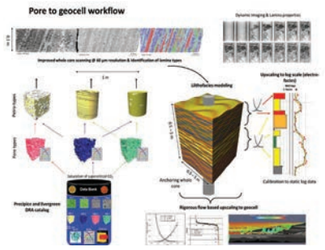


Illustration of pore to geo-cell workflow to support the Surat CCS project.

CASE STUDY

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 will be 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 will impact on modelling permeability and reactivity of the Precipice reservoir. These key sedimentological and diagenetic attributes are expected to impact the Kv of storage reservoir permeability.

Hyperspectral scanning of drill cores has recently become 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 is 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 is relatively new and although remote airborne and core-based sensors are widely available, field-based systems are rare and still require development.

Achievements to date include:

» 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.

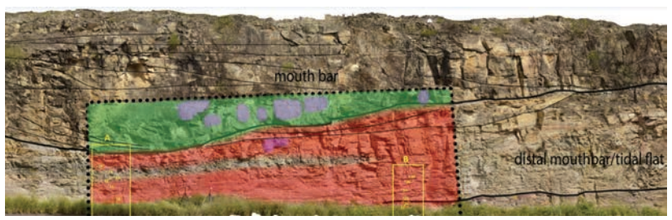
» Formation mineral details can be recognised based on the HyLogger™ data interpretation to a level needed to inform variations in permeability.

» 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.

CASE STUDY

Precipice Sandstone outcrops provide accurate measurements for reservoir modelling

The objective of this work is 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 will improve 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 takes 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 has 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 will be 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,

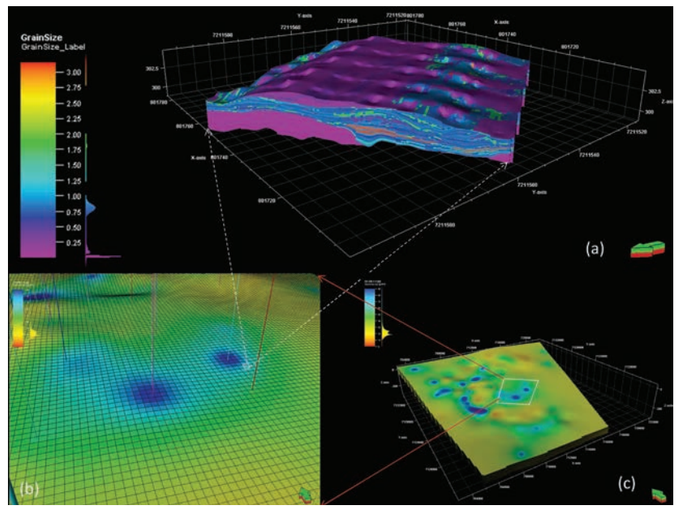
» developed a catalogue of sedimentary geobodies, their dimensions and their sedimentary features, to assist in subsurfacing modelling of the Precipice Sandstone reservoir flow units,

» 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.

Reference

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



Size comparison of local model and outcrop model. (a) Grain size distribution in outcrop of Isla Gorge 2; (b) GR distribution between wells; (c) local model with densely drilled well data. Note that Isla Gorge is not from the square area in figure b.

CASE STUDY

Assessing the longer term fate of dissolved CO_2

Numerical simulations are 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 has been 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 $(k_v/k_h)^{1/2}$ times the isotropic estimate, a result that was confirmed by numerical simulations.

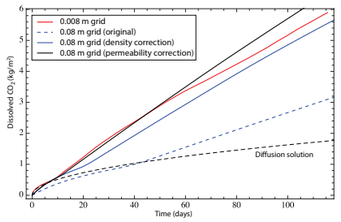
A sub-grid-scale scheme, for reducing the error in the numerical predictions of long-term CO_2 dissolution due to convective mixing, was developed. Several possibilities for implementing the scheme using grid-corrected properties were proposed and assessed using numerical simulations. This correction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

Key outcome:

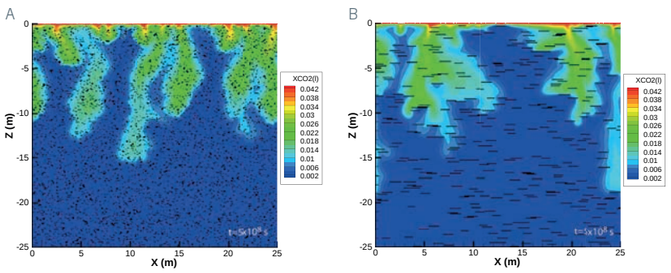
» The results obtained in this project can be implemented in commercial simulation software to improve the modelling of the short-term and long-term behaviour of injected carbon dioxide.

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.

CASE STUDY

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 develops 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 will be 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 builds 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 will extend the workflow to accurately describe flow and storage in this reservoir at larger scales. The results of the project will initially be specific to the Surat Basin demonstration project. However, the workflow developed will be applicable to other CCS Demonstration projects in Australia and globally.

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

Three parallel components are being undertaken:

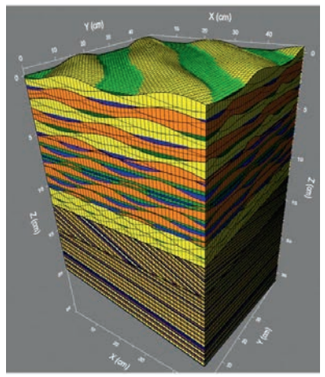
» Building an integrated geological description and calibrated static and flow property database from pore to whole core scales on a continuous 100 meters of core from West Wandoan Well 1.

» 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)

CASE STUDY

Characterising the Surat CO_2 storage complex; the Moolayember Formation

The purpose of this project is to acquire more knowledge of the mineralogy and chemical composition of the Moolayember Formation at the Glenhaven site. It assesses 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 has been 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.

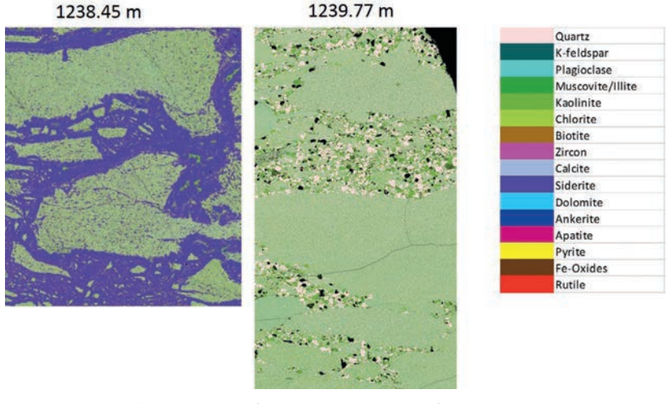
The Precipice Sandstone (thickness ranging between 70-80 m) is stratigraphically located between the Evergreen Formation and the Moolayember Formation. If the GHG stream is injected, it will first migrate up towards the Evergreen Formation due to buoyancy, but as GHG dissolves in the Precipice aquifer 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 will produce:

- 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

CASE STUDY

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 will act 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 thereforeprovides more complete information of stratigraphy that influence the regional conceptual models used in modelling.

The research integrates 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 are a particular focus. The methods include:

- 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 includes:

- 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

CASE STUDY

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 will inform early project stakeholder engagement, shape environmental monitoring at the CTSCo Surat Basin project site and ultimately assist 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 is 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 is therefore highly sensitive to indicating a leakage signal using a process-based monitoring approach. Sensor installations are 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 appear to lose accuracy at higher concentrations, oxygen sensors may potentially lose accuracy at lower concentrations, and there is 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 still extremely sensitive to leakage signals and even with sensor error, leakage would be detected early and would be clearly identifiable.

It will be 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.

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)

Reference

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

CASE STUDY

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 compares multiple CO_2 flux monitoring systems and develops automated data visualisation tools. This project plans to demonstrate CO_2 flux monitoring as a routine, non-specialist activity that addresses 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 has 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 will incorporate a 3D sonic anemometer, which will provide 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 is necessary to ensure the accuracy of CO_2 concentration measurements and therefore requires a robust calibration methodology.

Simple Measurement-Model Verification

» Once the sensors have been 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 will be compared to that predicted by the dispersion model.

Full System Verification

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

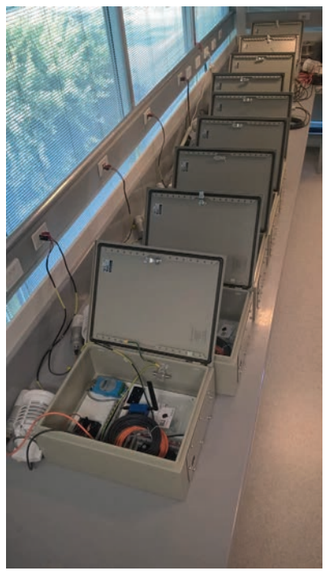
Field deployment testing - Area of null detection

» The data collected will also allow 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 will also be undertaken and a comparison of the results produced.

Success will 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

CASE STUDY

Using vegetation as a CO_2 sensor

Correct attribution of near-surface leakage signals is 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.

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 is to characterise all potential isotopic inputs and an assessment of the sensitivity of the system to each input will be used to identify the most feasible approach to monitoring using isotopes in the Surat Basin.

The results of this research will contribute 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.

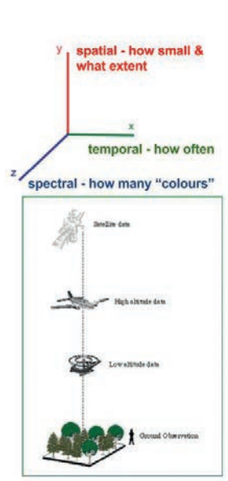
Near surface gases attributed to emissions can trigger project shutdown, intensive quantification activities, surrender of credits and loss of stakeholder trust. It is critically important that a thorough assessment of the potential for isotopes to be used as tracers of leakage be undertaken. This project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

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.

CASE STUDY

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 is developing a robust modelling and predictive framework that can be applied to all components of a near-surface monitoring and verification program planned for the Surat CCS demonstration project. This statistical framework will allow 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 can then be 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 are looking for evidence of the "absence of anomalous gas signals" in environmental measurements. They need assurance that measurements below specified threshold values can be reliably interpreted as confirmation of the integrity of the CO_2 storage reservoir.

This project will demonstrate 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" is 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)

CASE STUDY

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 is to develop a dual-phase geochemical model across the Evergreen Formation and Precipice Sandstone, which will explore the dynamic changes in the solute plume in greater detail and will assist 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.

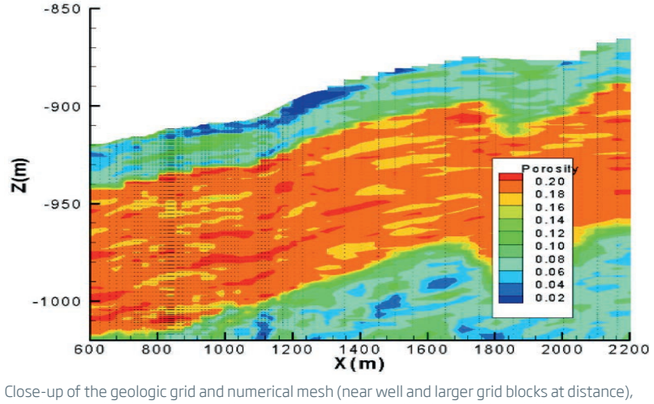
The type and degree of changes in the water composition under CO_2 injection and storage conditions will be assessed for the Glenhaven site, through two complimentary geochemical modelling approaches:

» The overall trend in water compositional changes over time is assessed using reaction path modelling, as implemented in The Geochemical Workbench software. The principle water speciation and fluid-mineral reactions are determined, which feeds into the second approach.

» 2D reactive transport modelling at reservoir scale will be 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 will provide 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 will be assessed using up-to-date regional data and the most advanced simulation software.

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



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.

Reference

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

CASE STUDY

Predicting CO_2 solubility at large scale dynamic modelling

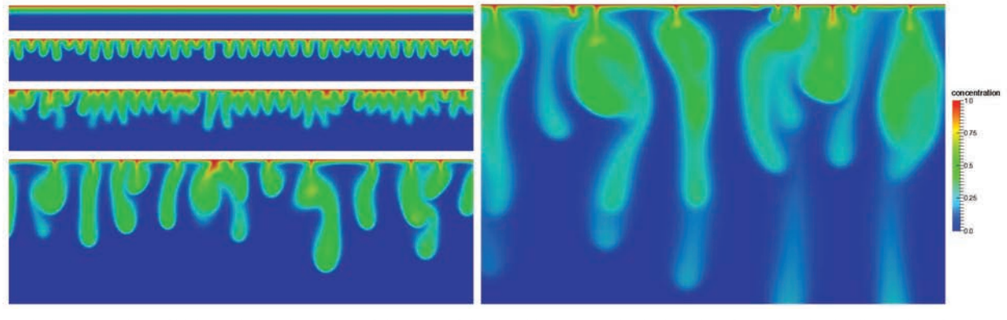
Dissolution of injected CO_2 into formation water is a key storage mechanism, in addition to residual trapping of gas, and is important for limiting the eventual migration of the plume. CO_2 dissolution is well understood at laboratory scale. Using this information at the reservoir scale requires deeper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



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

Reference

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

CASE STUDY

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 is 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 is 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 is 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 will provide 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 will be conducted after CO_2 injection. The comparison between the baseline and monitoring surveys will provide 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.

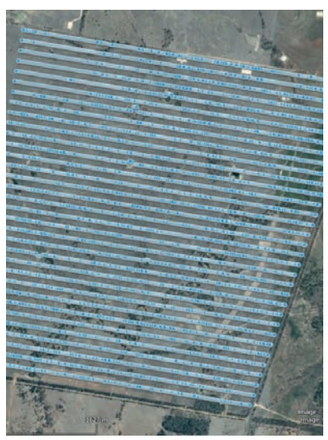
The project deliverables;

- 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 is 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

CASE STUDY

Feasibility Study for a Southern Surat project

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 has been 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 is the Mimosa Syncline to the west of the Moonie Oilfield. Researchers will explore techniques to measure and improve storage efficiency in this non-anticlinal setting. The strategy involves 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 will validate water quality interfaces as predicted by prior studies in the most prospective CO_2 storage intervals. The study will use 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 falls into five areas:

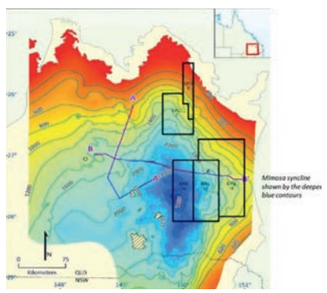
- *Fluid properties*–trends in water quality (potable/non-potable aquifer boundaries) with depth from the shallower northern to deeper Southern Surat Basin and limits on heavy metal release under CO2 injection.
- *Injectivity*–optimised injection stream (CO_2/water) to maximise injectivity and pore space 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 comprises 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

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

CASE STUDY

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 is 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 will study 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 want to generate a methodology that will 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 proposes to measure the headspace quality at the near surface water level as an inference to water gas components.

New knowledge will be developed by:

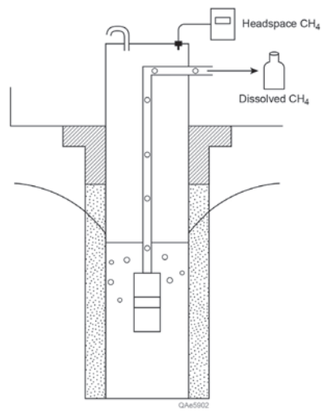
» Literature review of previous work, from unconventional oil and gas literature, assessment of available data of the Surat dataset, and decision to use either a custom code (most likely) or off-the-shelf software.

» 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

CASE STUDY

How can isotopic distribution identify naturally occurring CO_2

Correct attribution of near-surface leakage signals is 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 optimize best practice.

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

The results of this research will contribute 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 is 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.

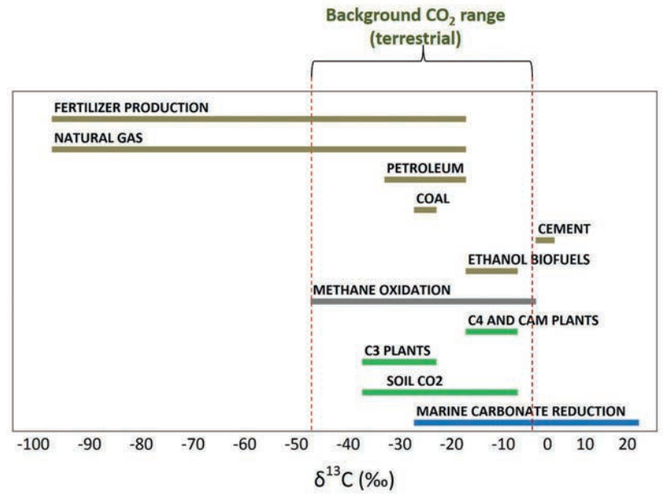
» Prediction of the geochemical signature of leakage and the sensitivity of the system for indicating leakage using the isotopes measured.

» 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)

CASE STUDY

Optimizing 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 proposes further application of a process-based approach to environmental assessment.

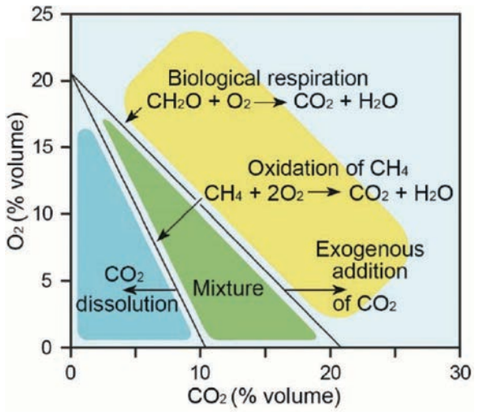
Soil gas baselines show increasing presence of CO_2 due to climate change. Thus with baseline CO_2 concentrations trending upward, current methods will result in false positive fugitive claims that could severely impede CCS projects and public acceptance of CCS. For this reason, a process-based approach has been 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 updates process-based attribution methodology for methane-rich sites.

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

The overall objective is 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.



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

Objectives are:

- 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)

Southern Perth Basin

Photo courtesy of the Department of Mines and Petroleum, WA

The SW Hub commenced as Australia's first flagship CCS project in December 2011. It considers 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 can be 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 is 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
- Field Validation
- New Correlation
- Permitting & Public Communication
- New Application
- New Service
- New Software

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.	
Publc 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

CASE STUDY

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 is of great importance for the characterisation of the reservoir, seals and structures in the area. Often, the positioning of the seismic source pointsis not easy or convenient. These issues arise 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 is likely to cause significant disturbance to the landowners. Gate removal and fence demolition are both impactful, and the trucks may leave very large footprints over soft ground. It is 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 would be used to demonstrate to the community their low environmental impact.

This project describes 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 are 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.

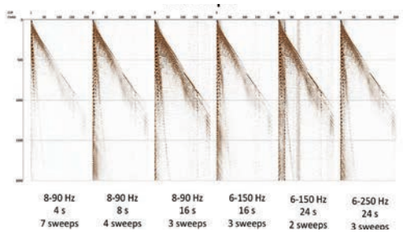
» The results of the new survey demonstrated that high resolution surveys were achievable for imaging the top 1000m of sediments and improving our understanding of the fault patterns.

» 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.

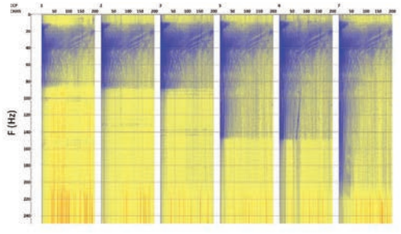
» It showed it was possible to utilise UNIVIB trucks in the existing large-size 3D survey, to close the gaps in survey coverage where access is otherwise not possible, due to local land conditions.

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.

CASE STUDY

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. 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.

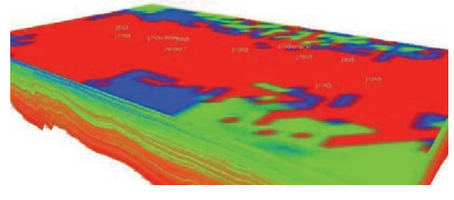
Both methods predict CO_2 plumes to develop and remain around the injection wells for the long term; the main difference being that the plume predicted by the 'Sedsim' input spreads more than the conventional model.

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.

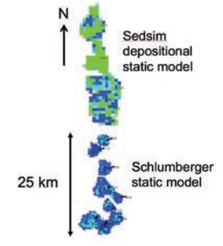
Having an alternative approach to depict the geological framework allows building confidence and reducing risk and cost of obtaining accurate representation of the reservoirs and the forward models.

Reference

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



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).



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)

CASE STUDY

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:

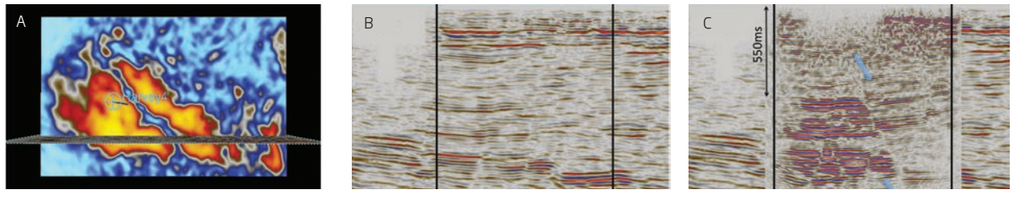
- Several faults are seen in the Nested 3D data, which were not previously identifiable in the regional 3D cube. This includes faults at different scales.
- All discontinuities (large and small) are of a much higher fidelity in the Nested 3D survey.
- Some faults appear to propagate near to the surface but are of a small-scale throw.
- Faulting in the area is highly complex.
- The Harvey-4 well appears 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 allow for the interpretation of faults, previously unidentified in the regional 3D survey.
- Even some deep, large-scale faults are 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.

CASE STUDY

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 uses 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 has been 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.

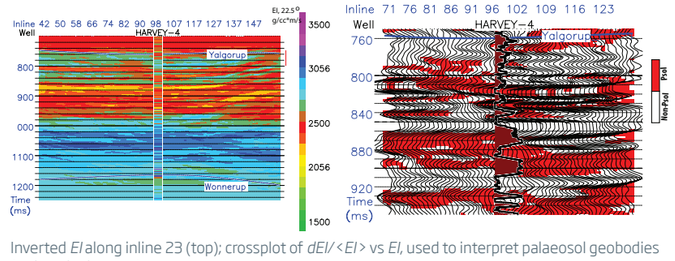
Recent results:

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 are of good quality, so we expect 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).

CASE STUDY

Research delivers more information on structure of the Lesueur storage complex

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

Currently, data is sparse and more confidence is needed is the storage potential for the basin. Ambiguities are 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.

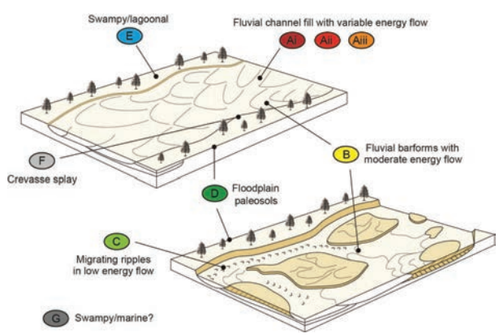
Work is on-going and recent results show:

- There is 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 are 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 are 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 differs significantly, as do 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.

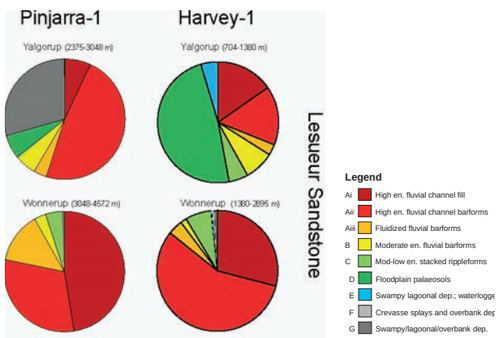
The drilling, coring and logging program comprising three wells: Harvey-2, Harvey-3 and Harvey-4 have been completed. Analysis is ongoing.

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.

CASE STUDY

A fresh look at faulting to inform deployment decisions

The available seismic data for the South West Hub clearly indicates that multiscale faults affect 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 targets the evaluation of the faults hydraulic behaviour, i.e. the faults sealing potential for across-fault and up-fault flows. A secondary objective is to investigate the distribution of sub-seismic fractures and their impact on the trap integrity and reservoir compartmentalisation.

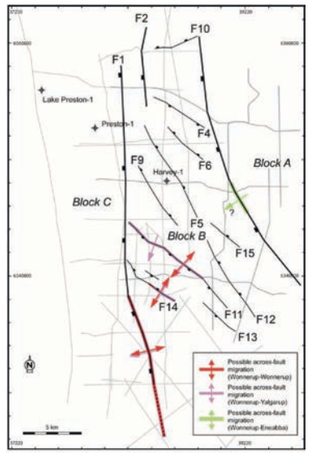
A new geological model, consistent with the integration of the latest 2D seismic reflection survey and available geophysical data, has been built. It integrates five stratigraphic horizons tied to formation tops in the new Harvey-1 data well (Neocomian UC, top basal Eneabba Shale, top Yalgorup, top Wonnerup 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 represents a first-order geological model, and the acquisition of additional seismic and well data is critical to reduce remaining geological uncertainty and further constrain the structural framework.

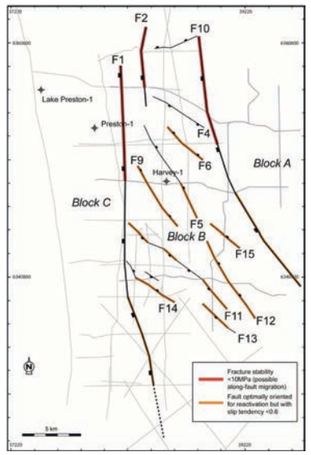
Key findings from the study:

- 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 are 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 are located to the north of the SW Hub.
- The study provides a useful input into dynamic models to test compartmentalisation and containment.

Reference

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





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

CASE STUDY

Mapping lithofacies: validating storage potential in unconventional storage structures

The goal of the multidisciplinary work presented by this study is to understand the geological and geophysical parameters that will 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 are 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 feeds into and supports 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.

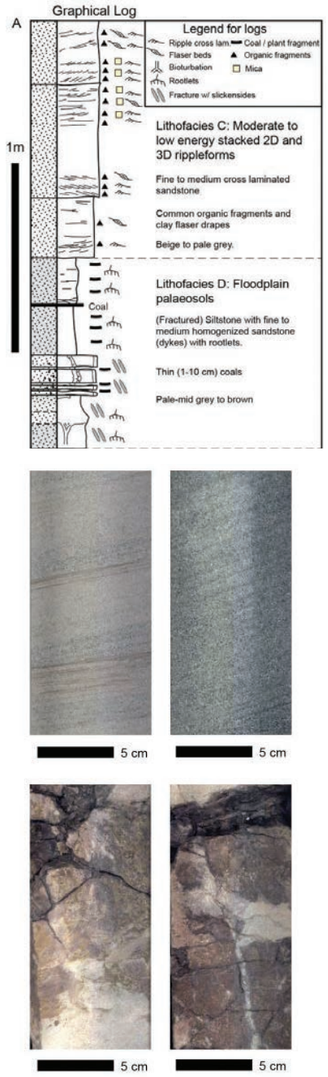
The outcomes of the work indicate significant differences between the Upper and Lower Members of the Lesueur Sandstone in terms of sedimentology, petrophysical, geomechanical and elastic properties. The deep saline aquifer equivalent to the Wonnerup Member of the Triassic Lesueur Sandstone represents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

Good reservoir properties are 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 give 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 has been identified for future studies.

By contrast, the overlying Yalgorup (704-1380m) is 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 remain 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.



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.

Reference

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

CASE STUDY

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.

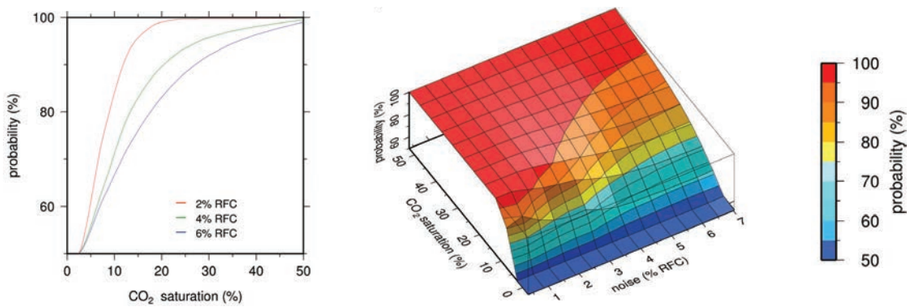
These objectives were addressed by modelling seismic, electromagnetic and gravity responses of idealised, conceptual models of two recently-approved flagship CCS projects; the SW Hub in Western Australia and the CarbonNet project in Victoria. Baseline and several data vintages (each representing the 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.

CASE STUDY

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 examines such responses, and their suitability for determining vertical permeability is then ascertained by numerical modelling combined with notional inversions and data-worth analyses.

The analyses suggest 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 is 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.

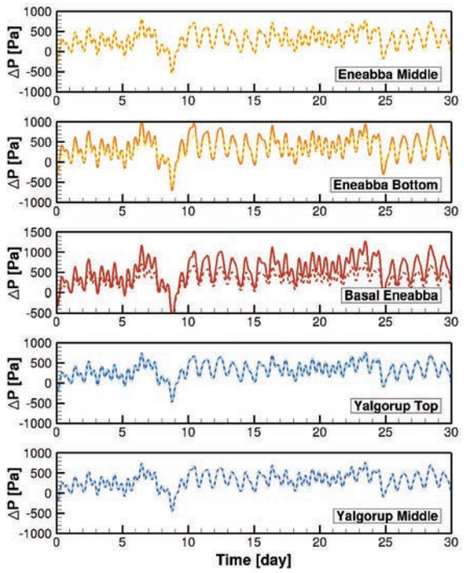
» Hence, even with sensitive sensors and regionally induced gradients, the permeability estimates are related to the local conditions.

» 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 will 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.

CASE STUDY

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.

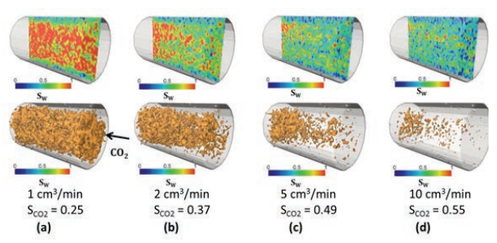
» Structural and residual trapping are likely to be viable storage mechanisms in clean quartz, and siliciclastic rock reservoirs that exhibit weakly water-wet characteristics.

» 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.

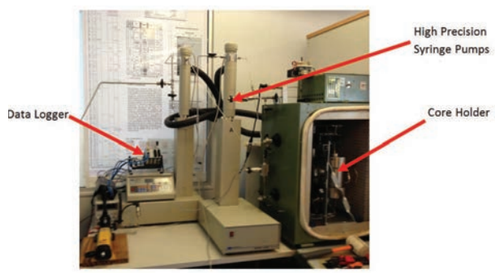
» It was proven by micro-computed tomography experiments that residual trapping is a viable storage mechanism at the pore-scale in clean sandstone.

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.

CASE STUDY

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.

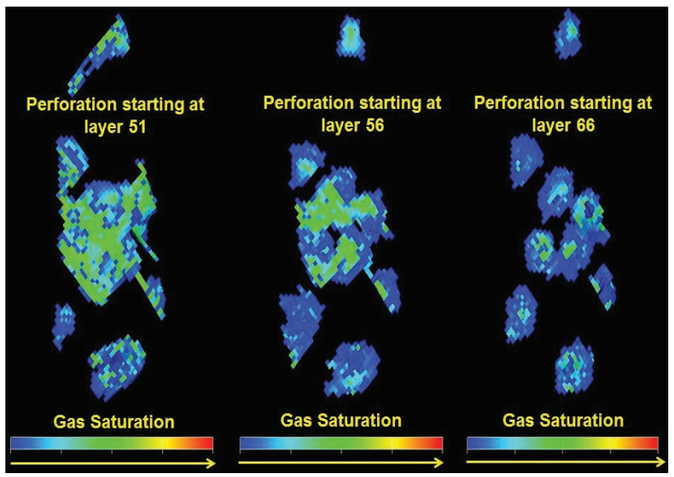
The methodology used technically feasible engineering designs to optimise both of the above trapping mechanisms in the Southern Perth Basin storage formation by determining the most feasible injection schemes. The aim was to estimate the relative economics of different injection schemes with different 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.



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

Reference

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

CASE STUDY

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.

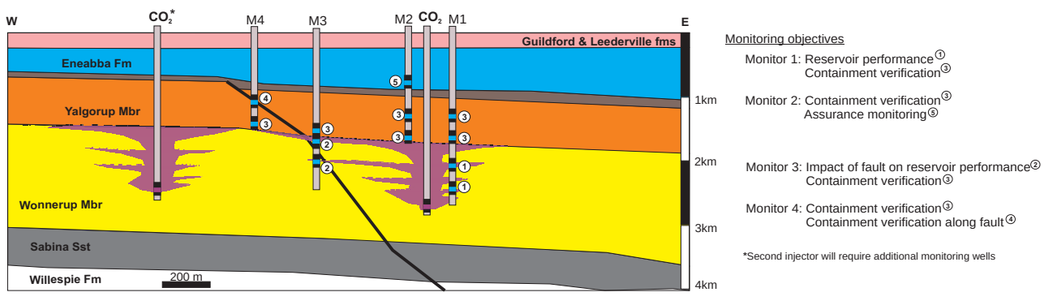
In Western Australia, 100km south of the city of Perth, the SW Hub is targeting the saline aquifer of the Lesueur Sandstone at a depth of 2-3km for commercial-scale CO_2 sequestration. In support of the drilling of these wells, there is a need to consider the relative location of the wells and the monitoring 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 will allow 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.



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.

Reference

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

CASE STUDY

Understanding geochemical baselines for the Lesueur Formation

This project reports 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 have been 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 indicates 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.

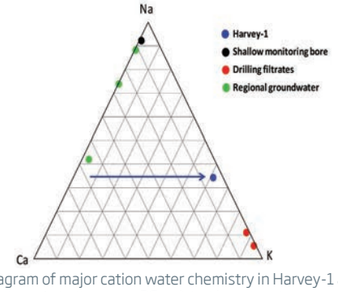
Only after this point, do changes in pH occur. These reactions illustrate the importance of clays and feldspars contributing to changes in the mineralogy. These preliminary models contain a large number of assumptions (e.g. formation fluid chemistry is unknown).

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 that enables us to see discrete changes in the mineralogy caused by the passage of CO_2.

Reference

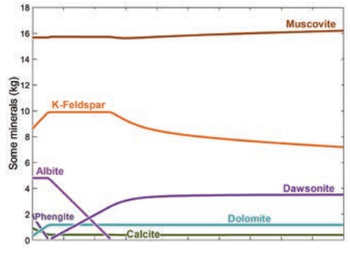
L. Stalker, et al 2013, w (7-1111-0200)

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.

CASE STUDY

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 is deploying 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 will comprise 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 will be 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, will be 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 will be 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 can also be used to build images of the subsurface. This informationcan 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 will be made with the available data and, where possible, 1D images will be 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.

CASE STUDY

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

This project is developing 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 are:

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 include:

» 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 include:

» 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).

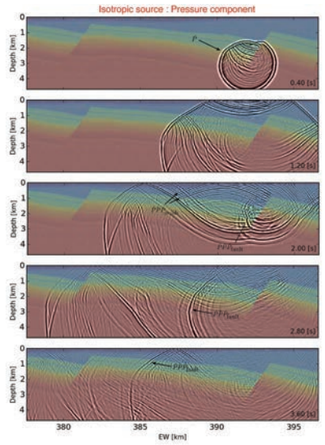
» Analysis of 75 days of passive recordings for analysis of site-dependent signal/noise conditions and ambient seismic noise versus time and sensor depth.

» 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 has already commenced and will help define the natural low level seismicity of the area. The project will improve 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.

CASE STUDY

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 suggest:

» The Wonnerup exhibits 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.

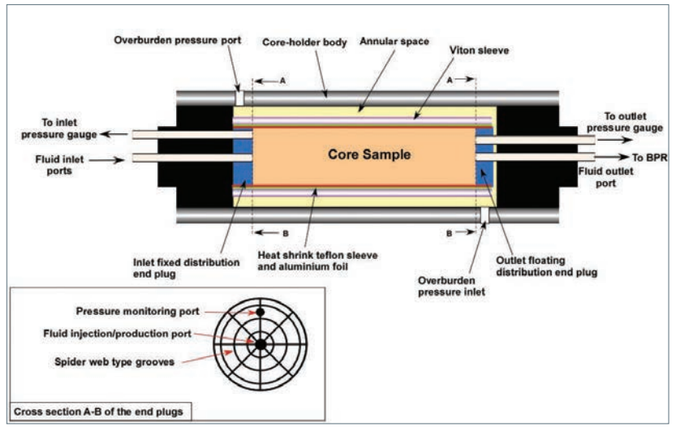
» The geochemical analysis of the fluid samples, collected during the core-flood experiments, have also revealed that the petrophysical alterations caused to the rock samples is due to the dislodgment and transport of the fine clay particles within the pore space of the rock.

» The computer modelling shows that the experimental conditions used are unlikely to result in major mineralogical and fluid changes, which is confirmed in the results of the core-flood eluent chemistry.

Further work continues to understand injectivity for this reservoir.

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)



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

CASE STUDY

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

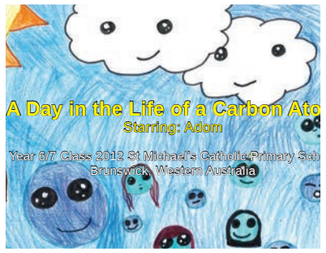
In total there were 125 landholders of whom 75 granted access for the 3D seismic test. Of the 125 customer file notes, every alternate file note was scrutinised in detail. This resulted in 63 records being analysed for this research. Of those, 37 allowed access for the 3D seismic testing while 26 did 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 will be essential if the project is to progress 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.

CASE STUDY

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

The CO_2 storage concept in the South Perth Basin relies 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 is a key focus for these types of storage sites.

This work will characterise 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 builds 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 will be 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 will be tested in a series of dynamic simulation scenarios to better understand storage potential. However, the study aims 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 will be a 3D model that can be used to easily identify the areas that either need more data or have the highest chance of success for injectivity and containment, which is 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.

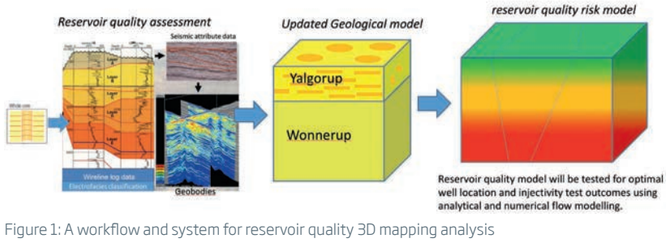


Figure 1: A workflow and system for reservoir quality 3D mapping analysis

Reference

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

	Core facies (Olierook)	Image Facies (Baker Hughes)	Expert petro-facies (Pevzner)	Electrofacies (Emelyanova)	DMP Static model facies (ODIN)
Higher energy deposition sand	A i-iii	J, G, D	E1	F1, F4, F5	High energy fluvial
Moderate energy deposition sand	B	K		F3	
Lower energy deposition sand	C	E	E2	F2	Low energy fluvial
Low quality baffle	D, F		E3	F6	Paleosol
Medium quality baffle	E, G	C	E4	F7	Overbank

Decreasing reservoir quality

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

CASE STUDY

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 aims 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 delivering new, high-resolution seismic data which includes a combination of nested surface 3D seismic data in combination with 3D Borehole seismic data that will enable 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.

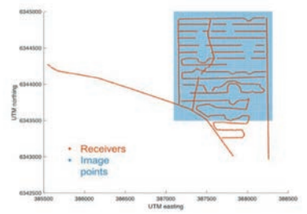


Figure 1: Survey layout: source lines are shown in red, image area in blue

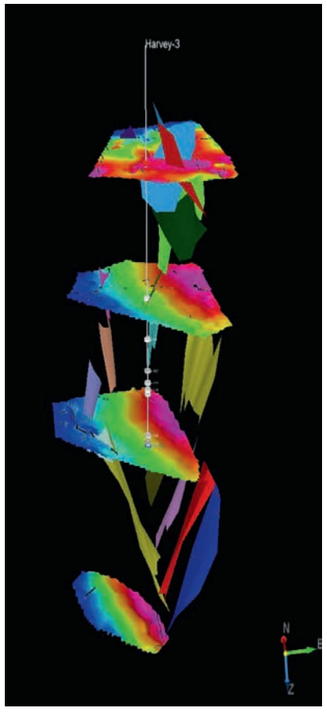


Figure 2: Geological interpretation of the H-3 nested 3D with top formations and faults

Reference

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

CASE STUDY

Using multiple barriers to contain CO_2

This project's goal is to improve knowledge of the nature of the Yalgorup Member. It tests 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 will evaluate 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 will assist to carry out initial connectivity assessment and investigate baffle distribution.

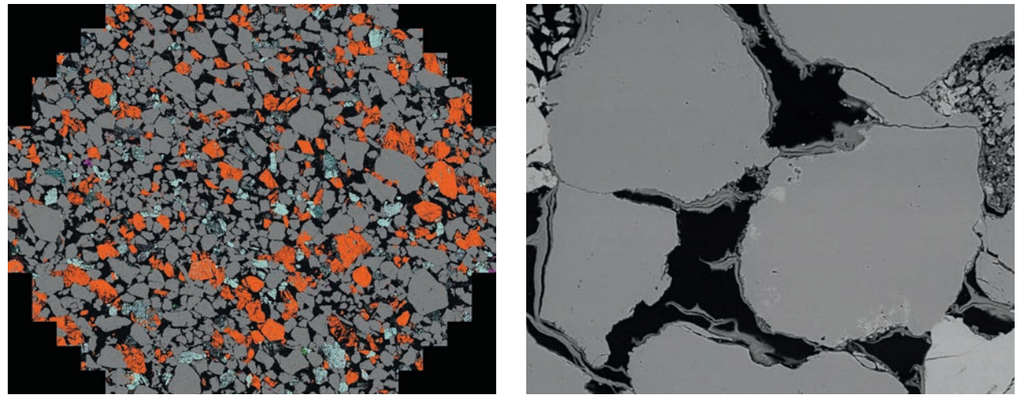
The project is articulated around four modules:

- 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 are used as a proxy for evaluating the existence of fluid compartments. Comparing fluid inclusion data and experimental electrical resistivity measurements data, the results show similarity and the contrast in salinity between the Yalgorup and the Wonnerup Member appears to be real but small. A salinity of 45,000 ppm or 45g/L for the Yalgorup Member is 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.

CASE STUDY

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 are 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 is 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 include:

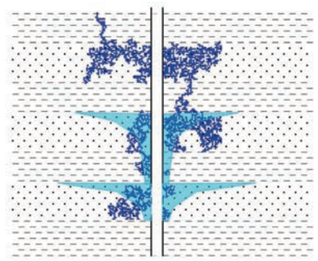
- low-permeability intraformational seals or baffles,
- residual (capillary) trapping, and
- dissolution of CO_2 in the formation water.

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 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.
- 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 proposes 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)

CASE STUDY

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 is 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 assesses 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.

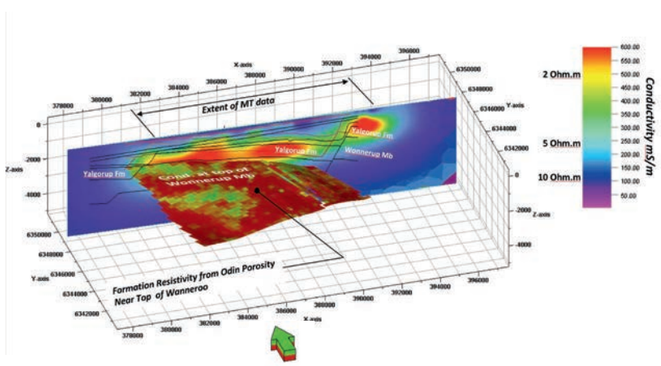
Pressure monitoring requires investment and planning up front however, once the initial is made it is a sensitive and relatively inexpensive system to maintain. Seismic surveys bring difficulties in access and costs however it provides 3D visualisation of the plume. Inclusion of permanent buried arrays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

Gravity, MT and EM methods are well suited to complementing the pressure and seismic data. The technology is rapidly developing, producing increased resolution and reducing costs. The technologies are also relatively cost effective to deploy and permanent stations can be set up to remotely produce and return data.

The deliverable provides 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)



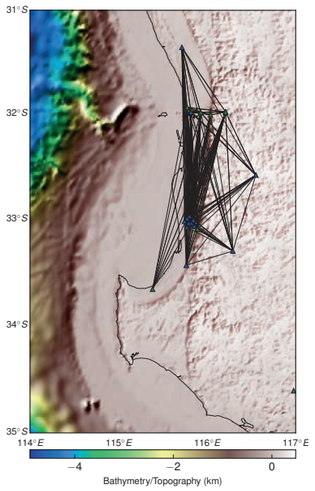
First pass MT derived resistivity (17 stations) versus calculated resistivity at top of Wonnerup

CASE STUDY

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 require 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.



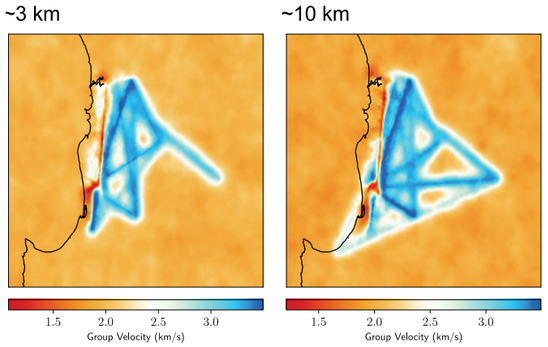
Seismic ambient noise correlation raypaths between station pairs

This research is 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 consists of 7 near surface and autonomous stations located in the South Perth Basin area. The sensor choices and network design are 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 have been 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 provide repeatable imaging without any acquisition cost except the running expenses of a seismic station. This information is used for CO_2 injection monitoring or used to design the active 4D seismic monitoring strategy.

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



Ambient seismic noise tomograms

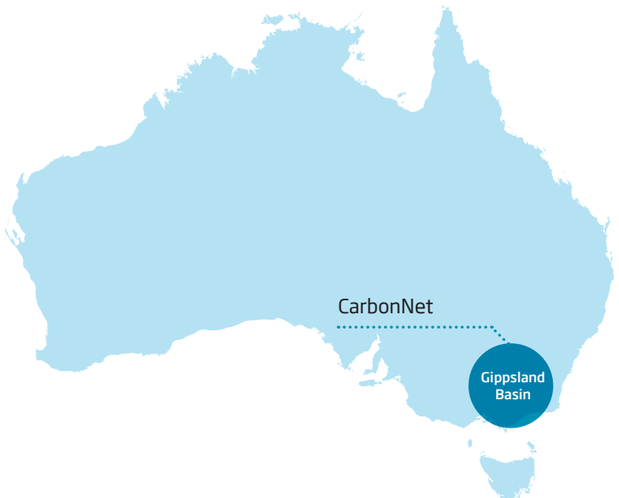
Reference

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

Gippsland Basin

Photo courtesy of CO2CRC

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

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*	● ● ●

Scale Key

- In lab
- In Field

Delivery Key

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

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

CASE STUDY

Marine monitoring for CCS will have to account for large natural variations.

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

Storage offshore at Sleipner and Snøhvit has been successful, but the monitoring techniques there focused on marine seismic, and did not fully investigate effects at the seabed or in the water column.

The project provides an assessment of some proposed techniques for this type of "shallow focussed" monitoring that may be used in offshore Gippsland. The methods considered may be useful for defining baselines and checking for some aspects of possible environmental impact. The study will inform the first phase of purchasing of marine monitoring assets, funded under the Commonwealth educational infrastructure funds (EIF), leading to more detailed investigation of their capabilities.

Existing expertise and databases in CSIRO Oceans and Atmosphere Flagship (O&A) have been used to assess the ability to measure the ingress of stored CO_2 into the water column, and to quantify the size and type of loss of containment at the seabed that could be detected. O&A has baseline data and experience, relevant to the likely storage areas, covering tide and current patterns, seasonal and spatial variations in seawater composition, instrumentation, and modelling. This report investigates some elements of a model monitoring programme, namely measurement of water chemistry, and acoustic mapping.

Key conclusions are:

» Water sampling, from a combination of fixed moorings and gliders, would be able to monitor a region of order 10 x 10 km^2 and detect a specific type of leak to the seafloor (point source, 10 kt/yr) anywhere in that area with high confidence and low false alarm rate. Leaks of this size are very unlikely and would probably be detected in other ways much earlier.

» Natural variability causes changes in water chemistry that are equivalent to much larger releases, so the main application of this type of monitoring would be to characterise the natural background ("baseline") and hence show that environmental impact (in the specific sense of acidification of the water over a large area) was negligible.

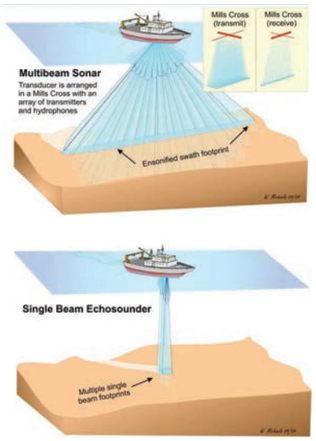
» Monitoring by acoustic methods is extremely sensitive to bubble streams. The background noise level (mainly biota) is very variable, but streams corresponding to only 10 t/yr should be readily detectable above environmental clutter with high confidence of low false alarm rates.

» Seafloor mapping will reveal a multitude of features of unknown provenance or duration, and this type of monitoring would have to be approached with an awareness of the need to control false alarm rates.

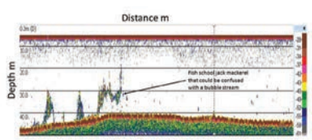
» Field assessment of the technologies described will be a priority for future work along with the collection of baseline datasets for potential storage locations along the Gippsland coast.

Reference

Hardman-Mountford, et al 2015, An initial study of the utility of some marine M&V methods for subsea CCS: Bass Strait Case Study (7-0314-0230)



Example of the operations of a multi-beam and single-beam echo-sounder for mapping the seabed and water column.



Example of 120 kHz Simrad EK 500 volume reverberation data in 40 m depth of a fish school located close to the sea floor. This feature may look similar to a low flow gas bubble stream and could only be verified with video or temporal sampling.

CASE STUDY

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.

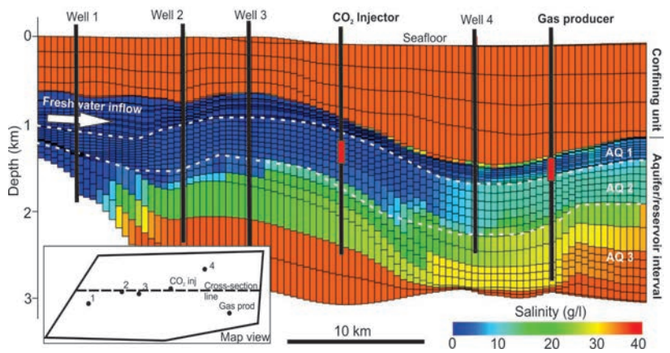
» Changes in formation water salinity occur mainly along the transition between freshwater and higher salinity water.

» 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 could provide 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.

CASE STUDY

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 is 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.

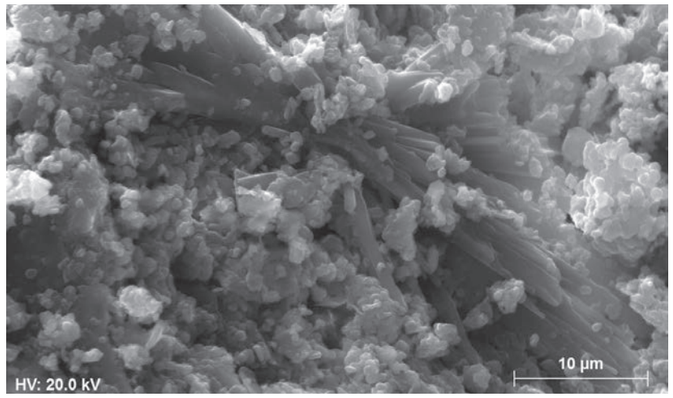
» Reduction of NMR signal after exposure to $scCO_2$ indicates that some of the waters inside the samples were reduced by CO_2.

» 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.

Reference

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



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

CASE STUDY

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 are:

» 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.

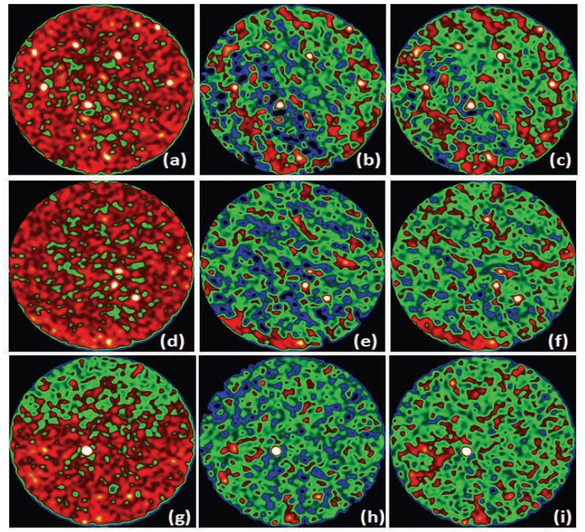
» Buoyancy forces during N_2 injection can reveal vertical pathways for subsequently injected CO_2 and therefore gain a better site characterisation.

» 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.

Reference

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



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.

CASE STUDY

Improved mapping of intraformational seals in the Gippsland Basin

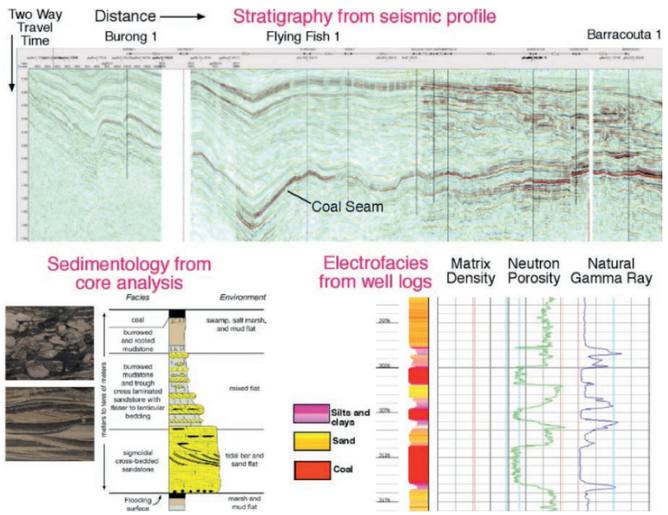
This project provides a detailed understanding of the stratigraphy and structure of the Latrobe Group, with particular emphasis on the seal lithologies within the unit (largely coal and shale).

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 is 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.



Methods of study: integrating seismic, well logs and core

Outcome:

» The single major outcome of this research project will be a better 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)

CASE STUDY

Interactions of CO_2 with Basal Coal Seams in the Gippsland Basin

This study characterises 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 uses 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 are available, a range of coals have been investigated in the project to identify the potential for consistent behaviour. Experiments have focused on available Victorian brown coals; however, these are lower in rank than the deeper intraformational coals. Coals of similar rank to that expected for the intraformation coals have been investigated. These coals are 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:

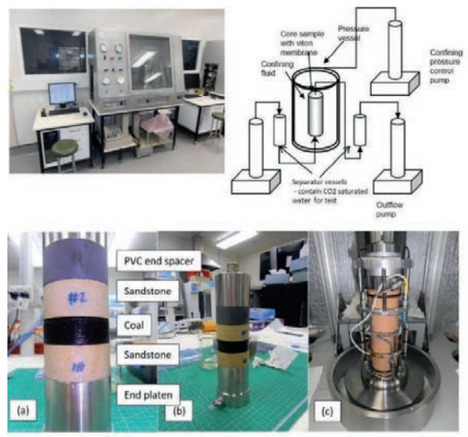
» Low rank Latrobe formation coals had relatively low entry pressures equivalent to a maximum CO_2 column height of 26m

» 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)

CASE STUDY

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 uses 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 will be 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 will be assisted by a number of Ocean Bottom Seismographs (OBS), which will be 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 will allow 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 utilizes an efficient and reliable data management system.

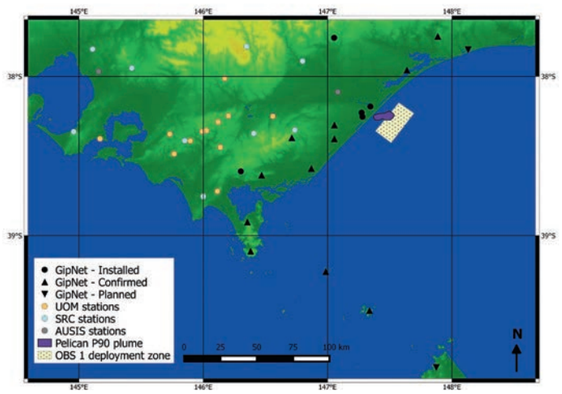
Key project outcomes:

» The development of protocols for optimising seismic monitoring in coastal regions where seismic noise, mainly caused by ocean waves, is 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

CASE STUDY

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 will investigate the nature, origin and biological significance of these 'channels'/ seabed features, initially from existing literature and datasets, with follow-up field survey. This investigation will provide novel insights into dynamic processes in the nearshore Australian seabed. Understanding links between these features and biotic communities will improve ecological understanding and assist conservation of these marine ecosystems. Understanding acoustic, visual and geochemical signatures associated with these features will inform baseline monitoring needs for potential future marine monitoring and verification (MM&V), and permit 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, have been identified; their location does not correlate with specific features on the seabed.

Hydrogeology

» There is 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 are characterised by high diversity, few common species and high spatial and temporal variability.

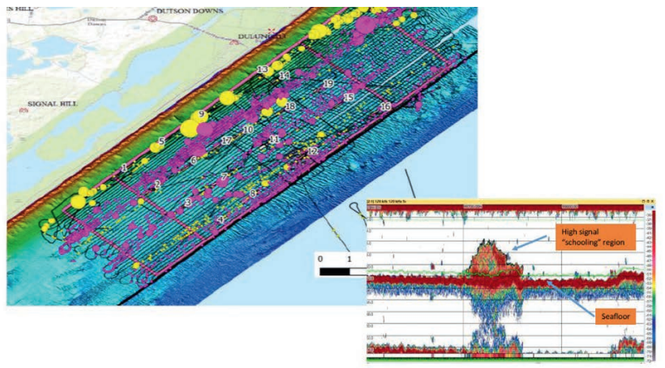
» The patchy, highly abundant and diversity in faunal assemblages also mean there is a need to find individual taxa or groups of taxa which can be shown to respond to elevated carbon dioxide (CO_2).

Outcomes:

» Determine the origin and composition of seabed features and produce an assessment of the nature of the seabed features identified and their associated biotic communities. This will inform the risk profile of CarbonNet operations and 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).

CASE STUDY

Configuring environmental marine monitoring in the Bass Strait focussed on CO_2 storage

Understanding the possible environmental impact of subsea CO_2 storage is a challenging task globally and especially in offshore Gippsland where there is high levels natural variability in marine conditions.

This project addresses three key technical challenges necessary for developing assurance monitoring approaches for subsea CCS operations:

- The "signal-to-noise" problem: distinguishing CO_2 release signatures from similar naturally-occurring variability to reduce detection false alarm rates in future baseline monitoring design.
- Characterising impact: determining the level of CO_2 release that would be associated with environmental impact at a range of scales.
- Attributing impact: distinguishing changes resulting from other drivers and pressures in multiple-use zones (e.g. climate change) from the activities of CCS operations.

Recognising this knowledge gap, the Commonwealth Education Investment Fund (EIF) funded the purchase of state-of-the-art equipment to investigate shallow-focused marine monitoring.

Project scope:

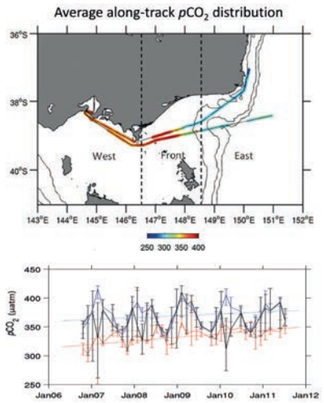
- Experimental investigation of optimal sensor configurations in a monitoring network design.
- Numerical investigation of 3D plume structure using a coupled hydrodynamic-carbonate system model.
- Investigation of natural variability in monitoring targets from by a network of sensors on fixed platforms (moored buoys, landers).
- Investigation of natural variability in monitoring targets from integrating autonomous vehicles with a fixed sensor network.
- Investigation of variability in biological indicators of environmental impact.
- Integration and synthesis.

Project outcomes:

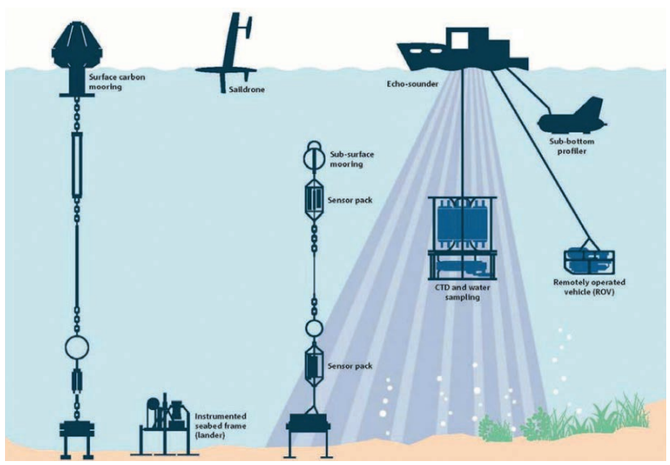
- Establishment of robust criteria, thresholds and approaches for assurance monitoring in shallow-coastal seas.
- Specifically, it will provide a framework for developing targeted and cost-effective baseline monitoring, making it simpler to address legislative and social licence imperatives, thereby accelerating progress towards storage demonstration.

Reference

A. Ross, et al 2017, Methodology to deploy shallow-focused subsea CCS technologies (7-0816-0305)



Bass Strait: climatology of CO_2 system and hydrology. Average along track CO_2 distribution (top) and spatially-averaged pCO_2 timeseries (bottom)



Gippsland monitoring network Marine

CASE STUDY

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

This project goal is 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, CH_4, 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 are realised by:

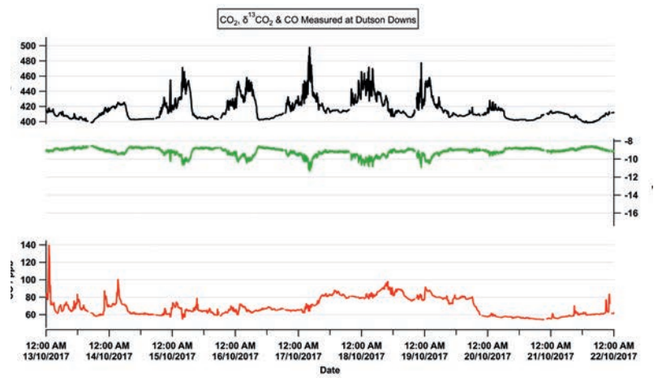
- assessing the spatial variability by deploying additional fixed and mobile *in situ* CO_2 measurements throughout the Gippsland Basin;
- combining these measurements with a high spatial and temporal resolution regional atmospheric model to incorporate the influences of topography and meteorology
-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

The desired outcomes of the project are:

- 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

CASE STUDY

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 studies 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 is 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 will be the main mineral reactions, leading to an increase in Fe^{2+} concentration (up to > 500 mg/L over 1000 years).

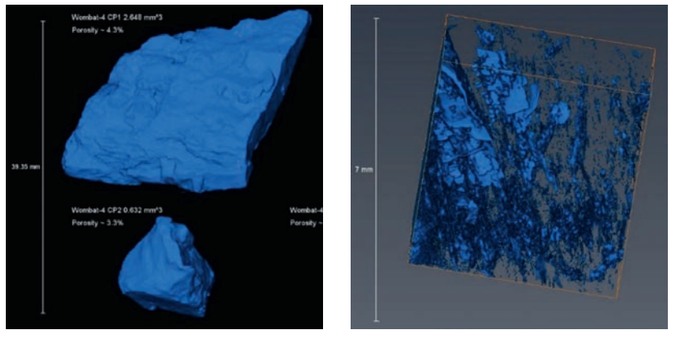
The release of Fe^{2+} is consistent with previous experimental work, which showed that Fe^{2+} was one of the most mobile ions and it was released from carbonates (such as siderite). Further, it was noted that water composition in S5 would stabilise within 5 years. Dissolution and precipitation of other 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). Top: porosity scanning of samples and Bottom: pore voids are not connected

CASE STUDY

Evaluating Alternative CO_2 trapping in the Gippsland Basin

To date, standard petroleum industry software has been used it 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 uses 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 is to estimate the size of the effects, providing insights on limitations on injection pressures.

Modelling approach:

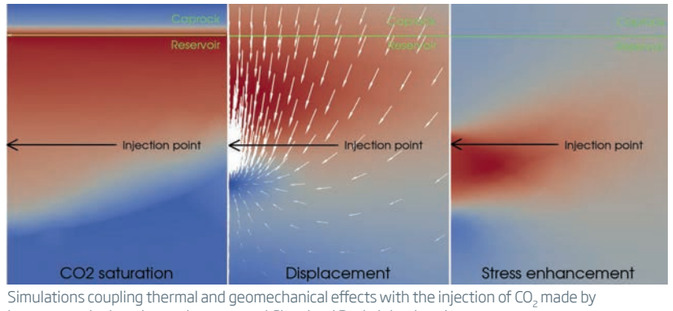
- Compare to simplified semi-analytical results.
- Extend to more realistic properties.
- Extend to more general geometry.
- Apply to specific conditions of Kookaburra site.
- Extended Model.
  - Realistic fluid properties, with dependence on temperature and pressure.
  - Radial thermal conductivity.
  - 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 is 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 is a thorough evaluation of the adequacy of the existing models being used within the Gippsland Basin for the candidate site. These results will then be 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

Otway Basin

CASE STUDY

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:

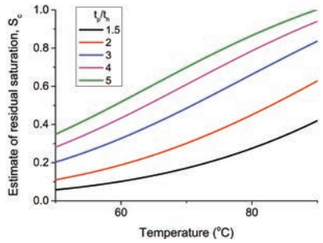
» The temperature dependent behaviour of the partition coefficients for a number of reactive ester tracers was determined. This information will lead to more accurate predictions of residual CO_2 saturation in instances where these chemical tracers are used for the single well chemical tracer test.

» 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.

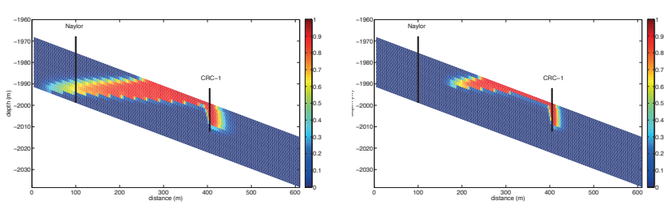
» Future work could include slim tube experiments packed with various sediments to experimentally determine the breakthrough curves for chemical tracers. This information could be used with future field studies to determine the possible influence that sorption onto sediment surfaces actually has on the 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.

CASE STUDY

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.

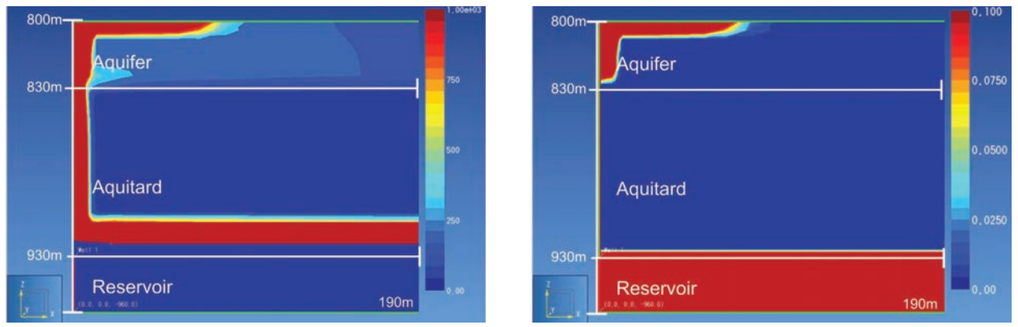
In this model, CO_2 was allowed to move via buoyancy from the storage reservoir into an overlying monitoring aquifer. With consideration for the minimum leakage criteria of carbon storage for climate abatement, a minimum detection limit (MDL) that a shallow groundwater monitoring system would have to 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 (top) and plume (bottom) after 10 years of flow.

CASE STUDY

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.

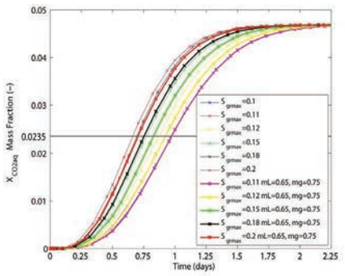
» Fluid sampling using the U-tubes was completed consistent with the test plan. The noble and organic tracers were added to the injection stream as planned and were measured during production stages at concentrations that were more than sufficient for analysis.

» 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.

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.

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)

CASE STUDY

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 aims 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 involves 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

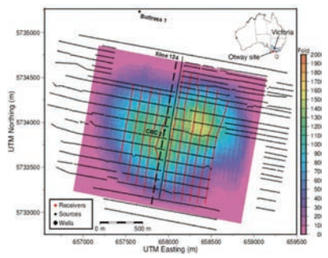
» Installing powered seismic recording facility in a dedicated container (Seismic Lab) in the vicinity of CRC-2 wellhead, to house the seismic and iDAS recording equipment.

More recently, the CO_2 injection phase and the first seismic survey were completed.

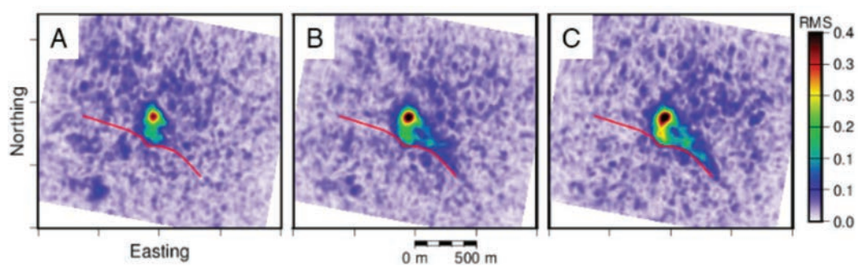
» The baseline survey was acquired in March 2015 followed by three monitor surveys in January, February , March and April 2016 after injection of 5, 10 and 15 kt of CO_2, respectively. Time lapse difference images show a clear anomaly localised around the injection well. The anomaly is initially approximately 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.

CASE STUDY

CO2CRC Otway Stage 3, Feasibility & Design

The CO2CRC Otway Stage 3's primary project objective is 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 current "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 are;

- 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 will ultimately act as the injector well for Stage 3.

Sub-Project 3. Site Appraisal (Otway 3 injection interval).
Analysed data from CRC-3 will 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 will 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 will be developed in which various measured mechanical properties are 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 uses digital core analysis and modelling techniques to develop a multi-scale workflow which consistently addresses the impact of small-scale geological heterogeneity on the static and dynamic rock properties.

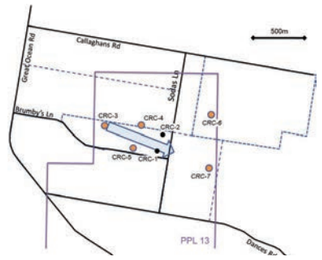
Sub-Project 7. Final Stage 3 Design, Long Lead Procurement and Approvals
This task completes the Define study for Stage 3, with the team finalising the basis of design (BOD) and Project Execution Plan from a technical and operational planning basis.

The outcome, after the successful completion of this Otway Stage 3 Evaluate and Define Project is 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 will pursue 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 will also be tested.

It is 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.

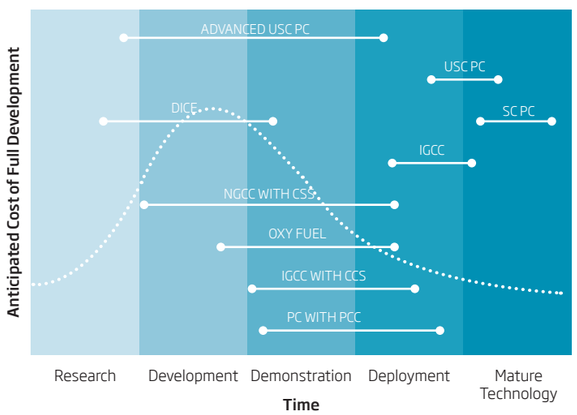
CO_2 Capture Processes

Photo courtesy of the Callide Oxyfuel Project

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 aims 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

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	○ ● ○
Post Combustion Capture	*Examine the nature and implications for the deportment of trace element species during oxy-fuel combustion at scale*	● ● ●
	Validate the environment performance of emissions and waste disposal from an amine post combustion capture process at commercial scale	● ● ●
Integrated Gasification Combined Cycle	*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	● ●
Techno-Economic Assessments	*Test innovative concepts to lower the cost of IGCC technology for application in Australian conditions*	● ●
	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

CASE STUDY

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 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 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 Points:

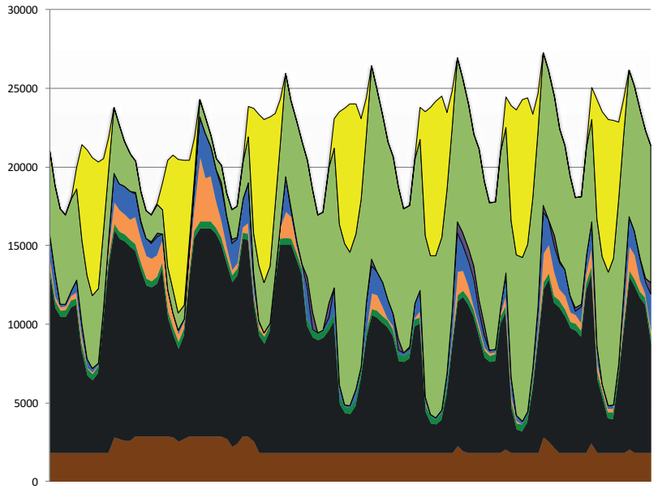
- Including energy supply, each energy technology brings with it a different set of grid services such as low emissions, inertia, frequency control, flexibility etc.
- The NEM is unique, compared with other international grid systems, as it consists of 5 state-based grids that are only weakly interconnected.
- 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:

- 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 HELE+CCS will be required to deliver the required resilience for grid stability. It can also deliver the deepest decarbonisation ambitions at lowest 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).
- In high renewables scenarios, the existing fossil-fuelled power plant (especially black coal) will have to become increasingly more flexible on a daily basis.

Reference

G. Bongers, et al 2016, The value of flexible and firm capacity in decarbonising Australian grids (1-0816-0288)



Modelled 7-day generation – high renewables scenario

CASE STUDY

Modelling Energy and Grid Services (MEGS) – continuing case studies

The objective of this work is to understand the short and medium-term impacts of the various State and Federal renewable targets.

The electricity grid in Australia is changing from a centralised coal-based generation system, to a grid with increasingly larger amounts of weather dependant wind and solar. Technology options, policy positions and societal expectations are all contributing to the changes taking place.

A project on Managing Flexibility Whilst Decarbonising Electricity – the NEM concluded:

- It is important to consider the whole system across all timescales to 2050 and beyond.
- A secure grid requires a range of essential services.
- The solution will be diverse.
- Providing reliable low emissions electricity comes at a cost.

More scenarios are required to explore the implications of renewable penetration on the NEM.

Implications of State Governments Emissions Reduction Policy

The work will look at the 2025 target for Victoria (40% renewable generation) and the 2030 target for Queensland (50% renewable generation) by running all combinations with and without those constraints. Other states will follow their specified renewable policies for all runs, except NSW which has no target.

MEGs Development for WA

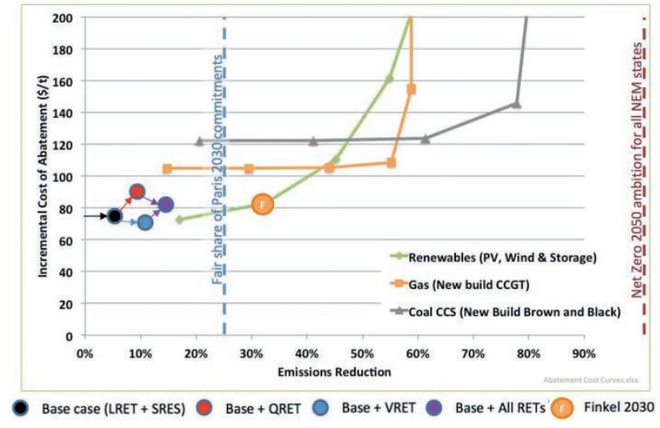
A MEGs model for the Western Australian South West Interconnected System (SWIS) will be developed built and delivered to ANLEC R&D. Development of the model will be undertaken in consultation with WA electricity generation expertise and stakeholders.

Outputs will include:

- Scenario modelling outputs including a base case
- Finkel 2030 and Finkel 2050
- Scenarios nominated with WA stakeholders.

Reference

G. Bongers, et al 2017, Modelling Energy and Grid Services (MEGS) – Continuing case studies (1-0917-0308)



Comparison of alternative decarbonisation pathways

CASE STUDY

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.

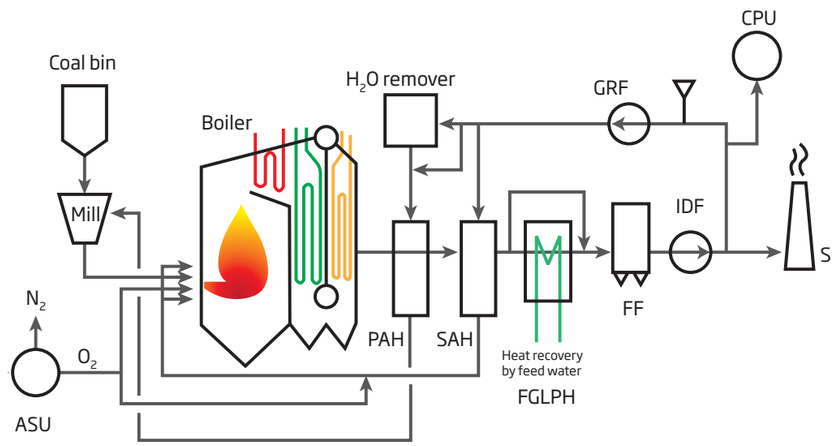
2004

» 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/Low Emission Technology Australia (LETA) 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

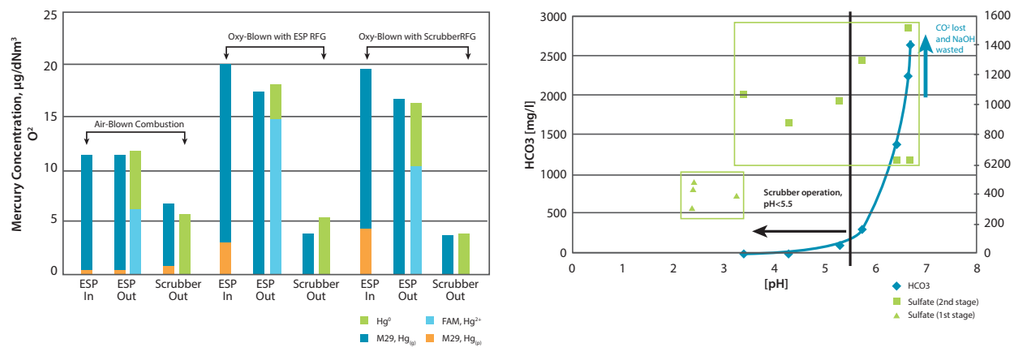
» It was found that gaseous mercury (Hg^0) in the flue-gas could be effectively removed using the carbon dioxide compression circuit during 'back end' carbon dioxide processing and may result in making a dedicated mercury removal unit redundant.

» 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.

CASE STUDY

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:

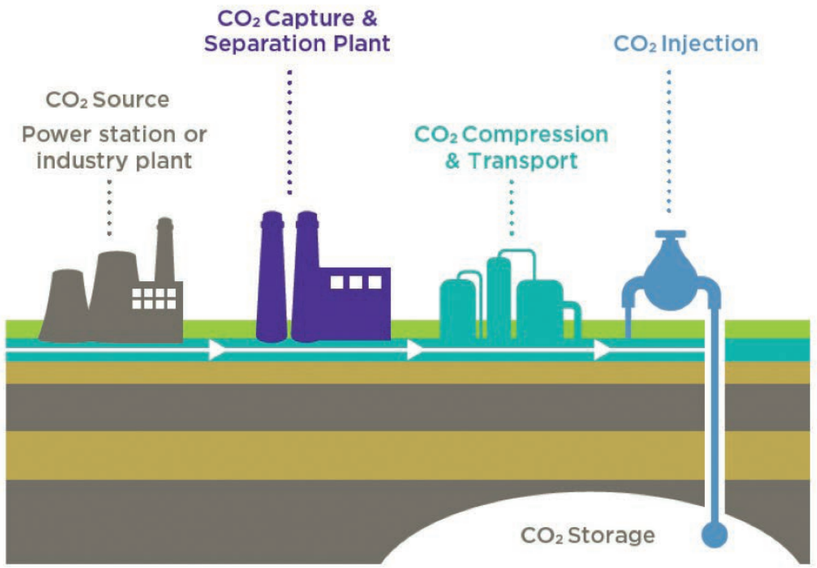
» recap the rationale for Australia to invest in CCS to meet energy security, decarbonisation and retention of our trade exposed industries in a low carbon economy;

» 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).

Reference

C. Greig, et al 2016, Development of a CCS roadmap for Australia (1-1115-0287)



What is CCS?

CASE STUDY

Pressurized 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 involves 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.

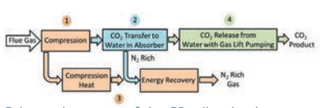
» Both systems require flue gas extraction from the main flue gas duct at the bottom of the stack and return of treated flue gas from the capture plant to main power plant stack.

» Apart from the flue gas interconnection, the main interface requirement of the aqueous system is the significant energy input required for flue gas compression.

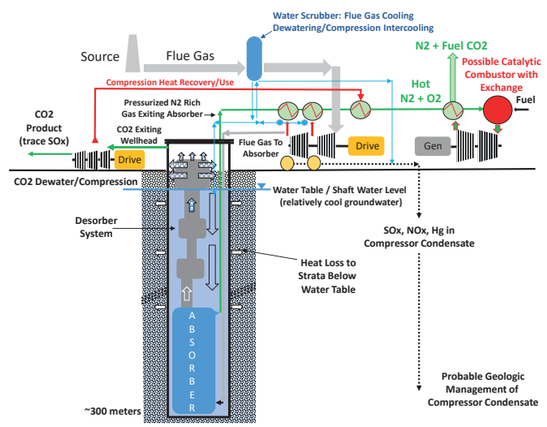
The ASPEN process simulations found that there were key design elements for successful application of the technology. One of these elements is the heat integration of the compression and expansion stages of the process. Optimised integration is necessary to minimise the parasitic power consumption of 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

CASE STUDY

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:

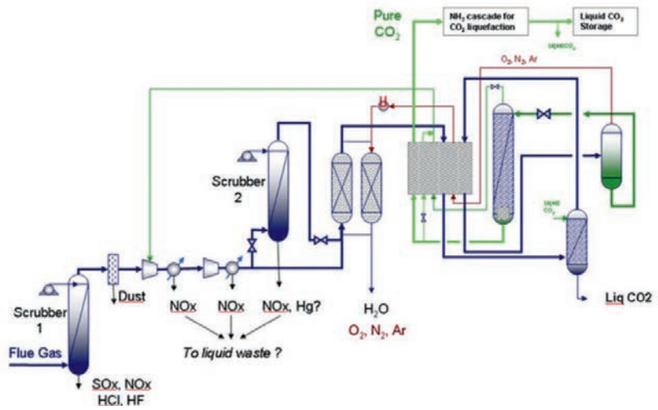
- pre-treatment of biomass such as bagasse to aid digestion in ethanol production,
- the recovery of rare earth elements from coal and ash wastes, and
- pre-treatment of ores used in mineral carbonation to improve their reactivity to form carbonates
- Higher acid concentrations are achieved for the acids 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.

Reference

T. Wall, et al 2015, Impurities in Oxy-fuel CO_2 compression: stability, disposal and utilisation (6-0215-0243)



Simplified schematic of Callide Oxy-Fuel CO_2 purification unit.

CASE STUDY

Environmental performance of Oxy-fuel technology rigoursly 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.

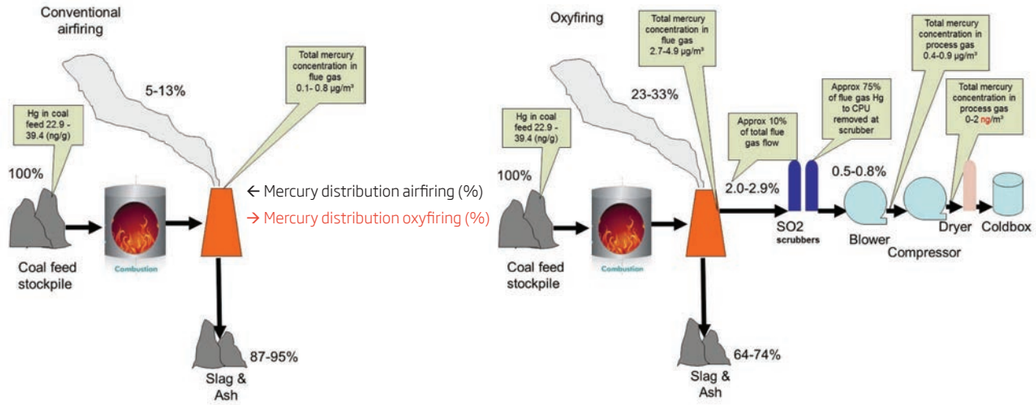
This study was based on a field experiment carried out at the retro-fitted *Callide A* power plant in December 2012. The power plant is capable of both oxy and air firing and the experiment involved both modes. Measurements were made of the trace metal and particulate matter emitted during the firing 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, SO_x 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)



CASE STUDY

Review of flue gas sulphur removal technologies at small scales

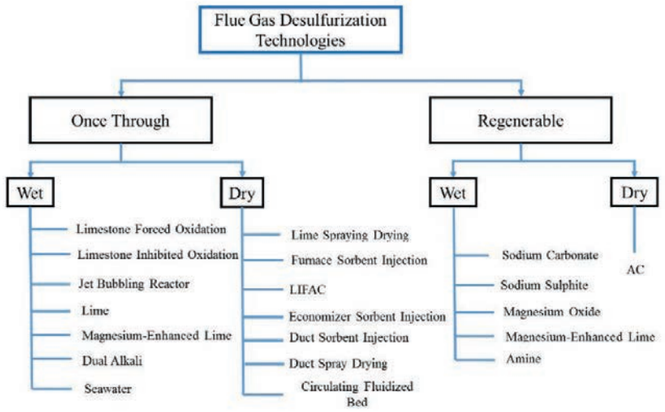
Sulphur removal from flue gas is well-established for commercial scale power generation. However, these are too expensive for low cost small scale deployment, where alternative technologies might appear.

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 has 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 will engage Huaneng CERI and CSIRO Energy Technology Australia.



Classification of available Flue-Gas De-sulphurization Technologies (FGD) technologies.

Reference

J. Yu, et al 2016, Scoping Study of technological options for SOx treatment (4-1115-0255)

Alternative Capture Concepts

CASE STUDY

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 current and novel solvents (some of these are still under early phase research and development).

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 will not only inform 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.

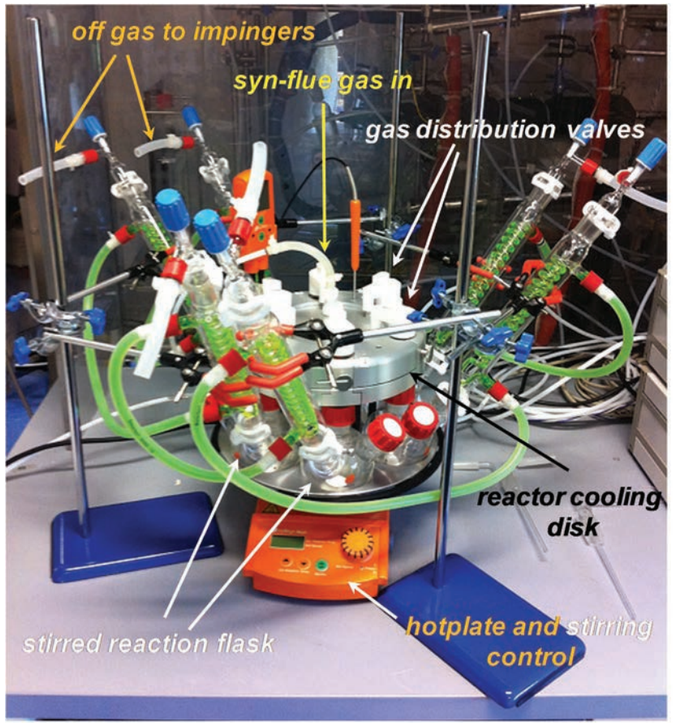
The two key solvents studied were:

» 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.



Carousel six-port reactor system used in the solvent degradation (ageing) experiments.

Reference

P. Jackson, et al 2013, Environmental Impacts of Amine based CO_2 Post Combustion Capture (PCC) Process (4-0910-0067)

CASE STUDY

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.

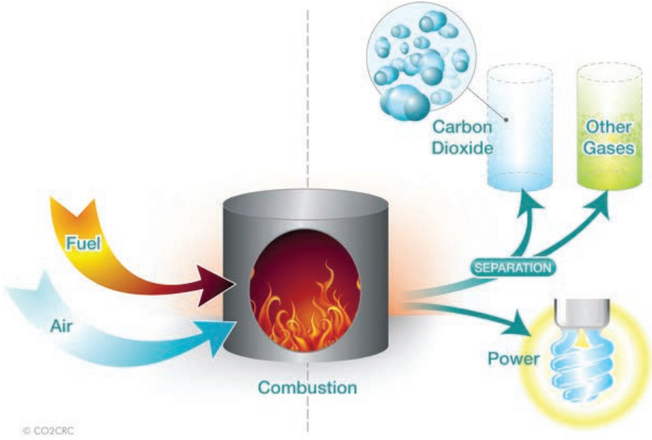
Air emissions from power plants must be compatible with the environment to be a long-term viable solution. Since the reduction of carbon dioxide emissions from fossil fuel power plants will require the application of new technologies, emissions from these technologies must be understood.

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.

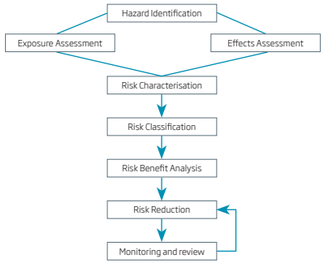
In this study a modelling framework for undertaking a risk assessment for population exposure to formaldehyde is described. The modelled results showed that after installing PCC technology there may be an increase in overall atmospheric concentrations of formaldehyde – however in all cases the increased 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 forms 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.

CASE STUDY

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:

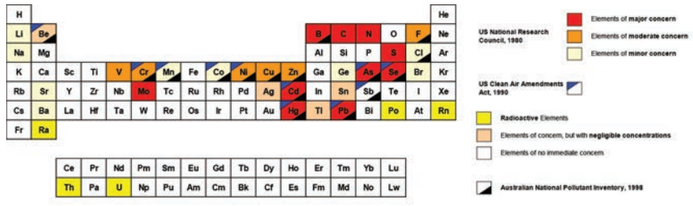
» Apart from mercury, the selected elements are mostly retained within the Acid Gas Scrubber (AGS), with very little carry-over into the ASE (absorber/stripper).

» 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

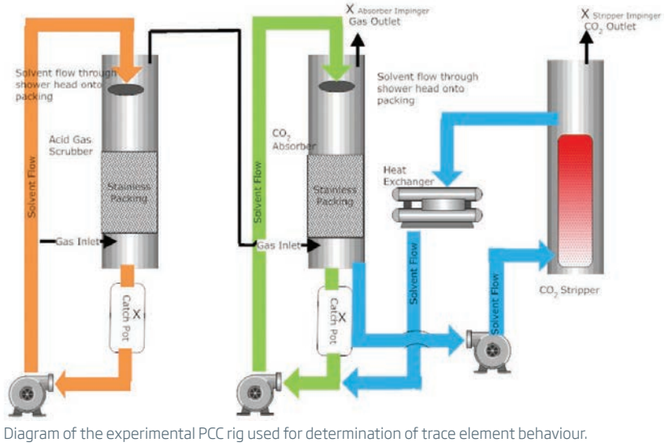


Diagram of the experimental PCC rig used for determination of trace element behaviour.

Reference

M. Azzi, et al 2013, Impact of Flue gas impurities in PCC plants (4-0411-0131)

CASE STUDY

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:

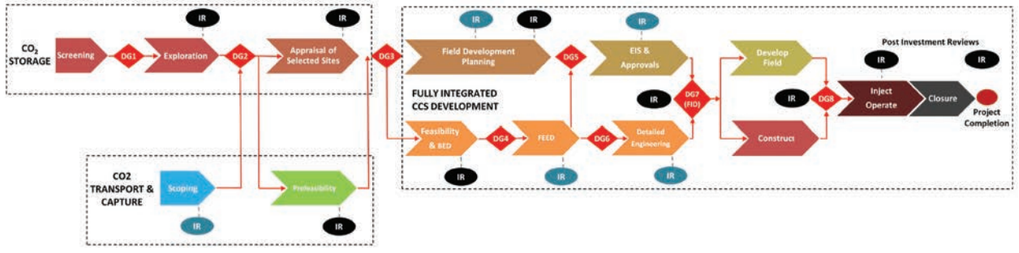
» Uncertainty and increase in cost estimates are typical in first-of-a-kind and early mover projects.

» 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.



Decision roadmap indicating main focus of investment decisions towards an integrated project.

Reference

C. Greig, et al 2014, Guidelines for scoping & estimating early mover CCS projects (1-0512-0205)

CASE STUDY

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.

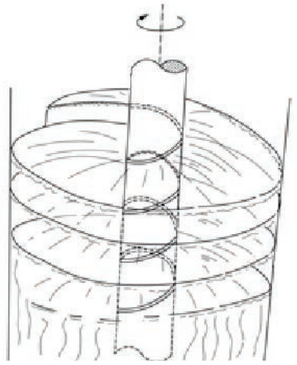
Overall capital cost savings are estimated to be approximately 30%, based on the elimination of the packing and the reduction in column diameter. Elimination of the flue gas blower provides a minor capital cost saving and, additionally, it provides the opportunity of a net reduction in electrical power 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)

CASE STUDY

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.

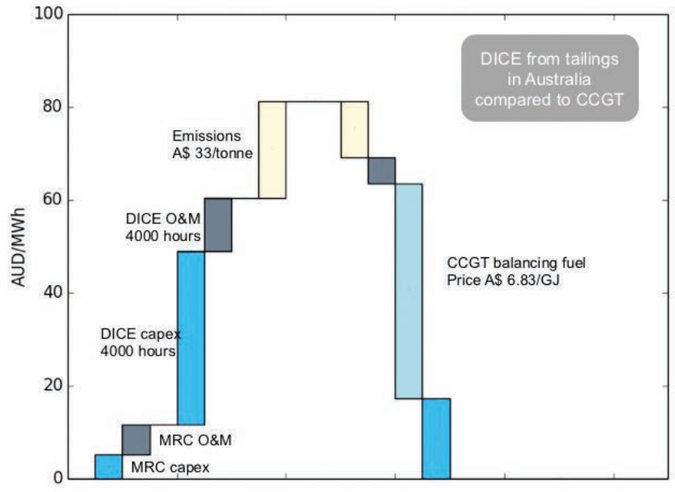
DICE emissions are lower than conventional pulverised coal technology. Carbon Capture and Storage (CCS) offers the possibility of deep emission reductions with the potential of reduced cost. The small modular nature of DICE may open the potential for a matched CCS module that can be manufactured in the 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 analyses 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.

CASE STUDY

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.

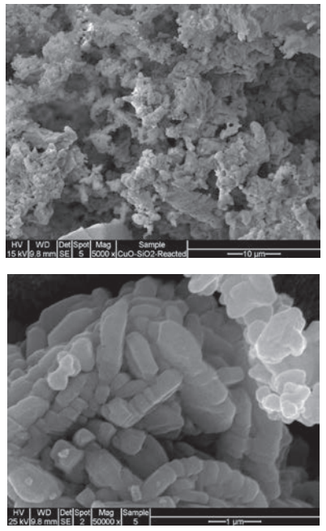
» Detailed assessments of scaling parameters for the reduction reactor were carried out by a combined set of theoretical analyses and mathematical modelling.

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.

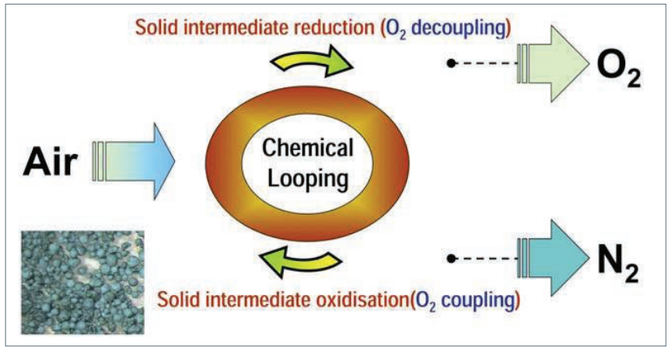
Consistent with most other low emissions technologies, the study suggests carbon pricing is necessary before such processes can become economically viable.

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

CASE STUDY

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.

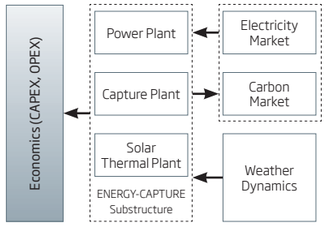
» Five possible operating modes were recognised and discussed in detail, to provide a clear perspective of the solar-thermal plant operation in this integrated process situation.

» 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.

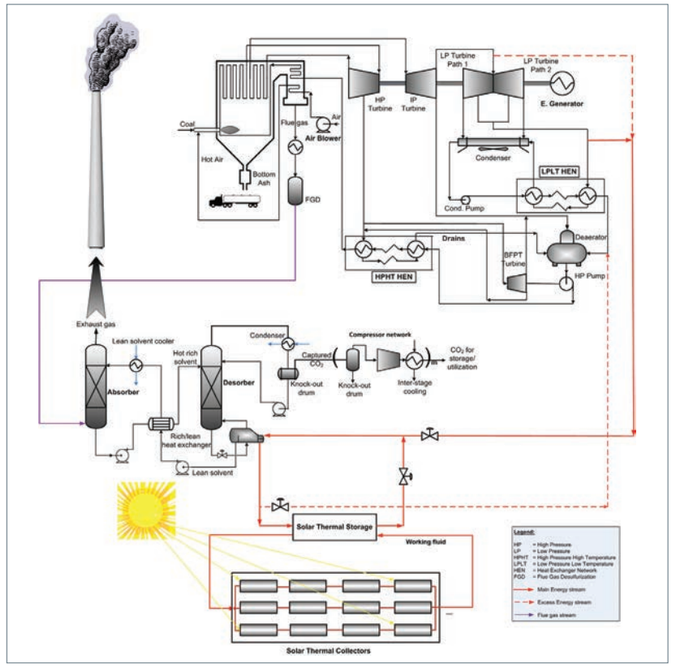
» Coal-fired power plants can operate sustainably in the future using carbon management systems built on model-based optimisation, such as the one proposed in this work, for flexible operation of PCC plants.

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.

CASE STUDY

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.

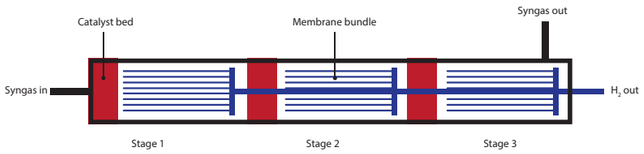
» A hydrogen flux of 0.4 mol m-2 s-1 at 400°C has consistently been achieved using Pd-coated vanadium tubing. This flux is independent of membrane thickness. Several hydrogen separation modules, up to 1000 cm^2 in total membrane area, have been fabricated and tested.

» 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 cm2 membrane module



Schematic diagram of multi-stage CMR with separate conversion and separation zones.

CASE STUDY

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 has implemented a concept testing program of research that has canvassed the best ideas for cost reduction to capture, in an Australian context of fuel, environment and grid systems. This wide ranging program has 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

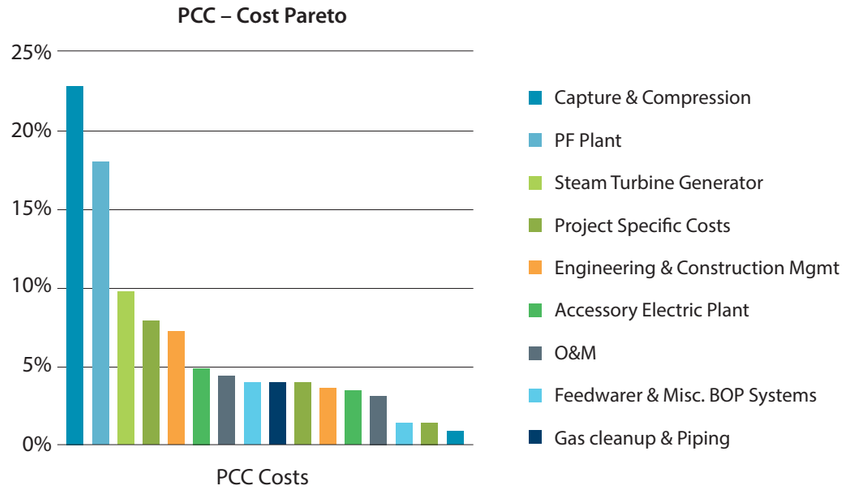
» Pilot-scale oxy-fuel combustion of Victorian brown coal

» Solids disposal and utilisation in IGCC

» Metal foam heat exchanger for dry cooling

Reference

Internal ANLEC R&D Research Portfolio



Australian CCS Research Services 2010–2018

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

Gorgon Project*
Commercial CO_2 injection project

**not ANLEC R&D related*

Callide Oxyfuel Project

CTSCo

LETA

Queensland University of Technology

Stanwell Corporation

University of Queensland

Curtin University

SW Hub

WA ERA

CSIRO

University of Western Australia

WA DMP

Macquarie University

University of Newcastle

Coal Innovation NSW

University of Sydney

University of NSW

University of Adelaide

FEI Canberra

Australian National University

Department of Industry & Science

Geoscience Australia

**not ANLEC R&D related*

CO2CRC

Global CCS Institute

University of Melbourne

Monash University

Otway – CO2CRC

CarbonNet

ACI

anlecr&d

anlecr&d

For further information please contact:

Dr Noel Simento
Managing Director
E: admin@anlecrd.com.au

PO Box 3391
MANUKA
ACT 2603

www.anlecrd.com.au

This publication is supported by

Australian Government
Department of Industry, Science, Energy and Resources

The Australian Government Department of Industry, Science, Energy and Resources through the National Low Emission Coal

LETA
Low Emission Technology Australia

An Initiative of the Australian Coal Industry