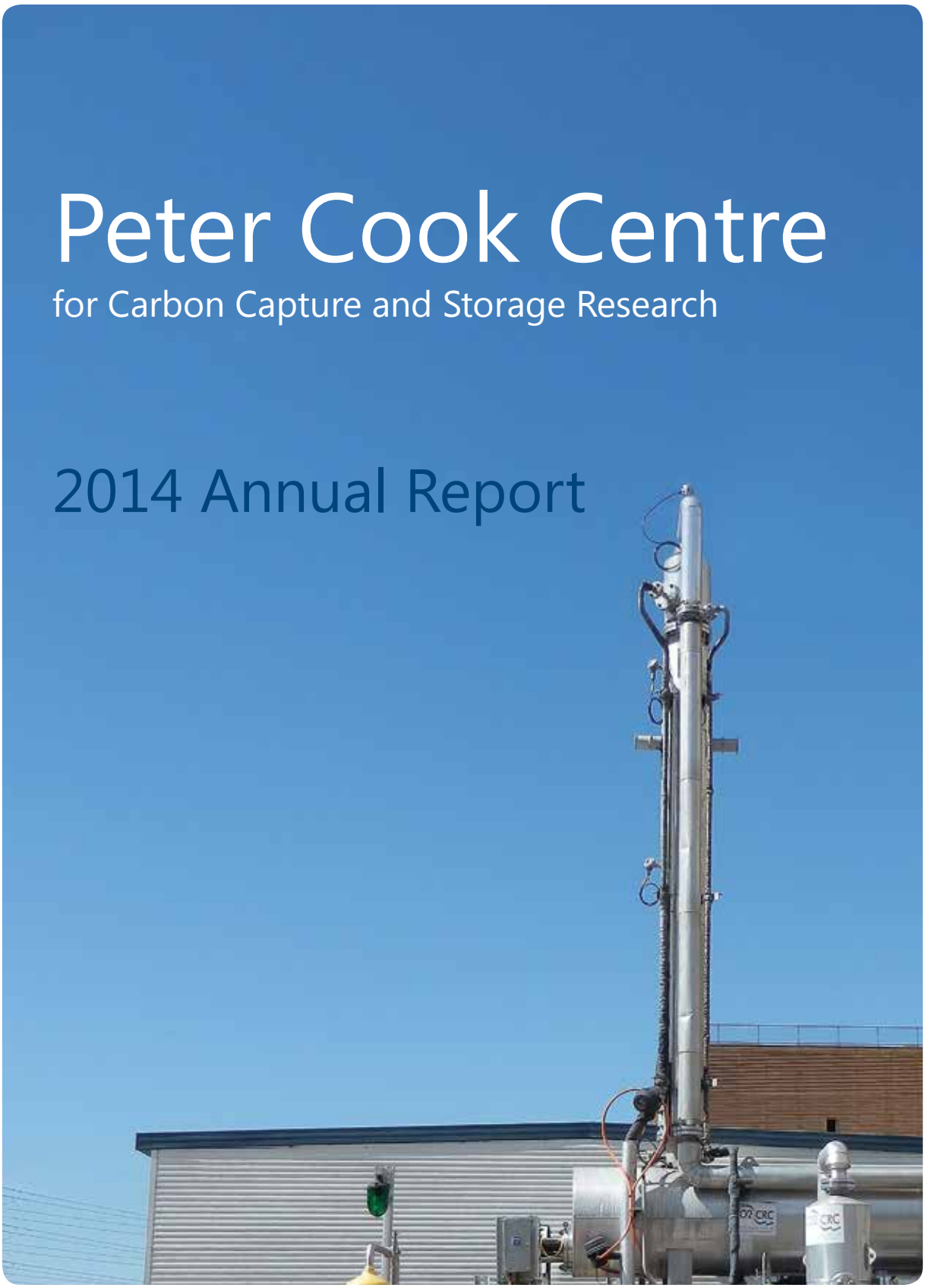
Peter Cook Centre

for Carbon Capture and Storage Research

2014 Annual Report



THE UNIVERSITY OF MELBOURNE

Overview

The Peter Cook Centre for Carbon Capture and Storage (CCS) Research is a world class research centre based at the University of Melbourne. The research we perform underpins the development of enhanced technologies for carbon capture and storage in Australia. Working closely with our partners from industry, government and academia the Centre's outputs will provide the foundation for future commercial investments in CCS by delivering the next generation of skills, and research and development services.

Mission statement

To develop environmentally and socially acceptable, cost effective carbon capture and storage solutions for a carbon constrained world.

Vision

The development of scientific and engineering expertise and personnel in Australia to enable the deployment of advanced carbon capture and storage technologies, thereby contributing to the nation's economic, environmental and social well-being.

Front Cover: Centre researchers have access to state of the art demonstration facilities such as the industrial-scale carbon capture pilot plant at GDF SUEZ Australian Energy Hazelwood Power Station, Victoria.

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Director's Report

The Peter Cook Centre for Carbon Capture and Storage Research is a cross-faculty, collaborative research centre at the University of Melbourne. Our focus is the development and application of carbon capture and storage (CCS) as key technologies for greenhouse gas remediation and control in a carbon constrained world. Our work is organised into two main programs which have significant overlap. The Capture Program is focused on the development of technologies to capture CO_2 from a range of industrial sources and to look at opportunities to utilise that CO_2. We are particularly focused on reducing the cost and environmental impact of CO_2 capture and the program is focused around solvent, membrane and adsorption systems for capture. The Storage Program is focused on developing a deeper understanding of the CO_2 storage process in subsurface structures with the aim of reducing storage risks.

We were set up with the generous support of Rio Tinto, the Victorian Government Department of State Development Business and Innovation (DSDBI) and the Cooperative Research Centre for Greenhouse Gas Remediation (CO2CRC) to ensure a centre of excellence in Australia that is competitive and recognised in the international arena in the field of CCS research.

2013 was our first year of operation, although our work builds on a decade of research in this area through the CO2CRC. In 2014 we have concentrated on growing our links with companies and government organisations interested in carbon capture and storage. For most of this year Shelley Reed has been helping us with business development.

One of the highlights this year is the development of our new carbon capture and storage laboratories at the University of Melbourne. This was made possible through an Education Infrastructure Fund grant and injects over $12M of infrastructure into our research effort. This fund was obtained through the CO2CRC and support from our sponsors. Also the technology for carbon capture based around the precipitating carbonate system UNO, which we believe has significant potential, has been taken up by Barry Hooper in a small spin out company for commercialisation.

We welcome Barry Hooper as an Associate of the Peter Cook Centre. In addition, Professor Michael Crommelin, the ex-Dean of Law at the University of Melbourne and very active in energy and resources law has joined the Peter Cook Centre to help us with legal issues associated with carbon capture and storage.

Centre Performance Highlights

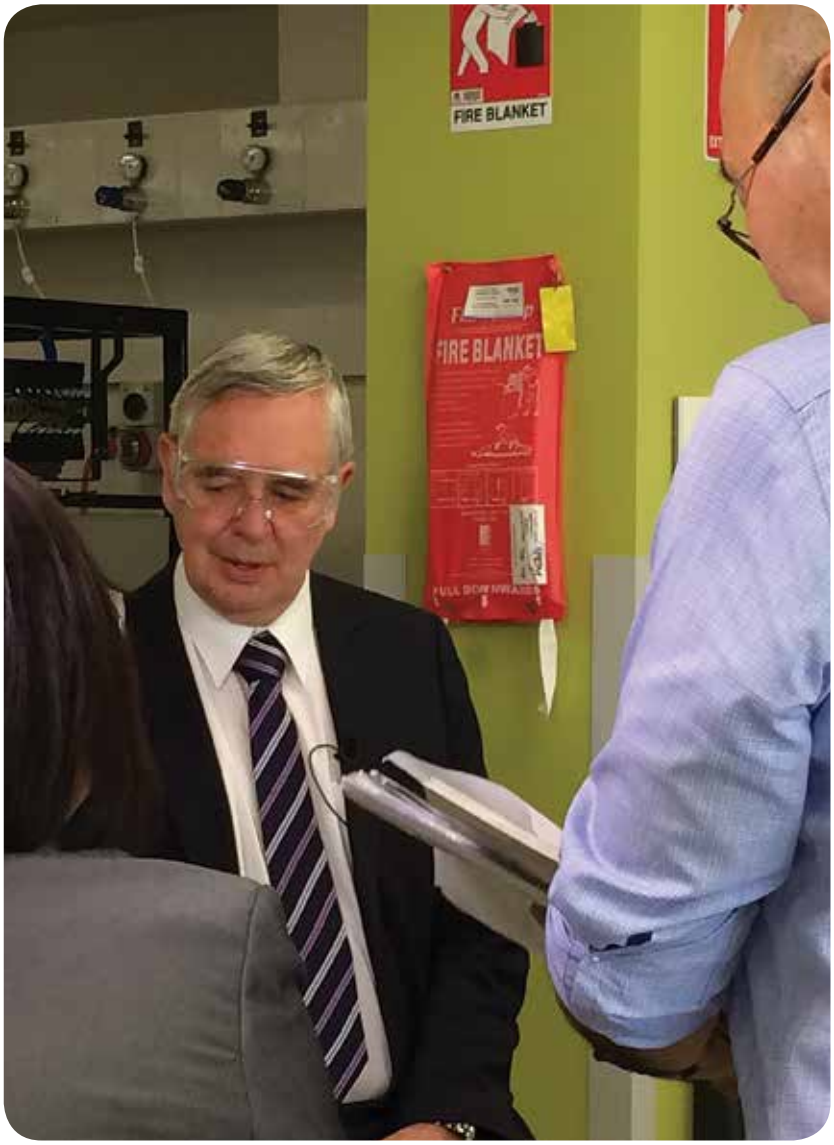
In 2014 we published 34 articles in peer reviewed journals, one edited book and one book chapter. Our researchers have a high profile at national and international conferences on carbon capture and storage with over 85 presentations at conferences, four of these were Keynote and Plenary Lectures and 8 invited presentations.

Education and Training

In 2014 we had 21 postgraduate students and 7 early career researchers actively involved in carbon capture and storage research. They form the basis for the next generation of scientists and engineers knowledgeable in this area.

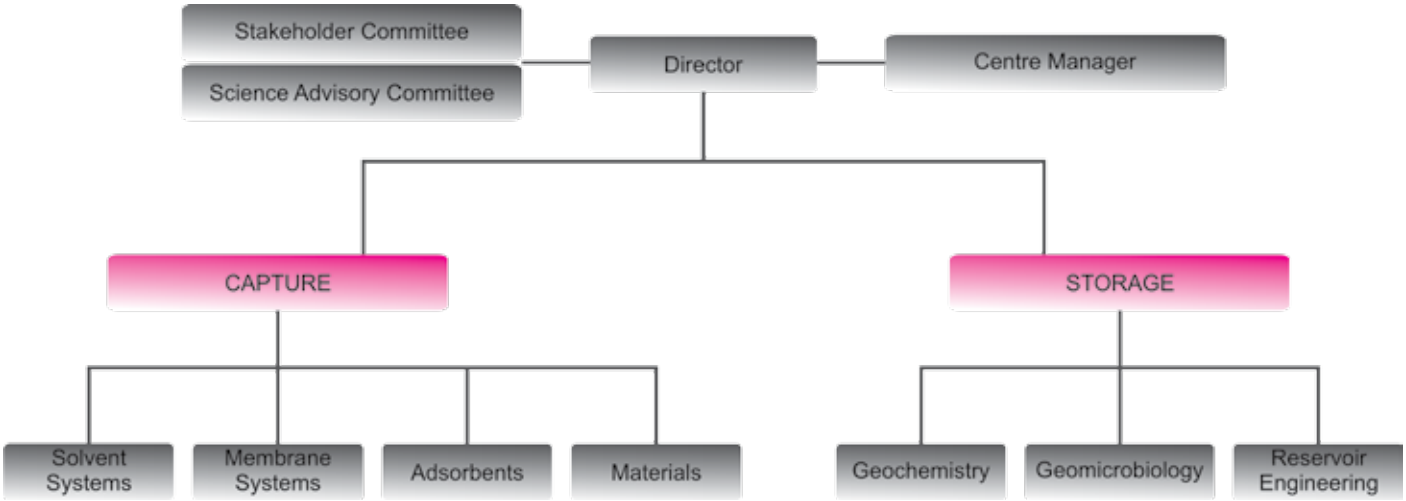
On behalf of the members of the Peter Cook Centre for CCS Research, I would like to thank the University of Melbourne, the CO2CRC, the State Government of Victoria and Rio Tinto for their financial support and valuable input to our Stakeholder Committee and Science Advisory Committee.

Laureate Professor Geoff Stevens
Director



Professor Geoff Stevens was filmed for inclusion in a documentary for the NHK Enterprise (NEP). NEP is an affiliated company of NHK (Japan Broadcasting Corporation). See p 23 for details.

Management Structure and Personnel



Stakeholder Committee

The Stakeholder Committee comprises representatives from Rio Tinto, the Victorian Government Department of State Development, Business and Innovation, the CO2CRC and the University of Melbourne. The committee meets twice a year to receive updates on the Centre's activities and provide feedback to the Centre Director.

Dr Malcolm Garratt (Chair)
Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Dr Richard Aldous
CEO
Cooperative Research Centre for Greenhouse Gas Technologies, Australia

Mr Manjula Antony
Manager, Research & Development
Department of State Development, Business and Innovation, Australia

Professor Peter Cook
Principal Advisor, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Dr Jon Davis (until October 2014)
Chief Advisor, Energy and Climate Technology
Rio Tinto, Australia

Mr John Krbaleski
Director, Energy Technology and Innovation
Department of State Development, Business and Innovation, Australia

Professor David Phillips
Head, School of Earth Sciences
The University of Melbourne, Australia

Mr Alex Zapantis (from October 2014)
Principal Adviser, Product Stewardship
Rio Tinto, Australia

Invited attendees:
Professor Geoff Stevens
Director, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Dr Michelle de Silva
Manager, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Professor Ralf Haese
Storage Program Leader, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Ms Shelley Reed
Business Development Manager, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Ms Franca Tomaras (Committee Secretary)

Science Advisory Committee

The Science Advisory Committee (SAC) is an expert panel providing overarching advice on storage and capture research programs, monitoring progress of research and providing a vehicle for advice on other associated aspects of CCS deployment. The committee is comprised of a variety of experts with a primary focus on carbon storage, but will be expanded to cover those priorities as directed and endorsed by the stakeholder committee.

Dr Malcolm Garratt (Chair)
Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Professor John Burgess
Principal
Niche Tasks, Australia

Professor Peter Cook
Principal Advisor, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Dr Jon Davis (until October 2014)
Chief Advisor, Energy and Climate Technology
Rio Tinto, Australia

Dr Clinton Foster
Chief Scientist
Geoscience Australia, Australia

Mr Geoff Gay
Senior Manager, Corporate Strategy & Development
Energy Australia, Australia

Professor Frank Larkins
Professor Emeritus
The University of Melbourne, Australia

Dr Matthias Raab
Program Manager Geological Carbon Storage
Cooperative Research Centre for Greenhouse Gas Technologies, Australia

Professor Jim Underschultz
Chair of Petroleum Hydrodynamics
The University of Queensland, Australia

Mr Alex Zapantis (from October 2014)
Principal Adviser, Product Stewardship
Rio Tinto, Australia

Invited attendees:
Professor Geoff Stevens
Director, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Dr Michelle de Silva
Manager, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Professor Ralf Haese
Storage Program Leader, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Ms Shelley Reed
Business Development Manager, Peter Cook Centre for CCS Research
The University of Melbourne, Australia

Ms Franca Tomaras (Committee Secretary)

Science Advisory Committee - International Group

The International Group is associated with the SAC and comprises established and respected CCS experts who can offer advice and guidance from the international perspective. For practical reasons, the international group is engaged as a virtual network, communicating by email and video conference as appropriate.

Dr Karl Gerdes
Consultant
Davis, California, USA

Kevin Dodds
Lead Geological Integrity & Monitoring
BP, Houston, Texas, USA

Professor Sally M. Benson
Director, Global Climate and Energy Project
Stanford University, California, USA

Research Program Leaders

Capture Program Leader, Professor Geoff Stevens

Solvent Systems
Research Leader: Professor Geoff Stevens

Membrane Systems
Research Leader: Professor Sandra Kentish

Adsorbents
Research Leader: Professor Paul Webley

Materials
Research Leader: Professor Greg Qiao

Storage Program Leader, Professor Ralf Haese

Geochemistry
Research Leader: Professor Ralf Haese

Geomicrobiology
Research Leader: Dr John Moreau

Reservoir Engineering
Research Leader: Professor Stephan Matthäi
(Appointed 2014; commencing in 2015)

Legal and Social Policy Program Leader, Professor Michael Crommelin

Centre Manager

Dr Michelle de Silva

Centre Researchers

Research Scientists and Engineers

Dr Jay Black
Dr Gabe da Silva
Dr Qiang Fu
Dr Paul Gurr
Dr Shinji Kanehashi
Dr Andrew Lee
Dr Josephine Lim
Dr Kathryn Mumford
Dr Nathan Nicholas
Dr Berkay Ozcelik
Dr Colin Scholes
Dr Jin (Eric) Shang
Dr Ranjeet Singh
Dr Kathryn Smith
Dr Penny Xiao

Research Assistants

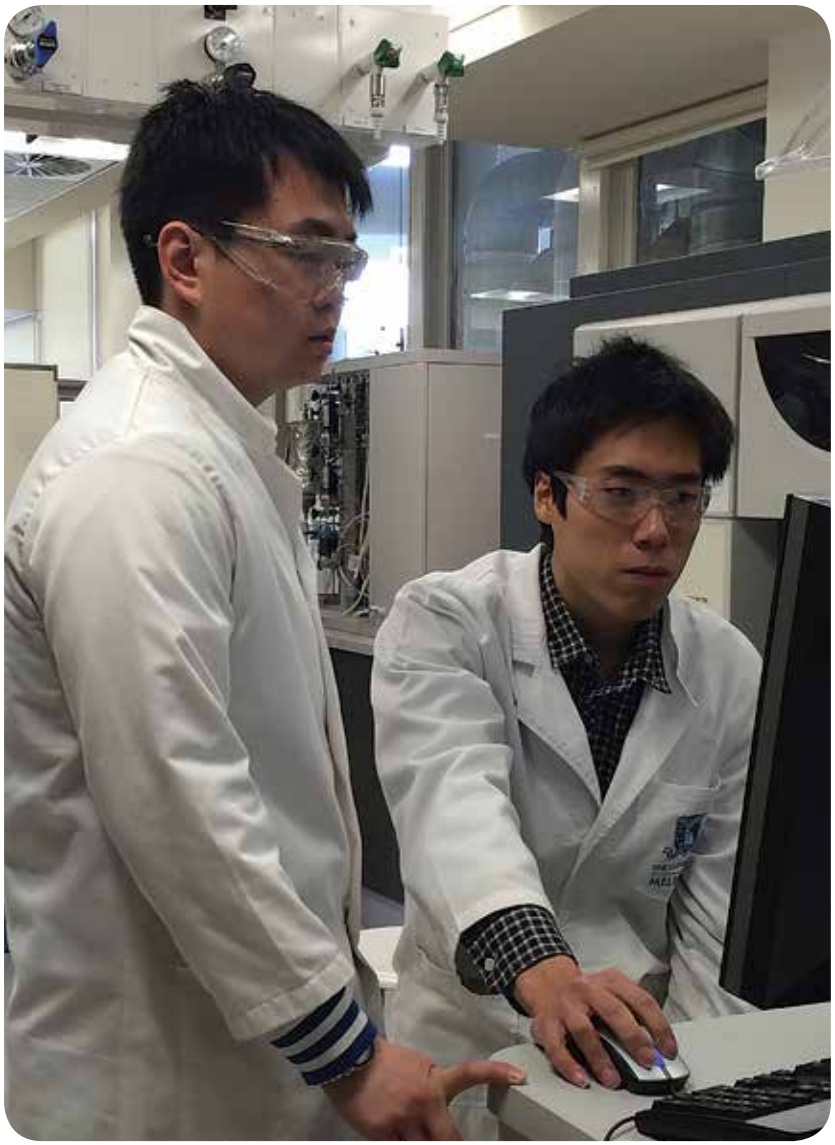
Ms Alita Aguiar
Mr Jeffri Gouw
Mr Indrawan Indrawan

Postgraduate Students

Mr Syed Anas Ali
Ms Hirra Azher
Mr Cesar Castaneda
Mr David Danaci
Mr Andri Halim
Mr Guoping Hu
Mr Jinguk Kim
Mr Hiep Thuan (Bill) Lu
Mr Brian Maring
Mr Nouman Mirza
Mr Andre Mu
Mr Augustine Ntiamoah
Ms Nasim Pour
Mr Joel Scofield
Mr Willie Tang
Mr Hendy Thee
Mr Yue (Frank) Wu
Mr Ke Xie
Mr Joel Yong
Mr Qinghu Zhao
Ms Qi Zheng

Associate

Mr Barry Hooper



Postgraduate student Yue (Frank) Wu (left) working with research assistant Indrawan Indrawan (right).

Research Program Highlights

Capture Program

The primary aim of the Capture Program is to reduce the cost of carbon dioxide (CO_2) capture from a range of sources including coal and gas fired power stations, from steel and cement production, as well as removal of CO_2 from natural gas. The program is also focused on the environmental impact of this technology and the lifecycle of materials used in any applicable processes. We are interested in exploiting the captured CO_2 and have a portfolio of projects examining utilisation strategies.

The program is focused around four technologies, solvent systems, membranes and materials, and adsorption. All of these have application in specific areas and research is being undertaken across a spectrum of work, from the fundamental through to demonstration in operating plants.

Solvent Systems

Understanding the kinetics of carbon dioxide absorption

Guoping Hu, Nathan Nicholas, Sandra Kentish, Geoff Stevens

Carbon dioxide emission is recognised as a significant driver for climate change. Carbon capture and storage (CCS) is an efficient and effective way to significantly reduce carbon dioxide in the atmosphere. Before CCS can be deployed on a large scale, the cost of capture needs to be reduced (currently 0.03-0.09 US$/kWh). Several methods for capturing carbon dioxide such as absorption, adsorption, membrane, cryogenic separation and the combination of some of these techniques have been proposed, of which absorption is one of the most promising methodsfor industrial utilisation today.

Solvents (including monoethanolamine, ammonium, amino acid salts, ionic liquids, and their blends) have been used for carbon dioxide absorption research for a long time. However, there are still some difficulties in their industrialisation. Potassium carbonate is another good solvent for carbon dioxide capture because of its low regeneration energy, low degradation and corrosion. A shortcoming of potassium carbonate is its slow kinetics. The most efficient method for improving absorption kinetics is adding promoters like amines, arsenate, amino acids, boric acid, carbonic anhydrase and vanadium. Current promoters are not attractive as they exhibit certain undesirable qualities, such as poor performance, high cost and high toxicity. This project is focused on studying the performance of more efficient, environmentally friendly, economically acceptable promoters.

CO_2 capture using deep eutectic solvents (DES)

Nouman Rafique Mirza, Nathan Nicholas, Geoff Stevens

Deep eutectic solvents (DES) are novel solvents with multiple applications. Advantages of these solvents lie in their ability to be biodegradable, non-toxic in nature, non-flammable, having negligible vapour pressure, low price and easy manufacturing with high purity. To develop thermodynamic models involving these solvents, their critical properties have to be estimated. To achieve this, a combination of modified Lydersen-Joback-Reid method and Lee-Kesler's mixing rules has been applied to estimate the critical properties of 33 different deep eutectic solvents. Normal boiling temperatures and acentric factors have also been determined. The accuracy of the method has been tested by making independent estimates of densities (based upon estimated critical properties) and comparing these with published literature values. Deviation from 0.0% to 15.3% has been observed for estimated density values. An overall absolute deviation of 4.4% is observed for the whole range of studied DESs. Maximum deviation is observed when DESs contain one or more aromatic components. The method gives satisfactory results for deep eutectic solvents resulting from different molar ratios of same precursors. It also takes into account the temperature variation of estimated densities and gives reasonable results. Experiments on vapour-liquid equilibria (VLE) of various DESs-CO_2 systems are also being conducted in the laboratory, which will enable the determination of Henry's constant.

Pilot plant testing of a precipitating potassium carbonate process for CO_2 capture

Kathryn Smith, Indrawan, Jeffri Guow, Kathryn Mumford, Nathan Nicholas, Andrew Lee, Sandra Kentish, Trent Harkin, Abdul Qader, Clare Anderson, Barry Hooper, Geoff Stevens

A precipitating potassium carbonate (K_2CO_3) based solvent absorption process has been developed for capturing CO_2 from industrial sources such as power plant flue gases. Demonstration of this process has been completed using both a laboratory based pilot plant located at the University of Melbourne and an industrial pilot plant located at Hazelwood Power Station in Victoria, Australia. The laboratory scale pilot plant has been designed to capture 4 - 10 kg/hr of CO_2 from an air/ CO_2 feed gas rate of 30 - 55 kg/hr. The power station based pilot plant has been designed to capture up to 1 tonne / day of CO_2 from the flue gas of a brown coal fired power station. Trials have been completed with both pilot plants using solvent concentrations ranging from 20 to 45 wt% K_2CO_3 with and without rate promoters. Performance data collected from each pilot plant has been collected over a range of operating conditions and then used to validate and further develop Aspen Plus simulations for this process.

Rate based modelling of precipitating absorption columns in carbon capture

Yue Wu, Kathryn Mumford, Sandra Kentish, Geoff Stevens

The use of potassium carbonate (K_2CO_3) solvent in carbon dioxide (CO_2) capture processes, especially for removing CO_2 from flue gases in coal-fired power plants, has gained momentum in recent years. CO_2 absorption efficiency can be improved by using higher K_2CO_3 concentration, and simultaneously the precipitation of potassium bicarbonate ($KHCO_3$) at higher K_2CO_3 concentration will reduce the solvent circulation rate thus lowering the cost on solvent regeneration equipment and regeneration energy. However, due to systematic stability and operating difficulties, the concentration of K_2CO_3 solvent was limited below 30 wt% by industry to avoid the precipitation phenomena during the CO_2 capture process. While the kinetics in low K_2CO_3 concentration solvent for CO_2 capture process has been studied extensively using experimental and numerical techniques, studies of high K_2CO_3 concentration with precipitation have drawn more attention recently.

This study conducts a review of high K_2CO_3 concentration based CO_2 absorption processes, along with a kinetics study on the $KHCO_3$ precipitating process including crystal nucleation rate and growth rate. In addition, modelling and simulation of CO_2 capture based on high concentration of K_2CO_3 solvent has been investigated and studied using an ENRTL model on the CO_2-K_2CO_3-$KHCO_3$-H_2O Vapour-Solid-Liquid-Equilibrium (VSLE) system. The model and simulation could further support the high concentration of K_2CO_3 based solvent system with a range of promoters, which provides guidelines on how to overcome operational instability and operating issues in pilot plants and industries.

Membrane Systems

Development of novel mixed matrix membranes for CO_2 capture
Shinji Kanehashi, Sandra Kentish
Recent interest in environmental problems is focused on global warming induced by carbon dioxide (CO_2) emissions from large fixed sources such as power plants and iron foundries. Membrane-based CO_2 capture is an advantageous technology because of its low energy requirement, ease of maintenance and compact design. In these applications, chemical stability, thermal resistance and high gas permeability and selectivity are desirable characteristics.

Mixed matrix membranes (MMMs) combine the benefits of both polymer and inorganic fillers and have become attractive materials for gas separation in recent years. In the present study, MMMs consisting of the commercial aromatic polyimide Matrimid®5218, as a host matrix, and inorganic materials such as zeolite, mesoporous carbon, silica and/or metal organic frameworks as a filler phase, are prepared by a casting method. Results with MMMs under dry conditions consistently show enhanced gas permeability with no loss in selectivity. These results can be correlated using a simple free volume relationship. When the gas is humid, the permeability is reduced, with the smallest decline when hydrophobic nanoparticles are used. This implies that optimum performance is achieved using high porosity, hydrophobic nanoparticles. In future work, we will compare these systems upon exposure to SO_2, NO and H_2S. We will also scale up our manufacturing capacity to make a small spiral wound module.

Development of CO_2 selective ultra-thin film composite membranes via CAP nanotechnology for industrial use
Jinguk Kim, Qiang Fu, Sandra Kentish, Greg Qiao
The overall cost of carbon capture and storage is dominated by the carbon dioxide (CO_2) capture step due to the low CO_2 partial pressure (13 v/v%) and the large gas volume (11,000 tonne CO_2/day) released from a typical coal fired power plant. Therefore, many efforts have been made to reduce the cost of CO_2 capture. To cope with the massive flux of flue gas, new membrane materials have been investigated with high CO_2 permeability and CO_2/N_2 selectivity. However, there is a gap to be filled between industrial demand and research outcomes. It is proposed in the literature that a CO_2 permeance over 1000 GPU (1 GPU = 10^{-6} cm^3 cm^{-2} sec^{-1} $cmHg^{-1}$) and a CO_2/N_2 selectivity over 20 is required for the CO_2 separation membranes to satisfy cost-effective CO_2 capture in industrial practice. Otherwise, a large membrane surface or highly compressed feed gases are required to achieve the necessary CO_2 flowrates.

This research focuses on the preparation of ultra-thin film composite membranes consisting of an ultra-thin selective film (< 100 nm) and a highly permeable gutter layer deposited onto a porous substrate. The selective layer is fabricated by a recently developed nanotechnology, namely the continuous assembly of polymers (CAP). The new approach allows the fabrication of surface-confined and cross-linked selective layers with the thickness controlled at the nano-scale. Consequently, we improved the CO_2 permeance by the reduction of the membrane thickness and achieve impressive CO_2/N_2 selectivity with hybrid nanoparticles, leading to economical CO_2 capture with high gas productivity.

Purification of MEA solutions using nanofiltration and electrodialysis
Josephine Lim, Alita Aguiar, Colin Scholes, Sandra Kentish, Geoff Stevens
Monoethanolamine (MEA) is commonly used in natural gas sweetening to selectively absorb CO_2 from a mixed gas stream. It has high CO_2 loading capacity and the reactions are fast compared to other amine based solvents. When applied to post-combustion capture, a major drawback from this operation is the formation of heat stable salts (sulfates, oxalates, acetates, nitrates and other species), which result from the parasitic reactions between MEA and other impurities (especially SO_2 and NO_2) in the feed gas stream. Since the formation of heat stable salts (HSS) can lead to corrosion, a fraction of the degraded solvent must be continuously purged from the system and replaced with fresh solvent.

In this project, the potential use of nanofiltration and electrodialysis as an *in situ* treatment of degraded MEA solution is investigated. Results using aged MEA solvent, supplied by CSIRO from their pilot plants shows that electrodialysis can be used to remove the bulk of the charged contaminants. However, nanofiltration is more effective at removing some of the heavy metals.

The impact of water on the performance of cellulose acetate membrane for CO_2 separation
Hiep Lu, Colin Scholes, Shinji Kanehashi, Sandra Kentish
Dense cellulose triacetate (CTA) membranes have been widely utilised in industrial gas separation processes. The commercial readiness as well as the competitive gas separation performance makes CTA an ideal candidate in capturing carbon dioxide. One of the typical challenges in membrane separation is the presence of water vapour, in either industrial gas processing streams or flue gases. Although the manufacture of membrane modules for CTA is well developed, the effect of water vapour, including the decline of membrane performance by plasticisation, clustering as well as competitive sorption, is still not fully understood. In addition, the accelerating demand of brown coal in the global electricity market will also result in flue gases that are contaminated with saturated water at different pH depending on actual processes.

This study develops a review of the impact of water on CTA in both membrane permeation and sorption kinetics. The study investigates the impact of water at pH3, pH7 and pH12.8 on the performance of CTA membrane, including the kinetic sorption, gas separation performance and chemostability. It is found that the existence of highly alkaline conditions decomposes the original membrane structure and thus increases the membrane diffusivity and solubility. The study suggested that it is necessary to reduce the direct contact between high alkaline condition to membrane unit by improving the membrane pre-treament stages and/or developing alternative membrane modules.

Development of novel polymeric membranes for CO_2 capture
Joel Scofield, Sandra Kentish, Greg Qiao
Thin film composite (TFC) membranes containing polymeric selective layers have been investigated for their carbon dioxide separation performance as a potential technology for carbon capture and storage. Optimisation of the membrane performance through the addition of polymeric additives has demonstrated improved membrane fluxes while maintaining selectivity towards CO_2 which will ultimately lead to reduced separation costs.

Block copolymers are one class of membrane materials being investigated. Polymers containing ethylene oxide segments have shown good separation due to favorable interactions between the CO_2 and the ether oxide moieties. Traditionally a hard segment has been introduced to provide mechanical strength for stable membrane layer formation however more recently block copolymer additives containing a PEG selective component and a highly permeable component such as PDMS or fluorinated components have been combined with a rigid PEBAX matrix. Block copolymers containing PEG provides compatibility between the highly permeable segments of the block copolymer and the hard PEBAX matrix.

A range of different block copolymers have been incorporated into TFC membrane active layers containing up to 60-70 wt% of the additive. Block copolymers containing PEG and either PDMS or a fluorinated component were synthesised and blended with a matrix to form membranes which showed increases of up to 250% and 400% in the CO_2 flux, with moderate drops in the CO_2/N_2 selectivity. Additional star-like microgel additives are being studied to investigate the impact of polymer morphology on gas separation performance while having the benefit of being able to be synthesised on an industrial scale.

Membrane pilot plants for CO_2 separation
Colin Scholes, Geoff Stevens, Sandra Kentish
The Membrane Pilot Plant located at the Hazelwood Power Station, in the Latrobe Valley, Victoria, is one of the few plants designed to test membranes for post-combustion capture in the world. The pilot plant is designed to trial both membrane gas separation and membrane gas-solvent contactor technologies. It is the largest such facility for testing membrane gas separation technology in Australia, and for membrane gas-solvent contactor technology it is almost unique world-wide. The pilot plant facility can capture up to 1 tonne of CO_2 per year from brown coal flue gas, and is primarily designed to test novel membrane materials for performance in post-combustion scenarios, verify proof of concept in membrane module design, as well as provide important information on membrane process configurations performance.

Membrane contactors for CO_2 separation
Colin Scholes, Sandra Kentish, Geoff Stevens
Membrane gas-solvent contactors are a hybrid technology that use solvent absorption to capture CO_2 but places a membrane between the gas and solvent phases to regulate mass transfer contact area and control phase flow. This approach also ensures issues in solvent technology such as flooding, foaming and entrainment are prevented as the two phases are separated by the membrane. This technology has substantial potential to revolutionise solvent absorption processes for both absorption and desorption. The key is development of the membrane material that can ensure a high CO_2 mass transfer to minimise contactor area while at the same time being resistant to the solvents used. Significant research has been undertaken into both porous and non-porous contactor technology for this application, with the focus on increasing the overall mass transfer to achieve high CO_2 flux.

Mixed gas and vapour separation performance in membranes
Colin Scholes, Geoff Stevens, Sandra Kentish
Membranes operate under mixed gas conditions in industry and therefore it is important to understand their separation performance under multiple feed gas conditions. Multiple gases present will compete with each other for sorption into the membrane and therefore influence permeability through a non-porous membrane. This often results in a reduction in CO_2 separation performance for most membranes due to the presence of competitive sorption. If vapours such as water or heavy hydrocarbons are also present, then their ability to condense within the polymeric matrix of a membrane becomes critical in separation performance. Since these vapours can also lead to swelling or plasticisation of the membrane and ultimately membrane failure. Understanding and modelling multiple gas permeability and separation performance is important because it enables the novel polymeric membranes being developed to be simulated for industry gas conditions. This provides critical insight into whether their laboratory performance will withstand industry conditions.

The fabrication of thin films on hollow fibre membrane contactors for promoting the absorption of carbon dioxide
Joel Yong, Sandra Kentish, Frank Caruso
Membrane contactor operations make use of a hydrophobic membranes as barriers between a gas phase and a liquid phase during the gas-liquid absorption of CO_2. The CO_2 in the gas phase diffuses through the pores of the membrane into the liquid solvent and can then be carried away for stripping and purification. However, current membranes face serious issues with pore wetting which significantly reduces the rate of CO_2 mass transfer. Previous studies have shown that a monolayer chemical adsorption of carbonic anhydrase (CA) onto membrane contactor surfaces can enhance the CO_2 absorption activity significantly. We have developed a technique to fabricate a thin film containing CA in multilayers on top of a porous flat sheet membrane through layer-by-layer (LbL) electrostatic adsorption. This LbL technique creates a thin dense film on the membrane surface, which increases the hydrophilicity of the membrane but reduces the overall surface pore size significantly. Therefore, the pore wetting tendencies of the membrane change after LbL treatment. We are in the process of investigating the effectiveness of the thin films on hollow fibre membrane contactors for CO_2 absorption.

Adsorbent Systems

CO_2 capture from natural gas: Development of adsorbents and accompanying processes

David Danaci, Ranjeet Singh, Penny Xiao, Paul Webley

The work undertaken on dual cation zeolites was discontinued, as our results showed that our desired effect was not controllable and a different approach to tailor the adsorption kinetics of CO_2 and CH_4 was then investigated. The new approach involves a core-shell zeolite material, whereby a zeolite with high CO_2 capacity is encapsulated within a zeolite with slow CH_4 diffusion, in theory enabling good CO_2/CH_4 separation as well as having a high capacity. Work is currently being undertaken on improving the outer shell of the particles, as we have not yet been able to devise a shell without cracks.

The work regarding hydrophobic adsorbents is drawing to a close, and fluorinated zeolite materials were synthesised with a significant reduction in water uptake. Optimum synthesis conditions were also determined; however, binary adsorption data between CO_2 and H_2O is required in order to give an ultimate conclusion on the success of these materials. While completing the previous work on ZIFs -8, -14 and -71, interesting behaviour was observed with regard to the temperature dependant adsorption properties of these materials. Work was started to investigate the adsorption properties over a range of temperatures and gases to investigate this in depth. A commercial carbon adsorbent was obtained from the manufacturer and work is scheduled to investigate the adsorption properties for CO_2/CH_4 separation.

Tuning flexibility in zinc metal-organic frameworks: Synthesis, structure and gas adsorption properties

Yingdian He, Jin Shang, Ranjeet Singh, Paul Webley

The last decade has witnessed intensive studies on gas adsorption and separation using flexible metal-organic frameworks (MOFs) as they offer a myriad of material design opportunities based on their high porosity and unique structural flexibility. However, rational design of novel flexible MOFs and tuning their structural flexibility constitute challenges in the field. We are investigating the flexible tuning in a rigid layer-pillared MOF by replacing the rigid pillar ligand with a flexible substitution. The MOF materials are solvothermally synthesised and characterised by multiple techniques. The novel flexible MOF is highly crystalline and thermally stable up to 200°C in air. Interestingly, the crystal structure is responsive to external stimuli (pressure and temperature). We observed temperature dependent reversible crystal phase transformations by *in situ* synchrotron PXRD study, which indicates the intrinsic dynamics of the structure. The CO_2 and CH_4 sorption measurements of the material exhibit typical step isotherms with very large hysteresis for the flexible MOFs families. The reversible structural transformations upon inclusion and exclusion of CO_2 molecules were confirmed by *in situ* synchrotron PXRD depending on CO_2 pressure. Importantly, the sorption experiment results show that it adsorbs substantial CO_2 of 75.5cm3/g at 195K but negligible N_2 at 77K under atmospheric pressure, which might indicate the molecular sieving effect for the narrow pore (NP) phase of the material. Moreover, it selectively adsorbs CO_2 over CH_4 and N_2 at room temperature, making it a promising candidate for carbon capture. This simple strategy of converting rigid MOFs to flexible structures could shed light on the development of novel flexible MOF structures to enhance gas separation performance.

Study of advanced vacuum swing adsorption cycles for CO_2 capture from post-combustion flue gas streams

Augustine Ntiamoah, Jianghua Ling, Penny Xiao, Paul Webley

Among the technologies that are under development to control CO_2 emissions from flue gas streams is the pressure/vacuum swing adsorption (PSA/VSA) technology. Efforts are currently being made to improve adsorbents and process cycles to achieve more efficient and cost-effective separations. We have designed and experimentally tested several advanced vacuum swing adsorption cycles for post-combustion CO_2 capture using zeolite 13x, a commercial adsorbents and our newly developed experimental PSA/VSA rig consisting of four adsorber columns. Product streams containing 85-95% CO_2 at recovery rates ranging from 60-75% have been obtained using a relatively high desorption pressure of 8 kPa. Average power consumption for the various cycles is around 0.3 MJ/kg CO_2 which is lower in comparison with many reported values in the literature. Simulations have also been performed using the commercial Aspen adsorption simulator to help in the analysis of the experimental results.

Investigation of sustainability of bioenergy with CCS (BECCS) as a CO_2 removal technology

Nasim Pour, Paul Webley, Peter Cook

Bioenergy with carbon capture and storage (BECCS) is a CO_2 removal technology in which biomass takes CO_2 from the atmosphere during photosynthesis. When the biomass undergoes the processes to release its energy the CO_2 produced is sequestered, transported and stored in geological formation. In this way, a negative flow of CO_2 from the atmosphere to subsurface is established.

In many climate models without

BECCS, achieving the 350-450 ppm atmospheric CO_2 target by 2100 would not be possible. However, there are some concerns regarding BECCS. For instance, biomass is a limited resource and large-scale exploitation might lead to competition over productive lands with food production. If it is not planned in sustainable way, it could cause significant deforestation, food scarcity and loss in biodiversity. Likewise, the CCS process involves technical and environmental complications especially in the storage step. Thus, if BECSS cannot assure sustainable resource and storage it cannot be a viable option for CO_2 mitigation. Moreover, economic viability, compatibility with social welfare and equity, and supportive regulatory framework to facilitate its large-scale deployment are necessary in order to make BECCS a realistic CO_2 mitigation option. This project aims to investigate the potential of BECCS deployment as a CO_2 removal technology within a sustainable framework.

Low cost oxygen production by swing pressure adsorption with oxygen selection absorbents

Willie Tang, Ranjeet Singh, Penny Xiao, Paul Webley

The separation of air has conventionally been achieved by the cryogenic liquefaction and distillation of air into its component fractions. However, this technology is very energy intensive and costly. For small-scale on-site applications, adsorption processes provide a more cost effective alternative for oxygen and nitrogen gas requirements. Currently, nitrogen selective adsorbents, such as zeolites, are employed for this separation. As atmospheric air contains four times more nitrogen than oxygen, the current research aims to develop oxygen selective adsorbents to improve the efficiency of adsorption-based air separation processes. This can also lead to smaller adsorption systems producing similar throughputs. Iron and cobalt porous organic polymers made up of porphyrin building blocks were synthesised, characterised and evaluated. At ambient temperatures, the polymers showed oxygen selectivity (up to 1.3). The selectivity of the cobalt polymer was shown to increase by increasing the cobalt content in the polymer. At cryogenic temperatures, both the oxygen selectivity and capacity were improved significantly (up to 14.7) as nitrogen gas experienced a molecular sieving effect. This was attributed to the shrinking of the pores to below the kinetic diameter of a nitrogen molecule (3.64 Å) but still allowing oxygen molecules (3.46 Å) to enter the structure. Most significantly, repeated adsorption-desorption cycling showed the oxygen uptakes by these polymers were fully reversible. There is scope to increase the cobalt content in the polymers to improve the oxygen selectivity for ambient temperature applications. Process simulations showed adsorption systems using these polymers are able to achieve an oxygen stream up to 98% purity.

Gas diffusion in molecular trapdoor zeolite

Xueying Zhang, Jin Shang, Paul Webley

The study of gas diffusion in zeolites is of great significance because of its broad applications in catalysis and gas separation processes. Previously researchers have applied both macroscopic and microscopic experimental techniques to investigate transport and self-diffusion in zeolites. In addition, recent years have also seen theoretical methods such as kinetic Monte Carlo, molecular dynamics and transition-state theory adopted in the understanding of gas-zeolite interaction. Earlier works have illustrated that factors such as zeolite topology, adsorbate shape, concentration and temperature would all affect the diffusion process.

This study focuses on gas diffusion in a typical molecular trapdoor zeolite (chabazite; CHA) using combined experimental and computational methods. By tuning parameters such as the Si/Al ratio, cation type and experimental conditions, we expect to understand the diffusive properties of different gas species in CHA channels. In addition, computer simulation will be applied to the fundamental probing of interactions between the gas molecules and zeolite framework. Several models will be formulated to describe the energetic heterogeneity of CHA and its influence on gas diffusion and separation. By comparing experimental results with simulation data, we will narrow down the key parameters during diffusion and thus pave the road for improved separation kinetics in CHA.

Electrical swing adsorption: A low energy option for carbon dioxide capture

Qinghu Zhao, Penny Xiao, Paul Webley

Compared with conventional temperature swing adsorption (TSA), electric swing adsorption (ESA), as an emerging CO_2 capture technology, has certain advantages including shorter regeneration time and higher adsorbent regeneration efficiency. In this project we will investigate the electrical swing process using novel metal-organic framework materials. As part of the project we will develop complete ESA models with Computational Fluid Dynamics (CFD) and use these models to predict and understand the effect of voltage, current, electric power, electrification time, and flow rate of feed gas on CO_2 capture efficiency. In our preliminary simulations, we have found that the distribution of fluid velocity of feed gas in the channels of monolith parabolic, which will degrade CO_2 capture efficiency. Geometric factors, reactor shape and channel distribution of the monolith will therefore need to be considered. Finally, we will develop new ESA cycles for a specific adsorbent according to different conditions for different industrial applications.

Materials Development

Polymer metal-organic framework composite structure for CO_2 capture applications

Ke Xie, Qiang Fu, Greg Qiao, Paul Webley

Metal-organic frameworks (MOF) are good candidates for gas separation due to their molecular sieving properties and high thermal stability. MOFs are cast into membranes or blended with polymer matrix to produce mixed-matrix membranes (MMM). Neither of these techniques is optimal as the resultant membranes can have poor mechanical strength, defect-prone features and processing difficulties.

In this study, the amino-functionalised MOF (UiO-66-NH_2) and the bromide functionalised MOF (UiO-66-Br) nanometric crystals (30~50 nm) were successfully prepared and characterised by XPS, XRD, TGA, SEM and TEM. UiO-66-Br was used to initiate the polymerisation of polyethylene glycol acrylate (PEGA) via atom transfer radical polymerisation (ATRP) resulting in a MOF composite. We could control the grafting density and the degree of polymerisation of PEGA by carefully tuning the feed ratio of PEGA and UiO-66-Br in the ATRP process. The resultant composites were characterised by XPS, XRD, DLS, TGA, SEM and TEM. All these results indicated the successful preparation of polymer-MOF composites with tuneable morphology. In future work, CO_2 sorption measurements (compared with light gases like CH_4 or N_2) will be performed to reveal the CO_2 capture capability of the membranes.

High molecular weight amorphous poly(ethylene oxide)/Pebax® thin film composite membrane for CO_2 capture applications

Qiang Fu, Andri Halim, Sandra Kentish, Greg Qiao

A multi-block high molecular weight amorphous poly(ethylene oxide)/poly(ether-*block*-amide) (HMA-PEO/Pebax® 2533) thin film composite (TFC) blend membrane was fabricated for CO_2 separation from light gas N_2. The novel multi-block HMA-PEO copolymers ($M_n \approx 10$ kDa) were synthesised *via* condensation polymerisation. The Pebax® 2533/HMA-PEO TFC blend membranes were prepared by blending up to 66 wt. % HMA-PEO relative to Pebax® 2533 and spin-coating the mixture on a highly permeable polydimethylsiloxane (PDMS) intermediate layer which was pre-coated onto a polyacrylonitrile (PAN) microporous substrate. Their ability to selectively separate CO_2 from N_2 was tested at different conditions; the temperature and pressure dependence of gas permeance and selectivity was studied. The TFC blend membranes afforded a great improvement of CO_2 permeance (*ca.* 1,000 GPU) as a result of the addition of HMA-PEO. Furthermore, the selective layer presented outstanding CO_2 separation properties; CO_2 permeability of 780 Barrer and CO_2 permeance of 2,000 GPU with CO_2/N_2 selectivity of 40. These results surpassed the most recent upper bound and make novel HMA-PEO an attractive additive for advanced CO_2 separation membranes.

Thin-film composite membranes consisting of triblock copolymers for CO_2 gas separation

Paul Gurr, Sandra Kentish, Greg Qiao

The aim of this project is to improve the separation capabilities of gas separation membranes through the synthesis of novel block copolymers via controlled and precise chemical synthesis, analysis and testing. In recent approaches dense membranes have been fabricated to identify their permeability to CO_2 and selectivity over other gases. Previous limitations in dense membrane manufacture have resulted in a more expedient alternative approach to membrane evaluation. Thin-film composite membrane substrates (TCMs) have been prepared which consist of stable polyacrylonitrile (PAN) substrates coated with a protective crosslinked polydimethylsiloxane (PDMS) layer. This protective, or gutter, layer affords a smooth surface to which very thin selective layers are applied. Our current goal, to achieve commercially competitive membranes, is to increase their CO_2 permeability whilst maintaining the relative flow of other gases (CH_4 and N_2). We investigated a series of well-defined polymers consisting of chemically and thermally resilient polyimide (PI) linked to flexible and permeable PDMS. TCMs were prepared by spin-coating solutions of these polymers onto PAN/PDMS substrates and their gas performances were determined for five different gases (CO_2, N_2, CH_4, H_2 and O_2). Improved wettability of the typically incompatible polyimides with the PDMS substrate was achieved through varying the ratios of each component in the PI-PDMS polymers. TCMs were successfully prepared using polyimides with increased permeability to CO_2 which had previously not been reported. Using similar synthetic approaches other classes of polymers, which have previously been unable to form TCM's, are being investigated with the aim to improve their gas separation properties within the commercial target range.

Cross-linked amphiphilic micelles based on poly(ethylene glycol)/poly(dimethylsiloxane) brush diblock copolymers

Andri Halim, Paul Gurr, Anton Blencowe, Sandra Kentish, Greg Qiao

A series of well-defined amphiphilic brush diblock copolymers comprised of hydrophilic poly(ethylene glycol) (PEG) and hydrophobic poly(dimethylsiloxane) (PDMS) were synthesised and characterised. Monomethyl ether PEG (MeO-PEG) was initially functionalised with 2-bromoisobutyryl bromide to afford a macroinitiator suitable for atom transfer radical polymerisation (ATRP). The MeO-PEGs and their functionalised derivatives were characterised by matrix assisted laser desorption ionisation time-of-flight mass spectroscopy (MALDI ToF MS) and ^{1}H nuclear magnetic spectroscopy (NMR). The macroinitiator was then chain extended via "grafting through" of monomethacrylate PDMS with photoactive 2-(methylacyloyloxy) ethyl anthracene-9-carboxylate embedded into the PDMS brush to yield photocrosslinkable PEG/PDMS brush diblock copolymers. The photocrosslinker and resulting PEG/PDMS copolymers were characterised with ^{1}H and ^{13}C NMR. ATRP afforded a series of PEG/PDMS brush diblock copolymers of varying PEG to PDMS ratio with high conversions (88-96%) achieved for several molecular weights of MeO-PEGs macroinitiator. Subsequent self-assembly of these brush diblock copolymers in dimethylformamide afforded micelles with hydrodynamic diameters (dH) in the nanometer scale (56 to 205 nm), as determined by dynamic light scattering (DLS). Photocrosslinking of micelle core was achieved upon exposure to UV-radiation (> 300 nm), and monitored using ultraviolet-visible spectroscopy (UV-Vis) analysis. Following re-dissolution in chloroform, DLS revealed that the micelles were stabilised by [4+4] photodimerisation of the anthracene groups located in the PDMS core.

PhD student Qi Zheng

Research Program Highlights

Storage Program

The Storage Program is focused on developing a deeper understanding of the process of storing CO_2 in subsurface structures with the aim of reducing the storage risks and developing monitoring and control technologies. The Program is focused on the study and assessment of potential CO_2 storage sites through the provision of research, technical review and advice. Research and development projects aim to reduce the risks associated with CO_2 storage, for example, by assessing seal integrity, by predicting the dynamics and reactivity of the CO_2 plume and by developing technologies and procedures to improve injectivity, subsurface monitoring options and CO_2 leakage mitigation measures. The CO_2 Storage research team is multidisciplinary with particular strengths in geochemistry, geomicrobiology, numeric modelling of reservoir processes and geophysics including seismic interpretation.

Postgraduate student Anas Syed Ali

Geochemistry

Injectivity enhancement by acid stimulation
Syed Anas Ali, Jay Black, Ralf Haese
In some sedimentary basins CO_2 storage is restricted by insufficient injectivity. This study explores opportunities for enhanced injectivity through acid stimulation in siliciclastic reservoirs. Acid promoted mineral dissolution can increase permeability and thus injectivity. The reservoir engineering technique associated with acid stimulation has been a common practice in the oil and gas industry mainly aimed at dissolving the fines resulting from formation damage during drilling. The technique has been applied in both sandstone and carbonate units using a range of acid mixtures and procedures to improve productivity in the near wellbore environment. Our objective is to apply this knowledge and evaluate the efficiency of matrix acidizing as a measure to enhance permeability primarily in the near wellbore environment and thus enhance CO_2 injectivity. A coupled reactive-transport model will be developed and acid stimulation will be simulated under variable conditions. Complementary laboratory experiments will be undertaken to test and validate the model parameters. A case study will be chosen and conditions for enhanced injectivity will be modelled at field scale.

Geochemistry of CO_2 storage in the Darling Basin (NSW)
Jay Black, Ralf Haese
This project will determine, for the first time, the formation water composition in the Darling Basin and will undertake geochemical modelling to predict fluid-rock reactions under CO_2 storage conditions in prospective reservoirs of two sub-basins of the Darling Basin. The formation water composition is a key parameter for modelling the hydrodynamics and geochemical reactions under CO_2 storage conditions however, drill mud frequently contaminates near wellbore formation water diminishing sample integrity. Here we will apply a tracer to the drill mud to determine the degree of contamination and use it to reconstruct the true water composition. This approach will be compared to and validated by applying the most advanced commercial water sampler (Modular Dynamic Tool with Compositional Fluid Analyser, Schlumberger). Outcomes of this study are 1) the evaluation of a low-cost method for determining formation water composition and 2) an estimate for the carbon trapping capacity by mineral precipitation in two targeted reservoirs.

Mineral dissolution rates under CO_2 storage conditions
Jay Black, Ralf Haese
Modelling geochemical changes under CO_2 storage conditions necessarily involves the use of thermodynamic and kinetic databases. These databases have been developed by compiling experimental results from a large number of studies carried out under different conditions and for different purposes. The database typically only gives a median value for a property, but the uncertainty of the value is not accounted for. The very high CO_2 concentration in a CO_2 storage aquifer poses specific conditions which may inhibit or accelerate mineral dissolution rates. Given these uncertainties, laboratory-based mineral dissolution experiments are carried out to account for CO_2 storage conditions. In first instance, the reactivity of chlorite will be determined. Chlorite is a common clay mineral in prospective Australian reservoirs and contains abundant Ca, Mg and Fe. These cations may be mobilised through mineral dissolution and later precipitate as carbonates enhancing the CO_2 mineral trapping capacity. Later, other minerals such as feldspar and illit will also be tested. The experimental results will be compared to existing values given in commonly used databases in order to validate their accuracy when modelling geochemical reactions in CO_2 storage aquifers.

Reactive barrier formation for CO_2 leakage mitigation
Cesar Castaneda, Geoff Stevens, Ralf Haese
One of the main purposes of CO_2 sequestration is to keep CO_2 underground in a safe and permanent environment. However it is possible that unwanted CO_2 migrates from the geological containment due to different leakage pathways. These pathways could occur in aged wells in undetected high-porosity zones or in pre-existing or induced fractures by geomechanical forces. This work evaluates different possibilities of materials and techniques that may seal or avoid leakage of CO_2. Some materials such as cements and geopolymers can be used to remediate leakage from wells. Other substances such as gels and foams have been suggested for the remediation of leaks. However, most of these materials are not suitable for sealing, since they have a high viscosity and do not flow easily underground. Thus, the main focus of this study is to develop a procedure that can be applied in deep subsurface systems and is able to stop the CO_2 leakage. The proposed technique is based on the use of an aqueous solution as a reactant, which in contact with CO_2 reacts chemically producing a precipitate that fills fractures and pores and stops the leakage. Reactions of CO_2-rich water in contact with injected silica- or calcium-rich brine are modelled simulating anticipated geochemical reactions in case of a leakage scenario. This will also inform future laboratory-based experiments.

The Otway 2B Extension Test 1: Differences in formation water quality related to CO_2 impurities
Ralf Haese, Jay Black, Hong Vu, Dirk Kirste, Rajindar Singh
The cost of CCS could be reduced if safe storage of CO_2 with impurities such as

SO_2, NO_2 and O_2 can be demonstrated. In this field test at the CO2CRC Otway site, we determine differences in reservoir water quality in response to the injection of CO_2-saturated water with and without gas impurities. The experiment commenced at the beginning of October 2014 and consists of two phases where CO_2 is delivered from the COSPL- operated oxyfuel capture facility in Queensland. In phase 1, pure COSPL product is injected and mixed with water at depth resulting in CO_2-saturated water in the reservoir where it remains in contact with reservoir rocks for three weeks. In phase 2, the COSPL product is artificially enriched with SO_2 (100 ppm), NO_2 (50 ppm) and O_2 (0.5%) leading to a different initial water composition as compared to phase 1. Water samples will be taken on three occasions during each phase using the U-tube system. A key question will be whether water acidity will increase through the formation of sulphuric and nitric acids. Preliminary modelling suggests the natural water buffer capacity (alkalinity) will prevent a detectable increase in acidity. Other changes in water properties, however, will be detectable.

Long-term changes in the reservoir mineralogy imposed by different levels of CO_2 – a natural analogue study
Karen Higgs, Ralf Haese, Sue Golding, Ulrike Schacht, Maxwell Watson
One of the limitations in predicting the geochemical evolution of a reservoir under CO_2 storage conditions is the rare opportunity to validate model results against observations in natural reservoirs. The Lower Cretaceous Pretty Hill Formation in the Otway Basin (Victoria / South Australia) had been segmented into a number of confined reservoirs due to tectonic activity, which were later charged with different levels of CO_2. Gas samples from different sections of the Pretty Hill Formation show a large range of current CO_2 concentrations between <5 mol% to > 90 mol%. This circumstance offers an exceptional opportunity to characterise the diagenetic changes to the reservoir rocks controlled by different levels of CO_2 over geologic time. Specifically, we will determine mineralogical and petrophysical changes and compare the observational data to the modelled evolution of the reservoir.

Geochemical impacts and monitoring of CO_2 storage in low-salinity aquifers
Kyle Horner, Eric Tenthorey, Dirk Kirste, Ralf Haese
The potential for CCS adversely impacting on potable groundwater resources is of concern to regulators and the community. This project will identify risks and recommend mitigation strategies in relation to CO_2 storage in the freshwater-dominated Surat Basin (Queensland). This project will reduce operational and early investment risks for industry, reduce the risk of public opposition to CO_2 storage and provide advice to regulators by addressing the following four project objectives and making results publicly available:

1. Determine the integrity of the Evergreen Formation as an effective seal.
2. Determine fluid and mineral trapping capacity for CO_2 in the Precipice Sandstone and the Hutton Sandstone reservoirs.
3. Develop a reactive transport model for CO_2 and impurities (SO_x, NO_x, O_2) determining reactions affecting injectivity and the long-term containment of chemicals.
4. Determine potential impacts of leakage on overlying freshwater aquifers and develop monitoring indicators.

Geomicrobiology

Microbial responses to dense phase CO_2
Andre Mu, Ralf Haese, Timothy Stinear, John Moreau
Microorganisms play an important role in the Earth's carbon cycle and understanding their responses to anthropogenic carbon loading is an important area of research. Subsurface CCS strategies are currently being implemented to reduce CO_2 emissions to the atmosphere. The aim of this study is to determine the effects of dense phase CO_2 injection on the native aquifer microbial community. Understanding these effects are important for predicting how this community will respond metabolically and physiologically, and to determine whether undesired enrichment for certain microbial populations (e.g. methanogens) can occur.

The persistence and increase of *Proteobacterial* sequences and the apparent decline of *Firmicute*-like sequences post-CO_2 injection suggests selective adaptation or recovery to changes in ground water chemistry as a result of CO_2 sequestration. The impacts of an observed loss of single carbon cycling genes central to the acetyl-CoA pathway of the predominant, autotrophic *Firmicute* genus, *Carboxydocella*, have on the physiology of the microbial community are unknown. Understanding the effects of dense phase CO_2 on microbial ecology at the genetic level can provide crucial insights to the formation and regulation of biofilms under CO_2 stress, and how biofilm formation may reduce CO_2 leakage by reducing aquifer porosity.

Awards and Achievements

Academic and Research Staff

Professor Ralf Haese received the CO2CRC Award of Appreciation at the CO2CRC's annual Research Symposium 2014. Ralf received the CO2CRC award for his outstanding contribution to the CO2CRC Reactive Rocks Project and his leadership in the preparation of a special volume in the journal *Chemical Geology*, for which he has served as a guest editor.

Peter Cook Centre for CCS Research Director **Professor Geoff Stevens** won a University of Melbourne Excellence Award in 2014. Geoff was awarded the Patricia Grimshaw Award for Mentor Excellence in recognition of his excellence in the mentoring of University colleagues, both professional and academic. Award recipients are acknowledged for their outstanding contributions as mentors, involving: a sustained record of effective mentoring; exceptional skills in the provision of support and the sharing of knowledge; and respect for the development of colleagues as individuals.

Dr Jin (Eric) Shang received the Chancellor's Prize for his PhD thesis for Science and Engineering. He was awarded the John Melvin Memorial Prize for Best PhD Thesis in the School of Engineering 2013. Eric was supervised by Professor Paul Webley, with a PhD thesis topic of *Novel Separation Mechanism for CO_2 Capture – Molecular Trapdoor Effect*. During his PhD he discovered a new separation mechanism which changed our understanding of how adsorbents discriminate between molecules in gases. His work forms the basis of ongoing research program, now funded by the Australian Research Council (ARC).

Jin was a finalist UNSW Energy Future Collaborative Innovation Awards 2014 in the "Smart adsorbents for gas separation" category. He was awarded the 2013 Chinese Government Award for Outstanding Self-Financed Students Abroad. The ceremony was held on 29 April 2014.

Postgraduate Students

Jinguk Kim was awarded People's Choice Award for Best Presentation for his presentation "Development of CO_2 selective ultra-thin TFC membranes via CAP nanotechnology for industrial use" at the *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Nouman Mirza was awarded the People's Choice Award for his poster "Estimation of critical properties of deep eutectic solvents" at the *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Andre Mu's paper Mu, A., Boreham, C., Leong, H.X., Haese, R.R. and Moreau, J.W. (2014) Changes in the deep subsurface microbial biosphere resulting from a field-scale CO_2 geosequestration experiment. *Frontiers in Microbiology,* **5,** was one of the "Top 10 most viewed and downloaded" papers for May 2014 in the journal.

Willie Tang was awarded the Best Student Poster Award for his poster "Porphyrin-based polymers with improved oxygen selectivity for air separation applications" at the *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Frank Wu received an award at the 2014 Australian Institute of Energy National Postgraduate Student Energy Awards in October - Group A (Carbon Reduction) Highly Commended. This was a national poster competition promoting interaction of postgraduate research students with the energy community.

The Clive Pratt Scholarships are made possible through a bequest in memory of Henry Reginald Clive Pratt. The travel scholarships are open for award annually, for students in Chemical Engineering and/or Biomolecular Engineering at the University. In 2014 Centre members **Joel Scofield** and **Willie Tang** were amongst the recipients of this award.

David Danaci was awarded the Best Tutor in Chemical and Biomolecular Engineering Semester 1 2014. **Joel Yong** received an honourable mention for Best Tutor in Chemical and Biomolecular Engineering Semester 2 2014.

University Portfolio Holders

Geoff Stevens, Associate Dean (Engagement), Melbourne School of Engineering

Sandra Kentish, Head of Department of Chemical and Biomolecular Engineering

John Moreau, Research Higher Degree Program Coordinator, School of Earth Sciences

Greg Qiao, Assistant Dean (Research), Melbourne School of Engineering

Serving the Scientific Community

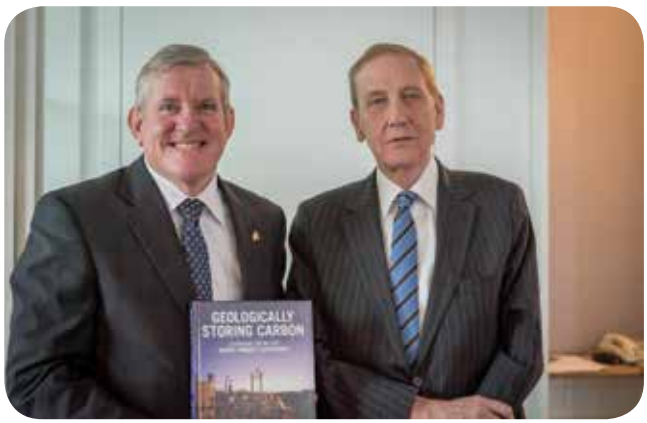
Conference Contributions

Peter Cook
Session Chair: Industry and integration challenges, *National CCS Conference – CCS in Action: Today, Tomorrow & Beyond*, Sydney, NSW, Australia, 31 August-3 September.

Sandra Kentish
Local Organising Committee: *13th International Conference on Inorganic Membranes*, Brisbane, QLD, Australia, 6-9 July.

Greg Qiao
Member, Conference Committee: *35th Australasian Polymer Symposium (35APS)*, Gold Coast, QLD, Australia, 12-15 July.

Geoff Stevens
Member, Symposium Advisory Committee: *2014 Australia-China Symposium on Energy*, Taiyuan, China, 13-15 May.



Minister Ian Macfarlane (left) launched the book "Geologically Storing Carbon: Learning from the Otway Project Experience" which was edited by Professor Peter Cook (right).

Editorial Board Appointments

Sandra Kentish
Editorial Board Member of *Recent Innovations in Chemical Engineering* (Bentham Science), 2007-present

Editorial Board Member of *Food Engineering Reviews* (Springer), 2008-present

Editorial Board Member of the *International Journal of Polymer Science* (Hindawi), from 2014

Greg Qiao
Member of the International Advisory Board for *Macromolecular Bioscience* (Wiley)

Member of the International Advisory Board for *Macromolecular Materials and Engineering* (Wiley)

Geoff Stevens
Member of the Editorial Board of the Elsevier journal *Hydrometallurgy*, 1994-present

Member of the Editorial Board of the *Chemical Engineering Journal* (Elsevier), 1999-present

Paul Webley
Member of the Editorial Board and Separations Subject Editor, *Chemical Engineering Research and Design,* a publication of the Institution of Chemical Engineers

Editorial Roles

John Moreau
Associate Editor of *Geochimica et Cosmochimica Acta* Elsevier), 2013-present

Geoff Stevens
Associate Editor of the Taylor & Francis journal *Solvent Extraction and Ion Exchange*, 1996-present

Associate Editor-in-chief, *Chinese Journal of Chemical Engineering*, from 2013

Paul Webley
Editor, *Separation and Purification Technology,* from 2014

Other Roles

Peter Cook

Panellist: Alternatives for energy supply: Shale gas and fracking and the role of renewable energies. International expert workshop Australia, Asia, Europe and Climate Change, Melbourne, VIC, Australia, 17-18 November.

Member, Advisory Board, Saskpower Boundary Dam Project, Canada

Sandra Kentish
Research Advisory Committee: National Centre of Excellence in Desalination, April 2010 onwards

Geoff Stevens
Secretary General of the International Committee for Solvent Extraction, since 1996

International Honorary Member of the Japan Society of Ion Exchange (JSIE), 2011-present

External Independent Director, Institute for Technology Research and Innovation (ITRI) Board, Deakin University, Australia, 2011-2014

Director, O'Brien Institute and O'Brien Foundation

Paul Webley
Member of the Board of Directors, International Adsorption Society, since 2010

Public Outreach and Publicity

The book "Geologically Storing Carbon: Learning from the Otway Project Experience" was launched at Parliament House, Canberra by Federal Industry Minister, Ian Macfarlane on Thursday 28th August. This book presents the findings of ten years of research by more than a hundred CO2CRC researchers. Published by CSIRO Press and Wiley, and edited by Peter Cook, this major volume is nationally and internationally very significant to the vital issue of decreasing greenhouse gas emissions from fossil fuels.

The release received media attention from ABC Rural http://www.abc.net.au/news/2014-09-01/book-on-research-findings-from-otway-ccs-launched/5702990?&section=news

Peter Cook's book "Clean Energy, Climate and Carbon" was released in Korean.

Engagement

The Peter Cook Centre for Carbon Capture and Storage Research was established with a view to building capability and an outstanding centre of CCS excellence to underpin the deployment of CCS technologies in Australia. The Centre has strong international collaborative links, with students, postdoctoral fellows and senior researchers from overseas, including China, Japan, South Korea, UK and USA. We highlight some of the engagement activities with which the Centre took part in 2014.

Professor Geoff Stevens (left) hosting the Minister of the Environmental Protection Administration of the Republic of China (Taiwan), Mr Kuo-Yen Wei (right).

Engaging with Canada

Professor Sandra Kentish is collaborating with the Centre for Water, Earth and the Environment (INRS) in Quebec, Canada to develop a process for the sequestration of carbon dioxide into a mineral form. This work has advanced to a pilot plant scale with a 20 litre facility operating at the Holcim Joliette cement plant in Quebec. A patent has been filed to protect the intellectual property that has been developed (Mercier, Blais, Puthiya, Pasquier, Cecchi, Kentish, Carbon Dioxide Chemical Sequestration Of Industrial Emissions By Carbonation Using Magnesium Or Calcium Silicates, World Patent, 2013131193 A1, Canadian Patent 2771111 A1) and opportunities are being investigated to apply the same technology to the local steel industry. Sandra has been appointed as an invited Professor of the INRS since 2011 in recognition of her important contribution to this work.

Professor Peter Cook, a member of the Saskpower International Advisory Board for Boundary Dam, attended the formal opening of the Boundary Dam CCS Project in September 2014, delivered a paper to the preceding conference and also was the for part of the Conference.

Engaging with China

Australia-China Joint Coordination Group on Clean Coal Technology (JCG) Partnership Fund

The Australian Government's Department of Industry (DoI) invited the Australian Academy of Technological Sciences and Engineering (ATSE) to manage the Australia-China JCG Partnership Fund. Under the Fund, Associate Professor Shufeng Shen from the School of Chemical and Pharmaceutical Engineering, Hebei University of Science and Technology, China, visited the Peter Cook Centre for CCS Research in March 2014. During the visit researchers exchanged recent research and experience on advanced absorption technology, especially on promoted carbonate solvent, and discussed a potential collaborative project based on amino acid precipitation process. Associate Professor Shen had previously held a postdoctoral research position in the Department of Chemical and Biomolecular Engineering with Professor Geoff Stevens (2007-2010). His return visit has helped to maintain the close relationship and research discussion on promoted carbonate solvents between his group in China and researchers at the University of Melbourne.

Engaging with Japan

Members of the Peter Cook Centre for CCS Research took part in a documentary for the NHK Enterprise (NEP). NEP is an affiliated company of NHK (Japan Broadcasting Corporation) that organises symposia and events and creates programmes for NHK. The film was used in one of the sessions of the "Start of Hydrogen Energy Era" Energy Symposium in Japan on Tuesday 18 November 2014. The documentary focused on Victoria's research outcomes so far highlighting issues of significance to CCS in Australia for Japan's CO_2 reduction, the potential of CCS and comments on Japan's hydrogen chain project from the view point of CCS development. The hydrogen project will be developed by Kawasaki Heavy Industries (KHI). The seven minute footage featured the University of Melbourne and the laboratory facilities at the Centre as well as other relevant locations around Victoria.

NEP also made a 50 minute programme about the symposium itself which was broadcast throughout Japan on 31 January 2015.

Engaging with Korea

The Korean translation of Professor Cook's book "Clean Energy, Climate and Carbon" was published in 2014 and discussions are underway with the aim of producing a Korean version of his more recent book "Geologically Storing Carbon: Learning from the Otway Project Experience".

Engaging with the Republic of China (Taiwan)

The Centre had the pleasure of hosting a visit from the Taiwan delegation led by Mr Kuo-Yen Wei, Minister of the Environmental Protection Administration of the Republic of China (Taiwan) in July 2014. The Taiwan EPA is actively learning and assessing the feasibility of promoting CCS in Taiwan to mitigate climate change and reduce carbon emissions. Minister Wei and the EPA delegation took the opportunity to discuss CCS research with the Centre's research programme leaders and enjoyed a tour of the research facilities. We believe that further exchange opportunities will arise from this initial connection.

Engaging locally

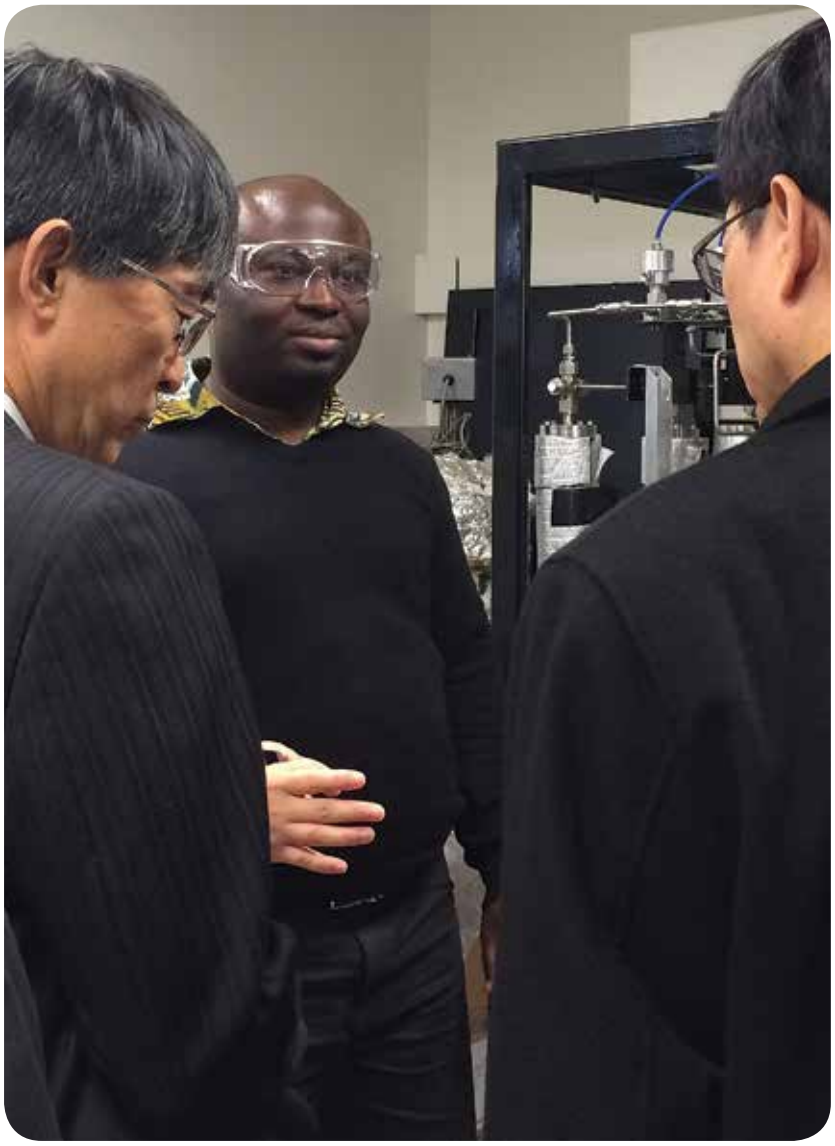
Securing Australia's Future Working Group

During 2013, Professors Peter Cook and Sandra Kentish served as chair and member respectively, of the Expert Working Group for Project Six - Engineering Energy: Unconventional Gas Production, of the Securing Australia's Future program. This program of six projects, identified by the Prime Minister's Science Engineering and Innovation Council (PMSEIC), was co-ordinated by the Australian Council of Learned Academies (ACOLA) with funds made available by the Australian Research Council. As a result of participating in the Working Group, Peter Cook gave a number of presentations on shale gas during 2014. This work has also led to the Australian Academy of Technological Sciences and Engineering (ATSE) organising a two-day conference on unconventional gas in Sydney in September 2015 to address the policy issues.

Seminar Series

The Peter Cook Centre for CCS Research Seminar Series brings together staff, students and visitors to present and discuss their latest research findings. The Seminar Series provides members with an opportunity to keep up to date with the research activities and overall direction of the research within the Centre as well as the latest local and international research developments.

Date	Speakers	Topic
19 March	Dr Jay Black	Reservoir mineral reaction rates under CO_2 storage conditions
5 May	Professor T. Alan Hatton, Massachusetts Institute of Technology, USA	Public Lecture Taking charge of carbon capture: Electrochemical strategies for reduction of greenhouse gas emission
21 May	Ms Alia Ben Ghachem, INRS-ETE, Canada	Mineral carbonation of CO_2 with calcium bearing material
18 June	Dr Li Sheng, Chinese Academy of Sciences, China	CO_2 capture using hot potassium carbonate and its application into power and steel industries
16 July	Mr Augustine Ntiamoah	CO_2 capture by temperature swing adsorption: Search for efficient, innovative process cycles
20 August	Mr Brian Maring	PhD Completion Seminar: Simplified adsorption process modelling for rapid adsorbent screening and cycle design for post-combustion CO_2 capture applications
17 September	Dr John Moreau	Metagenomic analysis reveals new insights into subsurface microbial responses to a CO_2 injection experiment in the Otway Basin, Victoria
15 October	Mr Joel Yong	Enzyme-based membrane contactors for enhancing CO_2 capture
17 December	Ms Nasim Pour	Bioenergy with CCS (BECSS), a sustainable carbon removal technology (?)



PhD student Augustine Ntiamoah explains his research to Centre visitors.

Presentations

Keynote and Plenary Lectures

Cook, P. (2014) What can we do to get CCS going in Australia?. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Plenary lecture)

Smith, K., Mumford, K., Lee, A., Nicholas, N., Indrawan, I., Gouw, J., Thanumurthy, N., Anderson, C., Harkin, T., Qader, A., Hooper, B., Kentish, S. and **Stevens, G.W.** (2014) Development of a precipitating solvent absorption process for capturing CO_2 from industrial sources. *Society of Chemical Engineers Japan (SCEJ) 79th Annual Meeting*, Gifu, Japan, 18-20 March. (Plenary lecture)

Stevens, G.W. (2014) Global warming, greenhouse gases, energy usage and separations technology. *2014 Australia-China Symposium on Energy*, Taiyuan, China, 13-15 May. (Plenary lecture)

Stevens, G.W. (2014) Global warming, greenhouse gases, energy usage and separations technology. *Engineers Australia Convention 2014, Practical Response to Climate Change (PRCC)*, Melbourne, VIC, Australia, 24-27 November. (Keynote speaker)

Conference Presentations

Ali, S. and Haese, R.R. (2014) Injectivity enhancement by acid stimulation. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Anderson, C., **Hooper, B.**, Qader, A., Harkin, T., Smith, K., Mumford, K., Pandit, J., Ho, M., Lee, A., Nicholas, N., Indrawan, I., Guow, J., Xiao, G., Thanumurthy, N., Temple, N., Stevens, G. and Wiley, D. (2014). Recent developments in the UNO MK 3 process – A low cost environmentally benign precipitating solvent process for CO_2 capture. *12th International Conference on Greenhouse Gas Control Technologies (GHGT12)*, Austin, TX, USA, 5-9 October.

Black, J. and Haese, R.R. (2014) Geochemical characterisation and modelling for the NSW CO_2 storage assessment program in the Darling Basin. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Black, J.R. and Haese, R.R. (2014) Batch reactor experimental results for GaMin'11: Reactivity of siderite/ankerite,labradorite,illite and chlorite under CO2 saturated conditions. *12th International Conference on Greenhouse Gas Control Technologies (GHGT12)*, Austin, TX, USA, 5-9 October. (Poster presentation)

Black, J.R. and Haese, R.R. (2014) CO_2-water-rock interactions: Mineral reactivity under CO_2 storage conditions. *Australian Earth Sciences Convention 2014*, Newcastle, NSW, Australia, 7-10 July.

Borduas, N., da Silva, G., Murphy, J.G. and Abbatt, J.P.D. (2014) Atmospheric sources and sinks of amines, amides, and isocyanic acid (HNCO). *248th ACS National Meeting & Exposition: Chemistry & Global Stewardship*, San Francisco, CA, USA, 10-14 August.

Castaneda, C., Stevens, G. and Haese, R.R. (2014) Reactive barrier formation for CO_2 leakage mitigation. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Chaffee, A., Webley, P., Xiao, P., Singh, R., Shang, J., Maring, B., Danaci, D., Ntiamoah, A., Ling, J. and Tang, W. (2014) Overview of adsorption based CO_2 capture: 2010–2014. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Cook, P., Causebrook, R., Gale, J., Michel, K. and Watson, M. (2014). What have we learned from small-scale injection projects? *12th International Conference on Greenhouse Gas Control Technologies (GHGT12)*, Austin, TX, USA, 5-9 October.

da Silva, G. (2014) Oxidation of amines in the atmosphere: A theoretical examination of the role of unimolecular peroxyl radical reactions. *248th ACS National Meeting & Exposition: Chemistry & Global Stewardship*, San Francisco, CA, USA, 10-14 August.

Danaci, D., Singh, R. and Webley, P. (2014) Fluorination of FAU type zeolites for enhanced hydrophobicity. *6th International Federation of European Zeolite Associations (FEZA) Conference*, Leipzig, Germany, 8-11 September. (Poster presentation)

Danaci, D., Xiao, P., Singh, R., Shang, J. and Webley, P. (2014) An overview of the work undertaken on CO_2 separation from natural gas by the adsorbents team from 2010 to now. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Fu, Q., Kentish, S. and Qiao, G. (2014) The effect of soft nanoparticles morphologies on thin film composite membrane performance. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Grigorescu, M., Hodgkinson, J., Haese, R.R. and McKillop, M. (2014) Mineral character of sedimentary facies associations, Lower Jurassic, Surat Basin, Queensland. *Australian Earth Sciences Convention 2014*, Newcastle, NSW, Australia, 7-10 July.

Haese, R.R., Black, J., Kirste, D. and Singh, R. (2014) The Otway 2B extension test 1: differences in formation water quality related to CO_2 impurities. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Haese, R.R. and Watson, M. (2014) Comparison of the mineral trapping capacity in three reservoirs with variable mineral compositions under CO_2 saturated conditions. *12th International Conference on Greenhouse Gas Control Technologies (GHGT12)*, Austin, TX, USA, 5-9 October. (Poster presentation)

Haese, R.R. and Watson, M. (2014) Mineral trapping capacity in reservoirs with variable mineralogies: a mass balance approach. *Australian Earth Sciences Convention 2014*, Newcastle, NSW, Australia, 7-10 July.

Harkin, T., **Qader, A.**, Indrawan, I., Gouw, J., Rabindran, A., Xiao, G., Anderson, C.,

Pandit, J.K., Ho, M., Smith, K., Mumford, K., Lee, A., Nicholas, N., Hooper, B., Stevens, G. and Wiley, D. (2014) Outcomes from the UNO MK 3 power station pilot plant trials. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

He, Y., Shang, J., Gu, Q., Singh, R., Xiao, P., and Webley, P. (2014) Tuning of porosity on a metal-organic compound: synthesis, structure and gas adsorption properties. *International Symposium NANOPOROUS MATERIALS-7*, Niagara Falls, Canada, 22-25 June.

Horner, K. and Haese, R.R. (2014) Characterisation of potential CO_2-water-rock dynamics during geological sequestration in a low salinity, silicate reservoir system. *Australian Earth Sciences Convention 2014*, Newcastle, NSW, Australia, 7-10 July.

Kanehashi, S. (2014) Development of polymer composite membranes for carbon dioxide capture. *6th HOPE Meeting with Nobel Laureates*, Tokyo, Japan, 10-15 March.

Kanehashi, S., Chen, G., Miyakoshi, T., and Kentish, S. (2014) Pure and mixed gas permeation properties of mixed matrix membranes. *10th International Congress on Membranes and Membrane Processes*, Suzhou, China, 20-25 July.

Kanehashi, S. and Kentish, S. (2014) Water impact on CO_2 separation performance in mixed matrix membranes. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Kentish, S. (2014) Carbon Capture research within the Peter Cook Centre - An overview of recent results. *National CCS Conference – CCS in Action: Today, Tomorrow & Beyond*, Sydney, NSW, Australia, 31 August-3 September. (Invited speaker)

Kentish, S., Stevens, G and Scholes, C. (2014) The use of gas separation membranes in carbon dioxide capture. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Kim, J., Fu, Q., Kentish, S. and Qiao, G., (2014) Development of CO_2 selective ultra-thin TFC membranes via CAP nanotechnology for industrial use. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Kim, J., Fu, Q., Kentish, S. and Qiao, G. (2014) High performance PEG-based ultra-thin mixed matrix membranes for CO_2 separation. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Kirste, D., Haese, R.R., Boreham, C. and Schacht, U. (2014) Evolution of formation water chemistry and geochemical modelling of the CO2CRC Otway Site residual gas saturation test. *12th International Conference on Greenhouse Gas Control Technologies (GHGT12)*, Austin, TX, USA, 5-9 October. (Poster presentation)

Kirste, D., Haese, R.R., Pearce, J., Golding, S. and Frank, A. (2014) Reactive transport modelling of CO_2 storage with co-contaminants. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Ling, J., Ntiamoah, A., Xiao, P., Webley, P. and Zhai, Y. (2014) Effects of operating parameters on VSA process for CO_2 capture. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Lu, H., Scholes, C., Chen, G., Kanehashi, S. and Kentish, S. (2014) The impact of water on the performance of cellulose acetate membrane for CO_2 separation. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Mu, A., Boreham, C., Leong, H., Haese, R.R. and Moreau J.W. (2014) Metagenomic study of microbial changes during supercritical CO_2 injection into a 1.4 km-deep sandstone aquifer. *15th International Symposium on Microbial Ecology (ISME15)*, Seoul, South Korea, 24 - 29 August.

Mirza, N., Nicholas, N. and Stevens, G. (2014) Estimation of critical properties of deep eutectic solvents. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Nicholas, N., Lee, A., Smith, K., Mumford, K., Thee, H., Endo, K., Indrawan, I., Gouw, J., Thanumurthy, N., Kromer, N., Wolf, M., da Silva, G., Kentish, S. and Stevens, G. (2014) Understanding and improving the K_2CO_3-CO_2 capture system. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Ntiamoah, A., Ling, J., Xiao, P. and Webley, P. (2014) CO_2 capture by temperature swing adsorption: experimental and simulation studies. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Ostertag-Henning, C., Risse, A., Thomas, B., Rosenbauer, R., Rochelle, C., Purser, G., Kilpatrick, A., Rosenqvist, J., Yardley, B. Karamalidis, A., Griffith, C., Hedges, S., Dilmore, R., Goodman, A., Black, J., Haese, R.R., Deusner, C., Bigalke, N., Haeckel, M., Fischer, S., Liebscher, A., Icenhower, J.P., Daval, D., Saldi, Knauss, K.G., Schmidt, M., Mito, S., Sorai, M. and Truche, L. (2014) GaMin'11 – an international inter-laboratory comparison for geochemical CO2 - saline fluid - mineral interaction experiments. *12th International Conference on Greenhouse Gas Control Technologies (GHGT12)*, Austin, TX, USA, 5-9 October.

Qiao, G. (2014) Game-change thinking in new gas membrane design and fabrication. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Qiao, G.G. (2014) An update on nano-engineered thin films via the continuous assembly of polymers (CAP) process. *2014 IUPAC World Polymer Congress (MACRO 2014)*, Chiang Mai, Thailand, 6-11 July.

Rémy, T., Danaci, D., Peter, S.A., Van Tendeloo, L., Couck, S., Shang, J., Kirschhock, C.E.A., Martens, J.A., **Baron, G.**, Webley, P.A. and Denayer, J. (2014) Separation of carbon dioxide and methane over Rb- and Cs-ZK-5 zeolites. *AIChE 2014 Annual Meeting*, Atlanta, GA, USA, 16-21 November.

Scholes, C. (2014) 'To infinity and beyond' with membrane gas separation. *4th*

Membrane Society of Australasia Early Career Researcher Symposium, Geelong, VIC, Australia, 19-21 November.

Scholes, C.A., Stevens, G.W. and Kentish, S.E. (2014) Performance of perfluoropolymers membranes for CO_2 separation in the presence of water and hydrocarbon vapours. *10th International Congress on Membranes and Membrane Processes*, Suzhou, China, 20-25 July.

Scholes, C., Stevens, G and Kentish, S. (2014) Revolutionising solvent absorption through membranes. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Scofield, J.M.P. (2014) High performance thin-film composite membranes based on amphiphilic block copolymers. *2014 AIE National Postgraduate Student Energy Awards* in conjunction with *All-Energy Conference & Exhibition*, Melbourne, VIC, Australia, 15-16 October. (Poster presentation)

Scofield, J., Gurr, P., Kentish, S. and Qiao, G. (2014) High permeance PEG-fluorinated based block polymer for enhanced CO_2 gas separation membranes. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Scofield, J., Fu, Q., Gurr, P., Kentish, S. and Qiao, G. (2014) The effect of selective layer morphology and structure on membrane gas permselectivity: a review. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Scofield, J.M.P., Gurr, P.A., Kentish, S.E. and Qiao, G.G. (2014) Thin-film composite membranes based on amphiphilic block copolymers. *10th International Congress on Membranes and Membrane Processes*, Suzhou, China, 20-25 July.

Shang, J., Li, G., Danaci, D., He, Y., Xiao, P., Singh, R., Liu, Z. and Webley, P. (2014) Revisiting the molecular sieving mechanism on Zeolite A for $CO_2/N_2/CH_4$ separation: the influence of presorbed species. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Smith, K., Indrawan, I., Gouw, J., Thanumurthy, N., Mumford, K., Xiao, G., Rabindran, A., Harkin, T., Anderson, C., Lee, A., Nicholas, N., Li, S., Temple, N., Qader, A., Hooper, B., Kentish, S. and Stevens, G. (2014) Pilot plant trials for CO_2 absorption using K_2CO_3 solvent. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Stevens, G., Smith, K., Nicholas, N., Lee, A., Mumford, K., Thee, H., Endo, K., Indrawan, I., Gouw, J., Thanumurthy, N., Kromer, N., Wolf, M., da Silva, G., Xiao, G., Rabindran, A., Harkin, T., Anderson, C., Li, S., Temple, N., Qader, A., Hooper, B., and Kentish, S. (2014) Post combustion capture of CO_2 using solvent based processes. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Stevens, G.W. (2014) CO_2 capture research in Australia, *Australian Academy of Technological Sciences and Engineering (ATSE) /Chinese Academy of Engineering (CAE) Low Emissions Fossil Fuels Workshop Workshop on Low Emissions Fossil Fuel*, Melbourne, VIC, Australia, 26 March.

Tang, W., Danaci, D., Singh, R. and Webley, P. (2014) Porphyrin-based polymers with improved oxygen selectivity for air separation applications. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Teh, N., Barifcani, A., Webley, P., Pack, D. and Tade, M. (2014) Optimisation of Vacuum Swing Adsorption (VSA)/ Cryogenic hybrid process for CO_2 capture and its design. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Vu, P.H., Mu, A. and Moreau, J.W. (2014) Biodegradation of thiocyanate by *Burkholderia* at neutral pH. *Australian Earth Sciences Convention 2014*, Newcastle, NSW, Australia, 7-10 July.

Wu, Y., Mumford, K., Smith, K., Nicholas, N. and Stevens, G. (2014) Rate based modelling of K_2CO_3 precipitating absorption columns in carbon capture. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November. (Poster presentation)

Xiao, P., Ntiamoah, A., Ling, J., Danaci, D., Shang, J., Singh, R. and Webley, P. (2014) CO_2 capture from flue gas streams by adsorption technology. *2014 CO2CRC Research Symposium*, Torquay, VIC, Australia, 25-26 November.

Invited Lectures and Seminars

Black, J.R. (2014) CO_2-water-rock interactions: How geochemistry affects the CO_2 storage potential of sedimentary basins. School of Earth Sciences Seminar, The University of Melbourne, Melbourne, VIC, Australia, 15 May.

Haese, R.R. (2014) Geochemical impacts and monitoring of CO_2 storage. ANLEC R&D Science Day, Sydney, NSW, Australia, 4 September.

Kentish, S.E. (2014) The Department of Chemical and Biomolecular Engineering, A Research Powerhouse, HRL Limited Seminar, Melbourne, VIC, Australia, 19 November.

Kentish, S.E. (2014) What is the role of fossil fuels into the future? IPCC Working Group III: What's in it for Australia, Public Lecture, Australian-German College of Climate & Energy Transitions, Melbourne, VIC, Australia, 8 May.

Mu, A. and Moreau J. W. (2014) Microbial responses to CO_2 injection. Seminar, Korean Institute of Geoscience and Mineral Resources, Dajeon, South Korea, 4 September.

Scofield, J.M.P., Gurr, P.A., Kentish, S.E. and Qiao, G.G. (2014) Thin-film composite membranes based on amphiphilic block copolymers, Myeongji University, Yeongin, South Korea, 28 July.

Scofield, J.M.P., Gurr, P.A., Kentish, S.E. and Qiao, G.G. (2014) Thin-film composite membranes based on amphiphilic block copolymers, Hanyang University, Seoul, South Korea, 29 July.

Smith, K.H., Thanumurthy, N., Indrawan, Temple, N., Mumford, K.A., Li, S., Lee, A., Nicholas, N., Anderson, C., Hooper, B., Kentish, S.E. and **Stevens, G.W.** (2014) Demonstration of a promoted precipitating potassium carbonate solvent absorption process for CO_2 capture, Research and Development Department, Qingdao Institute of BioEnergy and Bioprocess Technology (QIBEBT), Chinese Academy of Sciences, Qingdao, China, 21 October.

Stevens, G.W. (2014) Global warming, greenhouse gases, energy usage and separations technology. School of Chemical Engineering, University of Adelaide, Adelaide, SA, Australia, 14 March.

Professor Ralf Haese at the CO2CRC Otway Project, south-western Victoria.

Publications

Edited Book

Cook, P. J. (2014) *Geologically storing carbon: Learning from the Otway project experience*. CSIRO Publishing, Collingwood, VIC (ISBN: 9781486302307).

Book Chapter

Wiley, D.E.; Kentish, S.E.; Fimbres Weihs, G.A.; Ho, M.T. and Neal, P.R. (2014) Well to wheels environmental considerations. In Clark, R.; Thomson, M. (eds.), *Transport Fuels from Australia's Gas Resources: Advancing the nation's energy security.* UNSW Press, Sydney, Australia, pp. 162 – 206.

Refereed Journal Articles

Anderson, C., Hooper, B., Qader, A., Harkin, T., Smith, K., Mumford, K., Pandit, J., Ho, M., Lee, A., Nicholas, N., Indrawan, I., Guow, J., Xiao, G., Thanumurthy, N., Temple, N., Stevens, G. and Wiley, D. (2014) Recent developments in the UNO MK 3 process – A low cost environmentally benign precipitating solvent process for CO_2 capture. *Energy Procedia,* **63,** 1773-1780.

Azher, H., Scholes, C.A., Stevens, G.W. and Kentish, S.E. (2014) Water permeation and sorption properties of Nafion 115 at elevated temperatures. *Journal of Membrane Science,* **459,** 104-113.

Berean, K., Ou, J.Z., Nour, M., Latham, K., McSweeney, C., Paull, D., Halim, A., Kentish, S., Doherty, C.M., Hill, A.J. *et al.* (2014) The effect of crosslinking temperature on the permeability of PDMS membranes: Evidence of extraordinary CO_2 and CH_4 gas permeation. *Separation and Purification Technology,* **122,** 96-104.

Black, J.R. and Haese, R.R. (2014) Batch Reactor experimental Results for GaMin'11: Reactivity of Siderite/Ankerite, Labradorite, Illite and Chlorite Under CO2 Saturated Conditions. *Energy Procedia,* **63,** 5443-5449.

Black, J.R. and Haese, R.R. (2014) Chlorite dissolution rates under CO_2 saturated conditions from 50 to 120 °C and 120 to 200 bar CO_2. *Geochimica Et Cosmochimica Acta,* **125,** 225-240.

Cook, P., Causebrook, R., Gale, J., Michel, K. and Watson, M. (2014) What have we learned from small-scale injection projects? *Energy Procedia,* **63,** 6129-6140.

Fong, J.C.L.Y., Anderson, C., Hooper, B., Xiao, G., Webley, P.A., Hoadley, A. (2014) Multi-objective optimisation of hybrid CO_2 capture processes using exergy analysis. *Chemical Engineering Transactions*, **39,** 1501-1506. DOI:10.3303/CET1439251

Fu, Q., Wong, E.H.H., Kim, J., Scofield, J.M.P., Gurr, P.A., Kentish, S.E. and Qiao, G.G. (2014) The effect of soft nanoparticle morphologies on thin film composite membrane performance. *Journal of Materials Chemistry A,* **2,** 17751-17756.

Gurr, P.A., Scofield, J.M.P., Kim, J., Fu, Q., Kentish, S.E. and Qiao, G.G. (2014) Polyimide polydimethylsiloxane triblock copolymers for thin film composite gas separation membranes. *Journal of Polymer Science Part A-Polymer Chemistry,* **52,** 3372-3382.

Haese, R.R. and Watson, M. (2014) Comparison of the Mineral Trapping Capacity in three Reservoirs with Variable Mineral Compositions under CO2 Saturated Conditions. *Energy Procedia,* **63,** 5479-5482.

Halim, A., Fu, Q., Yong, Q., Gurr, P.A., Kentish, S.E. and Qiao, G.G. (2014) Soft polymeric nanoparticle additives for next generation gas separation membranes. *Journal of Materials Chemistry A,* **2,** 4999-5009.

Halim, A., Reid, T.D., Ren, J.M., Fu, Q., Gurr, P.A., Blencowe, A., Kentish, S.E. and Qiao, G.G. (2014) Soft nanoparticles assembled from linear poly(ethylene glycol) and linear brush polydimethylsiloxane diblock copolymers. *Journal of Polymer Science Part A-Polymer Chemistry,* **52,** 1251-1262.

Kirste, D., Haese, R., Boreham, C. and Schacht, U. (2014) Evolution of formation water chemistry and geochemical modelling of the CO2CRC Otway Site residual gas saturation test. *Energy Procedia,* **63,** 2894-2902.

Li, G., Xiao, P., Zhang, J., Webley, P.A. and Xu, D. (2014) The role of water on postcombustion CO_2 capture by vacuum swing adsorption: Bed layering and purge to feed ratio. *AIChE Journal,* **60,** 673-689.

Li, S., Jin, H.G., Gao, L., Mumford, K.A., Smith, K. and Stevens, G. (2014) Energy and exergy analyses of an integrated gasification combined cycle power plant with CO_2 capture using hot potassium carbonate solvent. *Environmental Science & Technology,* **48,** 14814-14821.

Lim, J., Scholes, C.A., Dumee, L.F. and Kentish, S.E. (2014) Nanofiltration for the concentration of heat stable salts prior to MEA reclamation. *International Journal of Greenhouse Gas Control,* **30,** 34-41.

Mu, A., Boreham, C., Leong, H.X., Haese, R.R. and Moreau, J.W. (2014) Changes in the deep subsurface microbial biosphere resulting from a field-scale CO_2 geosequestration experiment. *Frontiers in Microbiology,* **5**.

Nicholas, N.J., da Silva, G., Kentish, S. and Stevens, G.W. (2014) Use of vanadium(V) oxide as a catalyst for CO_2 hydration in potassium carbonate systems. *Industrial & Engineering Chemistry Research,* **53,** 3029-3039.

Ostertag, H., Risse, A., Thomas, B., Rosenbauer, R., Rochelle, C., Purser, G., Kilpatrick, Rosenqvist, J., Yardley, B., Karamalidis, A. *et al.* (2014) GaMin'11 – an International Inter-laboratory Comparison for Geochemical CO2 - Saline Fluid - Mineral Interaction Experiments. *Energy Procedia,* **63,** 5538-5543.

Pasquier, L.C., Mercier, G., Blais, J.F., Cecchi, E. and Kentish, S. (2014) Parameters optimization for direct flue gas CO_2 capture and sequestration by aqueous mineral carbonation using activated serpentinite based mining residue. *Applied Geochemistry,* **50,** 66-73.

PhD student Nouman Rafique Mirza

Pasquier, L.C., Mercier, G., Blais, J.F., Cecchi, E. and Kentish, S. (2014) Reaction mechanism for the aqueous-phase mineral carbonation of heat-activated serpentine at low temperatures and pressures in flue gas conditions. *Environmental Science & Technology,* **48,** 5163-5170.

Remy, T., Gobechiya, E., Danaci, D., Peter, S. A., Xiao, P., Van Tendeloo, L., Couck, S., Shang, J., Kirschhock, C. E. A., Singh, R. K., Martens, J. A., Baron, G. V., Webley, P. A. and Denayer, J. F. M. (2014) Biogas upgrading through kinetic separation of carbon dioxide and methane over Rb- and Cs-ZK-5 zeolites. *RSC Advances,* **4,** 62511-62524.

Scholes, C.A., Freeman, B.D. and Kentish, S.E. (2014) Water vapor permeability and competitive sorption in thermally rearranged (TR) membranes. *Journal of Membrane Science,* **470,** 132-137.

Scholes, C.A., Ho, M.T., Aguiar, A.A., Wiley, D.E., Stevens, G.W. and Kentish, S.E. (2014) Membrane gas separation processes for CO_2 capture from cement kiln flue gas. *International Journal of Greenhouse Gas Control,* **24,** 78-86.

Scholes, C.A., Motuzas, J., Smart, S. and Kentish, S.E. (2014) Membrane adhesives. *Industrial & Engineering Chemistry Research,* **53,** 9523-9533.

Scholes, C.A., Qader, A., Stevens, G.W. and Kentish, S.E. (2014) Membrane gas-solvent contactor pilot plant trials of CO_2 absorption from flue gas. *Separation Science and Technology,* **49,** 2449-2458.

Scholes, C.A., Ribeiro, C.P., Kentish, S.E. and Freeman, B.D. (2014) Thermal rearranged poly(benzoxazole)/polyimide blended membranes for CO_2 separation. *Separation and Purification Technology,* **124,** 134-140.

Scholes, C.A., Ribeiro, C.P., Kentish, S.E. and Freeman, B.D. (2014) Thermal rearranged poly(benzoxazole-co-imide) membranes for CO_2 separation. *Journal of Membrane Science,* **450,** 72-80.

Shang, J., Li, G., Singh, R., Xiao, P., Danaci, D., Liu, J.Z. and Webley, P.A. (2014) Adsorption of CO_2, N_2, and CH_4 in Cs-exchanged chabazite: A combination of van der Waals density functional theory calculations and experiment study. *The Journal of Chemical Physics,* **140,** 084705.

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Financial Summary

2014 Calendar Year Actual Income and Expenditure

	CCS Research Projects (includes government research grants, CO2CRC, ANLEC and BCIA funding)		Peter Cook Centre Stakeholder Support (DSDBI, CO2CRC, UoM, Rio Tinto)	Education Investment Fund (EIF; Research Infrastructure)	The University of Melbourne extra contribution (PhD Stipends)	TOTAL
	Cash	In-Kind				
Storage Program Income	$88,968	$248,260	$455,726	$1,342,734	$0	$2,135,688
Storage Program Expenditure	$162,306	$248,260	$217,041	$682,502	$0	$1,310,109
Net Surplus/ (Deficit) Storage	**($73,338)**	**$0**	**$238,685**	**$660,232**	**$0**	**$825,579**
Capture Program Income	$1,912,097	$613,071	$0	$2,493,987	$30,875	$5,050,030
Capture Program Expenditure	$1,503,845	$613,071	$0	$256,975	$30,875	$2,404,766
Net Surplus/ (Deficit) Capture	**$408,252**	**$0**	**$0**	**$2,237,012**	**$0**	**$2,645,264**
Centre Operations Income	$0	$0	$997,460	$0	$0	$997,460
Centre Operations Expenditure	$0	$0	$468,819	$0	$0	$468,819
Net Surplus/ (Deficit) Centre Operations	**$0**	**$0**	**$528,641**	**$0**	**$0**	**$528,641**

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